SUBSTATION PLANT AND EQUIPMENT

A Survey of the Practice and Principles
of Modern Substation Engineering
with particular Reference to
Recent Developments

By
CHARLES H. PIKE
Stations Department, Central London Electricity, Ltd.

WITH 212 ILLUSTRATIONS

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PREFACE

NOWADAYS substations are vital links in the chain of circuits along which electrical energy is transferred from the generating stations to the machines and apparatus in which it is utilised to produce other forms of energy.

In the early days of electricity supply—when energy was used for lighting only—distribution was effected from small generating stations equipped with steam-engine-driven dynamos. At a later stage high-voltage generation and transmission of A.C. were inaugurated—largely as the result of the genius of Ferranti—and transforming stations subsidiary to the generating stations became necessary for the L.V. A.C. distribution which was developed concurrently—but to a limited extent. When the practicability and the advantages of high-voltage generation and transmission had been firmly established new generating stations equipped with steam turbo-alternators were commissioned ; but many of the D.C. stations continued to operate for a long time after this, until over a period of years they were gradually superseded by substations taking a high-voltage bulk supply from the, then, large and efficient major generating stations. The substations were usually equipped with A.C.–D.C. conversion plant so as to permit utilisation of the existing L.V. D.C. networks whenever practicable. Some undertakings adopted A.C. distribution when extensions were necessary and then, at a later date, proceeded to change over the entire D.C. system, or the greater part of it, to A.C. working. At the present time many undertakings supply both A.C. and D.C. ; although generally the A.C. load predominates, consequently substations are often equipped with plant for both H.V. A.C. and L.V. D.C. distribution. The development of the National Grid System resulted in the small and inefficient generating stations being shut down and their supply areas fed from main substations connected to the national transmission network interconnecting the generating stations selected for operation. Prior to the Grid a few power companies were already operating extensive transmission networks each separately supplied from a number of generating stations running in parallel and employing transmission substations for stepping-up the generated voltage or stepping-down the transmission voltage. Converting stations taking a high-voltage supply and feeding the D.C. conducting systems of traction undertakings were in operation in the early part of the century ; since then the number of such substations has, of course, increased considerably. Present practice favours exclusively the use of D.C. for traction service.

At one time the energy requirements of industrial and other large consumers were met by giving supplies from the L.V. networks; or sometimes the consumer operated a relatively small generating plant; but with the increasing use of electricity for a greater variety of purposes many industrial plants had to be given a H.V. bulk supply, in some cases to supplement or replace the output of their own generators. To-day a number of industrial concerns operate privately modern H.V. generating stations and supply systems; but generally a bulk supply of energy is transformed in a main substation and distributed either at low voltage, or at high voltage to a number of works substations. Converting stations are also frequently required for industrial purposes.

Since each substation is designed for a specific purpose, and in accordance with its electrical position in a particular power system, to meet the various requirements of the several classes of service, an extensive variety of equipment is employed.

The aim of this book is to give an account of modern substation engineering which is sufficiently theoretical to appeal to those who are interested in the basic principles involved in the design, construction, and operation of the various units of equipment, but is at the same time practical. For this reason mathematics have been avoided as far as possible, but for a complete understanding of the book some knowledge of mathematical electrical theory is essential. Elementary principles are restated whenever this has been considered necessary, and in connection with circuit-breaking and mercury-arc rectifiers some reference to the contemporary theory of conduction in gases and liquids was unavoidable.

The scheme of the book is to first deal with substations generally—in the introductory survey—mentioning certain subjects which are discussed at greater length later, and indicating some of the distinctive features of each class of substation. Then in the first chapter the operation of modern power systems is discussed, with special reference to the control of the voltage, magnitude, and direction of the A.C. energy flowing in the circuits, in order to demonstrate some of the factors deciding the operational characteristics of certain units of substation equipment, and also as a matter of general interest. Each subsequent chapter deals with a particular class of equipment—or some aspect of it. Actually, the book consists of a collection of what may be termed technical essays.

Since in one volume it is impossible to give an exhaustive account of all the equipment used in substations, the subject-matter and the illustrations have been selected with the idea of giving information about the more recent developments and not with the intention of compiling a complete theoretical and practical treatise on substation engineering. For this reason it may be found that the treatment is somewhat uneven as the result of excluding information that is already available in numerous excellent textbooks, or is not required by those actively engaged in the operation, installation, and maintenance of substation equipment.

In several instances certain subjects, or units of equipment, have been discussed and illustrated in two or more chapters from more or less different aspects ; but all information on a particular subject can be found by reference to the index.

Certain information has been included by kind permission of the Institution of Electrical Engineers. Further acknowledgment of this valuable assistance will be found under the illustrations which are referred to in the relevant text.

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SUBSTATION PLANT AND EQUIPMENT

Chapter I

INTRODUCTORY SURVEY

FOR economic reasons electrical energy is generated, transmitted, and distributed at the highest voltages practicable—the higher the voltage the smaller is the cross-section of the conductors required to convey a given amount of energy, and the losses are lower. There are, however, other considerations involved—such as first cost and expediency. The higher the voltage the greater is the cost of insulating the circuits and associated equipment ; additional stages of transformation may be necessary, and there is the all-important consideration of danger to human life. In practice, the voltage employed for a specific purpose is such as will best satisfy both technical and economic requirements, with due regard to the other factors which may have to be taken into account. Among these may be mentioned the necessity to reduce the size and number of cables in congested city streets and the limitation of fault current.

Fault Current Limitation

With the growth and interconnection of power systems the short-circuit currents to be dealt with by the switchgear at various parts of the system must be limited, otherwise the cost of the equipment would be uneconomic. In other words, the cost of switchgear capable of interrupting the maximum short-circuit current without undue risk of fire and explosion would constitute a disproportionate share of the capital cost of a power system. By adopting the highest voltages practicable the short-circuit current for the same kVA. interrupted is effectively limited, and, moreover, the additional stages of transformation which may be required also serve to increase the impedance of the system. The total impedance between a fault and the source of energy, i.e. the combined impedance of all the alternators, transformers, and circuits through which current flows into the fault, plus the impedance of the fault itself, is the factor ultimately deciding the value of the kVA. to be interrupted by the switchgear, or in some cases the fuses, controlling the supply circuits.

A fault close to a generating station results in a certain amount of voltage decrement, but at the more remote parts of the system the drop in generating voltage, if any, is not sufficient to produce any appreciable easement of circuit-breaking conditions.

The present tendency is towards the use of far higher voltages for transmission and H.V. distribution than were considered necessary or practicable some years ago. The highest voltage in use for transmission is 287 kV.—that of the Boulder Dam-Los Angeles overhead line ; and in Paris a 220 kV. single-core oil-filled cable installation has been working satisfactorily for some years.

Standard Voltages

In this country the standard A.C. voltages used (apart from other non-standard voltages) are :

(*a*) Generation : 6·6, 11, 22, and 33 kV.

(*b*) Transmission : 132, 66, 33, 22, and 11 kV. With large power systems the first two are often used for primary transmission and 33, 22, and 11 kV. for secondary transmission.

(*c*) H.V. distribution : 11 and 6·6 kV.

(*d*) L.V. distribution : 400 v. between phases, 230 v. to neutral.

D.C. voltages of about 230, 460, 650, and 1,500 volts are also in use, the last two being generally employed for traction systems. The voltages standardised are, all things considered, those most practicable for the conveyance of energy along the circuits of the particular section of a power system for which they are used, as indicated above. In general, the voltage or voltages employed for a circuit or a group of circuits (in short, a network) depends on either or both the distance the energy has to be conveyed, and its bulk.

Since each range of voltages has a distinct field of application all power systems generating at high voltage and distributing at a lower voltage consist of at least two networks, and large systems of several. Consequently, at points where energy is transferred from one network to another these are linked together by transformer substations which, apart from effecting the necessary change of voltage, also function as centres for controlling, in some way, the energy passing through them. When the energy is to be utilised as D.C. convertor or rectifier substations are required.

Classes of Substations

Substations may be classified according to the purpose for which they are used. In practice some substations are equipped for more than one purpose, but it is convenient to classify them as :

(1) Transformer stations for :

(*a*) Stepping-up the generated voltage to that of the transmission network.

(*b*) Stepping-down the primary transmission voltage to that of the secondary transmission network.

(*c*) Stepping-down the transmission voltage to that of the H.V. distribution network.

(*d*) Stepping-down the H.V. distribution voltage to that of the L.V. distribution network.

(2) Convertor or rectifier stations for :

(*e*) D.C. power and lighting.

(*f*) D.C. traction.

In addition there are substations—such as switching stations—which do not come into one of the above classes.

All A.C. substations are equipped with at least one or more transformers, some form of switch- or fusegear for controlling the incoming and/or the outgoing circuits, and a certain amount of ancillary gear. The extent and character of this, and the capacity, form, and detail of the main equipment, are, in general, determined by the duty for which the latter is designed. Thus, the equipment of each class of substation has certain more or less distinctive features.

Transmission Substations

Class (*a*) transmission substations are involved in the transfer of large blocks of energy from the busbars of the generating stations to the main transmission network, consequently the transformers are of high capacity. Units of 93,750 kVA. capacity are actually in use. For controlling the voltage, power factor, and loading of individual circuits the transformers are usually fitted with on-load tap-changing gear, or separate equipment may be used.

High-rupturing-capacity circuit-breakers are essential since the fault kVA. to be interrupted can reach extremely high values due to the proximity of the substation to one generating station and, generally, its interconnection with others via the transmission network. To ensure rapid fault clearance, and the minimum degree of disturbance to the system as a whole, the fault protection gear, initiating the tripping of the circuit-breakers, is of a high-speed type capable of exercising the maximum degree of discrimination.

The higher-voltage windings of the transformers are usually—in this country—connected either to the 132 kV. Grid or to a transmission network operated by a supply company or authority. Most generating stations are connected to both the Grid and a local transmission network, through separate substations. In some cases local transmission is effected at the generated voltage, otherwise step-up transformer substations are employed.

The primary transmission voltage is often stepped-down to that of a secondary transmission network for supplying main distribution substations in areas where it is not economical or expedient to transmit at the higher voltage on account of the low load density. In urban and industrial areas bulk supply is given to distribution undertakings—not operating generating stations—from the main transmission network through a step-down substation, which may be located adjacent to the main distribution station, or actually on the same site or in the same building. These arrangements reduce the length of the secondary transmission circuits to a minimum ; in fact, the secondaries of the transmission transformers and the primaries of the main distribution transformers are often connected to the same busbars.

Substations in classes (*a*) and (*b*) are generally similar as regards their equipment, which is generally located outdoors, as the high voltages involved do not favour indoor construction.

Switchgear is mostly of the open-type ; the O.C.B.'s are single-phase —three to each circuit—and isolation is effected by air-break switches mounted on a lattice structure, or on ferro-concrete supports. Metalclad gear is also used to a certain extent, especially for lower-voltage transmission circuits. At step-down transmission substations voltage control equipment is often used either for straight voltage regulation or load and power-factor control.

Main Distribution Substations

The equipment of main substations operated by distribution authorities depends largely on the nature of the area supplied in each case. In densely loaded city areas the total capacity of the transformers concentrated in a main substation may be in the region of 50,000 kVA., although the extent of the area covered by the H.V. distribution network is less than a square mile. City substations take a bulk supply from a transmission network which usually interconnects several generating stations, consequently this factor influences the type of switchgear and the layout adopted to meet the severe fault conditions which may arise. For this reason high-rupturing-capacity circuit-breakers are used, and complete metallic enclosure of the busbars, busbar selector switches, and other components is favoured so as to minimise the risk of fire and explosion. Moreover, metalclad switchgear occupies less space than any other form of H.V. switchgear of equal capacity ; this is an important consideration in city areas where space is limited and extensions have to be made to meet growing load demand. Generally the equipment of city substations will be of an indoor type. Voltage regulation of densely loaded networks is conveniently effected by means of on-load tap-changing transformers, or separate equipment, at the main distribution substation. In major substations with H.V. feeders to important industrial substations the switchgear layout and the type of fault protection employed will be such as should ensure a high degree of continuity of supply. For suburban and rural H.V. distribution the type of equipment used in the main substations will again depend on the nature of the area supplied.

In outlying suburban districts outdoor type transformers are often installed in compounds and the switchgear located in a small building. As the lengths of the H.V. feeders to the transformers supplying the L.V. networks are usually widely different, and their load currents unequal, voltage regulation is most effectively carried out by automatically controlled equipments located at strategic points of the network.

Suburban substations are frequently located at places sufficiently remote from the generating stations that the impedance of the transmission system is high enough to effectively limit the maximum possible value of the short-circuit kVA. which may have to be interrupted by the circuit-breakers. Consequently these are often of a different type from those adopted in substations where a higher value of short-circuit kVA. is available. Truck-type switchgear is often installed when circumstances favour its use. In most rural areas the whole system has to be designed with the object of keeping the distribution costs low ; in consequence main substations are often equipped with the simplest types of units and ancillary gear practicable. The transformers, higher- and lower-voltage switchgear may all be of the outdoor class, but sometimes it is more economic to use indoor lower-voltage switchgear since generally the short-circuit kVA. available is not excessive.

Industrial Substations for H.V. Distribution

Many industrial power systems are supplied from main distribution substations of capacities exceeding those of the substations operated by small distribution undertakings, and equipped to ensure the absolute maximum degree of security, since the effect of even a momentary interruption to supply, resulting in the stoppage of the industrial plant, may be very costly. Such stations incorporate the most reliable equipment obtainable, and in some cases a great variety of equipment is installed to meet special requirements. Often in large steel and similar works the H.V. feeders from the main substation supply H.V./L.V. transformer substations, convertor substations, and large H.V. motors for industrial drives. The switchgear required for a plant of this description usually includes units of several different types each of which is particularly suitable for a specific purpose.

Low-voltage A.C. Distribution Substations

Class (*d*) substations for stepping-down the H.V. distribution voltage for supplying L.V. networks may be equipped with one or more transformers, the total capacity of which may be anything from a few kVA. to several thousand kVA. Low-capacity substations are usually equipped with the simplest of switchgear or fusegear, or may be simply a pole-mounted transformer with a fuse and air-break isolating switch on the H.V. side and fuses on the L.V. side.

Large-capacity H.V./L.V. transformer substations are commonly employed in industrial plants where the load density is high due to local concentrations of motors and apparatus, or for supplying heavy current industrial equipment such as large electric furnaces. With these special voltage regulating equipment is fitted to the transformer, or separate regulators used, for current control. The L.V. distribution is usually effected by a considerable number of radial circuits to the various parts of the plant, as by this means a failure of any one circuit results in the least interruption of production. In consequence, a distinctive feature of many industrial substations is the comparatively large number of L.V. circuit-breakers installed to control the outgoing circuits. These are, of course, the main circuits supplying a number of branch circuits each of which is separately fused.

For public electricity supply the L.V. distribution substations consist of transformers and switch- or fusegear located in small buildings; chambers on consumers' premises; pavement pits; kiosks; and in suitable areas, either partially or wholly outdoors with suitable enclosure; or pole-mounted. In many cases the number of switch- or fusegear units installed is reduced to an absolute minimum to avoid unnecessary expense.

D.C. Substations

The three forms of conversion equipment used in substations associated with L.V. D.C. networks for public supply are: motor convertors, rotary convertors, and mercury-arc rectifiers. The A.C. stator of a motor-convertor is wound for direct connection to the high-voltage supply, but with rotaries and rectifiers step-down transformers are required to obtain the necessary low-voltage supply to the slip rings and the anodes respectively. Rectifiers are of either the glass-bulb or steel-tank type. At one time small capacity rectifiers were of the former type, as vacuum pumping equipment and mercury seals had to be used with the steel-tank type to prevent the ingress of air. In recent years pumpless steel-clad units for medium outputs have been developed, thus combining the advantageous features of both types.

For supplying three-wire networks motor and rotary convertors can be designed for dealing with the out-of-balance current—if it is not excessive—or separate equipment may be used. With rectifiers the latter is essential, unless a bank of two or three units is installed.

Some years ago it was common practice in D.C. substations to use large-capacity batteries of accumulators operating in conjunction with the conversion plant, but nowadays this is by no means standard practice, since in many cases, as the result of changing over to A.C., only a small D.C. load remains. This is generally due to the fact that it is considered more economic to continue supplying D.C. for certain classes of consumers' apparatus than to incur the cost of changing this over. When both D.C. and A.C. networks are supplied the conversion plant may be installed in the main distribution substation (which was probably a D.C. substation in the first place); or the demand for D.C. may be met by small rectifiers on consumers' premises.

Most of the D.C. distribution substations equipped in recent years are designed for automatic or remote control; in fact, as an alternative to changing over to A.C. distribution to meet growing load demand some distribution undertakings installed additional non-attended D.C. substations simply because it was becoming impossible to increase the capacity of the main substation or the outgoing feeders, and/or maintain the statutory voltage at all parts of the network.

For industrial plants D.C. substations are often essential. In addition to the three forms of conversion equipment already mentioned, these are frequently equipped with motor generators. All types of rotating conversion plant can be designed to operate with a leading power factor, so that, apart from their normal function, they can also be used to correct a lagging power factor resulting from the use of induction motors. This may be also corrected by banks of condensers; or synchronous motors.

The equipment of substations supplying D.C. traction systems has been developed along lines which permit of remote control from a central control room, this having been achieved with both rectifier and rotary substations. Present practice favours the installation of rectifiers, which have decided advantages. For traction service conversion equipment must be capable of withstanding heavy sustained overloads and excessive momentary overloads. D.C. circuit-breakers are designed for the rapid clearance of short-circuits on the conductor systems.

The type of high-voltage switchgear installed for controlling the incoming supply of D.C. substations is determined by much the same factors as apply in the case of A.C. substations, and the detail of the ancillary equipment depends largely on the character of the main equipment and the purpose for which it is used.

Chapter II

THE CONTROL OF ENERGY IN A.C. SYSTEMS

THE function of certain items of substation equipment, and the factors governing their design, are best understood by considering the operation of an electricity supply system as a whole. The efficient operation of an extensive system depends upon being able to control: the voltage of each network more or less independently; the division of load between generating stations running in parallel; the loading of individual transmission circuits; the maximum fault kVA.—this implies the limitation of fault current and the rapid disconnection of an electrically defective unit or circuit so as to interrupt the excessive flow of energy as quickly as possible.

Control of the energy in an A.C. system is effected primarily at the generating stations, but every substation on the system is also, in effect, a centre at which some degree of control is exercised over the energy passing through it. The nature of the control equipment installed depends on the purpose for which the substation is used; thus at those stations where the voltage of a network, or of individual circuits, is regulated the transformers may be fitted with on-load tap-changing gear, or separate regulators used for the purpose. Under modern conditions the most important item of control equipment is the switch- or fuse-gear, which must be capable of interrupting successfully the maximum fault kVA. which can flow through the circuit it controls, since a failure to do so will result in the disconnection of healthy units or circuits elsewhere, and in consequence create a widespread disturbance likely to produce interruptions of supply at various parts of the system. For this reason considerable attention has been devoted in recent years to the development of equipment for the control of the high values of fault current associated with present-day supply systems.

Voltage Control

Owing to the impedance of conducting systems there is a voltage-drop along the circuits. At the substations there are voltage-drops in the transformers additional to those in the circuits. The voltage available at any point of the system is, therefore, the generated voltage less the total IZ drop to that point. Consequently, with fluctuations in the load current, and changes in the impedance values of the networks arising from alterations in the number of transformers or circuits in operation, there would be a wide variation in the voltage of the energy delivered to consumers if the voltages were not regulated to meet changing conditions. Distribution undertakings have a statutory obligation to maintain the voltage of the energy they deliver within specified limits—plus or minus 6 per cent. of the declared voltage—so that at some point in the system the voltage must be controlled to meet this requirement.

When a system comprises a number of radial feeders of practically equal lengths, more or less evenly loaded and supplied from a single generating station, if the total voltage drop does not exceed, say, 20 per cent. of the busbar voltage, the L.V. network voltage can often be maintained satisfactorily by regulation at the generating station. With systems supplied from a number of generating stations running in parallel this is not practicable, since it is then necessary to operate the transmission network without reference to the maintenance of statutory voltage in the distribution networks. In practice, the voltage of the transmission network under particular load conditions may be exactly opposite to that required at the L.V. network under the same conditions ; that is to say, the transmission voltage may be high at low loads and low at heavy loads ; consequently, in most cases, the voltage of the distribution system has to be regulated independently, and over a range wide enough to allow the statutory voltage to be maintained irrespective of the bulk supply voltage. Actually, bulk suppliers are permitted a voltage variation of 12½ per cent. above a minimum, and within this limit the generating station voltages are regulated to meet operating requirements.

In this country most stations are connected to the Grid, and also to a local system, consequently voltage control has to be effected to meet the operating requirements of both systems ; and voltage regulating equipment may be installed in the transmission substations for the purpose of regulating the division of the total system load between generating stations and the transmission circuits, which are also used as interconnectors.

Interconnection of Power Systems

An interconnector is a circuit connecting two systems, generating stations, substations, or networks—not otherwise connected directly together—so that they can be operated in parallel and energy transferred from one to the other. Either can be used to supply a part of the load, or, in favourable circumstances, the entire load of the other, thus providing an alternative supply at some part of the system in the event of a failure of the normal source. Apart from the technical advantages certain financial benefits are obtained by interconnection of generating stations. Peak loads can be reduced, and plant load factors improved thereby, since heavy overloads can be distributed over the system, and the loads at the various power stations kept more constant. Small, relatively inefficient generating stations need only be operated during the hours of peak load, and by this means the large, more efficient stations can be operated at their maximum capacity more or less continuously. It is also possible for one station to deal with the whole of the wattless kVA. of the load, so that the stations supplying the true kW. will be operating with power factors in the neighbourhood of unity, and, therefore, under the most favourable conditions. In the case of a circuit connecting two D.C. generators in different stations, each of which is supplying an isolated network, energy can be transferred along the interconnecting circuit from one end to the other, and one generator relieved of load by the other, simply by adjusting the voltage of one or both generators so that there is a difference of voltage between the two ends of the interconnector. The transfer of A.C. energy into an interconnector is complicated by the inductance of the circuit ; a difference of voltage between the ends of the circuit will cause current to flow, but this will be lagging to some degree ; in other words, the kVA. transmitted will be at less than unity power factor, even if the power factor of the load is unity, because of the inductance of the circuit.

Consider, for example, a circuit connecting the secondaries of two identical transformers in different stations each supplying an equal load at the same power factor and voltage. In these circumstances no current will flow in the interconnector, since the voltages applied to both ends of the circuit are equal in magnitude and, let it be assumed, in phase with each other. If the secondary voltage of one transformer is adjusted there will be a difference between the applied voltages, consequently current will flow along the interconnector from the transformer with the higher voltage to the other ; but owing to the inductance of the circuit the current will be lagging with respect to the voltages at both the sending end and the receiving end of the interconnector. Thus the transformer at the sending end will export kVA. at a lagging power factor which will reduce the kVA. loading of the transformer at the receiving end. If, however, the value of the wattless current exported is greater than the wattless component of the load current supplied by the transformer at the receiving end, the surplus wattless current will flow around the circuit to no purpose. On the other hand, if the wattless current exported is equal to, or less than, the wattless component of the load current supplied by the transformer at the receiving end, this unit will be relieved of a certain amount of wattless load, and is therefore capable of a greater kW. output. The energy component of the kVA. exported also relieves the transformer at the receiving end of the interconnector of kW. loading ; so that it is clear that if the load on this unit increases beyond its capacity, the excessive kVA. can be imported from another transformer along the interconnector by voltage regulation. In practice the inductance of the circuit limits the amount of energy that can be transferred by in-phase voltage control as, although an interconnector can by this means be loaded to its full kVA. capacity, the energy component may be small and the wattless component excessive, so that the resultant circulating currents may increase the temperatures of the circuits and transformers to the full load limits, even though the kW. loadings are comparatively low.

For this reason more efficient loading of interconnectors can be obtained in some cases by phase-angle control. This is effected by adjusting the phase of the voltage applied to one end of the interconnector relative to the phase of the voltage applied to the other end. By this means, although the r.m.s. values of the voltages are the same, there will be difference in the instantaneous values of the voltages at every point of the cycle due to the fact that one lags with respect to the other. Thus, by advancing the phase of the voltage applied to one end of an interconnector current will flow, but due to the inductance of the circuit this will lag as before. Since, however, the voltage at the sending end leads the voltage at the receiving end the degree of lag between this and the current will be less than that between the voltage and the current at the sending end. The power factor of the kVA. received will, therefore, be higher than would be the case if the same kVA. were transmitted by in-phase voltage regulation.

The foregoing is a simple statement of a complex problem, which is also dealt with below in connection with the parallel operation of generating stations the voltages of which may also be controlled for the purpose of transferring energy along interconnectors, and thereby dividing the total load on the system so as to secure the efficient loading of individual stations and circuits. For controlling the voltage, power factor, and loading of each interconnector of an extensive system special equipment is installed in the step-up transmission substations. The necessity for such equipment will be understood by considering the problems associated with the operation of a large number of generating stations all feeding into a common network and usually also supplying local isolated networks.

An interconnector between two generating stations is, in effect, an extension of the busbars to enable the stations to operate in parallel, although complications arise on account of the inherent characteristics of the interconnecting circuit and the need to keep the busbar voltages at values to meet local requirements. Nevertheless, the fundamental principles involved in the parallel operation of two power stations are essentially the same as for two alternators in parallel, so that the latter problem will first be considered.

Parallel Operation of Generators

The electrical output of an alternator operating as an isolated unit is determined by the mechanical power developed by its prime-mover—usually a turbine. By increasing the excitation the voltage and the current increase, but as the mechanical power developed, with a fixed governor setting, remains practically the same the higher kVA. output is only available at a lower power factor. The power load can only be increased by adjusting the setting of the turbine governor at the same time as the voltage ; this must be raised to pick up more load to increase the retardation, due to the interaction between the stator flux, produced by the main current, and the rotor flux due to the D.C. field, so as to prevent the alternator speeding up with increase of torque. The speed of the alternator determines the frequency, consequently it must be kept reasonably constant. If the mechanical power developed by the turbine is increased, without increasing the excitation, the alternator will speed up until the generated voltage is raised—as the result of the higher speed—to a value sufficient to pick up more load so that the retardation balances the greater torque.

When two D.C. generators are operated in parallel any desired division of load is obtained by adjusting the excitation, since the current delivered by either machine is proportional to the difference between its E.M.F. and the terminal voltage, which is, of course, equal to the busbar voltage. Also, since the speeds of the two machines need not be identical, the governors of the prime-movers automatically take care of the change in load imposed by the new conditions of excitation.

With two alternators in parallel the speeds are of necessity identical (if the machines have an equal number of poles—otherwise the speeds must be such that each machine generates at the same frequency) and the division of the kW. is unrelated to the excitations (except in a minor degree), but is dependent on the amounts of steam admitted to the turbines. In other words, the required division of kW. loading is obtained by direct adjustment of the governor settings. In practice the governors of machines of equal capacity are given similar settings with the object of effecting an equal division of the total load under all conditions ; any increase of load automatically results in the admission of more steam to both turbines due to the momentary drop in speed actuating the governor mechanism ; which also reduces the quantity of steam when the speed tends to rise with a decrease of load. Since governor mechanisms always differ slightly, due to their inherent mechanical characteristics, the power developed by each turbine of a number in parallel will also differ slightly, consequently there will be a tendency for the units with the higher torque to increase their speed.

Considering two units ; the rotor of the one (A) which has the greater force applied to its shaft will tend, for an instant, to run faster than that of the other unit (B). This results in A's rotor taking up a position slightly in advance of B's so that A's voltage reaches its maximum value slightly before B's ; as shown in Fig. 1 (*a*), where the E.M.F. vector of B lags behind that of A. The phase difference between the two E.M.F.'s produces a resultant voltage V_{AB} which causes a current (*OS*) to

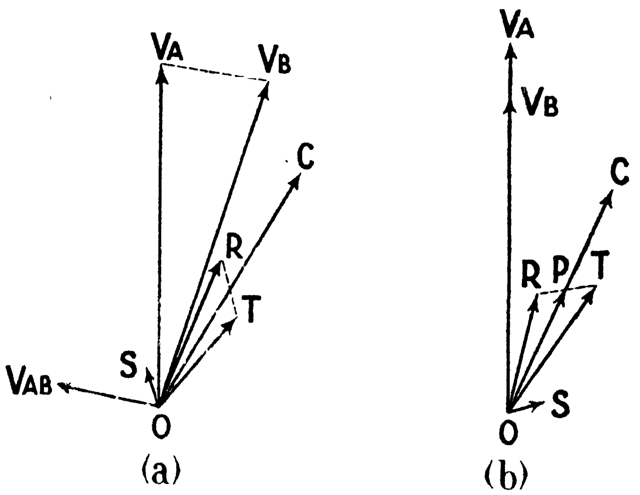


Fig. 1.—Vector diagrams of alternators in parallel

flow round the circuit formed by the two units in parallel. This current lags behind V_{AB} by nearly 90° and is, therefore, nearly in phase with the voltage of the leading unit A whose current becomes the sum of OS and $C/2 = OR$, assuming that each unit carries half the load initially, while the current in B becomes the difference of OS and $C/2$—that is, OT. Thus the lagging unit is relieved of part of its load, and there is also an alteration in the phase of the generated currents which generally favours the recovery of the lagging machine, although more so with leading than with lagging loads.

From the foregoing it is apparent that alternators, once they are paralleled, tend to share the load in proportion to the power outputs of their prime-movers, and also to maintain each other in step, at constant speed, by means of a circulating current flowing round the loop of the stator windings so that the leading machine gives out power which, except for resistance losses, is employed in motoring the lagging machine so as to equalise the torque on each rotor shaft.

When the load on each unit is almost equal there is no permanent phase difference between the E.M.F.'s as the rotors will oscillate slightly relative to each other, but when there is a considerable difference in the power developed by each turbine there will be phase difference corresponding to the division of load. If the generated voltages are different this causes a circulating current to flow round the machine windings (Fig. 1 (*b*)), so that the load on A becomes OT, which is greater, but more lagging that before, while B carries the load OR. The actual power loading of the units is unaltered but the machine whose excitation is increased carries more of the wattless load.

Division of Load between Interconnected Stations

Disregarding the impedance of the interconnecting circuit the above discussion applies equally to two separate power stations, and two approximate axioms can be stated : (*a*) For a power load to be transmitted a phase displacement must exist between the two ends of the line. (*b*) For a wattless load to be transmitted a voltage difference must exist between the ends of the line.

Considering the operation of two interconnected power stations, if these are equally loaded and there is no energy flowing in the interconnector, when it is required to change the division of load the steam supply to the turbines in one station is increased, and reduced in the other. The resulting phase displacement produces the voltage difference required between the ends of the circuit for the transfer of energy from the leading station to the lagging station. Again, a sudden increase of load on one station causes its voltage to lag, and energy is transferred along the interconnector. Oppositely, if the load on the station being assisted by the interconnection decreases, the angle between the voltages of the stations also decreases and less power will be transferred along the interconnector.

Thus, the two stations share the load in accordance with their governor characteristics, and the interconnector load adjusts itself to the steaming conditions. By adjusting the busbar volts, the station with the higher voltage can be made to carry more of the wattless load. Since the load on an interconnector is determined by steaming conditions it is apparent that any adjustment made to regulate one interconnector will also affect the loading of any others supplied from the same busbars ; the circuits supplying local load will not be affected—even if they are in the form of ring-mains—since they do not connect two separate sources of supply. Again, it is seldom practicable to control the power factor of the load on the interconnector by adjusting the station busbar voltages, consequently it is usual to provide apparatus for the independent control of the voltage in the interconnected circuit, so that the station voltages can be maintained at values to satisfy any local requirements. In the case of stations operating in parallel with more than one other station, apparatus may also be installed for phase-angle control of each interconnector to allow an independent adjustment of the load on each. Four classes of apparatus are used for voltage and/or phase-angle control : induction regulators, step-by-step boosters, on-load tap-changing transformers, moving coil regulators. The same four classes of apparatus are also used for normal regulation of distribution voltages.

Stability of A.C. Systems

The interconnection of large systems has brought into greater prominence problems of power limit and stability, which depend upon the combined characteristics of the generating plant, load, and interconnecting circuits. A system may be said to be stable if it is capable of maintaining constant load, or of sustaining a change in load under any practical condition of operation. This definition can be amplified for constant-voltage systems by stating that the voltage should remain substantially constant during normal operations, and should not be appreciably affected by changes in load or circuit conditions.

In practice small fluctuations in voltage, which do not affect the stable operation of a system, are experienced. A further qualification is required for A.C. systems with synchronous machines operating in parallel; the synchronous machines should remain in synchronism during normal operation, and, after any disturbance, should regain equilibrium and continue to run in synchronism. The principal types of disturbance which occur in a large supply system are load fluctuations, switching operations, and faults. A change in the load, or in the constants of the circuit, requires a corresponding change in the load angle between the machines.

The load angle is the angle between the centre line of the rotor (i.e. the axis of the rotor exciting coils) and the component of flux corresponding to the terminal voltage. In the case of an alternator the load angle arises as the result of the torque applied to the shaft by the turbine advancing the rotor from the true synchronous position, to a position determined by the load. Both the stator and rotor fields act as though they were rotating magnets, and the attractive force between the two fields tends to restore the rotor to the synchronous position. As the output is increased, at first, the restoring force becomes greater with greater displacement between the magnets, but later reaches a maximum, and diminishes as the distance between the magnets weakens their effect upon each other. At this stage the alternator would fall out of step with the other machines in parallel, and since the voltages would then be of opposite polarity, the unstable machine would be equivalent to a short-circuit on the busbars. Returning to the question of stability, with a change in load, or the constants of the circuit, the inertia of the rotors of the machines prevents the change in load angle taking place instantaneously, and as the new angle is approached, it also causes the rotors to overswing. The rotors oscillate about the new angle and finally regain equilibrium, provided that the first overswing does not cause the unstable load angle to be exceeded.

A switching operation may alter the characteristics of the circuit and, therefore, the load and the critical load angle. The equilibrium of the system is thus disturbed, and oscillations set up. If the unstable load angle is exceeded the system may fall out of step. In practice the turbine governor tends to prevent any change in speed; the speed variation on throwing off the maximum load is limited by the governor to a permanent value of about 3 or 4 per cent. above normal speed, but there is a temporary variation from 6 to 10 per cent. due to the normal delay in action of the governor.

Behaviour of Alternators under Fault Conditions

The effect of a fault upon the stability of the system depends upon whether the normal load on the alternator is raised or lowered. Short-circuits between lines will in general have a low resistance, while a single-phase short-circuit to earth may be of either high or low resistance. A low-resistance fault reduces the power transmitted to the system, while a high-resistance fault has the effect of increasing the load. If the power supplied by the turbine remains constant the additional load under the latter condition must be supplied from the stored mechanical energy of the system, and all synchronous machines (i.e. rotary convertors, etc.) may then act as generators. A three-phase short-circuit near the alternator is equivalent to opening the normal load circuit. When such a fault occurs the power transmitted may fall to zero. It may be of interest to consider what takes place when a number of alternators operating in parallel in the same station are subjected to a heavy short-circuit close to the station, and with no external reactance. Under these conditions the voltage at the alternator terminals will be reduced to practically zero as all the machines will be feeding into the fault, and their E.M.F.'s will be entirely expended in circulating the fault current around the local circuit formed by the stator windings, the busbars, and the short-circuit.

The current flowing at any instant during the period of short-circuit depends, therefore, on the impedance of the circuit and the E.M.F. available. The effect of the short-circuit current is to reduce the E.M.F. rapidly, so that by the time the switch has cleared the fault the recovery voltage may be practically zero and the synchronising torque of the alternators will have disappeared. During the first period of the short-circuit the speed of all the machines will fall because the turbines are quite unable to provide the excessive energy required to maintain the current at its initial value. As the short-circuit current falls, the energy required will be reduced very rapidly, and the turbines may actually speed up during the latter portion of the short-circuit unless the fault is cleared very quickly.

Factors affecting Transient Stability

If the sets are identical as regards inertia they may fall or rise in speed equally, but if they are of different sizes the change in speed will not be the same. When there are synchronous machines running on the system the conditions are further complicated as the inertia of these machines causes them to act as generators for a short period, and feed into the short-circuit. They may also fall out of step owing to lack of synchronising torque. When the short-circuit is interrupted by the operation of the circuit-breaker the turbo-alternator will accelerate, but not necessarily at the same rate even if the sets are identical, for the rate of acceleration will depend on the characteristics of the respective governors. It is probable that the various machines will be far out of phase, if not fully out of synchronism.

After the fault has been cleared, whether normal running will be resumed automatically by the alternators coming into step again depends on (*a*) the amount of the phase displacement between the machines, (*b*) the recovery voltage, i.e. the alternator E.M.F. immediately after the short-circuit has been cleared. The phase displacement cannot be controlled, but it is possible to influence the recovery voltage by rapid automatic voltage regulation in conjunction with exciters capable of a high rate of response to an increase in their field current, so that the alternator voltage rises rapidly to a value sufficient to improve the synchronising torque.

The effect of automatic voltage regulation is, of course, limited according to the magnitude of the short-circuit current, as it is not practicable to provide exciters to deal with very heavy currents since these would be of very large size.

Effect of Synchronous Plant

If the voltage of the alternators, at the instant of fault clearance, is at such a value that the torque is sufficient to keep them in step, a considerable amount of swinging or surging will probably take place before they finally remain in step. Here, again, if there is synchronous plant running on the system a further factor comes into play, and if such plant forms a big percentage of the load it may cause a shutdown due to the generators being out of step with the synchronous plant, although in step between themselves.

This condition is not, however, very likely to occur, as there are few cases where the amount of synchronous plant is sufficient relative to the capacity of the system. Should the alternators have fallen out of step with each other either during the short-circuit or after its removal, i.e. when the machines are accelerating, it is uncertain whether they will pull into step again. If the difference in speed is small they will probably resynchronise, but with a large difference in speed they will not synchronise, and it will then be necessary to disconnect the machines from the busbars and synchronise them again.

Stations Operating in Parallel

So far only a single station operating on its own network has been considered. When there are two or more stations operating in parallel the conditions are more complicated. First, it is most unlikely that the units in the various stations are similar, and their inertias will therefore be different. (The inertia of each unit is, of course, the combined values of turbine and alternator.) Secondly, the governor characteristics will probably be different, and lastly the interconnecting lines affect the synchronising torque between the various stations in a way which reduces the torque available. For a given phase difference between two stations a greater terminal voltage is required to produce the necessary synchronising torque, as compared with generators in the same station, because of the impedance of the interconnecting circuit.

In the foregoing discussion of transient stability the short-circuit conditions assumed are the most severe that can occur. Actually much depends on the character of the fault and its position on the system in terms of impedance ohms. If the short-circuit is some distance from the generating station, then the current will be limited not only by the impedance of the alternators, but by the additional impedance of the conductors, transformers, and other apparatus between the station and the fault. Modern alternators have sufficient reactance to safeguard them even in the event of a dead short-circuit at the terminals. With very extensive systems it is usual to increase the total impedance of the system by the inclusion of reactors at strategic points.

Dissipation of Fault Energy by Circuit-breakers

Apart from the question of stability it is essential to limit the fault currents so as to restrict the mechanical and thermal stresses associated with the flow of current through conductors. A complementary factor is, therefore, the time taken to clear the fault, hence the need for high-speed protective gear in conjunction with quick-acting circuit-breakers for preventing the maintenance of a condition of excessive energy flow leading to both destructive stresses and instability. The circuit-breaker is, in effect, the means of dissipating the excessive energy resulting from a fault.

Circuit-breaker Requirements

Under modern conditions some oil circuit-breakers are required to clear circuits in which the fault energy is as much as 1,500,000 kVA. This means that approximately 69,000,000,000 ft.-lb. of energy must be dissipated at the switch contacts in a fraction of a second. The requirements of an efficient circuit-breaker are that it shall carry the normal rated current continuously without undue heating, repeatedly make and break all currents up to a specified value, and withstand the mechanical and thermal stresses associated with these currents without distress, or dangerous rise in temperature. Although in discussing the control of energy in A.C. systems it is convenient to state that the circuit-breaker interrupts the current, this is, strictly speaking, incorrect.

Actually the current ceases to flow at a point of reversal, and is prevented from restarting through the inability of the voltage difference between the circuit-breaker terminals to break down the dielectric properties of the medium in the gaps between the separating contacts. The restoration of electric strength in gaseous media under pressure proceeds very rapidly when the current has ceased to flow; hence, the voltage difference which is mainly effective in breaking down the gaps is that present across the circuit-breaker terminals during the first few microseconds after the cessation of current. When the current falls to zero the voltage available for breaking down the dielectric medium between the separating contacts is the normal-frequency voltage plus a high-frequency voltage arising from the oscillatory nature of the circuit.

It has already been shown that the presence of reactance in the circuit has the effect of limiting the fault current so that the rupturing duty of a circuit-breaker is to some extent determined by the value of the reactance ; this also has another effect on the circuit-breaking process.

Restriking Voltage

The reactance depends, of course, on the natural inductance of the circuit, and it is now known that circuits having relatively high natural frequencies, due to low self-inductance and/or capacitance, are more difficult to interrupt than similar systems with low frequencies. The cause of the high-frequency restriking voltage wave is, of course, the presence of inductance and capacitance together in an A.C. circuit. The combination is equivalent to an inductance in series with the breaker, and a condenser across the breaker terminals. While the contacts are closed the condenser is short-circuited and the current through the breaker is determined by the inductance.

The power factor will then be zero lagging, and at zero current the impressed E.M.F. is a maximum. If the contacts are suddenly opened at a current zero no current is interrupted, but the E.M.F., at its maximum value, is suddenly applied to an inductance and a capacitance in series, consequently the condenser will charge up to double voltage and discharge back to the supply in the usual oscillatory manner with frequency $= \frac{1}{[2\pi\sqrt{(LC)}]}$.

The slope of the first half-cycle of this wave is the measure of the rate of rise of restriking voltage which, for a perfect circuit-breaker, depends, therefore, on two factors : (*a*) the natural oscillating frequency ; (*b*) the value of the impressed E.M.F. at the moment of contact separation. The conditions for obtaining relatively high rates of rise at the generating voltage are met when the maximum generating or synchronous plant is connected, and when a fault occurs adjacent to the breaker, eliminating the modifying effect of additional cables or transmission lines between the breaker and the fault.

Severe rates will occur with faults near breakers in base-load stations, if cubicle-type switchgear with short air-insulated connectors to generators is employed, and especially with moulded stone or masonry structure where the effective earth is remote from the busbars.

Factors influencing Restriking Voltage

The inclusion of a reactor in the oscillating circuit will still further increase the rate, and in combination with the above factors will produce the highest possible rate obtained in practice. The use of reactors at substations will also give high frequencies for faults near the reactor, and high rates of rise of restriking voltage if the reactor represents an appreciable percentage of the impedance of the system to that point; especially so if high fault kVA. is possible. On high-voltage systems high rates will occur with breakers adjacent to transformers, and with the fault close to the line side of the breaker. The rate of rise of restriking voltage at the power station end will again be more severe than at the feeder end, when similar transformers are used. The worst case will be that when the minimum length of transmission line is connected to the system on the breaker side of the fault.

Factors tending to reduce rates of rise are the presence between generator and fault of lead-covered cables, metalclad switchgear, condenser-type busbars and bushings, and the connection of parallel feeders not short-circuited by the fault. From measurements made on an actual network it was found that the first peak of restriking voltage arising under the worst fault conditions will be of the order of 1·5 to 2 times the power-frequency voltage, so that it is obvious that the restriking voltage characteristics of a network can be a factor seriously influencing circuit-breaker performance.

Origin of Faults

Since the necessity for controlling the excessive flow of fault energy in a circuit arises in the first place from the passage of current between two or more conductors normally insulated from each other, various precautions are adopted against the failure of the insulation of the components of a power system. Apart from accidents, faults originate as the result of the circuit insulation failing through its inability to withstand the electrical, mechanical, and thermal stresses encountered during normal and abnormal operation. In addition to withstanding the normal stresses continuously, the insulation should be unaffected by the transient stresses arising from causes outside the system, and faults within the system.

The two principal sources of excessive electrical stress are the transient overvoltages produced by lightning and switching. Of these, the former is probably the more important as far as outdoor air-insulated circuits and apparatus are concerned.

Lightning is responsible for the most severe abnormal voltage-stresses to which overhead lines, and the transformers, etc., associated with them, may be subjected in service.

Switching surges are, in general, of relatively low amplitude and represent comparatively low rates of change of voltage.

Statistics obtained from observations on high-voltage transmission systems over a number of years show that on these systems about 93–95 per cent. of all surges, originating from causes other than lightning, have crest values less than four times the crest value of the normal working voltage of the system to earth. Values up to six times normal have been recorded, but their occurrence is rare.

Thus, switching transients can be adequately guarded against by correct proportioning of insulation, but lightning produces transient voltages having both high amplitude and rapid rate of rise. Surge voltages caused by lightning are frequently limited only by the electrical breakdown strength of the insulation on the transmission line, and amplitudes as high as fifteen to twenty times the peak value of the normal system voltage to earth are sometimes encountered. In the case of overhead systems special protection is, therefore, required.

Load Stability

In addition to achieving transient stability of a system by controlling the fault energy to prevent conditions leading to widespread disturbances, it is also essential to ensure the load, or steady-state stability of a system ; that is to say, it must be capable of supplying the maximum possible load demanded without any part of the system falling out of synchronism, or being disconnected through overload. Load stability depends largely on the maintenance of the system voltage. An alternator operating on an induction-motor or synchronous-motor load has a load limit beyond which it becomes unstable unless the voltage can be maintained. With an asynchronous load an increase in the load current beyond the load limit causes the voltage to fall, and, although the load may remain constant, the excitation required is greater. An even greater excitation is therefore required to restore the voltage to normal, and in order to prevent the voltage falling it is necessary that the excitation should be increased immediately at a higher rate than the increasing demand for excitation. The excitation response required to restore the alternator voltage is therefore determined by the rate at which it tends to fall ; this in turn depends upon the time-constant of the alternator under the particular conditions of operation.

With a synchronous load an increase in the load angle of an alternator operating above the load limit is cumulative ; the rate of increase depending on the inertia of the alternator, and the accelerating torque. The latter, which is equal to the difference between the applied torque and the torque—in terms of load—which can be transmitted by the system, increases rapidly as the load angle widens. The excitation required to maintain the system at normal voltage also increases with the load angle, and approaches infinity at an angle of 180°. If the excitation can be increased sufficiently at a rapid rate before the angle becomes appreciably greater than 90°, stability should be maintained. Steady-state stability is obtained by operating a system so as to ensure that the generating plant on load has a sufficient overload capacity to meet sudden demands ; and employing effective automatic voltage regulation of the alternators. In practice the limit of steady-state stability is seldom reached, except on very rare occasions, when a bad fault trips out a number of generating units and the plant remaining on the system is not equal to the load.

Frequency Control

Power systems are usually operated, when there are a number of generating stations in parallel, by arranging for one station to maintain the frequency while the other stations each carry a load allocated by a central control from time to time to meet changing conditions. The station maintaining the frequency picks up the excess load as it comes on the system, the steaming conditions being adjusted for constant speed, and drops load as the total load on the system decreases. Thus, the other stations are not required to make sudden alterations to their steaming conditions, thereby ensuring that no fluctuations of speed occur to produce disturbances in the system. The load on each station is, of course, varied in accordance with the load cycle of the system, which can be closely estimated.

So far little reference has been made directly to substations or their equipment, the purpose of this chapter being to show the relation between a power system as a whole and its substations, which are vital units of the system, since their constituent equipment functions to control the normal and abnormal flow of electrical energy in the networks associated with them, after it has left the generating station. In the subsequent chapters various classes of substation equipment are discussed in detail.

Chapter III

THEORY OF CIRCUIT-BREAKING

ALTHOUGH circuit-breakers are usually employed for normal switching operations each unit is designed to break, or make, the maximum current that can flow in the circuit it controls, under short-circuit conditions—when the current is limited only by the inherent impedance of the network. Circuit-breaking is effected by the separation of two or more contacts in such a way that the intervening space is filled with a good insulating medium as quickly and consistently as possible: and circuit-making by the rapid closure of the contacts with a definite action which ensures that complete contact will be made even when there is a short-circuit on the system. As faults sometimes originate during normal switching-in operations a circuit-breaker has to be capable of closing on to the fault, and opening immediately after without sustaining serious damage. Efficient circuit-breaking is achieved by control of the arcing which occurs, even with normal load currents. No arcing would take place if the medium between contacts was a perfect non-conductor, for then the current would be interrupted immediately the metallic circuit was broken; but this is not the case.

Conduction in Dielectric Liquids and Gases

A current in a metallic conductor is a stream of free electrons (negatively charged particles) flowing towards a point of positive potential. Conduction in liquids is due, roughly, to the transfer of electrons from the negative to the positive electrode by ions (charged molecules). For the purpose of this discussion a normal molecule (or an atom) may be considered as constituted of a positively charged nucleus surrounded by the same number of electrons as there are units of positive charge. A positive ion has less, and a negative ion more, than the normal number of electrons. In liquids containing positive and negative ions a current will flow, if a potential difference exists across the space in which the ions are situated, because of their movement under the influence of the electric field. The charged molecules act as current carriers bridging the space between the electrodes. Each ion is attracted to the electrode of opposite polarity, but only a proportion of them complete the journey owing to the processes of re-combination and diffusion. Oppositely charged ions attract one another and re-combine to form neutral systems which are no longer effective in conduction. The rate at which re-combination proceeds depends on the number of collisions between oppositely charged ions. With the removal of the electric field the current ceases and re-combination proceeds until the ions have disappeared. De-ionisation also occurs by the diffusion of ions to the sides of the enclosure. The conductivity of a liquid depends on the degree of ionisation, i.e. the number of ions present, and the value of the current flowing on the rate at which ions reach the electrodes. Ionisation of insulating oil is due to dissociation of the impurities present.

A current in a gas is a stream of electrons—as in metals—which are emitted from the negative electrode (cathode); but the conductivity is due initially to the presence of free electrons between the electrodes. In an electric field the electrons are accelerated towards the anode and collide with gas molecules, which they ionise by detaching electrons; thus positive ions and more free electrons are produced. With low field strengths re-combination of the electrons and ions, and diffusion, occur as in liquids.

Arc Formation

With an electric field approaching the breakdown value, ionisation of a gas results in electron emission from the cathode due to photo-electric action and positive-ion bombardment. A spark passes between the electrodes when the current rises from an extremely low value to one, of the order of amperes, sufficient to produce intense luminosity by radiation of visible and ultra-violet rays.

Breakdown of dielectric liquids begins when, at a critical voltage, ionic conduction increases rapidly; but sparkover actually occurs in a gaseous path formed between the electrodes, and the mechanism of final breakdown is similar to that operating in gases. In liquids, at low potentials the current is minute, as most of the ions re-combine because of their relatively low velocity. Since the velocity of the ions is directly proportional to the strength of the electric field, as this increases a lesser number of ions re-combine on their way to the electrodes and the current increases. A maximum steady value of the current is reached when the electric field is sufficiently strong to remove all the ions before appreciable re-combination can occur. Even though the potential be increased greatly the current remains constant, but at a certain critical potential the ions are moving with sufficient velocity to ionise the neutral molecules with which they collide, thus producing fresh ions. As the rate of ion production at this stage exceeds the rate of re-combination the effect s cumulative, the current increases very rapidly and free electrons are emitted from the cathode to form a spark. Sustained arcing occurs only f the resistance of the circuit is low enough to permit a sufficient flow of current to maintain the electro-physical actions causing electron emission. As, however, the heat generated by the passage of the current through he electrodes volatilises material from these to form an easily ionised apour—in other words, a path of low resistance—the potential required to maintain the arc is considerably lower than that initiating the processes causing sparkover.

During the closing of contacts, although arcing occurs, this is not, of course, maintained—due to metallic contact being made. With contacts operating under oil the action of the initial spark on the oil produces gases, so that the subsequent arc is a stream of free electrons through ionised gases. Normally, the arcing period when closing is short ; but with contacts breaking circuit in oil, although at the instant of separation conditions are similar to those existing when making, the unavoidable persistence of the arc for a fraction of a second complicates the breaking process because of the highly ionised gases and vapours being formed and the carbonisation of the oil taking place during the arcing period.

Interruption of Circuits by Diminution of Current

When a circuit is broken, while arcing persists current continues to flow in the circuit. Electrons must, therefore, be leaving one conductor and moving across the break to the other, since the arc-current consists of a stream of electrons emitted from the cathode. The initial sparkover is due to the electro-physical actions resulting from the acceleration of the free electrons present in the gap at the instant of contact separation ; but once struck, the arc—which is made up of both electrons and ions—is self-sustaining, in the absence of factors causing a diminution of the current. From the cathode there is thermionic emission due to the formation of an intensively hot spot at the arc-root, and photo-electric emission due to the radiation energy of the arc. To interrupt a circuit it is, therefore, necessary that there should be a diminution of current so as to extinguish the arc and thus stop emission from the cathode.

In D.C. breakers the arc is extinguished by elongation ; which increases its resistance so that the current is reduced progressively.

A.C. Circuit-breaking

With A.C. breakers the occurrence of a current zero every half-cycle forces a periodic arc extinction ; but final interruption is not secured at the first current zero. The arc restrikes a number of times—determined by the potential gradient across the gap, and its conductivity, subsequent to each current zero. Ionisation of the dielectric is maintained by the intense heat of the arc causing thermal agitation of the molecules, and by other processes. Final extinction of the arc at an early current zero depends on the rapid decrease of the conductivity of the arc-path.

In practice, conductivity of the arc-path is decreased ~~by various~~ means ; for the present consider A.C. circuit-breaking in a gas when the restoration of the dielectric strength depends on natural de-ionisation. As contact separation commences ionisation of the gap begins, due to thermionic emission from the negative contact. Since the faces of the contacts are not perfectly smooth the final separation is at one or more points on the surface. There is a local concentration of current, the density rises and the metal heats to a temperature depending on the total current flowing. From the hot points electrons leave the metal and enter the gap, but, initially, they do so gently. This is the first stage in any break of circuit. Once the electrons are free in the gap, if the field is strong enough, they are accelerated to a velocity producing sufficient ionisation of the dielectric for the arc to strike.

Prior to the arcing period metallic vapour is already being formed to a degree depending on the heat-dissipating capacity of the contacts. When the arc strikes the production of vapour increases greatly, and a low resistance path for the flow of arc current is provided by the formation of an easily ionised medium. As the current approaches zero the conditions for ionisation become less favourable so that the rate of ionisation is decreasing. At some instant before current zero the rate of re-combination may become equal to the rate of ionisation, and thereafter exceed it. From this instant the mixture of gas and metal vapour in the gap must become less conductive and attain increasing electric strength. The potential gradient building up across the gap after the arc extinction will increase the production of electrons and ions by collision and may, together with thermal ionisation in the still hot gases, be responsible for a higher rate of ionisation than re-combination, thereby leading to a restriking of the arc until the next current zero.

TABLE I.—PERFORMANCE OF MODERN-TYPE O.C.B. WITH EXPLOSION POTS

Line Voltage, kV.	*Breaking Current, Amps.*	*Single-phase, kVA.*	*Duration, Half-cycles*		*Length of Arc, Inches per Break*	*Pressure in Explosion Pot, Lb./sq. in.*	*Average kV. per Inch of Arc kV.*
			Of Short-circuit	*Of Arc*			
7·5	18,000	135,000	7	1·3	2·5	376	1·5
7·5	18,000	135,000	6	1·0	1·8	224	2·18
7·5	19,000	142,500	6	1·9	3·8	488	0·98
7·5	19,000	142,500	8	1·2	2·0	240	1·87

When the rate of re-combination is sufficient to produce, in the short interval of time available, an electric strength between the contacts that will withstand the maximum potential applied, the arc will not restrike.

The foregoing is a general account of the circuit-breaking process, preliminary to a detailed discussion, in subsequent chapters, of the principles and operation of various types of interrupting devices. In all these, however, the basic principle involved is that of building up the electric strength of the medium in the break faster than the rate of rise of the restriking voltage, in the shortest time practicable.

Factors affecting Circuit-breaker Performance

The problems associated with the design of circuit-breaking devices to meet the high-rupturing duties required under modern conditions are considerable, since their performance may be affected by several factors. Among these is the rate of rise of restriking voltage which cannot be determined precisely as, not only does it depend on the characteristics of the associated network, but it is also modified by the arc itself. Again, at the higher voltages leakage current due to the capacitance of the circuit may also influence the breaking process.

When dealing with heavy currents the performance of a breaker may be affected by electro-magnetic forces between current-carrying parts. If these form a " loop " circuit, since conductors in which current flows in opposite directions repel each other, and vice versa, there will be forces tending to bend the fixed members and throw off the moving member. Apart from forces acting on the assembly as a whole, there is a tendency for certain forms of contacts to be blown apart, due to current flowing through the body of each contact of a pair in different directions. This is because, as it is impossible to produce dead-true faces, contact surfaces touch only at a number of points or lines, to which the current flow converges in one contact and diverges from in the other. Thus as the result of the change in the direction of current flow there is mutual repulsion between the faces. The blow-off forces between some forms of air-break contacts are considerable, due to the effect of the surfaces being pinched together so that current passes up the body of one contact and down that of the other, the arrangement forming two mutually repelling conductors.

In consequence of the factors influencing circuit-breaking the duration and effects of the arc vary even when equal currents are interrupted in identical circumstances. This is shown by the data in Table I, which relates to an O.C.B. with a modern form of arc control device shrouding the contacts. The inconsistent performance, although not critical, is appreciable, and the type of breaker concerned is generally more consistent than the so-called plain-break type ; so that it is clear that in selecting a breaker for a particular duty due regard must be given to operating conditions. That modern circuit-breakers do achieve a high standard of performance is a significant proof of the attention devoted to their manufacture.

Chapter IV

OIL CIRCUIT-BREAKERS

THE basic components of an oil circuit-breaker are the fixed and moving contacts operating under oil. Contacts may be classified as either " plain " or " shrouded," although, as in practice both are sometimes used in combination, the classification may only apply as between arcing contacts. These close in advance of the main contacts and open after them, thus relieving the latter of the making and breaking duty ; the main contacts being designed for the sole purpose of carrying the normal current continuously and through-fault currents for a few seconds. Normally, both arcing and main contacts conduct in parallel. Some types of breaker do not employ special arcing contacts. In this discussion " contacts " implies those which are utilised for the purpose of arc control.

" Shrouded " contacts are so called because they operate within a pot distinct from the main tank, or other form of oil container enclosing all three phases, or each phase separately. " Plain " contacts are enclosed only by the tank common to the three phases, or each phase, in the case of single-phase units ; although specially designed chambers are sometimes used to enclose plain contact systems for the purpose of effecting arc control similar to that obtained by some forms of shroud.

Curcuit-breaking in Oil with Plain Contacts

In oil circuit-breakers arc control is effected by de-ionising the gases, or by rapidly removing them and substituting fresh oil. Actually both de-ionisation and substitution occur together, but one of the actions will predominate according to the particular arc control method employed.

Despite its name the plain contact type of oil circuit-breaker without special arc control arrangements is in reality a device for extinguishing an arc in a gas bubble, which is produced by the action of the arc on the oil. Since the arc temperature is in the region of 3,000° C., very rapid and violent changes occur through the decomposition of the oil in the vicinity of the arc, various gases being formed—mostly hydrogen and acetylene. As the gas is surrounded by oil a gas bubble is formed around the arc between each pair of contacts. The gas bubble is highly conductive, because the intense heat dissociates the hydrogen and ions are produced, the process being termed thermal ionisation. Thus in the case of the plain contact breaker, as no special arrangement is made to forcibly remove the ionised arc products, arc control is largely dependent on the de-ionisation of these.

After each current zero the arc restrikes only when there are sufficient electrons present between the contacts, and the potential gradient, i.e. the volts per unit length of break, is such that the electrons and ions attain a velocity high enough to maintain the phenomena causing emission from the cathode. Thus to create conditions unfavourable to restriking, diffusion and re-combination of electrons and ions must occur, together with : cooling of the contacts to prevent thermionic electron emission ; and cooling of the gas bubble and the surrounding oil to reduce thermal ionisation. By compressing the gas bubble the electrons and ions are brought into closer association, consequently the rate of re-combination varies directly as the pressure. Cooling the gas decreases ionisation due to molecular collisions by reducing the velocity of the molecules. Compression of the gas is effected by the oil in the tank opposing the expansion of the gas bubble ; but it is essential that there should be an air cushion above the oil to permit its upward movement.

Apart from the necessity of high pressure for the purpose of de-ionisation, the size of the gas bubble around each pair of contacts must also be restricted to prevent the bubbles bridging the phases, or forming a path to earth. The final size of the gas bubble depends on the ratio of air cushion to oil volume, because the expanding gas reaches a state of equilibrium only when the air cushion is compressed to an appropriate reactionary pressure. For effective arc control it follows that the internal pressure of the gas bubble will be high, and the pressure on the tank walls and top-plate correspondingly high. In consequence of there being a number of variables affecting the quantity of energy in a faulty circuit, the arc energy varies on each occasion that the circuit is interrupted, so that the arc bubble is likewise variable as regards size and rate of expansion. The production of the arc bubble sets up a sudden hydrostatic pressure which is transmitted in all directions.

Thus in a three-pole double-break oil circuit-breaker of the conventional type with a common tank, there are, during the arcing period, six arc bubbles producing pulsating hydrostatic pressures which are not only of different phase, but are also reflected irregularly from the various surfaces of the tank, and obstructed unequally by one another, and other obstructions in the tank. For this reason, the maximum stresses likely to occur in the tank and top-plate of a plain contact breaker are practically indeterminable, and the enclosure has to be particularly robust.

Importance of Oil Quality and Quantity

In view of the important function of the oil as an arc controlling agent the maintenance of a high dielectric quality is essential, since the presence of water and solid impurities will be detrimental to the circuit-breaking process, although they may not have a critical influence on the dielectric strength under normal conditions. Furthermore, the oil in the tank must be maintained at the correct level. Insufficient oil may lead to gas explosions by reason of the gas escaping, and coming to rest on top of the oil before this reaches the top-plate of the breaker. In this case burning may occur above the oil level, or when the ratio between air and oil reaches a certain value, the mixture becomes explosive so that, if for any reason a spark is formed simultaneously—for example, a discharge spark on the bushing flange of an insulator—this may cause an explosion. This class of explosion is not usually disastrous.

An excess of oil may be equally dangerous because of the insufficient air cushion to absorb the impact pressure of the oil, which is inelastic and possesses considerable inertia. The result of this is that excessively severe impact pressures are transmitted to the tank walls and top-plate, which effect may burst the tank and/or distort the structure. In any case there is at least the danger of hot, burning oil being expelled from the vents provided for the escape of the gas, and through the joint of the tank. The most severe stresses arise when a circuit-breaker fails to interrupt a fault, or the internal insulation fails. Unless the circuit supplying the defective breaker is cleared rapidly the unit will almost certainly be wrecked.

Plain Contacts

Arcing contacts of the plain type play a critical part in circuit-breaker operations ; their duty being especially severe in comparison with that of shrouded contacts in which a more definite control of the arc products is achieved with the object of rapidly producing a high dielectric strength between the separating contacts. Many forms of arcing contacts are in use ; representative types are shown in Figs. 2 (*b*), 4, 14, and 20. Both main and arcing contacts are designed to have an adequate heat-dissipating capacity so as to obtain a satisfactory performance under normal and abnormal conditions.

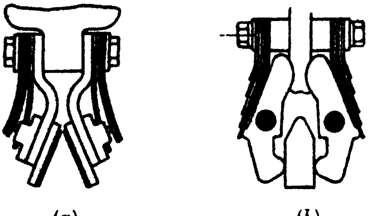

(*a*) (*b*)

Fig. 2.—OIL CIRCUIT-BREAKER PLAIN CONTACTS

(*a*) Main, 45° finger type.
(*b*) Arcing, high-pressure type.

The normal current capacity of main contacts depends largely on their contact resistance. The theory of contact resistance is usually based on the assumption that the so-called contact resistance is simply the ohmic resistance of a number of microscopic projections or points which actually make up the contact surface. However carefully the surfaces are ground and lined up, the actual contact is obtained at one or several points only, depending upon the flexibility of the material. These contact points, which carry all the current between them, are of a certain length and consequently have a definite ohmic resistance. On these assumptions the contact resistance depends upon:

(1) The contact pressure; which controls the height or length of the contact projections through crushing, until their flattened surface is large enough to resist the external pressure.

(2) The specific resistance of the material. The contact resistance is a function of the specific resistance of the surface material, or, assuming clean contacts, it is proportional to the specific resistance of the material.

(3) Crushing strength of the material. The softer the material the more the contact points are flattened and their number increased with a given contact pressure. A soft material will, therefore, give a lower contact resistance than a hard one.

The size of the contact area is of less importance than the total pressure on the contact, as the conductivity is proportional to the pressure. By increasing this, the smaller is the contact area required. Since it is impracticable to make plane surfaces touch all over, without excessive pressure, most contacts are designed to achieve a multi-line contact rather than depend on obtaining a large number of point contacts distributed over a comparatively large surface.

Forms of Plain Contacts

Generally, the most widely used form of contact is the wedge and finger type (Figs. 2 (*a*) and 3 (B)), as it is self-aligning and the vertical position of the moving contact is not particularly important since contact pressure of the fingers is reasonably constant with variations of wedge position. The pressure of the fingers on the wedge is further assisted by the mutual attraction of the fingers. Particular care is taken to arrange the fingers of arcing contacts so that they cannot touch each other and "weld" just as the moving contact leaves them. With finger-type contacts there is a circulation of oil between the separate fingers which makes for a high thermal capacity.

Butt-type main contacts (Fig. 3 (A)) are a simple form whose application is generally confined to very low current values, and in particular to industrial units. Heavy current low-voltage

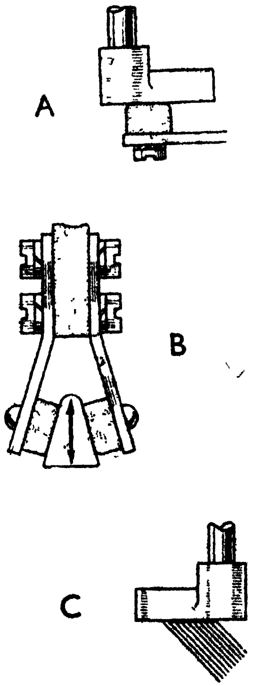


Fig. 3.—TYPICAL FORMS OF OIL CIRCUIT-BREAKER CONTACTS

(A) Butt. (B) Wedge and finger. (C) Butt and brush.

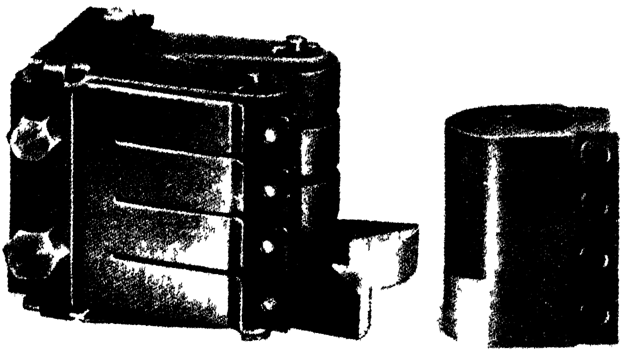


Fig. 4.—Copper-Tungsten Arcing Tips on Auxiliary Contacts of Small Oil Circuit-Breaker

breakers often have arcing contacts of the butt type with main contacts of the brush type (Fig. 3 (C)), which are quite unsuitable for breaking an arc.

The materials used for circuit-breaker contacts are copper, brass, silver, and tungsten. Copper is largely used for both fixed and moving contacts, but the tendency to weld has been responsible for the use of copper to brass contacts in many designs in which welding has been eliminated even when making on to a severe short-circuit on two successive occasions. Silver is used as plating on main contacts, as the tarnish film produced by heating is a good conductor ; it is also employed extensively for isolating-plug contacts.

Silver is only admissible under oil for permanent current-carrying facings which are not required to interrupt current ; thus, with heavy-current breakers all main fixed and moving contacts are silver-plated, but not the arcing contacts—due to the more rapid burning of silver than copper.

The use of silver for arcing contacts appears to contaminate the oil with silver shreds and particles which, remaining partly or wholly in suspension, pave the way for flashovers and breakdowns. Copper-tungsten is used to some extent for arcing contacts, the tungsten being applied to the copper as a facing to the surfaces on which arcing occurs, as shown in Fig. 4. A copper-tungsten facing has the effect of raising the resistivity of contacts, since tungsten has a comparatively low conductivity, and, in many cases, their interface resistance. Both these factors tend to increase the temperature-rise. Again, it seems probable that gap ionisation is intensified and the arc length becomes greater, but despite these disadvantages the great hardness, and the extremely high melting and volatilising temperatures, of tungsten decide its use in certain circumstances.

Speed of Break

In addition to having adequate heat-dissipating capacity, to restrict the production of metallic vapour and assist the cooling of the ionised gases, contacts are designed to promote rapid initial separation, as the speed of break controls the arc to a great extent. There is, however, a limit to the speed of breaking high-voltage circuits in oil ; this being reached when the arc is lengthened so rapidly that its resistance forces the current down at such a rate as to give rise to excessive voltages.

These may have a more dangerous effect than the fault current since, apart from straining the insulation of the system, they increase the re-striking voltage. The total ~~break energy is the~~ product of kW. and time of arc duration, so that no useful purpose is served by excessive speed of break as this results in a longer arcing time increasing the distress, and the possibility of failure owing to the difficulty of disposing of the highly ionised products. The ideal speed is difficult to determine since it is obviously essential to reduce the arcing period to a minimum when the arc energy is itself a maximum, i.e. when the circuit-breaker is interrupting the heaviest currents. But it is also necessary to ensure that the arcing time is not unduly long when breaking any other currents within the range of its rating. When the breaker is operating below its maximum rating the electro-magnetic forces acting on, and accelerating, the contacts on the moving element are reduced.

(The repulsive electro-magnetic forces arise from the current flowing in the loop circuit formed by the fixed and moving contact elements of the conventional double-break type. This will be appreciated by studying the illustrations of double-break units.) For example, a plain-break oil circuit-breaker tested at 100 per cent. of rating had an arc duration of 0·04 sec.; at 15 per cent. rating this increased to 0·07 sec. It is obvious that by incorrect design the condition can arise where failure may occur at a lower rating even when a satisfactory performance is obtained at the maximum rating; and the effect of the rate of rise of restriking voltage is emphasised.

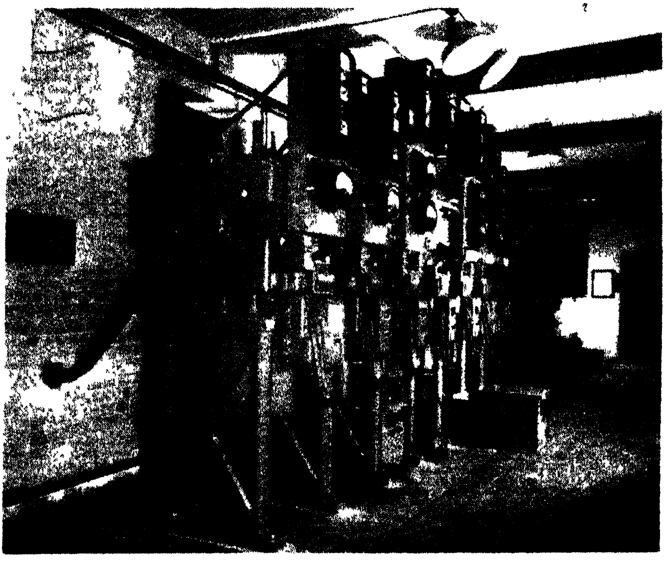


Fig. 5.—PLAIN BREAK SWITCHGEAR WITH VERTICAL ISOLATION 11 kV. 150 MVA. RUPTURING CAPACITY, INSTALLED IN A CENTRAL ELECTRICITY SUBSTATION. (*J. G. Statter & Co., Ltd.*)

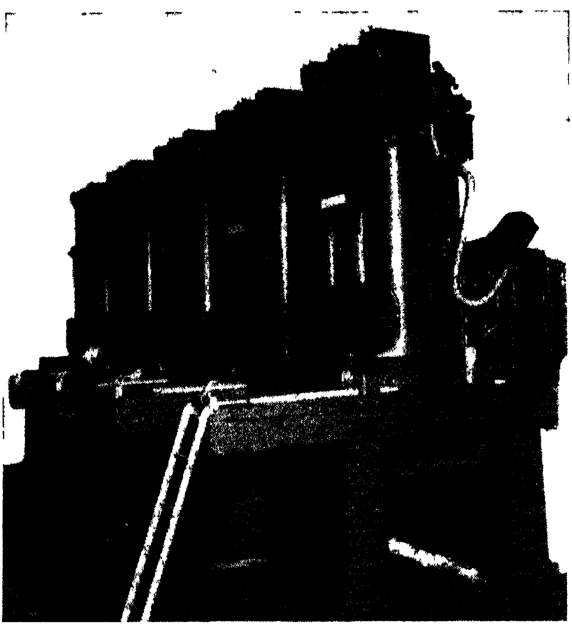


Fig. 6.—33 kV., 1,500 MVA. SWITCHGEAR (*British Thomson Houston Co., Ltd.*)

By using a number of breaks in series a high equivalent speed is obtained since the requisite separation of contacts occurs with less travel than in the usual two-breaks-per-phase type. This tends to shorten the whole unit and to promote its compactness. also the oil volume is used to better advantage for cooling as well as the absorption of stress. Although the total volume of gas bubbles formed on breaking a given kVA. may be the same in both types, the splitting up of the total volume of gas, in the multi-break type, into a number of smaller bubbles gives a larger contact surface for cooling between the bubbles and the oil.

In ~~this country oil circuit-breakers~~ with two breaks per phase are ~~most favoured~~; six breaks in series have been used for 132 kV. gear, and on the Continent as many as ten breaks in series. The present tendency at the higher voltages is towards single-breaks, which is actually a return to an old idea, the adoption of which was made practicable by the advent ~~of modern~~ arc control devices.

One advantage incidental to the single-break construction is the freedom from the electro-magnetic forces acting on the moving elements which, in the double-break type, may amount to several tons under short-circuit conditions. The effect occurs just at the moment when the closing mechanism commences to compress the accelerating springs, and the solenoid has to close the circuit-breaker under these conditions. In consequence, it is extremely difficult to secure latching when this is essential, or in the more usual case, to prevent the contacts welding during the short time-interval before the automatic protective gear operates to release the trip-free device. In the single-break unit there is no loop circuit and, therefore, no electro-magnetic forces. Typical single-break units are shown in Figs. 6 and 7.

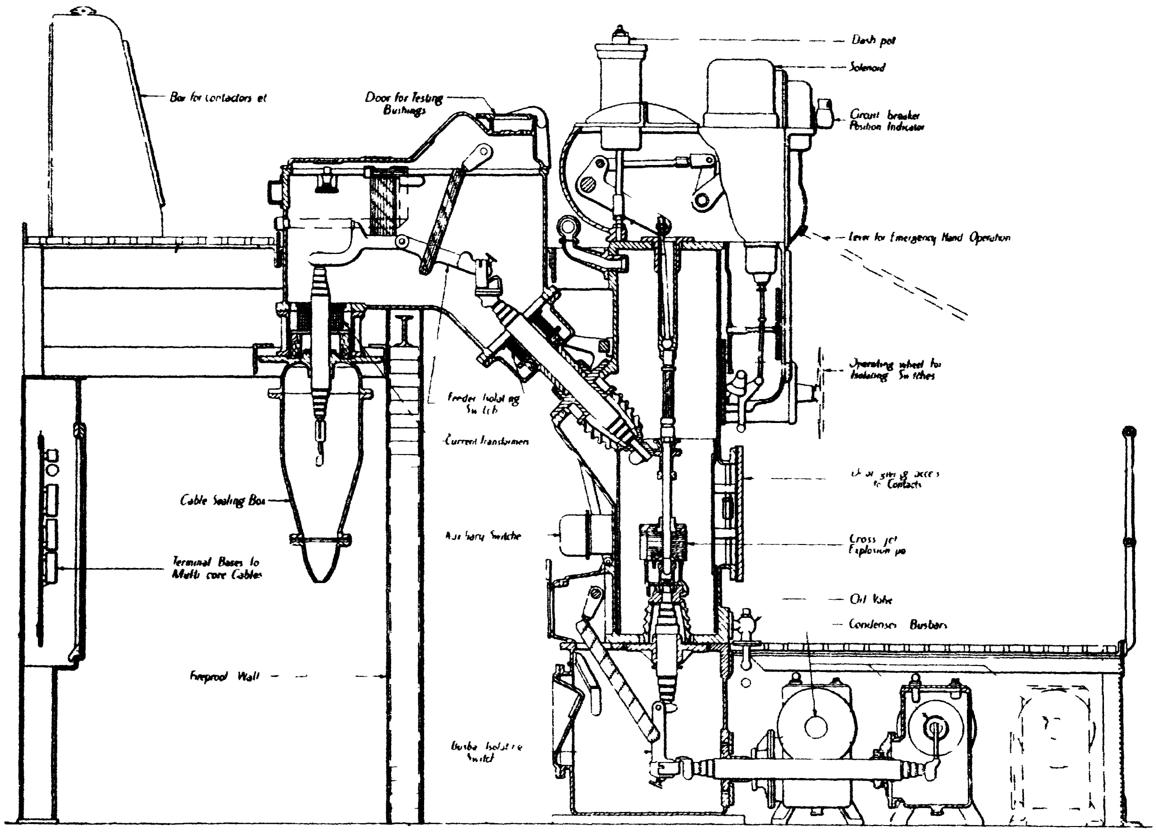


Fig. 7.—CROSS-SECTION OF TYPICAL 33 KV., 1,000 MVA. SB18 EQUIPMENT. (*Metropolitan-Vickers Electrical Co., Ltd.*)

Arc Control Devices

Since in breakers without some special form of arc control the arcing period is comparatively long, as conditions favourable to final extinction are not generally attained until a wide separation of contacts is reached, the mechanical stresses in the tank structure can be of very high magnitude; consequently breakers of this type are provided with tank structures of robust design. In addition, for high-voltage, high-rupturing-capacity breakers a large volume of oil is required. Some years ago the rapidly increasing dimensions of tanks, compelled by growing values of short-circuit currents arising from the development of the Grid, forced attention to the necessity for an alternative to the orthodox type of circuit-breaker if the dimensions of high-capacity units were to be kept within economic limits. This requirement led to the development of arc control devices, which in some cases brought about radical changes in breaker design—in fact, nowadays, the design of the breaker is often determined by the arc control method used. The development of arc control devices—most of which take the form of a shroud—has enabled more consistent results to be obtained, together with faster operating times, to meet the requirements of interconnected networks, and to supplement the increase in the speed of protective systems evolved for the purpose of reducing the total operating time of the relay and breaker in combination.

Furthermore, the arc control device has permitted a considerable reduction in the tank volume required for the successful interruption of a given kVA., with a consequent decrease in the oil content, thereby lessening the fire risk associated with the dissipation of fault energy under oil.

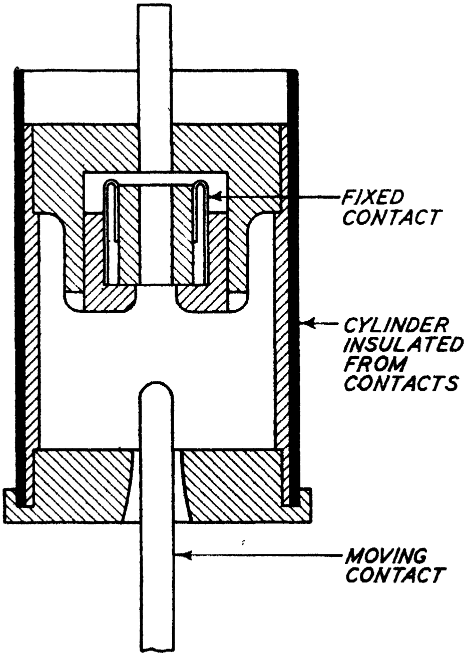


Fig. 8.—Explosion pot

The Explosion Pot

Arc control devices rapidly remove and/or de-ionise the arc products, and generally create conditions favourable to the automatic introduction of cool, non-ionised dielectric. The elementary arc control device is the shroud known as the explosion pot, shown in

Fig. 8. This is a strong insulated chamber mounted as a housing for each fixed contact with an aperture at the bottom through which the moving contact passes.

The primary function of the device is to confine the pressures set up within the pot so that as the moving contact leaves the aperture the oil remaining in the chamber is ejected directly into the arc path. This action, together with the de-ionising effect of the high pressure, which also increases the speed of break by accelerating the moving contact, ensures that the dielectric strength of the path between the separating contacts builds up at such a rate that the circuit is finally interrupted at an early current zero.

In addition to reducing the arcing time by maintaining a high pressure in the arc bubble, the explosion pot reduces considerably the stresses set up in the breaker tank and structure. For instance, in the case of two tests with the same kVA., interrupted in each, the arcing period with plain contacts was 2 cycles, and the steady pressure on the tank sides 125 lb. per sq. in., whereas with shrouded contacts these values were 1 cycle and 45 lb. per sq. in. respectively.

Oil-blast Explosion Pot

Fig. 9 shows an oil-blast explosion pot enclosing three contacts so arranged that two breaks in series are obtained ; a blast of oil being automatically forced across the final, main break. The fixed contact is resiliently mounted, and just below it an intermediate floating contact is fitted to a horizontal baffle of strong insulating material. The moving contact is a hollow rod with holes in the lower surface.

When the breaker is closed the floating contact is trapped between the two main contacts. As the breaker opens the floating and moving contacts move together during the first part of the stroke, and a short arc is drawn between the fixed and floating contacts. This arc forms gases in the upper chamber and the oil therein is compressed.

When the floating and moving contacts separate at the limit of travel of the former a second arc is

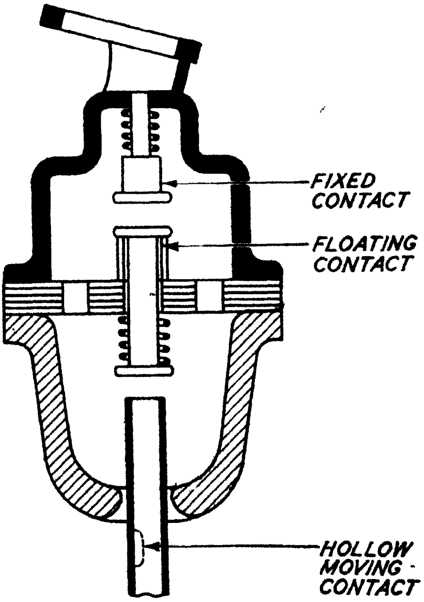


Fig. 9.—Oil-blast explosion pot

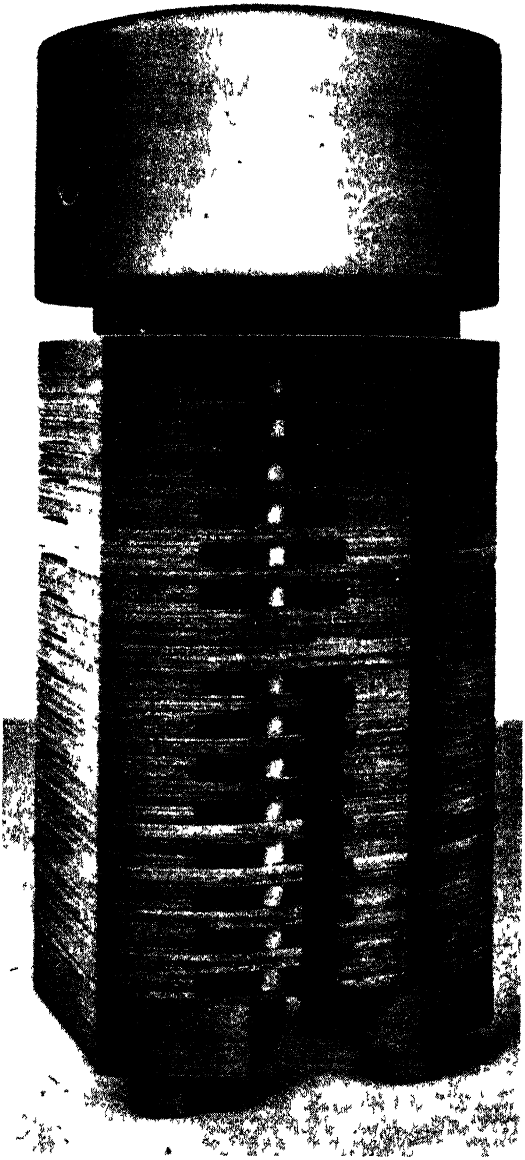


Fig. 9A.—TYPICAL DE-ION GRID CONTACT—132 kV. (*English Electric Co., Ltd.*)

struck between them, and at the same time the top of the hollow moving contact is uncovered. The pressure created by the first break in the upper chamber forces oil through the holes in the baffle into the bottom chamber, so that the arc products are forced out through the moving contact and fresh oil introduced at each current zero. This action effectually establishes a barrier of high electric strength between the main break contacts, final interruption being obtained before the rod leaves the chamber.

De-ion Grid Oil Circuit-breaker

One form of shroud which differs in principle from the plain explosion pot is that used in the De-ion Grid oil circuit-breaker. The de-ion grid is exclusive to " English Electric " oil circuit-breakers in this country, and was one of the first arc control devices to be placed in commercial service. Its outstanding characteristics are rapid and efficient operation at both high and low values of arc current, thereby ensuring consistent performance throughout the range of the circuit-breaker rating. The device is so constructed that the relatively cool and un-ionised gas, which is produced immediately upon the formation of the arc, is allowed to escape across the arc path

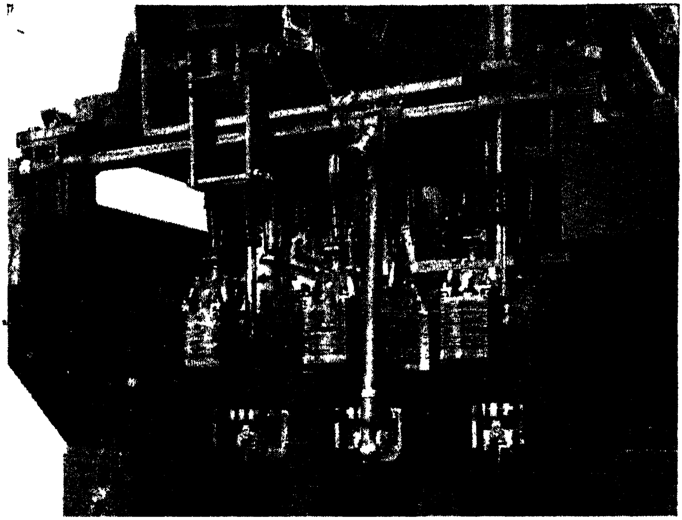


Fig. 10.—A 33,000 VOLT OIL CIRCUIT-BREAKER WITH THE TANK REMOVED TO SHOW THE DE-ION GRID CONTACTS

(*English Electric Co., Ltd.*)

through suitably disposed vents: by this action the arc is cooled and de-ionised, the process continuing right up to the moment of extinction. Iron inserts are employed to control the arc magnetically by the natural attraction between them and the circular field due to the arc current, and to force it into close contact with the oil.

The de-ion grid contact consists of an enclosure formed by specially shaped laminations of insulating material, with iron plates interposed at intervals, and provided with vent outlets. A typical 132 kV. de-ion grid contact is illustrated in Fig. 9A. De-ion grid contacts fitted to an oil circuit-breaker are shown in Fig. 10; and Fig. 10A shows the constructional details of the device, and the magnetic control effect.

All the insulating laminations and the iron plates are so contoured that a narrow vertical slot with oil pockets on either side is formed in the interior; the slot being cut away at one side only, to permit the entry of the moving contact bar. The iron plates, which are interposed between the laminations at regular intervals, are specially proportioned, and are shrouded by the insulating material. The complete structure, or stack, is carried by a fixed-contact enclosure which is secured to the foot of the circuit-breaker bushings.

Self-aligning, spring-finger-type fixed contacts, constructed of heavy-section copper, are used. These contacts are so arranged and shaped that the arc is drawn away from the main current-carrying surfaces, and transferred to a separate and easily assembled arcing horn (Fig. 10A), thus reducing the burning or pitting of the main contacts. Removal of the arcing horn enables the main finger contacts to be readily inspected, without dismantling other portions of the assembly.

The moving contact bars are "U"-shaped, and constructed of high-conductivity copper bar of rectangular section, the contact surfaces being

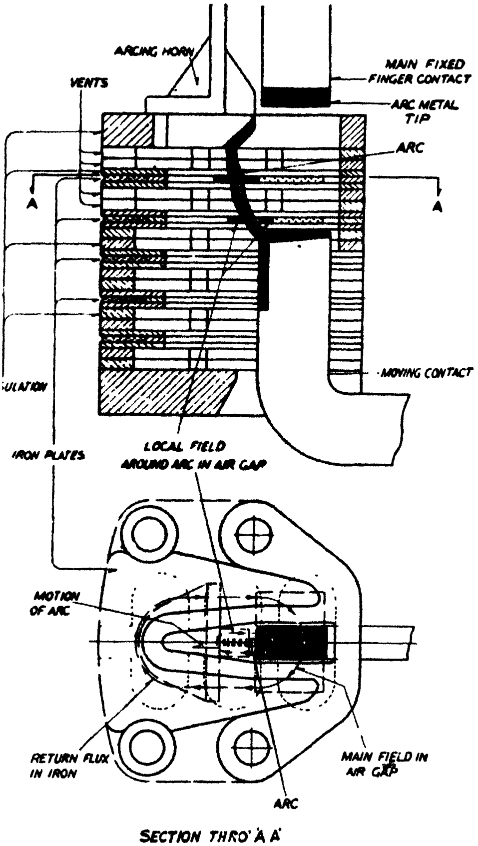


Fig. 10A.—CONSTRUCTIONAL DETAILS OF DE-ION GRID ARC CONTROL DEVICE, SHOWING MAGNETIC CONTROL EFFECT. (*English Electric Co., Ltd.*)

tipped where necessary with special arc-resisting alloy. For the higher voltage ratings the contacts are of the butt type; and for abnormally heavy-current ratings, additional contacts for carrying the main current are provided, and located external to the arc control enclosure. With the latter arrangement, however, final circuit interruption occurs within the de-ion grid enclosure.

On opening circuit, the arc is drawn between the fixed and moving contacts which, being of substantial construction, ensure a cool arc root. The arc then continues to be drawn out in the oil-filled narrow slot, thereby causing a rapid evolution of cool un-ionised gas which, in escaping through the vents, de-ionises the arc path.

The magnetic effect of the iron plates, together with the natural movement of the arc, force the latter into close contact with the oil contained in the internal pockets. This ensures an accelerated flow of de-ionising gas, and makes the fullest use of the cool de-ionising effect, with the result that the electric strength of the arc path at current zero is raised in the shortest possible time to a point at which the arc cannot restrike.

Cross-jet Explosion Pot

A form of shroud developed in recent years is the cross-jet explosion pot (Figs. 7, 11, 12, and 13). The pot consists of a metallic upper portion, housing the fixed contact, to which the jet plates of insulating material are fixed (Fig. 13). This stack of plates is arranged so as to form a series of channels at right angles to the normal arc path, i.e. horizontally when the moving contact moves vertically downwards. The moving contact just clears these plates where it passes through the central passage, consequently there is little tendency for any arc products to be expelled downwards.

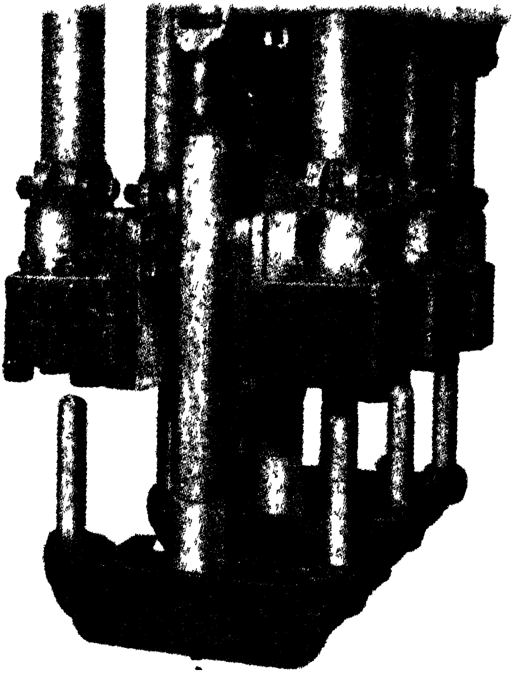


Fig 11. Cross jet pots on a 1,200 amp. 6·6 kV. oil circuit breaker
(Metropolitan-Vickers Electrical Co., Ltd.)

The complete assembly forms a shroud with narrow passages through which the pressure developed in the pot tends to expel oil into the main tank, and a reserve oil chamber connecting with that in which the arcing occurs. The operation of the device is shown diagrammatically in Fig. 13. During the initial opening period the pressure generated in the space between the fixed and moving contacts is directly relieved by leakage around the tip of the latter, and is also communicated to the reserve oil chamber. As the arc lengthens a section of it is driven into the jets (also termed arc-splitters), but the movement of the reserve oil horizontally through the jets is checked by the pressure of the arc itself until the current zero, when the comparatively cool oil is forced across the arc-path. Although only a portion of the arc products are violently expelled through the jets, de-ionisation of the remaining gas takes place by pressure and cooling so that conditions unfavourable to restriking are rapidly created at an early current zero.

A special form of cross-jet pot is used in the breakers illustrated in Fig. 6, this being compensated so that the cross-jet effect when interrupting varying amounts of fault energy is adjusted accordingly. Thus a more consistent performance is obtained over a wide kVA. range, and the possibility of the device failing to successfully interrupt the circuit with relatively low fault currents—due to the correspondingly low pressure developed—practically eliminated.

Cross-jet pots are used for circuit-breakers of both the single- and double-break class. A cross-section of a single-break unit is shown in

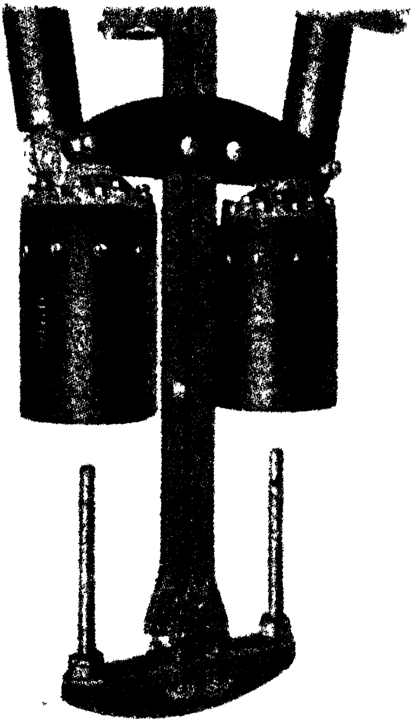


Fig. 12.—One phase of an 800 amp. 66 kV. cross-jet oil circuit-breaker

(*Metropolitan-Vickers Electrical Co., Ltd.*)

Fig. 7, and the application of cross-jet pots to double-break units in Figs. 11 and 12. The contacts used with the pot are of the rod and socket type.

In Fig. 11 it should be noted that the rod-type contacts are used only as arcing contacts additional to main contacts of the butt and brush type, whereas the rod-type contacts shown in Fig. 12 are used to carry the normal load current, and interrupt short-circuit currents. The design of the single-break units shown in Figs. 5, 6, and 7 is largely due to the adoption of cross-jet arc control.

Cross-jet Box Circuit-breaker

The cross-jet principle is also adopted, in a modified form, for improving the performance of an otherwise standard type of plain contact breaker (Fig. 14). This is not fitted with explosion pots but depends on an arrangement of insulating barriers inside the tank to form a cross-jet box, which is essentially an enclosed chamber A (Fig. 15), with an orifice B. Each phase has its own cross-jet box, the orifice B being adjacent to the contacts and level with the point of break. A special arc runner is fitted to one fixed contact of each phase (Figs. 13, 15, and 16). As the contacts separate the gases formed generate a pressure in the chamber A. The arc runner serves to control arcing conditions and, therefore, pressure distribution in the box so that the internal pressure is relieved through the orifices. Consequently, the oil forced directly across the arc path of each phase sweeps out the gas through the orifices to the chimney C, which has free access to the buffer air, the oil separating chamber, and gas vent. This action is maintained until sufficient oil of high dielectric strength has been forced into the arc path to prevent restriking of the arc.

The Impulse Breaker

Oil-blast arc control devices function automatically by the action of the arc itself; the impulse oil circuit-breaker is designed to avoid dependence on the action of the arc by arranging for an oil jet to be provided at the critical moment by the movement of a piston acting on the oil. The principle of the impulse breaker is shown in Fig. 17. A mechanically produced oil blast is superior to that produced by explosion chamber pressure, as with the latter method arc control is comparatively inefficient at low currents. With the impulse breaker arc control is equally efficient at all currents and it has a much faster operating time than other breakers, this being as low as less than three cycles. A cross-section of a typical impulse unit is shown in Fig. 18.

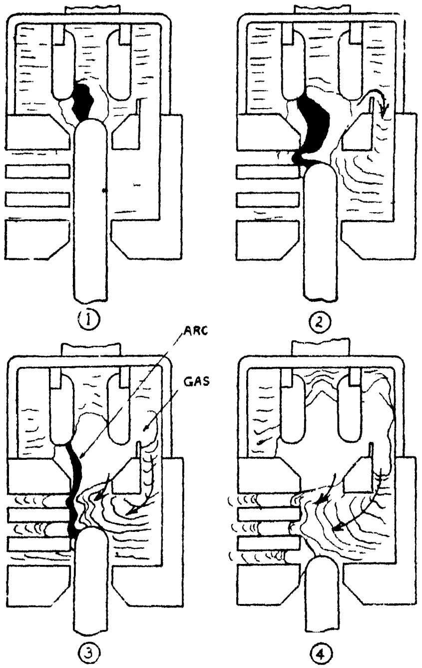


Fig. 13.—FOUR STAGES IN THE OPERATION OF A MET-VICK CROSS JET EXPLOSION POT

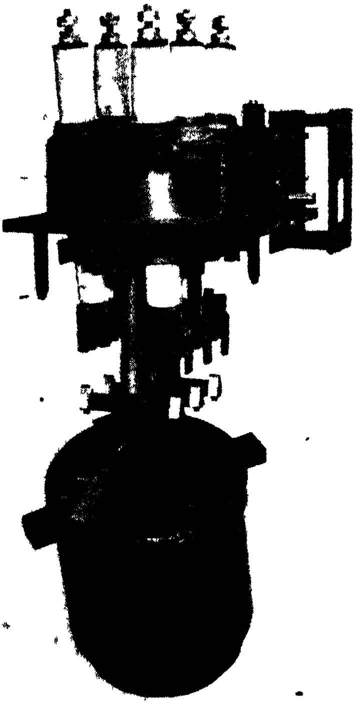
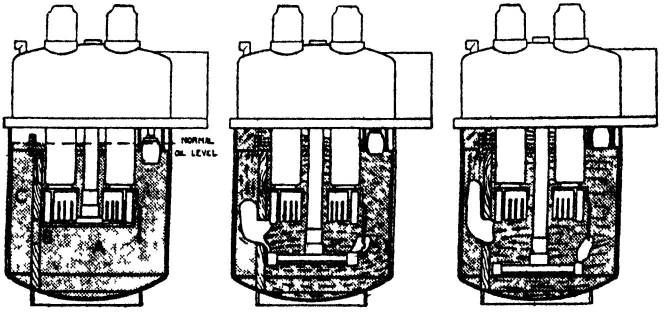


Fig. 14.—ARC CONTROL BREAKER, WITH TANK LOWERED SHOWING PART OF CROSS-JET BOX

(*British Thomson-Houston Co., Ltd.*)

The breaker consists essentially of a central bushing along the axis of which the moving contact slides. The front end of this bushing is enclosed by a bakelite tube at the far end of which are the arc splitters and the fixed contact. The space between the central bushing and the tube forms the path for the impelled oil, which then returns between the outside of the bakelite tube and the en-



Contacts closed Contacts separating Contacts open

Fig. 15.—OPERATION OF THE CROSS-JET BOX
(*British Thomson-Houston Co., Ltd.*)

closing porcelain rainshield. A stress distributor is fitted at the interrupting end. Ordinary bushing current - transformers are used, and are placed over the central bushing. In order to speed up the operation of the breaker it is actuated pneumatically from a compressed-air reservoir.

The breaker is tripped by admitting air above the closing piston 4, which drives the impulse piston 18—acting on the oil—through a mechanical coupling. For the first half-cycle the breaker opens at a very high speed—the contacts are, in fact, accelerated at a rate fifty times that due to gravity—and then, to eliminate any unnecessary drawing-out of the arc, the contacts are slowed down again. As this occurs, oil at a pressure of approximately 250 lb. per sq. in. is forced across the break,

KEY TO FIG. 16

1 Removable Ratchet Handle for Breaker raising and lowering device.
2 Incorporated raising and lowering mechanism with Truck.
3 Arc Runner.
4 Breaker Balancing Piston.
5 Guiding Spike.
6 Trip Coil.
7 Operating Trunnion.
8 Safety Shutters and Housing for Busbar and Circuit Plugging Contact Sockets.
9 Operating Handle for Breaker.
10 Breaker Insulator (paper or porcelain).
11 Breaker Plugging Contact Connection and Plug.
12 Breaker Plugging Contact Socket.
13 Insulator for Breaker Plugging Contact Socket—Busbar side.
14 Insulator for Breaker Plugging Contact Socket—Circuit side.
15 Busbar Chamber, Busbars, and Connections.
16 Terminal Board for Small Wiring.
17 Insulator for Cable-box.
18 Cable-connector.
19 Cable-box.
20 Arcing Contact—fixed.
21 Arcing Contact—moving.
22 Main Contact Finger—fixed.
23 Main Contact Blade—moving.

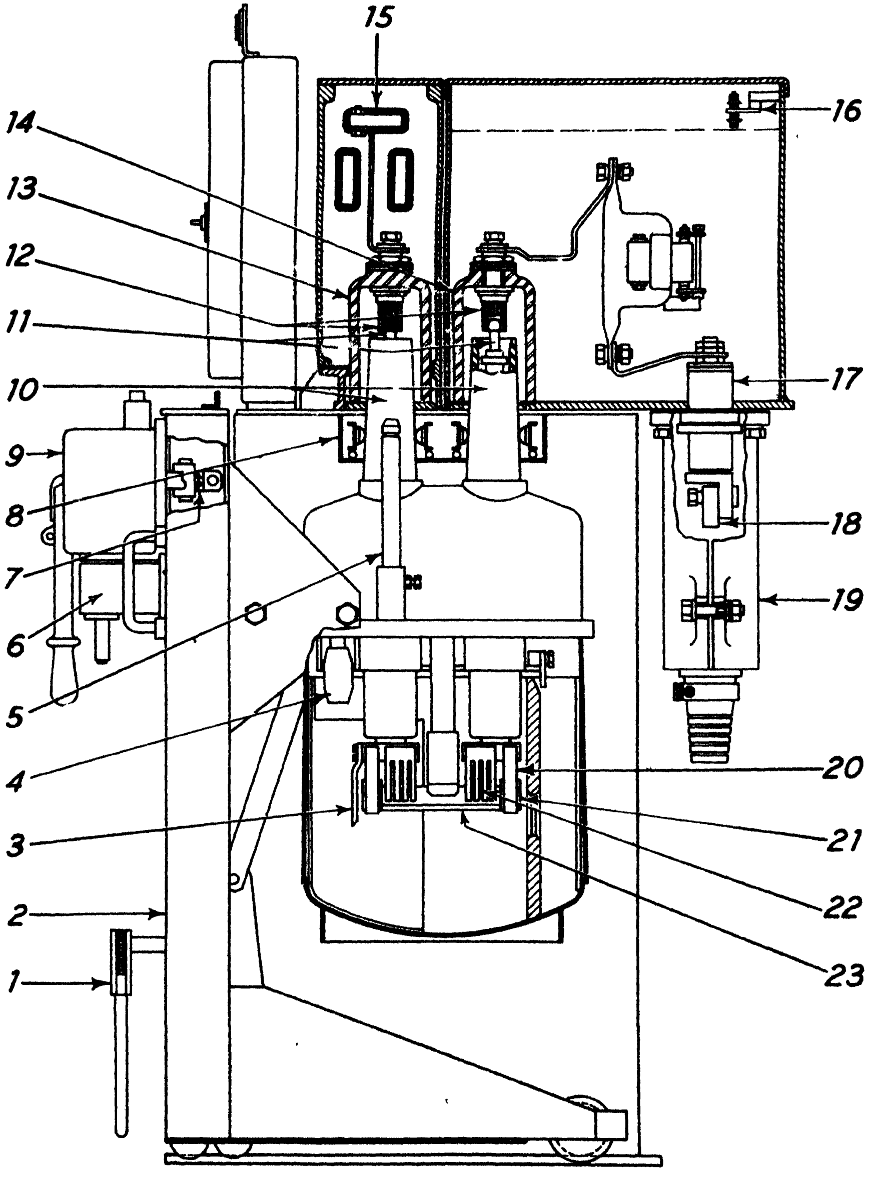


Fig. 16.—SECTION THROUGH A TYPICAL H.V. DISTRIBUTION EQUIPMENT SHOWING DETAILS OF PARTS

(*British Thomson-Houston Co., Ltd.*)

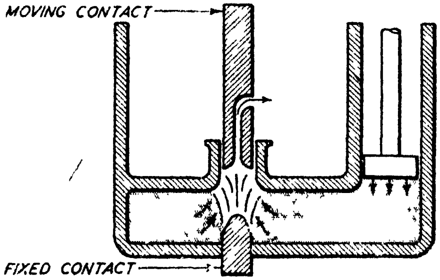


Fig. 17 – Impulse circuit-breaker

thus driving the arc into the splitters where it is finally extinguished. There are actually two breaks, one being opened by the oil pressure against a spring. Opposite each break is an independent set of arc splitters. After the arc has been interrupted and the oil pressure has returned to normal, this secondary break automatically recloses; the moving contact is finally retracted to the "off" position by the spring 16.

An added advantage of the impulse breaker is that the oil content is very low. In the case of the breakers illustrated in Figs. 18 and 19 the oil content is only one-quarter of that of the type it supersedes, a single-phase unit requiring less than 250 gallons.

The impulse breaker was designed for 132 kV. service where extremely fast interruption is necessary. It is considered unlikely that the design will be used below 110 kV., as for these voltages there is not the same necessity for ultra-rapid fault clearance. The breaker is described here, as it represents an important advance in design and illustrates certain fundamental aspects of arc control.

Operating Mechanisms

For manually operated breakers a simple closing mechanism arranged to give considerable leverage during the final part of the stroke is provided. With remote operation the closing mechanism is usually actuated by a D.C. solenoid, an A.C. motor, or compressed air—as with the impulse breaker (Fig. 18)—the former being more commonly adopted in view of its greater advantage as regards speed, and because the solenoid exerts its greatest pull at the end of its stroke. The fastest operating time is achieved with pneumatic operation, but this method is not, of course, generally used.

D.C. solenoid operation requires a D.C. supply which in large stations is available from an emergency battery, and in some small stations from an operating battery of about 30 volts, with trickle charging equipment.

A.C. can, of course, be rectified for operating D.C. solenoids, but the disadvantages during a total shut-down are obvious. The definite operation of closing mechanism is essential, as when making on to a short-circuit the current may have a peak value equal to 2·55 times the r.m.s. value of the A.C. component at breaking, since decrement does not occur during the initial period to assist the making operation. Should the breaker trip gear be released before the breaker is fully closed, even to the extent of being actuated as soon as, or probably before, the arcing

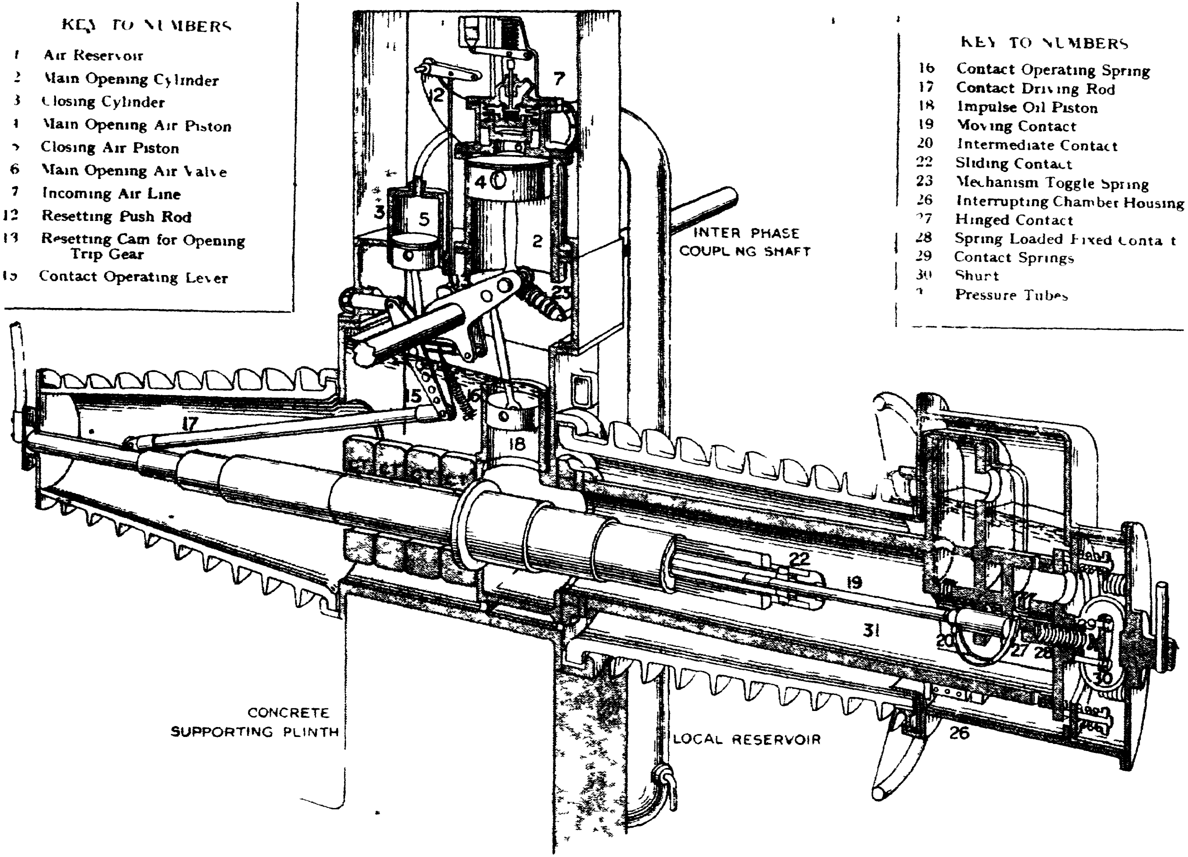


Fig. 18.—CROSS-SECTION OF IMPULSE BREAKER (*Metropolitan Vickers Electrical Co., Ltd.*)

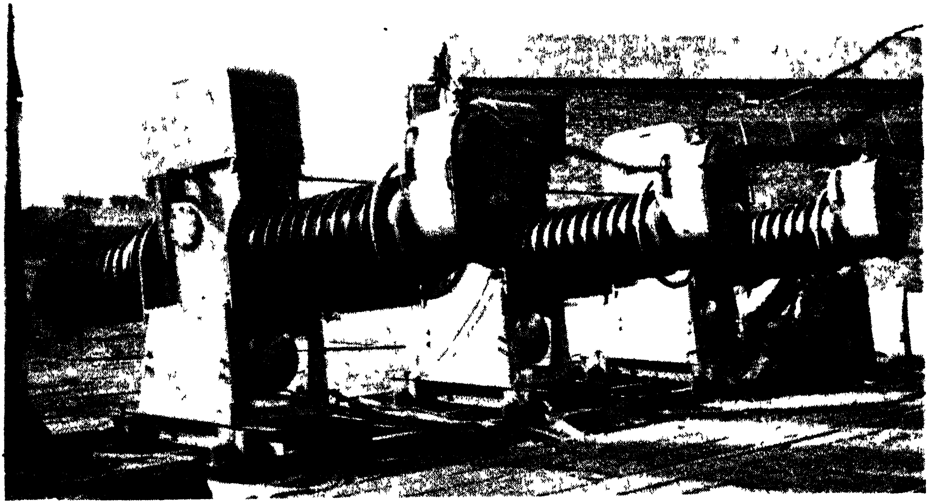


Fig. 19.—THREE 132 kV. IMPULSE BREAKERS ON TEST
(*Metropolitan-Vickers Electrical Co., Ltd.*)

contacts touch, the throw-off springs are not fully compressed and in consequence the opening speed may be reduced.

When making a faulty circuit, once the current has commenced to flow the electro-magnetic forces oppose the pull of the closing mechanism, and, moreover, these forces may be unbalanced where three moving contacts are carried on a crossbar. Again, should the pull of the mechanism almost balance the repulsive forces there is a tendency for the moving element to hover on the arcing contacts.

Within certain limits a high speed of break is of importance in reducing the volume of gas liberated and minimising contact damage. Although a slightly delayed opening may reduce the current as the result of decrement in the system, it follows that, once started, the contacts should complete their travel in the shortest time practicable. High speed of opening is obtained by powerful accelerating springs, but on short-circuit the electro-magnetic forces also repel the moving contacts, thus increasing the speed of break. To avoid damage at the end of the stroke some form of dashpot or buffer is provided to bring the moving system to rest without undue shock. In the smallest breakers simple buffer springs are used, and in larger breakers a piston moving in an oil cylinder. The opening speed of a breaker can be seriously retarded by the pressure of the gas on the moving elements, which effect is more pronounced in older designs where the contact carrying rods pass through the top-plate to atmosphere, due to the unbalancing of pressures on those parts of the moving system inside, as against those outside. Most modern breakers have the whole of the operating mechanism, except the final link to the actuating member, within the breaker chamber, thus giving equal pressures on all parts. In the case of the breaker illustrated in Figs. 14, 15, and 16, to prevent a tendency to reclose due to the pressure in the enclosure acting on the operating rods passing through the top of the cross-jet box, a compensating piston is provided.

A large proportion of the work required to operate a circuit breaker is accounted for by the contacts; the form used having a considerable bearing on the expelling force of the breaker. Some contacts are 100 per cent. expelling, for instance, the spring-loaded butt type, whereas others of the rod and socket, or sleeve, type are 100 per cent. holding, and require a force of the same magnitude to withdraw as to close. Furthermore, on short-circuit, the members of some forms of contacts may be drawn together, so adding to the load and leading to a substantial increase in the total friction.

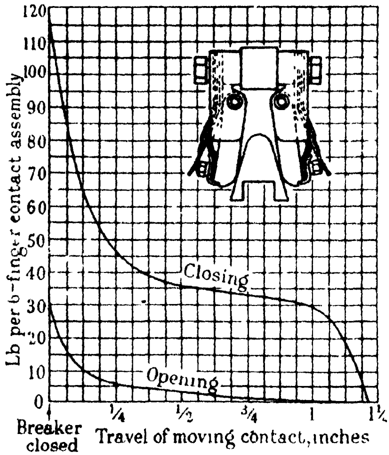


Fig. 20. FRICTIONAL CHARACTERISTICS OF PIVOTED-TYPE ARCING CONTACTS (*Journal I.E.E.*)

Fig. 20 shows the frictional characteristics of the arcing contact illustrated. In the case of the typical main finger contact shown in Fig. 2 (*a*), the force to close against one single finger, when the contacts have silver surfaces, changes from 0 to 21 lb. over the travel, and with hard copper surfaces, from 0 to 13 lb. This type of finger has a small self-expelling force of initially 2·5 lb., falling to zero over its travel.

Methods of Isolating

Isolation is effected by air-break or oil-immersed links or switches; or by withdrawing the breaker plugging-contacts from the busbar and circuit sockets. Indoor air-break isolators are a feature of switchgear of the cubicle type for up to about 11 kV. service, and of special cellular types up to 33 kV. With high-voltage outdoor open-type breakers various forms of air-break isolators are employed.

With metalclad substation switchgear the breaker plugging-contacts are withdrawn by either a vertical drop-down or a horizontal draw-out movement; or oil-immersed isolators are used. Truck-type switchgear is an economical form which is often used when the breaker capacity is not required to exceed 250 MVA. at 11 kV. A special type of unit with a withdrawable truck and vertical isolation of the breaker is shown in Fig. 16.

Fig 21.—A TYPICAL RING MAIN UNIT FOR CONTROLLING THE H.V. CIRCUITS OF A DISTRIBUTION TRANSFORMER SUBSTATION

An internal isolation automatic circuit breaker is used with isolating switches of the rack-down withdrawable pattern (*Switchgear & Cowans, Ltd*)

Horizontal draw-out isolation applied to three-phase single-break units is illustrated in Fig 6. With the equipment shown in Fig. 7 isolation is effected by oil-immersed links the details of which are clearly indicated A ring-main unit, consisting of two oil-links and a circuit-breaker, is shown in Fig. 21. The links enable the substation to be isolated from the network—if similar links are provided at the other ends of the sections of ring-main—but when the ring circuit must be maintained the breaker can be isolated from the busbars by means of the internal isolation gear actually located inside the breaker tank. By manipulating the handwheel shown plugging-contacts sliding in insulating tubes are withdrawn from the busbar and circuit sockets ; the lower ends of the plugging-contacts are connected to the fixed contacts of the breaker. When the breaker is isolated it can then be withdrawn. Access to the contacts and oil is by means of a hinged top-plate. This method of isolation permits the circuit-breaker to be located in the position shown, thus giving the maximum support to the tank and comparative freedom from the risk of structural distortion.

Vertical isolation is largely used with single-busbar metalclad switchgear for breaker capacities of from 50 to 250 MVA., and has its major application in distribution work where the inherently compact arrangement is valuable by reason of the small space usually available.

Horizontal isolation is adopted for both single- and double-busbar metalclad gear for 150 to 250 MVA., or more. With this method of isolation an oil-immersed busbar selector switch can be conveniently fitted above the breaker.

With metalclad switchgear above about 33 kV. it becomes difficult to so design plug and socket contacts that they shall be free from corona. Further, the size of higher-voltage breakers is such that the space required, and the effort necessary for the isolating movement when a withdrawal method is used, has led to the development of equipment with a fixed breaker and oil-immersed isolators.

When practicable switchgear is usually fitted with interlocks to ensure the operation of the breaker isolators, etc., in proper sequence and to prevent mal-operation. Mechanical interlocking methods are usually adopted, since electrical interlocking necessitates a number of auxiliary contacts and devices. Interlocking is generally arranged to prevent :

(*a*) The racking-in or out of a closed breaker so as to avoid making or breaking circuit on the isolating contacts.

(*b*) The removal of the tank with the breaker in the service position ; or the racking-in of a breaker with the tank off.

(*c*) The movement of an off-load busbar selector while the breaker is closed ; or the movement of an on-load busbar selector unless both sets of busbars are in parallel.

In general, high-voltage breakers with arc control devices represent modern practice, especially for large capacity units ; but in the medium range of breaking capacities of up to 250 MVA. at 11 kV., the so-called conventional plain-break type is still widely used—and even above this rating. Typical examples of plain-break switchgear are shown in Figs. 5 and 21. Low- and medium-voltage breakers are not usually fitted with arc control devices ; in principle they are essentially plain-break types and do not call for any special comment.

The present tendency is towards the increasing use of air-breakers or high-rupturing-capacity fuses whenever practicable so as to avoid the disadvantages associated with the use of oil as a dielectric medium.

Chapter V

AIR CIRCUIT-BREAKERS

OIL has a definite sphere of usefulness for high-voltage circuit interruption, a field in which it possesses advantages that outweigh its major disadvantage of "inflammability," but for the interruption of medium-voltage A.C. circuits air is universally available as an economical alternative in certain cases. For D.C. breakers air is, of course, the only practicable dielectric.

Two main types of air circuit-breakers are in common use, both of which are—with appropriate modifications—employed to interrupt either A.C. or D.C. In one type final interruption occurs between carbon breaks, or arcing contacts, and in the other between metallic contacts within a magnetic field produced by a magnetic blow-out. To some extent the design of the breaker is influenced by the particular method of arc control adopted. Generally, a D.C. breaker incorporating a blow-out is characterised by comparatively light mechanism and contacting parts and a more or less elaborate arc chute, circuit interruption being entirely dependent on the rapid lengthening of the arc within the chute to such a value that the circuit conditions are incapable of maintaining it. The A.C. breaker usually has a more robust mechanism, and heavier contacts than a D.C. breaker, for the same normal current, on account of the exceedingly high fault currents that can flow in certain circumstances. The extinction of the A.C. arc is, however, assisted by the occurrence of a current zero twice every cycle, consequently a magnetic blow-out may not be included, or may be relatively small and simple in form.

Brush-type Breakers

Apart from the arc control method, ~~air~~ breakers are mostly distinguished by the form of main contacts employed. One form frequently adopted consists essentially of two ~~stationary~~ copper contacts arranged vertically, and bridged by a moving laminated brush contact. The latter is built up of special alloy or copper leaves which retain their flexibility under almost any condition, and will not take a permanent set. In large-capacity breakers the brush is made up of a number of narrow units, thus ensuring good distribution of contact over the whole surface, and providing ventilating spaces between the individual main laminated members. This reduces the temperature rise for given conditions of load, and increases the capacity on A.C. by reducing the skin effect.

Two main methods of applying the brush contact to the solid fixed contacts are generally used. In one the brush makes a practically end-on, or butt contact, which enables considerable pressure to be applied to the brush with only a slight spreading of the laminations, so that a good self-cleaning contact is obtained. With the other type, the contact surface of the brush is inclined at an angle to the fixed contact, less pressure being required for the same amount of spread.

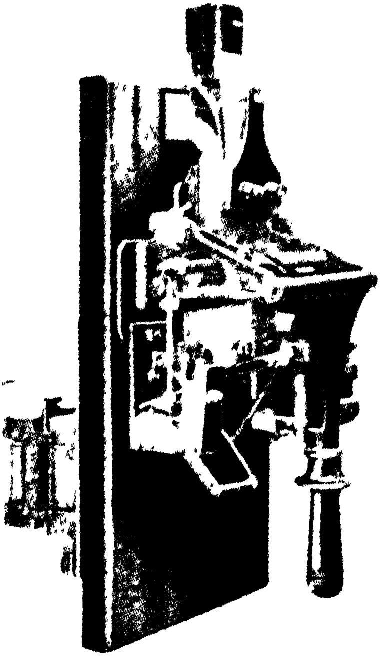


Fig. 22. 1,200 AMP. 660 VOLT AIR CIRCUIT-BREAKER
(*Metropolitan Vickers Electrical Co., Ltd.*)

Operation of Brush-type Breaker

The brush type of construction is utilised for both A.C. and D.C. breakers; an example of the latter being shown in Fig. 22. This, and similar types of breakers, are closed by applying pressure to the brush, which is held in position by latching the toggle link mechanism. When the breaker is tripped under normal load conditions the moving element is accelerated at a comparatively slow rate by a combination of forces produced by the throw-off springs, the pressure on the brush, the weight of the moving element, and the electro-magnetic repulsion between the fixed and moving contacts—due to the current flowing round the "loop" circuit formed by them. With heavy overload and fault currents the breaker is opened very rapidly by the electro-magnetic forces, these being proportional to the square of the current—the other accelerating forces are negligible in comparison.

In breakers with carbon arcing contacts the circuit is interrupted in three successive stages by three sets of contacts. Referring to Fig. 22, first the main contacts formed by the laminated brush open, then the auxiliary copper contacts, and lastly the carbon contacts. The latter two sets of contacts are provided in parallel with the main contacts to protect them from the destructive action of the arc. The carbon contacts are mounted on springs so as to ensure that they break last and make first. Arc extinction occurs between the carbon contacts whose separation lengthens the arc, thereby increasing the resistance of the circuit by increasing the resistance of the arc itself, thus the current rapidly diminishes until the arc becomes unstable. Carbon is used for the final break as it does not volatilise easily and form conductive vapour unfavourable to rapid arc extinction.

Magnetic blow-outs make use of the interaction between two magnetic fields ; the field surrounding the arc, and the field due to the passage of the main current through a coil wound on an iron core fitted with special pole faces. The arc is struck within these pole faces, consequently the field due to the blow-out coil forces the arc upwards so that it lengthens very rapidly. An effective type of blow-out is the one fitted to the breaker illustrated in Fig. 23. The pole faces act as an arc chute, and the large cooling surfaces of the structure adjacent to the contacts tend to reduce the quantity of metallic vapour formed, and de-ionise the vapour that is produced.

Line Contact Breaker

The breaker shown in Fig. 23 is a " line contact " type, the name being derived from the fact that a set of hard copper blades is used for the main moving contact instead of a laminated brush. The moving contact is made up of a number of blades with a vee-shaped contact surface which bed into corresponding grooves in the fixed contact blocks, as shown in Fig. 24. The number of blades required for a particular breaker is determined by the current rating, each blade being suitable for 125 amperes. Referring to Fig. 24, the blades A are carried by a horizontal thrust bar of special section D. Pressed-steel hook-shaped plates C, riveted to the rear of the copper blades, pass round the upper portion of the thrust bar in such a manner as to lock the blades securely in position, but to permit their easy removal if necessary. In order that the full pressure of the blade is borne by the bevelled sides, and full advantage taken of the wedging action, the leading edge of the blade is flattened so that it cannot bed in the bottom of the groove in the block E. This has the further advantage of allowing any dirt which may collect on the block to escape instead of preventing the blade from making contact. The pressure between the blade and the contact block is maintained by the spring B, which is located between the steel plates

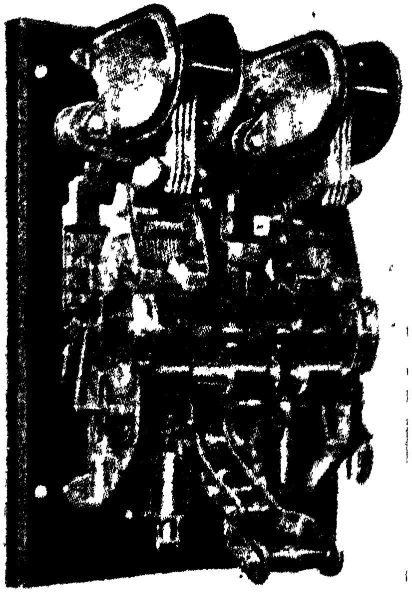


Fig. 23.—4,000 AMP. LINE CONTACT CIRCUIT-BREAKER. (*General Electric Co., Ltd.*)

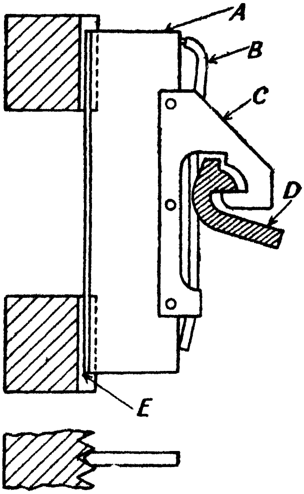


Fig. 24.—Sectional view of main-line contact blades of a line contact air circuit-breaker

and presses on the rear flat edge of the blade. The points of contact of the springs on the front of the thrust bar and the plates at the back are so disposed as to keep the lower corner of the blade, which is slightly rounded, in firm contact with the bottom block. Each blade, therefore, carries an equal amount of current, and overheating of any one section of the contact assembly prevented. By reason of the large mass of copper adjacent to the line of contact the current-carrying capacity of the line contact breaker is relatively high as the heat developed is rapidly dissipated by the large cooling surface of each blade.

Careful attention is given to obtaining the most suitable blade pressure so that the contact resistance is reduced to the lowest practicable value consistent with easy operation of the breaker. The pressure on each of the four line contacts of a blade is 14 lb. The spring exerts a total pressure of 28 lb. on the complete blade, and the 14 lb. pressure on each contact surface is obtained by the wedging action of the 60° faces. During the closing operation the blades slide upwards in their grooves so that the contacts are self-cleaning—any dirt or oxide which may have collected on them is removed.

Medium-voltage High-rupturing-capacity A.C. Breakers

Although in general, the rupture of a D.C. arc is more difficult than that of an A.C. arc, in which the current becomes zero twice every cycle, the current-making problem with A.C. is much more difficult than with D.C. because the initial current peak can reach 2·55 times the breaking-capacity current, whereas the D.C. breaker has only to make a current equal to its rupturing capacity. Since the electro-magnetic forces are proportional to the square of the current, they amount to six times as much with A.C. as with D.C., and the problems of contact-welding are correspondingly greater. Under modern conditions the initial current peak may be in the neighbourhood of 44,000 amps. when a breaker closes on to a L.V. short-circuit.

A three-phase air breaker which has been recently developed by the British Thomson-Houston Company especially for the control of high-current-capacity A.C. circuits up to 660 volts is shown in Fig. 25. Two main types are in use which differ in respect of their main contact arrangements, otherwise their constructional features are generally similar. An important feature common to both types is the form of the

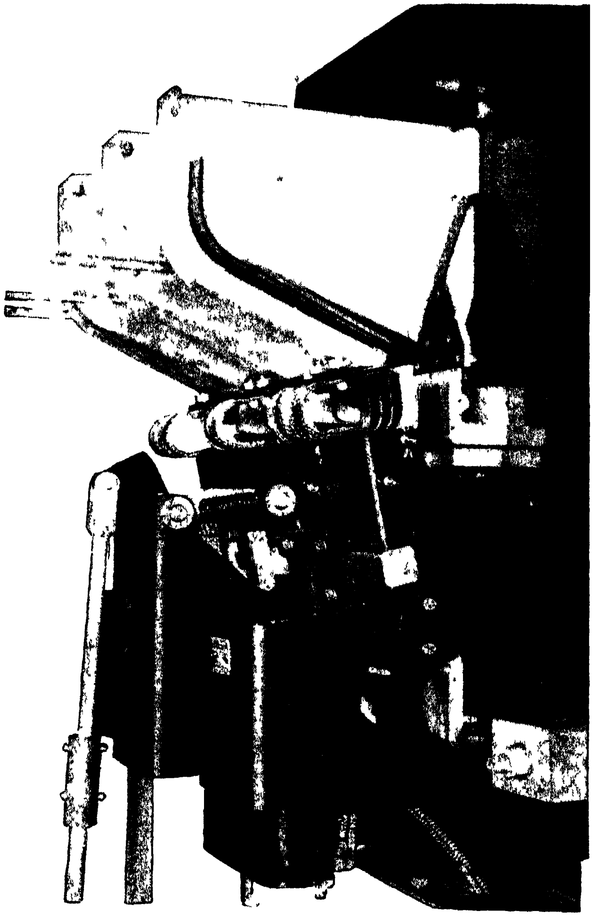
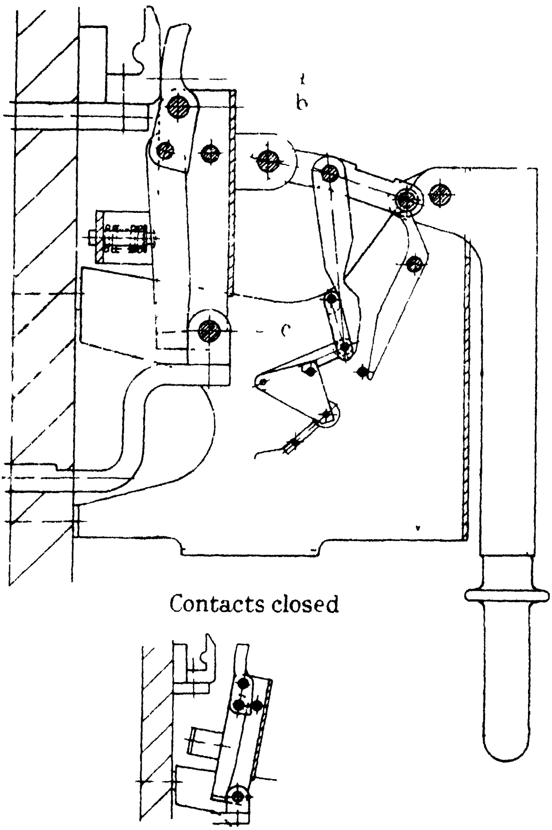


Fig. 25.—THREE-PHASE MEDIUM-VOLTAGE AIR CIRCUIT-BREAKERS, SHOWING SLIT ARCING HORNS

One half of arc chute removed. (*British Thomson-Houston Co., Ltd.*)

arcing contacts which are of the butt (or contactor) type. In the 800 amp. rating breaker (Figs. 25 and 26) one set of contacts suffices for both normal and abnormal requirements, while in the breakers rated at 1,600 amps. and over, special main contacts are incorporated (Fig. 27).

With some arrangements of metallic arcing contacts, in which the magnetic loop effect and the pinch effect blow them open, serious welding and burning of the points of contact occur at as low as 15,000 (peak) amps. Better performance can be obtained by carefully bedding the contacts, but as after the first opening operation the surfaces are pitted and burned, such bedding is of no practical value. Moreover, after a fault clearance the breaker may have to be re-closed immediately so that there is no time to put the contacts into really serviceable condition. The arcing contacts of the B.T.H. breakers are designed to control satisfactorily 20,000 amps. without spot welding taking place. Up to 25,000 (peak) amps. only very slight spot welding takes place, which is easily broken by the inherent wipe or shear action of the contacts. The only practicable way of improving this performance is to use such high contact pressures that considerable crushing of the metal at the contact points occurs. Increasing the thermal capacity of the contacts by increasing their size does not effect any improvement in respect of non-welding. The most economical way, therefore, to deal with peak currents of more than 25,000 amps. is to resort to multiple contacts. The upper limit of 25,000 amps. per contact is true only of breakers which are designed to close on to a short-circuit and latch home, i.e. are fitted with time-delayed tripping devices. For breakers fitted with instantaneous tripping devices, by virtue of the short time they have to carry the current, it is possible to increase the rating of a single contact to 50,000 (peak) amps.



Contacts closed

Fig. 26 Operation of 800 amp circuit-breaker contacts. (*Journal I.E.E.*)

An essential feature of the breaker is the special "compensated" arrangement of the moving element which permits the moving arcing contact to pivot about *b* (Fig. 26, top), as the result of the moving element being straightened (Fig. 26, bottom) by the repulsive force of the current in the "loop" circuit of the breaker. Thus, the final break occurs on the tips of the arcing contacts, and the butt faces of these contacts are not involved to any great extent, as their tips are designed solely for the purpose of arc extinction.

Each pair of the arcing contacts shown in Figs. 25 and 26 has a normal continuous-load capacity of 200 amps., thus once the rupturing capacity, and in consequence the peak-making capacity, of the breaker has been determined, the number of arcing contacts is fixed so that the normal rating of the breaker is also fixed. The breaker rated at 800 amps. has, therefore, four pairs of arcing contacts (Fig. 25), but with the type rated at 1,600 amps. and above, additional main contacts are used,

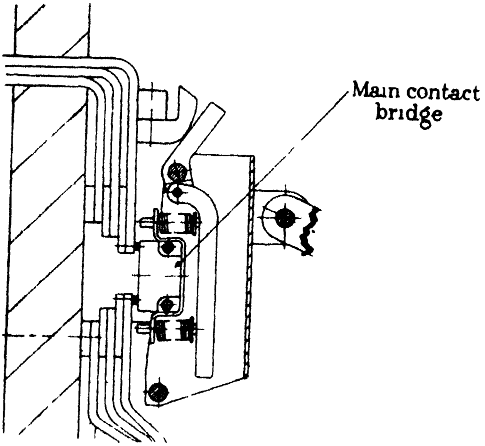


Fig. 27.—MAIN CONTACTS OF 1,600 AMP. CIRCUIT-BREAKER. (*Journal I.E.E.*)

arranged as shown in Fig. 27. These pin-type contacts are silver-faced and will carry 25,000 (peak) amps. per contact satisfactorily. The main contacts are subdivided in exactly the same way as the arcing contacts because, when breaking faulty circuits, the main contacts have to carry the peak rating of the breaker, which occurs before the tripping impulse can have released the breaker and transferred the current to the arcing contacts. To ensure correct operation of the compensated contacts the magnetic blow-off effect is reduced to extremely small proportions in this breaker by making the bridging member as short as possible, and arranging the main lead-in conductors as far away as possible.

Arc Chutes

An essential component of this class of breaker is the arc chute. Currents up to 37 kiloamperes can be successfully broken in 2½ cycles at 440 volts recovery voltage without arc chutes ; but the arc is, in some cases, so uncontrolled that it causes arcs to earth, and between phases, unless clearances and spacings are prohibitively large. Thus, the use of an arc chute makes a considerable difference to the dimensions of a breaker. The requirements of a successful arc chute are : first, the minimum magnetic field should be applied which is able to keep the arc moving continuously up into the chute, and ensure that it is extended sufficiently to extinguish at the first or second current zero. Any greater magnetic field than this unduly elongates the arc, developing unnecessary arc energy with the adverse effects of high recovery transients due to pre-zero current-suppression. Secondly, the distance between the plates of the chute should be large enough to ensure that the free movement of the arc is not impeded by strangulation. Thirdly, the distance between the ends of the arcing horns incorporated in the chute should be sufficient to prevent restriking due to cathode-spot emission.

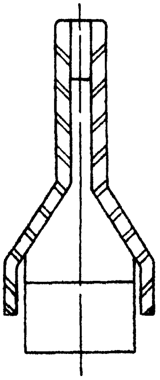


Fig. 28.—FRONT SECTIONAL ELEVATION OF ARC CHUTE (*Journal I.E.E.*)

These requirements are met by the horn and chute structure (Figs. 25 and 28) fitted to this class of circuit-breaker. No magnetic blow-out coil is provided, the inherent blow-out effect of the loop being more than sufficient to force the arc into the chute at currents between 2,000 and 37,000 r.m.s. amperes at 440 volts recovery voltage.

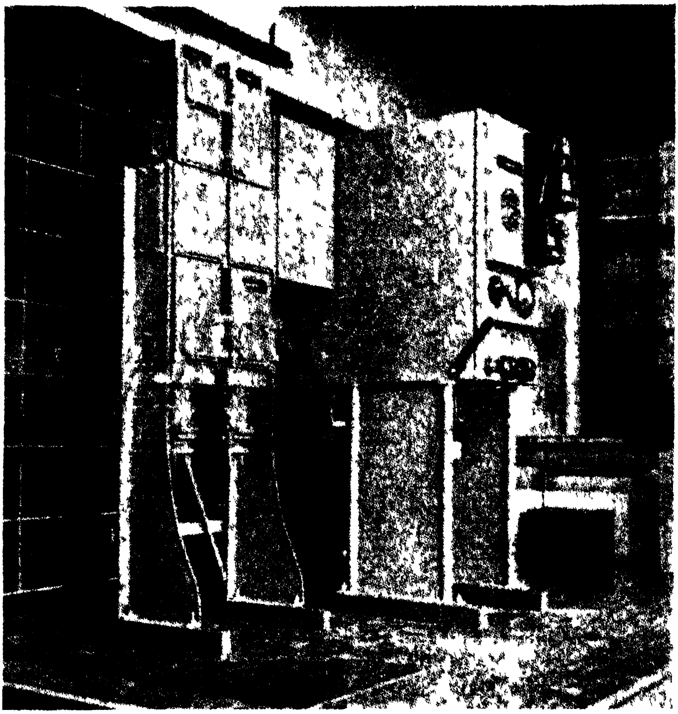


Fig 29—800 AMP SOLENOID OPERATED TOTALLY ENCLOSED AIR CIRCUIT BREAKER, AND 60 AMP H R C. SWITCH FUSE UNITS, 400 VOLT, 25 MVA. (*British Thomson Houston Co , Ltd*)

The effectiveness of the arc chutes is greatly increased by fitting correctly designed phase barriers between them. The arc in the chute is accompanied by the release of considerable arc energy, most of which is expended in heating up the ambient air to incandescence, leading to high pressures. Some more of the energy is used up in volatilising the metal of the contacts and arcing horns. This results in incandescent air and metal vapour being ejected from the top of the arc chute. On heavy currents the arc itself also partially leaves the top of the chute. It is necessary to ensure that these gases are cooled and the metal vapour condensed before they are allowed to strike earthed metal, or mingle with those from a neighbouring phase. This is ensured by U-shaped phase barriers which direct the gases into the cold ambient air.

Breakers for heavy-rupturing-capacity duty can be totally enclosed (Fig. 29).

By this arrangement, the metalclad principle, now so universally adopted for high-voltage oil-break switchgear, can be extended to medium-voltage air-break gear. In the totally enclosed type, a vent is provided for the relief of internal pressure developed during operation. The breakers may be operated either by hand or by solenoid, additional hand operation being provided in the latter case. It will be noted that the distance between the arcing contacts when open is comparatively small; this is generally true of all breakers in which the arc is controlled by magnetic blow-outs and/or arc chutes. When these devices are not used a long break between arcing contacts is essential. With the compensated type of arcing contacts, arcing times of less than half a cycle are obtainable.

High-speed D.C. Breakers

In some circumstances—notably for traction service—D.C. breakers with a very high speed of operation are installed to prevent flashovers on the rotary convertors, or "backfires" of mercury-arc rectifiers. With the former the breaker operates so as to stop the current rise, and reduce it below the flashover value in a time slightly less than that required for a commutator bar to pass from one brush-arm over to the next of opposite polarity; and with the latter to prevent excessive heating of the anodes. In D.C. circuit-breaking rapid fault clearance is obtained by a combination of high breaking speed and a powerful magnetic blow-out. Fig. 30 shows a high-speed D.C. breaker in which the separation of the contacts is relatively small, and effected by powerful springs. Under this condition the arc can only be extinguished by lengthening it artificially, consequently when the contacts open, the arc is blown upwards by a powerful blow-out magnet excited by series coils, and designed to give a field of intense strength, but of small area, around the contacts. As the

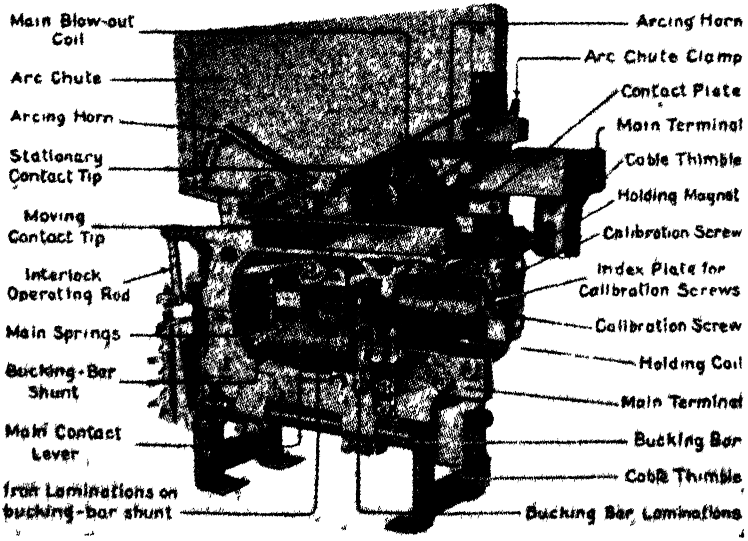


Fig. 30.—D.C. HIGH-SPEED CIRCUIT-BREAKER. (*British-Thomson-Houston Co., Ltd.*)

contacts begin to separate, the flux set up by the blow-out magnet forces the arc up into the long, narrow slots in the arc chute, where it quickly cools and collapses. The arcing spaces are narrower than the contact tips, thus increasing the resistance of the arc stream for a given length, and producing a maximum cooling effect for the metallic vapours. To ensure high-speed clearance special means are provided for automatic operation on fault currents.

In series with the contacts is an inductive shunt made up of iron laminations (this is the "bucking-bar" shunt in Fig. 30), and connected in parallel with this is the "bucking-bar." The latter is located in the gap between the poles of the electro-magnet, which holds the contacts in the closed position by attracting a small laminated armature (on the moving contact arm) bridging the gap in the holding magnet. Under normal load conditions the current divides equally between the "bucking-bar" and the "bucking-bar" shunt circuits. On the occurrence of a fault in which the rate of rise of the current is high, the inductive shunt diverts the greater proportion of the current through the "bucking-bar," and the magnetic field due to this deflects the holding coil flux from the armature to the iron contained in the loop of the "bucking-bar." If by this action the flux passing through the armature is reduced to a predetermined value, the armature is released, and the main contacts return to the open position with an extremely rapid action.

This type of circuit-breaker can be used up to 3,000 volts D.C. with slight modifications. In some cases the high-speed breaker does not open the main circuit, but shunts the current through a resistance which reduces it to below a dangerous value.

High-voltage Air-blast Breaker

Successful arc extinction in air depends on the rapid removal of the mixture of metallic vapour and ionised air which is the basis of the arc, and the inflow of non-ionised air between the contacts in place of the incandescent mixture. This principle is involved, more or less, in all air-breakers. In the case of the type with magnetic blow-out and/or arc chute a powerful upward air-blast across the contacts and through the arc chute occurs, which is initiated by the blow-out effect. With the high-voltage air-blast breaker used for the interruption of A.C. circuits a magnetic blow-out is not employed

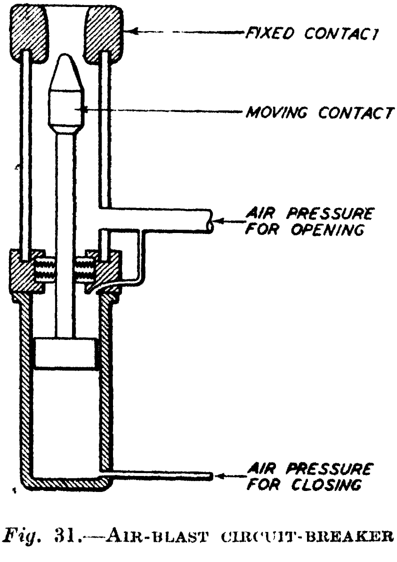


Fig. 31.—Air-blast circuit-breaker

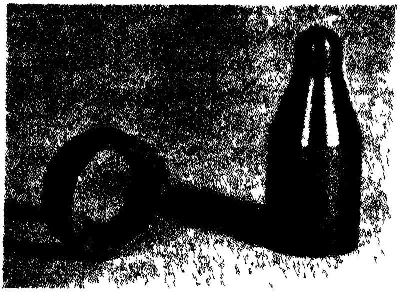


Fig. 32.—MALE AND FEMALE CONTACTS FOR AIR-BLAST GEAR

but compressed air is adopted for both arc extinction and the mechanical operation of the unit.

Fig. 31 shows the essential features of one type of air-blast breaker. This is closed by applying pressure to the underside of the piston, and is opened by applying pressure through the small pipe leading to the top of the piston. Compressed air is supplied from the same source to a chamber surrounding the moving contact, so that as soon as the piston has moved away from the fixed contact there is a blast of air at high pressure upwards between the contacts, which blows away the ionised air. Typical contacts for this form of breaker are shown in Fig. 32. The male plug consists of a copper body on to which has been cast a copper-tungsten skirt and a tungsten tip extremity. The female ring is wholly of tungsten.

Another type of air-blast breaker consists of several pairs of "horned" contacts in series, each situated in a separate arc chute. One contact is fixed and the other is moved rapidly by the air-blast, admitted when the circuit has to be interrupted, and the arc blown up the arc chute. In this country 3·3 and 33 kV. air-blast breakers are used successfully, but to a limited extent.

3,300 Volt Air-break Circuit-breaker

Apart from artificial air-blast high-voltage units, normal types of air-breakers have also been introduced for a limited range of high voltages. A typical 3,300 volt air-break circuit-breaker is shown in Fig. 33. This type was developed by the English Electric Company on the basis of certain fundamental principles of design which had been found to result in a very satisfactory performance when applied to 400 volt air-break circuit-breakers. The extension of these principles to high-voltage air breakers involved a new conception of contact arrangement to incorporate arc transference, and also of a de-ionising chamber capable of dealing with larger powers and higher voltages. This development led into new ground, as at the higher voltages larger breaking capacities became necessary. To ensure speedy positive interruption at these capacities demanded means for moving the arc promptly from the arcing contacts to the de-ionising chamber, introducing voltage into the arc in a smooth but rapidly increasing manner. Development towards this end led to the design of breaker shown in Fig. 33, which, fitted with the special form of arcing chamber shown in Fig. 34, is capable of performing a

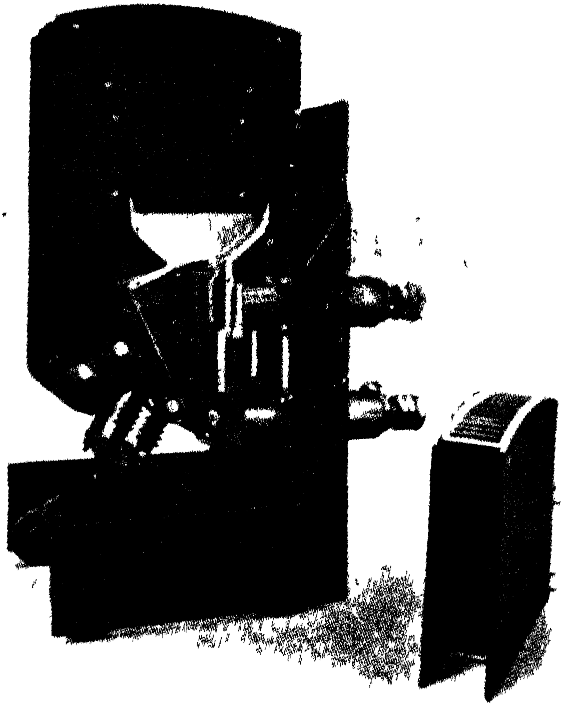


Fig. 33.—3,300 VOLT AIR-BREAK CIRCUIT-BREAKER

One arcing chamber removed, showing contacts in the closed position. (*English Electric Co., Ltd.*)

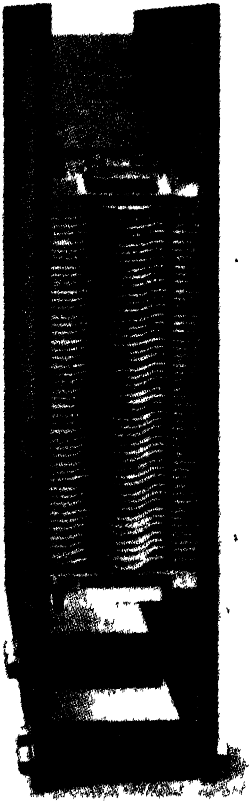


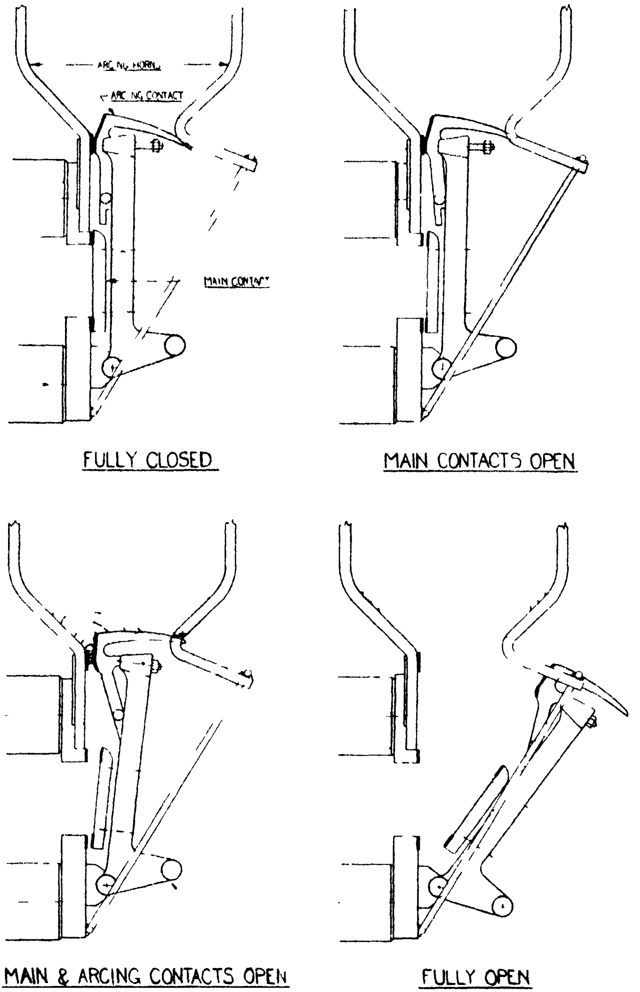
Fig. 34.—ARRANGEMENT OF PLATES IN A 3,300 VOLT ARCING CHAMBER, VIEWED FROM UNDERSIDE

(*English Electric Co., Ltd.*)

B.S.S. duty-cycle with values of fault kVA. which at one time could only be controlled by oil circuit-breakers.

No magnetic blow-out device is used, but a number of conducting plates of magnetic material are incorporated in the arcing chamber, magnetic control being effected by self-induction in the plates.

The contact system consists of two sets of contacts (Fig. 35): the main contacts, which serve only to carry the load current; and the arcing contacts, which protect the main contacts from deterioration during interruption. In addition two fixed arcing horns are used in conjunction with the contact system. The moving member of the contact system carries the spring-loaded arcing contact as well as the main contacts.



FULLY CLOSED

MAIN CONTACTS OPEN

MAIN & ARCING CONTACTS OPEN

FULLY OPEN

Fig. 35.—CONTACT-OPENING SEQUENCE OF 3,300 VOLT AIR BREAK CIRCUIT-BREAKER. (*English Electric Co., Ltd.*)

The arcing contact passes through a slot in the base of the front horn in the arcing chamber, and has an extended tail, which, in the closed position, maintains the arcing contact in close proximity to this horn. The operation of the breaker will be understood from Fig. 35.

The main contacts open first, the arcing contacts being temporarily maintained in the closed position by virtue of their being pivoted, as shown; when the arcing contacts open the arc travels up to the position shown in Fig. 35. The tail of the front arcing contact facilitates the transfer of the arc from this moving contact to the front horn in the arcing chamber at an early period in the formation of the arc, consequently the final break takes place between the arcing horns in the arcing chamber.

Single-phase and three-phase tests have been made on these breakers up to voltages as high as 5,000 volts, ranging in current value from a few amperes to over 20,000 amperes symmetrical r.m.s. "breaking," and crest values of current of over 60,000 amperes have been dealt with on "making" shots. The arcing time is limited to approximately two half-cycles at both the 100 per cent. and 10 per cent. duty cycles. The breaker action provides an overall operation time of approximately five half-cycles.

The circuit-breakers can be mounted in totally enclosed sheet-steel housings, and the usual form is the familiar withdrawable truck-type construction. The breaker illustrated in Fig. 33 is of this type. Alternatively, the breakers can be mounted in sheet-steel cubicles, suitably interlocked, and without the withdrawable feature.

The advantages claimed for high-voltage air breakers as compared with oil circuit-breakers are greater safety, due to the absence of the risk of fire and explosion; avoidance of the need to store, pipe, and filter oil, together with some lessening of the expense of inspection and maintenance.

Air-break units are being used to an increasing extent for both medium and high voltages. In America, for instance, air-blast circuit-breakers with ratings up to 15 kV., and 2.500 MVA. are being extensively adopted for indoor service. For outdoor work the field is being developed and the range extended to higher voltages.

Chapter VI

HIGH-RUPTURING-CAPACITY FUSES

AT one time the fuse was only suitable for the interruption of circuits in which the fault currents were of relatively low value, but the modern fuse in its more advanced forms is a reliable piece of apparatus with a precision performance capable of interrupting the high fault currents resulting from the progressive increase in the short-circuit capacity of distributing networks, both at high and medium voltages. In some circumstances H.R.C. fuses are now used instead of a more expensive circuit-breaker especially for industrial and rural distribution, and in many cases the inverse time/current characteristic obtainable with modern types permits reliable discrimination, for protection purposes, in relation to the circuit-breakers and other fuses used on the network.

Four main types are in general use : (1) cartridge, (2) liquid, (3) expulsion, (4) oil-immersed.

H.R.C. Cartridge Fuses

The cartridge type consists of a fuse element surrounded by an arc-extinguishing filler in the form of a granular non-conducting material, the whole being totally enclosed in a tubular insulating container. The special capabilities of the type arise largely from the control of the arc by a solid instead of a gaseous or liquid extinguishing agent. H.R.C. cartridge fuses are now made with breaking capacities such as to permit their use on high-power systems, typical three-phase rupturing capacities being 25 MVA. at 440 volts, and 300 MVA. at 33 kV. The semi-enclosed, re-wirable porcelain fuse is not usually suitable for interrupting more than 3 MVA. at 440 volts.

A suitable solid fuse-filler has a greater arc-extinguishing capacity not only than air but also than oil, owing to its property of absorbing and cooling metallic vapour produced by the arc. Most of the vapour is condensed at points remote from the arc, though some enters into combination with the filler. The resultant hot column of filler and vapour sets up a high, stable, and consistent arc voltage, which in practice may be as high as 1,000 volts per inch or more. This high value is dependent partly on the effect of pressure caused by the metallic vapour itself ; many designs, therefore, employ complete enclosure and high mechanical strength to allow this high pressure to build up, and to be resisted. Others provide a deliberate release for the pressure. The effect of the arc voltage in reducing the current to zero may be visualised as the introduction of a steadily increasing resistance in the current path.

The function of the usual oil or air circuit-breaker operating on A.C. is to prevent re-establishment of the arc when it is momentarily extinguished as the result of the current passing through zero, either on the first or a subsequent occasion. Before the current zero the voltage drop in the arc is small, generally, compared with the system voltage, so that the arc has little direct effect in reducing the current, which in a circuit of low power factor will continue to lag by nearly 90°. A similar action takes place in many fuses ; for example, all high-voltage fuses except the filled cartridge fuse appear to operate in this way. The latter, whether for high or low voltage, develops an arc voltage immediately the element vaporises that is usually high enough to initiate an immediate reduction of current at whatever point in the voltage wave the arc may commence.

At the same time the effect of suddenly introducing a high resistance is to advance the phase of the current, and, if the arcing period is as long as about $\frac{1}{4}$ cycle, the current by the time extinction occurs will have been forced approximately into phase with the voltage. Since the action does not depend on the natural passage of the short-circuit through zero, the fuse has a similar performance with both D.C. and A.C.

The filler has the property of being able to abstract a large amount of energy from the circuit. For example, a filler of silica, used in conjunction with a silver fuse-element, can absorb approximately 2 kW.-sec. per gramme. The greater part of the energy absorbed is used in fusing together the grains of filler surrounding the arc. The smaller the cross-section of the element the easier will be the duty of the fuse since there is less metallic vapour to be cooled by the filler. The opposite is often the case with other types of fuse, particularly those depending for arc extinction on a gaseous blast effected by the arc itself, since a large quantity of metal may, within certain limits, be advantageous as it tends to strengthen the blast.

The cartridge fuse is designed with the object of reducing the cross-section of the element within practicable limits. Some reduction can be effected by giving the fuse a low fusing factor, i.e. the ratio between the current that will blow the fuse in a specified time and its continuous rating. Fusing factor is, however, largely determined by other considerations, such as the extent to which overload protection is required.

In addition to interrupting short-circuits a fuse may be required to operate on dangerous overloads, in which case the maximum fusing factor of 1·6 specified in B.S.S. No. 88 is preferable, in order to prevent interruptions of supply by momentary overloads. For some purposes a fusing factor of 1·2 may be desirable, but it is often necessary to obtain a factor as high as at least 3·0 by selecting a fuse of higher current rating than the full load current of the circuit ; for example : fuses for motor circuits, for house-service use, and on the H.V. side of distribution transformers. In these, and other instances, the function of the fuse may be to give short-circuit, and not overload, protection.

Cartridge Fuse Elements

Methods of reducing the cross-section of cartridge fuse elements are: to use a metal of high electrical conductivity and high melting-point; increasing the dissipation of heat from the element, resulting in the use of a smaller section for a given fusing current; and subdividing the circuit through the fuse into a number of parallel elements, thus securing a very appreciable reduction of the total section, on account of the increased surface for heat-dissipation. A high rate of heat dissipation is inherent in the cartridge fuse because the relatively high thermal conductivity of the filler results in greater dissipation than from a wire surrounded by air, the corresponding increase in fusing current being about 2·9 times for the same cross-section.

Another factor contributing to the reduction of cross-section is the conduction of heat along the element. Most fuses are short enough for the end caps or terminals to have an appreciable heat-dissipating effect in the direction required. In addition, many designs, instead of using an element of the same section throughout its length, employ a type having one or more parts of reduced section (referred to later as " necks "), the heating of which determines the fusing current. Conduction along the element away from the neck thus reduces the cross-section required. Generally, the elements of all types of cartridge fuse are designed so that the end sections are of greater current-carrying capacity than the centre, with the object of dissipating the heat from the centre where the real break occurs.

Current Restriction

A small section of element also produces a very valuable current-restricting effect, because the smaller the section of the element of a fuse the more quickly does fusion occur under short-circuit conditions. If the prospective current is high and the thermal capacity of the element low, fusion takes place before the full prospective current of the circuit is reached, so that both the current at which arcing commences and the pre-arcing time are low. (The term " prospective current " has arisen because H.R.C. fuses act so quickly that the short-circuit current is interrupted before it reaches the maximum or " prospective " value possible with given circuit conditions.) Again, a low thermal capacity means that the energy to be dealt with by the fuse in the subsequent arcing period is reduced. Thus, if a reduced short-circuit current results from the use of a small cross-section, an easement of the breaking duty (equivalent to an increase in breaking capacity) is obtained in addition to that resulting from the reduction in the quantity of metal to be volatilised.

Current restriction is a factor of great importance in the design and application of fuses. Some types of fuse employ a high-resistance wire in parallel with a silver element so that this blows first, leaving the high-resistance wire to carry the current ; this wire increases the resistance of the circuit, thereby limiting the current to be interrupted. With A.C. the current-limiting effect is dependent also on the phase instant of the short-circuit.

Mechanism of Fusion

The exact way in which fusion occurs depends on whether the fuse is interrupting A.C. or D.C. : but, in general, when short-circuit current flows through the fuse—since for pure metals the resistance increases very considerably with temperature, while the specific heat does not vary greatly—the temperature of the element rises at an increasing rate until the melting-point is reached. The temperature then remains steady while the power developed by the current is devoted to supplying the latent heat of fusion, after which it rises at a rate which is further increased on account of the change in resistance on passing from solid to liquid. As the element vaporises, arcing commences and the voltage drop across the fuse becomes the maximum possible with the circuit conditions. At final clearance the resistance of the arc path builds up as the temperature falls ; the fuse voltage diminishes in a relatively gradual manner, the current correspondingly falling to zero. The method of operation is such as to prevent the setting up of high-frequency voltage oscillations.

The core of fused filler remaining after operation must have a satisfactory insulation resistance ; otherwise the resulting leakage current, apart from being in itself highly objectionable, may, while the fuse is still hot after operation, have a sufficiently high value to release appreciable energy in the fuse at a rate which grows as the resistance falls, until a violent "delayed failure" occurs. The breakdown voltage of the fused core is also important and, although much lower than that of the pure filler, it is, in good designs, of the order of several times the working voltage, and in general is at least as high as that of the insulation of the rest of the system.

Construction of Cartridge Fuses

The metals principally used for fuse elements are : silver, copper, aluminium, and zinc. Silver, apart from its high cost, is on the whole the best metal for fuse elements as it is free from oxidation. Aluminium, which has sometimes been used, has the disadvantage of forming a very marked skin. In certain bimetallic fuses silver or copper is combined with low-melting-point tin alloy.

There are two general types of filler : (1) The inert filler which in being fused by the arc gives rise to only limited chemical action. The most usual material of this sort is silica in one or other of its forms; the chemical action involved is the formation of small quantities of the silicate of the element metal. (2) The filler which gives off gas when heated by the arc, the action being endothermic. Pressure-relief vents are generally used, and need careful design to prevent emission of flame, and a too free release. The commonest example of this class of filler is calcium carbonate in the form of powdered or granulated marble, the gas evolved being CO_2, which is believed to assist in arc extinction.

High mechanical strength of the fuse body is usually considered necessary, and for this reason bodies are commonly made of ceramic material of a grade having special resistance to heat and internal pressure. On the other hand, at least one type of high-performance fuse successfully employs a comparatively light tube of fibre, in conjunction with pressure relief; in some ratings the gases are discharged into a separate chamber formed by the annular space between the main fuse tube and a surrounding outer tube. There is no marked distinction between low- and high-voltage cartridge fuses as the details of construction do not vary greatly; the principal differences arise from the necessity of using a longer element in the latter case.

Types of Fuse

Cartridge fuses for low and medium voltages can be divided into those using an element of one metal only, and those with composite elements. Where there is only one metal silver is almost always used. Except for ratings below about 10–20 amps., subdivision of the elements is usually employed. The paralleled elements are sometimes used in a single-bored body, while other designs employ a " honeycomb " type of body, each bore carrying only one or two elements. Occasionally the silver elements are paralleled by one or more fine wires of resistance alloy, which have been regarded as assisting in short-circuit interruption. Most designs used necked elements to promote cool operation and to reduce voltage

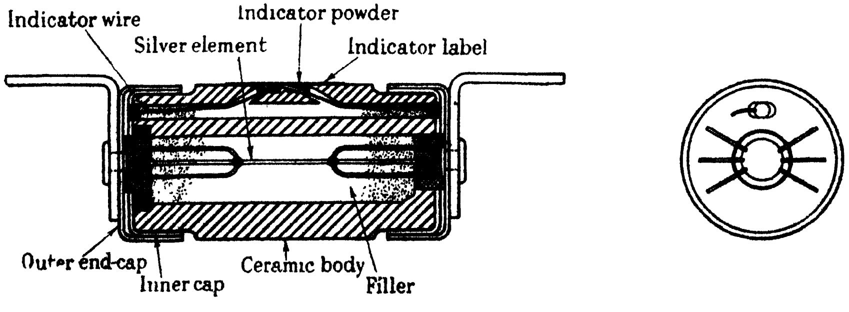


Fig. 36.—TYPICAL SILVER-ELEMENT MEDIUM-VOLTAGE CARTRIDGE FUSE (*Journal I.E.E.*)

surges. Heat insulation may be provided at the neck or necks to reduce the total loss in the fuse. A typical design of fuse with silver elements is shown in Fig. 36.

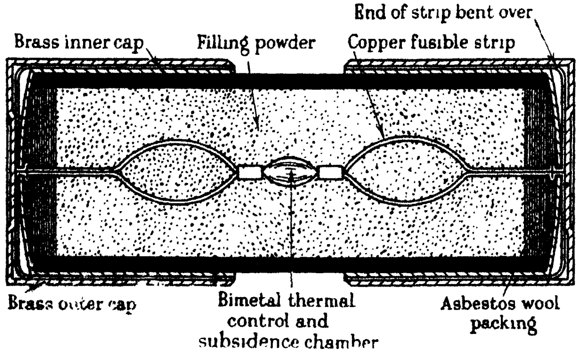


Fig. 37.—TYPICAL BIMETALLIC MEDIUM-VOLTAGE CARTRIDGE FUSE. (*Journal I.E.E.*)

The object of the composite-element construction is to afford longer time-lags on overload than are associated with simple silver elements, and to facilitate cool operation, and consequently a low fusing factor. In one form, a copper or composite copper/silver element is provided with two necks, and with a complete gap bridged by a mass of low-melting-point tin alloy of large cross-section. Short-circuits are interrupted by fusion of the neck or necks, the alloy being left intact. Overload operation results from the alloy being melted by the heat generated at the necks, and the time-lag is largely dependent on the time necessary for the heat transfer. A typical design is shown in Fig. 37. In a type introduced more recently the element is of silver carrying a blob of solder. Under overload conditions the silver reaches a temperature at which amalgamation between the silver and the solder occurs, and the resulting increase in resistance causes fusion. Short-circuits are cleared by the silver fusing in the normal manner. Where indication of operation is required, a fine wire in parallel with the main elements is provided. Fusion of this wire either fires a small quantity of a mild explosive to give indication by charring a paper label, or releases a small indicating spring.

H.V. Cartridge Fuses

In some designs of high-voltage cartridge fuse the arrangement is generally similar to that used at lower voltages, but with an appropriately increased length of body. In others, particularly for 11 kV. and upwards, the required length of element is obtained by winding it in the form of a helix on a ceramic core of star-shaped cross-section running along the axis of the fuse tube, the space between the two members containing the filler. This arrangement would be ineffective with a fluid filler, but in a powder of suitable dielectric properties the current continues to follow the helical path after arcing has commenced. The element, in certain designs, is of uniform section, but is provided with heat insulation near

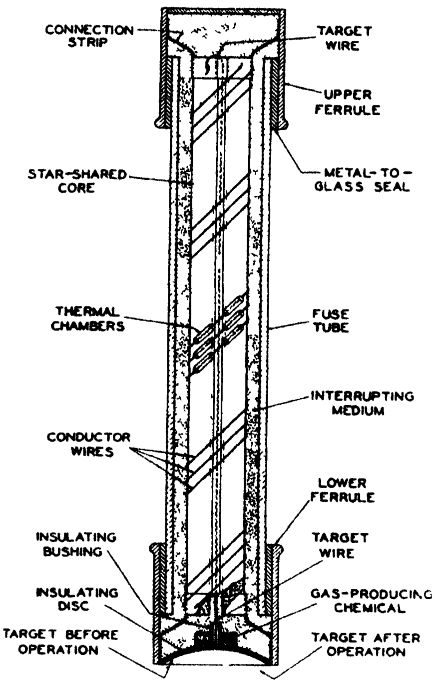


Fig. 38.—TYPICAL SPIRAL ELEMENT HIGH-VOLTAGE CARTRIDGE FUSE
(*Journal I.E E.*)

the middle of its length to initiate fusion there under overload conditions. In other designs, while no definite neck is arranged, there is a slight variation of section to reduce voltage surges produced by simultaneous fusion of the whole length of the element. Alternatively, reduction of surges is obtained by using high-resistance parallel elements whose resistance increases considerably with the passage of current immediately before fusion. For this purpose tungsten is used, as it has a high melting-point of over 3,000° C. A high-voltage fuse with helical element is shown in Fig. 38.

With high-voltage cartridge fuses the necessity for special arrangements to reduce heating of the fuse are less important than at the lower voltages, because currents are lower and cooling is better. When indicators are fitted they are designed to be visible at a distance if the fuse is to be used for outdoor work. Fusion of the indicator wire, usually, either releases a spring operating an indicating plunger or fires an explosive to expel the plunger. The movement can be used in some designs for remote indication, or to operate a switch which prevents single-phasing by opening all phases when a fault occurs in one.

Liquid-filled Fuses

Fuses of the liquid type are used extensively for the interruption of high-voltage circuits, being particularly suitable for outdoor distribution networks. Two representative liquid fuses are the S & C carbon tetrachloride and the Quenchol fuse. Ranges of these fuses are available for systems operating up to 132 kV., and for rupturing capacities ranging from 5 to 1,000 MVA. These chemical-extinguisher types of fuse operate in a manner similar to that of the oil circuit-breaker, the gap in the circuit being formed, when the fuse element has blown, by the action of a spring ; and the arc is extinguished in the liquid dielectric. Tests have been made of this type of fuse to determine the capacity of 132 kV. units with a view to obtaining an economical method of tapping main transmission lines. Short-circuit tests up to 992 MVA. were cleared successfully in times ranging from 1 to 2 cycles, and short-circuits up to 300 MVA. in ¾-cycle. Under this condition the fuses were well within their capacity and showed no signs of distress. The essential function of the high-voltage fuse mechanism is the introduction of a gap of sufficient dielectric strength to prevent the recovery voltage from re-establishing the arc. The action must take place in the minimum period of time, otherwise, at heavy currents, the thermal effect of the arc will completely destroy the fuse, thereby causing a fault on the high-voltage network.

Construction of Liquid Fuses

The liquid fuses shown in Figs 39 and 40 are of simple construction, the main features of each being generally similar. The fuse element consists of two wires in parallel the fuse wire or link, and the strain wire. The former is a low-resistance wire of low tensile strength, and the latter a high-resistance wire of high tensile strength, which carries little current, its primary purpose being to take the strain of the helical spring. Inside the spring is a flexible copper cable for carrying the normal current through the fuse, thereby preventing overheating of the spring, and ensuring its effectiveness when required to function as the means of introducing the break in the circuit.

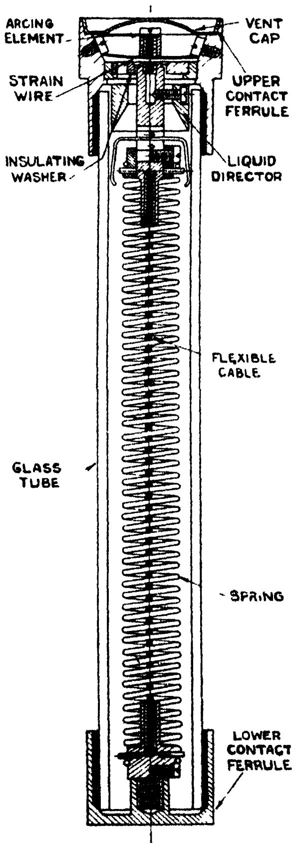


Fig. 39. —SECTIONAL VIEW OF S & C HIGH-VOLTAGE LIQUID FUSE

Operation

Attached to the upper end of the spring is a plunger—termed the liquid director—which is part of the electrical circuit, the fuse element being fixed to it, as shown in Figs. 39 and 40. The upper end of the fuse is fitted with a vent or valve cap. With this type of fuse the melting of the low-resistance fuse wire shunts the current through the strain wire which, being of low current-carrying capacity, instantly melts and allows the spring to contract. As the plunger descends the arc is drawn into the liquid, which is forced up through the liquid director. The liquid is rapidly vaporised by the heat of the arc, and a high pressure is developed which forces the vapour around the arc stream. This action results in the rapid de-ionisation of the arc path as the current approaches zero, so that the dielectric strength of the gap necessary for the final interruption of the circuit builds up very rapidly; being accomplished in ½ to 2 cycles. When interrupting heavy overloads the glass tube is strong enough to withstand the internal pressure developed, but under severe short-circuit conditions the vent or valve cap blows away to relieve the excessive pressure.

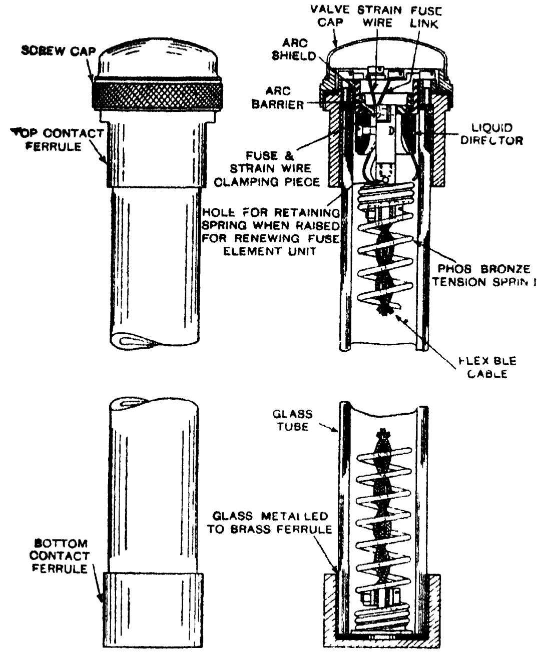


Fig. 40.— Sectional Arrangement of Types III and IV Quenchol Liquid Fuse for High Voltage

Each type of fuse varies as regards the details of construction according to its rating. Two main types of S & C fuse are in use, designated as B and D, which cover a range of 2·2 to 132 kV., and ½ to 400 amps. The Quenchol range is divided into four types for voltages from 3·3 to 110 kV., and fusing currents from 1 to 200 amps. For types I and II the two wires of the fuse element are surrounded by a cork casing, which confines the arc at the instant of break and prevents undue shock to the glass. In types III and IV the fuse element is enclosed in a separate chamber at the top of the fuse. This chamber is formed by the arrangement of steatite barriers carried by the element ring. Under severe fault conditions the first effect of the pressure generated in the chamber is the ejection of the valve cap, while at the same time the arc barrier prevents this pressure from being communicated to the glass tube. As soon as the plunger begins to descend the pressure in the tube is relieved by the arc barrier being blown from its seating. When very severe faults are being interrupted, the retaining pieces holding the arc shield in position are bent upwards, and the arc shield itself is ejected. This form of construction enables a high breaking capacity to be obtained.

The Quenchol liquid is a special mixture of chlorinated hydrocarbons with powerful arc-extinguishing qualities, and high dielectric strength which remains effective over any range of temperatures encountered in

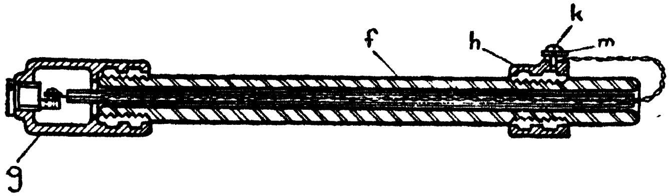


Fig. 41.—SECTIONAL ARRANGEMENT OF AN 11,000 VOLT G.E.C. EXPULSION FUSE, SHOWING THE INTERNAL ASSEMBLY

f = Barrel ; *g* = Expansion chamber ; *h* = Bottom contact ; *k* = Terminal.

practice. When tested with a standard B.S.S. oil gap, i.e. 15 mm. spheres and a 4 mm. gap, breakdown occurs at 45 to 50 kV., as compared with a B.S.S. minimum for oil of 30 kV.

Expulsion Fuses

A typical expulsion fuse is shown in Fig. 41. Circuit interruption depends on the generation of pressure by the fusion of the wire in the expansion chamber *g*. The wire connecting the two fuse terminals is made up in such a way as to ensure the portion in the expansion chamber melting first. The pressure developed expels the remaining portion of the wire, and the hot ionised gases, out of the open end of the barrel *f*, consequently a long insulating path is introduced between the terminals to prevent re-establishment of the arc after a current zero. The time taken for interruption depends on the value of the current through the fuse. Tinned-copper fuse wire is used in the type illustrated and it is, therefore, easily renewable. Expulsion fuses are in use for circuits up to 66 kV., and for normal currents up to 200 amps. Although their rupturing capacity is generally lower than that of liquid fuses, certain types have interrupted faults estimated at 500 MVA. at 66 kV.

Oil-immersed Fuses

The oil-immersed fuse consists simply of a wire connected to terminals under oil. If of small cross-section the wire may be enclosed by some arrangement providing mechanical support. In the case of the fuses used in the switch-fuse in Fig. 49, below 10 amps. normal current the fuse element consists of a fine wire enclosed in a small glass bulb, to provide the necessary mechanical strength, which breaks when the fuse wire blows. Above 10 amps. a bare-wire fuse element is used as the cross-section is sufficient to provide the required mechanical strength. The fuse element, of either type, is fitted with two terminals for inserting in the contact clips which are attached to tension springs as shown in Fig. 49. This arrangement combines a short length of wire, and, therefore, a small quantity of metal to be volatilised, with a long clear break.

The oil-immersed fuse is also employed for the protection of the high-voltage winding of potential transformers.

Chapter VII

SWITCH-FUSEGEAR

FOR the control of some power circuits automatic circuit-breakers are not required as the amount of fault energy that can flow under the worst conditions is such that fuses can be adopted for successful circuit interruption, in conjunction with a non-automatic switch for normal control. Various types of switches and fuses are used in combination for both H.V. and L.V. circuits. Of particular interest are recent developments effected to obtain full advantage of the high-rupturing capacity of modern fuses.

H.R.C. Switch-fusegear

Certain non-automatic switches employed in conjunction with H.R.C. fuses are capable of making and carrying the short-circuit current permitted by the maximum size of fuse that can be accommodated in the switch-fuse. The effect of this is to convert the switches to the equivalent of non-automatic circuit-breakers with a low ratio of rupturing capacity to normal continuous-current rating. To obtain a high standard of performance contacts and operating mechanisms have been designed to meet modern conditions of high-fault kVA. In the case of contacts: first, they must be able to meet their making-capacity rating without blowing-off, or undue burning. Secondly, they must be such that an inherent blow-out effect is obtained without any multi-turn blow-out coils. Thirdly, they must carry their continuous current without overheating. A form of contact which meets these requirements is shown in Fig. 42.

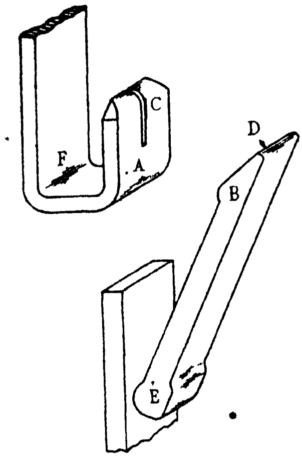


Fig. 42.—CONTACTS FOR SWITCH-FUSE. (*Journal I.E.E.*)

Magnetic blow-off forces are kept to a minimum by keeping the dimensions AF and AE small. Above 10,000 (peak) amps. multi-contacts are used to subdivide the current. The good making and breaking characteristics are obtained by using butt contacts with a wiping action upon closing. The configurations of the contact surfaces ensure that the arc originates at AB and travels up to CD.

Powerful arc chutes are adopted in conjunction with this type of contact. Whilst the quick-make/quick-break mechanisms which are very common on low-duty switch-fuses are satisfactory for certain applications, they are not suitable for the high-duty switch-fuse. Such mechanisms fail because they are unable to force the contacts right home when they have been burned by current making and breaking. This failure is due to roughening, and the presence of copper beads. Recent types of mechanism are designed to ensure positive operation. A complete switch-fuse unit consisting of a 200 amp. non-automatic air-break switch and H.R.C. fuses is shown in Fig. 43. This unit has contacts of the type shown in Fig. 42; the special arc chutes should also be noted.

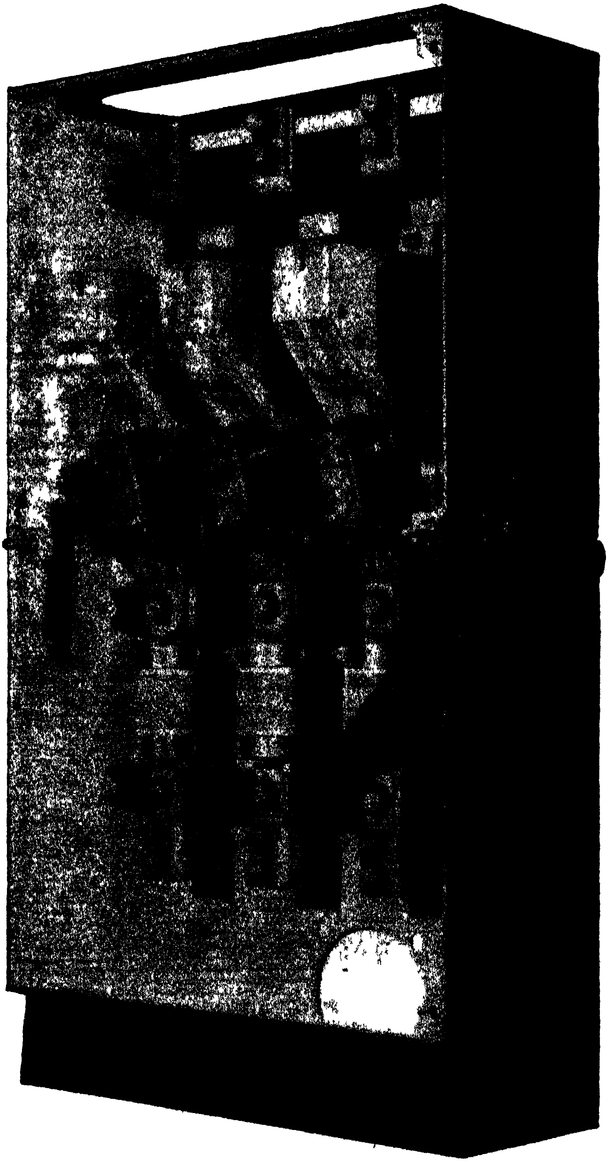


Fig. 43.—200 AMP. SWITCH-FUSE; COVER REMOVED
(*British Thomson-Houston Co., Ltd.*)

When the cover is on, the case is divided into two compartments by an insulating barrier, the switch being located in one part and the fuses in the other, access to the latter compartment being obtained through a hinged-front lid. The operating handle is brought to the outside of the case, all live parts are enclosed and the necessary interlocks provided to ensure complete safety to the operator. The proportions of the closing mechanism and the design of electrical contacts allow the switch to be closed safely on to a fault having a prospective short-circuit current equivalent to 25 MVA. This equipment is also illustrated in Fig. 29.

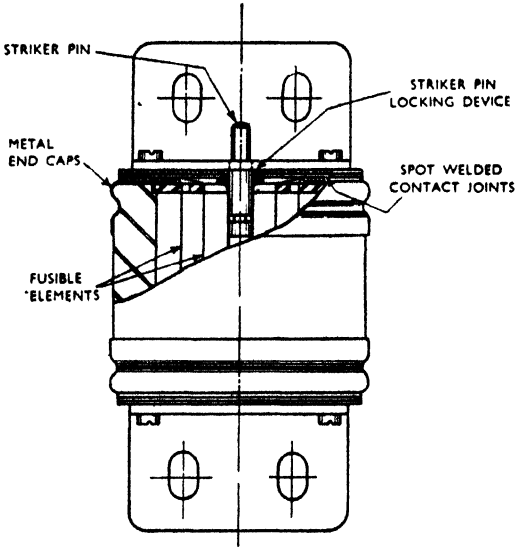


Fig. 44.- H.R.C. FUSE WITH STRIKER PIN FOR TRIPPING SWITCH. (*Johnson & Phillips and Electric Transmission, Ltd.*)

Switch-tripping Fuses

A disadvantage associated with the use of fuses for the interruption of faulty three-phase circuits is that all three fuses must blow before the circuit is entirely disconnected. Thus if only one fuse blows, as may be in the case of a fault from one line to earth, the circuit is maintained via the other two lines, and motors may continue to run as modified single-phase machines, the two healthy lines carrying the whole electrical input to the motor. This may lead to overheating of the cables and motors, with consequent risk of breakdown later. To avoid this it is advisable to use an automatic switch-fuse operated by a suitable protective device.

A device recently introduced to prevent single-phasing is the EETEE/JP, H.R.C. fuse incorporating a striker pin for tripping the switch. Fig. 44 shows a fuse of this type.

The fuse, of the filled cartridge type, has silver elements for carrying the main current and a shunt wire of high-resistance tungsten to which the current is transferred when the silver elements melt. In series with the tungsten wire is a weak fusible section connected directly to the striker pin. The weak section dissipates shortly before final clearance of the circuit and causes ignition of a small chemical charge contained below the piston of the striker pin. Although the chemical charge is too small to produce any destructive effect, when it is fired the striker pin is forced outwards to operate the trip of an associated switch. The mechanical movement of the striker pin is effected in approximately $\frac{1}{4}$ second. This short interval ensures that the actual electrical interruption through the tungsten element has long been completed before the striker pin has operated the trip mechanism.

Tests show that the striker pin begins to move 3 to 5 cycles after interruption is complete. After operation it is important that the striker pin should not be forced back into the fuse, otherwise it might be possible to re-close a switch with the fuse blown. A locking catch is, therefore, provided to prevent this. An additional feature of the striker pin is that its position gives an immediate indication of a blown fuse.

When used in conjunction with L.V. air-break gear the fuses are fitted into a case with a switch, in the form of a modified air circuit-breaker, which can be latched in. A quick-break action of the switch when opening ensures that the circuit cannot be disconnected slowly; in fact, the opening speed is entirely out of the control of the operator.

A typical switch-fusegear installation incorporating tripping fuses is shown in Fig. 45. The switch contacts are of the contactor type making line contact under high pressure. Both in making and breaking circuit, a very definite wiping action occurs at the contact faces, thus maintaining a good and clean contact surface at all times. The contacts are of the single-break type, the heel portion being permanently connected to the lower fixed contact by a flexible copper jumper. Arc chutes, together with arc runners on the main moving contacts, promote rapid attenuation of the arc.

The H.R.C. tripping fuse with its ultra-rapid cut-off is also the basis

Fig. 45.—AIR-BREAK SWITCH-FUSEGEAR INCORPORATING FUSES WITH STRIKE-PIN DEVICE
Two oil-immersed switches are also shown. (*Johnson & Phillips, Ltd.*)

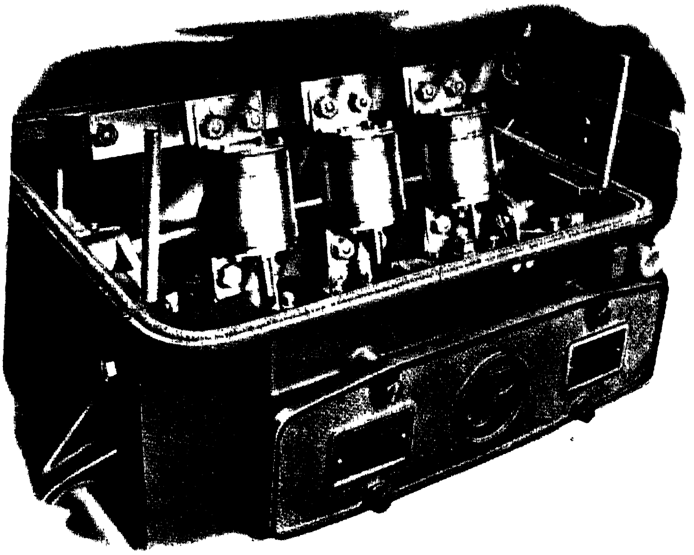


Fig. 46. Tripping Fuses applied to Oil Break Switchgear
(*Johnson & Phillips, Ltd.*)

of a high-breaking-capacity type oil-break switch for use on low-voltage systems. The unit is shown in Fig. 46. Three fuses are carried on a chassis in such a way that the tripping plunger impinges on the same trip bar as is provided for the overload and other protective devices. By this means a breaker of relatively low breaking capacity is immediately converted to one of much higher breaking capacity. In addition, it provides for three-phase tripping if only one fuse blows. Access to the fuses is obtained by removing the top cover, which is interlocked so that it cannot be removed unless the circuit-breaker is open and isolated.

Tests on a particular type of oil-breaker demonstrated that, when not associated with H.R.C. fuses, their capacity for making on to an existing fault would be limited to approximately 15 MVA. at 400 volts. Later tests with fuses proved that the breakers are good for 30 MVA., and even at this value no distress in operation was indicated. Closing on to peak currents of about 89,000 amps. was accomplished without difficulty, and the ultra-rapid action of the fuses limited the burning of contacts to mere pinheads. The rapid cut-off action of the fuses makes it impossible for an operator to be in trouble when closing on to a fault as the fuse functions as a " force-trip " device.

Outdoor-type Isolating-switch-fuses

Liquid and expulsion fuses are used in combination with outdoor-type link-switches to form what are, in effect, switch-fuse units for the control of H.V. overhead systems. By this means inexpensive, but effective, switching can be provided for networks of limited fault-current capacity where the demand for energy is insufficient to warrant a more costly arrangement.

In some cases the fuse itself is designed with a special cartridge so that it can be used as an isolating switch as well. An isolating switch employing an expulsion fuse for the link, and suitable for the protection of distribution transformers up to 200 kVA., and voltages up to 11 kV., is shown in Fig. 47. The fuse is shown in the open position. It is arranged for vertical mounting at a convenient height for pole operation, the fuse barrel being in an upright position when closed and opening outwards. The fuse holder consists of a hollow porcelain barrel fitted with a contact at each end, the lower contact being capable of swivelling in a vertical plane on a hinge mounted on the lower of the two insulators which hold the fuse in position.

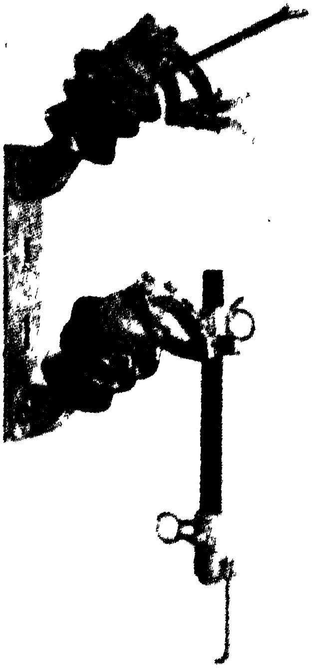


Fig. 47.—11 kV. ISOLATING SWITCH-FUSE EMPLOYING AN EXPULSION FUSE FOR THE LINK

(*General Electric Co., Ltd.*)

Both contacts on the fuse barrel are fitted with eye-rings into which a hooked operating rod can be inserted. By pulling the upper eye-ring the fuse can be pulled out of the top insulator contacts after the manner of an isolating switch. In the isolated position, the lower eye-ring is accessible and the fuse unit can be removed for rewiring by inserting the hook of the operating rod and giving an upward jerk.

Arcing horns are fitted to the upper contact of the fuse unit and to the fixed contact of the upper insulator, thus enabling the isolator to open circuit under light load conditions. Currents up to 8 amps. at 11 kV. can be safely ruptured by the horns.

Fuse-isolating Switches

Some fuse-isolating switches automatically isolate the circuit when the fuse has blown, thus avoiding manual operation of isolators. A typical equipment is illustrated in Fig. 48. The important feature of this unit is the fact that when the fuse is blown the barrel is automatically released from the top contact and held suspended from the bottom bracket, thus indicating the exact position of the blown fuse. The fuse is of the expulsion type; it is easily re-wirable and has a three-phase breaking capacity of 36 MVA.

The fuse element consists of a short length of fuse with one end attached to a brass connector lug, and the other silver-soldered to a length

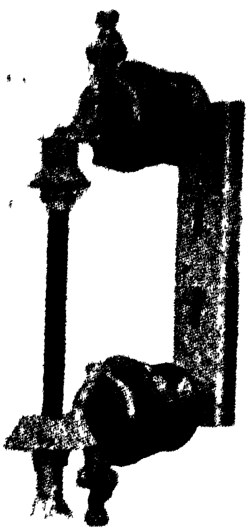


Fig. 48.—COMBINED FUSE AND AUTOMATIC ISOLATING SWITCH FOR CIRCUITS UP TO 22 KV.

(*General Electric Co., Ltd.*)

of tinned-copper flexible cord. The actual fusible element is encased in a length of bakelised sleeving. The complete fuse element is threaded through the bore of the fuse barrel, the top end being attached to the top contact, and the bottom end to the release levers. The tension of the fuse element is such that the release levers are set so that they register with a catch seating on the bottom fixed insulator. When the fuse melts the levers are released, allowing the fuse carrier to drop to the bottom contact, where it is prevented from falling to the ground by means of two spigots with hard rubber buffers. This combination of fuse and automatic break switch is used for protecting transformers and distribution lines against limited fault currents. Alternatively, the various types of switches and fuses of the outdoor class are mounted as separate components of a complete substation equipment.

Oil-immersed Switch-fuses

In situations where the expenditure for oil circuit-breaker equipment would be uneconomic, but at the same time air-break gear is not permissible, oil-immersed switch-fuses afford inexpensive and efficient protection, with a definite breaking capacity, for certain high-voltage circuits. For example, small consumers at outlying points on a system are often supplied by oil-immersed switch-fuses when a comparatively expensive automatic circuit-breaker installation would not be a commercial proposition. With power transformers of medium kVA. the switch-fuse gives adequate protection on the H.V. side against short-circuits, leaving the protective apparatus on the L.V. side to take care of overloads. Ring-main isolator equipment is also used in conjunction with oil-immersed switch-fuses for the purpose of connecting a series of stations into the ring.

A typical oil-immersed switch-fuse is shown in Fig. 49. This consists of a steel-plate tank, having suitably spaced lining and phase barriers, with a fuse for each phase mounted between contacts fixed to the inside of a hinged lid. When the lid is closed the contacts engage with fixed contacts carried by insulators secured to the sides of the tank. When the lid is open the moving contacts, and consequently the fuses, are out of circuit and clear of the oil.

The equipment is used for circuits up to 11 kV., and the fuse elements of two types (see page 75) have a range of up to 100 amps., normal current. A steel-plate hinged lid is operated by a loose handle which normally lies flat against the top of the cover. This is first raised to the vertical position by means of the long lever and from this position it is lowered to the fully open position by means of the second handle at the top of the cover. Fig. 49 illustrates this operation. An interlocked isolating device is provided which enables the top lid to be closed and bolted down before the fuse is put in circuit, thereby avoiding the risk of the lid being closed on to a live faulty circuit, and being blown open. One set of three insulators inside the cover is mounted so that it can be rotated from outside the tank by a handle at the side. The contacts at the lower end of these three insulators engage the contact clips fitted to the fixed insulators which pass through the tank.

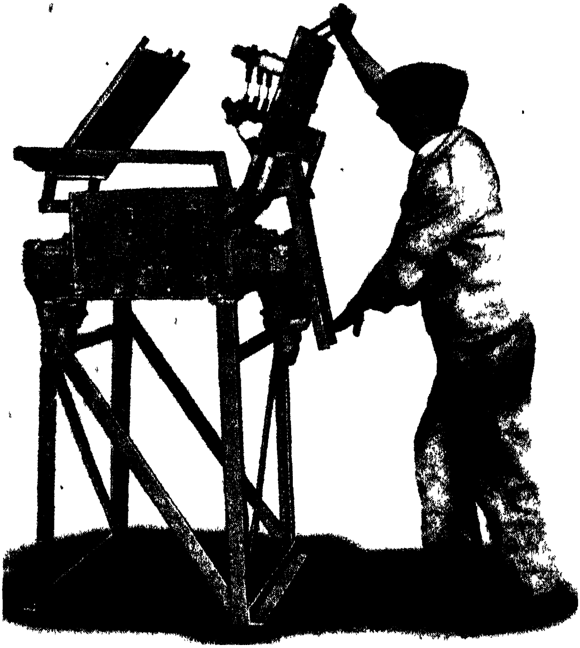


Fig. 49.—OIL-IMMERSED SWITCH-FUSE, SHOWING THE LID OPEN FOR ACCESS TO THE FUSES

(*English Electric Co., Ltd.*)

The fuse proper is connected between one fixed contact and one movable contact. As the fuse is carried between springs, the small movement of the movable contact does not distort it. The isolating device is interlocked with the lid in such a way that :

(*a*) The top lid cannot be opened or closed until the handle of the device is in the " off " position.

(*b*) The isolating handle cannot be moved to the " on " position until the lid is fully closed.

The isolating device is suitable for breaking small currents such as transformer exciting currents, and line charging currents, of the order of 5 amps. at 11 kV., or 10 amps. at 6·6 kV.

When the lid is opened to gain access to the fuses a protecting cover is automatically brought into position over the top of the switch-fuse, thereby protecting the live parts from accidental contact, and preventing

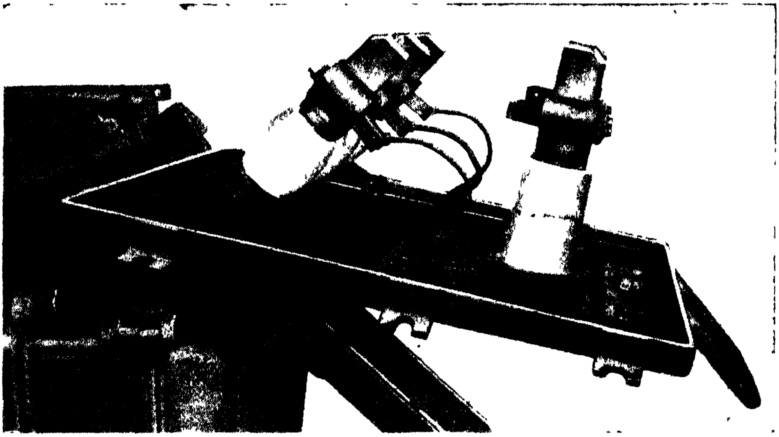


Fig. 50.—OIL-IMMERSED SWITCH-FUSE UNIT, SHOWING THE LID OPEN WITH EARTHING BRAIDS IN POSITION. (*English Electric Co., Ltd.*)

the entry of dirt or moisture whilst the lid is left open. By the use of this device the switch-fuse is suitable for isolating a circuit for any length of time. In the normal operating position of the unit the protecting cover stands in an almost vertical position exhibiting a "danger" notice.

Special provision is made in these switch-fuses for earthing and testing cables. Permanent earthing sockets contained in screwed plugs are provided inside the lid opposite each phase, as shown in Fig. 50. To earth the circuit the fuses are removed and a set of short flexible leads is connected at one end to the fuse sockets, while the other ends are plugged into the earth sockets. By closing the lid which contains the earth sockets, and then the isolator, earthing is completed. To test the circuit, the metal plugs in the lid are removed and replaced by three insulated terminals suitable for "loop" or insulation tests.

Chapter VIII

POWER TRANSFORMERS

BASICALLY the transformer is a simple piece of equipment ; the complicated appearance of some modern units results from the addition of various components to meet requirements of high voltage, high efficiency, and large capacity.

Without entering fully into the theory of the transformer it may be of assistance to briefly restate the elementary principles involved. When an alternating voltage is applied to the primary winding of a transformer, with the secondary circuit open, a small current—lagging nearly 90° ($\frac{1}{4}$-cycle) behind the applied voltage—flows in the primary circuit only. This no-load current is the vector sum of two components ; the current required for the no-load energy losses, and the magnetising current. The first component is associated with the iron losses—the copper loss is negligible —and is in phase with the applied voltage, while the second, lagging 90° behind the applied voltage, serves to magnetise the core and create the flux which induces the voltage in the secondary winding. The ~~value of~~ the magnetising current is limited by the back E.M.F. it induces in the primary ~~winding~~ by virtue of the ~~inductive nature~~ of ~~that~~ winding. The back E.M.F. opposes the applied voltage, thereby limiting the effective voltage available for circulating magnetising current in the primary circuit.

The secondary voltage is given by the formula :

$$E = \frac{4.f.n\,\Phi\,T}{10^8} \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where E = r.m.s. value of the induced voltage.
f = form factor of the applied voltage wave (1·11 for a sine wave).
n = frequency of the supply.
Φ = total magnetic flux through the core.
T = number of turns in the winding.

The formula (1) applies to both the back E.M.F. induced in the primary and the induced voltage in the secondary ; the value of the voltage induced in each winding is directly proportional to the flux and the number of turns on the winding, and as the flux is common to both windings the voltage induced in a single turn of each will be practically the same. Furthermore, the difference between the applied voltage and the primary back E.M.F. is small, consequently, ~~the ratio of~~ the voltages of the two windings—the transformation ratio—is equal to the ratio of the numbers of turns, i.e.:

$$\frac{V_p}{V_s} = \frac{T_p}{T_s} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where V_p and V_s are the voltages of the primary and secondary circuits respectively, T_p and T_s being the corresponding number of turns.

Also, for practical purposes, the primary kVA. = the secondary kVA., and the current in the windings will be in inverse proportion to their voltages. For example, a transformer with a transformation ratio of 15 to 1 connected to a 6 kV. supply will have a secondary voltage of 400, and when the current in the primary is 10 amps. the current in the secondary will be 150 amps.

On open circuit the transformer acts as a single winding of high self-inductance, and the open circuit power factor averages about 15 per cent. When the secondary circuit is closed the value of the current that flows in the secondary winding is determined by the magnitude of the induced voltage, and the impedance of the whole circuit. The secondary load current produces a flux in the core, in phase with the current, which tends to reduce the effect of the self-inductance of the primary. Thus the primary current increases and produces a flux equal and opposite to that due to the secondary current, so that the core is maintained in its initial state of magnetisation, i.e. the open-circuit magnetisation. For this reason the iron loss is independent of the load. The total current in the primary winding is the vector sum of the primary load current and the no-load current.

Impedance Voltage

Actually, as the primary and secondary windings cannot occupy the same space the magnetic fluxes due to the primary and secondary currents do not exactly balance each other; there is a stray or leakage flux which induces a back E.M.F. in both windings. In the primary winding this back E.M.F. is additional to the original open-circuit back E.M.F. and acts to reduce the magnetising current with increasing load, consequently the induced secondary voltage is also reduced. In the secondary the effect of the leakage flux is to induce an E.M.F. opposing that induced by the main flux so that the voltage available at the terminals is further reduced. Thus there is a reactive voltage-drop in each winding, additional to the drop due to the resistance, which is comparatively small; and the sum-total effect of the various voltage-drops is manifested at the secondary terminals as the impedance voltage-drop of the transformer.

The impedance drop is usually expressed as a percentage of the normal primary voltage, and varies directly as the load, within the normal limits of loading: i.e. an impedance voltage of 5 per cent. at full load would be 2½ per cent. at half load, and 6¼ per cent. at 25 per cent. overload.

Since the effect of the transformer impedance is to cause a progressive decrease in the output voltage as the load increases, this, together with fluctuations of the supply voltage, may necessitate some means of controlling the system voltage, either by apparatus auxiliary to the transformer, and in certain circumstances located at a position on the network not directly associated with the transformer, or by on-load tap-changing gear integral with the transformer.

Principles of Tap-changing

Tap-changing equipment is dealt with in a later chapter, but certain principles involved can be conveniently discussed at this stage. From formula (2) $\left(\frac{V_p}{V_s} = \frac{T_p}{T}\right)$ it is clear that with V_p constant, the value of V_s can be varied by changing the ratio of T_p to T_s—the turns ratio. The function of tap-changing voltage control equipment is to enable the turns ratio to be varied, within limits determined by the particular requirements, by adjusting the number of turns on either the primary or secondary windings, or both. As the number of turns on each winding is, of course, fixed, variation of the turns ratio is effected by adjusting the number of turns actually in circuit, tappings being taken from the winding, or windings, for this purpose. Although the effect of adjusting either the primary or secondary turns is the same, the fundamental cause of the variation of secondary voltage differs according to which winding is tapped. The effect of adjusting the number of primary turns in circuit is to change the self-inductance of the primary winding, which determines the value of the back E.M.F. opposing the applied voltage. The change in the value of the back E.M.F. brings about a corresponding change in the value of the magnetising current which results in an alteration in the value of the flux in the core inducing the secondary voltage. Thus, when the number of primary turns is decreased, the inductance—which varies as T_p^2—also decreases, and the magnetising current increases; the opposite being the case when the number of primary turns in circuit is increased. The variation of magnetising current produces a corresponding variation in the value of the total flux so that, for a constant number of secondary turns, the volts induced per turn are increased or decreased according to whether the magnetising current is higher or lower than its original value. The secondary voltage is the product of the induced volts per turn and the number of turns in series. The effect of adjusting the number of primary turns in circuit is further demonstrated by considering what happens when, for instance, the supply voltage drops and it is required to restore the secondary voltage to its former value. With the decrease in the voltage applied to the primary the magnetising current is reduced. To induce the same secondary voltage as before, the magnetising current must be increased to such a value that the volts induced per turn are the same as before the decrement of the applied voltage. The magnetising current is increased by decreasing the number of primary turns actually in circuit until the total flux in the core is restored to its previous value ; but as the total flux is proportional to the product of the magnetising current and the number of primary turns (the ampere-turns), since the number of turns is now less, there has to be a proportionally greater increase in the value of the magnetising current. This can only result from an appropriate decrease in the value of the back E.M.F., which is effected by reducing the self-inductance of the primary winding. Since the self-inductance varies as T^2 and the total flux as T—with a given magnetising current—only a small variation in T is required to effect a relatively large alteration in the total flux ; consequently the increase in magnetising current to compensate for the reduction in turns is also relatively small. This will be understood by considering the fundamental relations of the quantities involved.

Now, where L is the self-inductance : $L \propto \Phi\ T$,
and where A is the magnetising current : $\Phi \propto A\,T$,
therefore : $L \propto A\,T^2$.

Since the back E.M.F., $E \propto L : E \propto T^2$. From the above it follows that, since the magnetising current A varies as the difference between the applied voltage and the back E.M.F., an appropriate alteration of T automatically adjusts L and, therefore, E, so that A has a new value corresponding to the total flux required to induce the same secondary voltage as obtained before the decrease in the applied primary voltage.

Also from formula (1)—page 85—it is clear that E, Φ, and T are interdependent, the values of the first two being governed—with a given applied voltage—by T.

Voltage control by adjustment of the number of secondary turns in circuit is very simply explained by reference to formula (1) when E is the voltage induced in the secondary ; an increase in the number of turns produces an increase in the secondary voltage—and vice versa. In this case, with the same value of total flux, the volts induced per turn are the same, and the total voltage in the winding is greater, or less, according to whether there are more, or fewer, turns in series. To maintain a constant voltage, any variation of the flux, due to variation of the primary voltage, can be counteracted by adjusting the number of secondary turns.

Limitation of Short-circuit Current

Although the impedance of a transformer has an adverse effect on the voltage regulation it also limits the current that can flow under short-circuit conditions. This characteristic of the transformer is of great utility under modern conditions when the interconnection of large-capacity systems makes available a tremendous amount of fault energy. Transformers are built to withstand the internal stresses arising from a dead short-circuit at the secondary terminals for a period long enough to permit the circuit-breaker to clear the fault. The value of the short-circuit current, when this is limited by the transformer impedance only, is given by the percentage impedance voltage at full load. Thus, the current in the secondary winding is equal to $\frac{100}{Z \text{ per cent.}}$ times normal full-load current, where Z per cent. is the percentage impedance voltage at full load. For the purpose of current restriction the impedance voltage of small transformers is usually about 5 per cent., and for large high-voltage units, about 10 per cent.

Transformation Losses

During the process of transformation a certain percentage of the energy input is lost, being manifested as heat, the dissipation of which is a major problem in transformer engineering. Energy is lost in both the iron and the copper. The iron loss is made up of the eddy-current loss and the hysteresis loss, the first resulting from the currents circulating in the closed metallic circuits formed by the core laminations, due to the E.M.F. induced in them by the alternating flux ; and the second, from the energy expended in destroying the residual magnetism in the core at each reversal of the flux, i.e. every half-cycle. The eddy-current loss is proportional to B^2 (B is the flux density in lines per sq. cm.), and, in practice, the hysteresis loss is also approximately proportional to B^2. The latter is frequently quoted as being proportional to $B^{1\cdot 6}$, but although this is accurate for low flux densities, it is definitely not true for high flux densities. The hysteresis loss is more correctly expressed as being proportional to B^x, where x gradually increases and may reach a value as high as 4 when the flux density is 14,500 lines per sq. cm. As Ohm's Law applies to the circuits in the core around which the eddy-currents circulate, the core is made up of thin silicon steel laminations of high electrical resistance. Since the eddy-current loss in each lamination is proportional to the square of its thickness, the laminations are as thin as the mechanical properties required will permit, and are insulated from each other so as to obtain a large number of high-resistance electrical circuits. By these means the eddy-current loss in the iron is minimised. Typical laminated cores are shown in Figs. 51 and 52. In the latter, the sheets of pressboard used as additional insulation to divide the large core into sections should be noted. This is a usual practice with large cores as the voltage induced in them is considerable.

Another precaution adopted to reduce the eddy-current loss is to carefully insulate the clamping bolts, passing through the core, from both the clamping plates and the laminations.

The hysteresis loss is kept as low as is practicable by using low-loss laminations and keeping the flux density reasonably low, the value of the latter being a factor determining the dimensions of the core ; which must be maintained within economical limits.

The copper loss is the energy dissipated as heat due to the resistance

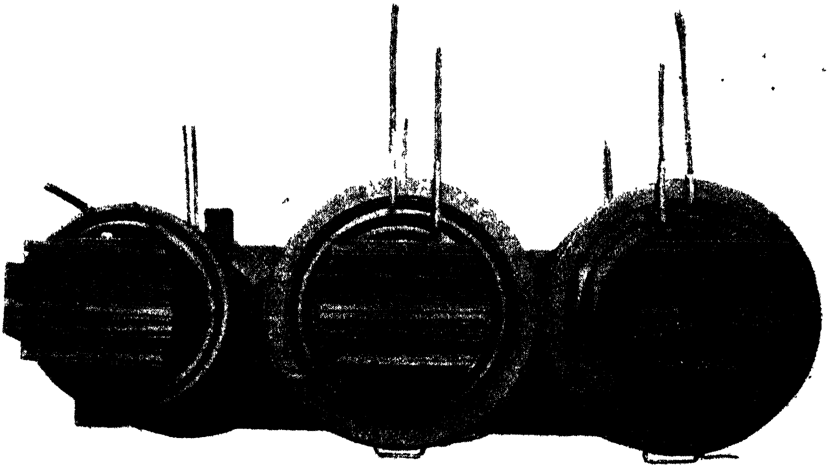


Fig. 51.—CORE CONSTRUCTION AND AXIAL COOLING DUCTS OF THREE-PHASE TRANSFORMER (*Johnson & Phillips, Ltd.*)

of the windings, the loss in watts being equal to I^2R. The value of R is directly proportional to the total length of the copper circuit in both windings, and inversely proportional to the cross-sectional area, so that for a given current density R depends on the length of each turn, which is determined by the perimeter of the core, and the total number of turns required, both quantities being definitely related to the flux density. Each winding can be considered separately, the resistance of the transformer being, of course, the sum total of the primary and secondary resistances. The relations of the quantities in the iron and copper circuits are apparent from formula (1)—page 85.

From this : if, for instance, with a given cross-sectional area of core the total flux is increased by increasing the flux density, for the same induced voltage the number of turns may be reduced, which decreases the resistance of the winding. Again, decreasing the flux density by increasing the area of the core to obtain the same total flux will increase the length of each turn, and, since the same number of turns is required, the resistance of the winding. Thus, the flux density, which largely determines the iron loss, will also indirectly determine the resistance of the windings in so far as length of each turn is concerned. The only dimension of the copper circuit that is independent of the flux density is the cross-sectional area of the conductors ; as the copper loss (I^2R) varies inversely as this, the current density will be a determining factor in the total loss. Reducing the current density to below a certain value is a much too

Fig. 52.—Large core, showing laminated construction and cooling ducts
(*Hackbridge Electric Construction Co, Ltd.*)

expensive method of reducing the copper loss; but this is always kept as low as possible by using circular coils and minimising the eddy-current loss in large conductors. Coils are, of course, made circular to satisfy both mechanical and manufacturing requirements. Circular coils necessitate a special form of core construction which has the minimum periphery for a given cross-sectional area. The ideal would be to have a truly circular core, but this would necessitate a different width for each lamination, which is impracticable. By using several sizes a good approximation to the circular form can be obtained. This method of core construction is shown in Fig. 51. Heavy-current windings are divided into a number of parallel strands, or separately insulated conductors, in order to reduce eddy-current losses (due to the leakage flux) in the copper circuit to a minimum.

From the previous discussion it is clear ~~that~~ the flux density is the critical value ~~which determines the total~~ loss in a transformer. To reduce the ~~iron~~ loss by decreasing the flux density entails, either the use of ~~a~~ greater quantity of iron, which increases the length of each turn in the windings, or else, a greater number of turns. In either case the copper loss is increased. Opposit~~ely,~~ ~~an~~ increase in the flux density reduces the copper loss but results in a higher iron loss. From this it follows that a transformer can be designed so that—within the limits imposed by the necessity for maintaining the required electrical characteristics—the ratio of iron loss to copper loss is such that the unit will have its maximum efficiency in the region of its most usual load. For example, a transformer that only operates at full load for a few hours a day, and is for the greater part of the time under-loaded, should have a ratio of iron loss to copper loss which will give the highest "all-day efficiency"; its maximum efficiency being at, say, three-quarter load. The all-day efficiency is defined as :

$$\frac{\text{kWH. output per 24 hours}}{\text{kWH. output per 24 hours} + \text{kWH. wasted per 24 hours}}.$$

The iron loss is approximately constant at all loads, and the copper loss varies as the square of the current, consequently, a distribution transformer, for instance, on circuit continuously and only lightly loaded for the greater part of the day should have a relatively low iron loss.

Dissipation of Heat

The energy loss in a transformer is manifested as heat, which is partially removed by the cooling medium—air or oil—in direct contact with the core and windings and partially absorbed by the materials used in the construction of these. Starting from cold, with a constant load the temperature of the materials rises until the heat is being dissipated at the same rate as it is being generated, the temperature being then maintained at a constant value. At some particular load—the value of which varies according to the ambient temperature—the temperature rises to the maximum value permitted. Above this load the heat is generated at a faster rate than it can be dissipated and the temperature rises. Unless the temperature-rise is checked, either by reducing the load or by some means increasing the rate of heat dissipation, the temperature may reach a value that will produce a serious deterioration of quality in the materials, with a consequent danger that the internal insulation of the transformer may fail when subjected to the maximum electrical or mechanical stresses encountered during operation. At the same time, for commercial reasons, it is necessary to employ the expensive materials used to the best advantage, i.e. to obtain the highest continuous output from a transformer without exceeding the maximum temperature permitted for the particular class of material utilised. To this end, considerable attention has been given to the problem of transformer cooling, transformers being classified according to the cooling method employed. Here again, the cooling method adopted for a particular unit is usually dictated by economic considerations, as there is a limit to the cost that may be incurred in obtaining a high output; the initial cost and the annual expense involved with elaborate cooling equipment may not be justified by the increased output made possible thereby. Oppositely, the provision of an auxiliary cooling equipment, operated only when the load on the transformer exceeds a certain value, may be definitely advantageous in circumstances where the load is not greater than 50 per cent., say, of the rated output of the unit with the auxiliary cooling equipment in operation, for the major part of the day. Cooling equipments are discussed in Chapter IX.

For the present it may be said that with many transformers effective cooling can be economically obtained by the natural dissipation of the heat from the surfaces of the core and windings in contact with the cooling medium. In oil-immersed units the heat is finally dissipated from the external cooling surfaces in contact with the atmosphere. The problem of cooling large transformers arises from the fact that the output of a particular design increases as the fourth power of the linear dimensions, and the losses as the cube; but the surface area available for cooling increases only as the square. Thus in order to take advantage of the greater output and efficiency obtainable with a certain design of transformer by simply increasing the linear dimensions, it is necessary to provide, either more surface area in contact with the cooling media, or increase the rate at which the heat is removed by increasing the rate at which the cooling media flow over the hot surfaces. Both these methods may be used in combination. In practice, both the internal surface area and the rate of flow of the cooling medium over this are increased by the provision of numerous unimpeded paths at various parts of the transformer to allow the medium unrestricted access to the hot surfaces. The paths, or ducts, are formed in various ways according to the type and size of the transformer.

Arrangement of Cooling Ducts

Most transformers have ducts between the core and the lower-voltage winding, and between the latter and the higher-voltage winding. Above a certain size the windings are subdivided so as to ensure efficient cooling. In some large transformers the system of ducts throughout the windings is such that every turn is always in contact with oil. The possibility of hot spots is thus entirely eliminated. Core-type transformers are provided with axial oil ducts (or air ducts), formed on both sides of each winding by the insertion of insulating spacers extending the full length of the core. With the larger transformers, cylinders of insulating material are used in addition to the vertical spacers. The exact arrangement depends on the type of coil employed. Axial oil ducts are clearly shown in Fig. 51—where three stages of the transformer assembly are depicted. Above a certain size it is necessary to provide radial ducts to supplement the axial cooling. Fig. 53 illustrates one method of obtaining radial cooling ducts between each section, consisting of a disc coil, and axial ducts between the winding and the insulating cylinder around the core. The ducts arranged in a complete assembly of high-voltage and low-voltage coils for one phase of a transformer are shown in Fig. 54.

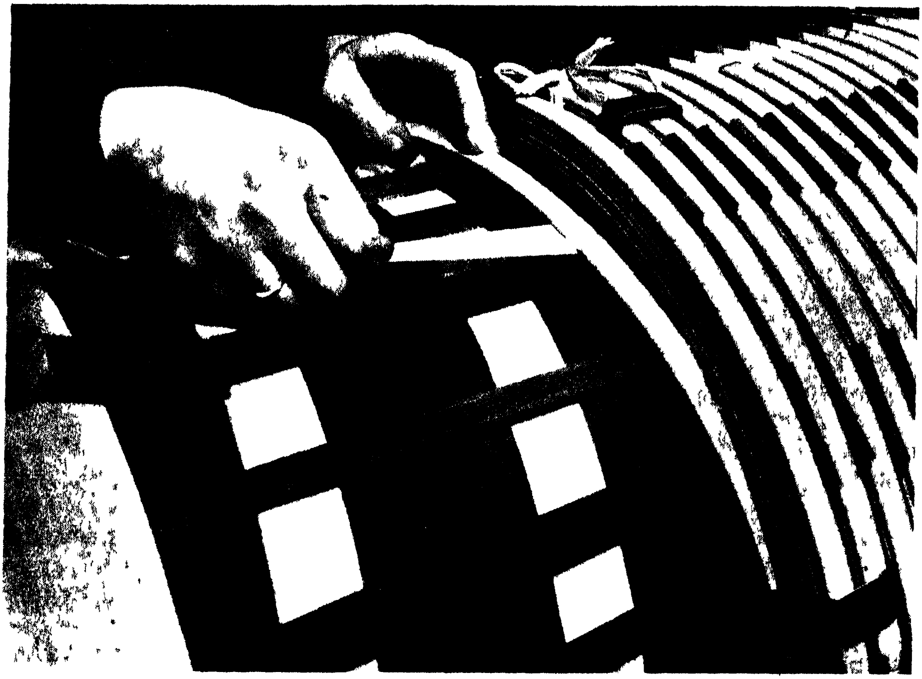


Fig. 53.—METHOD OF OBTAINING AXIAL AND HORIZONTAL COOLING DUCTS
(*British Electric Transformer Co., Ltd.*)

In shell-type units the coils are only partly accessible, being embedded in the core, and the direct cooling of the coils is not as good as with the core-type. On the other hand, a greater surface area of the core is in direct contact with the bulk of the cooling medium. By careful design the cooling is made equally effective in both types.

The surface area of some large cores is not sufficient to dissipate the heat generated in the interior, and the internal temperature would exceed a safe value unless special cooling measures were adopted. The temperature-rise in the core has to be limited for three reasons: first, to prevent the transfer of heat from the core to the winding; second, to avoid ageing the iron; and lastly, to safeguard the core-plate insulation. Since the eddy-current loss in each lamination is proportional to the square of its thickness, a failure of one layer of insulation would have a cumulative effect. As the result of the increased current circulating in the section of the core with defective insulation there would be a correspondingly greater temperature-rise in that section, which would promote deterioration of the plate insulation in adjacent sections. Eventually, the high general temperature developed in the core, by the cumulative failure of its insulation, would produce dangerous hot spots in the major

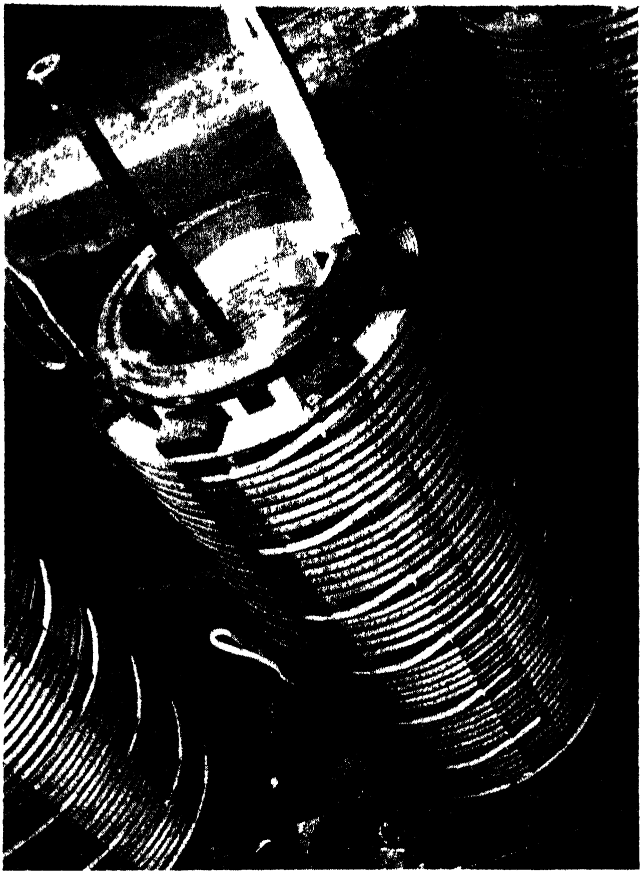


Fig. 54.—COMPLETE H.V. AND L.V. COILS FOR ONE PHASE OF A TRANSFORMER. (*British Electric Transformer Co., Ltd.*)

insulation between the core and the windings. The plate insulation is highly important as an essential part of the core construction adopted to reduce eddy-current loss and heating, but being a poor conductor of heat it impedes the passage of heat in a direction at right angles to the plane of the laminations. Modern methods of insulating laminations permit the maximum conduction of heat through the core without sacrificing electrical strength. Usually some form of varnish impervious to hot oil is employed, with additional sheets of pressboard between sections of the core ; or a " flash " enamel with asbestos sheets between sections. The thickness of the insulation is kept to a minimum to obtain the maximum heat conduction, and also to avoid any serious increase in the size of the core.

The core temperature of large transformers can of course be kept low by a low flux density, but the amount of material that would be required for a given total flux would increase the cost of the unit to an uneconomic figure. The economical alternative is to provide cooling ducts in the core.

For the best results, the ducts should be located at right angles to the laminations, as the coefficient of heat transmission through a core normal to the plane of the laminations is comparatively poor. As, however, the cost of cooling the core so as to limit the temperature-rise to a specified value is the factor which usually decides the particular method adopted, in many cases it is more economical to arrange the ducts in the plane of the laminations, as this is easily done. This type of duct is shown in Fig. 52 ; which is a view looking down on to the top of a large core.

The importance of ducts in some designs is indicated by the fact that a large core without them may have a difference of as much as 42° C. between the interior and the surface. With three ducts in the plane of the laminations this difference will drop to about 13° C., and with five ducts it may be as small as 7·5° C. Cooling ducts are not customary for the cores of relatively small transformers, and even large units have been built without them. On the other hand certain special types of transformers, such as furnace transformers, have both vertical and horizontal ducts in the core. Although winding ducts and core ducts are a far less expensive method of limiting the temperature-rise than employing low flux and current densities, they do increase the dimensions of the core and windings to an appreciable extent. With large transformers the increase would be considerable in the absence of the various cooling systems developed to obtain a more effective utilisation of the cooling media. The cooling of transformers, and the systems employed, are discussed at some length in the following chapter.

Chapter IX

COOLING OF TRANSFORMERS

THE primary consideration in operating transformers—and similar static equipment—is that the temperature of the unit should not exceed a specified maximum value ; the actual value depending on the part of the transformer at which the temperature is measured. In any transformer the ultimate limit to the output is the maximum temperature that the heat-vulnerable materials used in the construction will withstand continuously without deteriorating at an excessive rate. Excessive temperature has an ageing effect on the iron, but the most vulnerable material in a transformer is the insulation. With the latter, some deterioration takes place at all operating temperatures and a maximum temperature is specified for each class of insulation so as to ensure that both the mechanical and electrical strength is maintained during the commercial life of the unit. The commercial life of a transformer is usually reckoned as about twenty years ; that is to say, a depreciation of 5 per cent. per annum is allowed. A very much longer life is probable, but the insulation should retain adequate strength for at least that period when loaded continuously so as to maintain a constant temperature equal to the maximum permissible temperature-rise. The output corresponding to the latter is termed the " continuous maximum rating," which is defined as a statement of the operating limitations, assigned to the transformer by the manufacturer, giving the maximum load at which it may be operated for an unlimited period under certain specified conditions, and at an ambient temperature not exceeding a standard reference ambient temperature.

Mechanical Strength of Insulation

The insulations used in transformer engineering are chiefly those of the fibrous organic class such as paper, pressboard, cotton ; and in this case the useful life of a transformer appears to be determined by the rate of deterioration of the mechanical strength of the material with time and temperature—apart from failure under transient mechanical or electrical stresses. That mechanical strength is a controlling factor has been revealed not only by experience in service, but also by research which has shown that all fibrous organic insulations deteriorate mechanically when subject to high temperature, the rate being a function of time and temperature. The material becomes discoloured, loses its flexibility, and at excessively high temperatures becomes very brittle and carbonised.

Furthermore, deterioration occurs more rapidly when the material is immersed in transformer oil than in air. The average results of tests indicate that the rate of mechanical deterioration is doubled for every 8° C. increase in temperature. Insulation must be strong enough to withstand the high mechanical stresses set up by the abnormal current-rushes encountered in practice. These occur during normal switching-in operations and under fault conditions. Since the intensity of the mechanical stress set up in transformer windings varies as the square of the current flowing, the insulation is subject to severe stress during switching-in due to the excessive primary current ; but the worst condition arises when a dead short-circuit occurs across the secondary terminals. The magnitude of the stress also depends upon the instantaneous value of the voltage when the short-circuit is made. For instance, in a transformer having an impedance of 5 per cent., the initial stresses under short-circuit conditions would be 400 times as great as those under normal full-load conditions when making the short-circuit at maximum voltage, i.e. at the peak of the voltage wave; but when making the short-circuit at zero voltage the resulting stresses in the windings would be approximately 1,600 times as great as those under normal full-load conditions, on account of the " doubling effect."

Thus it is apparent that a transformer whose insulation has deteriorated mechanically through overheating may be incapable of withstanding the severe stresses arising during short-circuit, and electrical failure will follow as the result of the damage to the dielectric between conductors.

Effect of Temperature on Dielectric Strength

Apart from the failure of the insulation by mechanical action, breakdown under high transient electrical stress may also occur as the direct result of the material having been subjected to excessive temperature. The effect of heat on the electrical strength of solid insulation arises from the fact that no material is an ideal insulator. All insulating material has a finite resistance, and current sufficient to cause permanent damage will flow through it if the voltage is raised to a high enough value. With increasing temperature the resistance decreases until the conductivity is such that the insulation is unable to prevent the passage of energy sufficient to damage it permanently. In the early stages of deterioration the value of the insulation resistance is such that

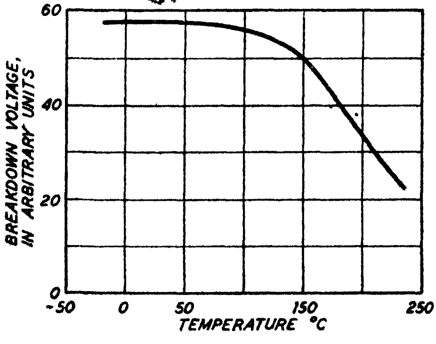


Fig. 55.—EFFECT OF TEMPERATURE ON ELECTRICAL STRENGTH OF INSULATION breakdown will not necessarily occur, but nevertheless once the insulation has been overheated for an appreciable length of time the possibility of failure under transient voltage conditions is always present, especially when operating a transformer at its maximum permissible temperature. The effect of temperature on electrical strength for a particular insulating material is shown in Fig. 55; most insulations have a breakdown voltage/temperature curve of an approximately similar shape.

Permissible Temperature-rise

The selection of a permissible safe temperature for insulation, and, therefore, for the transformer in which it is used, is complicated by the fact that there is no critical temperature above which very rapid deterioration occurs, and below which no deterioration occurs, and it is impossible to fix exactly the temperature above which a transformer should not be operated. Actually, insulation can be subjected to relatively high temperatures providing that their duration is sufficiently short; thus, transformers can carry safely for a few seconds short-circuit currents with attendant temperatures as high as 250° C. Also it is permissible to operate transformers at frequent, but short, intervals, at temperatures not advisable for continuous operation.

TABLE II.—TYPES OF TRANSFORMER COOLING

Class	*Type Letters*	*Primary Cooling. Medium and Circulation*	*Secondary Cooling. Medium and Method*	*Temp.-rise Limits Degs. C.**
Natural .	AN	Air - Natural	—	55
	ON	Oil Natural	Air—Natural	60
	OFN	Forced		65
Artificial .	AB	Air-blast	—	55
	OB	Oil Natural	Air-blast	60
	OW		Water	60
	OFB	Forced	Air-blast	65
	OFW		Water	70

* Windings: Average temperature-rise measured by increase of resistance. Class A insulation. Permissible temperature-rise of oil (Class A) for all types, 50° C.—by thermometer. Ambient temperatures: Air, peak value 40° C. and average value of 35° C. over 24-hour periods; water, 25° C. Tabulated data based on B.S.S. No. 171—1936.

In practice the temperature-rise limits stated in "B.S.S. No. 171—1936 for the Electrical Performance of Transformers for Power and Lighting" are usually accepted. These are shown, for different types of cooling, in Table II. The temperature-rise values are based on the maximum temperature that the insulation will withstand continuously over a given life period under C.M.R. conditions; but since the heating of the windings will be more or less unequal the limiting temperature is actually that of the hottest spot in the insulation. That is to say, when any one spot in the insulation reaches this temperature, the transformer is carrying its maximum safe load. The hottest spot generally occurs at some internal point in the winding ; its temperature is the true basis of the calculation and measurement of safe thermal rating.

Classes of Cooling

Since the output of a transformer is limited by the maximum temperature permissible for the insulating materials used, the output is finally determined by how fast the heat generated can be dissipated, and this in turn depends on the cooling apparatus employed. Cooling may be either " natural " or " artificial " ; or a combination of both may be used, in which case it is termed " mixed." The various methods in common use are shown in Tables II and III. The particular method adopted for a transformer will depend broadly on the capacity and location of the unit, and the nature of the load—despite the higher cooling rate obtainable with artificial methods, below a certain size this is not generally economic on account of the cost of the additional apparatus involved.

With natural cooling the heat is dissipated from the hot surfaces in contact with the atmosphere by radiation and convection ; artificial cooling is effected by either an air-blast, or water circulated through a coil located inside the oil tank, or used in an external oil cooler. Mixed cooled units are naturally cooled up to a certain load ; above this load the artificial cooling equipment is brought into operation. Transformers are either " dry " or " oil-immersed " according to whether air or oil is the primary cooling medium in direct contact with the core and windings. Dry-type units are generally of relatively small capacity, and are cooled either naturally by radiation and convection from the hot surfaces, or artificially by an air-blast through the casing and cooling ducts.

TABLE III.—MIXED COOLING OF TRANSFORMERS

Natural Method	*Alternative Additional Artificial Method*	*Type Letters*
Oil circulation by thermal head only, with indirect air cooling.	Air-blast cooling	ON/OB
	Forced-oil circulation	ON/OFN
	Forced-oil circulation with air-blast cooling .	ON/OFB
	Forced-oil circulation with water cooling . .	ON/OFW

In the case of transformers with dual cooling the permissible temperature-rise, without the artificial cooling in operation, is the same as for an ON unit, and with it, is that for the particular type of artificial cooling in use.

Most transformers are of the oil-immersed type, since oil has superior dielectric properties and is a more efficient cooling medium than air. Natural, or self-cooled oil-immersed transformers are further distinguished by the way in which the oil is circulated. With type ON units the oil circulation is natural, that is, produced by the convection currents resulting from the thermal head only; type OFN units have forced circulation by external pumps. In both cases the hot oil is cooled by radiation and convection from the surfaces of the tank and cooling system in contact with the atmosphere.

Theory of Cooling

Irrespective of the particular method employed, for cooling to take place there must be a temperature difference between the core and the windings, and the cooling media; the cooling rate being determined by the temperature-difference If a body receives internally as much heat per unit time as it gives up from its external surface, then the temperature at any given point inside or on the surface remains constant; but from point to point there is a change of temperature. This condition may also be expressed by the statement that there is a temperature-gradient from the inside to the surface. When a cold transformer is switched on to a steady load, as the transformer heats-up the temperature-gradient will gradually increase until thermal equilibrium is established, i.e. the rate of heat removal is equal to the rate of heat production, and the transformer temperature is constant.

In any type of transformer, the initial transfer of heat is effected by conduction in the copper and iron, where it is being generated, to the surface in contact with the primary cooling medium. This has a double function. First, its temperature will—for a specified maximum winding temperature—determine the temperature-gradient, so that it is thereby the means of promoting the conduction of heat from the windings and core. Secondly, it is the agent which absorbs the heat from the hot surfaces. The heat is dissipated finally either by diffusion in the primary medium—as with air-cooled dry transformers—or, in the case of oil-immersed units, by means of a secondary indirect cooling medium—air or water—which absorbs the heat from the primary medium.

The heating in a transformer is more or less unequal, consequently the temperature-gradient varies between any internal point and any external point; there will be a maximum value and a minimum value. This condition arises because of the uneven temperature distribution in the body of the transformer and in the oil. In the core there is a flow of heat in a direction parallel to the plane of the plates, and also at right angles to it. Parallel to the plates there is an unbroken metallic path and the heat conductivity is high, but at right angles there are alternate layers of metal and insulation and the heat conductivity is poor. The heat generated in the conductors also has to pass through an appreciable thickness of insulation. With coils immersed in oil the heat conductivity is improved because the oil fills up the interstices; and also, if the conductors consist of flat strip, as in this case the contact surface between adjacent conductors is greater than with any other shape.

In addition to the temperature-gradient within the mass of the body of a transformer, there is a sudden temperature drop from the surface to the oil, due to the oil film adhering to the surface. Thermal convection currents do not flow in oil films, and the heat is conducted across them ; but they are poor conductors, hence the sudden temperature drop. The effect of the film varies according to the manner in which the oil is circulated. Air films have a similar effect at air-cooled surfaces. Since the maximum permissible temperature of a transformer is determined in relation to that of the hottest spot, the critical gradient is the one existing between the hottest spot in the windings and the hottest oil. Unfortunately, it is not practicable to measure the hottest spot temperature directly, but a maximum value may be specified for the copper from the experimentally determined temperature characteristics of the windings for each particular type of transformer. The limiting value of the copper temperature—as measured by increase in resistance of the winding connected between terminals—is specified, so as to ensure that the temperature of the hottest spot in the insulation does not exceed the maximum value permitted for the particular class of insulation. The maximum temperature of the oil can, of course, be measured directly.

Conduction of Heat

In oil-immersed transformers the conditions governing the conduction of heat from the windings to the oil may be expressed in a general form :

$\frac{Tg}{C}$ where Q is the quantity of heat flowing per second.

Tg is the temperature-gradient.

C is the conductivity of the heat path.

$Tg = T_c - T_o$; T_c being the copper temperature, and T_o the oil temperature.

From the expression it is apparent that with a constant maximum value of T_c, Q will vary directly as T_o. Thus the maximum output of a transformer for a given copper temperature depends on the oil temperature, since this controls the rate of heat conduction from the core and windings. With naturally cooled units the oil temperature is finally determined by the ambient air temperature T_a, and the maximum safe load is reached when the temperature-gradient is such that the unit is in a state of thermal equilibrium when T_c is the maximum permitted. Any increase in load will produce an increase in the internal temperature as the result of the higher temperature-gradient, which can only be established by T_c rising above the maximum permissible value. All three temperatures, T_c, T_o, and T_a, are definitely related and, in the case of type ON units, T_o depends upon the rate at which the oil circulates and this in turn is determined by T_c and T_a. The value of the latter influences the rate of heat conduction through the path consisting of the oil film adhering to the internal surfaces of the tank structure, the walls of the structure, and the air film adhering to the external surfaces—and, therefore, the rate at which the heat of the oil is dissipated to the atmosphere, which is the secondary indirect cooling medium that finally removes the heat from the vicinity of the transformer.

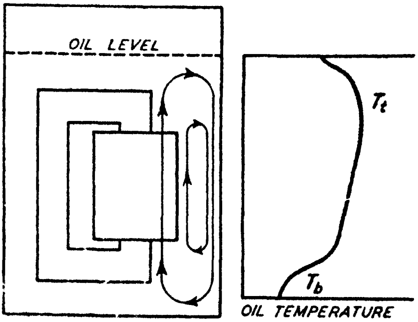


Fig. 56.—TEMPERATURE DISTRIBUTION AND CONVECTION CURRENTS IN OIL-IMMERSED TRANSFORMER

The thermal head required for circulating the oil arises as the result of the dissipation of heat from the external cooling surfaces producing a temperature distribution in the oil generally similar to that shown in Fig. 56. At the bottom of the tank the temperature is T_b, and as the oil moves upwards its temperature rises, reaching a maximum value T_t somewhere near the top. Above this point the temperature begins to decrease as the oil passes outwards to the tank, and sinks down, the heat being transferred to the tank walls. The convection currents resulting from the thermal head are also shown in Fig. 56. As an ON transformer heats up, the rate of oil circulation increases until the heat is being conveyed to the tank wall just as fast as it can be dissipated into the atmosphere, but above a certain load—the C.M.R. at the specified ambient temperature—the surface area of the tank will not be sufficient to dissipate the heat fast enough to prevent an excessive temperature-rise. Thus, the external cooling surface area available is the factor ultimately deciding the rating—under specified conditions—of naturally cooled oil-immersed transformers. Oil circulation is assisted, as the transformer heats up, by the decreasing value of the oil viscosity with increasing temperature. Fig. 57 illustrates this; the

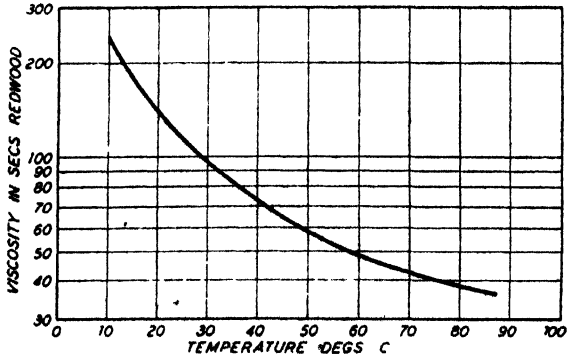


Fig. 57.– VISCOSITY/TEMPERATURE CURVE FOR TYPICAL TRANSFORMER OIL (LOGARITHMIC SCALE) viscosity/temperature curve shown is that of a typical transformer oil.

During its passage through the cooling ducts the oil is partly impeded by the resistance of these since they cannot be made unduly large. For this reason OFN cooling makes use of a pump to obtain a more vigorous oil circulation so that the oil is forced through the cooling ducts into the crevices of the windings, and the oil film adhering to the hot surfaces more or less broken up. On this account a more economical design of transformer is often made possible by adopting OFN cooling above a certain size.

The distinction between natural and artificial cooling is that with the former the cooling rate is definitely fixed by the area of cooling surface and the ambient air temperature, and the oil temperature—governing the internal temperature-gradient—cannot be controlled independently of the load. With artificial cooling the oil temperature can be controlled within the limits set by the particular cooling equipment employed.

TABLE IV.—COOLING OF TYPE ON/OFB TRANSFORMER, 45,000 KVA.

	Full Load	*¾ Load*	*½ Load*
Fixed loss, kW.	90	90	90
Load loss, kW.	330	186	82.5
Total loss, kW.	420	276	172.5
Temperature-rise of copper, degrees C.	55	55	55
Gradient, degrees C.	20	11	5
Oil temperature-rise, degrees C.	35	44	50
Radiating surface required for ON cooling	1	0.52	0.29

ON cooling up to at least half-load, after which the OFB cooling is brought into operation.

The effect of being able to control the oil temperature, and in consequence, the temperature-gradient, of a transformer is that for a given area of cooling surface the output for a specified copper temperature is considerably increased. This is demonstrated by the data in Table IV, which refers to a mixed cooled unit, i.e. it is naturally cooled up to a certain load determined by the temperature of the unit—in this case, at least half-load—after which the artificial cooling equipment is brought into operation. From the tabulated data it is clear that for the same temperature-rise of the copper, at the loads shown, it is possible to double the output of the transformer as an ON unit by artificially reducing the temperature of the oil, and thereby establishing a temperature-gradient high enough to promote the conduction of heat at the required rate. The table also shows the radiating surface that would be required for ON units of capacities equivalent to full load and ¾ load of the 45,000 kVA., ON/OFB transformer.

Methods of Natural Cooling

The physical dimensions of a transformer are determined in relation to the effectiveness of the type of cooling equipment that can be most suitably adopted for any particular operating conditions, or location. Thus each of the various types of cooling equipment in general use has some outstanding advantage which recommends its application in specific circumstances ; simplicity is desirable but not always obtainable economically, in which case a comparatively elaborate cooling system may be the better proposition.

The simplest type of cooling is that of AN units which are simply exposed to the atmosphere although enclosed in some form of protective casing, with the attendant disadvantages of such an arrangement. Most transformers are enclosed in some form of oil tank. The form of tank used for a naturally cooled transformer varies according to its output, so as to obtain the maximum cooling surface without an uneconomical increase in the overall dimensions of the unit beyond those determined by the volume of the core and windings, and insulation requirements. For units of small output a plain sheet-steel tank suffices. Since the losses in a transformer increase approximately as the cube, and the tank surface only as the square of the linear dimensions, it is usually uneconomical to use plain tanks with units above about 25 kVA., due to the large surface required, and the consequent increase in oil quantity. On this account various forms of tank construction have been developed. An interesting example is that shown in Fig. 58, which is a special form of plain tank offering ample cooling surface having regard to the high voltages and low currents involved. To increase the surface area of some small units the tank sides are corrugated or ribbed, as illustrated in Figs. 59 and 60. General practice is to employ tubular tanks up to 8–10,000 kVA. (at 33 kV.),

Fig. 58.—500 kVA., 66/11 kV. THREE-PHASE ON UNIT
(*Brush Electrical Engineering Co, Ltd.*)

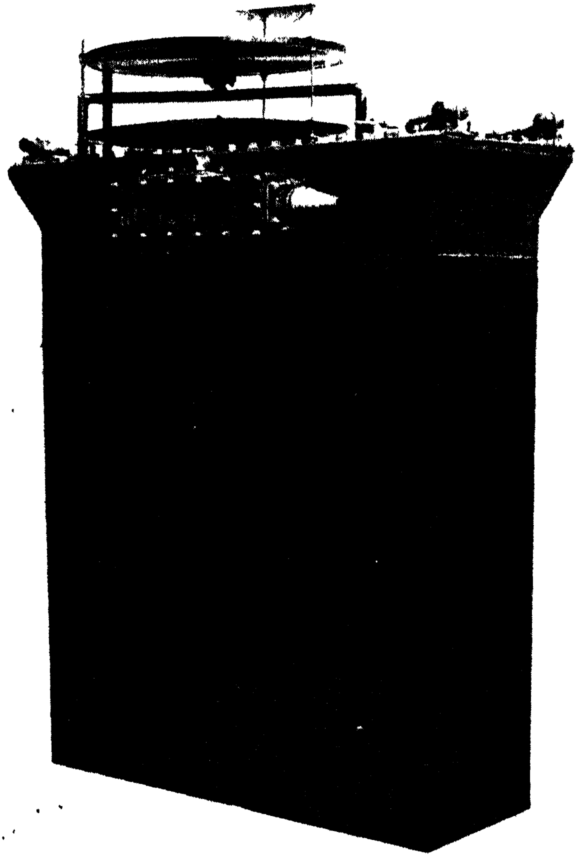


Fig. 59.—150 kVA., 11,000/415 VOLTS HERMETICALLY SEALED TRANSFORMER
(*British Electric Transformer Co., Ltd.*)

the cooling tubes fitted to the tank proper being of circular or elliptical section, electrically welded to the tank sides. Fig. 61 is a good example of a tubular tank transformer with four rows of tubes. The tubes are bent to an approximately streamlined shape to ensure an unimpeded oil flow. To obtain greater cooling surface the tubes are often gilled—wound with a long helix of steel strip on edge, in contact with the tube surface (Fig. 62). A large number of radiating fins are thus provided. Tubular tanks are very effective, although the cooling surface is not—with natural cooling — as efficiently utilised as that of a plain tank with an equivalent surface area. This consideration is, of course, outweighed by the other advantages. The relatively lower radiation efficiency of the tubular construction is due to the tubes being comparatively close to each other, which results in a diminishing value of watts per sq. cm. that can be dissipated for each row of tubes added to the tank.

The cooling arrangements of naturally cooled oil-immersed units are determined not only by the kVA. capacity, which decides the amount of surface required, but also, in the larger sizes, by questions of handling and transport. Where transformers are within the capacity range that can be effectively and conveniently cooled by the tubular tank this type has the advantages of simplicity and low cost. Above approximately 10,000 kVA., at 33 kV., transformers are usually equipped with de-

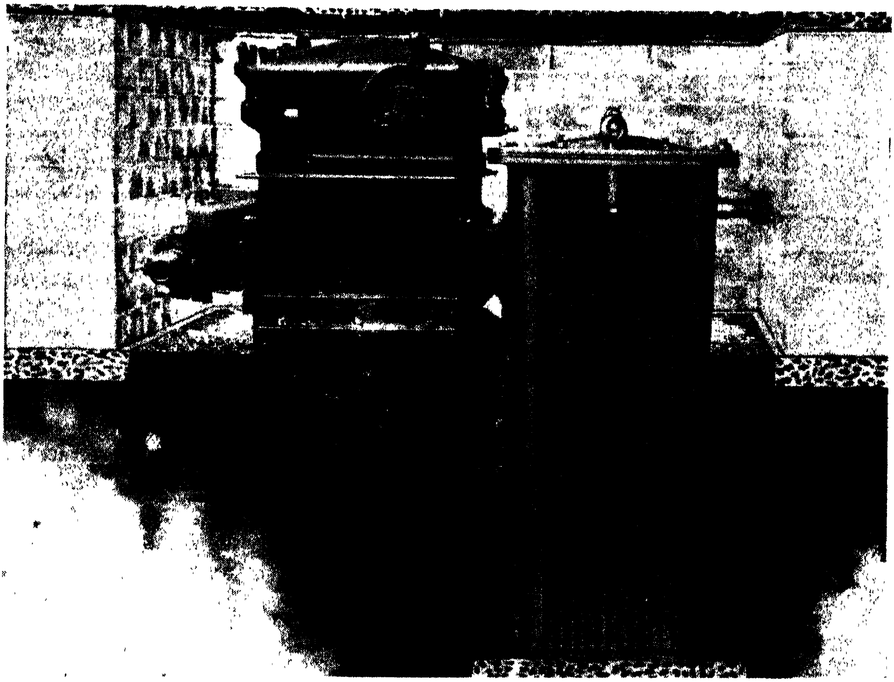


Fig. 60.—Sectional view of 150 kVA. buried-type transformer fitted with a Long and Crawford oil switch-fuse installed in a brick pit under a footpath (*Hackbridge Electric Construction Co., Ltd.*)

tachable radiators (Fig. 63), or separate coolers (Fig. 64). For the same tank size, either of these provide a greater cooling surface than could be obtained by the use of a tubular tank fitted with the maximum number of tubes practicable. Conversely, on large units they usually permit the use of a smaller tank than would be possible for a tubular tank transformer of equal capacity. Furthermore, both detachable radiators and separate coolers enable a concentration of cooling surface to be effected and a large area of tank surface exposed to direct contact with the atmosphere, which also facilitates the fitting of the transformer accessories, and on-load tap-changing gear when used. The radiators in Fig. 63 are of welded construction throughout, each unit consisting of a bank of seamless steel tubes welded at top and bottom into a long box-shaped header of fabricated steel. Usually, each header is connected to the transformer by means of an oil-tight flanged joint to allow of disconnection and assembly. A special cam-operated poppet valve, controlled by a small external handle, is provided at each connecting point between tank and radiator so that, without removing any oil from the main tank, any radiator may be detached for inspection and repair, even,

Fig. 61.—3,000 kVA., 66/11 kV. THREE-PHASE ON UNIT WITH TUBULAR TANK. (*Brush Electrical Engineering Co., Ltd.*)

if necessary, while the transformer is in operation. The radiator itself must, of course, be drained of oil before this is done, the bottom header of each being provided with a drain cock for this purpose. The temporary reduction of the cooling surface will restrict the maximum permissible output of the transformer.

Above a certain size it is common practice to fit a separate cooler, this being simply an extension of the detachable radiator principle. An ON transformer with a separate cooler is shown in Fig. 64, and mixed cooled units with separate twin coolers in Figs. 65 and 70. With these the whole of the cooling tubes are arranged in banks adjacent to the transformer, and so disposed as to ensure the most efficient circulation of the ambient air. The top and bottom are usually connected to the transformer tank in a manner similar to that shown in Fig. 64. A valve is fitted in each connecting pipe to allow disconnection and erection of the cooler without draining the oil from the main transformer tank. The cooler may be divided into two sections, duplicate connections being provided between it and the transformer. Generally, the separate cooler has the same advantages as detachable radiators. Separate coolers—and, to a lesser extent, detachable radiators—enable natural cooling to be adopted for units of far greater output than that practicable with tubular tanks. The available cooling surface can be considerably increased as a cooler can be designed without its dimensions being restricted by those of the transformer ; the cooler can, in fact, be located at some distance from the transformer if this is necessary on account of

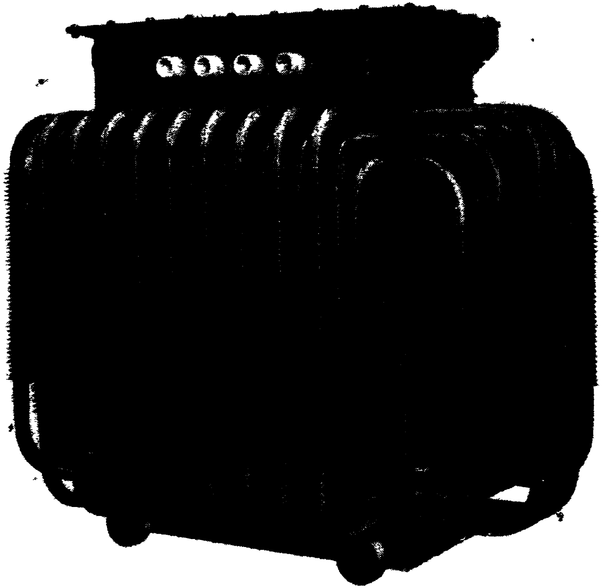


Fig. 62.—600 kVA., 11,000/400 VOLTS TRANSFORMER WITH GILLED TUBES

(*Johnson & Phillips, Ltd.*)

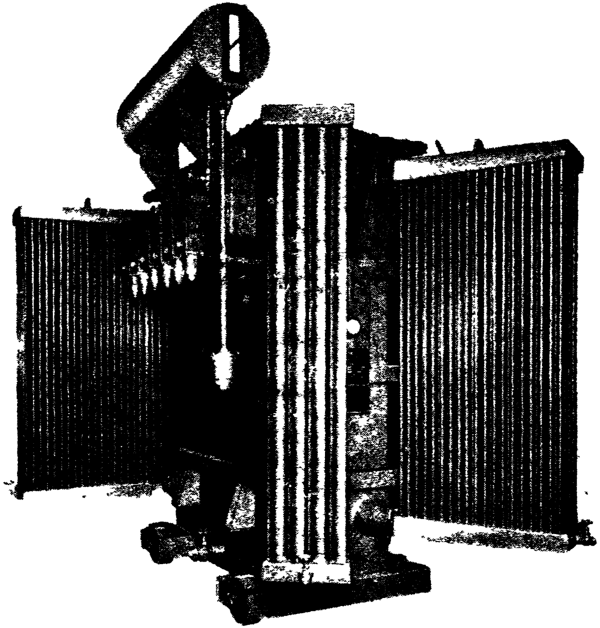


Fig. 63.—6,000 kVA., 3,300 11,000 VOLTS TRANSFORMER WITH DETACHABLE RADIATOR

(*Johnson & Phillips, Ltd.*)

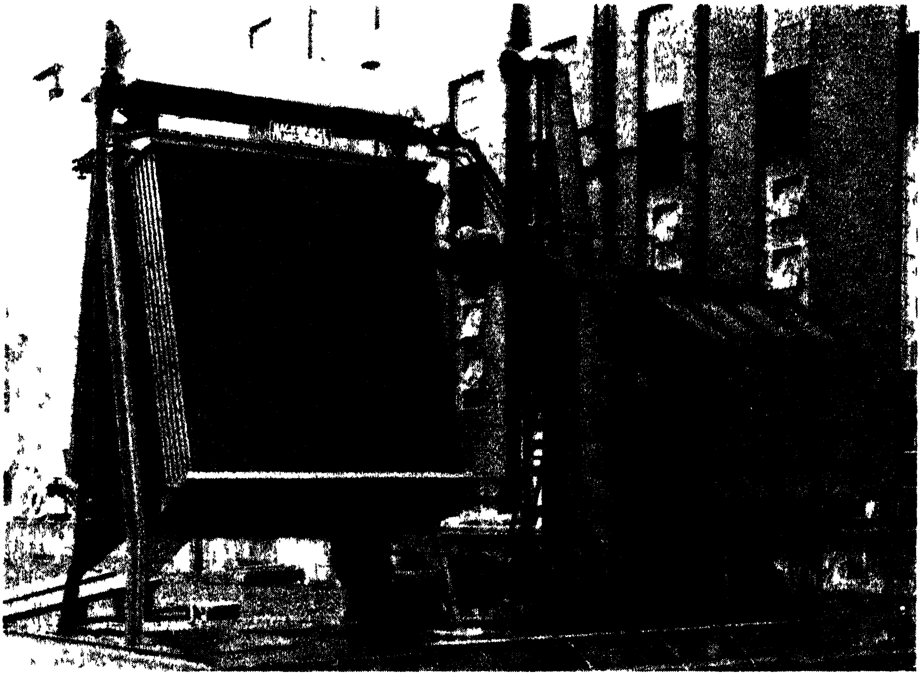


Fig 64.—12,500 kVA, 33/6·6 kV. ON TRANSFORMER WITH SEPARATE "A" TYPE COOLER AND ON-LOAD TAP-CHANGING EQUIPMENT
(*Hackbridge Electric Construction Co., Ltd.*)

any limiting conditions existing at the site where the unit is installed. With a separate cooler the maximum cooling surface can be obtained for a minimum tank size, but at the same time the tank surface is also available for the dissipation of heat, being freely accessible to the surrounding air. Sometimes the separate cooler is designed to enable a fan to be fitted at a later date in order to increase the output to meet a growing load; the transformer would, when adapted, come into the category of mixed cooled units. Coolers are made in various shapes, and two coolers of a standard type are often used with large transformers, as in Figs. 65 and 70.

A method of cooling OFN-type transformers is to produce a strong flow of air over the cooling surfaces of specially designed radiators located at the base of a "chimney." Various forms of chimney are employed. Fig. 66 shows a group of OFN transformers which are cooled by the strong natural draught through the brick towers removing the heat from the oil circulating around "Serck"-type radiator units located in the towers. Another chimney-type cooler is shown in Fig. 67. Here the draught is induced by the twin funnels located above the "Serck"

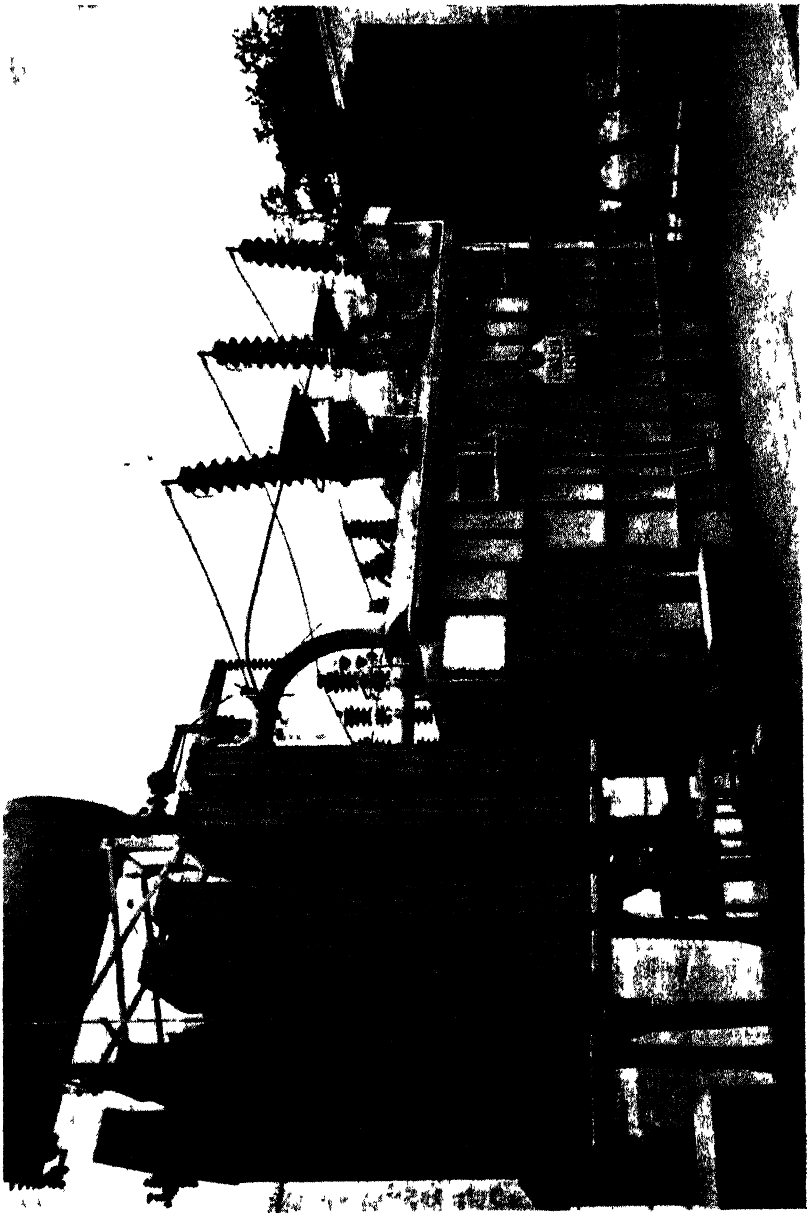


Fig 65 —A 30,000 kVA, 132 33 kV ON/OFN TRANSFORMER WITH ON LOAD TAP CHANGING GEAR

(*English Electric Co, Ltd*)

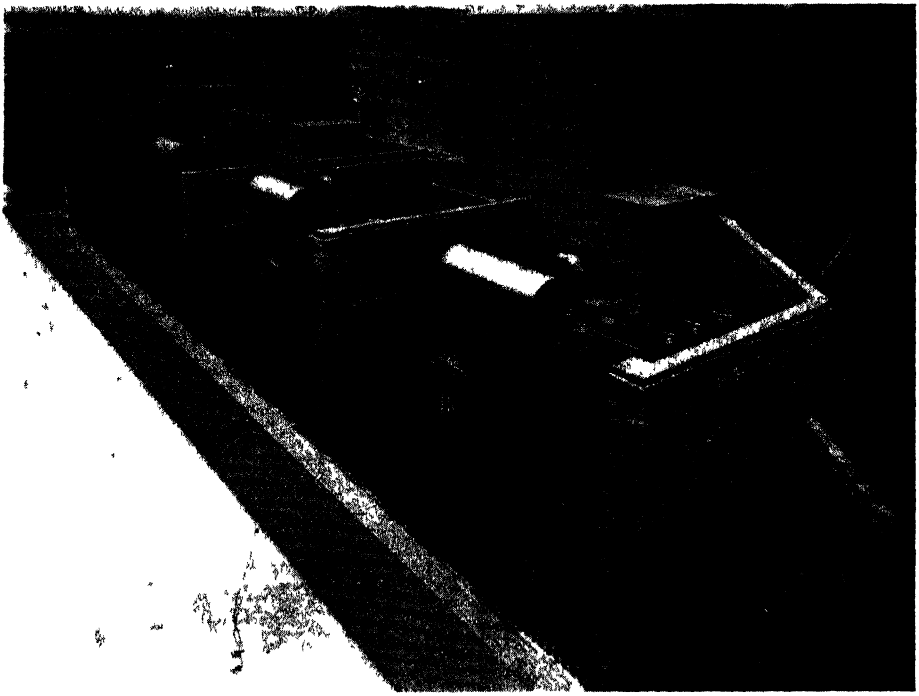


Fig. 66.—FOUR 15,000 KVA., 33/11 KV. OFN TRANSFORMERS WITH BRICK TOWER COOLERS AND ON-LOAD TAP-CHANGING EQUIPMENT
(*Hackbridge Electric Construction Co., Ltd.*)

radiator banks. The pumps for the forced-oil circulation are clearly shown ; also the arrangement of valves to enable one section of the cooler to be shut down for maintenance, while the transformer is operated on reduced load with the other section in use.

Artificial Cooling Systems

Although naturally cooled units are built with capacities above about 10,000 kVA., to meet special circumstances where the inherent simplicity of the type is advantageous, for most requirements very large naturally cooled units—as distinct from mixed cooled units—are not commercial, and the economical alternative is to adopt an artificial or a mixed method of cooling, which permits a more effective utilisation of the cooling media. Artificial cooling involves the use of either air-blast or water, with or without forced-oil circulation. The various methods are shown in Table II. In many cases the inherent self-cooling capacity of a unit may be such that up to as much as two-thirds of its rated output it is unnecessary to employ artificial cooling all the time, and the auxiliary cool-

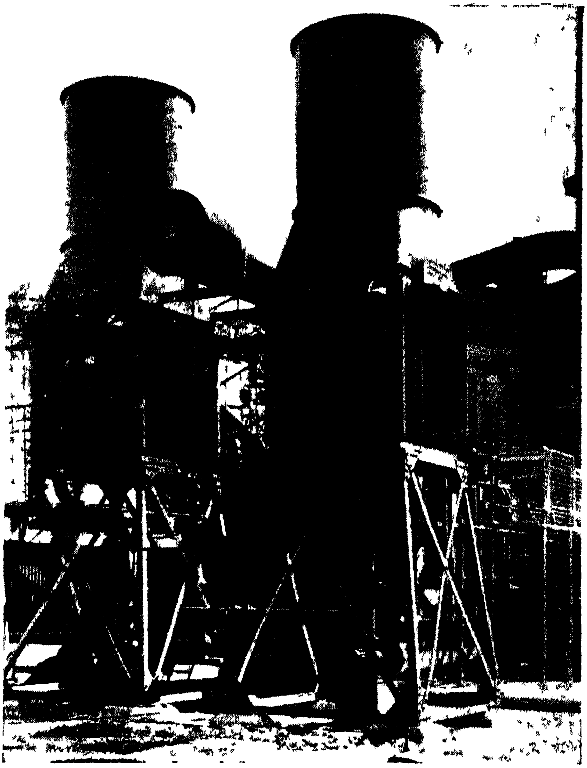


Fig. 67.—"SERCK" TYPE CHIMNEY COOLER
(*Hackbridge Electric Construction Co., Ltd.*)

ing equipment is only used when the transformer temperature reaches a predetermined value. The various combinations used for mixed cooling are shown in Table III. The obvious method of achieving more effective cooling when air is used either as the primary or secondary cooling medium is to increase the velocity of the air so that the heat is removed from the hot surfaces, and from the immediate vicinity of the transformer, at a greater rate than is possible by natural means. Thus, the output of ordinary type ON units can be increased by installing ventilating plant for the whole of the station, or compartment; but strictly this is not a form of artificial cooling, although it may be the most satisfactory way of utilising the installed kVA. capacity to the best advantage. The ventilating plant of air-blast cooled transformers is integral with the unit, and specially designed to ensure the maximum cooling effect. A vigorous movement of the air over the radiating surfaces breaks up the air film normally adhering to them, so improving the transfer of heat, since air films are poor conductors, and convection currents do not flow in them.

Air-blast Cooling

Dry-type units are artificially cooled by a motor-driven blower creating an air-blast over the hot surfaces of the core and windings. In dirty situations the air is usually filtered, to prevent dirt being deposited in the internal ventilating ducts of the transformer, either by conditioning the whole of the air intake to the station or compartment, or by a filter of

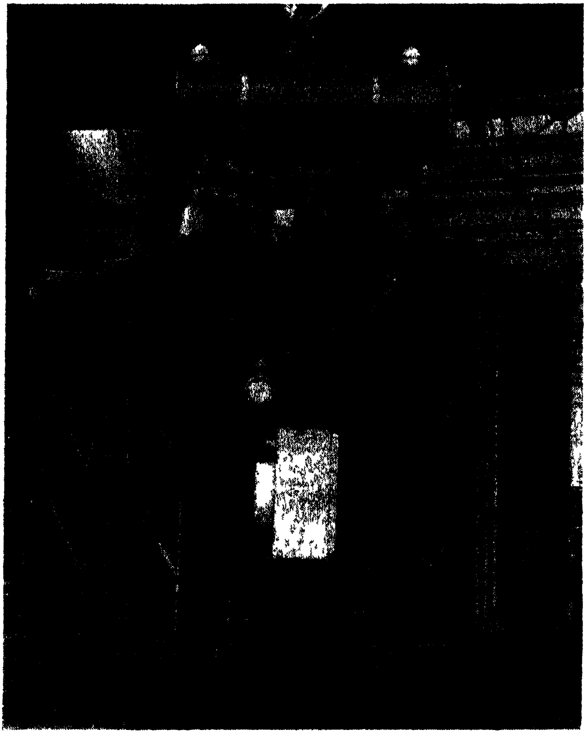


Fig. 68.—A 5,000 kVA., 106/26·5, 6·3 kV. ON/OB UNIT
(*Hackbridge Electric Construction Co., Ltd.*)

the viscous type fitted to each unit. The disadvantage of type AB transformers is that the efficiency is low at light loads in consequence of the energy required for the blower motor representing a constant loss; but usually this factor will be outweighed by the other reasons favouring the installation of dry transformers. These are often used—even for medium outputs—when it is considered that the risk of fire in hazardous surroundings is reduced by avoiding the installation of oil-immersed units.

Air-blast cooling can be applied to oil-immersed units simply by directing the current of air from a fan on to the tubes of an ordinary ON transformer, but for the best results it is necessary for the air-blast to be directed so that an equitable cooling of the radiating surfaces is achieved. A good example of air-blast cooling is shown in Fig. 68, applied to one unit of a three-phase bank. Each unit has its own motor-driven blower which supplies air to the chutes directed on to the detachable radiators, but this is not a common arrangement. A general practice is to use air-blast equipment in conjunction with separate coolers. When the transformer is operated as a mixed cooled unit the cooler is often an orthodox ON type suitably modified, such as that in Fig. 70, which shows a type ON/OFB unit. In this case forced-oil circulation is used in addition to air-blast cooling so that, since circulating the oil under pressure is a very efficient means of preventing hot spots in the windings, the arrangement permits either a greater output than that permissible for a unit of identical dimensions in which the oil circulates by natural convection only, or a reduction in the dimensions for the same output. The latter

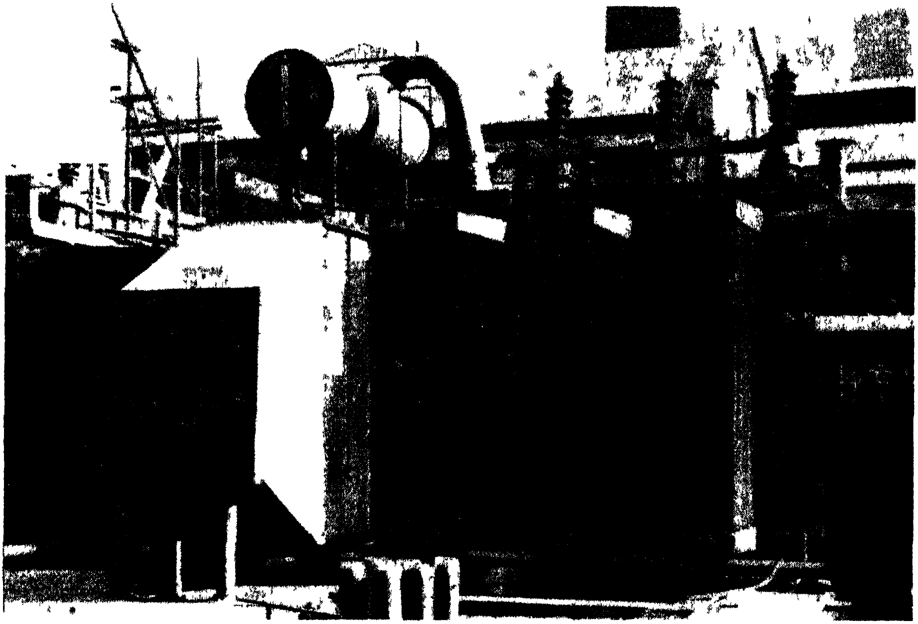


Fig 69 —THREE PHASE ON/OB TRANSFORMER WITH RADIATOR TYPE COOLER
(Hackbridge Electric Construction Co., Ltd.)

may be effected by reducing the volume of the oil ducts or by increasing the flux density, or by a combination of both. When forced-oil circulation is arranged for constant operation the transformer cooling method is classified as "simple natural," but used as an alternative additional method of cooling, with or without some other form of artificial cooling, it is classified as mixed cooled. Fig. 65 shows an ON/OFN unit.

Generally most air-blast cooled units come into the category of mixed cooled, since by this means considerable economy in the energy consumed by the motors of the auxiliary cooling equipment is possible by making use of the self-cooling capacity of the unit. The equipment is then controlled automatically by transformer temperature value, with additional manual control when required. When the utmost simplicity is desired, or the transformer operates constantly at approximately full load, the cooling equipment starts up when the unit is switched in. The oil coolers of air-blast cooled units are usually arranged as external tube banks in the form of an A, V, or other convenient shape, or a radiator-type cooler may be used, similar to that shown on the left of Fig. 69. This particular cooler is used in connection with the type ON transformer, with gilled-tube detachable radiators, also shown in Fig. 69. The whole combination forms an ON/OB unit. External oil coolers facilitate the fitting of on-load

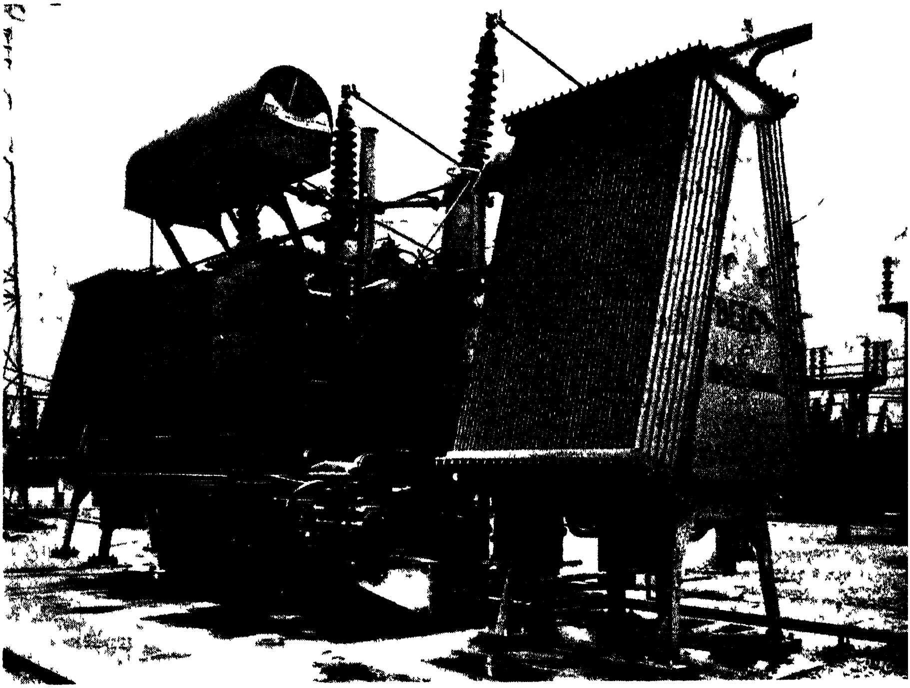


Fig. 70.—A 45,000 kVA, 132/33 kV, THREE PHASE ON/OFB TRANSFORMER WITH ON-LOAD TAP-CHANGING EQUIPMENT (*British Electric Transformer Co., Ltd.*)

tap-changing gear by making the tank surface available. The ON/OFB unit illustrated in Fig. 70 has fans fitted at the base of each cooler, and has an ON rating of approximately half-load. Units fitted with "A," or similar type, coolers are used with appropriate modifications, for the following types of cooling:

ON.
ON/OB, fans fitted.
ON/OFN, pumps fitted.
ON/OFB, fans and pumps fitted.

Water Cooling

Air-blast cooled types are very common, since effective cooling is achieved with simple equipment, but there are many circumstances in which water cooling offers decided advantages. Water-cooled units are customarily installed at hydro-electric stations where an abundant water supply is available, but they are used elsewhere when a cheap, pure, and reliable water supply is available. Two distinct types are employed: OW, in which the oil circulation is natural; and OFW, in which forced-oil circulation is used.

In both types the water may be circulated either by gravity or a pump. Generally, it is not economical to employ water cooling for units of less than about 1,000 kVA., but in special circumstances this may be the only practicable method of cooling a transformer of much less than this capacity, to obtain the required output from a unit whose dimensions are limited by the space available for installation. Transformers located in poorly ventilated chambers or compartments—such as pavement pits used for urban distribution systems—would be, when space restrictions limit their dimensions, incapable of anything like their rated capacity unless suitable ventilation can be arranged. When this is not practicable water cooling is the only method available.

The cooling coils through which the water circulates are fitted inside the tank, or arranged in the form of an external cooler, thus the surface of the tank is perfectly accessible for fitting tap-changing gear, or other accessories. The volume of the water-cooled type is less than that of any other of a given capacity, which fact leads to the installation of this type where space is limited. As a high ambient temperature usually prevails in confined situations, water cooling meets both these conditions. The neat and simple appearance of water-cooled units is shown in Figs. 71 and 72. Both these are OW units with internal cooling coils, the position of each coil being apparent from the shape of the tank, and the water connections.

Internal cooling coils are usually of tinned-copper tubing, the whole coil system being arranged in several parallel circuits. Fig. 73 shows a typical coil, which is detachable for transport purposes. The main part of the tank is visible on the left. At one time, with the steel coils then in use, there was a danger of water leaking into the oil through a faulty tube, and thereby lowering the dielectric strength of the oil to a degree which sometimes led to an internal fault in the transformer. With modern components this danger is extremely remote as, apart from careful construction, if the oil conservator is located at a sufficient height, and the coil divided into a number of parallel circuits, the oil can usually be maintained at a slightly higher pressure than the water.

The possibility of water leaking into the oil is completely removed with OFW cooling, since in this case the oil pressure is constantly maintained. A combination of forced-oil circulation with water cooling is more effective than any other method, consequently OFW units have a high output per unit of volume. For this reason OFW cooling has been adopted for some of the largest transformers ever built, notably for a particular installation in which the capacity of each unit is 93,750 kVA. The cooling equipment of these units is similar to that shown in Fig. 74. Each equipment is divided into two complete sections, only one being in operation at light loads, the other starting up automatically when the load increases to a predetermined value. The pipe lines which permit oil filtering while the transformer is on load should be noted in Fig. 74.

The relative effectiveness of the various types of cooling may be judged by the temperature-rise permitted in each case. With mixed cooled transformers the permissible temperature-rise—and in consequence, the rating—without the alternative additional artificial cooling in operation, is the same as for an ON unit ; and with it, is that for the particular type of cooling employed.

Since forced-oil circulation prevents wide temperature variations, the average temperature of the windings when this is used is higher for a given maximum or hot spot temperature. All types of cooling with forced-oil circulation are, therefore characterised by higher observable temperatures for the same maximum thermal stresses. They have the advantage that the circulation is positively controlled and not influenced by imperfections in operating conditions which would seriously affect the relatively feeble circulation due to natural convection.

Maintenance of Oil Quality

Conservators are fitted to most outdoor transformers, and generally to all units operating at approximately 33 kV., and over ; also for lower voltages than this when the transformer operates under exceptional conditions such as occur in a hot or humid climate, a corrosive atmosphere, or where the loading is such as to cause wide variations in operating temperature. The conservator provides for expansion of the oil in the main transformer tank which can thus be kept completely filled. By this means the area of hot oil in contact with the atmosphere is strictly limited, and the formation of sludge and the collection of moisture due to condensation are practically eliminated. The oil in the conservator remains at a low temperature since, due to the small diameter of the interconnecting pipe, it is practically unaffected by the circulation of the oil in the main tank. The application of conservators will be clear from the illustrations of various transformers. With increasing temperature the oil in a transformer expands and air is expelled from the conservator, or if this is not fitted, from the air space in the tank. When the oil cools air is drawn in, and since it is essential that this air should be dry, conservators, and some indoor transformers without them, are fitted with a breather for absorbing the moisture in the air. The breather may be of either the silica gel or the calcium chloride type.

The advantages of the former are, briefly, that the breather charge lasts considerably longer than with the calcium chloride type ; that the charge can be reactivated simply by heating, whereas the chloride breather must be refilled with fresh material ; that the silica gel breather is cleaner and less liable to corrosion.

The quality of transformer oil must be high, and maintained so, since it acts both as a dielectric and the medium by which the heat is transferred from the core and windings to the secondary cooling medium. Oil should conform to B.S.S. No. 148, especially in respect of the limits regarding the formation of sludge. This term is applied to a soapy, dark-coloured substance caused partly by oxidation of the hot oil in contact with the atmosphere. Sludge is a very undesirable substance to have inside a transformer tank, since it is a poor conductor of heat and has a great affinity for water. When sludge is formed it is usually deposited on the core and windings, and often clogs the oil ducts, with the result that the dissipation of the heat generated by the losses is very seriously affected. In consequence, hot spots may develop to such an extent that excessive deterioration of the insulation may occur leading to complete failure. The formation of sludge is cumulative, and likewise its effects. The deposits, being poor conductors of heat, produce an increased internal temperature, and at the same time the oil becomes more viscous and consequently less effective as a cooling medium, so that the temperatures of both transformer and oil increase, and the formation of sludge is further accelerated.

In connection with the formation of sludge it has been suggested ("Fluid Filling-Media for Electrical Apparatus," *Journal I.E.E.*, 1940, Vol. 86) that through curing the tendency of a transformer oil to form sludge by refining it to a high degree, the oils used to-day develop acidity instead. This causes more or less serious corrosion at various parts of the transformer. On this account the general conclusion was that it seemed preferable to tolerate a greater percentage of sludge in the interest of reducing the acid formation. To this end it was also suggested that Class B oils, which nowadays have a comparatively low sludge value, should be used in preference to Class A oils. Although these have practically zero sludge value, the development of acidity is greater than with Class B oils. With hermetically sealed transformers the amount of oil available for oxidation is so very limited that acidity is unlikely to develop to any extent. In any transformer it is, of course, essential that the oil level be maintained to avoid overheating on account of the consequent loss of tank-radiating surface, and of the quantity of cooling medium. Transformers in tubular tanks will be especially affected should the oil level fall below the top of the cooling tubes.

Relief diaphragms and vent pipes are usually fitted on large transformers of all types, or to meet special conditions. Some type of temperature indicator is essential to the safe operation of a transformer; the various instruments used are discussed in Chapter XI.

Chapter X

SPECIAL TYPES OF TRANSFORMER

THE various forms of transformer used for specific applications are fairly well represented in the illustrations associated with the chapter on cooling methods ; the particular application of each unit illustrated will be appreciated from the details of the voltages, etc., given. In some cases it will be noted that a transformer may have two secondary windings, thus enabling different voltages to be obtained from the same unit.

Buried Transformers

Certain forms of transformer have been developed to meet special circumstances, one of these being the " buried " type which is installed below street level and, therefore, depends for its cooling largely on the

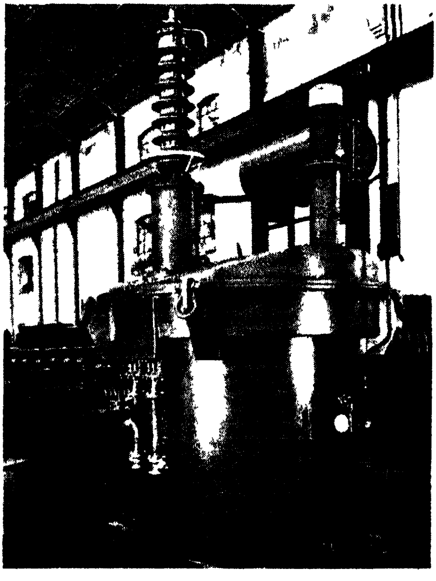


Fig. 71.—SINGLE-PHASE OW UNIT (*British Electric Transformer Co., Ltd.*)

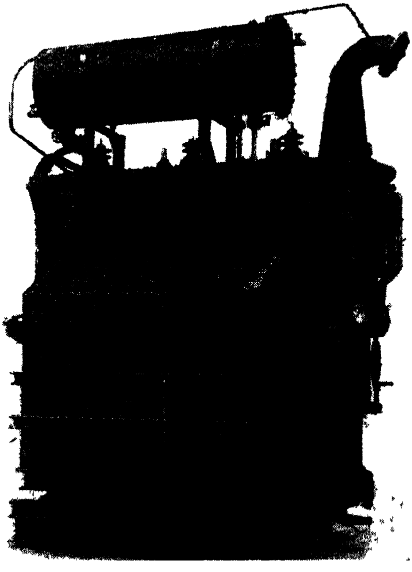


Fig. 72.—A 10,000 KVA., 21/3·18 kV. 3-PHASE OW TRANSFORMER WITH ON-LOAD TAP-CHANGING EQUIPMENT (*Hackbridge Electric Construction Co., Ltd.*)

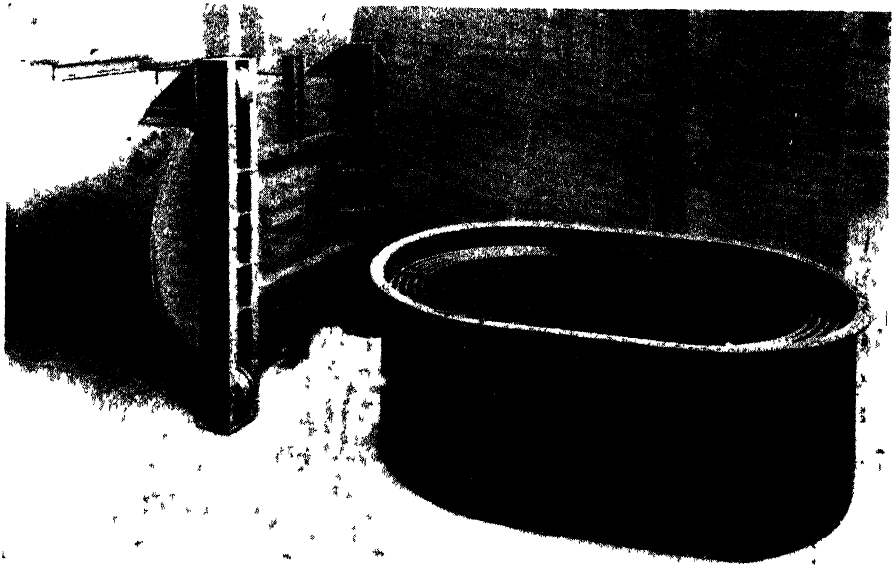


Fig. 73.—TYPICAL COOLING COIL AND TRANSFORMER TANK
(*Hackbridge Electric Construction Co., Ltd.*)

thermal conductivity of the surrounding soil. Fig. 60 shows one method of installing a buried-type transformer which has a corrugated tank surface for greater heat dissipation. The lower portion of the unit is buried direct in the ground, but the top is accessible through a manhole, together with an H.V. switch-fuse to control the incoming supply. The cable glands are also accessible through the manhole so that, if necessary, the transformer may be disconnected and removed bodily. The sides of the tank are tapered for easy removal, and the tank is specially treated to render it non-porous.

Hermetic Sealing

A similar type of unit is shown in Fig. 59 , the sides of the tank are ribbed and the transformer is hermetically sealed to avoid contact between the oil and atmosphere. Thus in damp and dirty situations the risk of oil contamination is eliminated. The ordinary breather will absorb moisture from air inspired as the transformer cools ; but breathers require regular attention and afford no protection against the flooding of underground transformer chambers or pits. The hermetically sealed unit is completely protected against this contingency, and furthermore, there is no waste of oil, and very little maintenance and inspection are required. In the transformer illustrated in Fig. 59, the essential provision

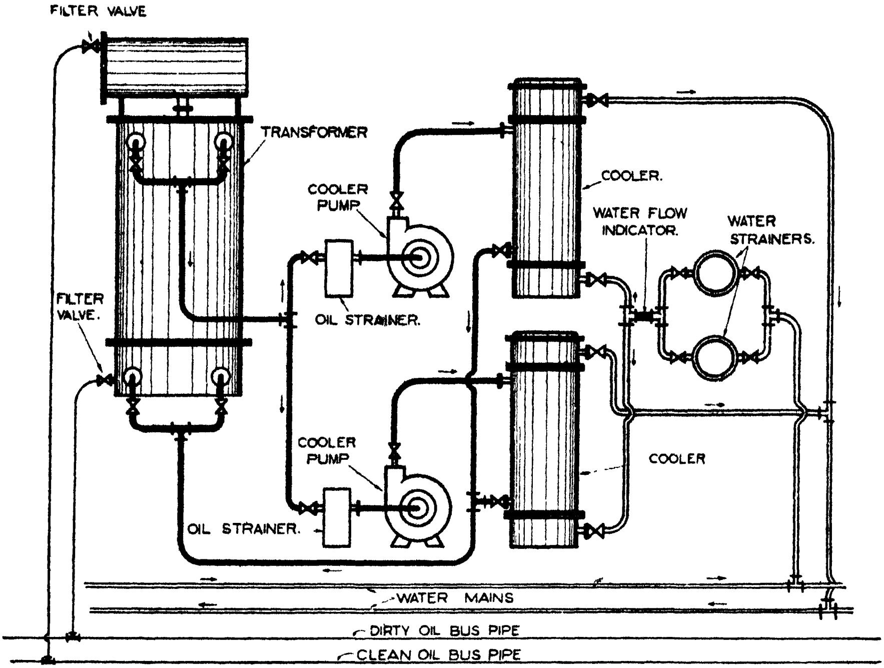


Fig. 74.—Cooling equipment of a large OFW transformer (*Hackbridge Electric Construction Co., Ltd.*)

for expansion and contraction of the oil due to temperature variations is made by means of a flat cylindrical expansion chamber attached at its centre to the tank lid so that its interior is in communication with the main tank. The expansion chamber—which with normal temperature variations is usually filled with oil—has flexible corrugated ends which are free to " bulge " outwards or " buckle " inwards, thus allowing for the expansion and contraction of the oil. The special construction adopted guards against any effects of fatigue of the metal due to repeated movement. The oil chamber is provided with a light sheet-iron cover, not shown in the illustration. So as to ensure that the correct quantity of oil is used the final filling is done whilst the transformer is hot. This is always necessary in order to prevent the expansion chamber being overstrained when the transformer reaches its maximum temperature.

Double Tank Unit

Another type of transformer which, installed in an outer tank buried in the soil, constitutes an underground distribution substation is illustrated in Fig. 75 (an X-ray view) and Fig. 76 (a sectional elevation).

The double-tank type is of a special design which makes it particularly useful for its purpose as a small-capacity distribution unit The large outer case of specially treated non-porous steel has a water-tight cast-iron manhole lid flush with the ground. The specially constructed oil-immersed naturally cooled transformer just fits into this chamber. Connections to the H.V. and L V. cables are made by means of porcelain insulator terminals from which removable leads are taken to porcelain bushings on the transformer. The transformer is hermetically sealed by an air chamber, into which it breathes, situated in the space behind the cooling tubes. This is clearly shown in Fig. 76. The transformer is filled when hot through the valve on the top cover. " Off-load " tap-changing is provided, adjustment being made by the handwheel shown in Fig. 76.

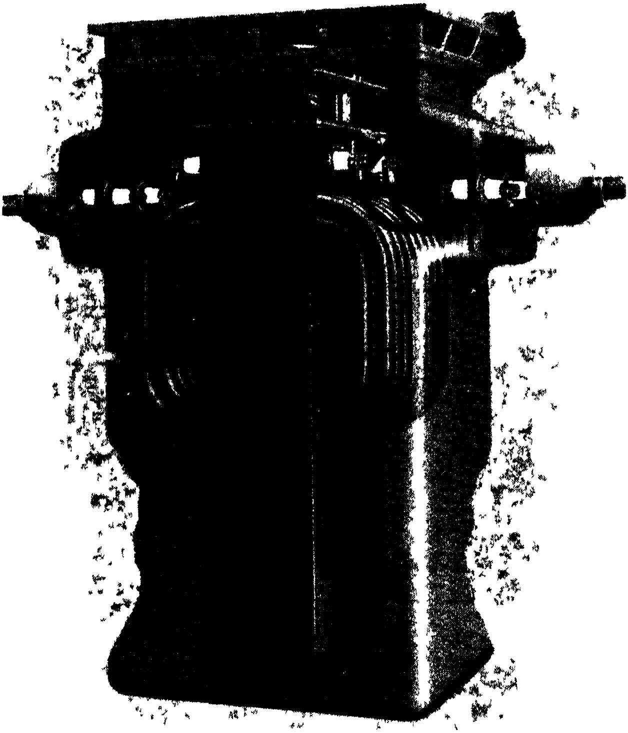


Fig 75 200 kVA , 6,000/250 VOLTS DOUBLE TANK BURIED-TYPE TRANSFORMER
(Hackbridge Electric Construction Co., Ltd)

With buried-type transformers there is a limited amount of heat dissipation from the lid of the chamber in contact with the atmosphere, but the cooling (and consequently the rating) of a buried unit depends largely on the rate at which the heat is removed by the surrounding soil. This in turn depends upon the thermal resistivity of the soil, each class of which has a widely different value. Generally, soils which hold a relatively high percentage of moisture have a low thermal resistivity, while porous soils have a high thermal resistivity. Examples of these two classes are clay and sand, while light loamy soils have a thermal resistivity between these extremes ; but much depends on the drainage facilities. A gravel or chalk soil, although itself porous, may have as

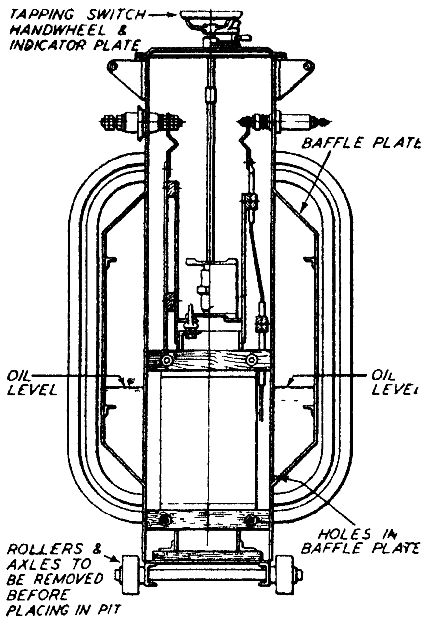


Fig. 76.—GENERAL ARRANGEMENT OF TRANSFORMER USED IN DOUBLE-TANK TYPE UNIT SHOWING HERMETIC SEALING

(*Hackbridge Electric Construction Co., Ltd.*)

low a thermal resistivity as clay if the strata below it tend to prevent the water from draining away, or if it is low-lying, and subject to waterlogging through proximity to a river or the sea. For certain soils the thermal resistivity varies with the season. With clay the variation is unimportant, but with sandy loam the thermal resistivity varies considerably over a period of the year, while in sand the variation is even more marked. In general, the low values occur in the spring and the high values in the autumn. Since the thermal resistivity (or, conversely, the heat conductivity) of the soil determines the rate of heat dissipation from a buried transformer its rating will, therefore, be governed by strictly local conditions. Owing to the restricted heat dissipation which is possible the maximum rating for the double-tank type is 200 kVA., and for the ribbed type (Fig. 60) 150 kVA.

Non-inflammable Filling Media

To avoid the fire risk associated with the inflammable nature of the hydrocarbon transformer oils, non-inflammable filling media are being used to an increasing extent for certain applications. These are largely composed of chlorinated diphenyls which have a breakdown strength similar to that of oil, and are non-sludging. The effectiveness of the chlorinated diphenyls as cooling media depends on obtaining a low value of viscosity, and this tends to increase as the degree of chlorination increases. For use as a filling medium for transformers the maximum chlorination compatible with suitable viscosity is 48 per cent. The shape of the viscosity/temperature curve is very steep compared with that for transformer oil, but the 48 per cent. liquid is just suitable. Its viscosity at 35° C. is approximately the same as that of a Class A oil at 20° C. At 60° C., however, it is much thinner than Class A oil, but at 0° C., while A30 grade transformer oil is perfectly fluid, the 48 per cent. diphenyl is quite viscous. Thus, at high ambient temperatures it would possess an advantage over oil as regards cooling by convection, but at 20° C. this advantage would be reversed, and at temperatures approaching zero the diphenyl would be definitely dangerous, its actual cold point being minus 9° C. For this reason low temperatures should be avoided ; but for cases where this is not possible a scheme has been proposed ("Fluid Filling Media for Electrical Apparatus," *Journal I.E.E.*, 1940, Vol. 86—discussion, page 321) whereby the viscosity of the chlorinated diphenyl compounds may be kept low, at low ambient temperatures, by fitting heating coils in the fluid, thermostatically controlled if necessary. The transformer could then be warmed up before being put on load, or could always be kept warm ready for immediate use. Incidentally, it is conducive to longevity if large transformers are not allowed to suffer wide changes of temperature which enforce relative movement of conductors and insulation, and of the windings and core.

The commercial chlorinated diphenyls have practically no sludge value as determined by the standard method prescribed for oils, and, in addition, there is extremely little acidity developed during the sludge test. This is in itself a good indication of the stability of the fluid at the sludge temperature of 150° C.

Since the non-inflammable compounds are inherently more expensive than transformer oils, when the former are used it is necessary to design the tanks and cooling systems with special regard to fluid economy. Skilful design, in producing a high ratio of cooling surface to volume, with rapid circulation, would limit the quantity of fluid required. The low viscosity of the compounds at ordinary working temperatures facilitates rapid circulation, and permits the use of smaller cooling ducts than when oil is employed as the cooling medium.

Chlorinated diphenyls are not generally suitable for switchgear applications, because of the liability of objectionable dissociation products being formed in the main arc-rupturing and isolator chambers.

A typical non-inflammable liquid dielectric is "Permitol." This is a mixture of chlorinated compounds with a cold-setting point lower than that of oil.

Fig. 77 shows a transformer in which Permitol is used as the filling medium. The unit is designed to comply with B.S. requirements, but in the details of its construction differs from oil-immersed transformers on account of the solvent action of the Permitol dielectric on some materials normally used in transformer engineering, and the need to minimise the volume of the dielectric. The construction of the coils and core is similar to that of oil-immersed units except that all the materials and treatments used are specially selected to be unaffected by the dielectric. At the same time, as the specific inductive capacity of Permitol is nearly the same as that of the solid insulations used in the transformer, there is a better distribution of stress which makes for economy in the use of material. The design is made as compact as possible

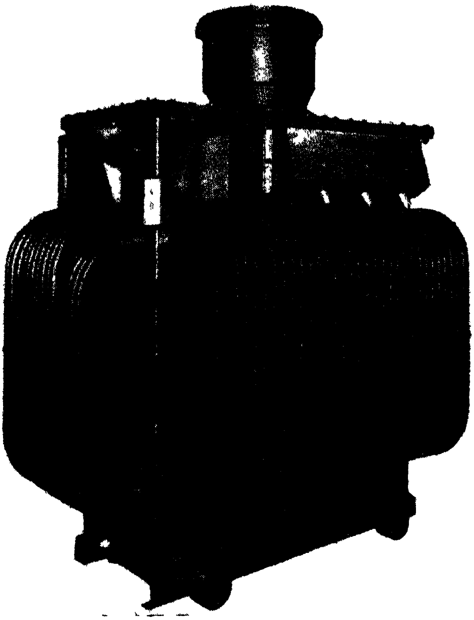


Fig. 77.—1,000 KVA. TRANSFORMER FILLED WITH PERMITOL NON-INFLAMMABLE LIQUID DIELECTRIC

(*British Thomson-Houston Co., Ltd.*)

to reduce the volume of the dielectric. Off-circuit tapping switches with handles for external operation are fitted as standard to avoid having to break hermetically sealed joints to change taps. Tanks are of normal construction except that tubes of special section are used to reduce the dielectric content, and the sampling valve is located at top instead of at the bottom of the tank. This is because the liquid is heavier than water, and although it is practically non-hygroscopic, in the remote event of any moisture entering the hermetically sealed transformer it will float on the surface instead of settling at the bottom. Conservators and breathers are not, of course, required with the hermetically sealed units.

For the relief of internal pressure under fault conditions a relief diaphragm is provided designed to operate at a higher pressure than will be encountered in normal service. A relief pipe connecting the vent to the outer atmosphere is provided when possible. Where this is impracticable a gas absorber is bolted over the diaphragm to absorb any gases caused by an internal fault. Although these gases are non-poisonous and non-explosive, they are, nevertheless, unsuitable for human respiration, and so should not be allowed to accumulate in an enclosed space.

The cost of transformers with Permitol dielectric is relatively high, consequently their application is limited to positions where transformer oil would constitute a serious hazard in the event of fire. In many cases it is often impossible, or very expensive and inconvenient, to install oil-immersed units with adequate safeguards against fire. To locate such transformers in safe positions, usually remote from the most economic point of application, involves increased cable costs and losses. For such problems Permitol, and non-inflammable filling media generally, offer an economical solution.

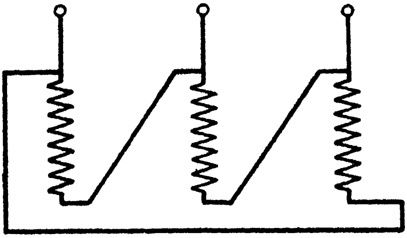


Fig. 78.—DELTA CONNECTION

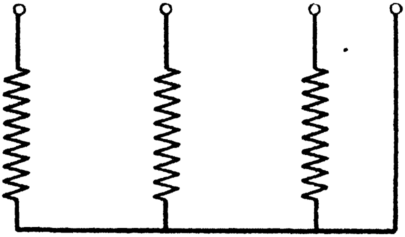


Fig. 79.—STAR CONNECTION

Transformer Connections

The most usual way of connecting together the three phases of a transformer winding is either in delta (Fig. 78) or star (Fig. 79). With the first the winding of each phase has the full line volts applied across it but carries only $1/\sqrt{3}$ of the line current. Each phase of the star-connected winding has only $1/\sqrt{3}$ of the line volts applied across it but carries the full line current. Windings connected in either of these two ways are used in various combinations. A frequent combination is to connect the primary in delta and the secondary in star. This enables an earthed neutral to be obtained for protective purposes and, in the case of distribution transformers, a four-wire supply, while the delta winding provides a closed circuit for the third harmonic component of the no-load current. Star-delta units are used for the highest voltages, the higher- and lower-voltage windings being connected star and delta respectively. Star-star connections are sometimes used as this results in a slightly cheaper unit in most cases, although unbalanced loading is apt to cause serious distortion of the secondary star, the star point shifting to give a very high voltage on one phase and a very low one on another. The difficulties of voltage distortion on unbalanced loads may be overcome by providing a third set of windings connected in delta, and insulated from both primary and secondary windings. Such a winding is known as a "tertiary," and can also be used to provide a path for the third harmonic component of the magnetising current.

Tertiary windings are also used—with various combinations of main windings—to supply additional power loads, such as station auxiliaries or static condensers for power factor correction, and to interconnect three supply systems.

Delta-delta banks of three single-phase transformers are sometimes used as this arrangement enables two units to be used in " open-delta," or V connected, should one unit fail. The output of the two units so connected will be only about 85 per cent. of the rated capacity of the two transformers when used in combination with the third for three-phase supply.

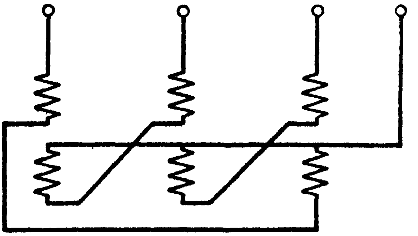


Fig. 80.—INTERCONNECTED-STAR CONNECTION

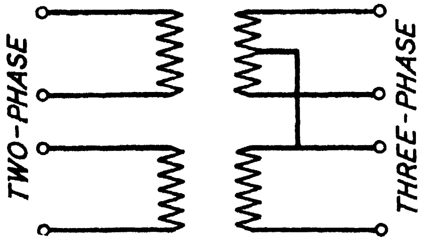


Fig. 81.—SCOTT CONNECTION

The interconnected-star connected winding is used for certain special applications, and it is made up of two windings on each limb of the transformer interconnected as shown in Fig. 80. As with the star connection each winding carries the full line current, and a neutral point is available, but the voltage between line and neutral is the vector sum of two voltages displaced by an angle of 60° (or the vector difference between two voltages at 120°). The interconnected-star winding is used for the control of the load and the power factor of interconnecting circuits (see page 151). For three- to two-phase transformation, or vice versa, the Scott connection is generally employed. The connection is shown in Fig. 81, the three-phase side being made up of one winding, which has applied to it the full voltage between phases of the supply, and from which a midpoint tapping is taken to one end of the teaser winding—designed for $\sqrt{3}/2$ times the voltage between phases. Both primary windings are designed for the full line current. The secondary two-phase winding is arranged as shown in Fig. 81. A neutral point can be provided for the primary winding by taking out a tapping on the teaser winding, at a point from the end joined to the main winding, equivalent to 29 per cent. of the full line voltage. Two single-phase units Scott connected are sometimes used for three- to two-phase supply, one being the main transformer, and the other the teaser transformer of the bank.

Furnace Transformers

Electric furnaces are extensively used in industry, as they permit easy and convenient control of the generation and transfer of heat, and also of the physical changes and chemical reactions in the furnace charge. The two types of electric furnace in most general use are the arc furnace, and the resistance furnace ; and usually special transformer equipment is necessary for the reduction and variation of the supply voltage to a suitable range of values. The successful operation of the arc furnace depends on the transformer being designed to withstand the very severe duty that is the normal function of such equipment.

Arc furnaces are used in connection with various metallurgical and chemical processes, but they are mostly used for melting steel and maintaining it at a high temperature during refining, alloying, etc.

Graphite or carbon electrodes are contained in a chamber lined with refractory material, the heat required being generated by arcs formed between these electrodes and the furnace charge. In many cases the charge is cold at the commencement of the cycle of operations and requires a maximum energy input at the higher values of voltage available to break it down into the molten condition. During this portion of the duty-cycle, lasting from 1½ to 2 hours, frequent and heavy overload conditions, amounting at times to short-circuits across the transformer secondary windings, are encountered. As the cycle proceeds the heat receptivity of the charge and the energy input required decline, and refining, if carried out, necessitates a comparatively small input at reduced voltage for 4–7½ hours, depending on the particular product of the furnace.

Fig. 81A shows a typical arc furnace transformer with a high-voltage primary. On account of the low voltage, the heavy-current secondary winding has only a few turns of large-aggregate cross-section, and consists of several coils connected in parallel. A concentric winding arrangement is used, the secondary winding being placed on the outside, making it more convenient to carry away the heavy-current secondary connections.

Since it is impracticable to bring out tappings from the secondary winding, due to the large cross-section necessitated by the heavy current, variation of the secondary voltage is generally obtained by means

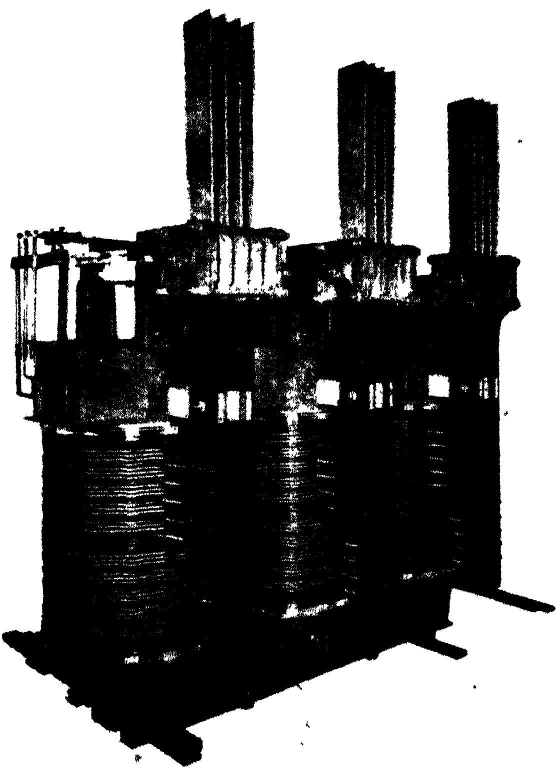


Fig. 81A.—THREE-PHASE 2,460 KVA. ARC FURNACE TRANSFORMER, 20,000/180·79 VOLTS
(*British Thomson-Houston Co., Ltd.*)

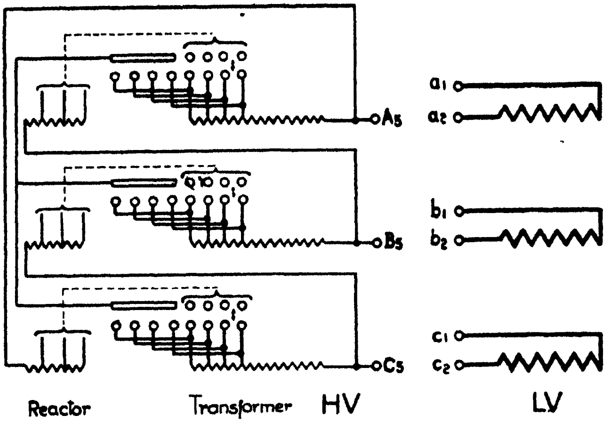


Fig. 81B.—DIAGRAM OF CONNECTIONS FOR FURNACE TRANSFORMER

Transformer provided with tapped primary winding arranged for delta or star connection to give wide range of secondary voltage.

A terminal link board (not shown) can be provided such that either ⅓, ⅔, or all the series reactance can be included for each of the four higher secondary voltages as may be found desirable.

of tappings on the primary windings. The number of turns in the primary winding is increased to effect a corresponding reduction in secondary voltage over the required range. In addition, on three-phase transformers required to give a practically constant current output, a reduction of secondary voltage to 57·7 per cent. of its initial value can be obtained economically by changing the primary winding connections from delta to star. A common arrangement of windings, combining both the above methods and giving a voltage range down to 35 per cent. of the maximum voltage in seven steps, is shown diagrammatically in Fig. 81B.

If, however, a constant kVA. output is required at the lower secondary voltages, as distinct from constant current output, the delta/star winding arrangement offers no advantage, and voltage control must be effected by primary tappings only. Owing to the high heat contents of the furnace and the charge, momentary discontinuance of the energy supply is unimportant, therefore it is not usually necessary to fit on-load tap-changing to the transformer, and off-load tapping switches of a specially robust design to meet the frequent operations are generally adopted. With large transformers the tapping switches may be motor driven and arranged for electrical remote control. Interlocks with the primary circuit-breaker are provided so that the tap changer cannot be operated inadvertently with the transformer excited.

For most types of arc furnaces high reactance is required in the supply circuit to stabilise the arc and to reduce peak loads on the system during the melting period; consequently, transformers may have a reactance of the order of 20–25 per cent. Generally it is more economical to achieve this partly by inserting a reactor in series with the primary winding rather than to design the transformer with an inherent reactance of the required value. With the delta/star primary winding arrangement, when the winding is star-connected, the transformer reactance is usually in itself sufficient without the need for additional external reactance and the reactor is only connected in circuit when the delta connection is in use ; i.e. for the higher range of secondary voltages. Furthermore, since the reactance of the transformer itself will, when provided with primary tappings for secondary voltage variation, increase with a reduction in the secondary voltage, if the external series reactor is provided with tappings these can be selected on each of the four higher secondary voltages to give a substantially constant reactance over a great part of the secondary voltage range. The application of a tapped reactor is shown in Fig. 81B.

Resistance furnaces are used for processes requiring a constant temperature or a slow temperature cycle (e.g. heat treatment, annealing, etc.). The heat is generated by resistance units of special alloy, or in certain cases by the resistance of the charge itself. For the operation of resistance furnaces constant current is required, not constant kVA., and in many cases only infrequent voltage adjustment is necessary. This is carried out by tapping boards or by a standard type of manually-operated off-load tapping switch.

Some types of large resistance furnace have a number of heat zones, and in such cases the heating units in each zone are separately supplied by low-voltage transformers which are in turn supplied from a main step-down unit taking a high-voltage supply from the system. The relative temperatures of the various zones can be adjusted by tapping links on the individual low-voltage transformers, whilst the temperature cycle of the furnace as a whole is controlled by primary tappings on the main transformer in much the same way as for arc furnaces.

The cooling arrangements employed for furnace transformers depend on the conditions obtaining in each case. For small resistance-type furnaces naturally air-cooled dry transformers are frequently used as, although more expensive than oil-immersed units, they have lower fire hazards and can, therefore, be located close enough to the furnace to economise in secondary leads. Transformers filled with non-inflammable liquid dielectric are also used under such conditions. Oil-immersed, self-cooled units are usually employed for large resistance furnaces, and for arc furnaces up to about 5,000 kVA. ; but where space is limited, and generally for transformers above this capacity, forced-oil circulation with water cooling is frequently employed. Cooling water has to be provided for the furnace and is therefore available.

Chapter XI

THE CONTROL OF TRANSFORMER TEMPERATURE

THE fundamental limit to the load a transformer can safely carry is the maximum temperature that the insulation can be subjected to continuously without excessive deterioration ; in other words, the thermal capacity of the insulation. Since the temperature of the hottest spot in the insulation is the true measure of the output of a transformer in terms of its thermal capacity, the maximum safe load can be determined by observing a temperature that has a definite known relation to that of the hottest spot. The limit of safe load is reached when the temperature value observed attains a predetermined maximum, the exact value depending on how the temperature indication is obtained.

TABLE V.—TEMPERATURE LIMITS FOR TRANSFORMERS WITH CLASS " A " INSULATION

Continuous Max. Temp. ° C. (a)	*Type of Cooling (b)*			
90	Dry	AN	AB	
95	Oil-	ON	OB	OW
100	immersed	OFN	OFB	
105	(c)			OFW

(a) Peak values 5° C. higher are permissible, providing the average temperature over a 24-hour period does not exceed the figure shown. (This does not apply to water-cooled types where a constant ambient temperature exists.)

(b) With " mixed cooling " the maximum permissible temperature will depend on whether the transformer is on the " natural " or " artificial " rating.

(c) For all oil-immersed types the continuous maximum permissible oil temperature is : Class A, 85° C. ; Class B, 75° C.

The maximum or hottest spot temperature allowable continuously for Class A insulation is 105° C., and the permissible temperature limits for the different types of cooling are determined by the permissible difference between the maximum temperature and the mean copper temperature—as measured by increase of resistance. Maximum permissible temperatures for the various types of cooling are shown in Table V. The values in this table are based on the temperature-rise limits, and the standard reference ambient temperatures of B.S.S. 171—1936—as measured by the methods stated therein. Although in the specification the permissible values given are temperature-rises, in practice, transformers are not usually operated by reference to temperature-rise as it is more convenient to directly measure a temperature that can be accepted as the temperature of the unit. Quite frequently, however, the temperature of the transformer is practically disregarded—provided it is by no means excessive—and the unit loaded in accordance with its rated output. If the unit is designed to comply with the B.S.S.—as is generally the case—the rated output is equivalent to the continuous maximum rating, as defined, and which is the basis of the specification.

Permissible Overloads

Now the C.M.R. is determined in relation to the standard reference ambient temperatures stated in the specification, that is to say, the output stated on the rating-plate of the transformer has a value based on the assumption that the ambient temperature obtaining is equal to the standard reference value ; but it is evident that under actual service conditions the ambient air temperature, for instance, will seldom approach and rarely be maintained at 35° C.—the specified value. Thus, when the ambient temperature is below the standard value, the maximum transformer temperature will be less—with rated output—than that permitted by the specification ; consequently, the unit is then capable of a greater output, either continuously or for a period, than that corresponding to the C.M.R. That transformers may be overloaded—in relation to their rated output—when the ambient conditions are favourable is recognised by the B.S.S., which tabulates data for the calculation of the permissible duration of overloads for different types of cooling when the ambient temperature is below the standard reference value. The stipulation is made that the rated voltage and frequency must be maintained, and that the application of overloads must be effected with discretion. " Short-time " overloads should be followed by a period of at least four hours' duration at the same (or less onerous) loading conditions as preceded the application of the overload. The permissible duration of the overload will depend on the transformer temperature already reached before overloading takes place.

In practice, loading should be controlled by reference to an observable temperature, not by a calculated value, and it is clear that since the B.S.S. permissible overloads are based on the maximum temperature-rises allowed it is possible to operate transformers solely on the basis of their thermal capacity—in terms of maximum observable temperatures—and that this does not infringe the implied intentions of the specification. It is interesting to examine the extent to which a particular type of unit may be overloaded by an example based on the tabulated data. When the ambient temperature is the standard reference value specified, a 4,000 kVA. 11 kV. type ON transformer starting with a temperature not exceeding the ambient temperature (i.e. quite cold, having been off load for a period long enough to enable it to cool down after being on load previously) will be capable of 10 per cent. overload for 170 minutes, and 100 per cent.

overload for 20 minutes. If the same unit had been continuously excited, with the secondary open-circuited, then its temperature would be such that for 10 and 100 per cent. overload the times would be 130 and 14 minutes respectively. After continuous running at normal rated load no overload is permissible.

The effect of an ambient temperature lower than the standard reference maximum value of 40° C. is demonstrated by the fact that when the ambient temperature is 25° C. (maximum daily average 20° C.) the particular transformer being considered is capable of 10 per cent. overload continuously—even when it has been operating at normal rated load. Starting from cold, 100 per cent. overload can be carried for 30 minutes ; after continuous excitation on open circuit for 20 minutes ; and after continuous running at normal rated load for two minutes.

Methods of Operating Transformers

From the foregoing it is apparent that transformers can safely carry loads in excess of their rated output, and can in fact be loaded on the basis of the maximum temperature permitted. This method of loading has certain definite advantages as compared with the rather common method of operating transformers by reference to their ampere loading. With the latter method, above a certain load another unit is switched-in without regard to the temperature of the unit, or units, already on load, which may be such as will permit a reasonable overload for a fairly long period. By making use of the overload capacity it is often possible to avoid putting another unit on load, thus reducing switching operations to a minimum. This is desirable since during switching operations a transformer is always subject to pressure-rises and current-rushes, both of which tend to weaken the insulation between turns of the coils, electrically and mechanically, thereby increasing the possibility of ultimate breakdown, and short-circuit between turns. Modern units are, of course, built to withstand switching transients ; but even so, it is always advantageous to minimise the disturbances on a high-voltage system resulting from switching-in transformers.

Another method of operating a group of transformers aims at maintaining a high group efficiency ; the loading of each unit being decided by the output at which its efficiency is a maximum. Above this output a point is reached where—despite the fact that each unit may be underloaded—the highest percentage efficiency of the group is maintained by switching in another transformer in parallel with those already on load. In this case thermal loading will produce a greater percentage loss, unless the maximum efficiency occurs at approximately full thermal load. However, where several transformers are installed in an unattended station with a low load factor, and short-time load peaks occur, loading the units on a thermal basis may permit one, or more, to be kept off load—at least for certain seasons of the year. By this means the transformer losses on light loads are reduced to a minimum, and a higher annual efficiency of the group obtained. Perhaps the greatest benefit of being able to operate transformers on the basis of their thermal capacity arises at times of emergency, when the minimum of plant is available.

Measurement of Temperature

To enable thermal loading to be effected with impunity, and, generally to guard against excessive temperature, it is essential to be able to measure accurately some temperature which can be accepted as a safe guide to the operation of the transformer. Since the true rating of a transformer is determined by the temperature of the hottest spot in the insulation it would be preferable to be able to measure this temperature, but it is not yet possible to do this directly. The winding temperature, however, can be determined in two ways : (1) by measuring the increase of winding resistance with temperature ; (2) by thermo-couples embedded in the winding acting as temperature detectors. The first method is not suitable for operating purposes as it would entail shutting-down the unit to make the necessary measurements ; but it is of exceptional utility for determining permissible temperature-rise limits from which the approximate relation between oil and winding temperatures may be established. As the resistance of copper varies in direct proportion to its absolute temperature, the ratio of the hot to the cold temperatures of the windings is derived from the ratio of their hot and cold resistances. Since temperature measurements by this method are not available for continuous observation, and measurement by thermo-couples is generally impracticable and always very expensive, in practice it is necessary to employ methods of determining transformer temperature which are free from these disadvantages. The most usual method with oil-immersed transformers is to measure the temperature of the hottest oil ; a maximum permissible temperature value being determined from a knowledge of the relation between this and the hottest spot, or winding temperature. The temperature relations are fairly definite, the average winding temperature being approximately the same amount greater than the average oil temperature as the hottest spot temperature is greater than the hottest oil temperature.

Permissible Oil Temperature

For operating purposes critical values of hottest oil temperature can be stated by the transformer manufacturers from a knowledge of the internal temperature distribution of the unit concerned, determined experimentally. For example, one recommendation is that when a transformer is designed to comply with the B.S.S. which permits a maximum oil temperature of 85° C. continuously, an alarm should be given at 90° C., and the unit should be automatically tripped out of service at 95° C. In this particular case the latter temperature value will be proportional to the maximum internal temperature beyond which the thermal capacity of the transformer will most probably be exceeded. Once a transformer has been subjected to a really excessive temperature the risk of complete failure is always present, and the transformer should preferably be re-insulated.

With some types of transformer the limits fixed for the temperature-rise of the windings necessitate a reasonably low oil temperature, but in many types the maximum permissible temperature of the oil is determined partly by its relation to the hottest spot temperature, and partly by the maximum temperature that the oil itself will withstand continuously while maintaining its quality as both a cooling medium and a dielectric. B.S.S. No. 148, "Insulating Oils for Electrical Purposes," recommends that Class A oil should be used when the maximum oil temperature exceeds 80° C., while Class B oil may be used when the maximum oil temperature does not exceed 75° C. For a transformer rated in accordance with the B.S.S. temperature limits Class A oil should be used, since the 50° C. temperature-rise permitted for the oil allows a maximum oil temperature of 85° C., but often Class B oil is used instead ; sometimes, because it is considered that acid formation is reduced when Class B oil is substituted for Class A oil. Apart from this, the use of the former would be justified in units whose maximum oil temperature does not exceed 75° C., as the result of favourable ambient temperature or load conditions. At the same time the lower permissible temperature-rise of Class B oil may prevent a transformer being loaded to the full extent of its thermal capacity since the relatively excessive oil temperature corresponding to the maximum permissible winding temperature will accelerate the

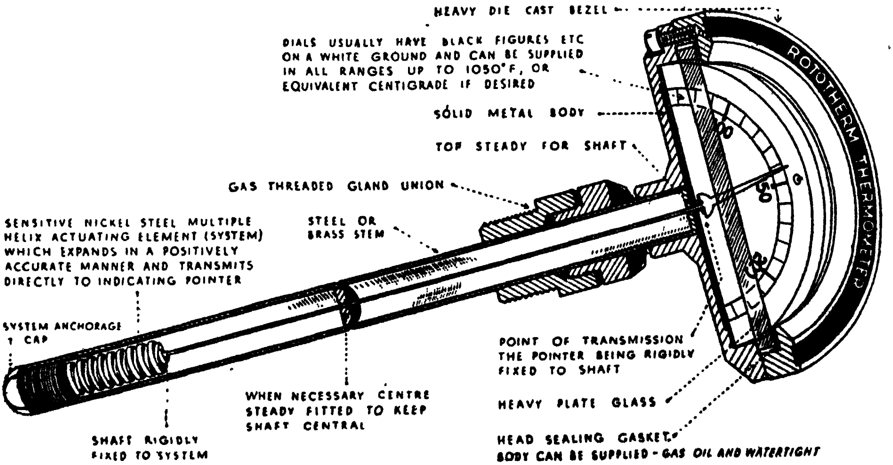


Fig. 82.—CONSTRUCTION OF ROTOTHERM DIAL THERMOMETER
(*The British Rototherm Co., Ltd.*)

formation of sludge. When a transformer with Class B oil is operated in the region of its thermal capacity the oil, and the transformer, must be kept thoroughly clean.

Bimetallic Dial Thermometers ✓

Several types of thermometric devices for indicating oil temperature are in common use. Glass thermometers have a limited application, but it is usually preferred to be be able to observe a dial reading. One instrument used for indicating oil temperature is the Rototherm dial thermometer, a sectional drawing of which is shown in the self-explanatory Fig. 82. The essential, and most unique feature of the thermometer is the temperature-sensitive element, which consists of a bimetallic strip. As the strip is composed of two metals—whose coefficients of thermal expansion are widely different—firmly bonded at their face of contact, it will change shape as the temperature varies. The torque produced in the element by this means is applied to rotate a spindle carrying a pointer. Rotötherms are either inserted in the transformer pocket or fitted permanently when the unit is built. An important precaution to observe with this type of thermometer is that the stem is long enough to reach to the end of the pocket so as to immerse at least three inches in the oil. If the stem is too short the instrument may not be indicating oil temperature at all, but merely that of the hot vapour above the oil level.

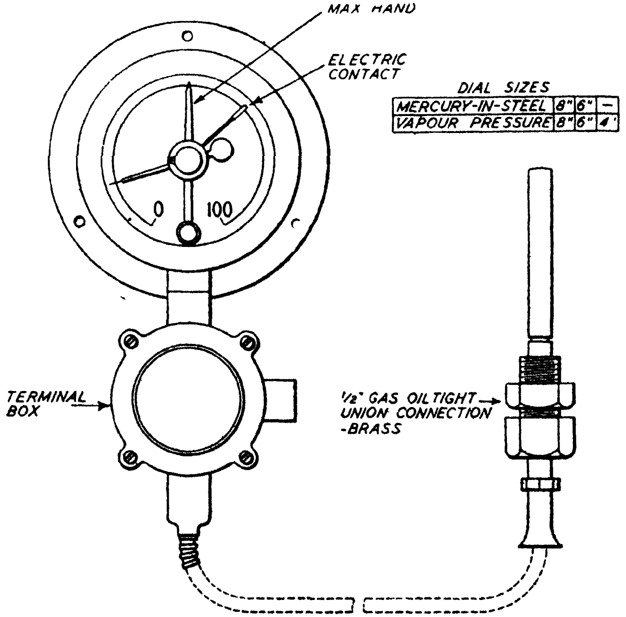


Fig. 83.—ACCOSON VAPOUR PRESSURE THERMOMETER
(*A. C. Cossor & Son (Thermometers), Ltd.*)

Bulb Thermometers

Another type of thermometer used extensively for the measurement of hottest oil temperature is that consisting of a bulb connected to an indicating instrument by capillary tubing. The temperature-sensitive medium is either mercury or alcohol. Bulb thermometers containing mercury

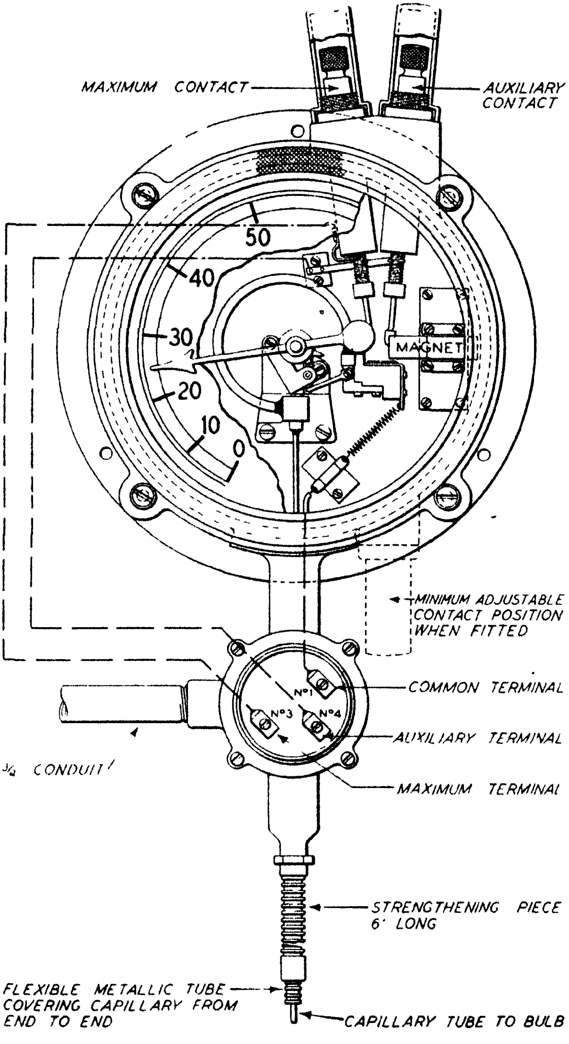


Fig. 84.—MECHANISM OF VAPOUR PRESSURE THERMOMETER DIAL INDICATOR. (*A. C. Cossor & Son* (*Thermometers*), *Ltd.*)

are known as the "mercury-in-steel" type, because a steel capillary is used, and those containing alcohol, with a copper capillary tube, as the "vapour pressure" type. A complete vapour pressure equipment is shown in Fig. 83, and the mechanism of a typical indicator in Fig. 84. The operation of the V.P. type depends on the fact that the vapour pressure of a pure volatile liquid is a function of its temperature. The bulb is partly filled with liquid, the remaining volume, together with the capillary and the Bourdon tube of the indicator, being filled with vapour. An increase in pressure causes a deflection of the Bourdon tube. The M.I.S. type operates by the change of liquid volume.

Thermostatic Alarms and Control

For transformers without auxiliary cooling plant, operating on a definite load cycle in attended substations, it is usual to rely on thermometers with a maximum temperature hand operated by the pointer, as shown in Fig. 83 : but in other cases some form of contact-making thermometer is used for the notification of excessive temperature, the control of auxiliary cooling equipment, and the disconnection

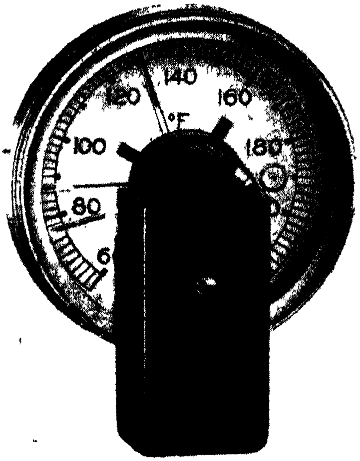


Fig. 85.—ROTOTHERM WITH MAXIMUM AND MINIMUM CONTACTS
(*The British Rototherm Co., Ltd.*)

of the unit in the event of a dangerous over-temperature arising. If only an alarm is required, in addition to a visual indication, an adjustable electric contact fitted to the indicator (Fig. 83) is sufficient, but for the control of other circuits two or more contacts are used. Fig. 85 shows a Rototherm dial thermometer fitted with one maximum and one minimum contact for accurate thermostatic control. In conjunction with a suitable relay, this is used for controlling auxiliary cooling equipment, which starts up at a predetermined temperature, but will not shut down until a certain minimum temperature is reached. This arrangement is essential to prevent the equipment constantly starting and stopping when the load is such that the temperature is only just sufficient to close the maximum contact. When only a maximum temperature control or alarm is required, without a visible indication, the Rotostat shown in Fig. 86 can be used. This acts on the same principle as the Rototherm thermometer.

Standard types of bulb thermometers are used for control purposes which may have indicators with as many as four adjustable contacts. Fig. 87 shows a waterproof type for outdoor use with adjustable maximum, minimum, auxiliary maximum, and auxiliary minimum contacts. The interior mechanism is similar to that of the two-contact model shown in Fig. 84, in which a spring-loaded moving contact, connected to the common terminal, moves up towards the fixed contacts as the temperature rises. By rotating the fixed contacts, the distance that the moving contact has to travel to make the circuits can be varied, the rotation of the fixed contacts being communicated to small pointers which indicate the setting of the contact concerned on the subsidiary dials shown in Fig. 87. A special relay is incorporated in this model for controlling the circuits to the auxiliary cooling, etc., and ensuring a delayed action if necessary.

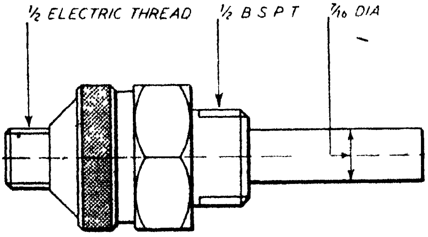


Fig. 86.—CONTACT-MAKING ROTOSTAT
(*The British Rototherm Co., Ltd.*)

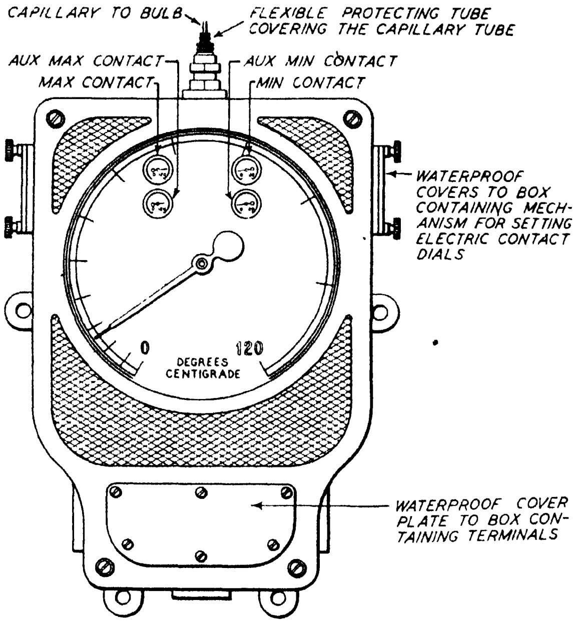


Fig. 87.—V.P. THERMOMETER DIAL INDICATOR WITH FOUR CONTROL CONTACTS
(*A. C. Cossor & Son* (*Thermometers*), *Ltd.*)

Relation of Oil Temperature to Winding Temperature

When a transformer is loaded by reference to a predetermined maximum temperature value of the hottest oil, this value will probably be some degrees below the actual temperature limit since it is necessary to allow for discrepancy in the relation between the hottest oil temperature and the maximum winding temperature arising from the widely varying operating conditions likely to be encountered in practice. In consequence, it is not generally possible to load the unit to the full extent of its thermal capacity on the basis of the observable oil temperature. Every manufacturer can quote a safe overload value in terms of the oil temperature for each unit built, by making due allowance for the difference between winding and oil temperatures, but the value quoted is necessarily somewhat conservative because of the conditional discrepancy between the two temperatures. The difficulty of obtaining an accurate indication of winding temperature in terms of the hottest oil temperature arises because the transformer windings are, of course, always hotter than the adjacent oil, as there must be a temperature-gradient across the insulation if the heat generated in the coils is to be transferred to the oil. The gradient increases rapidly as the load increases, so that even under steady load conditions a measurement of the oil temperature is not truly representative of the maximum winding temperature, and when sudden overloads are applied the latter increases very rapidly, whereas the oil, owing to its bulk, may take several hours to reach a steady temperature. This is shown graphically in Fig. 88.

Thus for a rapid increase of load the time-lag between winding and oil temperatures may result in the maximum safe temperature of the windings being exceeded when the temperature of the oil is still relatively low.

When a transformer operates on a definite load cycle, and a period of heavy load is followed by a long period of light load, the hottest oil temperature is usually a sufficiently accurate guide, for should the maximum normal load be exceeded due to a sudden overload of short duration, the conservative overload rating is a safeguard against a dangerous winding temperature being reached. (In attended stations sudden overloads will, of course, be dealt with by the staff.) Excessive overloads are guarded against by discriminating overcurrent protection. In these circumstances, therefore, an over-temperature device actuated by hottest oil temperature can give adequate protection against steady overloads not covered by the overcurrent protection, but likely to produce dangerous thermal conditions. Actually, many transformers are not protected by any sort of thermal device, the overload or overcurrent protection being relied upon for disconnecting the transformer when the ampere loading is such as would create dangerous thermal conditions, if allowed to persist.

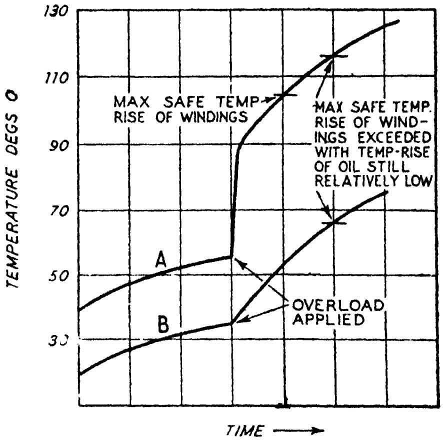


Fig. 88.—Effect of sudden overload on transformer temperatures

(A) Winding temperature. (B) Coil temperature.

Winding Temperature Indicators

When, however, it is required to load a transformer to the limit of its thermal capacity, or guard against sudden heavy overloads, but at the same time avoid shutting-down the unit unless it is absolutely necessary, then an indication of the winding temperature is essential, and to this end the winding temperature indicator has been developed.

This comprises electrical and thermal apparatus for adding the temperature difference between the hottest spot and the oil, to the temperature of the oil. The total temperature measurement thus obtained gives an indirect, but accurate representation of the maximum winding temperature. Generally, the temperature-gradient across the insulation of the coils composing the transformer winding is simulated by an arrangement of a heating element, or a coil, so designed that the difference between its internal and external temperatures is, at any load, the same as that of the transformer winding. This effect is obtained by energising

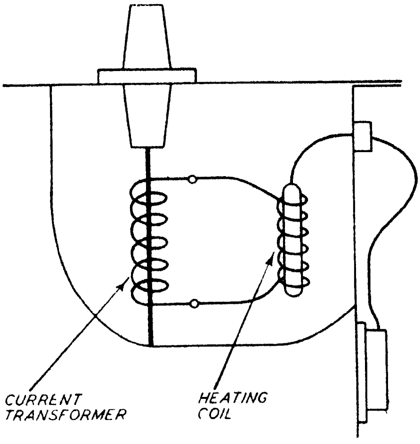


Fig 89 Principle of winding temperature indicator

the element from the secondary of a current transformer so that the current which flows through it is directly proportional to the main transformer current.

The principle of the winding temperature indicator is illustrated in Fig. 89, which is actually similar to the arrangement used by the British Electric Transformer Co., Ltd. The heating element consists of a coil which has the same ratio of copper loss (in watts)/heat dissipating area as the hottest coil in the main winding: the current in the coil varies directly as the load on the transformer, consequently the thermal characteristics of the winding are reproduced by the coil. The bulb of a standard type of vapour pressure thermometer is located in the centre of the coil, and since this is also immersed in the hottest oil, the total temperature affecting the expanding medium in the bulb is the sum of the oil temperature proper and the increase in oil temperature due to the local heating effect of the coil. Thus a true representation of the winding/oil temperature-gradient is given under all loading conditions, and the instrument presents a direct indication of the hottest spot temperature. The current transformer and the heating coil are mounted inside the transformer tank; only the thermometer dial is seen from the outside.

Two types of winding temperature indicator are manufactured by the Metropolitan-Vickers Electrical Co., Ltd.: the thermometer type for local indication, and the bridge type for distant indication. In both types the temperature conditions existing in the hottest part of the transformer windings are reproduced by a heating element supplied from a current transformer. The element may take the form of a high-resistance thermometer bulb or a metal foil heating device: the first is shown in Fig. 90, and the second represented diagrammatically in Fig. 91. Both types of element are located in the hottest oil, and surrounded by insulation so proportioned that the temperature-gradient between the element and the oil is the same as that between the main transformer windings and the oil. Since the element is being cooled in the same way as the transformer windings, the actual temperature of the element will, therefore, always be proportional to the temperature of the transformer windings at the hottest spot.

From data obtained experimentally, the excess temperature of the

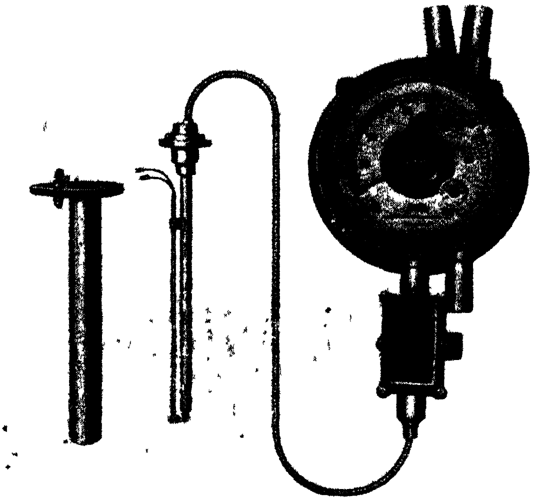


Fig. 90.—THERMOMETER-TYPE WINDING TEMPERATURE INDICATOR
(*Metropolitan-Vickers Electrical Co., Ltd.*)

hottest part of the windings above the hottest point of the oil is known very closely for various loads, and the indicating instrument is, therefore, calibrated to show a temperature value equal to that of the hottest part of the transformer windings under all load conditions.

Equipment of the thermometer type for local indication comprises a thermometer with a high-resistance bulb (Fig. 90) to which the leads from a current transformer are connected. The bulb, with its lagging, is housed in an oil-filled pocket.

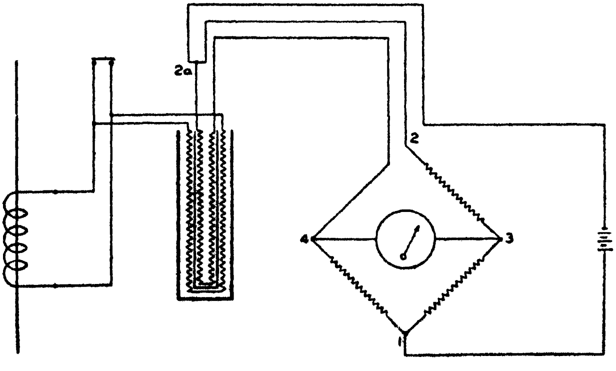


Fig. 91.—DIAGRAMMATIC ARRANGEMENT OF BRIDGE-TYPE WINDING TEMPERATURE INDICATOR
(*Metropolitan-Vickers Electrical Co., Ltd.*)

With the bridge-type indicator (Fig. 91) the leads from the current transformer are connected to a lagged metal foil heating element enclosed in the oil-tight pocket which contains the thermometer resistance unit—consisting of a non-inductive resistance fitted into a metal bulb. The resistance unit is connected so as to form one arm of a Wheatstone bridge, the other three arms being made up of suitable resistances of negligible temperature coefficient, mounted in, or near the indicator. The values of the three resistances are such that when the resistance unit (located in the transformer) has a temperature corresponding approximately to the maximum winding temperature at full load, the bridge is balanced and no current flows through the instrument connected between the points 3 and 4 (Fig. 91). An increase in the load on the transformer causes increased heating of the resistance unit and unbalance of the bridge. Current then flows through the instrument, which is calibrated in degrees C. to indicate the temperature of the hottest spot of the transformer winding. The equipment is operated by a low-voltage D.C. supply; either an accumulator, or a rectifier connected to the A.C. mains.

The bridge-type electrically operated indicator is used for distant indication, especially when the measurement of the temperatures of a number of transformers is centralised so that the temperature of any one unit can be read by means of a single indicating instrument, and a multi-way switch.

Thermometers for the remote indication of the oil temperature only are also used, being generally similar to the bridge-type indicator shown in Fig. 91, without the current transformer and the special heating element.

In principle the Hackbridge winding temperature indicator is similar to those already described, although the method of representing the maximum temperature of the windings has several unique features. The equipment consists of a current transformer—the core of which is fitted around any convenient lead carrying current to the main transformer—and a dial thermometer of conventional design. Fig. 92 shows the components of a complete equipment.

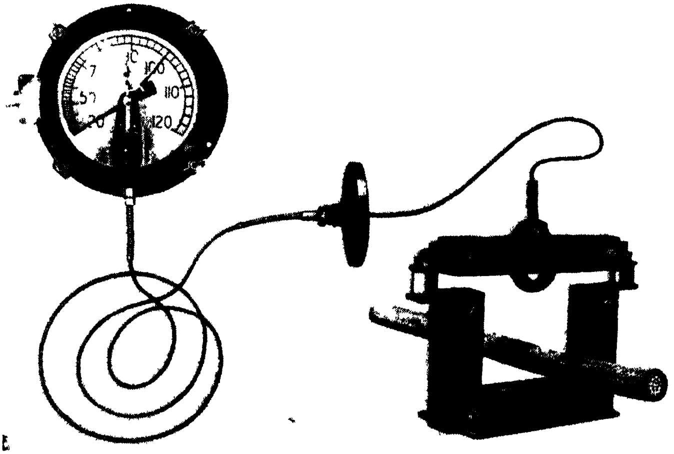


Fig. 92.—RING-BULB TYPE OF WINDING TEMPERATURE INDICATOR
(*Hackbridge Electric Construction Co., Ltd.*)

The thermometer bulb is in the form of a hollow ring of a high-resistance metal filled with an expanding medium, connected to a dial indicator by a flexible capillary tube. The hollow ring bulb is mounted on the core of the current transformer, and forms, in effect, a short-circuited turn. By this arrangement a current is induced in the bulb proportional to that flowing through the primary lead of the current transformer. As the bulb is located in the hottest oil, under no-load conditions the thermometer indicates the temperature of the surrounding oil in the usual way, but when the main transformer is on load the current induced in the ring bulb raises its temperature above that of the oil by an amount corresponding to the load This " boosted " temperature is transmitted to the dial indicator by the expansion of the fluid in the capillary system ; and the sum of the hottest oil temperature and the temperature-rise (above the oil) of the hottest spot of the windings can be read directly from the dial.

Winding temperature indicators—except the distant type—are used to control auxiliary circuits in the same way as oil-temperature thermometers with contact-making devices—as will be seen from Figs. 90 and 92. The use of a winding temperature indicator with all transformers of 10,000 kVA., and above, is recommended in B.S.S. No. 171—1936, Table 14, but the equipment is also adopted for smaller units if these form an important link in a supply system, or are subjected to arduous loading conditions. A particular advantage of operating a transformer by reference to maximum winding temperature is that the maximum safe load can be carried under any conditions. If, for instance, the transformer is operating at a low temperature—on account of light load or low ambient temperature—in emergency, a heavy overload can be applied until the indicator shows that the windings have reached the limiting temperature.

Temperature indicators are, of course, used in the operation of other forms of static equipment, such as the voltage regulators described in the next chapter.

Chapter XII

A.C. VOLTAGE CONTROL

EQUIPMENT for voltage control is generally installed for maintaining the system voltage within limits, but in some cases it is specially applied for controlling the load in a circuit. For certain circuits supplying industrial apparatus—such as electric furnaces—the value of the current can be controlled very simply by appropriate variations of voltage. At the other end of the scale, as exemplified by an interconnector transmitting a large quantity of energy, the problem of controlling the load is much more complex, and is effected by adjusting the power factor by voltage regulation, and in some circumstances by variation of the voltage-phase displacement. The control of load in interconnectors has already been discussed in Chapter II, page 9, and from this it is clear that if conditions are such that for complete load control it is necessary to adjust both the magnitude and phase of the voltage at either end of each interconnecting circuit, then apparatus for phase-angle control may be used in addition to that required for line voltage-drop compensation and power-factor control. The suitability of the different classes of voltage regulating apparatus discussed in this chapter for phase-angle control, when required, will be indicated in the appropriate place, but no detailed account of this application will be given as the subject is fairly involved and does not, in any case, come within the scope of this book. It should be noted, however, that for certain applications voltage regulators should not introduce voltage-phase displacement as the result of inherent characteristics of the equipment.

Broadly, there are two methods of applying voltage regulation to supply systems : (*a*) by installing the regulating equipment as near to the load as possible (which involves a large number of regulators) ; (*b*) by installing regulating equipment at a relatively small number of distribution centres. In this country regulators are rarely applied nearer to the load than the distribution transformer supplying the L.V. network. Some systems employ on-load tap-changing on the primary side of the distribution transformer when the unit is not too small, and with others various forms of regulator are used for the control of individual L.V. sections, or the output voltage of the transformers. Automatic control and line-drop compensation maintain the required secondary voltages.

When voltage control is effected at only a few centres the regulating equipment is usually installed in the main substations.

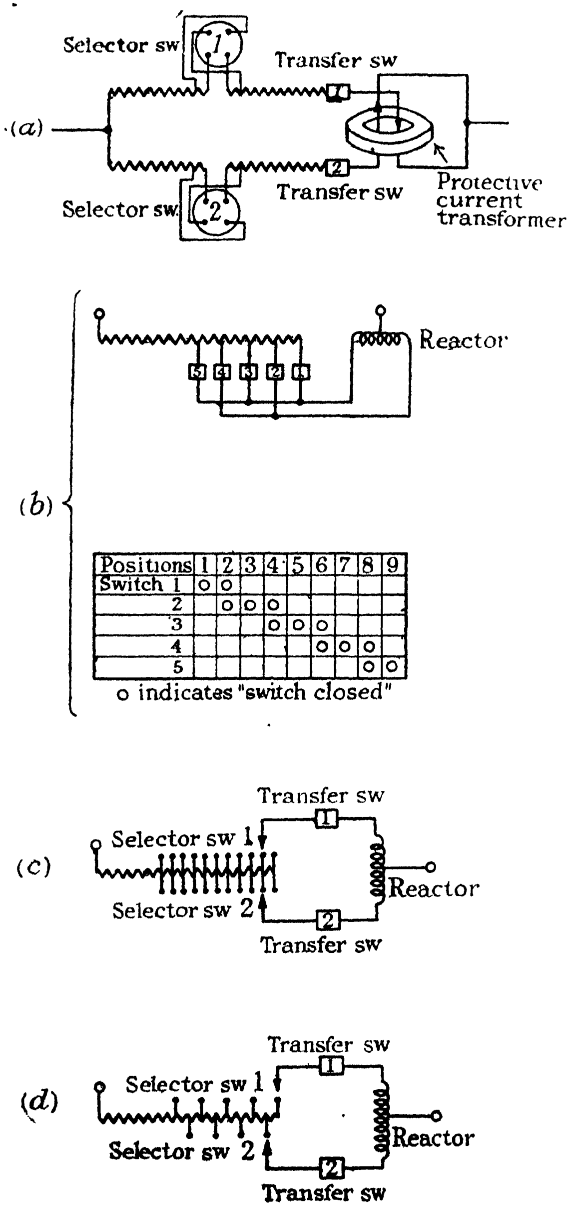
Transformer Tap-changing Gear

All forms of transformers are usually fitted with off-circuit tap-changing gear which can be adjusted externally, or may necessitate the tank being opened, but this class of gear is not, of course, intended for voltage control proper, being simply a means of enabling the transformation ratio to be adjusted to suit the average value of the supply voltage at various parts of the system. For continuous voltage regulation many transformers are now fitted with on-load tap-changing equipment with specially arranged circuits. All the various circuits used have two fundamental features in common : (*a*) some form of impedance is introduced to prevent short-circuiting of the tappings ; (*b*) a duplicate circuit is provided so that the load can be carried by one circuit whilst switching is being effected on the other, and the main circuit is not opened during a tap-change. The exact form of the circuit adopted varies considerably but the principal arrangements used are described below.

One method which has only a limited application in this country is to connect the coils of one side of the transformer in such a way that there are two windings (primary or secondary as the case may be) instead of the usual one. The arrangement is shown in Fig. 93 (*a*). Both windings are normally connected in parallel and share the load, but each has a tapping selector switch and a transfer switch, although normal operation is with the two windings connected to the same tap. The operation of changing taps involves six switching operations. Transfer switch No. 1 is opened, thus throwing all the load on to No. 2 winding. Selector switch No. 1 is moved one position, and then No. 1 transfer switch is closed, temporarily paralleling the two windings on unequal taps. A similar series of operations completes the tap-change movement on both windings. As each winding has to carry 100 per cent. overload temporarily, if the transformer is on full load, protective gear is necessary to guard against an incomplete movement of the tap-changer. This usually takes the form of a ring-type current transformer. The currents in the two primary conductors flow in opposite directions, so that voltage is induced in the secondary only when the primary currents differ, i.e. during a tap-change, and the transformer is tripped out if a tap-change is not completed.

With the circuit shown in Fig. 93 (*b*) only a single winding is used, and a current-breaking switch is connected to each transformer tapping. Alternate switches are connected together to form two common groups which are connected to the outer terminals of a mid-point auto-transformer or reactor, whose windings are designed to carry full-load current continuously. This mid-point reactor is a customary feature of tap-changing equipments, its purpose being to limit the current which flows in the local circuit formed when two tappings are connected together, otherwise a very large current would flow if the tapping points at different voltages were joined by a solid connection. The sequence of tap-changing with the scheme shown in Fig. 93 (*b*) is indicated by the table. In the first position, switch No. 1 is closed and the circuit is completed through half the reactor winding. To change taps one position, No. 2 switch is closed in addition to No. 1. The reactor then bridges a winding section between two taps and gives a voltage midway between them. For the next tap-change No. 1 switch is opened and No. 2 left closed. Circuit is then completed to the second main winding tap through half the reactor winding. The main transformer or reactor windings are not overloaded, and no protective gear is required to guard against incomplete operation.

The sequence of tap-changing involves closing one switch or two adjacent switches alternately. Owing to half the reactor winding being in circuit on adjacent taps unequal voltage-steps result, and sometimes a short-circuiting switch for



Positions	1	2	3	4	5	6	7	8	9
Switch 1	o	o							
2		o	o	o					
3				o	o	o			
4						o	o	o	
5								o	o

o indicates "switch closed"

Fig. 93.—Parallel- and single-winding schemes for transformers with tap-changers (*Journal I.E.E.*)

the reactor is added, but this is done only at the expense of simplicity in the operating mechanism.

This circuit involves large dimensions and oil quantity for the tap-changer if a large number of taps is used, particularly if the equipment is three-phase. A natural development of this arrangement is to use two selector switches, instead of the two groups of current-breaking switches, with transfer or series switches in the common leads to the reactor (Fig. 93 (*c*)). This has the advantages of the single-winding scheme (Fig. 93 (*b*)) and the relative movement of the switches to change taps is similar to that described for the parallel winding scheme, i.e. six movements to change one step, both selector switches being connected to the same tapping and both transfer switches closed in all operating positions.

With this arrangement the maximum number of voltage positions is restricted to the number of contacts in the selector switch. A greater number of voltage positions can be obtained with the circuit shown in Fig. 93 (*c*), by the movement of the switch being arrested half-way through a complete tap-change, i.e. the centre tap of the reactor is utilised as an operating tap, or the connections can be arranged as shown in Fig. 93 (*d*). In this case the tapping connections to the two selector switches are "staggered," and in all the full operating positions one transfer switch only is closed and half the reactor is in circuit on all tappings. This arrangement has the advantage that the reactor is never left connected across a winding section and so does not add to the open-circuit loss of the transformer in any of the positions, and the voltage steps are equal. The use of the mid-point reactor causes a non-uniform voltage variation in changing from one step to the next, but this is of no practical importance if the steps are sufficiently small, e.g. 1½ per cent. The conditions of the winding connections during a tap-change are shown in Fig. 94. The voltage in position (*c*) is midway between those of the two taps, but in positions (*b*) and (*d*) reactive drop is introduced by half the reactor winding. The magnitude of this drop is proportional to the inductance of the reactor, which is designed to be fairly small. This reactive drop cannot be avoided as, if the inductance is made very small so as to give a low drop with half the reactor winding in circuit, too great a magnetising current will be taken when the reactor bridges a pair of adjacent tappings. Usually the current drawn from the tapping section under these conditions is about 50–60 per cent. of full-load current. When the current broken during a tap-

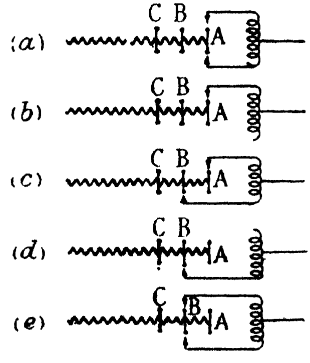


Fig. 94.—Showing operation of tap-changer with selector switches only

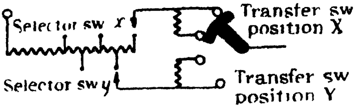


Fig. 95. TAP-CHANGING CIRCUIT WITH TRANSITION RESISTOR

change is sufficiently small transfer or series switches are not employed and a circuit similar to that in Fig. 94 is used, the current being broken and made on the selector-switch contacts. The process of tap-changing with this circuit will be apparent from Fig. 94, which shows the operations involved in changing from tap *A* to tap *B*. Equipment of this type is generally operated by some form of stored energy mechanism which ensures that a tap-change movement, once started, is definitely completed and the moving and fixed contacts correctly registered. Mechanical interlocks ensure that one contact completes its movement before the other starts to move.

The circuit of Fig. 94 is also used with a preventive resistor instead of a reactor, the resistor being short-circuited when the selector switches are in the normal operating positions. The use of resistors in place of reactors for the "transition" impedance was originally adopted for relatively small equipments only, but one advantage that is claimed, namely, that the circuit which has to be broken is non-inductive so that less relative wear is to be expected on the switch contacts, has been partly responsible for the extension of the principle to larger equipments which involve the use of separate transfer switches. One form of circuit which is used for this purpose is shown in Fig. 95. "Staggered" tappings are taken to a pair of independently operated selector switches and the transfer switch is moved between the two positions by a stored energy mechanism. Four fixed contacts are connected to a pair of resistors. In the position shown, one selector switch is joined to one tapping and the other to an adjacent one. The circuit is completed through one short-circuited resistor and the transfer switch in position *X*. To change taps the transfer switch is rapidly moved to the opposite position *Y* and selector switch *x* is then moved to the next position in readiness for the next tap-change. The movement of the transfer switch first removes the short-circuit from the resistor and later bridges the two resistors in series across the pair of tappings. It then completes circuit to the next tap through the second resistor, and finally short-circuits the latter.

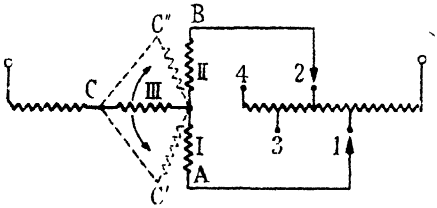


Fig. 96.- SINGLE-WINDING SCHEME WITH INDUCTION REGULATOR

In order to avoid voltage fluctuations during tap-changing one equipment employs an induction regulator (see page 163) to bridge adjacent tappings during a tap-change operation, thus obtaining perfectly smooth voltage variation. Fig. 96 shows a scheme adopted by one manufacturer. I and II represent the stator winding and III the rotor winding of an induction regulator which is capable of movement to effective positions C' to C''. Connections are made through two selector switches and "staggered" tappings on the transformer winding. With the rotor in position C'', the point C is substantially at the potential of point A on the stator winding, i.e. of tapping No. 1 and a short-circuiting switch (not shown) between A and C can be closed. To change the tapping position, the short-circuiting switch is opened and the rotor moved over to the position C'', when the point C is substantially at the potential of the next tapping (No. 2) and the short-circuiting switch (not shown) between B and C can be closed. Before the gear comes to rest, selector switch A moves to tap No. 3 in readiness for the next change.

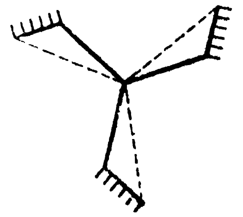


Fig. 97.—VECTOR DIAGRAM OF INTERCONNECTED-STAR TRANSFORMER WINDING FOR 60° VOLTAGE BOOST

With some interconnecting circuits in which a voltage phase-displacement is required for the complete control of the load, the characteristics of the system are often such that this can be effected by positive voltage boost at a fixed angle of 60° to the phase voltage. For this purpose a transformer with an interconnected-star secondary is used (see page 128), the auxiliary winding only being tapped. This arrangement is shown vectorially in Fig. 97. By this means the tap-changing has the double effect of altering the transformation ratio and of shifting the relative phase angle between the primary and secondary voltages, consequently by appropriate adjustments at each end of the interconnecting circuit load control can be effected. In practice, since the impedance characteristics of the line are known, the transformers and the associated tap-changing gear can be designed so as to enable the required amount of power to be transmitted.

Operating Mechanisms

The mechanisms for operating tap-changing gear vary in detail according to the manufacturer concerned, but most designs generally adhere to certain basic principles. In the larger equipments, where duplicate selector and transfer switches have to be operated in a definite sequence, the respective operating shafts are usually mechanically interlocked by gearing which includes some form of geneva gear wheel for the operation of the selector switches, and cams for the operation of the transfer switches. The motor is directly coupled to the mechanism so that movement is arrested if the motor stops.

In equipments where transfer switches are not used the tap-changer is frequently made in the form of a rotary switch which is operated through a multi-toothed geneva wheel, and completion of the switch movement

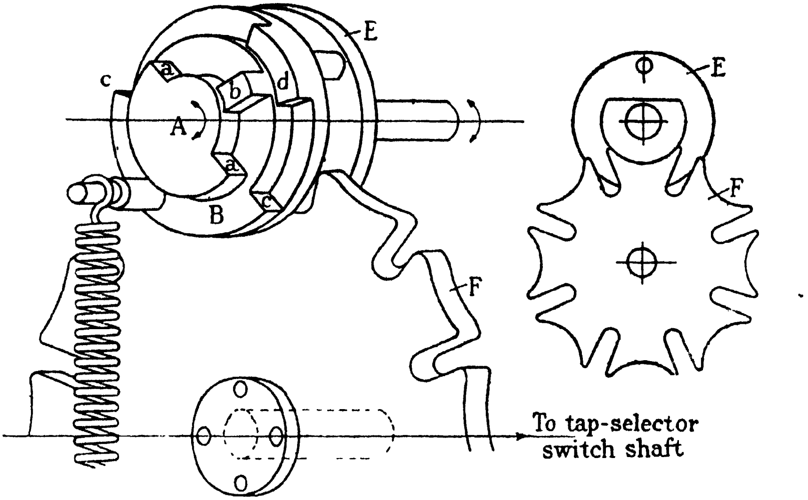


Fig. 98. – Spring-loaded quick-acting mechanism of tap-changer (*Journal I.E.E.*)

is assured by stored energy in one of four forms : (*a*) Springs. (*b*) Falling weight. (*c*) Flywheel. (*d*) Spring-loaded solenoids. An example of a spring-loaded quick-acting mechanism, which uses a geneva gear drive to the switch shaft, is shown in Fig. 98. Loose travel is provided between the driving shaft *A* and the operator wheel *E* of the geneva gear, so that quick action is possible when the spring is extended. A loose intermediate driving disc *B* has a projection *b* which engages with the faces *a* on the main shaft *A*. Other faces *c* of the disc *B* engage with a projection *d* on the operator wheel *E*. When shaft *A* is revolved, the loose travel is taken up and disc *B* revolved. The spring is extended, and when " top dead centre " is passed the spring is released to operate *E* rapidly, and so turn the geneva gear one tooth pitch. If the spring fails the mechanism still operates but without quick-break action, and is reversible at any point of the travel.

The falling weight design is based on the same principle, except that an offset weight is wound up, instead of a spring.

In the third type the motor is coupled directly to a flywheel. As it is brought up to speed a centrifugally operated device couples the tap-changer shaft to the flywheel and, after the shaft has been turned by the amount of one tap-change, the flywheel is uncoupled and the motor comes to rest. Solenoids with ratchet mechanism are sometimes used instead of a motor drive.

As will be observed from the illustrations of transformers with on-load tap-changing the equipment for this purpose assumes large proportions in relation to the size of the transformer proper, and is comparatively costly, although, of course, the most economical class of voltage regulating gear for certain applications. To enable tap-changing gear to be economically applied to units of fairly small capacity, in recent years mercury switches have been successfully used in place of the normal type of selector switch. These " mercury in glass " switches, which make or break contact when tilted, are generally employed with the circuit shown in Fig. 94. The switches of the three phases are linked together and are tilted in the required sequence by the operating mechanism. As very little force is required to operate the switches, some makers use an "induction disc " motor (see page 181) which is immersed in the oil.

Remote and Automatic Electrical Control

Tap-changers are usually operated electrically with additional means for manual operation, and arranged for remote electrical or automatic control. Two essential components of all control gear are (*a*) the mechanically operated contact (contact 55 in Fig. 99 (*a*) and (*c*)), to ensure that, when started, the apparatus continues to run for at least the distance of one tap-change (provided the auxiliary supply persists), and (*b*) the limit switches, to prevent overrunning of the gear. A circuit for the remote electrical control of a typical tap-changer is shown in Fig. 99 (*a*). A three-phase supply is used for the control circuit, and the direction of rotation of the three-phase induction motor (67) is determined by the closing of one of the two mechanically interlocked contactors 65 and 66. Two of the poles only of each contactor complete the circuit for the motor, the third pole being connected to the mechanically operated contact 55, which is open in each completed tap position, and is closed when a tap-change is in progress. Contact 55 and the third pole of 65 or 66 (depending on the direction of rotation) provide a hold-in circuit which ensures that the tap-changer movement is completed. The closing of either contact *R* or contact *L* energises the coil of contactor 65 or 66. The motor starts up and, if contact *R* or contact *L* is broken shortly after being made, the gear will run for one step and then stop. If contact *R* or *L* is held closed for a period corresponding to more than one tap-change, the motor will continue to run for a number of completed operations, but, if desired, the circuit can be modified to give operation by one step only each time contact *R* or contact *L* is closed.

The brake coil 67B is energised in parallel with the motor, and the braking force is applied when the supply to the motor is interrupted. In series with two of the motor leads are connected the heaters of the thermal overload relay 29, whose contacts are connected in the contactor coil circuits, so that the latter cannot be energised if the motor shows signs of distress. The limit switches are connected in the contactor coil circuit, and serve to prevent either contactor 65 or contactor 66 being energised to run the gear beyond the normal limits of travel.

With the circuit shown in Fig. 99 (*a*) it is necessary to hold the control

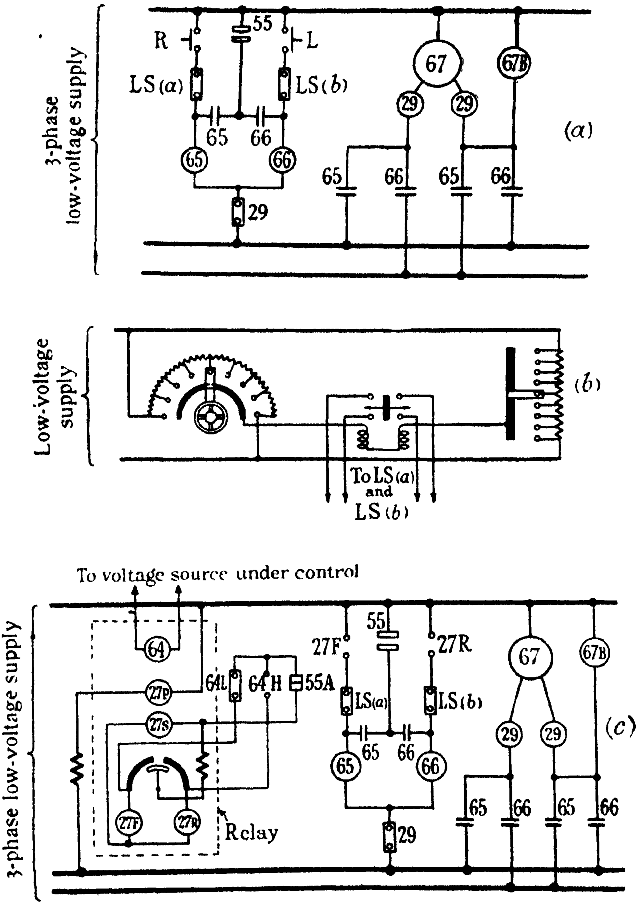
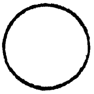
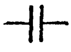
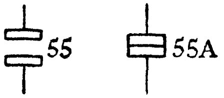


Fig. 99.—TYPICAL REMOTE ELECTRICAL AND AUTOMATIC CONTROL OF TAP-CHANGER (*Journal I.E.E.*)

switch while the tap-changer makes a movement of several tapping positions, and to avoid this a preselector form of control is sometimes used by means of which, once the control switch is set in the appropriate position, the gear will move through any required number of tap positions and then stop. One form of control for this purpose is shown in Fig. 99 (*b*). Two potentiometer resistances are connected across the supply; the left-hand one is connected to a rotary switch at the control point and the right-hand one is similarly connected to a rotary switch on the tap-changer mechanism. A directional relay is connected between the common connections of the switches, and the pairs of contacts on the relay occupy the positions of contacts *R* and *L* in the circuit of Fig. 99 (*a*).

With the gear at rest in a completed tap position, the contacts of both switches occupy the same relative positions and no current flows through the relay, but, if the handwheel of the control switch is turned in either direction, current will flow through the directional relay, which will then close one of its pairs of contacts to run the tap-changer for any desired number of complete tap positions until balance is restored to the relay. By this method, any number of tap-changers can be controlled

KEY TO FIG. 99

	Motor winding, coil of contactor or relay.
	Normally-open contacts, close when contactor coil energized.
	Normally-open contacts, close when relay coil energized.
	Normally-closed contacts, open when relay coil energized.
	Mechanically-operated contacts on tap-changer mechanism.
R.L.	"Raise" and "lower" contacts of control switch.
L.S.(*a*) L.S.(*b*)	Limit switches.
27	Time-delay relay.
29	Thermal overload relay.
64	Voltage-regulating relay.
64H, 64L	"High" and "low" contacts of voltage-regulating relay.
65, 66	Mechanically-interlocked 3-pole contactors.
67	3-phase motor.
67B	Brake coil

simultaneously by mounting more than one switch and potentiometer on the one handwheel.

The essential difference between circuits for automatic control and for remote control consists in the inclusion of a voltage regulating relay and time-delay relay in place of the control switch, as shown in Fig. 99 (*c*). The contacts 27*F* or 27*R* of the time-delay relay occupy the positions of contacts *R* or *L* of the circuit of Fig. 99 (*a*). In Fig. 99 (*c*) the relay coil 64 has applied to it the voltage which is to be controlled and makes either 64*L* or contact 64*H* when the voltage is lower or higher than normal. To prevent the tap-changer responding to momentary voltage fluctuations the closing of contacts 64*H* and 64*L* operates only on the circuit of a two-way time-delay relay 27 (see Fig. 100). A tap-change is only initiated by the eventual closing of the contacts 27*F* or 27*R* of the time-delay relay (after the voltage regulating relay contacts have remained closed for a definite period, which period is usually adjustable). In order to reset the time-delay relay, i.e. to open its contacts in readiness for the next tap-change, the circuit is completed through a second mechanically operated contact 55*A* on the tap-changer mechanism, which is closed when the gear is at rest in each completed tap position but opens during the period when a tap-change is in progress. When the voltage is either high or low, the relays will operate the tap-changer in the appropriate direction until the voltage is restored to normal and the voltage regulating relay balances again.

With the arrangement shown in Fig. 99 (*c*), if the supply to the relay coil 64 fails, contact 64*L* will be made and the tap-changer moves automatically to the position giving maximum voltage. To avoid this, " no-volt " contacts (not shown) are usually included in the circuit and are so connected that, when the voltage across the relay coil fails, the tap-changer either remains stationary or runs automatically to the position of minimum voltage. If the auxiliary supply were to fail during a tap-change the gear would remain at rest after the supply had been restored until contact 55*A* had been short-circuited or reclosed by turning the gear by hand. To avoid this, additions (not shown) can be made to the circuit so that the apparatus will respond immediately to restoration of the supply.

With the addition of a line-drop compensator (see page 172, where this is discussed in connection with the induction regulator), operated from current transformers, the effective " voltage balance point " of the relay can be arranged to increase automatically as the load increases, thus providing a compounding effect.

Voltage Regulating Relays

Voltage relays for the control of tap-changers (and other classes of voltage regulating equipment) vary widely in design and construction but many of them consist mainly of a solenoid operating on a vertical plunger connected to one end of a beam, pivoted at the centre, at the other end of which is a tension spring. Modifications of this arrangement are made to overcome certain inherent defects of the simple form of relay. In one relay of this type springs and hold-on coils have been eliminated, and a considerable increase made in the operating force available, by special design of the magnetic circuit, so that a two-way mercury switch can be used for the contacts (see page 182, in connection with the moving coil regulator). Another type of relay (Fig. 100), which is used in conjunction with the automatic control circuit shown in Fig. 99 (*c*), avoids the difficulty of pivots by suspending the solenoid core on two leaf springs which permit vertical but not lateral movement. The weight of the core is partly balanced by the pull of a spring which is capable of adjustment. At the lower end of the core a flexibly mounted contact connects with the higher or lower fixed contacts (64*H* or 64*L*) according to whether the voltage is high or low. Oscillations set up by momentary changes in the supply voltage are damped out by a vane working between the poles of a permanent magnet. The core has three stable operating positions (floating, high, and low) by virtue of the soft-iron disc at the top of the core, which works between the poles of three sets of permanent magnets. "Under-voltage" protection is provided by the lower contacts 64*UV* (Fig. 100). Sometimes a separate time-delay relay is used for each direction, but the relay in Fig. 100 includes at the bottom an induction-type time-delay relay which serves for both directions. The disc of the relay moves in either direction according to whether contact 64*H* or 64*L* remains closed, and the movable contact arm is driven from the relay spindle by gearing. The upper magnet carries an exciting winding 27*P* and a secondary winding 27*S* which is put in series with either the forward winding 27*F* or the reverse winding 27*R* on the lower magnet, depending on whether 64*H* or 64*L* is closed. Immediately after the disc has begun to rotate, contact is made on the drum contact to one side and the other, thus putting the remaining coil on the lower magnet in parallel with the coil already energised. In due course the contact arm makes circuit with the fixed contacts 27*F* or 27*R*. The time setting is adjusted by varying the

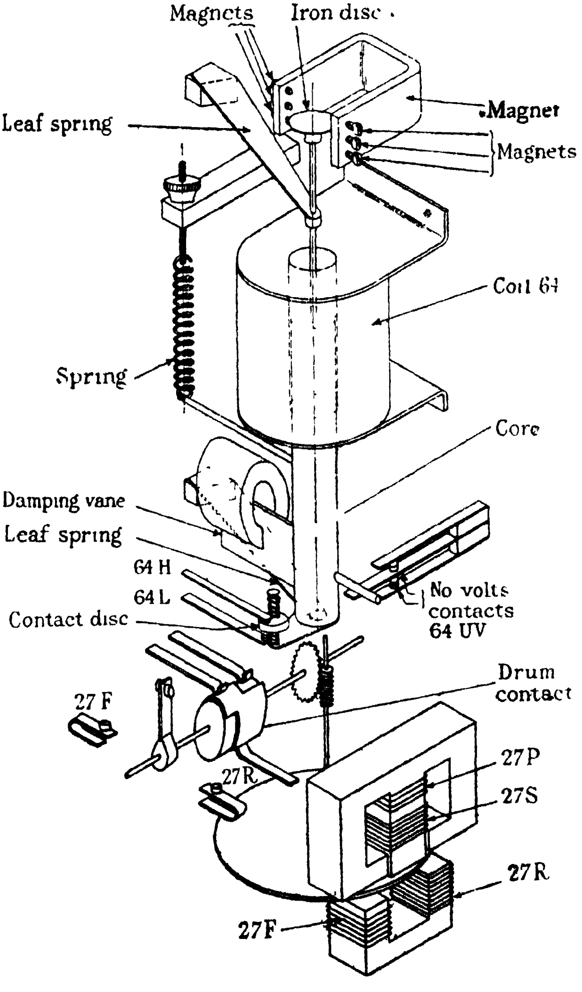


Fig. 100.—COMBINED VOLTAGE REGULATING AND TIME-DELAY RELAY. (*Journal I.E.E.*)

positions of the fixed contacts 27*F* and 27*R*. The relay is reset by the opening of the contact 55*A* (Fig. 99 (*c*)) during a tap-change, but it is of the "slow reset" type. This allows the time-delay to be set to correspond closely to the average voltage conditions. With instantaneously resetting relays the time-delay period, if interrupted by the momentary opening of the contacts 64*H* or 64*L*, must recommence from zero. In general the resetting time of the relay shown in Fig. 100 is about one-third of the time-delay setting.

Another form of voltage relay is based on the principle of resonance in a circuit consisting of an iron-cored reactor, a resistor, and a condenser in series (British Patent No. 414647). When such a combination is connected to an A.C. supply, near the saturation point of the reactor there is a critical voltage above which a large increase in the current takes place suddenly as the voltage is increased.

In the voltage regulating relay two such circuits are connected in parallel (Fig. 101 (*a*)) and are tuned to have slightly different characteristics, i.e. their critical voltages are of slightly different values. A magnetically operated contactor is connected in parallel with each condenser and, as the voltage becomes higher or lower than normal, the voltage across the condenser changes suddenly and so operates the associated contactor. The contact *L* remains closed while the voltage is low and until the critical voltage is reached, and contact *H* closes when the voltage becomes high and the critical voltage of the *H* circuit is reached.

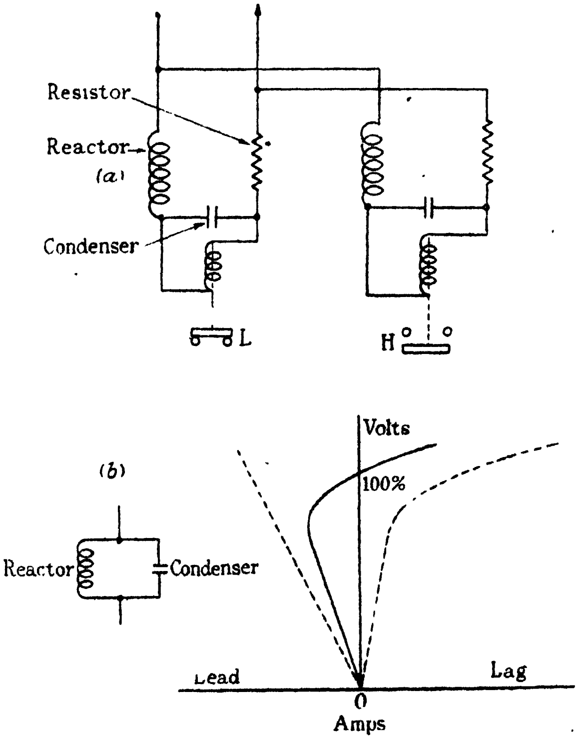


Fig. 101.—VOLTAGE REGULATING RELAYS USING SATURATED REACTORS AND CONDENSERS. (*Journal I.E.E.*)

A similar method employs a saturated reactor in parallel with a condenser (Fig. 101 (*b*)). As the voltage is increased the leading current through the condenser increases at a uniform rate, whereas the lagging current through the reactor departs from a straight-line law owing to saturation. The combined current of the two circuits in parallel follows the full-line curve of Fig. 101 (*b*), and it will be seen that the current is in phase with the voltage at 100 per cent. voltage but becomes leading or lagging as the voltage of the circuit drops below or rises above normal 100 per cent. value. The reactor and the condenser are put in series with one of the coils of an induction-type relay which is arranged so as not to exert any torque on its disc when the current and voltage are in phase, but turns the disc in one direction or the other when the current leads or lags the voltage.

Booster Equipments

Booster regulators can be used in conjunction with transformers—one booster unit to each transformer—for the simultaneous voltage control of all the circuits supplied by the transformer, or can be applied to individual circuits or groups. A booster equipment is made up of an exciting transformer and a booster, or series, transformer ; the first has a primary winding connected across the line whose voltage is regulated, and a low-voltage tapped secondary (Figs. 102 (*a*) and (*b*) and 103). By selection of tappings on the secondary a variable voltage is applied to the primary of the booster transformer and a voltage induced in its secondary winding –in series with the line—which voltage is added to, or subtracted from (when the connections to the booster primary are reversed) the line voltage. The exciting transformer may be of either the double-wound or the auto-transformer class, and various methods are in use for tap-changing to select the amount of voltage which is injected into the primary of the booster transformer and, hence, into the line. A feature of booster equipments is that the tap-changing is done with lower voltages and currents than with on-load tap-changing on the main transformer.

Figs. 102 and 103 show diagrammatically three typical arrangements of booster equipment ; one phase only is shown, although the construction of the transformers is three-phase and both the exciting transformer and the series transformer are accommodated in one tank. With booster units one point of the switching circuit is usually earthed if the exciting transformer is double-wound. When equal maximum values of buck and boost voltage are injected into the line, a centre tapping permanently connected to the exciting transformer secondary (Fig. 102 (*a*)) achieves the desired result. With this circuit only one end of the series transformer primary winding can be connected to different taps, one half of the winding being used for boosting and the other for bucking the line voltage. From Fig. 102 (*a*) it will be seen that as the connection to the series transformer is varied from the position shown the voltage applied to this is adjusted in steps, decreasing at first to zero at the centre point of the exciting transformer secondary, after which it increases, but as the polarity (instantaneous) of the connections to the series transformer is reversed, the induced voltage will be opposite to what it was before. The disadvantage of this scheme is that a large proportion of the copper in the tapped winding is inactive. An alternative arrangement is that shown in Fig. 102 (*b*). The centre points of the exciting transformer and of the primary winding of the booster are permanently connected, and the two contacts of the tap-changer are arranged to move in opposite directions by suitable gearing. In all the tap positions contacts *A* and *B* are equidistant from the centre tapping. At zero boost both are on the middle tap and, if the switch positions shown in Fig. 102 (*b*) give maximum boost, maximum buck is achieved when the positions are reversed. Current passes through the centre connection only during a tap-change, and energises a protective relay whose contacts close if the normal time of a tap-change is exceeded. Fig. 103 shows the connections of a booster equipment in which all the tapped winding is used in both the maximum boost and the maximum buck positions, the connections to the primary of the series transformer being reversed when required by specially arranged switches. The connections are similar to those of Fig. 102 (*b*), but the mid-point reactor, or choke, used during a tap-change is also shown, together with the switching arrangements. *A*, *B*, *C*, *D* and *E* are contacts—operated by a suitable mechanism—for selecting the tappings. *P* and *N* are contacts for reversing the direction of the voltage applied to yx, the primary of the series transformer. *S* short-circuits the mid-point choke, and *Q* short-circuits yx when no voltage boost or buck is being applied to the line. By this means the secondary of the series transformer is rendered non-inductive when it is not in use. The choke is normally short-circuited in order to divide the current equally between its two halves ; as the current flows through the choke in opposite directions this is, thereby, rendered non-inductive. The sequence of operations to change from normal (no buck or boost) to plus 1¼ boost is : *P* closes, *A* closes, *Q* opens, *S* opens, *B* closes, *A* opens, *S* closes. This completes one tap-change, *P*, *B*, and *S* being closed, and the voltage between $a5$ and $a4$ applied to yx. The only contacts closed

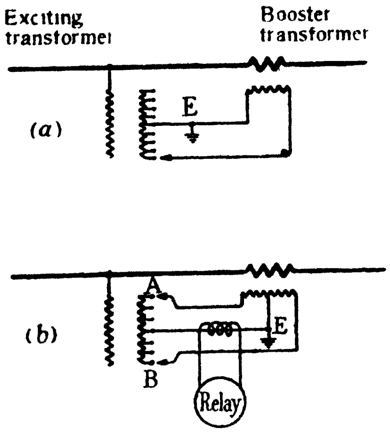


Fig. 102.—TYPICAL ARRANGEMENTS OF BOOSTER EQUIPMENTS in the normal position are *Q* and *S*.

The next tap-change to increase the percentage boost is effected in the same way, substituting *C* for *B* and *B* for *A* in the sequence of operation; and similarly for the other stages of boost.

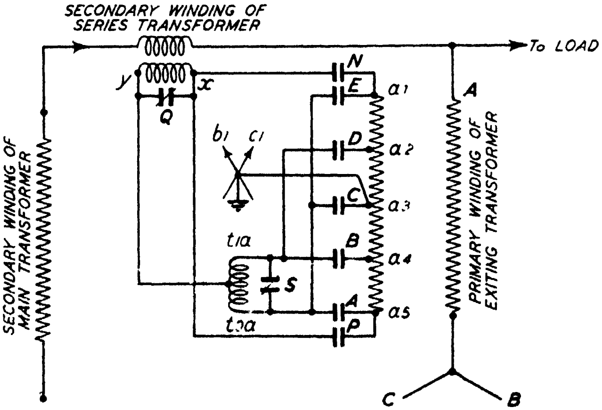


Fig. 103. SCHEMATIC ARRANGEMENT OF BOOSTER UNIT

Contacts shown in normal (no boost or buck) position. *Q* and *S* closed, all others open.

To apply a bucking voltage to the line, starting from normal, the sequence of operations is: *N* closes, *E* closes, *Q* opens, *S* opens, *D* closes, *E* opens, *S* closes. *N*, *D*, and *S* being closed, the voltage between *a*1 and *a*2 is applied to *yx* in opposite direction to that giving one stage of boost. The percentage buck is increased by the same sequence of operations as with boost, the appropriate contacts being involved. To decrease the percentage of boost or of buck the sequence of operations is the reverse of that for an increase. The above will be clear from a study of Fig. 103.

The selector gear usually consists of oil-immersed contactors operated in sequence by a cam mechanism; air-break contactors and a drum controller; or the latter.

Boosters are of particular utility if a heavy-current circuit is involved as, by suitable choice of voltage in the switching circuit, the current to be dealt with in the tap-changer can be kept within reasonable limits. By means of two boosters connected in the circuit complete control of the load in an interconnector can be effected, one equipment giving an " in-phase " boost, and the other a " quadrature " boost, i.e. a voltage lagging 90° behind the voltage on the supply side of the boosters. This arrangement is rarely used as it is costly.

Busbar voltage may be controlled by any type of equipment for regulating the output voltage of the transformers; but generally, either on-load tap-changers or boosters are used. When it is required to control the voltage of an individual circuit, this may be effected by tap-changing on a transformer supplying that circuit only; or by a booster, induction, or moving coil regulator.

For certain applications, such as low-capacity individual circuits, regulators are generally installed in preference to the other forms of gear. Moreover, regulators can be built economically as single-phase units, thus three such units are often installed when it is essential to control each phase of a three-phase circuit separately by reason of unsymmetrical loading. Three-phase regulators are, of course, less costly than three single-phase units, but in the particular circumstances referred to, the latter arrangement is often considered to be justified. The other two types of voltage regulating equipment cannot be conveniently designed for individual control of each phase, consequently their application is not always possible despite any other considerations that may be involved.

Static Balancers

To counteract the effect of out-of-balance current in a three-phase four-wire system an interconnected-star balancer may be used and remarkable improvement obtained by this means alone. The construction of an interconnected-star balancer is that of a 1/1 ratio three-phase auto-transformer with the sections of winding on each limb connected as shown in Fig. 104. With this arrangement if, for example, an out-of-balance current of 30 amperes is flowing in the neutral, then this current would be split up by the balancer which would transfer 10 amperes to each of the more lightly loaded lines, thereby relieving the overloaded line by 20 amperes. From the point of view of counteracting unsymmetrical loading it is preferable to install a number of small balancers near the load centres instead of one large unit at a distribution substation, but when it is not permissible to earth the neutral at more than one point it is essential to carry it as a continuous conductor throughout the system. In this case, if the neutral is interrupted the voltage of one phase may rise to the full line voltage to earth under fault conditions. This possibility has been eliminated by incorporating with the balancer a special high impedance choke, which is connected in the neutral conductor immediately in front of the balancer (Figs. 104 and 115). With single-phase three-wire distributors a mid-point balancer is sometimes used to deal with the out-of-balance current. Where undue variation of voltage arises from overloading as

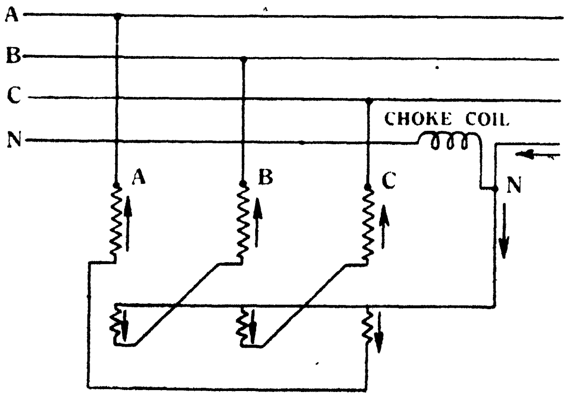


Fig. 104.—Interconnected-Star Three-Phase Balancer distinct from unsymmetrical loading an automatic voltage regulator is required to maintain the voltage, and in many cases this is used in combination with a balancer.

Both induction and moving coil regulators are very easily controlled by suitably arranged automatic gear actuated by a voltage relay, consequently they have been adopted for a variety of applications.

The Induction Regulator

Induction regulators are in use for controlling the voltage of circuits whose capacities range from a comparatively few kVA. at low voltage up to as much as 20,000 kVA., at 77 kV Regulators are built either as three-phase or single-phase units. Polyphase circuits are controlled by one three-phase unit—or for some applications " twin " units comprising two three-phase regulators—or by three, or two, single-phase units.

The basic principle of the induction regulator is that of injecting a voltage into the line which " boosts " or " bucks " the normal line voltage. Actually, the means by which the voltage variation is obtained by the use of single- or three-phase regulators differs somewhat ; in con-

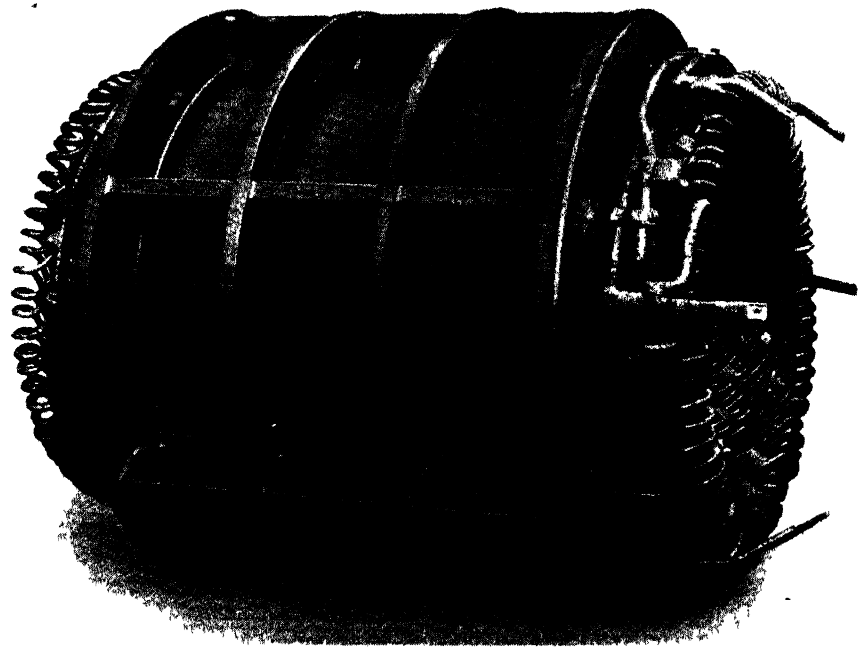


Fig. 105.—STATOR OF INDUCTION REGULATOR—THREE-PHASE
(*English Electric Co., Ltd.*)

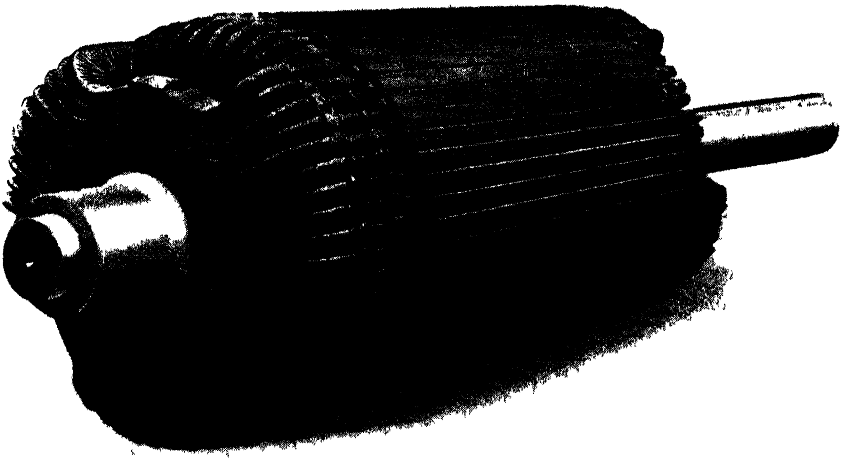


Fig. 106.—Rotor of induction regulator—three-phase
(*English Electric Co., Ltd.*)

sequence, each type has a distinct field of application. The internal construction of the regulator generally resembles an induction motor, as will be noted from Figs. 105 and 106, which show, respectively, the stator and the rotor of a polyphase type. The elementary arrangement of a single-phase unit is shown diagrammatically in Fig. 107, and the connection of the unit in the circuit in Fig. 108. Usually, the secondary, or series, winding is placed on the stator and the primary, or potential, winding on the rotor. The primary winding is connected across the supply, and the secondary winding in series with the line whose voltage is to be controlled. The rotor is held stationary, but its position can be adjusted relative to the stator.

When the primary of the regulator is energised the magnetising current creates a flux in the core of the stator and thereby induces a voltage in the series winding. In the position shown in Fig. 107 all the primary flux passes through the secondary coils, and the voltage induced in the secondary winding is equal to the primary, or line, voltage divided by the ratio of primary turns to secondary turns. As the primary core is rotated the amount of primary flux passing through the secondary is decreased until the core reaches a position at right angles to that shown. In this position no primary flux passes through the secondary coils, and the voltage induced in this winding is zero. The continued rotation of the core in the same direction again increases the amount of flux threading through the secondary, but it is now in the opposite direc-

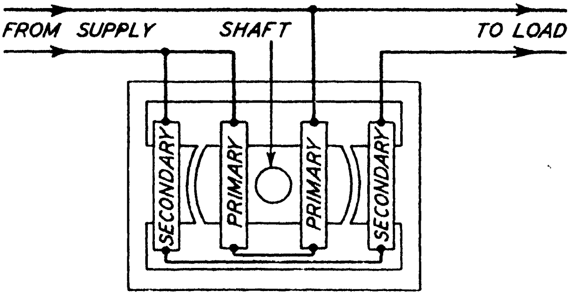


Fig. 107.—ELEMENTARY INDUCTION REGULATOR

tion, so that the direction of the induced voltage is reversed. By connecting the secondary winding in series with a feeder and the primary winding across the line, as shown in Fig. 108, the feeder voltage can be varied by adding to or subtracting from it—by adjusting the position of the rotor—the voltage induced in the secondary winding.

In the actual design of the induction regulator, the arrangement of cores and coils is a modification of that shown in Fig. 107, the coils being assembled in slots similar to those of an induction motor. By this means the changing of the amount and direction of the primary flux which threads through the secondary winding is more gradual than would be the case with the elementary design of Fig. 107, and a more uniform voltage variation is achieved.

In the single-phase regulator the excitation of the cores is also, of course, single phase. Thus the magnetising flux is an alternating one and always links the entire primary, or exciting, winding, and its direction is always parallel to that diameter of the rotor which passes through the centre of the exciting coils. The direction of this flux may, however, be varied with respect to the stator and, consequently, with respect to the series winding on the stator. The voltage induced in the series, or secondary, winding gradually varies—when the direction of the primary flux relative to the stator is also varied appropriately—from the maximum positive, through zero, to the maximum negative value. The induced voltage is always in phase with the primary excitation voltage and, therefore, is added directly to, or subtracted directly from, the line voltage. The fact that there is no phase displacement between the supply voltage and the line voltage on the load side of the regulator is an important and advantageous charac-

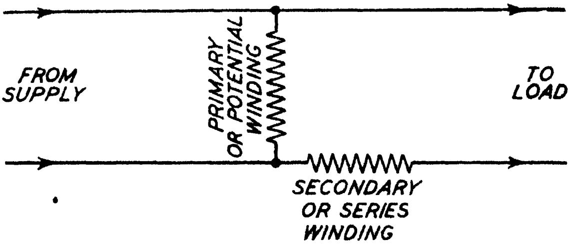


Fig. 108.—CONNECTIONS OF INDUCTION REGULATOR WINDINGS teristic of the single phase regulator in circumstances where phase displacement is not permissible, i.e. interconnectors and ring-mains. However, although several methods of connection are available for the grouping of single-phase regulator banks, certain of them bring about voltage-phase displacement.

The rotor of the single-phase regulator actually contains two windings : the primary and a second winding, short-circuited on itself and arranged at right angles to the primary winding. The object of this short-circuited winding is to equalise the losses, and the reactance of the regulator in its various positions of buck and boost. If the rotor were not provided with the short-circuited winding and were rotated from either maximum position so as to reduce the primary flux passing through the secondary winding, and if the line current remained constant, a gradually increasing voltage would be required to force the line current through the series winding, and a correspondingly increased flux would be induced in the core by this winding, thereby increasing the loss. This voltage would reach its maximum value when the rotor is in the neutral position, and the series winding would then operate as a reactance, an appreciable percentage of the line voltage being required to force the line current through the series coils. The voltage so used would be at right angles with the line voltage, but it would result in a lowering of the line voltage and in a reduction of the power factor.

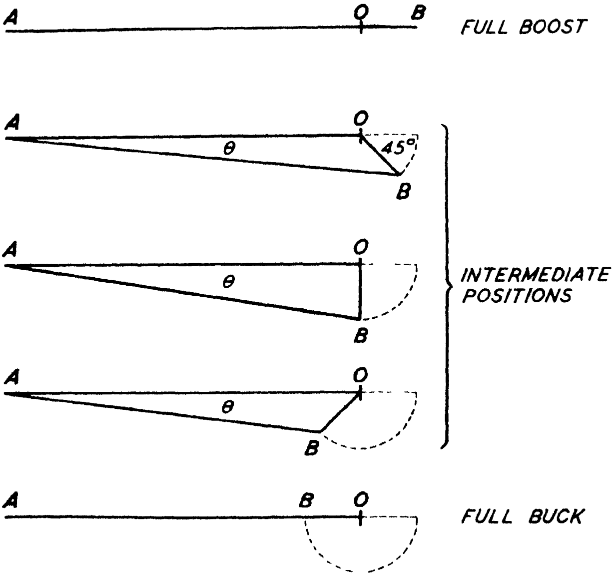


Fig. 109.—ILLUSTRATING REGULATION OF LINE VOLTAGE BY THREE-PHASE INDUCTION REGULATOR

AO is supply voltage.
OB voltage induced in series winding.
AB resultant line voltage.
θ angle of displacement between AO and OB.

Position of rotor relative to stator indicated by circular dotted line.

In three-phase regulators there is one potential winding and one series winding for each phase. The current in each winding is single-phase, but the magnetisation of the rotor core is produced by the combined action of the three potential windings so that a rotating field of constant magnitude results. The rotation of the field in a polyphase regulator, therefore, induces a voltage of constant value in each series winding irrespective of the rotor position, and the change in the line voltage is produced by a phase displacement of the induced voltage, and not by a change in the magnitude of the voltage as in the single-phase regulator. The phase of the induced voltage relative to the primary voltage is varied by adjusting the position of the rotor and, since the phase of the supply voltage is fixed, the line—on the load side of the series winding—has a total voltage equal to the vector sum of the supply voltage and the induced secondary voltage. Fig. 109 illustrates how the total line voltage can be controlled from full boost to full buck by varying the rotor position, AO being the incoming voltage to the regulator series winding, OB the voltage induced in the series winding, and AB the resultant line voltage.

With a polyphase regulator the phase of the total line voltage will, therefore, generally be different from that of the incoming line voltage. When it is necessary to avoid phase displacement in three-phase circuits either a twin unit is used, or three single-phase units. The rotors of the two regulators comprising the twin unit are mechanically coupled (Fig. 110), and the electrical connections are so arranged that each regulator contributes one half of the total voltage added to each phase, and the total voltage is always in phase with the incoming voltage, as shown in Fig. 111. The phase angle of one induced voltage is neutralised by the phase angle of the other.

Induction regulators are directly connected in high-voltage circuits up to a certain voltage which depends on the output ; but it is unusual for them to be included directly in circuits of more than 15 kV. For higher voltages both potential and series transformers are employed in the rotor and stator circuits respectively. The constructional features of induction regulators will be appreciated by considering typical units manufactured by the English Electric Co., Ltd.

The stator and rotor cores (Figs. 105 and 106) are built of thin laminations of non-ageing silicon steel of very high quality ; one side of each lamination being coated with an insulating material that does not deteriorate with heating. The stator and the rotor are assembled vertically, as shown in Fig. 112, and since they operate under oil, in both cores ample provision is made for the circulation of the oil, which is cooled by means of a tubular tank—in the same way as an ON transformer. Separate external radiators are used for very large units.

In view of the severe electrical and mechanical stresses to which the regulator may be subjected under fault conditions special attention is given to constructional detail.

The mechanism for operating the rotor is motor-driven, as shown in Figs. 110 and 113. A quadrant for the worm drive, which is of massive

Fig. 110 —Three phase twin regulator for 12,000 kVA. interconnector (*English Electric Co., Ltd.*)

design in order to withstand the severe torque produced under short-circuit conditions, is keyed on to the rotor shaft. The worm shaft is driven by the motor through spur gearing or worm-reduction gearing and each worm shaft is fitted with ball thrust bearings. A slow-speed high starting-torque motor is used, and a spring-loaded brake operates on a drum

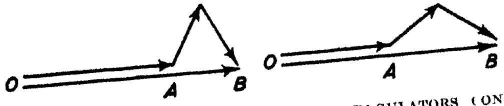


Fig. 111.—Vector diagram of twin regulators connected to avoid voltage phase displacement

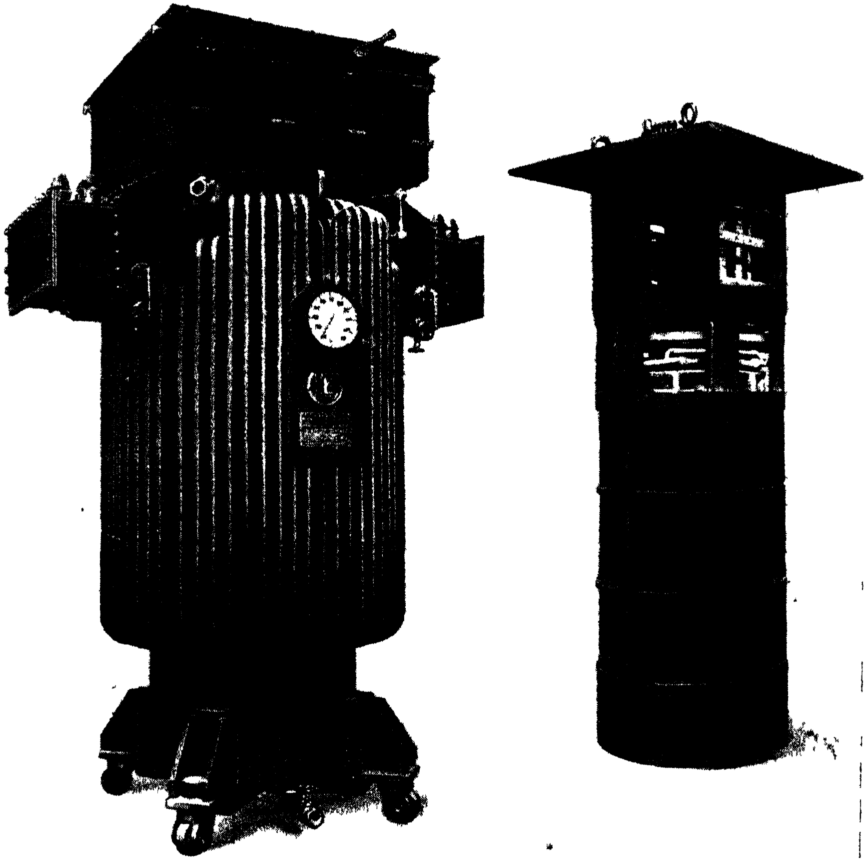


Fig. 112.—THREE-PHASE INDUCTION REGULATOR FOR 12,000 kVA., 6.6 kV. FEEDER
Left : complete unit. Right : internal assembly. (*English Electric Co., Ltd.*)

mounted on the motor shaft. The brake is released magnetically when the motor is switched on, and ensures that the operating mechanism stops instantly when the motor circuit is opened. With the exception of outdoor regulators, a handwheel is provided for emergency use (Fig. 110). The general features of representative types of induction regulators are shown in Figs. 112, 113, and 114.

The type of regulator used for a particular application is decided by both technical and economic considerations, but the latter will not be considered here, although it may be said that generally the cost of three separate single-phase regulators is high compared with that of a single

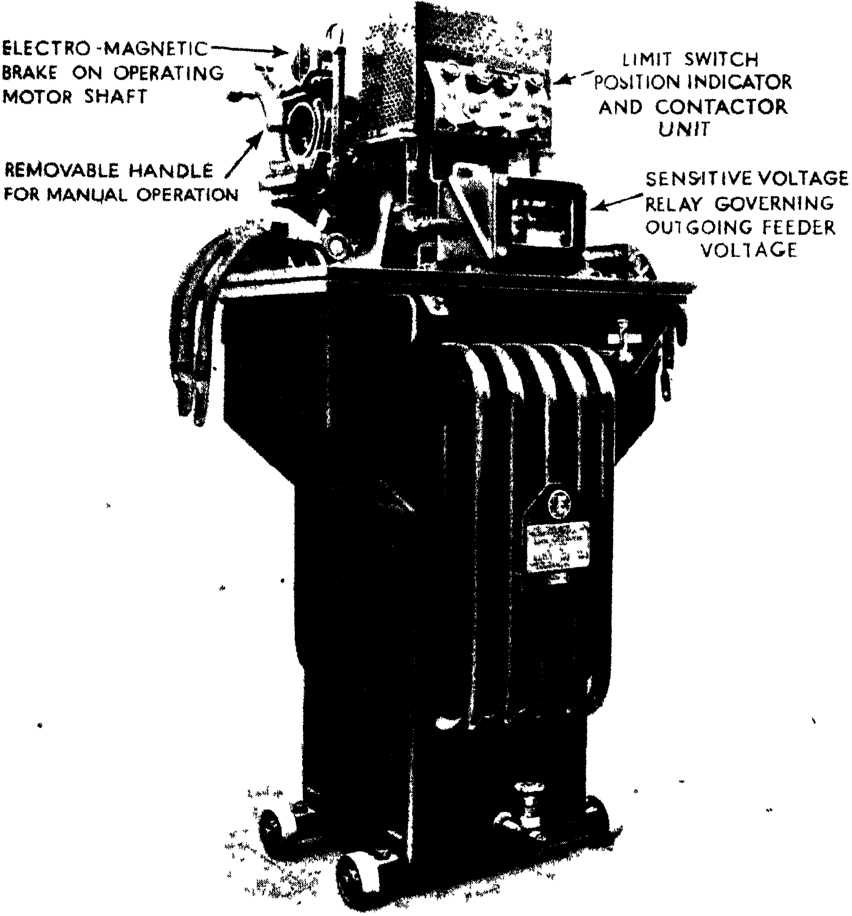


Fig 113.—THREE-PHASE AUTOMATIC INDUCTION REGULATOR FOR ± 10 PER CENT. VARIATION ON A 250 kVA, 400 VOLT FEEDER (*English Electric Co., Ltd.*)

three-phase regulator. There are, however, instances where banks of single-phase regulators are preferable. On four-wire distribution networks where considerable out-of-balance load is experienced the voltage between each phase and neutral can be regulated independently by means of a bank of three single-phase regulators. The economical alternative to this arrangement is a three-phase regulator together with an interconnected-star balancer, since the regulator gives the same voltage variation on all three phases and will not by itself compensate for unequal phase

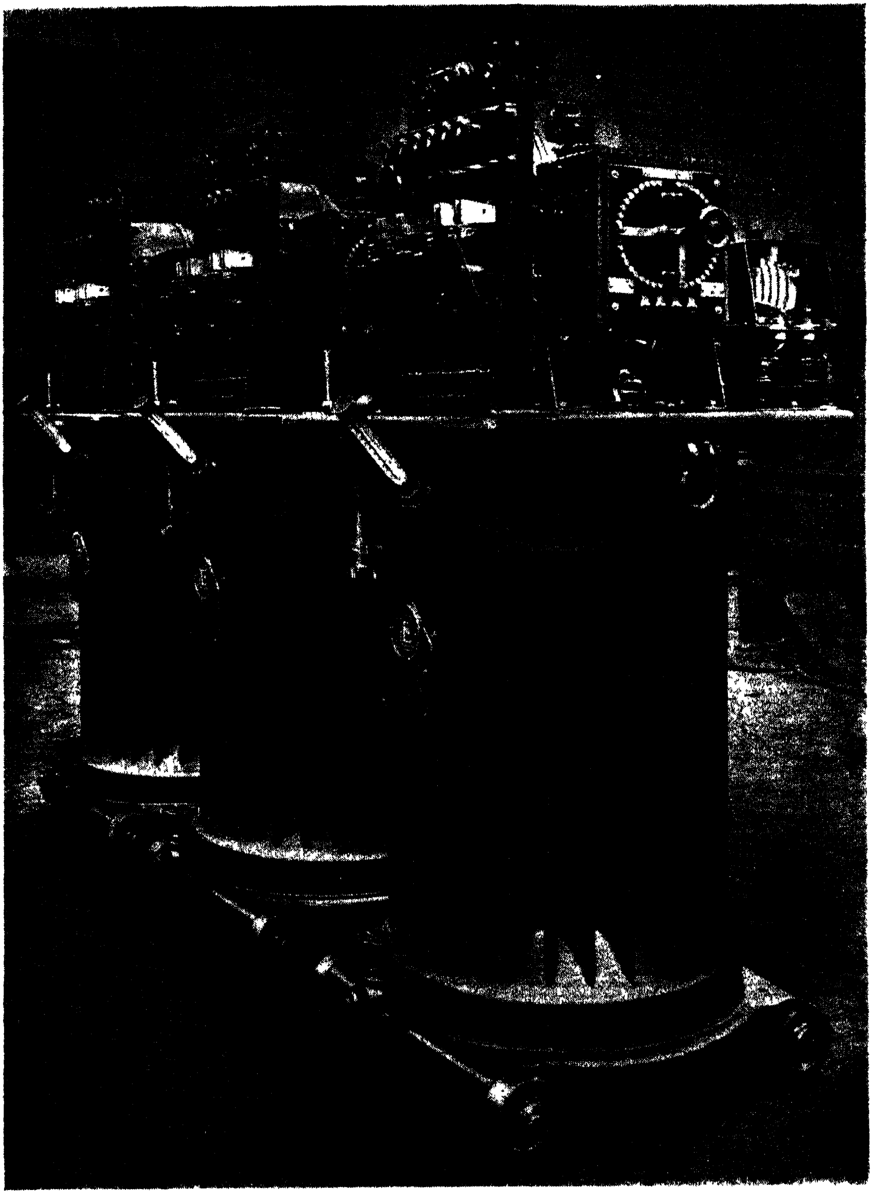


Fig. 114.—Three-phase bank of automatic induction regulators
(*English Electric Co., Ltd.*)

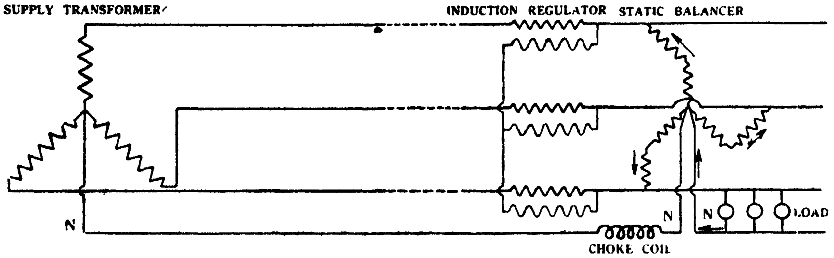


Fig. 115. ARRANGEMENT OF REGULATOR AND STATIC BALANCER
(*English Electric Co., Ltd.*)

voltages. Fig. 115 shows one circuit arrangement of a regulator and a balancer. The latter is located at the load centre but the former may be located either at the supply end or the load end of a circuit, the best position of the combined equipment on the system depends on local conditions. With the induction regulator placed at the supply end of the line, a line drop compensator may be incorporated in it so as to maintain a constant voltage at the load end. The compensator (Fig. 116) is made up of a variable resistance in series with a variable reactance, the values of both being adjusted so as to be proportional to the actual resistance and reactance of the line. Current from the secondary of a current transformer passes through the circuit; thus, since the current is proportional to the line current, the voltage drop across the resistance and the reactance in series is proportional to the line drop. The ends of the circuit are also taken to a potential transformer. Included in the loop circuit formed by the resistance and the reactance, and the secondary of the potential transformer, is the operating coil of a relay, which controls the position of the regulator rotor. Thus the actual voltage across the operating coil is proportional to the difference between the line voltage, and the line drop, consequently the relay can be made to adjust the induction regulator to compensate for the line drop.

If, for example, there is a 10 per cent. voltage drop at full load between the load centre and the regulator, which is designed to regulate the voltage by, say, 15 per cent. up and down, then the line compensator can be set so that the voltage, instead of remaining constant at the supply end of the line, will rise in proportion to the line voltage at such a rate as to give a 10 per cent. increase at full load; in this way constant voltage will be maintained at the load centre. When the induction regulator is placed at the load centre a line drop compensator is not required, the regulator maintaining constant voltage at this point under all conditions of load. Fig. 116 shows schematically the automatic control used for adjusting the regulator so as to maintain constant voltage with the regulator at the supply end of the line.

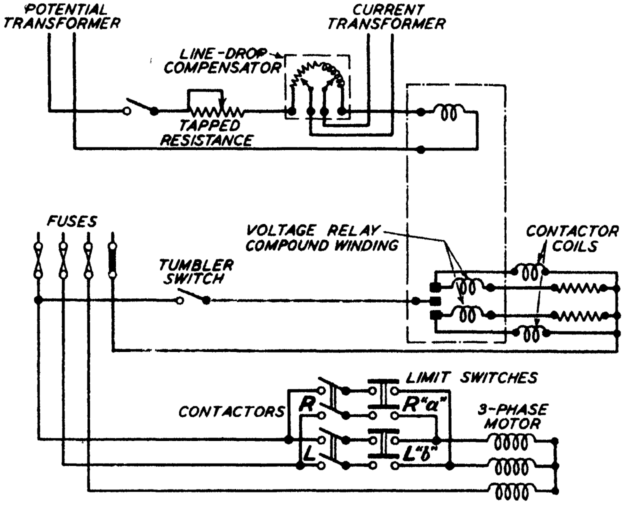


Fig. 116.—SCHEMATIC DIAGRAM OF AUTOMATIC CONTROL FOR INDUCTION REGULATOR

Contactor *R* closes to raise voltage.
Contactor *L* closes to lower voltage.

Compound windings of voltage relay give additional torque to the moving element when the contacts close, thus ensuring that these are held firm until the operation is completed. Limit switches are mechanically interlocked.

When single-phase regulators are used to avoid phase displacement their connection in the circuit has to be specially arranged. In the case of the four-wire system, which is practically limited to low-voltage distribution networks, the regulator primary windings should be star-connected, and the star point connected to the neutral of the system, as in Fig. 117. With this connection there is no voltage phase displacement, but it should be noted that the star point of the primaries must be connected to the neutral point, otherwise there is nothing to determine the phase voltages of the primary windings and unequal boosting may occur. If each regulator is subject to independent automatic operation there may also be instability. Ring-mains are frequently operated at 6·6 or 11 kV., three-wire, and where single-phase regulators are essential an interconnected-star balancer should be used with its star point connected to the star point of the regulators as an artificial neutral. Without this precaution serious troubles are likely to occur, particularly when switching the regulators into service. Three-phase three-wire systems may be regulated by means of three single-phase regulators with the primary windings connected between lines, or by means of two single-phase units connected " V," or " open-delta."

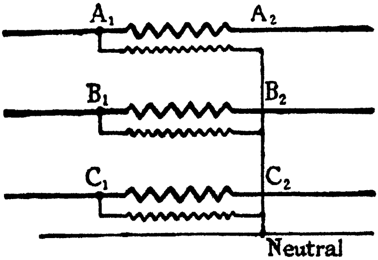


Fig. 117.—CONNECTION OF SINGLE-PHASE REGULATORS IN FOUR-WIRE SYSTEM FOR NO PHASE DISPLACEMENT

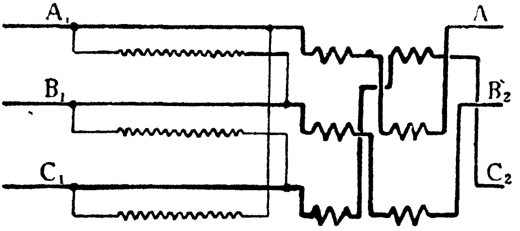


Fig. 118.—CONNECTIONS FOR THREE-PHASE REGULATION BY SINGLE PHASE UNITS WITH NO PHASE DISPLACEMENT

Fig. 118 shows the connections of induction regulators with "split" secondaries for three-phase three-wire regulation without phase displacement.

The adaptability of the induction regulator to automatic control makes it especially suitable for the regulation of parallel feeders, when it is necessary to maintain the voltage phase angle the same in all the feeders. For two feeders the regulators can be coupled mechanically, so that they always operate simultaneously, but this is not a very flexible arrangement, and various schemes have, therefore, been devised for simultaneous operation. The scheme shown diagrammatically in Fig. 119 has been used successfully with as many as four parallel feeders. A potentiometer resistance (1) is mounted on each regulator and has its sliding contact (2) geared to the regulator rotor. A sensitive polarised relay (3) is connected between the slider of the master regulator and each of the trailers. The contacts of this relay close the "raise" or "lower" voltage motor contactors, thus restoring the "trailing" regulator to the same angular position as the master. This system is very simple and will be recognised as an adaptation of the Wheatstone bridge and galvanometer. A centre-zero voltmeter (4) is connected between the centre point of the potentiometer resistance and the slider, and is scaled in electrical degrees displacement from neutral. By this means any regulator can be brought into the same angular position before switching it into service.

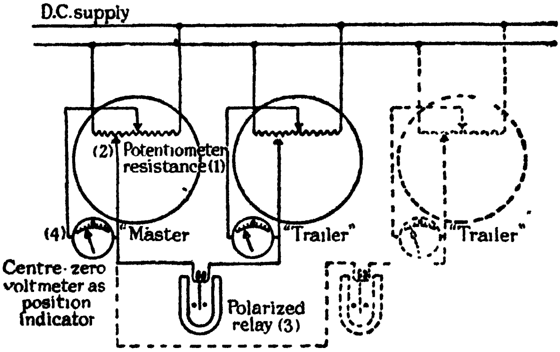


Fig. 119.—METHOD FOR CONTROLLING VOLTAGE OF PARALLEL FEEDERS SIMULTANEOUSLY
(*English Electric Co., Ltd.*)

The voltage control of a feeder to compensate for the load drop between two distribution centres, and maintain the same voltage at either end irrespective of the supply voltage, has been accomplished by means of a differential relay supplied from two potential transformers and a line drop compensator, as shown in

Fig. 120. The incoming volts plus the line-drop volts are balanced against the outgoing voltage and thus provide just the necessary boost according to the load.

The above applications of the induction regulator are, of course, only a few of the ways in which this form of voltage control is used. The equipment is also used for industrial purposes for maintaining constant voltage or current.

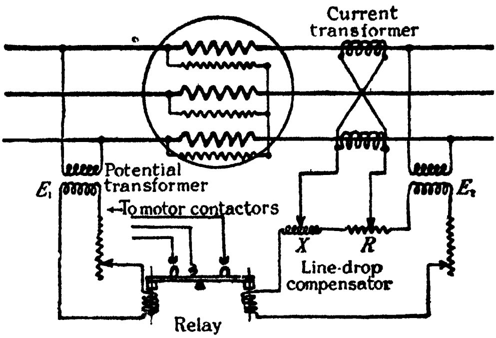
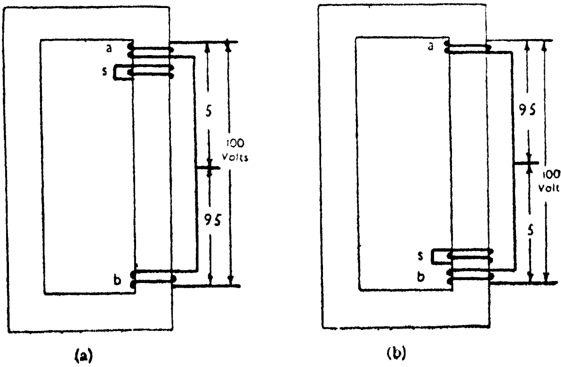


Fig. 120. VOLTAGE CONTROL BY DIFFERENTIAL RELAY (*English Electric Co., Ltd.*)

Load control of interconnectors is effected by induction regulators in the same way as described previously (page 9, Chapter II). When, for complete control, quadrature voltage control is necessary in addition to in-phase voltage control this is provided by means of twin-type induction regulators specially connected.

The Moving Coil Voltage Regulator

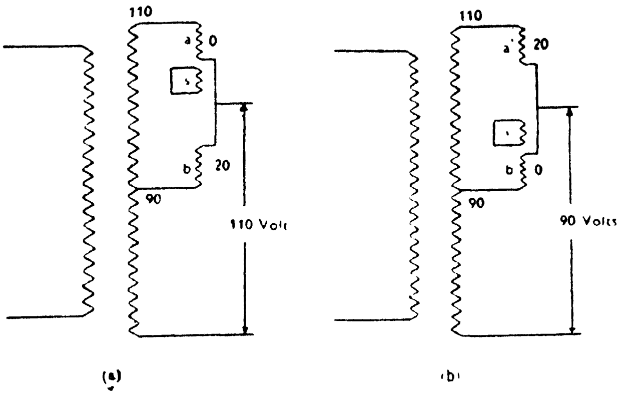
The principal function of any voltage regulator is to vary the voltage in a circuit, preferably smoothly, and without interrupting the load : this the moving coil regulator performs, by means of its characteristic feature —a short-circuited coil moving up and down the leg of a laminated iron core. There are many practical applications for this regulator, but the only one considered here is the control of voltage in an A.C. transmission or distribution circuit.



(a) (b)

Fig. 121. PRINCIPLE OF MOVING COIL REGULATOR

The essential components of the moving coil regulator comprise a two-legged core as used in transformer construction with coils *a* and *b* (Fig. 121) mounted respectively at the top and bottom of one leg, and a short-circuited coil *s* which is free to move up and down the leg between coils *a* and *b*. This arrangement is shown in Fig. 121. The moving coil is entirely isolated



(a) (b)

Fig. 122.—Circuits and operation of type A regulator

electrically, so that no flexible connections, slip rings, or sliding contacts are used. If a voltage be applied to coil *a* only, the resulting current will depend upon the impedance of the coil, this being determined by the position of the moving coil *s*; which is, in effect, the short-circuited secondary of a transformer whose primary is coil *a*. The flux due to the latter links with the moving coil *s*—to a degree determined by its distance from *a*—and induces an E.M.F. in *s*. This causes a current to circulate and create a flux in opposition to that due to coil *a*. Thus, the back E.M.F. induced in coil *a* and, therefore, its impedance are determined by the difference between the flux due to the current in this coil and that due to the current in the moving coil *s*. The path of the flux due to coil *a* is shown in Fig. 123. With the moving coil in the position shown no E.M.F. is induced in it, but as it is moved closer to coil *a* an increasing flux is created opposing that of coil *a*, the impedance of which is thereby smoothly reduced. The movement of the moving coil towards coil *b* has the effect of reducing the impedance of that coil. Hence, with the moving coil in the position shown in Fig. 121 (*a*), the impedance of the coil *a* will be small and of coil *b* large. If a voltage be applied across these two coils connected in series, then the greater part of the voltage will appear across coil *b*, and a small part only across coil *a*, as shown in the figure. With the moving coil at the bottom of the leg, as in Fig. 121 (*b*), the respective impedances of coils *a* and *b* are reversed, and the greater voltage will now appear across coil *a*.

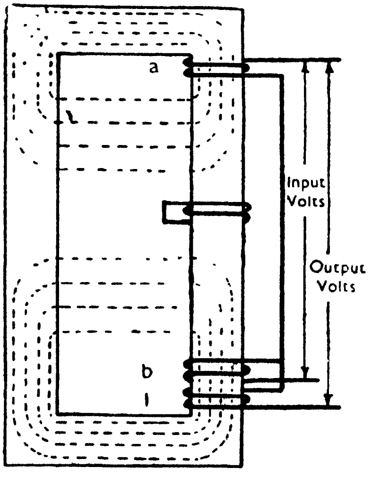


Fig. 123.—Moving coil regulator for voltage boost only

With the values assumed in the figures, and an impedance variation of 20/1, it will be seen that the voltage across coil *b* can be varied smoothly and uniformly from 5 to 95 volts by varying the position of the moving coil. In actual practice a range of 0–100 is obtained with the simple arrangement shown in Fig. 121.

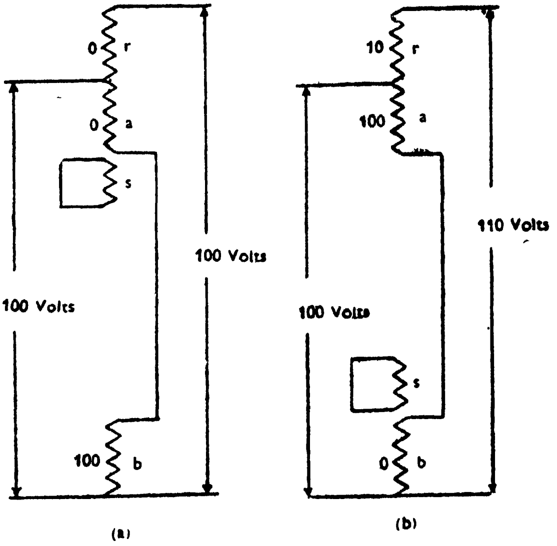


Fig. 124. OPERATION OF VOLTAGE BOOST REGULATOR

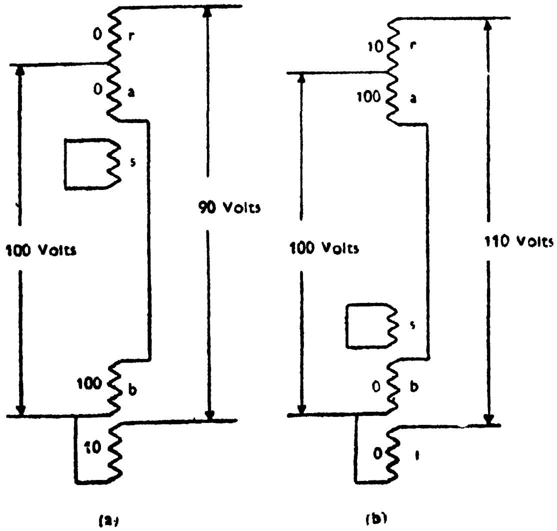


Fig. 125.—OPERATION OF REGULATOR GIVING BOTH VOLTAGE BOOST AND BUCK

However, such a wide range of voltage variation is only required in testing transformers and the like, for transmission and distribution circuits voltage variations of from 10 to 20 per cent. are sufficient. These variations can be obtained from the regulator in two ways, either by using the regulator in conjunction with a tapped transformer, as in Fig. 122, or by means of additional windings on the regulator, as in Figs. 123–125. In Fig. 122 the regulator, as previously described, is connected across a portion of the winding of the transformer. By suitably choosing these transformer tappings any desired range of voltage variation can be obtained. The arrangement shown in Figs. 122 (*a*) and 122 (*b*), representing the Ferranti type A regulator, gives a voltage variation of 90–110.

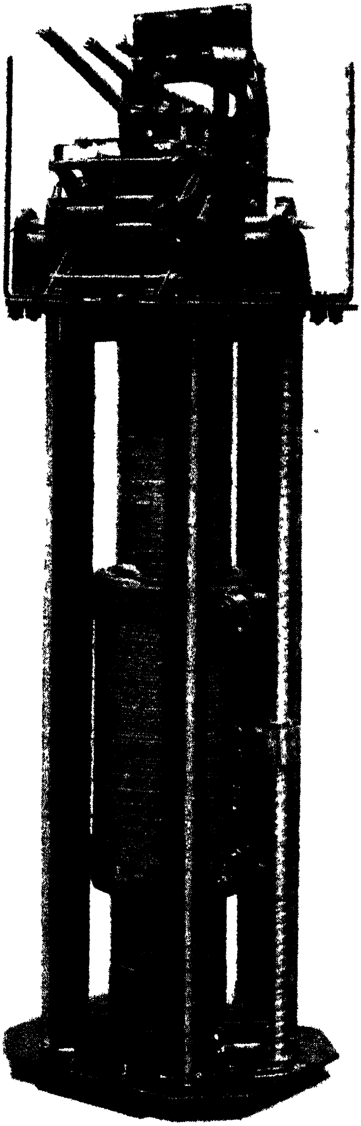


Fig. 126.—SINGLE-PHASE AUTOMATIC MOVING-COIL REGULATOR GIVING 0–12 PER CENT. BOOST IN A 50 kVA., 240 VOLT CIRCUIT (*Ferranti, Ltd.*)

For voltage control independent of a transformer, modified arrangements of the type A regulator are used, and designated type B regulators. With these, the voltage variation obtained by the method shown in Fig. 121 is stepped down to the desired value by means of an additional coil or coils connected in series with the line. An arrangement giving voltage boost only is shown in Fig. 123, and diagrammatically in Fig. 124. The voltage across the boosting coil *r* will be a constant fraction of the voltage across the adjacent coil *a*, depending upon the turns ratio of these two coils. In Figs. 124 (*a*) and 124 (*b*) it is assumed that coil *a* has ten times the number of turns as coil *r*. From the values given in these figures it will be seen that the output voltage varies from 100 in the minimum voltage position to 110 in the maximum voltage position. By reversing coil *r* its voltage would be subtracted from the input voltage instead of added to it, and the secondary voltage would then vary from 100 to 90 volts.

If it is required to both increase and decrease the voltage, that is, to buck and boost, a coil *l* similar to *r* is mounted at the bottom of the leg close to coil *b*, as shown in Fig. 125. Assuming that this bucking coil *l* has one-tenth of the number of turns of coil *b*, then with the moving coil in the minimum voltage position, as in Fig. 125 (*a*), the output voltage will be $100 - 10 = 90$ volts. Similarly, with the moving coil in the maximum voltage position, as in Fig. 125 (*b*), the output voltage will be 110 volts, the total variation being plus or minus 10 per cent. of the input voltage. By choosing suitable turn ratios for coils *r* and *l*, any desired values of buck and boost can be obtained; this being an important characteristic of the moving coil regulator. In most cases different values of buck and boost are required; in fact, all boost and no buck is common. The regulator is built, in general, on the same lines as ordinary transformers; the laminated iron core, coils, insulation, structural work, and general assembly being in accordance with standard transformer practice. The regulator can, therefore, be designed for high voltages and heavy currents, and the need for shunt- and series-transformers is avoided. Very small regulators for indoor service may be air insulated and air cooled, but all others are oil immersed in plain, tubular, or radiator tanks, depending upon the capacity.

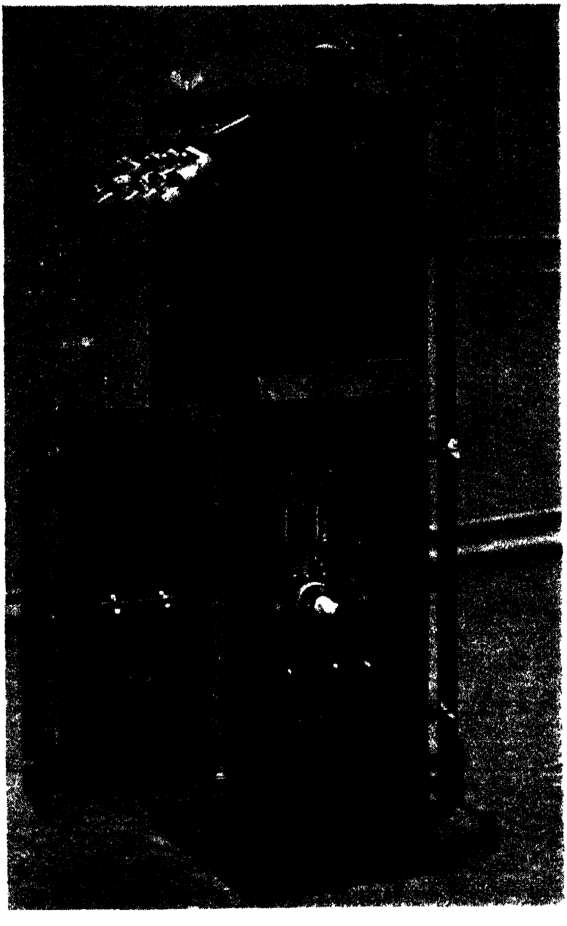


Fig. 127.—Single-phase automatic moving coil regulator, 30 kVA.

Incoming volts 264 236, outgoing volts 240–262 compounded. (*Ferranti, Ltd.*)

Single-phase regulators are of the divided core type, with circular concentric windings. In the smaller sizes the moving coil is carried in a non-magnetic frame operated by a square-threaded shaft, as shown in Fig. 126. In the larger sizes the moving coil is supported at both ends and operated by two square-threaded vertical shafts. Mechanical drive is by one or more induction disc motors through simple spur gearing, except in special cases, where ordinary three-phase induction motors are used. Three-phase regulators are made up of three modified single-phase units, assembled in triangular formation, with a central square-thread

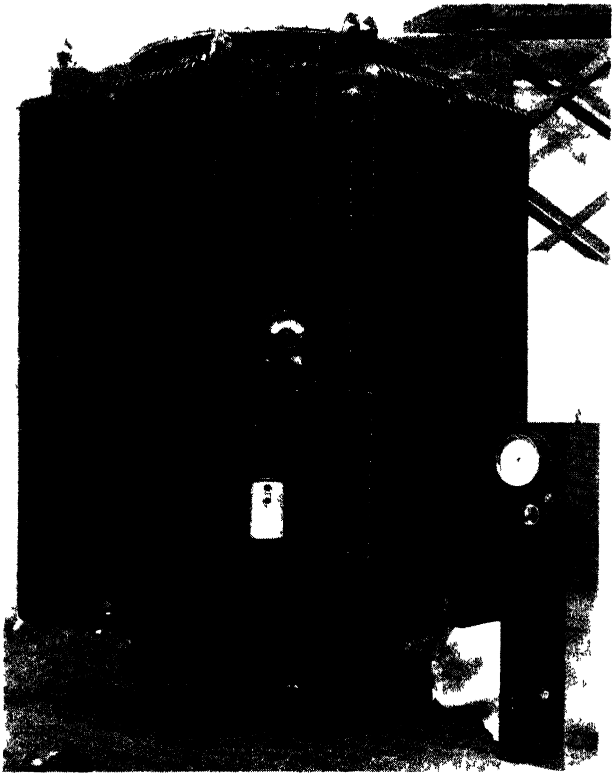


Fig. 128A.—MOVING COIL VOLTAGE REGULATOR GIVING A 20 PER CENT. VOLTAGE CONTROL IN A 7,500 KVA., 11 KV. THREE-PHASE CIRCUIT

External view showing cooling radiators, and automatic control gear pedestal on right. (*Ferranti, Ltd.*)

operating shaft. In all types of regulator, except the largest sizes, all the mechanical operating gear, including the motor, is oil immersed. The regulator, complete with its mechanical gear as a unit, is enclosed in a tank of standard transformer construction, as in Fig. 127 for a small single-phase unit, and Fig. 128A for a large three-phase regulator. Regulators are specially constructed, for special applications, in the form of feeder pillars, for installation in street pits or for pole mounting, etc.

An advantageous feature of the moving coil regulator for certain applications is that neither single- nor three-phase units have any voltage-phase displacement in any regulator position ; consequently it is suitable for the control of voltage, load distribution, or power factor in interconnectors.

Moving coil regulators can be operated in parallel with each other, simultaneous operation being ensured by coupling the regulators mechanically where possible, or alternatively, by electrical control. The regulators must, of course, have appropriate internal impedance values in the same way as when ordinary transformers are connected in parallel. Similarly, where regulated feeders are to be operated in parallel with unregulated feeders the combined impedance of regulator and feeder must be considered.

Another outstanding feature of the regulator is the simplicity of automatic control gear; the appearance of this being shown in Fig. 127. The simplification of this gear is primarily due to the very low mechanical power required to operate the regulator. The motor used is of the induction disc split-phase type, the driving element of which consists of iron-cored coils mounted on either side of a copper disc forming the rotor. The phase displacement is obtained either by connecting a condenser in series with one of the coils or, in some three-phase circuits, by connecting the coils between appropriate phases and neutral. The complete motor with four driving elements is shown in Fig. 129; and the diagram of connections in Fig. 130. A single two-way switch controls both starting and stopping, and direction of rotation. This type of motor is particularly suitable for automatic control as it can be designed to run at very slow speed, e.g. 150 r.p.m. or less, and the torque exerted at starting is very high, being much greater than the running torque. Furthermore, it takes no more current at starting than when running at full load so that electrical overloading is impossible and the motor can, therefore, be stalled without any risk of damage.

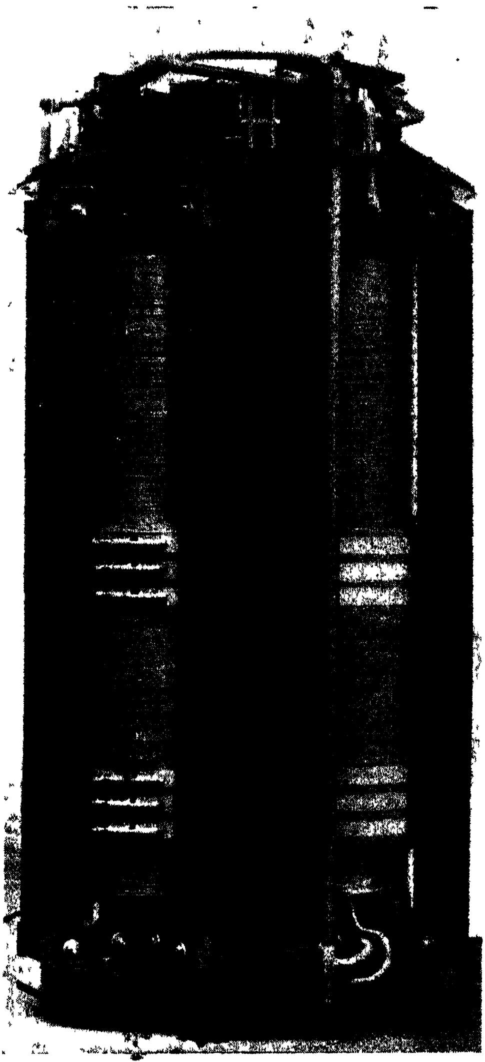


Fig. 128B.—MOVING COIL VOLTAGE REGULATOR GIVING A 20 PER CENT. VOLTAGE CONTROL IN A 7,500 KVA., 11 KV., THREE-PHASE CIRCUIT

Internal view, showing winding construction, motors, and mechanical operating gear at top. (*Ferranti, Ltd.*)

As a direct result of the characteristics of the induction disc motor the apparatus required for automatic operation of the moving coil regulator is reduced to a minimum. Due to the slow motor speed relatively little mechanical

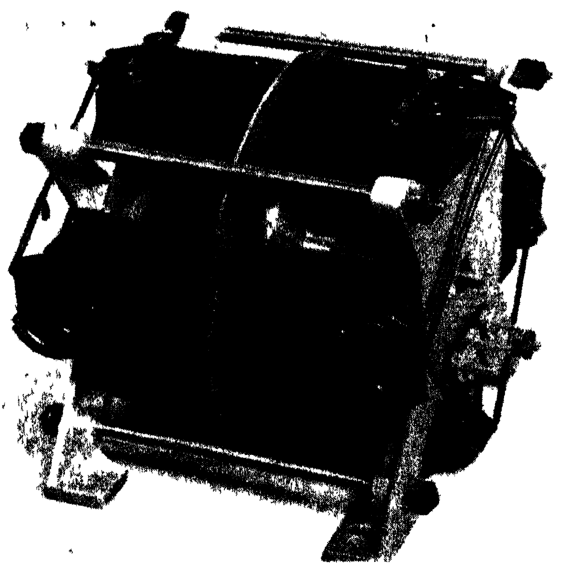


Fig. 129.—INDUCTION DISC MOTOR AS USED IN MOVING COIL REGULATOR. (*Ferranti, Ltd.*)

gearing is required, and for the same reason an automatic brake is unnecessary as the over-run is negligible. Also, the speed of operation of the regulator can be much slower, so that momentary voltage variations are too short in duration to cause appreciable response in the regulator. No time-delay relays are therefore used, and in consequence the regulator begins to operate immediately voltage conditions demand it. The current taken by the motor at starting is very low so that this is controlled by a small single-phase mercury switch instead of contactors. The voltage relay or contact-making voltmeter operates directly on the mercury switch. No limit switches or overload trip are necessary in the motor circuit by reason of its particular characteristics. With the moving coil regulator a special Astatic voltage relay is employed and, except in the larger sizes, the relay controls directly the driving motor, no auxiliary apparatus being required. With some large regulators—such as that in Fig. 128B—operation is by means of a large-diameter spur wheel, fixed to the top of the operating shaft, driven by a number of induction disc motors distributed around its circumference.

The Ferranti Astatic voltage relay consists of an electro-magnetic circuit with movable iron core or plunger. This is mounted vertically and moves up and down in simple guides, as shown diagrammatically in Fig. 131. The principle of design is such that the pull on the plunger for a given applied voltage is constant, and independent of position over a wide range of movement, which is a characteristic not possessed by certain other types of electro-magnetic relay. This effect is achieved by suitable impedance

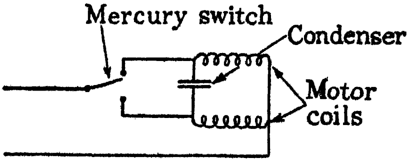


Fig. 130.—INDUCTION DISC MOTOR CIRCUIT AND CONTROL

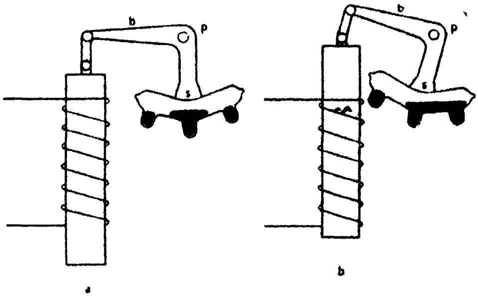


Fig. 131.—Diagram showing mechanical action of Astatic relay

characteristics of the electric circuit and by special construction of the magnetic circuit. If, therefore, the voltage is so adjusted that the pull is exactly equal to the weight of the plunger this will float in air, being maintained in a vertical position by the guides. Under these conditions the plunger will remain permanently in any set position. If it is forcibly raised or lowered by hand to another position it will also remain in that position until further disturbed. This fundamental characteristic of not tending to any one position has given rise to the name " Astatic " voltage relay.

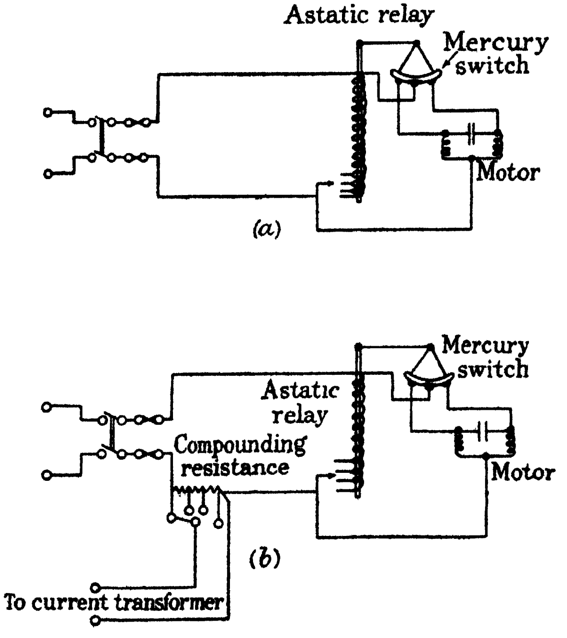


Fig. 132.—Typical automatic control gear circuits for moving coil regulator

(*a*) Circuit giving adjustable constant output voltage. (*b*) Circuit as (*a*), but with resistance compounding giving output voltage rising with load.

The plunger movement operates through a lever *b* to tilt a mercury switch *s* suspended from a fulcrum *P*, as shown in Fig. 131. The mercury switch is of the two-way type with three electrodes. In the normal position, i.e. when the pull on the plunger is astatic, the pendulum action of the switch will cause it to take up a neutral position as shown in Fig. 131 (*a*). If the volts rise slightly, the pull will increase, and the plunger will rise and tilt the mercury switch until the pendulum action of the switch movement balances the increase in pull. When the tilt is sufficient, the mercury makes contact between the middle and one of the outer electrodes, as shown in Fig. 131 (*b*), and starts the motor operating the regulator in the required direction.

With the astatic voltage relay the energy available for making contact is, with a 1 per cent. change in the voltage, 480 times greater than that in certain other types. Due to the special characteristics of the relay, which enable mercury switches capable of directly controlling loads of 2·5 kW. to be used, the control circuits are very simple. Two typical automatic control gear circuits are shown in Fig. 132.

Chapter XIII

CONVERTING EQUIPMENT

THE three forms of plant mostly used for A.C. to D.C. conversion are : (*a*) Rotary convertors. (*b*) Motor convertors. (*c*) Mercury-arc rectifiers. Motor generators are used for special purposes, but not generally for major substations.

The rotary convertor has a direct current armature of normal design, with the addition of tappings, on the end of the armature opposite to the commutator, taken to slip rings. The field system is generally similar to that of a direct current machine ; it may be shunt or compound excited and is usually fitted with interpoles. The operating characteristics, considered from the A.C. side, are those of a synchronous motor, i.e. the speed is constant, with a given frequency, and on the D.C. side those of a generator with the exception that the output voltage is not adjusted in the same way despite the fact that the excitation may be controlled by a field rheostat.

Although the rotary convertor is in effect both an A.C. motor and a D.C. generator, on account of the same armature and field coils being used in each case, the conditions of conversion are such that there is a fixed ratio between the D.C. voltage and the voltage applied to the slip rings.

The D.C. brushes are placed so as to obtain the maximum voltage available in the armature. When two tappings from the armature to slip rings coincide with the positive and negative brushes (see tappings to slip rings 1 and 4, Fig. 133) the D.C. voltage is equal to the maximum voltage applied to the slip rings. This maximum voltage is the peak value of the A.C. voltage so that in the ideal case, when the A.C. voltage follows a sine law with a maximum value equal to the D.C. voltage, the virtual (R.M.S.) value of the A.C. voltage $= \frac{\text{D.C. voltage}}{\sqrt{2}} = 0{\cdot}707$ of the D.C. voltage. This corresponds to the conditions in a single-phase convertor.

The speed of the armature being proportional to the frequency, as it rotates, the voltage between the two tappings (1 and 4) decreases, reverses, and reaches a maximum in the opposite direction when the tappings have rotated through one pole pitch. The voltage then decreases, reverses to its original direction, and again becomes a maximum when the tappings have rotated through another pole pitch. The

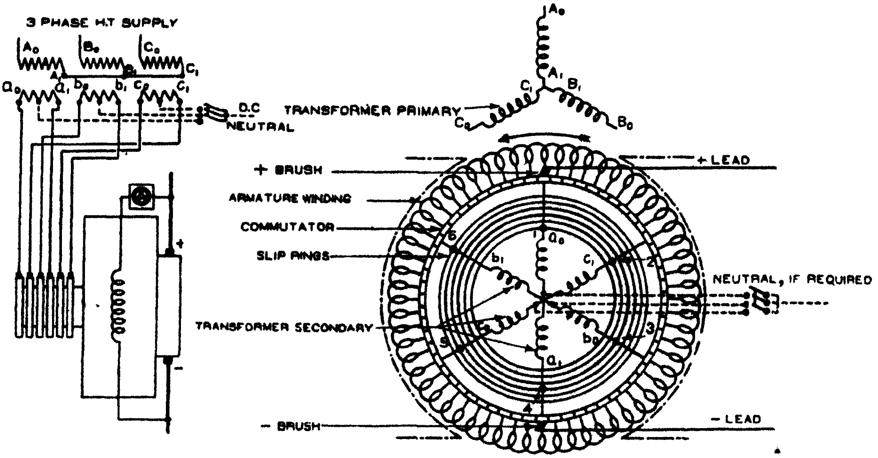


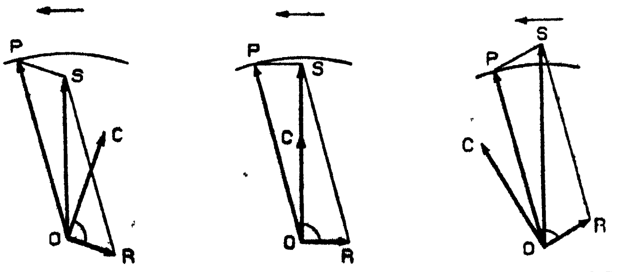
Fig. 133.—CONNECTIONS OF SIX-PHASE ROTARY CONVERTOR
Transformer connections : Y, primary ; diametrical, secondary.
(*British Thomson-Houston Co., Ltd.*)

rotational speed of the armature in r.p.m. is equal to $\frac{120f}{p}$, where f = the frequency and p = number of poles. In the case of the single-phase convertor the time taken for one complete revolution will be the same as that required for the A.C. voltage to complete one cycle.

Single-phase rotaries are not, of course, used in practice, six-phase units being customary ; the transformer secondary winding is suitably connected for this purpose, as shown in Fig. 133. Since the armature of the convertor carries both the A.C. for motoring and the generated D.C., and as the latter is also of an alternating nature, but is rectified by the commutator and brushes, the effective current heating the armature is the difference between the A.C. input and the D.C. output. As the temperature-rise of the armature is the factor largely determining the output of a D.C. machine, for a given size of armature a much greater output can, therefore, be obtained from it when used with a rotary convertor than would be permissible with a D.C. generator. The heating of the armature, due to the I^2R loss, becomes more uniform as the number of phases used is increased in consequence of the resultant current becoming more uniform. For this reason the six-phase winding is generally adopted, since for the permissible temperature-rise a greater output, or higher overload capacity, can be obtained, as well as an increased efficiency.

Rotary convertors may be started either from the A.C. or D.C. supply available. The former method is effected in a number of ways, the method generally employed being that using an induction motor which has a pair of poles less than the rotary convertor. At starting the stator windings are connected to the transformer secondary, and when the machine has run up to speed and is excited, the stator windings are connected in series with the slip rings, and the supply from the transformer. The motor acts as a synchronising reactor in series with the armature, so that when the armature pulls into step there is very little possibility of reversed polarity, and a failure to synchronise, because the rotating field in the armature is produced by a current which is not strong enough to reverse the residual magnetism in the field. As soon as the convertor is in step, the stator windings of the starting motor are short-circuited. Various modifications of this method of starting are used but they are all similar in principle.

On account of the fixed ratio between the voltages at slip rings and commutator, regulation of the D.C. voltage can only be obtained by adjusting the voltage at the slip rings. This can be effected by tappings on the transformer, an induction regulator or static booster connected between transformer and slip rings ; a synchronous booster connected in a similar manner, or by what is termed reactance control. The latter is the cheapest and simplest method of voltage control and is generally installed for conditions of service which do not require more than 10–20 per cent. voltage variation. This form of voltage regulation necessitates the introduction of additional reactance in the transformer, or a separate external reactor. The method by which the voltage at the slip rings is varied is illustrated in the diagram, Fig. 134, representing the voltage relations of a 1/1 transformer. By increasing the excitation of a rotary convertor the power factor of the A.C. input can be adjusted from lag to lead, and vice versa. It will be seen from Fig. 134 that if the excitation be adjusted so that the current is lagging, the effect of reactance is to lower the slip ring voltage; while if the excitation is adjusted to draw a leading current, the effect of reactance is to raise the slip ring voltage.



O C LAGGING BEHIND O S

O C IN PHASE WITH O S.

O C LEADING O S

Fig. 134.—Vector diagrams representing reactance control

O P is a vector representing the voltage at the H.T. terminals of the transformer, and is assumed constant.

O R is a vector representing the reactance voltage produced by the current O C passing through the reactance.

O S is a vector representing the slip ring voltage which is the resultant of O R and O P.

The application of a rotary convertor as a three-wire machine is effected by connecting a neutral to the secondary of the transformer as shown in Fig. 133. When the convertor armature is in the position shown, the secondary winding of the transformer lettered a_0 to a_1 is, for the particular instant, connected across the positive and negative brushes. At that instant, therefore, the centre of the transformer is at a potential of half the voltage across the D.C. brushes. As the armature rotates, the potential across the secondary winding decreases and reverses ; but it will be seen that the centre point of the secondary always remains at a potential of half the D.C. voltage. If this point is, therefore, connected to the neutral of a D.C. system, the rotary will maintain constant potential between the neutral and positive, and also between neutral and negative. When a load is connected between the neutral and positive, the out-of-balance current will flow along the neutral wire and divide at the transformer, half passing through one side of the transformer and half through the other, the current finally passing through the armature windings to the positive brush. This out-of-balance current on one side of the system causes a small *IR* drop, consequently the voltage on this side will drop slightly. In practice the amount of out-of-balance current is seldom such as to produce an excessive voltage difference between the two halves of the system.

The Motor Convertor

For connection to a high-voltage supply a transformer is required for the rotary convertor. One of the distinctive features of the motor convertor is that this is not required, up to about 11 kV., as the latter consists of an induction motor mechanically coupled to a D.C. generator, and, in addition, the rotor winding of the motor is electrically connected to the armature of the generator. The arrangement is shown in Fig. 135. The general theory of the motor convertor will be appreciated by considering a unit in which the motor and the generator each have two poles. Once the machine has been started the combined rotating element rotates at a speed corresponding to half the synchronous speed of the induction motor, or, in other words, the " slip " of the latter is 50 per cent. The rotating field set up in the stator by the supply current rotates relative to the rotor at a speed corresponding to half the periodicity of the supply, thus the E.M.F.'s induced in the rotor have a periodicity equal to half that of the supply circuit. When the generator and the motor have an equal number of poles, as the D.C. armature coupled to the motor is rotating at a speed corresponding to half the periodicity of the A.C. supply, the E.M.F.'s induced in the armature winding will have the same periodicity as those in the rotor winding. Provided the rotor and the armature are each wound with a suitable number of turns, by connecting the two windings together the speed remains constant as the motor convertor becomes, in effect, a synchronous machine by virtue of

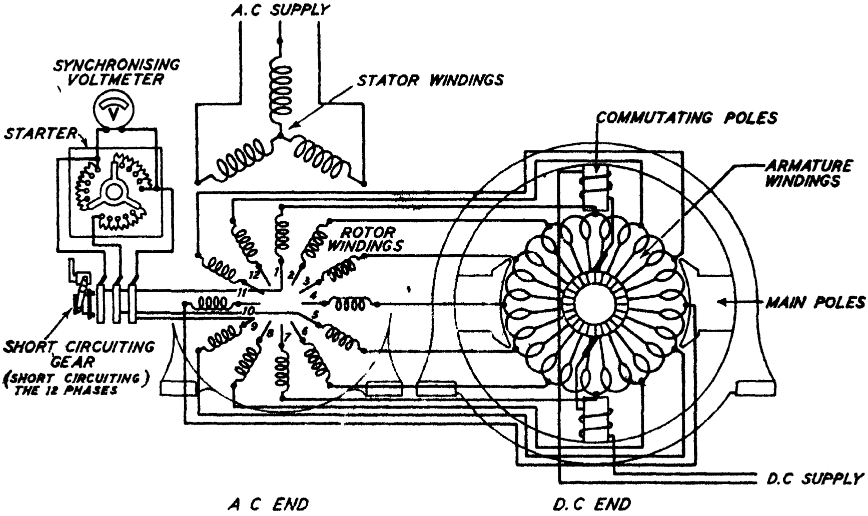


Fig. 135.—Connections of motor convertor. (*Bruce Peebles & Co., Ltd.*)

the interaction between the alternating flux in the armature and the D.C. field.

Owing to the induction motor having a speed corresponding to half the periodicity of the supply only one-half of the electrical energy supplied to the rotor is converted into mechanical energy, and transmitted by the shaft to the D.C. generator. The other half of the energy supplied to the rotor is transferred to the armature electrically by means of the interconnections. Thus the induction motor operates half as a transformer, while the D.C. generator acts half as a rotary convertor.

The rotor of the motor convertor is generally wound for twelve phases as this gives a very strong synchronising force and makes the machine exceedingly stable, and not likely to fall out of step due to disturbances on the A.C. system. Where the number of poles of the two portions of the set differ, the speed is inversely proportional to the sum of the number of poles of the motor and the generator. If f = frequency, n = r.p.m., p_M and p_G are the number of poles of the motor and generator respectively, then $n = \frac{120 f}{p_M + p_G}$.

Motor convertors are generally provided with three bearings, the electrical connections between the rotor and the armature being effected by leads through hollow portions of the shaft.

The convertor may be started either from the A.C. or D.C. sides. With the first method only three of the phase windings are used during the first starting operation. These are connected to the slip rings and the non-inductive starting resistance (Fig. 135), a section of which is gradually cut out to bring the speed near to the normal operating speed of the machine. On approaching synchronous speed the E.M.F.'s induced in rotor and armature will alternately be in opposition and conjunction, consequently the current through the starter will vary between a maximum and a minimum value as indicated by a voltmeter connected across the starting resistance. When the pointer of the voltmeter is practically steady the starter and the slip rings are short-circuited by special gear ; in the case of a three-wire D.C. unit, a double-throw switch.

When starting from the D.C. side is adopted it is necessary to use an ordinary D.C. starter and synchronising apparatus.

The slip rings are of small dimensions, their function being merely for starting the convertor and, in three-wire systems, to carry the out-of-balance current. The neutral wire is connected to the bottom three contacts of a double-throw switch used initially for starting, and then short-circuiting the slip rings, so that the connections to the rotor winding are similar to those of the three-wire rotary convertor shown in Fig. 133 ; in the case of the motor convertor the rotor winding is equivalent to the secondary winding of the transformer.

Synchronous-motor generators, rotary and motor convertors are all used for power factor correction in suitable circumstances, since it is possible to make them take a leading current by over-exciting the field.

Mercury-arc Rectifiers

The present tendency with regard to A.C. to D.C. conversion is to use mercury-arc rectifiers instead of some form of rotating convertor whenever practicable, since they have a higher efficiency, are noiseless, require little maintenance, and are very easily adapted to remote or automatic control.

Physical Theory of Mercury-arc Rectifier

An elementary form of mercury-arc rectifier consists of a glass container with a pool of mercury (the cathode) at the bottom, and an iron plate (the anode) at the top (Fig. 136). When an arc is struck between the mercury and the plate mercury vapour is formed ; this arrangement of electrodes in mercury vapour at low pressure possesses the property of allowing current to flow in one direction with only a small voltage drop, while acting practically as a non-conductor in the opposite direction. Now, conduction in gases and vapours (see Chapter III, page 23) depends on the existence of negatively-charged electrons and a positively-charged electrode. In the case of the mercury-arc rectifier a few free electrons are present before the arc is struck ; in fact, if this were not so it would not be possible to strike the arc, but the conductivity of the path between the cathode and the anode is maintained as the result of the arc heating the mercury. Electrons are emitted from the mercury, so that when the plate is at positive potential, and the mercury at negative potential, these negative electrons are attracted to the plate. The electron stream rapidly increases because, as the electrons originally produced travel at high speed towards the plate, they collide with neutral mercury vapour molecules and split up the bound charges of the latter, thus producing more electrons, and also positive ions; consequently the conductivity of the path is greatly increased. Moreover, as the positive ions are produced they move rapidly towards the mercury cathode, the upper surface of which is brought to a white heat as the result of the continuous bombardment, the electron emission being further increased thereby. Thus the rate at which electrons and ions are produced rapidly increases as the voltage approaches its maximum positive value, but, after this, the opposite is the case and the arc is extinguished as the voltage approaches zero.

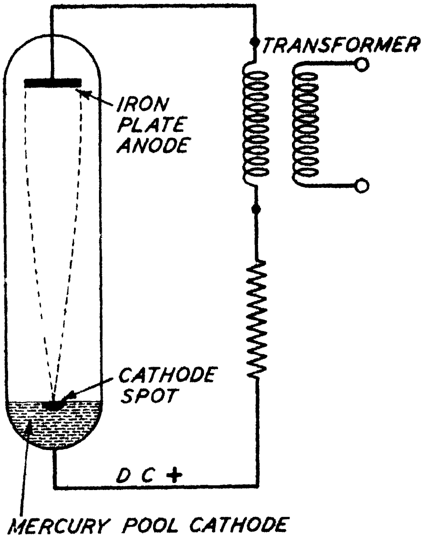


Fig. 136.—Elementary mercury-arc rectifier

The electrons also bombard the plate, when this is positive, but being free, i.e. unassociated with chemical atoms, they have no weighable mass and do not, therefore, raise the temperature of the plate to any appreciable extent.

Although electrons are emitted from the plate, the nature of the mercury is such that the emission from this is infinitely greater than that from the plate, which is comparatively negligible.

From the foregoing it will be apparent that if an alternating voltage is applied to a circuit consisting of the elementary rectifier and, say, a resistance connected between one terminal of the transformer secondary and the cathode (Fig. 136), during the half-cycle when the plate is positive the electrons will travel towards the plate, pass into it and flow, in effect, back to the cathode through the transformer secondary and the resistance. When, however, the voltage reverses, and the plate is negative and the mercury positive, electrons emitted from the mercury will not now travel towards the plate since this is of the same polarity as the electrons, but as the anode emission is negligible, the flow of electrons from the plate to the mercury of negative polarity is also negligible. Thus current will only flow around the circuit during the half-cycle when the plate is positive, and the D.C. through the resistance is uni-directional but periodic, the rectifier acting as a non-return valve in the A.C. circuit. Since the electrons flow around the circuit in a direction opposite to that in which, by convention, current is assumed to flow, the mercury cathode is the positive of the D.C. supply. In the conventional sense, when the anode voltage is positive, current flows from the transformer to the anode, through the rectifier to the cathode, and thence through the D.C. apparatus back to the transformer.

With the half-wave rectifier (Fig. 136) when the arc extinguishes at a voltage zero the vapour will become de-ionised in a few micro-seconds, so that when the voltage applied to the anode is again positive current would not flow until the initial ionisation had been produced by some specially arranged automatic device. Actually, mercury-arc rectifiers are not used for half-wave rectification, the biphase rectifier with two anodes being the simplest practicable arrangement. This is shown in an elementary form in Fig. 137. In this rectifier current will flow every half-cycle since one of the anodes is positive when the other is negative, but its use is confined to small power requirements. For substation rectifiers three, six, or twelve anodes may be used, the transformers having a corresponding number of phases. However, before dealing with the operation of multi-anode units it is necessary to consider the electrical theory of the rectifier in some detail; first, with reference to the two-anode unit represented in Fig. 137.

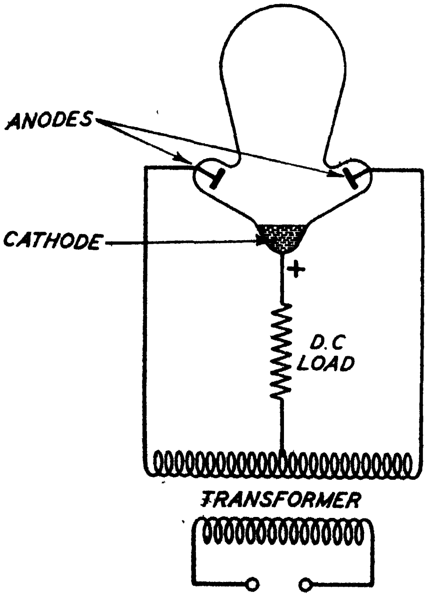


Fig. 137.—Simple arrangement of biphase rectifier

Electrical Theory

For an arc to be struck between two electrodes there is a minimum voltage which must be applied, the actual value depending on the distance between electrodes and the dielectric strength of the intervening medium. Thus, the arc between an anode and the cathode of a rectifier does not strike until the applied voltage reaches a certain value, and extinguishes as the voltage approaches zero at some value which is the minimum required to maintain the arc. During the time each anode is conducting by itself (in some multi-anode rectifiers there are always two anodes conducting) the D.C. output voltage at the cathode will vary with the applied A.C. voltage, its value being, very roughly, the A.C. voltage less the voltage-drop in the rectifier—the arc-drop. In the absence of modifying conditions—to be mentioned later—the wave-form of the D.C. voltage and current will be similar to that of the A.C. voltage, but as the latter is not applied to the cathode—via the arc—during the whole of the half-cycle, the D.C. voltage is available only while the arc is maintained. Thus the D.C. output of the rectifier during a half-cycle is less than it would be if the arc could be struck at the beginning and extinguished at the end of the half-cycle, from which it follows that the longer the anode is conducting during the half-cycle the greater will be the effective mean D.C. voltage acting in the load circuit.

If there actually was a period in which no anode was conducting it would be necessary to provide a means of maintaining the emission until the anode voltage had risen to a value sufficient to strike the arc, so as to obtain a continuous rectification. (In practice, a condition similar to this arises when the load drops to a very low value, and auxiliary anodes located much nearer to the cathode pool than the main anodes are used to maintain rectification.) Such a period does not, however, occur due to the reactance of the transformer modifying the circuit conditions so that just before one anode stops conducting another starts. Thus two anodes are conducting at the same time for a short period—in other words, they "overlap." Overlapping is caused by the opposite variation of the currents in successive anode circuits, each containing inductance in the form of a transformer winding, inducing voltages which have the effect of modifying the wave-form of the applied voltage.

Positive Space-charge

The voltage between the conducting anode and the cathode is of the order of 20 volts, but it is clear from Fig. 137 that the voltage between the two anodes is the full secondary voltage of the transformer. It might, therefore, be expected that an arc would strike between the anodes due to the presence of ionised mercury vapour. However, this does not happen normally owing to the presence of the positive ions mentioned earlier. When an anode is at positive potential the ions are repelled, but with the change to negative potential some of the remaining ions are attracted. These form a positive charge around the inactive anode—known as a positive space-charge—which effectually prevents the passage of current between the anodes. The space-charge acts as a screen which attracts any electrons emitted from the anode, and since they are brought into association with positive ions re-combination occurs, neutral molecules being formed. In effect the space-charge is also a back E.M.F. opposing the potential of the positive anode, and as it is concentrated in the vicinity of the negative anode the potential gradient in the rest of the space between the two anodes is very low, consequently there is little tendency for the electrons to pass through the ionic " screen."

Multi-anode Rectifiers

With the biphase or two-anode rectifier each anode conducts for a half-cycle; in the three-anode unit, supplied from a three-phase secondary (Fig. 138(*a*)), each anode conducts for one-third of a cycle only. Referring to Fig. 138(*b*), assuming that the output voltage wave-form, extended to zero by the thin lines, also represents that of the A.C. voltage applied to each anode in succession, and ignoring overlap: when anode 1 is conducting it will continue to do so until the voltage applied to anode 2 has risen to such a value that the voltage difference between anode 2 and the cathode is sufficient to strike an arc from that anode. Since the cathode voltage at any instant is determined by the voltage of the active anode, in this case anode 1, anode 2 will not strike until the difference between its increasing voltage and the decreasing cathode voltage is equal to the arc-drop. This condition is satisfied when the value of the A.C. voltage applied to anode 1 is the same as that applied to anode 2; in other words, when the instantaneous anode voltages are equal. As, at this instant, the voltage of anode 1 is decreasing and that of anode 2 increasing, the moment the latter strikes, the cathode voltage is thereafter determined by its increasing voltage, and since the voltage of anode 1 is decreasing there is no longer a sufficient voltage difference between this anode and the cathode to maintain an arc. Thus conduction will take place only between the cathode and that anode with the maximum positive voltage, the arc striking from each of the three anodes successively so that each conducts for one-third of a cycle; or more precisely, the middle two-thirds of the positive half-cycle of the A.C. voltage of the phase to which it is connected. The output voltage wave-form (shaded in Fig. 138(*b*)) comprises the tops of the successive positive half-cycles. Compared with the wave-form of the

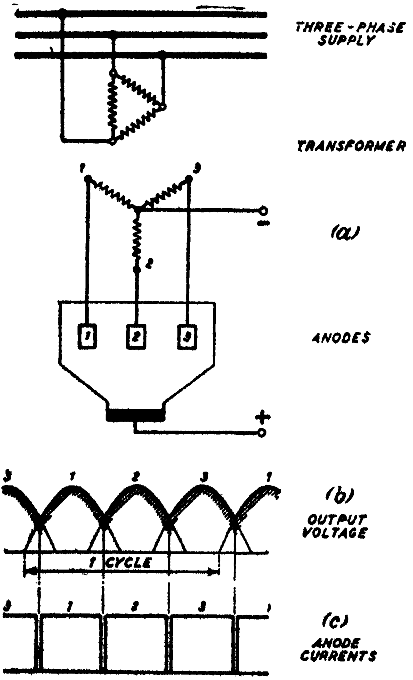


Fig. 138.—CONNECTIONS AND THEORETICAL WAVE-FORMS OF OUTPUT-VOLTAGE AND CURRENT OF THREE-ANODE RECTIFIER two-anode rectifier output that of the three-anode unit is considerably smoother.

A still more uniform output voltage is obtained with six anodes, but in this case each anode conducts for only one-sixth of a cycle. Similarly with a greater number N of anodes the output wave-form becomes correspondingly smoother, but each anode is in operation for only 1/N of a cycle. The disadvantage of increasing the number of anodes is that—in the absence of special arrangements—the transformer secondary phase is in use for a correspondingly shorter part of each cycle ; which is a factor deciding the size, and the cost, of the transformer required for a given rectifier output. For this reason the three-anode unit shown in Fig. 138(*a*) is an economical arrangement. The three secondary phases are star-connected, the star point forming the negative output terminal. The three secondary voltages are equal, but displaced in time by one-third of a cycle.

Effect of Overlap

Each anode takes over the whole of the output while it is connected to the cathode by the arc. If there was no inherent inductance in the D.C. circuit, i.e. only non-inductive resistance was present, the output current wave-form would be identical with the output voltage wave-form ; but generally the connected load circuits are inductive enough to smooth the current and keep it substantially constant ; although in some cases chokes are connected in the cathode circuit to smooth out the ripple of the D.C. output. Disregarding overlap, the anode currents can be represented by rectangular " blocks," as shown in Fig. 138(*c*), but actually due to the inductance in the anode circuits one anode does not stop conducting and the next start conducting instantaneously. The presence of inductance causes a delay in the extinction of the arc from one anode and a similar delay in the rise of the arc current from the succeeding anode. This is illustrated in Fig. 139. At the point *A* anodes 1 and 2 have equal voltages, but since the voltage of anode 1 is decreasing its current tends to collapse. The effect of this is to induce a forward E.M.F. in phase 1 of the transformer which tends to maintain the voltage applied to anode 1 and, therefore, the current flow. Simultaneously with the decay of current from anode 1 the current from anode 2 rises, and, in conse-

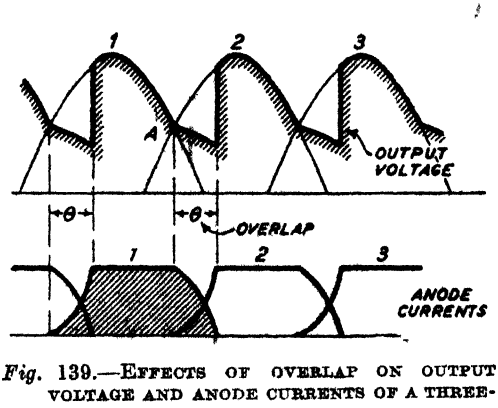


Fig. 139.—Effects of overlap on output voltage and anode currents of a three-anode rectifier quence, a backward E.M.F. is induced in the corresponding phase of the transformer in opposition to the voltage applied to anode 2. Thus the decreasing voltage of anode 1 is assisted by the induced E.M.F. to maintain the arc from that anode, and the increasing voltage of anode 2 is opposed by the induced E.M.F. so that this anode is prevented from taking over the whole of the output until after the period of overlap. During this period the voltages of anodes 1 and 2 are equal, and the output voltage of the two anodes in parallel becomes the mean of their respective phase voltages. The anode current wave-form is as shown in Fig. 139, the theoretical block shape being lengthened by θ, the period of overlap.

The output voltage wave-form is reduced in mean value by an amount proportional to the overlap, and since the duration of this is a function of the load current, the output voltage will fall with increase of load.

Voltage regulation of rectifiers is effected by transformer on-load tap-changing gear or some other form of A.C. equipment; or by special control grids in front of the anodes by means of which the degree of overlap can be varied.

Operating Characteristics

Apart from the transformer losses, the rectification losses proper are due to voltage-drops at the anode and cathode surfaces, and in the arc. The cathode drop is between 7 and 9 volts; which means that 7-9 watts are dissipated at the cathode for every ampere of arc current. The power is dissipated in emission of electrons, vaporisation of mercury, radiation and conduction of heat from the spot, etc. At the anode surface there is a drop of about 5 volts due to the space-charge concentrated there. In the arc there is a drop of roughly 0·1 volt per cm. of arc path, used in ionising the mercury vapour. The drop in the arc itself depends on conditions of load, temperature, and vacuum; but the anode and cathode drops are substantially constant. The total internal drop—the arc drop—is generally between 20 and 30 volts, and is approximately a constant of the rectifier, unaffected by load current in normal circumstances. The efficiency of a mercury-arc rectifier—excluding the transformer—for a specified kW. output, depends largely on the rated voltage, since the arc drop is constant. That is to say, with a given design of rectifier for a certain current rating, the output will be determined by the voltage, and as the arc drop is constant at any output voltage, the higher this is the smaller will be the percentage loss.

Backfire

The critical factor limiting the output of a mercury-arc rectifier is the temperature of the anodes. Excessive temperature is likely to produce a "backfire" (sometimes termed an "arc-back") due to the electronic emission from one or more anodes increasing to an appreciable value so that current passes from the cathode to the anode as well as in the—conventionally assumed—normal direction. Current may also pass directly between anodes, the effect of the positive space-charge being rapidly eliminated by the excessive electron emission. In both cases the backfire constitutes a short-circuit on the transformer, and generally, until the arc between anode and cathode is interrupted either internally or by opening the D.C. circuit, a short-circuit on the D.C. system if, of course, this is supplied from another source. Before the load circuit is opened D.C. will pass through the transformer and the fault kVA. to be interrupted by the high-voltage breaker will have a pronounced D.C. component. Should the D.C. circuit be opened first the internal short-circuit will persist either between anodes directly, or via the cathode pool.

The temperature of the anodes depends on the load current, and since the thermal capacity of the anodes is comparatively low, backfire will result if there is a high current density either over the whole anode surface due to excessive loading, or over a portion of it due to the concentration of current in one particular spot. Another cause of high temperature is a high pressure of mercury vapour either throughout the whole tank, or locally at a particular spot on the anode. The liability to backfire was at one time a disadvantage of the rectifier, but with modern units every precaution is taken to prevent this and performance characteristics at least as favourable as those of rotating convertors are obtained. Even if a backfire should occur it does not usually harm the unit in any way, and it can be put into service again immediately afterwards.

Main Features of Rectifier Units

The three main types of mercury-arc rectifier are : (*a*) glass-bulb air-cooled—Figs. 140 and 141 ; (*b*) steel-clad pumpless air-cooled—Figs. 142 and 143 ; (*c*) steel-tank water-cooled—Figs. 144 and 144A. Although differing in detail, all three types embody the same fundamental features. At the base of the rectifier chamber is a mercury pool. Mercury is used for the cathode because, while it readily vaporises, it can also be condensed and returned by gravity to the pool without loss of material ; and it is easily ionised. To start the rectifier it is necessary to produce a cathode spot by drawing an arc between the cathode and a small auxiliary anode, a process termed ignition. This initial ignition can be effected in various ways according to the type of rectifier, but the purpose is to inaugurate the electron emission essential to the rectifying action. In small glass-bulb units ignition may be obtained by making and breaking two parts of the cathode pool by tilting the whole bulb ; with larger units an ignition anode may be operated by means of an external solenoid (Fig. 141). Other types of rectifiers employ a central ignition anode (Figs. 143 and 144). Situated above the mercury pool, but below the main anodes, are the excitation anodes. These are provided because if the load current falls to a low value—less than one or two amperes in

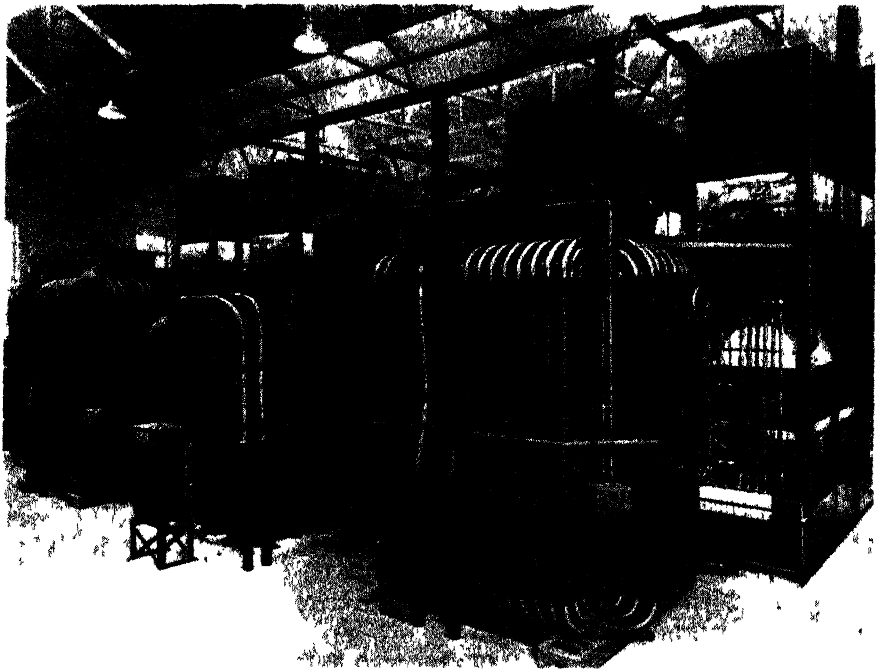


Fig. 140.—THE LARGEST GLASS BULB RECTIFIER SUBSTATION IN THE WORLD
Capacity 7,000 kW. at 500 volts D.C. (*Hewittic Electric Co , Ltd.*)

some cases—the arc from the main anodes will not maintain itself. The ignition anode may also be used for excitation if it is supplied from an auxiliary D.C. source, otherwise a set of two, three, or six excitation anodes is provided, energised from a tertiary winding on the main transformer; or a separate transformer. The excitation anodes maintain a current in a local circuit sufficient to keep the cathode spot in action. The temperature of the cathode spot is in the region of 3,000° C. Fig. 141 shows the excitation circuit of a glass-bulb unit—together with other detail—and it should be noted that the arrangement constitutes a simple two-anode rectifier which serves to keep a current flowing in the local circuits formed by the excitation anodes, cathode, and the transformer winding.

The main anodes are made of graphite or iron. Graphite is usually considered to be more suitable than iron, as with working temperatures of 400–600° C. impurities in the latter might lead to hot spots, backfire, and loss of vacuum. Some rectifiers have the anodes located at the end of side arms so as to protect the anode surfaces from the direct effect of the mercury vapour blast; with others sheet-metal anode shields are employed, and louvred apertures have been found very effective in reducing the tendency to backfire by minimising ionic bombardment during the negative half-cycles, when the positive ions are attracted to the anodes. Although the positive space-charge due to the ions is of value in preventing backfire between anodes, the impact of these on the anodes may produce electron emission from a hot spot.

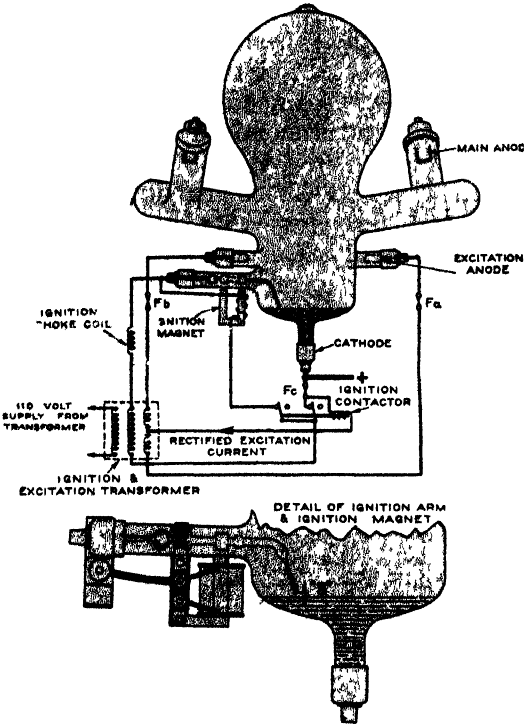


Fig. 141.—IGNITION AND EXCITATION CIRCUITS OF GLASS-BULB RECTIFIER

(*British Thomson-Houston Co., Ltd.*)

To assist in the prevention of backfires heavy-duty rectifiers have a special "grid" fitted in each anode shield, and located directly in the path between the anode and the cathode. When the anode is operating the grid will be at the potential of the arc and, therefore, at a lower potential than the anode, as there is a definite voltage drop at the anode surface. At the instant the arc goes out the grid will be at a negative potential with respect to the anode, and will attract positive ions during the short interval of time required for the anode itself to become negative. Thus the function of the grid is to accelerate the formation of the space-charge around the anode. Various shapes of grid are used, one of the most effective consisting of straight strips, usually made of graphite.

Cooling of the external surface of the chamber by air or water is necessary for the purpose of condensing the mercury vapour when it reaches the internal surfaces. The anodes and cathode pool are also cooled to keep the operating temperatures within safe limits.

Glass-bulb and certain steel-clad units are evacuated and then sealed off permanently; but with large steel-tank units this is not possible and pumps are employed to maintain the vacuum.

Glass-bulb Units

A limit to the capacity of a glass-bulb type of rectifier is set by the size of bulb that can be manufactured commercially. The limit is very approximately 600 amperes at 600 volts D.C. ; but glass-bulb units are conveniently and economically arranged in banks to give a parallel output of several thousand kW.

The bulb is so shaped that its dome forms a space in which mercury vapour can be condensed by the natural or forced air cooling ; and there may be three or six arms into which the anodes are sealed. The constructional features of the glass-bulb type are best appreciated by considering typical units.

Referring to the type shown in Fig. 141, the main anodes of these units are of graphite, grooved to assist the radiation of the heat developed in them, and mounted on stems made of the metal molybdenum. The stems are covered with glass, the coefficient of expansion of which enables it to be sealed to the metal without incurring any strain. The glass-covered stems are sealed into the glass of the anode arms, which are finally sealed on to the main bulb. In order to obtain as compactly as possible the spacing between the cathode and anodes necessary for the valve action of the rectifier, the anode arms on the bulb are bent at right angles. This shape also assists in preventing mercury from reaching the anodes. The construction of the excitation anodes is similar to that of the main anodes, but they are smaller, and are sealed into short straight glass arms located near the cathode (Fig. 141). The ignition anode (Fig. 141), which only operates during starting periods, is made of molybdenum wire coiled into a spring at one end. A small steel armature is mounted on this wire and is attracted downwards when the external electro-magnet is energised at starting, thus causing the ignition anode to dip into the mercury.

A number of cathode stems are sealed through the glass of the bulb in the same way as are the anode stems, so as to make contact permanently with the mercury.

A tertiary winding is usually arranged on the rectifier transformer to give the necessary supply for the rectifier auxiliaries. Referring to Fig. 141, the starting sequence of the type of unit shown is : (1) Ignition transformer unit made alive from tertiary winding ; (2) Current flows through ignition magnet. (3) Ignition anode is pulled down and dips in mercury, and, in doing so, ignition magnet coil is short-circuited ; (4) Ignition anode springs back and an arc is formed ; (5) Supply of ionised mercury vapour is produced and the excitation arc commences ; and (6) Excitation current operates contactor to disconnect ignition circuits. When the D.C. load circuit is closed the main anodes come into operation. A thermal relay is incorporated in the control circuit which functions to protect the bulb against sustained overloads below the setting of the circuit-breakers, and also serves to protect the bulb against overheating should the cooling fan fail. The relay is designed to have the same heating and cooling characteristics as the bulb. It is heated by the cathode current and cooled by the draught from the fan. The relay can be arranged to trip either the A.C. or D.C. circuit-breaker ; preferably the latter, for in that case if the trip is due to sustained overload the fan is left running to cool the bulb.

Automatic fan speed control can be adopted so as to vary the speed according to the load, thus economising power and maintaining the bulb at a more even temperature. The fan motor is fed through a three-phase saturable reactor which has an additional winding carrying the D.C. When the rectifier load is small, the reactor has sufficient impedance to absorb practically the whole of the voltage ; thus the fan motor does not then run, but when the load increases the D.C. winding saturates the core, thereby reducing the effective impedance in the motor circuit. At full load the reactor is completely saturated, so that the full voltage is applied to the fan motor which then runs at full speed. To simplify the arrangement, and avoid the necessity for any external heavy conductors, the reactor is mounted in the main transformer tank.

Pumpless Steel-clad Type

A unit which is generally similar to the glass-bulb type is the G.E.C. pumpless steel-clad rectifier shown in Figs. 142 and 143. This incorporates the advantageous features of both the glass-bulb and the steel-tank types—it does not require a pump but at the same time by using a special patent seal a steel container can be adopted, and furthermore, the unit can be effectively air cooled. The pumpless rectifier is of the side-arm type, its general arrangement being shown in Fig. 143.

The cylindrical main tank *A* forms the body of the rectifier, and it is enclosed within the cooling air ducting *B*. An insulating cylinder *U* supports the rectifier on its base-plate *T*. The mercury pool *E* at the bottom of the tank forms the positive pole of the

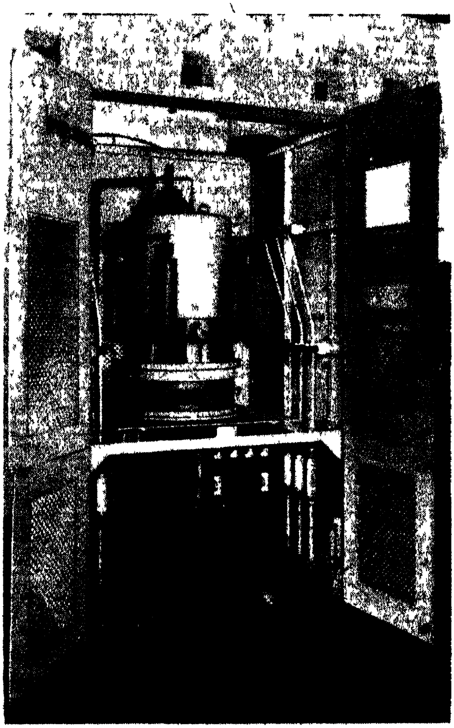


Fig. 142.—250 kW. 600 volts D.C. pumpless, air-cooled, steel-clad rectifier equipment (*General Electric Co., Ltd.*)

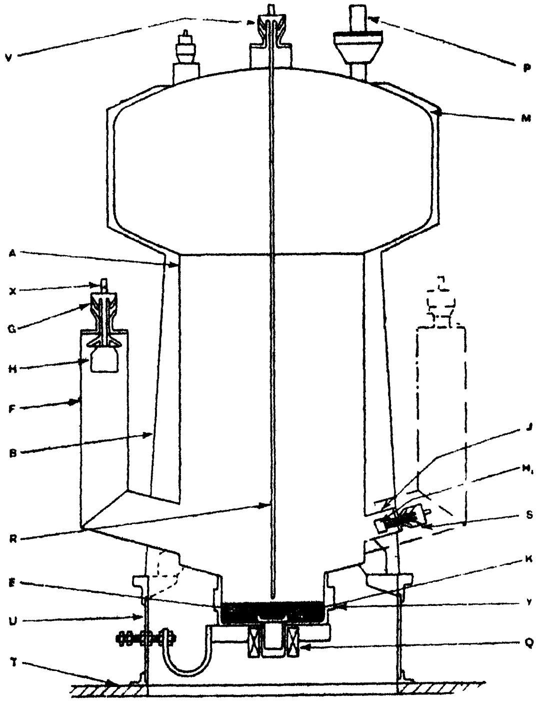


Fig. 143.—Diagrammatic arrangement of pumpless air-cooled rectifier. (*General Electric Co., Ltd.*)

D.C. supply. The side arms *F* welded to the main tank support their respective main anodes *H*, while the auxiliary anodes *H*1 are each mounted in the stub arms *J*. The upper portion of the cylinder, *M*, serves as a condensing dome for the mercury vapour and is partly enclosed by the cooling ducts.

On the exposed portion are mounted: the valve *P*, through which the rectifier is finally sealed off, and the lead-in insulator *V* for the ignition rod *R*. The side arm *F* is designed for the dual function of an anode shield, for preventing arc-backs, and a radiating surface for dissipating the heat generated at the anodes. Anode radiators can, therefore, be omitted, and connections made to the transformer by the terminal *X*.

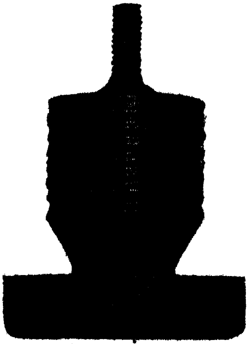


Fig. 143A.—G.E.C. patented vitric seal as embodied in anode of pumpless air-cooled rectifier

G.E.C. patented seals are used for the main anodes, the auxiliary anodes, and the cathode insulator; being located at *G*, *S*, and *Y* respectively. They are also used for the ignition anode insulator *V*, and for making the grid connections in grid-controlled rectifiers. The cooling air is supplied at a slight pressure from a fan located in a chamber below the rectifier (Fig. 142); it passes into the cooling space between the rectifier and the outer casing and is finally discharged through the opening at the top.

The patented vitric seal which is employed in the construction of G.E.C. pumpless units is shown in Fig. 143A. It consists of a number of thin mild steel cones separately coated with a special vitreous enamel. After assembly of the cones in the top and bottom members the whole is fused up solid in an electrically heated oven. The result is a unit having a high dielectric strength, and capable of maintaining an absolute vacuum.

To start the rectifier it is necessary that the anodes should be energised, and an electron-emitting region formed at the surface of the mercury cathode. On closing the O.C.B. of the transformer the required potential is applied to the anodes, and at the same time the ignition solenoid *Q* mounted external to the rectifier is energised so that the metal cup *K*, which is above the mercury surface before ignition, submerges, and the mercury trapped in the cup is brought out of contact with the starting anode *R*. As this breaks contact with the mercury an arc is formed, and electrons emitted from the cathode in sufficient quantity to enable the rectifier to start operating. The pumpless type of rectifier described above is made in sizes corresponding to a current range of 350–850 amperes for voltages up to 800. For voltages of 1,500 and 3,000, rectifiers of this type are available as single units giving an output of 1,000 and 1,500 kW.

Water-cooled Steel-tank Rectifiers

Rectifiers which operate under conditions where severe short-time overloading is experienced are usually of the water-cooled type. The main anodes are fitted vertically around the circumference of an annular plate in the centre of which is the dome of the steel tank. This is dished at the bottom to carry the insulated cathode

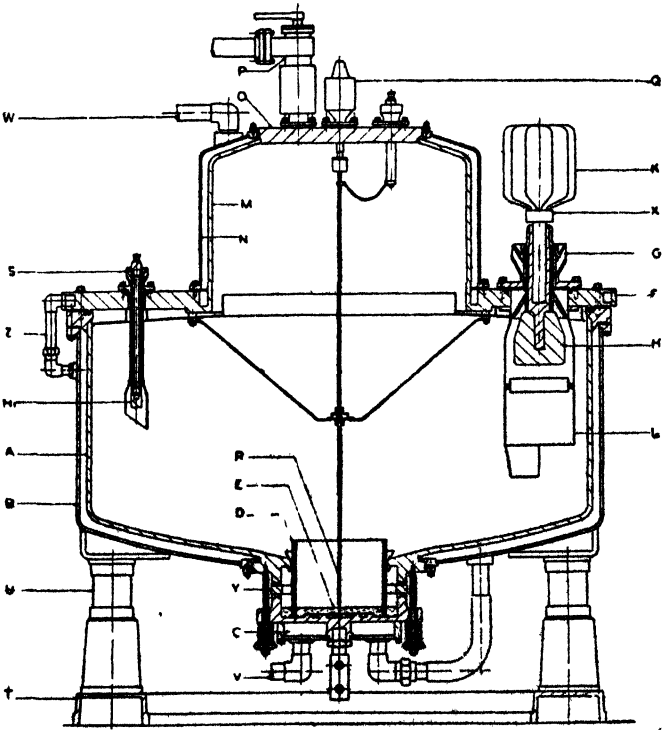


Fig. 144.—Constructional Features of Water-cooled Mercury-arc Rectifiers. (*General Electric Co., Ltd.*)

pool. The main chamber is water-jacketed, and is of welded steel-plate construction. Further cooling is provided by jacketing the anodes and by inserting cooling coils into the arc space. Alternatively, a jacketed condensing chamber may be carried on the anode plate to which the insulated anodes, with their connections, are fitted. As large rectifiers cannot be completely sealed off pumps are used to maintain the vacuum. In any case, even with perfectly tight seals, there is a gradual release of occluded gases from the walls of the steel-tank rectifier, which would in time seriously impair the vacuum. The pumping equipment usually consists of a combination of a rotary pump and a mercury diffusion pump. The latter is necessary since, although under ideal conditions it is possible to produce pressures as low as 0·1 mm. with the ordinary vacuum pump, it is still necessary to reduce the foreign gas pressures to 1 micron.

A typical water-cooled rectifier is illustrated in Figs. 144 and 144A. This type is made with six or twelve anodes and is intended for outputs of 1,000 amperes and upwards, with a working voltage up to 4,000. The main tank *A* is surrounded by a main water jacket *B*. Insulating columns *U* support the tank from the main base-plate *T*. At the bottom of the tank is the mercury pool cathode *E* in which is placed a quartz tube *D* which serves to maintain the arc in position. The cathode insulator with mercury seal is shown at *Y*.

The circular top-plate *F* is bolted to the main tank and carries the main anodes *H*, the auxiliary anodes *H*1, and the condensing cylinder with its surrounding water jacket *N*. The various units of the pumping equipment, which are shown diagrammatically in Fig. 144B, are secured to the tank. The ignition solenoid *Q*, and the valve *P* which connects the rectifier to the pumping equipment and the vacuum gauges, are mounted on the cover-plate *O* of the condensing cylinder. The anode is protected by a shield *L*, and the upper part of each anode stem is fitted with an air-cooled radiator *K* to facilitate the removal of heat generated at the anodes. The transformer secondary windings are connected to their respective anodes by means of the cable sockets *X*. The vacuum seals *G* and *S* are of the vitric type illustrated in Fig. 143A.

The water-cooling system is arranged so that the water first passes beneath the cathode pool, entering at *V*, and is then conducted by way of rubber hose to the bottom of the main water jacket *B*. Passing through the water jacket it enters the top-plate by a pipe connection *Z* and is led to the bottom of the condensing water jacket by means of radial holes in the top-plate. The water is finally discharged from the pipe *W* situated near the upper part of the condensing chamber.

If it is necessary to open the rectifier for any reason, by removing the top-plate bolts, the whole plate together with the vacuum pumping equipment can be lifted as one unit. The water jackets can be removed for cleaning and painting without breaking any vacuum joint.

The rectifier is started by closing the O.C.B., thus applying voltage

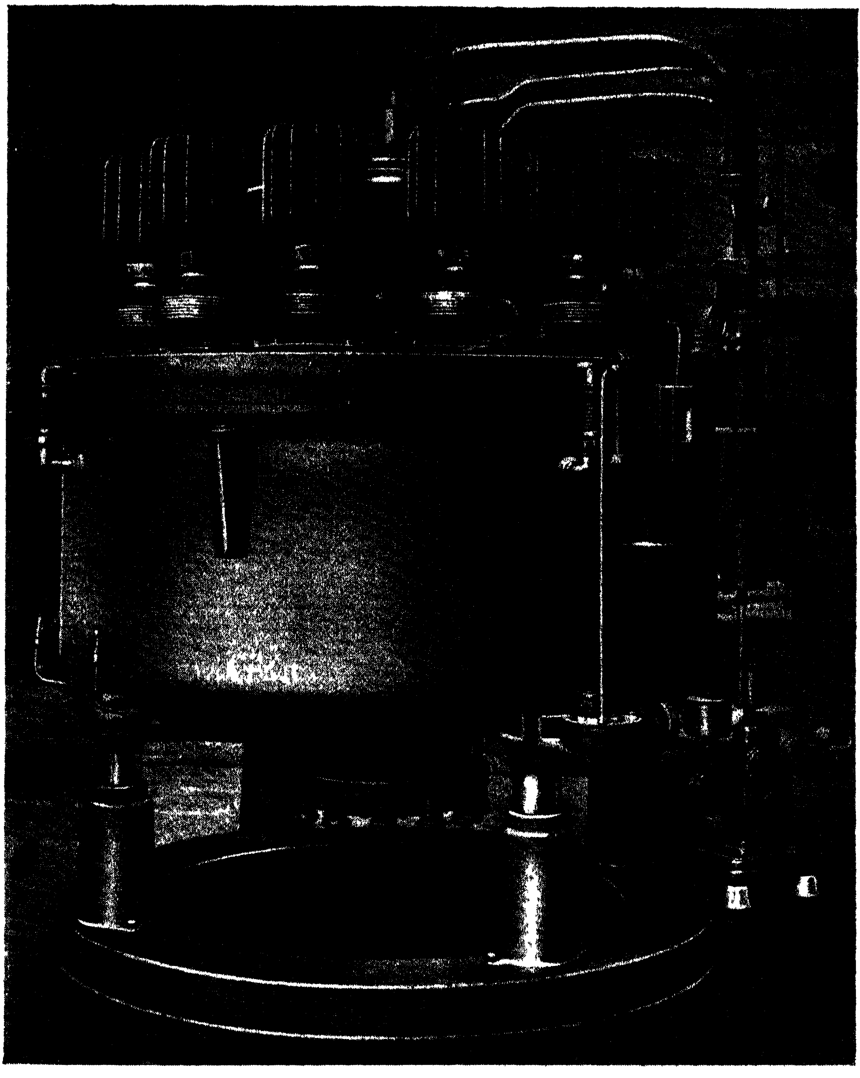


Fig. 144A.—Water-cooled mercury-arc rectifier, 1,200 kW., 630 volts (*General Electric Co., Ltd.*)

to the anodes. At the same time the solenoid Q is energised so that the starting anode R dips into the mercury pool E. As the starting anode is withdrawn an arc is struck and the unit comes into operation.

Vacuum Pumping Equipment

With the rectifier described above the vacuum pumping equipment shown diagrammatically in Fig. 144B is used. A similar combination of apparatus is generally used for most water-cooled steel-tank units. The mercury pump consists of a co-axial arrangement of nozzles, several stages in series being used to increase the range of pressure over which the pump will operate. As this pump cannot discharge against atmospheric pressure the oil-sealed rotary " backing " pump is also required. In the mercury pump mercury is boiled by a small electric heater, and the vapour resulting passes through the nozzles where it picks up air and gases from the rectifier. After each stage the vapour then passes into water-cooled chambers where it is condensed and returned to the boiler while the gases pass on to the next stage of the pump, or finally, to the discharge pipe.

The duty of the rotary pump is light, and by using an air receiver or " interstage " reservoir connected to the outlet of the mercury pump the backing pump is only required to operate for a few minutes each day. This arrangement necessitates a non-return valve of the barometric type between the interstage reservoir and the backing pump, and also an electrically operated air inlet valve to admit atmospheric pressure to the suction side of the backing pump when it is shut down. This obviates the possibility of oil vapour being drawn into the system from the pump.

For indicating the degree of vacuum and for operating vacuum relays associated with certain automatic control features of the water-cooled rectifier, gauges of the Pirani type are employed. This type of gauge, which is based on the Wheatstone bridge method of measurement and indicates the pressure in terms of the thermal conductivity of the residual gases, depends for its action on the dissipation of heat from a fine resistance wire heated by a current at constant potential. The heat dissipated is determined by the density of the gaseous medium surrounding it. Thus, the lower the foreign gas pressure the better will be the vacuum and the lower will be the dissipation of heat from the wire. The temperature of the wire will, therefore, depend on the degree of vacuum. Since the resistance of the wire increases with temperature, and the wire forms one arm of a Wheatstone bridge, the out-of-balance current flowing is made to indicate the degree of vacuum by connecting in the bridge circuit a milliammeter calibrated in microns (1 micron = 0·001 mm. of mercury).

Methods of Water-cooling

When a plentiful supply of water, free from excessive impurity or hardness is available, the rectifier may be cooled by passing the water through

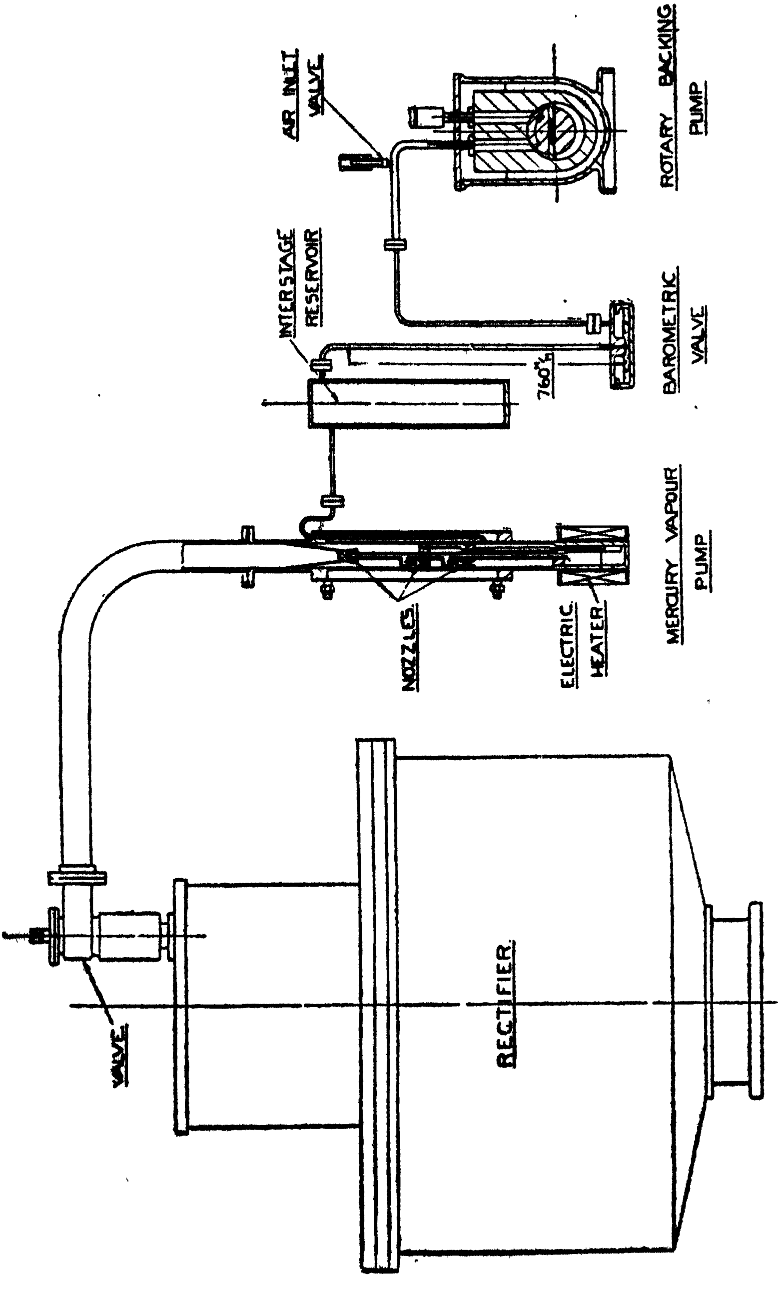


Fig. 144B.—DIAGRAMMATIC ARRANGEMENT OF VACUUM PUMPING EQUIPMENT FOR MERCURY-ARC RECTIFIER

(General Electric Co., Ltd.)

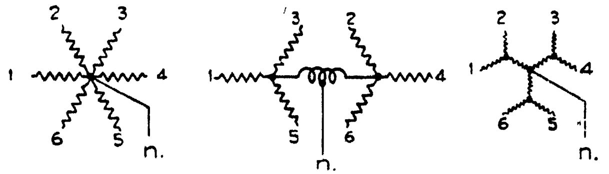
its jacket and then to waste. If this is not practicable an air-blast recooler is generally adopted. This consists of a suitably proportioned radiator through which air is blown by a fan, and a small pump for circulating the water continuously. Whichever system is used a thermostatically-operated valve is required to regulate the rate of water flow and so maintain the rectifier at the correct working temperature.

The jacket of the mercury-vapour pump must be provided with a separate system since it must operate whether the rectifier is on or off load. When a continuous supply of suitable cooling water is available this may be passed through the jacket to waste, but in general a closed system is to be preferred. This may take the form of a small air-blast cooler or a larger naturally air-cooled radiator.

Transformer Connections

For multi-anode rectifiers there are several arrangements of L.V. transformer windings and connections in use, three of which are shown in Fig. 145. With large-capacity rectifiers the number of anodes is often determined by the necessity to limit the fraction of a cycle during which each conducts, so as to avoid excessive heating. A large number of anodes requires a corresponding number of phases on the transformer, but since each phase conducts for only $1/N$ of a cycle (where N is the number of anodes) a large value of N will, for a given output, necessitate a transformer of uneconomic dimensions. For instance, with the simple six-phase connection each phase will carry anode current for a sixth of a cycle ; but the heating of a conductor which carries the anode current for a sixth of a cycle and zero current for the rest of the time is six times as great as that of a conductor carrying a continuous current of one-sixth the anode current value. (This is because the heat produced in a conductor is proportional to I^2R.) Thus the cross-section of the conductors must be such as will carry the anode current without excessive heating, but to avoid this the copper is idle for the greater part of the time.

Rectifiers for comparatively small outputs usually have three anodes supplied from a three-phase star-connected secondary winding, which permits a more efficient transformer utilisation. This is the simplest three-phase connection, but it suffers from the disadvantage



Simple six-phase. Six-phase double star. Six-phase fork

Fig. 145.—TRANSFORMER SECONDARY CONNECTIONS FOR OBTAINING SIX-PHASE RECTIFICATION

(*British Thomson-Houston Co., Ltd.*)

that D.C. magnetisation of the core occurs. To eliminate this the three-phase interstar connection is used. The simple six-phase connection, Fig. 145, does not employ the copper economically since each phase operates for only one-sixth of a cycle. The six-phase double-star connection with interphase transformer, Figs. 145 and 146, is very much used because by means of this arrangement the smooth output of the six-anode rectifier can be combined with the more efficient transformer utilisation of the three-anode unit. By dividing the six phases into two groups of three and joining the two star points through a phase-equalising reactor, or interphase transformer, this has the effect of spreading the duration of each anode current to one-third of a cycle. At any instant one anode of one group, and one of the other group, are in parallel operation so that the output voltage is the mean of the respective transformer phase-voltages. As each anode carries only half the output current, and does so for one-third of each cycle, the transformer secondary windings are smaller, for a given output, than those of the simple six-phase and six-phase fork arrangements shown in Fig. 145.

Interphase Transformer

The principle of operation of the interphase transformer is briefly as follows. Referring to Fig. 146, at some particular instant anodes 1 and 2 are operating in parallel and sharing the load equally. In this case their anode potentials must be equal, but, ignoring for the moment the effect of the interphase transformer and considering only the voltage induced in each secondary phase by the primary of the main transformer, as the voltage in phase 2 lags one-sixth of a cycle behind that in phase 1, when both phases are approaching their maximum positive value, the voltage derived from the main transformer and applied to anode 1 is greater than that derived similarly and applied to anode 2. Consequently, there is a tendency for more of the load current to flow through the circuit, including anode 1 and the interphase transformer winding N-$N1$, than through the circuit including anode 2 and the winding N-$N2$. The effect of this is to

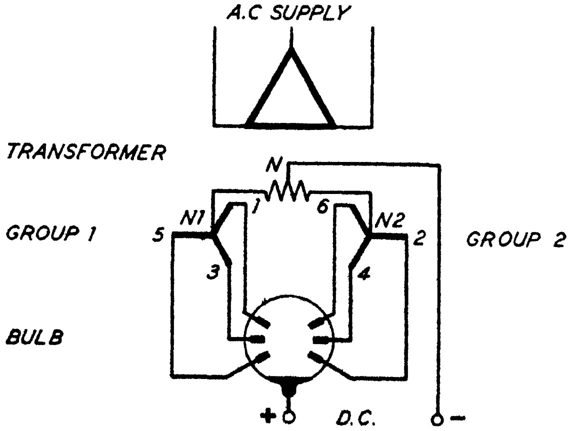


Fig. 146.—THREE-SIX-PHASE, PRIMARY DELTA, SECONDARY DOUBLE STAR WITH INTERPHASE TRANSFORMER

create a flux, in the core of the interphase transformer, which induces a voltage in N-$N2$ in such a direction as to reduce the voltage of phase 1, and increase the voltage of phase 2, by equal amounts. When the induced voltage of phase 2 becomes the greater, as that of phase 1 approaches zero, the current through anode 2 tends to increase and the effect of the interphase transformer is to reduce the voltage of phase 2 and increase that of phase 1. As the voltage in phase 1 diminishes that in phase 3 rises, so that when anodes 1 and 3 have equal potentials the latter takes over the load in parallel with anode 2—and similarly with the other anodes in succession. The interphase transformer is not, of course, able to equalise the potentials of anodes in the same group ; thus successive anodes of the two groups are made to work in parallel all the time. The voltage across the interphase transformer is at a frequency three times the fundamental, and of triangular wave-form. The magnetising current, also of triple frequency, flows through the closed circuit consisting of the two parallel anodes, and is superimposed on the load current. When no load current is flowing the triple frequency magnetising current cannot flow, due to the valve action of the rectifier, and for the full magnetising current to flow the load current must be at least equal in amplitude. Until this value of load current is reached the interphase transformer acts as an additional reactance in the anode circuits, which causes a high regulation, of approximately 15 per cent. in the case of the six-phase rectifier, from no load to very low load. This high regulation may be undesirable, but it can, however, be overcome by connecting a permanent load across the rectifier so that the full value of magnetising current is always flowing in the interphase transformer. The required load is generally of the order of 1 to 2 per cent. of full load. Another way of achieving this object is by supplying the triple frequency current from an external source. A third method, in six-phase units, is to disconnect one three-phase group and operate with one three-phase group only on light loads. A twelve-phase connection with three interphase transformers is sometimes used. The six-phase fork connection shown in Fig. 145 is frequently employed with six-anode rectifiers, as it avoids the high regulation associated with the use of an interphase transformer. Each branch carries current for one-sixth of a cycle, and the star for one-third of a cycle.

Grid-controlled Rectifiers

The anode shields of some mercury-arc rectifiers incorporate a de-ionising grid, the principle of which has already been discussed. A development of this form of grid is the controlled grid, which is fitted to certain types of rectifier for the purpose of regulating the ignition of the main anodes. This additional grid is similar to the normal grid, but is insulated from the anode shield so that a potential can be applied from an external source. The grid can be positively or negatively charged as required, and the value of the potential, and the instant at which it is applied, varied. By this means the striking of the arc from each main anode can be advanced or retarded, or entirely prevented. The controlling characteristic of the charged grid is utilised, in the grid-controlled rectifier, for several purposes, the most important in connection with the present discussion being : D.C. voltage regulation, suppression of fault currents, and inversion of direct into alternating current.

The principle of grid control will be understood by considering the physical aspects of its application. When no potential is applied to the grid, electrons emitted from the cathode will simply pass through the holes in the grid on their way to the anode, and the normal operation of the rectifier is not affected. If the grid has a negative potential applied to it the electrons will be repelled and, thereby, be prevented from reaching the anode when it is positive, consequently no current will flow. (When the anode is negative the electrons are, of course, repelled irrespective of the grid potential.) Current flow through the rectifier can thus be prevented by the application of a sufficient negative potential or bias. By making the potential of the grid negative before the start of the positive half-cycle of anode voltage it becomes possible to prevent the arc striking until the negative bias is removed, or a positive bias is applied. Thus the instant at which the anode begins to conduct can be controlled by providing some means of adjusting grid bias at the desired instant. Negative bias must be applied before the arc strikes, otherwise once the current has started to flow the positive ions present will be attracted towards the grid and effectually neutralise its negative potential so that it can have no effect.

From the above : the effect of the grid being at negative potential is to reduce or neutralise the effective positive potential of the anodes ; consequently by applying sufficient negative bias, ignition, or re-ignition after extinction, can be prevented or the instant of ignition controlled. The control grid may be connected to a source of negative D.C. potential which persists except when a positive debiasing potential is applied ; or may be normally neutral, and negatively charged only at the appropriate instant. Impulsive grid-bias potential is applied in the form of a steep-fronted wave.

The grid-controlled rectifier is of normal construction except for the extra insulated grid located in front of each anode ; but special equipment is required for applying and timing the biasing potentials.

Control of Grid Potential

Various methods of effecting grid control have been devised, among which the most practicable are : (*a*) those using synchronously-rotating mechanical parts, such as commutators or contact makers ; (*b*) those employing saturated transformers or similar devices for producing a peaky wave. One form of synchronous rotating device (Fig. 147) con-

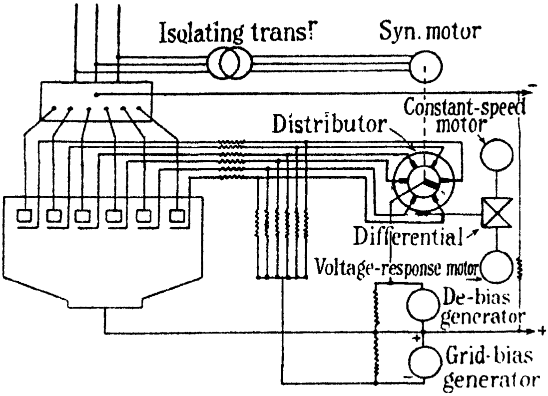


Fig. 147.—GRID-CONTROL CIRCUIT USING SYNCHRONOUS DISTRIBUTOR AND VOLTAGE-REGULATOR DIFFERENTIAL (*Journal I.E.E.*)

sists of a small commutator with brushes each of which is connected to a grid. The commutator has two diametrically-spaced live segments supplied from a debias generator; the remainder of the segments are idle and simply serve to avoid uneven wear. The commutator is driven by a synchronous motor; and the brushes are capable of being rocked relative to the commutator. A grid-bias generator supplies a steady D.C. negative potential to the grids, grid control being effected by the application of debiasing positive potential at an instant determined by the position of the brushes; consequently the striking of the arc can be advanced or retarded by brush-rocking.

This arrangement is used for voltage regulation; for normal voltage the striking of the arc is slightly retarded; to increase the D.C. voltage it must be advanced, and to decrease the voltage the striking of the arc must be further retarded. The effect of controlling the instant of ignition is to vary the period of overlap, and by this means regulate the effective mean D.C. voltage available. Level compounding can be achieved by making the device responsive to a voltage-regulating relay, but for parallel running and inverted working electrical or mechanical differentials are used. Fig. 147 shows a differential scheme in which the position of the brushes relative to the commutator is controlled by the momentary difference in speed between a constant-speed motor and a voltage-response motor. The speeds of these two motors are normally equal so that the brushes remain in one position, but with a change in output voltage the speed of the voltage-response motor alters, and the brush position is adjusted by the action of the differential until the regulation of the output voltage makes the speeds of the motors equal again.

This method of adjusting the brushes has proved more convenient than adjusting the synchronous position of the commutators because of the low inertia of the brushgear; the slight friction is also sufficient to prevent hunting. A steady negative bias of about 100 volts and positive peaks up to 300 volts are used.

A grid-control circuit using a peaked transformer is shown in Fig. 148. The transformer is specially designed to have a wave-form which enables the desired value of grid-potential to be applied at the appropriate instant. When used for voltage regulation some means of adjusting the phase of the voltage impulse to give the requisite variation of the ignition instant is necessary. The scheme shown in Fig. 148 employs a phase-shifting transformer in series with the winding of the wave-peaking transformer. The rotation of the phase-shifting transformer is achieved by means of a direct current spring-opposed torque motor whose armature is supplied at constant voltage while its field carries some given amount of the output current of the rectifier. Any desired characteristic can be arranged by rheostats connected in series with the motor armature, whilst further flexibility is also possible with the aid of additional shunt windings and screw adjustments. Owing to the inertia of the moving parts there is a practical limit to the speed of response of this arrangement, and to prevent hunting the control elements need to be suitably damped. Several variations of the scheme are possible.

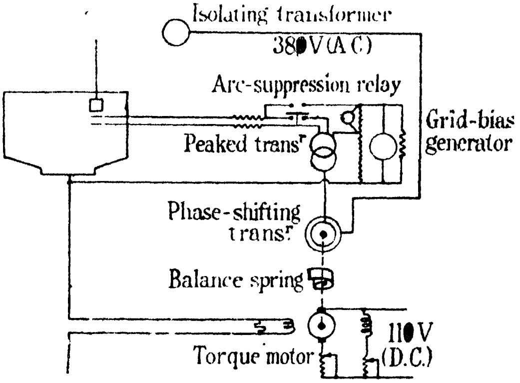


Fig. 148.- GRID-CONTROL CIRCUIT (SHOWN IN SIMPLIFIED FORM) USING PEAKED TRANSFORMER AND TORQUE MOTOR. (*Journal I.E.E.*)

Arc Suppression

Fig. 148 also shows the application of grid control for arc suppression. In this case, with the occurrence of a backfire or a short-circuit negative bias has to be rapidly applied to the grid, so that once the arc has extinguished it is prevented from restriking by the negatively-biased grid between the anode and the cathode. By this means, in the event of a backfire the electrons emitted from an anode cannot pass to the cathode or another anode. With a D.C. short-circuit the electrons from the cathode are prevented from reaching the anode. To attain the high speed of fault clearance possible with grid control entails the use of a high-speed relay, generally in the form of a miniature high-speed contactor, which can be designed to operate in about 2 milliseconds. An alternative method of control applied successfully employs thermionic devices of the gas-filled relay type, which are almost instantaneous in action.

Although arc suppression is becoming a common feature of mercury-arc rectifiers, in the event of a heavy D.C. feedback the A.C. wave with respect to one anode may be completely asymmetrical, in which case interruption has to be effected with a high-speed circuit-breaker.

Inverted Operation

When a rectifier operates for the inversion of D.C. to A.C. the positive of the D.C. supply is connected to the neutral point of the transformer low-voltage winding. The current still flows through the rectifier in the same direction, and it is made to flow by the D.C. voltage impressed against the back E.M.F. which is induced in the L.V. winding by another winding connected to an A.C. supply. This arrangement is necessary for wave-forming, and for determining the frequency of the A.C. voltage.

The function of the grid control is to regulate the transference of the arc from one anode to the next at the appropriate instant, and to prevent the striking of an arc from those anodes connected to phases in which, during one half of each cycle, the induced A.C. voltage is not opposing the applied D.C. voltage. By this means the arcs are struck from successive anodes in correct sequence and a true A.C. output obtained.

A disadvantage of the inverted rectifier is that it injects A.C. at a leading power factor into the A.C. system, consequently its usefulness is practically confined to regenerative braking in traction and rolling-mill operation. In these circumstances, as the transformer primary winding is normally connected to an A.C. supply during inverted operation, the back E.M.F. required in the secondary for wave-forming is the normal secondary voltage induced by the primary. To enable a rectifier to be used for both forward or inverted operation it is necessary to be able to either reverse the connections, i.e. to connect the positive of the D.C. system to the cathode or the transformer neutral, and oppositely in the case of the D.C. negative. When rectifiers are employed on traction systems utilising regenerative braking it is not possible to change over the polarity of the rectifier instantaneously so as to permit D.C. to be fed back at frequent intervals ; and the most suitable arrangement is to have a second rectifier permanently connected with reverse polarity across the D.C. system, to deal with the regenerated current.

Elimination of Harmonics

Due to the nature of the rectification process the D.C. output of a rectifier is not perfectly smooth, but contains a ripple or periodic variation which depends on the number of anodes and the A.C. frequency. In consequence harmonic frequencies are present which, being in the audible range, will cause interference in communication circuits if these are adjacent to circuits supplied by the rectifier. In cases where it is necessary to reduce the inductive effect of the harmonics, resonant shunts, or harmonic filters, are connected across the output terminals. A resonant shunt is made up of an inductance and capacitance in series. By this means the circuit is tuned for a particular frequency, and offers negligible impedance to the passage of current at the corresponding harmonic voltage. Thus, local circuits are provided for the principal harmonics, which are thereby eliminated from the D.C. system.

Chapter XIV

PREVENTION OF ELECTRICAL FAULTS

IN recent years considerable attention has been given to the prevention of faults apart from the development of gear for their rapid and successful interruption. The probability of faults occurring has been lessened by the elimination of defects in design and the use of improved insulating materials, so that nowadays units are less vulnerable to electrical and mechanical damage. Furthermore, apparatus has been developed for safeguarding certain units of equipment by limiting the stresses that can be applied to them. Some progress has also been made in the detection of incipient faults by periodical insulation tests, thus enabling units or circuits to be taken out of commission before a fault develops, with a consequent avoidance of damage and possible interruption to supply.

B.S.I. Classification of Insulating Materials

The various basic materials used for the manufacture of commercial insulations are classified by the British Standards Institution as follows :

Class O.—Cotton, silk, paper and similar organic materials when neither impregnated nor immersed in oil.

Class A.—Cotton, silk, paper and similar organic materials when impregnated or immersed in oil; also enamelled wire.

(An insulation is considered to be " impregnated " when a suitable substance replaces the air between its fibres, even if this substance does not completely fill the spaces between the insulated conductors. An impregnating substance must have good insulating properties, and must entirely cover the fibres and make them adherent to each other and to the conductor. Furthermore, it must not produce interstices within itself as a consequence of the evaporation of the solvent or through any other cause ; and must not flow at the temperature limit specified, or deteriorate at any excessive rate under prolonged action of heat.)

Class B.—Mica and asbestos and similar inorganic materials, in built-up form combined with binding cement. If Class A material is used in small quantities for structural purposes only, in conjunction with Class B insulation, the combined material may be considered as Class B, provided the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class B material.

Class C.—Mica without binding cement ; porcelain, glass, quartz and other similar materials.

Class D.—Synthetic-resin-impregnated coils.

In practice insulations are either one of the classified materials or frequently a combination of two or more ; thus the maximum permissible temperature in the latter case is that of the material whose properties are more readily affected by heat. Electrical equipment mainly incorporates the A and B classes of insulation, and excluding certain cases, the permissible temperature rise above ambient temperature is not greater than 55° C. and 75–80° C. respectively. For high-voltage oil-immersed equipment the basic materials are the fibrous substances of Class O which readily absorb oil, or varnish, and thus become Class A materials. They are manufactured in various forms.

Fabricated Class A Insulations

For high-voltage insulation the present tendency is towards the increasing use of untreated paper for the manufacture of tapes, boards, etc., which are oil-immersed and not subject to certain kinds of mechanical stress. When good mechanical properties are required in board, rod, and tube insulations these forms are fabricated from synthetic-resin-impregnated and coated papers and fabrics. Packs of prepared sheets are made into boards by subjecting them to heat and pressure. Tubes are formed by rolling the prepared sheets round a mandrel under heat and finishing off by stoving until the resin is transformed. Denser and more satisfactory tubes are made by compressing the roll while still in the mould to the exact size required, although tubes over about 8 in. diameter are usually only rolled to obviate the expense of the large moulds necessary. Paper is usually employed as the base material on account of the high electric strength obtainable, whereas with synthetic-resin bonded-fabric material this is much lower ; but as the mechanical properties of the latter are superior it is used for moderate insulation requirements. Improvements have, however, been made recently in the electrical characteristics of fabric-base material as the result of the demand, in connection with transformer and switchgear construction, for example, for a material having a higher impact strength than paper-base insulation. The improved fabric-base material has a minimum electric strength of rather less than half that of paper-base material.

The phenol formaldehyde (bakelite) class of resins are principally employed in practice for the impregnation of the basic materials used for the manufacture of laminated insulations. Bakelite resin is made by chemical reaction from phenol (carbolic acid) and formaldehyde (wood distillation product), and is dissolved in methylated spirit for application to materials either by coating or treating machines. Aniline-formaldehyde resins as developed commercially possess superior electrical and mechanical properties and are used for the fabrication of paper-base material (Panilax) in which the resin and fibre pulp are chemically united instead of the paper being impregnated or coated in the usual way. The electric strength of board pressed from this special paper is high, particularly in the direction of the paper layers, and the greater freedom from tracking compared with bakelised paper is noteworthy.

When used in air it is necessary that synthetic-resin-bonded materials should have a low moisture-absorption value ; but this is determined by the relative quantities of resin and base, which also influence the mechanical and electrical properties. Thus, the greatest moisture resistance is obtained with material containing a maximum of bakelite resin, but the low mechanical strength and inferior electrical properties of such material are not acceptable, and normally a resin content of 30 to 70 per cent. is used according to the predominating characteristics required.

Moulded bakelite is also used for insulation components. Resin in syrup form is intimately mixed with a filler, e.g. wood flour, to produce powders suitable for moulding. The application of heat with or without pressure causes the resin to change from complete fusibility and solubility to fusibility only, and finally inertness. The resin itself has a working temperature up to 110° C.

Other well-known forms of Class A insulating papers and cloths are made by the treatment of Class O materials with drying oils of the linseed-oil type to which natural gums and other ingredients are added.

Various materials containing rubber are by virtue of their thermal capacity Class A insulations, but, due to their comparatively low dielectric strength, they are, in general, used only for low- and medium-voltage applications.

Class B Insulations

Among the Class B materials is mica which has for many years been used in built-up forms for electrical equipment ; notably rotating machinery. Raw mica in sheet or slab form is actually a Class C material, and it is the splittings that accumulate when the rough mica from the mine is dressed and trimmed which are used for Class B mica insulations. These splittings, which were originally considered unsaleable, are built-up with shellac and other varnishes to produce micanite. This material, when first produced at the end of the last century, gave the electrical industry an insulation that could be made in sheets larger than those obtainable with natural mica. Moreover, it can be readily formed to the various shapes needed to cover conductors. The splittings, which are about 0·001 in. thick, are laid by hand or machine in overlapping layers to the required thickness, varnish or a powdered binder being simultaneously applied. By heating and pressing sheets are formed which can be hard and rigid, suitable for hot moulding, or completely flexible according to the amount and type of bonding. Other forms of micanite for wrapping purposes are composed of splittings and binder on backings of fabric, silk, or paper.

Micanite, once used extensively for the insulation of transformer windings and later replaced by cheaper and more adaptable materials, has recently once again proved its outstanding suitability for this purpose when found to be the only satisfactory insulation for the transformer windings of the Boulder Dam electrification scheme operating at the extraordinarily high voltage of 287 kV.

Asbestos products are used to a limited extent, but their poor electrical characteristics make them available for low-voltage insulation only. Glass in the solid form, and specially toughened, is now being used for certain types of insulator. Developments in the past few years have made it available in a new form which promises to establish glass products as high-quality Class B insulations.

From special glass, fibres of about 0·00025 in. diameter are drawn and spun into threads, which can be used for wire coverings or woven into cloth, tape, or sleeving. Although the glass itself possesses good electrical properties, the fabrics by their open structure have defects which are overcome by the use of suitable treating varnishes. In order to take full advantage of the excellent thermal characteristics of the glass much research has been in progress by varnish manufacturers to find an impregnant possessing high-temperature resistance. Some success has been achieved and treated glass products have been made which can be used under exceptionally severe operating conditions. Treated cloths and tapes are made in the standard thicknesses used for varnished cambrics. Other products such as synthetic-resin-bonded glass board; and combination materials incorporating micanite and glass fabric are also obtainable.

Among the Class C materials the most important—in connection with the present discussion—is porcelain, which is an insulation used almost exclusively when a dielectric capable of withstanding all weather and atmospheric conditions is required. A synthetic material has not yet been found which could supersede porcelain for outdoor service, but synthetic insulations, due to their greater toughness, accuracy in dimensions, and general suitability for machining have, however, replaced porcelain for insulating parts not exposed to the weather.

Treated Wood

Certain well-seasoned woods free from moisture are frequently employed as insulating members in electrical equipment because of their excellent mechanical properties. In order to prevent re-absorption of moisture wood must be impregnated either with oils or, still better, with appropriate synthetic resins. Considerable progress has been made in this direction, and nowadays, by a vacuum process, the liquid resinous compound enters the interstices of the cellular structure and by heat treatment the resin is polymerised, cementing the structure into an inert body of improved mechanical and electrical properties. Greater homogeneity of the material is attained by impregnating thin layers (veneers) of wood and bonding them together in hydraulic presses, the platens of which can be heated and cooled. Experience in recent years has indicated that the thinner the laminations are the higher will be the mechanical strength of the bonded plywood, but the cost of production also increases. New attempts to densify solid impregnated timber have recently produced a homogeneous material known as "Tensovic," which is claimed to be free from cracks and to have a tensile strength of over 30,000 lb./sq. in. coupled with good electrical properties.

Wood, in the form of pulp, is largely used for the manufacture of electrical papers. Chemical wood pulp stock, known as "kraft," is gradually replacing the more expensive rag papers made from linen, cotton, flax, etc., for the manufacture of synthetic-varnish-treated laminated materials.

Air-insulated Components

Air is, of course, a dielectric medium which is extensively employed between conductors or contacts supported by solid insulators. The use of air as an ambient dielectric for circuit-breakers has been discussed in previous chapters where the present tendency towards its adoption for high-capacity breakers up to about 15 kV. was pointed out. Air is also used between the busbars, connections, etc., of truck and cubicle-type switchgear up to about 11 kV., in conjunction with oil circuit-breakers. The objection to indoor air-insulated conductors at the higher voltages is the large spacings required to prevent flashovers due to ionisation of the air space by static discharges. In addition there is the danger of accidental faults resulting from the ingress of water or vermin, and the risk of personnel coming into contact with exposed conductors. Furthermore, air offers no support to the conductors during periods when they are carrying short-circuit current, consequently there is always the danger of the excessive electro-dynamic forces between conductors fracturing supporting insulators, in which case an internal fault may arise. For these reasons indoor air-insulated conductors are, in general, used only where adequate spacing can be provided, atmospheric conditions are favourable, and the maximum short-circuit current is limited.

A detailed account of the applications of the various insulations is outside the scope of this book, but in the following pages the subject is discussed generally with special reference to the problem of the prevention of electrical failures.

Machine Windings

The insulation of low-voltage machines is a combination of Class A and Class B materials, the former consisting of Class [illegible] materials treated with suitable varnishes. For large conductors cotton covering has been established practice for many years. Considerable attention has been devoted to the production of the correct type of impregnating varnish. The impregnation or dipping of armature coils and the heat treatment that follows is a process requiring care if varnish " throwing " and similar troubles are to be avoided. A recent tendency is to use an oleo-synthetic resin impregnant avoiding solvent, the resulting product having better penetration without spaces and possessing toughness rather than hardness.

Armature and stator slot linings are diverse in character, individual manufacturers using materials which their methods and experience dictate. Invariably the lining against the core punchings is a tough sheet insulation such as leatheroid or presspaper. The wrapping for the coil sides is usually varnished cloth, but flexible micanite combination materials such as mica cloth and the like are much in favour.

Taping of the end portions is done with half-overlapping layers of seamless bias varnish tape. The wedging of the coils in position is now done with wedges made from bakelite board.

Field coils are normally former wound with cotton-covered wire, and after thoroughly drying are impregnated with an asphaltum compound. The coil is then finally insulated with " Empire " cloth and tape, over which a finishing varnish is applied. The poles are sheathed with treated pressboard, and end washers of fibre or bakelite board are used when finally assembling the coil in position.

Mica and micanite are exclusively employed for commutators, and have, despite attempts at replacement, remained supreme. Mica is also used for insulating slip rings.

High-voltage A.C. machines are insulated with materials specially selected for the class of service to which they are applied, since such machines may have to withstand severe mechanical stresses ; as, for instance, when they are operated in connection with certain types of steel-works' drives.

Outdoor Bushings

Equipment operating at the higher voltages is usually filled with a fluid, semi-fluid, or solid-setting medium for the purpose of excluding air, but in the case of units connected to overhead lines it is not possible to avoid using air as an ambient dielectric medium between the terminal insulators. In this connection mention should be made of the rapid progress effected in the design and manufacture of high-voltage bushing-insulators since the inauguration of the National Grid, which necessitated the use of 132 kV. bushings, whereas before this bushings, and insulations in general, were seldom required in this country for more than 33 kV.

Terminal bushings are important components of most outdoor-type high-voltage transformers, switchgear, and other apparatus ; but they are also most vulnerable components of such equipment, being liable to

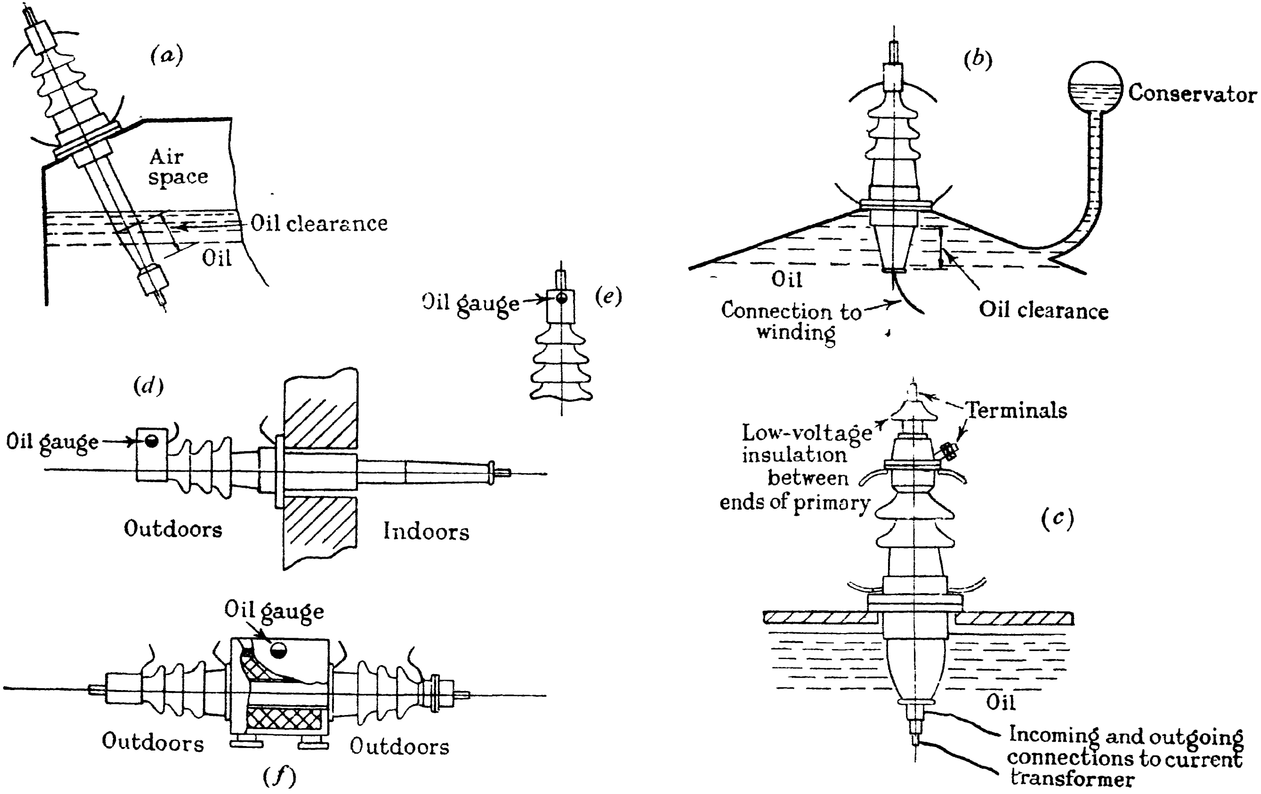


Fig. 149.—APPLICATIONS OF OUTDOOR BUSHINGS

(*a*) Oil circuit-breaker bushing.
(*b*) Power-transformer bushing.
(*c*) Multi-turn current-transformer bushing.
(*d*) Wall bushing.
(*e*) Roof bushing [otherwise as (*d*)].
(*f*) Straight-through current-transformer bushing.

(*Journal I.E.E.*)

mechanical damage as well as to electrical breakdown due to overvoltages or atmospheric pollution of the exposed surfaces ; in consequence, a high standard of performance is required to avoid faults. The principal purposes for which outdoor bushings are used will be appreciated by reference to Fig. 149 ; and various other illustrations throughout the book.

An outdoor bushing is a piece of apparatus which insulates a conductor passing through an earthed barrier, one end at least being exposed to weather conditions without cover. Up to about 11 kV. bushings are made of porcelain or glass throughout, but above this, although protection from weather is almost invariably secured by a porcelain or other ceramic insulating shell with weather sheds, various solid or fluid insulations are disposed between the conductor and the earthed flange. The external shell may or may not extend through the flange. The use of a toughened glass is quite a recent innovation, and while at present it is not used to any great extent development is proceeding. An advantageous feature of such glass is that it has greater mechanical strength than the ceramic insulations, which would be a distinct asset in the case of the largest bushings.

The principal alternative forms of main insulation are shown in Fig. 150. The simplest construction, Fig. 150 (*a*), suitable for units up to 11 kV., is a solid porcelain or glass insulator with the conductor secured either by metal end-caps or by a non-insulating cement. In such insulators the internal surface of the solid material is usually metallised, and connected to the conductor, to avoid excessive stress on the air between the solid insulation and the conductor. Another simple form of bushing, Fig. 150 (*b*), has the outer shell entirely filled with a fluid, such as air or oil, or a plastic solid, e.g. bituminous compound. This type is not suitable above 33 kV., because the plastic solids usually available will not stand very high stresses, or dissipate sufficient dielectric losses ; oil, though strong electrically if pure, suffers from alignment of impurities in the field which limit its applicability ; and air has definite limitations.

Cylindrical barriers, Fig. 150 (*c*), serve to prevent alignment of impurities in an oil-filled bushing, and thus raise the breakdown voltage. Typical barrier materials are bakelised paper (more precisely, synthetic-resin-bonded paper laminated material) ; forms of pressboard (e.g. elephantide) which absorb oil and therefore have a permittivity approaching that of oil, oil-impregnated paper, and porcelain. The filling material is usually a fluid or semi-fluid oil, which has the advantage of dissipating dielectric losses by convection. A simple form of bushing in frequent use for lower voltages employs a sleeve of bakelised paper, or other similar material, directly on the conductor, with air, oil, or compound between it and the inside of the porcelain. The bakelised paper then relieves the major concentration of stress ; and the stress in air, if it is the filling material, can be kept sufficiently low for use at the lower voltages of 22 or 33 kV. Another method is to wrap paper on to the

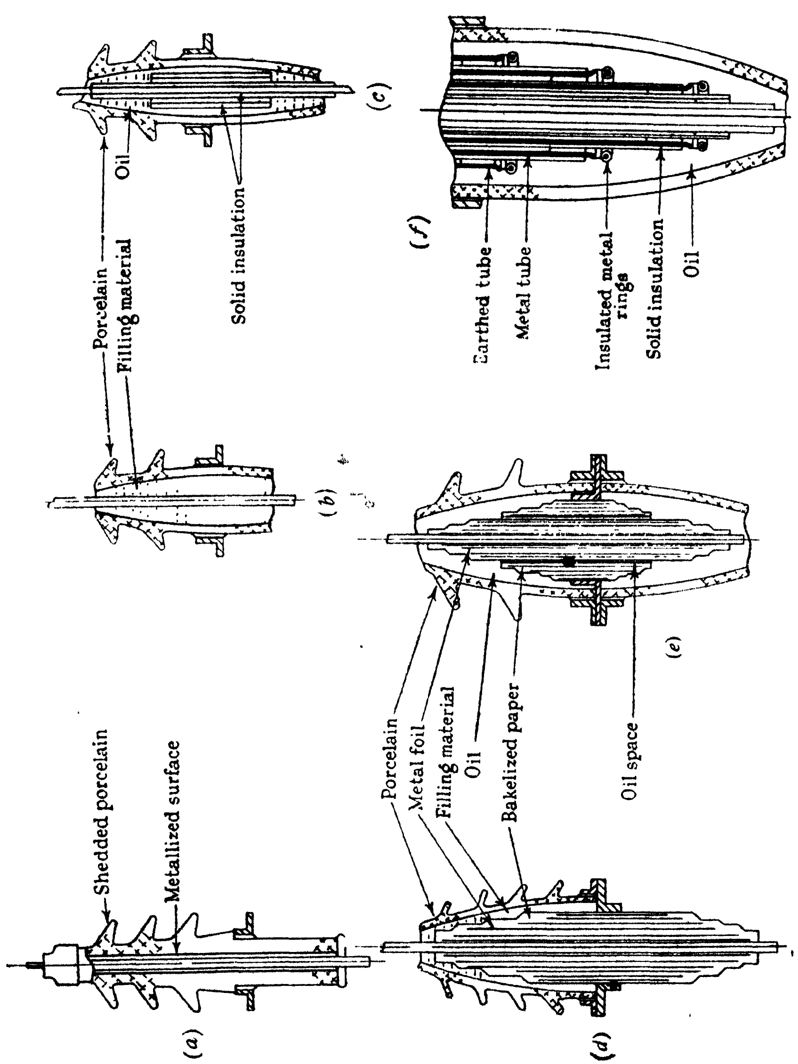


Fig. 150.—CONSTRUCTION OF TERMINAL BUSHINGS

(*a*) Solid porcelain bushing.
(*b*) Bushing with fluid or plastic filling only.
(*c*) Bushing with solid barriers.
(*d*) Bakelised-paper condenser bushing.
(*e*) Two-part condenser bushing.
(*f*) Bottom end of barrier condenser bushing.

(*Journal I.E.E.*)

conductor, filling the space between it and the flange, and then to vacuum-impregnate with oil similar to that used in the unit with which the bushing is associated. Bakelised paper has the advantage that it is both mechanically and in a large measure electrically independent of the porcelain shell or the filling material. With this class of insulation metal layers may be embedded in the material near the outside and in some cases the inside, and be connected to earth and the conductor respectively. The outside metallic layer transfers the heavy concentration of stress at the end of the flange into the bakelised-paper insulation, which has a higher electric strength than the surrounding air or oil. The inside metallic layer short-circuits any air between the conductor and the surrounding solid insulation.

Condenser Bushings

Above about 11 kV. still further precautions are necessary to avoid surface discharges, and condenser-type bushings are employed—exclusively so for the highest voltages. A series of metal layers is then embedded at frequent intervals throughout the solid insulation, as shown in Fig. 150 (*d*), proportioned so as to regulate the distribution of voltage along the surface and through the thickness of the material and thus reduce the clearances and diameter of the bushing. The whole assembly forms a series of condensers the voltage-drops across which vary inversely as their capacities. The filling medium is subject to low stresses only. Oil cooling is not usually necessary to dissipate losses, but is employed with advantage for the highest voltages by making the insulator in the form of two sections in series, concentrically arranged, with an oil space between which is not subject to any electrical stress. This type is shown in Fig. 150 (*e*).

Oil-impregnated paper is used in one type of condenser bushing instead of bakelised paper, certain advantages being claimed for this form of insulation ; notably, that the dielectric loss and power factor are much smaller and do not increase with temperature, and that the electric strength is much greater and does not decrease with temperature. Some of the advantages of a condenser bushing are obtained in conjunction with a barrier construction by interposing metal cylinders of calculated proportions at intervals as shown in Fig. 150 (*f*). Unless the edges of these cylinders are embedded in a dielectric of high strength, it is necessary to limit the edge stresses in some way. In Fig 150 (*f*) this is done by belling the ends and attaching insulated metal rings just beyond them (British Patent No. 338434). All-porcelain bushings of the condenser type have metallised surfaces forming the layers. Outdoor-type bushings are also used for indoor equipment in certain circumstances.

Switchgear Insulation

Most of the insulating components of switchgear are, in general, required to withstand mechanical stresses of varying intensities—in addition to electrical stresses—according to the precise purpose for which they are employed. The circuit-breaker of all types of switchgear units has to incorporate insulating materials which will not distort or break down under short-circuit conditions when the electro-dynamic forces are a maximum, or fail as the result of impact during operation. Thus the insulation associated with the support of the contacts, and the operating rods, must possess mechanical properties of a high degree.

The particular material or combination of materials adopted for circuit-breaker insulation depends on the type, voltage, rating, etc., but bakelised paper is used extensively, and porcelain, with or without paper insulations according to circumstances. Operating rods may be of treated wood, which is also used in laminated forms for phase barriers, tank linings, etc.

Spouts of withdrawable-type units are of bakelised paper or porcelain. When the former material is employed the finish is such that the insulation has a very low moisture absorption, so that although it is exposed to the atmosphere, in indoor stations there is no harmful effect unless the humidity is high. If this is the case, high-voltage insulation is liable to fail through condensation due to the presence of moisture, and to avoid this careful attention should be given to the heating and ventilation of switch chambers in which there is no inherent source of heat from transformers or other plant.

Busbar insulation is, of course, of critical importance, and it is because of the difficulties of providing adequate spacing and support of the busbars and connections of cubicle-type gear that this has been largely superseded by metalclad gear for large-capacity indoor equipments. In metalclad gear the busbar, circuit, and current transformer chambers are either oil or compound filled. With compound-filled units the conductors may or may not be taped. If taped, varnished " Empire " cloth, bakelised paper, or a micanite form of insulation is used ; in the absence of taping a greater thickness of compound is employed.

Compound filling offers a continuous support to all the conductors, as well as being a medium for excluding air, but it also forms, together with the conductor insulation, a very effective heat insulator. This limits the rating for a given cross-section of conductor, and for heavy currents special arrangements of conductors and/or oil filling are employed.

Transformer Insulation

The reliability of modern transformers, and similar apparatus such as reactors, etc., is due to the satisfactory solution of various insulation problems associated with this class of equipment. Insulation in general may break down in two ways : (*a*) by direct puncture through the body of the material, and (*b*) by creepage over the surface. To increase the strength against (*a*) the windings and insulations are designed so that there are no sharp corners at which there may be a concentrated electrostatic field, due either to the stress to earth or to that between windings, coils, or individual turns. Under normal working conditions the voltage stresses to which transformer insulation is subjected are : the stress on the " major " insulation (i.e. H.V. winding to L.V. winding and earth), which is the working voltage of H.V. winding to earth ; and the stresses on the "minor" insulation (i.e. the inter-turn and inter-coil stresses) which are proportional to the normal working volts per turn. The characteristics of insulating materials under power-frequency voltage stress are now well known, and the design of a transformer to withstand normal working conditions only does not present any difficulties.

The use of oil in the dual rôle of a liquid dielectric and a cooling medium constitutes a minor problem, however, because the oil is almost invariably used in conjunction with solid insulation. Since the permittivity (dielectric constant) of transformer oil is about one-half that of many of the solid insulations commonly used in transformers, when the two are used in series the stress on the oil is about twice that on the solid, as the division of the total voltage across two such dielectrics in series is, with equal thicknesses of each, inversely proportional to the permittivities. For instance, in the case of a solid material with a permittivity of 4 in series with oil of permittivity 2, with unit thicknesses of each two-thirds of voltage stress will be across the oil, and only one-third across the solid insulation. The electric strength of the solid material being considerably higher than that of oil, this division of stresses is the wrong way round, and unless the respective thicknesses are proportioned so that the voltage gradient across each is within the safe working limit, first the oil and then the solid will fail, due to corona discharge and overheating.

To obtain a more balanced design at the higher voltages the practice is growing of using absorbent cylinders, spacers, etc., for the support of transformer windings, and as barriers between the high- and low-voltage windings. Such cylinders absorb transformer oil and have a permittivity of the order of 3·5, as against a permittivity of about 5 for bakelised-paper cylinders; consequently, as the permittivity of oil is about 2·5, the absorbent insulation allows a better distribution of voltage stresses. A presspaper of high quality such as "Elephantide" is used for winding these cylinders, the layers being bonded together with a heat- and oil-resisting gum. By thoroughly drying out the cylinder before immersion in oil a high electric strength is obtained. An incidental advantage of the non-inflammable dielectric liquids is that the stress distribution is improved owing to the approximate equality between the permittivities of these and the solid insulations used.

Bakelised-paper laminated materials have the advantage of high mechanical strength. They are used for major insulation, and especially for tapping switches, supporting tapping and phase leads, cleats and core-bolt insulation, etc.

The conductors of high-voltage oil-immersed units are generally insulated with oil-impregnated paper; lower-voltage conductors may be covered with varnished paper, cotton, or some other form of insulation according to the voltage and capacity of the transformer. Inter-coil insulation consists of pressboard or bakelised-paper material in the form of spacers, washers, rings, etc.

Dry, air-cooled transformers are insulated with materials having a high-quality moisture-resisting finish ; major insulation, for instance, being of bakelised paper or micanite. For dry transformers, especially types such as low-voltage welding units which are required to operate for short periods at high temperatures, glass-fibre insulation has been used successfully. In damp locations glass insulation is particularly valuable. Fire risk is also reduced considerably since glass-insulated wire will not burn at temperatures below 470° C. The impregnating varnish may be destroyed above 250° C., but the spatial insulating properties of the glass are not altered in any way.

Glass-fibre insulation is not, as yet, applied to oil-immersed transformers. The high-thermal capacity of the glass insulation is, in this case, of little value since the maximum temperature permitted for the oil limits the final temperature of the windings. Furthermore the glass fibre is not particularly suitable for major insulation on account of the severe mechanical stresses encountered during operation.

Abnormal Insulation Stresses in Transformers

Under normal load conditions the voltage applied to a transformer is distributed evenly throughout the winding, but this is not the case immediately after switching-in, or under any other surge condition. Since the magnetic field takes time to build up, the initial voltage distribution depends on the capacitance values between turns and between coils throughout the windings. When a surge enters a transformer winding, during the first instant nearly all the voltage is concentrated on the end turn, since the capacitance between this turn and the adjacent turns is small in comparison with that of the remainder of the winding. Furthermore, since the winding comprises a system of inductances and capacitances the combination is oscillatory, and the surge is reflected from the earthed end, and from such points as where tappings are taken from the winding. To guard against the initial excessive voltage stress it is customary to use heavier or reinforced conductor insulation on the end turns, and sometimes at the tapping points. The extent of the reinforcement depends on the capacity and voltage of the transformer, and the type of winding. Usually about 3 to 5 per cent. of each end of the winding adjacent to a line terminal is reinforced, the extreme end turns being designed to withstand one-half to full-line voltage instantaneously, the other turns being graded down in steps to the normal amount of conductor insulation. Tapping points are generally arranged at the centre of the winding to avoid any reduction in the number of reinforced end turns in circuit. Switching surges do not, in general, constitute a very serious source of danger to modern transformer insulation ; but lightning disturbances give rise to the highest impulse-voltage stresses encountered in practice ; consequently, with outdoor gear it is necessary to guard against damage caused by lightning, the most vulnerable units being transformers and similar apparatus. Much attention has been devoted to the effect of the travelling waves produced either by a direct stroke to the overhead conductors or the earth wire, or by release of the induced charge on the line when the thundercloud, by which the charge is induced, discharges to the ground.

Impulse-voltage Protection

Insulation failures in transformers subject to impulse-voltage stresses are guarded against by : (*a*) proportioning the windings dimensionally to give a better inter-relation of the capacitances between coils and windings ; (*b*) by controlling the dielectric flux distribution by means of suitably disposed electrostatic shields ; (*c*) by reduction of the stress applied to the transformer by means of devices external to the unit. In practice the various methods may be used in combination. Method (*a*) is based on the theory that uniform distribution of the voltage is not essential ; the requirement being that there should be a uniform distribution of stress, with the same efficiency of utilisation of the insulation throughout the winding. The voltage distribution is largely determined by the thickness of the insulation between turns and coils, and this same factor determines the electric strength. It has been found possible to co-ordinate these values so that the impulse-voltages, whilst not necessarily uniform throughout the winding, are in proportion to the insulation strength at every point and result in substantially uniform stresses. The use of the insulation so as to provide the electric strength to control the corresponding electrical stresses has given rise to the term " stress-control " for this type of design.

Electrostatic Shielding

The voltage distribution throughout a transformer winding, following the application of an impulse at the line terminal, is due initially to electrostatic fields, determined by the relative values of the capacitances between adjacent turns and coils, and those between the winding and earth. (Since increased end-turn insulation results in reduced capacitance between end-turns and coils, and a reduction in the number of turns per coil at the line end as compared with the rest of the winding, both of these factors react adversely upon the initial impulse-voltage distribution and produce increased concentration of voltage at the line end. This tends to neutralise, to some extent, the advantage of the higher electric strength of the reinforced end insulation.)

Following the initial distribution, there is a series of complex oscillations involving the capacitances and inductances in the winding system, during which the transition from the initial to the final distribution takes place. Any improvement in the initial impulse-voltage distribution results in a reduction in oscillation voltage-stresses, and this is effected in the shielded transformer by obtaining a small shunt capacitance to earth as compared with the series capacitance.

There are several forms of shielded transformer, but the principles are exemplified by the original form, known as the "non-resonating" transformer. In this type the shields are applied in such a manner as to make the initial voltage distribution uniform, consequently there can be no oscillations, and the stresses throughout the winding will be uniformly distributed, i.e. with no initial concentration at the line end and no high internal concentrations subsequent to the initial voltage-rise. Suitably proportioned insulated shields, all connected to the line end of the winding, are mounted outside and around the H.V. winding. If the shielding is so proportioned that for every coil in the winding it supplies a charging current just equal to the earth capacitance current for that particular coil, then all of the shunt capacitance current will be supplied by this means and will not have to flow through the series capacitance of the winding. Hence the cause of non-uniform voltage distribution is removed.

A number of large transformers of this type have been manufactured, as well as many voltage transformers and small 132 kV. power transformers. At the present time, the principal application of "non-resonating" shielding is in connection with transformers for exceptionally high voltages, of the order of 220 kV., the impulse level of such units being so high that the most complete shielding is desirable in order to reduce internal stresses to a minimum. For relatively lower voltages, i.e. 132 kV. and below, a simpler type of shielding has been developed in which the shields are arranged so as to improve the initial voltage distribution without going to the full extent of producing uniform voltage distribution. The essential feature of the construction is that the shields are not all connected to the line end of the winding, but are subdivided into sections or "cascades," each being connected to a suitable point within the winding. In general, the shields consist of paper-insulated copper conductors wound around the outside circumference of the H.V. winding. When this type of shielding is used for delta-connected windings it is applied at both ends of the winding, so as to allow for the possibility of surges striking either end, or even both ends simultaneously.

In practice various degrees of shielding are adopted, the simplest being the electrostatic end ring, which is used to distribute the initial electrostatic field more uniformly across the first coil at the line end of the winding, thereby improving the radial voltage distribution.

In addition to, or instead of, specially designed transformers other methods external to the units are in use for protection against impulse-voltage stresses. Some protection against the stresses set up by lightning surges can be obtained if the lines and the transformers are shielded from direct hits by covering them with an earthed network. Complete protection in this way is difficult and expensive. Part protection is, however, a practicable proposition, and it has become a common practice in recent years to run one or more earth wires over the line conductors and to provide earthed shields over the substation.

Grading of System Insulation

Failure of transformer insulations within the tank, due to impulsive voltage stresses, can be guarded against by grading the system insulation so that sparkover should occur in the following order : line insulation, bushings, internal insulation of the transformer. To secure this it is necessary that the electric strength of the transformer insulation is greater than the sparkover voltage limit of the bushings under the same type of impulsive voltage stresses ; and that the sparkover voltage limit of the bushings should be greater than that of, at least, some of the line insulators adjacent to the transformer. With such an arrangement it is probable that the transformer insulation will be safeguarded by a sparkover elsewhere. The consequences of a failure of insulation within the tank are likely to be more serious than a bushing sparkover ; and similarly a bushing sparkover is more liable to effect continuity of supply than a line insulator sparkover. In order to afford the necessary degree of protection to the transformer bushings, the upper limit of the sparkover voltage of the line insulators adjacent to the transformer may be below the minimum sparkover voltage of the remainder of the line insulators.

Spark Gaps

A further restriction on the magnitude of surges arriving at the transformers may be obtained by means of spark gaps having a relatively lower flashover voltage than the line insulators installed at or near the substation. A common practice is to fit voltage-limiting spark gaps between bushing caps and tank covers of transformers. The insulation between the windings of a transformer and its frame can be regarded as a spark gap which will be permanently damaged in the event of a sparkover ; the problem of protecting a transformer from overvoltages by means of an external gap is really that of protecting one form of gap by another. Generally, the type of gap used is that known as the rod gap, a sparkover taking place between the ends of two rods set at such a distance apart that the impulse voltage necessary to cause sparkover is insufficient to damage the associated transformer winding. Another form of protective gap consists of two guard-rings, as shown in Fig. 151 applied to high-voltage bushings. Protective gaps are often adopted in combination with other stress-resisting methods inherent with the transformer. Two other devices are in use for reducing the stresses due to surges : lightning arresters, and wave flatteners or surge absorbers. Lightning arresters are, in effect, spark gaps so modified as to avoid some of the defects of the plain gap. Many forms have been devised to limit the amplitude of the incoming surge with small impulse ratio or time-lag, and without per-

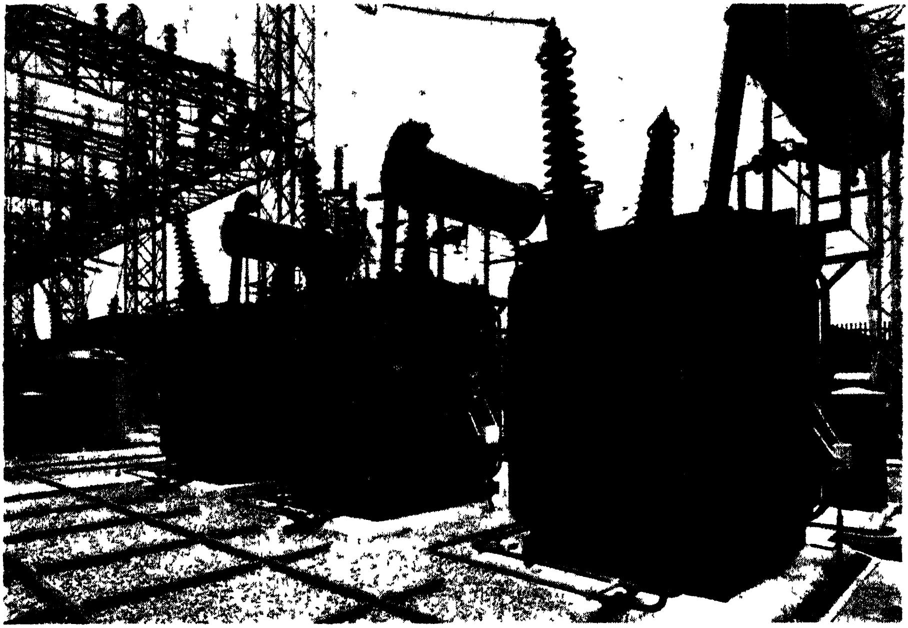


Fig. 151.—132 KV. OIL-IMMERSED THREE-PHASE BANK OF REACTORS INSTALLED IN A GRID SUBSTATION

The general view shows the high-voltage oil circuit-breakers and isolators in the background.

Normal rating of reactor bank 5,000 kVA., current 218 amps., reactance 10 per cent., short-circuit rating 500,000 kVA., throughput 50,000 kVA. (*General Electric Co., Ltd.*)

mitting the flow of power frequency current. Lightning arresters, a modern form of which is better described as a surge diverter, are specially applicable to systems of 11 kV. and less, to which, in the application of rod gaps to bushings a difficulty arises as a gap short enough to protect the transformer against overvoltages is liable to be bridged by birds, twigs, etc.

Surge Diverters

The components of a diverter consist of a resistance having a non-linear volt/amp. characteristic connected in series with a small spark gap between line terminals and ground ; the components being usually housed in a porcelain case. If the diverters are mounted on the transformer tank as an independent piece of apparatus, they take up considerable room and, moreover, external connections are required. For these reasons the Metropolitan-Vickers Company has developed and patented a transformer bushing in which are incorporated the components of a surge diverter. (*The Metropolitan-Vickers Gazette*, March 1939, page 61.)

The bushing has at present only been developed for voltages of 11 kV. and less, it incorporates a resistance in the form of a number of annular cylindrical blocks of " Metrosil " mounted end to end. A resistance made of this material has the property that the value of its resistance decreases rapidly as the voltage applied across its ends is increased ; the volt/amp. characteristic is of the form $V = KIa$, where K and a are constants. Actually the value of a is such that each time the voltage across the resistance is doubled the current is increased fifteen times. A spark gap is incorporated to prevent current flowing through the resistance under normal conditions, and consists of a number of specially shaped metal discs separated by porcelain distance pieces, the combination producing a number of small gaps in series. A gap of this type has a smaller time-lag than a rod gap. The upper end of the resistance is connected to the cap of the bushing, while the lower end presses against one pole of the spark gap.

Normal 50 cycle voltage is insufficient to break down the gap, but if a high-voltage travelling wave, coming from the line, strikes the cap of the bushing the spark gap flashes over, and the voltage across the " Metrosil " resistance rises. It only rises, however, to a value IR, and as the resistance drops rapidly with rise of voltage, the value IR remains within safe limits even though the current is large.

When the charge on the line has drained away, the voltage across the resistance drops to the normal 50 cycle voltage of the system, and a small follow current flows through the resistance, the magnitude depending on the instantaneous value of the 50 cycle voltage. The arc across the gap extinguishes as the voltage wave passes through zero, and it does not re-form as the resistance of the " Metrosil " has then become enormous.

Surge Absorbers

Wave flatteners, or surge absorbers, are designed to operate mainly upon the wave front and wave tail, and involve combinations of shunt capacitance, series inductance, and damping resistance. A typical surge absorber is shown in Fig. 152.

This consists of an air-cored inductance connected in series with the line and surrounded by, but insulated from, an earthed metallic case. The coil is, in effect, the primary of a transformer, and the earthed metal the secondary. When the unit is connected in series with a power transformer any impressed impulse-voltage will be concentrated mainly across the surge absorber and only partially across the transformer end turns. The surge energy is dissipated in the earthed metal by induction.

Earthing

A general practice adopted as a protective measure is to earth each network of a system at one or more points, this reduces the normal frequency voltage stresses under abnormal conditions, secures the maximum effectiveness of automatic earth-fault protective gear, and in the case of L.V. networks reduces to a minimum the danger to human life. The neutral point of star-connected alternators is earthed through a current-limiting resistance ; with star-connected transformers the earthing is either solid, or through a resistance or reactor. With a delta-connected winding, when a neutral for earthing is required this is effected by a neutral point reactor, which is simply an arrangement of interconnected-star windings, as shown in Fig. 80, page 128. This form of earthing is used for the Grid, where every 132 kV. transformer is star-connected on the higher-voltage side, and delta-connected on the lower-voltage side.

Fig 152.—SURGE ABSORBER 12 KV., 5 AMPS., USED FOR THE PROTECTION OF DISTRIBUTION TRANSFORMERS CONNECTED TO OVERHEAD LINES. (*Ferranti Ltd.*)

The L.V. neutral point of three-phase transformers is earthed in a variety of ways. Earthing may be direct and permanent, but with some units the L.V. winding is only earthed, by a special device, when a dangerous excessive voltage appears in the winding. A typical form of earthing device consists essentially of two disc electrodes connected to the L.V. neutral point and earth respectively. Between these electrodes is placed one or more specially prepared paper discs which serve as the dielectric, and are selected so as to puncture at voltages which can be approximately predetermined. When, due to a fault between the H.V. and L.V. windings, or due to electrostatic induction, the L.V. neutral point attains a voltage above earth greater than that which the paper discs can withstand, these are punctured and the L.V. neutral automatically earthed solidly. The L.V. neutral point of a transformer may in some cases be earthed through a resistance or through a fuse which is shunted by an ammeter and link. These enable the value of the leakage current to earth to be determined, while the fuse will automatically open the neutral connection should a heavy sustained earth fault develop, thereby giving an indication of the occurrence of such a fault.

Prevention of Accidental Damage

Complete metallic enclosure of high-voltage and, to a smaller extent, low-voltage equipment has made this less liable to damage by external agencies, particularly fire and explosion, protection against which is dealt with in a subsequent chapter. Electrical and mechanical interlocking of switchgear controls has been contrived with the object of eliminating faults due to erroneous switching and earthing. For instance, in the case of isolators with three positions " On," " Off," and " Earth " special attention has been given to designing these so as to prevent the operator moving the switch into the " Earth " position until a stop has been removed by a definite action such as opening a lock. Busbar selectors, isolating switches, and racking-levers, used for withdrawing circuit-breakers for isolating purposes, are generally interlocked with the operating mechanisms of the breakers so as to prevent their movement unless the circuit-breakers are open. With interconnected networks, where it is possible for two sections supplied from different sources to be out of synchronism, electrical interlocks are often provided to ensure that the synchroscope plug must be inserted before an interconnecting breaker can be closed. Being connected to the main circuits, instrument transformers are danger points in a high-voltage system since a fault in the transformer may lead to a fault on a main circuit, unless precautions are taken to prevent this. Current transformers should have an adequate short-circuit capacity and voltage transformers should, in addition to protection by suitable fuses, be included in the zone of a sensitive form of automatic fault protection. With the latter current-limiting resistances are used in series with the primary fuses.

Insulation Tests

All equipment, circuits, joints, etc., are usually subjected to the standard overvoltage test of twice system voltage plus 1,000 volts when first commissioned, and after repairs involving the insulations. Nowadays there is an increasing tendency to endeavour to prevent faults by periodical insulation tests which may indicate deterioration sufficiently pronounced as to justify attention being given before a fault actually develops. Insulation tests are either overvoltage tests or quality tests. There is a considerable difference of opinion as to the efficacy of overvoltage tests applied to solid dielectrics because such tests deliberately stress the insulation as a whole by the application of an excessive voltage to detect incipient weak spots. Unless an actual breakdown occurs it is not possible to say more than that the insulation has withstood a certain voltage ; but the repeated application of the test voltage may unduly strain, and thereby weaken, the sound portions of the insulation without any indication being given that this has happened, leading to a failure which otherwise might not have occurred. Nevertheless evidence has been offered as to the value of such tests in particular conditions ; and furthermore they are recommended in " Fire Risks at Generating Stations, etc." (H.M. Stationery Office, 1939), a report published by the Electricity Commission, in connection with the routine testing of switchgear insulation for the purpose of fire prevention. A.C. tests are preferable as they reproduce the correct voltage distribution in the insulation under test, but owing to the size of the testing equipment required to supply charging current they are only suitable for apparatus of relatively small capacitance. Generally D.C. overvoltage testing is employed since the testing equipment is then only required to supply a small leakage current.

Quality tests are made by measuring the dielectric loss or the insulation resistance ; the former being obtained in terms of power factor is therefore designated a power-factor test. Such a test is only practicable in the case of components having negligible inductance, e.g. H.V. switchgear units, with normal charging currents very nearly 90° leading, due to the inherent capacitance of the assembly. A power-factor test is carried out by applying an A.C. voltage to a component, or section of the installation isolated for the purpose, and measuring quantities that enable the power factor of the insulation to be determined. A perfect dielectric would have zero power factor, that is to say there would be no energy loss, but since all insulations absorb some energy the degree by which the power factor departs from zero is a measure of the dielectric loss. Consequently, records of periodical tests enable deductions to be made about possible deterioration of insulation leading to increased dielectric loss : but a test can only indicate the presence of a weak spot if the effect on the measurement is sufficiently large to be detected in relation to the effect of the insulation as a whole. In practice the usefulness of power-factor tests depends upon to what extent the system insulation can be divided into parts which can be tested separately. Some switchgear equipments are specially designed in order that each component can be isolated for testing purposes. Power-factor measurements are also used to determine the condition of insulating oil.

An insulation resistance test indicates mainly the moisture content of the insulation, and since a large number of insulation failures in service are due to moisture such a test, made with a D.C. ohmmeter (Megger), is a sensitive detector of deterioration of this type, as the leakage current is not masked by capacitance current. The great advantage of the ohmmeter is that it is easy to use and the test results are simple to interpret. Instruments are available for measuring insulation resistance values up to 20,000 megohms at 5,000 volts.

Tests of the electric strength and acidity of insulating oils are also made periodically for the purpose of eliminating avoidable breakdowns.

Chapter XV

PROTECTIVE SYSTEMS AND APPARATUS

DESPITE preventive safeguards insulation failures do, of course, occur and many protective systems for the rapid disconnection of faulty units and circuits are in use. The present tendency is towards the increasing application of high-speed protection in conjunction with quick-acting circuit-breakers so as to minimise the period of time for which excessive current flows and, thereby, avoid unnecessary prolongation of abnormal conditions likely to initiate insulation failure elsewhere ; or produce widespread disturbances leading to interruptions of supply in areas not directly associated with the original fault. Fault currents, and consequently the thermal stresses, and the mechanical stresses due to the electro-dynamic forces between conductors, are limited under short-circuit conditions by the impedance of the transformer windings, etc., connecting the networks ; and in some systems additional reactors are used for current limitation. These are simply inductances of low resistance, which are either wound on an iron core and oil-immersed (Fig. 151) or wound on a concrete former and air insulated (Fig. 153). Some restriction of short-circuit current may also be obtained by voltage decrement ; and in the case of earth faults, by the impedance of the earth connections, but under modern conditions the really important factor is the speed of fault clearance. In general, major units and circuits will be equipped with protective gear operating "instantaneously," while less important units and circuits so situated that the impedance between them and the source of supply is high enough to effectively limit the fault current may, for reasons discussed below, be protected by relays operating with a variable time-

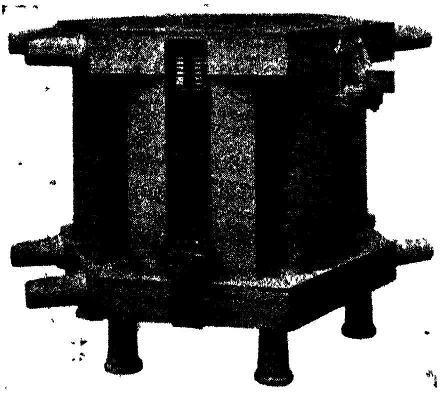


Fig. 153.—One phase of a three-phase bank of air-cooled, air-insulated concrete-type reactors for use on a 6,600 volt, 850 ampere circuit

Normal three-phase rating of reactor 390 kVA., reactance 4 per cent. (*General Electric Co., Ltd.*)

delay. Although with "instantaneous" systems no time-delay is purposely introduced, actually this term is relative ; there is, in addition to the operating-time of the O.C.B., the mechanical and magnetic inertia of the relay to be considered. Typical examples of the times taken for O.C.B.'s, in conjunction with instantaneous protection, to clear a fault are shown in Table VI.

TABLE VI.—OPERATING TIMES OF TYPICAL CIRCUIT-BREAKERS

Fault Clearance Times with Solenoid Operated Switchgear Working in Conjunction with Instantaneous Automatic Protective Systems	*11 kV. O.C.B. Distribution*				*33 kV. O.C.B. Power House*			
	At 10–15% Rating		*At 100% Rating*		*At 10–15% Rating*		*At 100% Rating*	
	Cycles	*Secs.*	*Cycles*	*Secs.*	*Cycles*	*Secs.*	*Cycles*	*Secs.*
(i) Opening time . .	4·0	0·08	4·0	0·08	6·5	0·13	6·5	0·13
(ii) Arc duration . .	3·5	0·07	2·0	0·04	3·0	0·06	1·5	0·03
(iii) Total break time, (i) plus (ii) . . .	7·5	0·15	6·0	0·12	9·5	0·19	8·0	0·16
(iv) Relay operating time .	6·0	0·12	4·0	0·08	3·0	0·06	3·0	0·06
(v) Fault clearance time, (iii) plus (iv) . . .	13·5	0·27	10·0	0·20	12·5	0·25	11·0	0·22

Forms of Protection

There are so many protective systems in use at the present time that only a few can be discussed in detail here, but generally each system functions as the result of one or more of the following abnormal conditions arising : (1) Excessive current (overcurrent protection) ; (2) Current flowing back to the source through the earth—other than normal leakage current (earth-leakage and differential protection) ; (3) Current flowing in an abnormal direction within the circuit (directional and differential protection).

An essential characteristic of a protective system is that it should discriminate between a fault within the zone it protects and a fault outside that zone. A " zone " includes all the equipment, cables, etc., which are protected as a unit by a combination of protective relays, current transformers, etc., operating to trip the one, or more, circuit-breakers which have to be opened to effectively isolate the faulty zone from the rest of the system. To avoid disconnecting healthy zones a protective system must discriminate, and possess sufficient stability to prevent operation even when the maximum short-circuit current possible flows through the healthy zone as the result of a fault outside it. The degree of discrimination and the margin of stability obtainable vary according to the class of protective gear adopted, consequently the latter is usually determined by the nature, and the relative importance of the circuit protected. Thus, protective gear used in practice may be of a simple

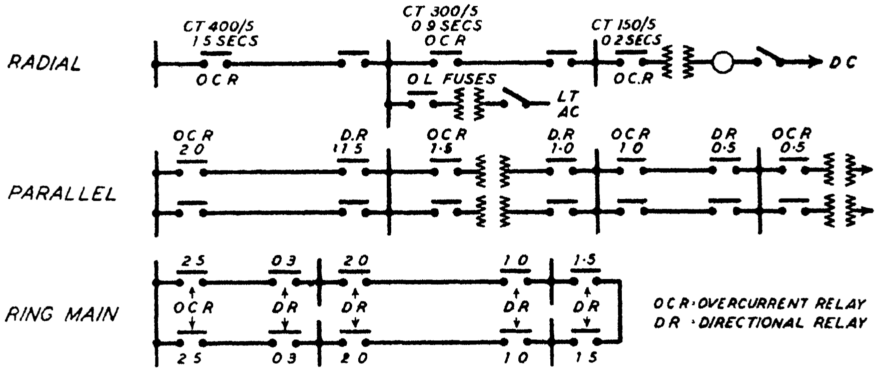


Fig. 154. TIME-GRADING OF DIFFERENT ARRANGEMENTS OF SUPPLY SYSTEMS

or a very elaborate nature, much depending, of course, on the expenditure permissible as an assurance against the risk of interrupting more circuits, and causing more damage than would probably be the case if the particular class of protective gear installed were selected as the result of technical considerations only.

The simplest form of protection is against overcurrent, which is effected by fuses, series trip-coils attracting armatures, or solenoids operating plungers, or relays. With all these devices a certain degree of discrimination can be obtained by arranging them so that with a given fault current each successive stage of protection operates after a time-delay, which is adjusted according to its position in the network. For instance, with the simple radial network shown in Fig. 154, by giving each protective device the minimum time-delay indicated, the C.B. nearest the fault can be made to trip before those farthest away. A protective system that discriminates by reason of different time-delays between successive stages of protection is said to be "time-graded."

The technical objection to the fuse as a protective device, apart from its function as a circuit-breaker, is the lack of discrimination. Although up to several times normal load the fuse has an inverse time current characteristic, above a certain current value all fuses in series blow instantaneously.

Attracted armature devices are used only for L.V. breakers, and some degree of discrimination is achieved by an oil dashpot. With the type of dashpot in which the disc or plunger is pulled out against the resistance of the oil this gives the tripping device a certain amount of discrimination at low overloads, but at high overloads it becomes instantaneous owing to cavitation between the disc or plunger and the oil surface. To avoid this another form of dashpot is used in which the piston is pushed into the dashpot, instead of being pulled out, thus putting the oil into compression.

Fig. 155 shows the characteristics of a compression type of dashpot, which is used in conjunction with the B.T.H. H.R.C. breakers described in Chapter V (see page 55).

Solenoid operated trips are also fitted with dashpots, or alternatively, a tripping fuse may be connected across the solenoid terminals so that this does not operate until the fuse has blown. Quite good discrimination can be obtained by this means up to a certain current value, beyond which the fuse blows instantaneously.

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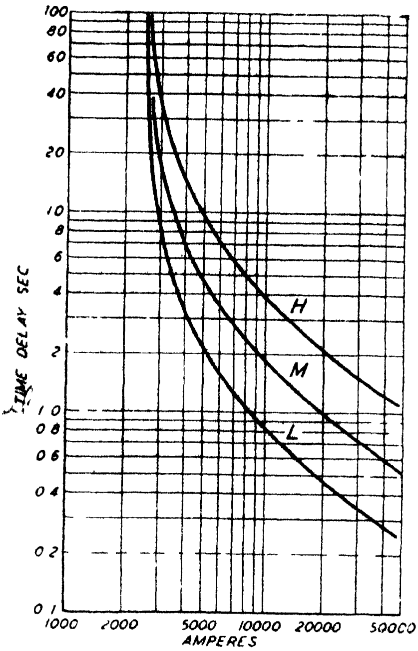


Fig 155.—CHARACTERISTICS OF COMPRESSION-TYPE DASHPOT FITTED TO 1,600 AMP. AIR CIRCUIT-BREAKER USING MEDIUM VISCOSITY DASHPOT OIL

Curve *H*, high setting of dashpot. Curve *M*, medium setting of dashpot. Curve *L*, low setting of dashpot. Series trip set to operate at 2,400 amps.

Induction Overcurrent Relays

The most common method of protecting H.V. circuits against overcurrent is by means of the well-known type of relay with an "inverse time definite minimum time" characteristic. A typical overcurrent relay is shown in Fig. 156, and diagrammatically in Fig. 157. The relay operates on the induction principle and consists essentially of a metal disc pivoted so as to be free to rotate between the poles of two electro-magnets (see Figs. 156 and 157). The disc spindle carries a moving contact which bridges two fixed contacts when the disc is rotated through an angle which is adjustable between 0 and 300° approximately. A spiral spring returns the disc to the reset position, the disc being compensated by means of graduated slots cut in its periphery, for the increasing torque of the spring due to its deflection. A permanent magnet provides the necessary damping. The upper electro-magnet (Fig. 157) has two windings, one of which, the primary, is connected to a current transformer in the line to be protected. This winding has a number of tappings which are connected to a plug-setting bridge which enables the number of turns in use, and consequently the setting, to be adjusted. The second winding is energised by induction from the primary and is in circuit with the winding of the lower electro-magnet. By this means the leakage flux from the upper, and the flux produced by the lower electro-magnets are displaced

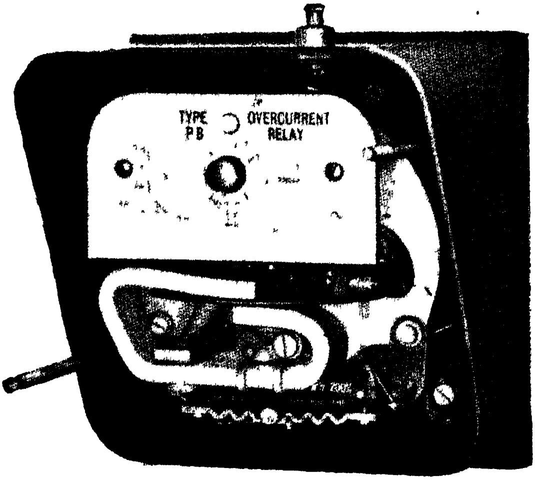


Fig. 156.—Single pole induction overcurrent relay (*Metropolitan Vickers Electrical Co., Ltd.*)

sufficiently in phase to provide the moving field necessary to rotate the disc.

The iron circuit of the upper electro-magnet is so designed that the total flux produced is limited; beyond a given value of primary current there is no appreciable increase in relay torque as the iron becomes saturated, and this results in a flattening-out of the time characteristic to a definite minimum (see Fig. 158). Standard relays can be adjusted to have a maximum definite time of two seconds, but four-second relays are used for special applications.

The plug-setting bridge is designed so that when the plug is withdrawn the relay automatically adopts the setting that it would have if the plug were inserted in the centre tap position. The setting may thus be changed on load without opening the C.T. secondary, and without the use of a spare plug. Another advantage is that the operation of the relay is assured even if the plug is inadvertently left out.

Overcurrent relays for use with C.T.'s having 5 ampere normal full-load secondary rating usually have the range of settings shown in Fig. 159.

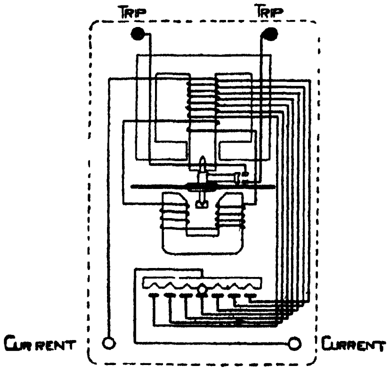


Fig. 157.—Diagram of internal connections of the single-pole relay

The selection block shown provides normally for 50, 75, 100, 125, 175, or 200 per cent. of the nominal rated current of the associated C.T., which implies that the secondary currents necessary to produce 5 amps. in the relay winding are 2·5, 3·75, 5, 6·25, 7·5, 8·75, and 10 amps. For use with C.T.'s rated at 1 amp. normal full-load relays are made with settings corresponding to from 0·5 to 2 amps. The relays are calibrated to remain inoperative at the particular percentage value, marked on the current-setting bridge, selected; but start to operate with currents approximately 30 per cent. greater than that corresponding to the setting in use. This will be apparent from Fig. 158 by considering the curve marked "relay set at 1·0." The standard connections of a three-pole overcurrent relay are shown in Fig. 160.

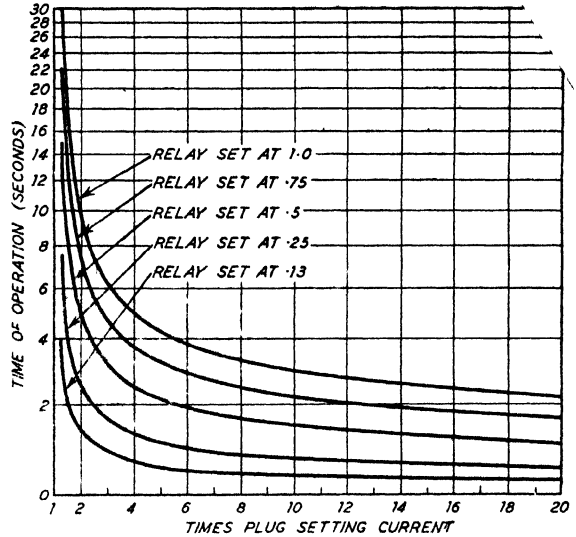


Fig. 158.—CHARACTERISTIC TIME-CURRENT CURVES WITH VARIOUS SETTINGS FOR OVERCURRENT RELAY

Adjustment of Time Settings

The time setting of overcurrent relays is adjusted by altering the position of a stop —against which the moving contact rests —and thereby, the distance between the fixed and moving contacts. The time setting is indicated by a pointer on a calibrated scale (Fig. 159). The figures on the scale are not actual times, but are multipliers to be used for converting into actual operating times a time taken from the nameplate curve. The operating times depend on the settings and the current flowing. For example, when the time-setting pointer is set at 1·0, a relay operating from a C.T. of ratio 100/5, and set at 100 per cent. on the setting bridge, would, as shown from the curve "relay set at 1·0" (Fig. 158), operate in 30 seconds with 130 amps. (= 1·3 × 100 amps.). Similarly with 2,000 amps. (= 20 × 100 amps.), i.e. 20 times the current setting, the relay operates, from the curve, in 2·2 seconds. If the time-setting pointer is set at any value other than 1·0, the above times of 30 and 2·2 must be multiplied by whatever value is used; e.g. with a pointer setting of 0·5, 30 becomes 30 × 0·5 = 15 seconds, and 2·2 becomes 2·2 × 0·5 = 1·1 seconds.

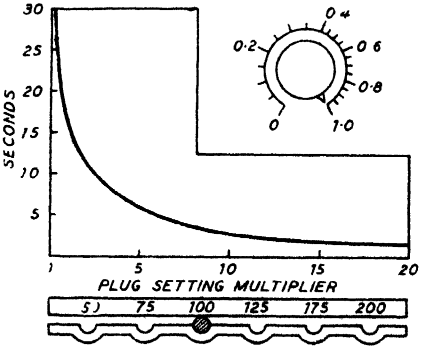


Fig. 159.—CALIBRATION PLATE, TIME AND CURRENT SETTING ADJUSTMENTS OF TYPE P.B. RELAY

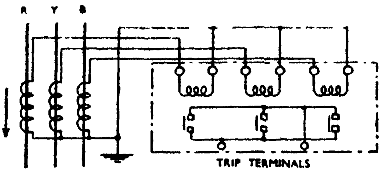


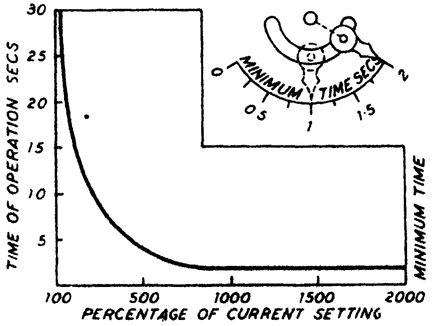
Fig. 160.– STANDARD CONNECTIONS
Three-pole type horizontal pattern relay connected for overcurrent protection.

With a setting of 200 per cent., 2,000 amps. is then only 10 times the plug setting current so that with a time setting of 1·0, from Fig. 158, the operating time is approximately 3·0 seconds; and correspondingly less with the lower time settings. Again, with a current setting of 50 per cent., and 1,000 amperes in the circuit, this will still be 20 times the plug setting current so that, as with the 100 per cent. setting, the relay will operate in 2·2 seconds when the time setting is 1·0. These current values are, of course, primary amperes, with the C.T. ratio assumed. Starting with a given value of primary amperes, if it is required to know the time the relay will take to operate, then it is simply a question of determining the ratio of primary current to setting current—in terms of primary amperes—referring to the curve and multiplying the time obtained from the 30 seconds scale by the time-setting factor.

With one make of relay the time adjustment is marked in terms of minimum times (Figs. 161 and 162), in this case the operating times must be scaled down in accordance with the minimum time indicated.

Earth-fault Protection

Relays described as overcurrent may also be used for earth-fault protection provided that no setting lower than 50 per cent. of the current transformer rating is desired. When used in combination with three C.T.'s the earth-fault, or earth-leakage relay, would be connected on the residual current principle, as shown in Fig. 163. With this arrangement when the current is flowing in the normal manner through the three phases the vector sum of the three currents is zero, and no voltage will appear across the relay terminals. In the event of an earth-fault occurring a fault current will return to the source through the body of the earth and the earthed neutral point of the transformer, or alternator, as the case may be; consequently the sum of the currents through the C.T.'s will no longer be zero, as the earth current does not return via a C.T. The resultant unbalance in the closed circuit formed by the three C.T.'s produces a voltage across the relay terminals, which, if the current



Figs. 161 AND 162.—CALIBRATION PLATE AND TIME-ADJUSTMENT LEVER OF TYPE I.C. OVERCURRENT RELAY flowing through it is sufficient, operates to trip the circuit-breaker. It follows that a low fault setting is advantageous, as the circuit may then be disconnected before the fault develops, in certain circumstances, into a phase fault. For this reason special relays with settings ranging from 0·1 to 0·7 secondary amps. are generally employed.

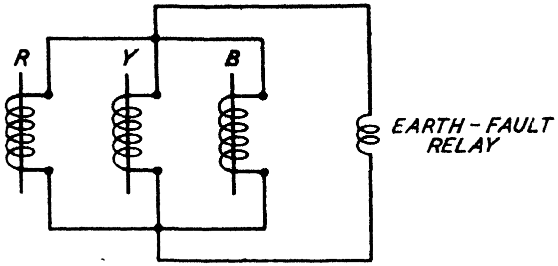


Fig. 163.—EARTH-FAULT RELAY CONNECTED ON RESIDUAL CURRENT PRINCIPLE

With overcurrent relays the settings are nominal settings and represent the current in the relay, expressed as a percentage of the rated full-load secondary current of the C.T., above which the relay operates. Where bushing C.T.'s of low ratio or poor characteristic are used, the actual primary current required to operate the relay will invariably be somewhat higher than that corresponding to the selected plug setting. This is particularly so in the case of earth-fault relays connected on the residual principle. As the impedance of bushing C.T.'s is low, when they are connected in parallel with an earth-fault relay on the residual current principle, part of the residual current will be shunted by the secondary windings of the two C.T.'s connected in the healthy phases, and hence is not available for operating the relay. Even with the average wound-type C.T.'s connected on the residual current principle, a low impedance relay is essential. From Fig. 163 it will be apparent that the distribution of the secondary current between the relay coil and the two C.T. windings will depend upon the relative impedance of the two paths, and if the relay has a comparatively low impedance its effective sensitivity will be increased. Nevertheless,

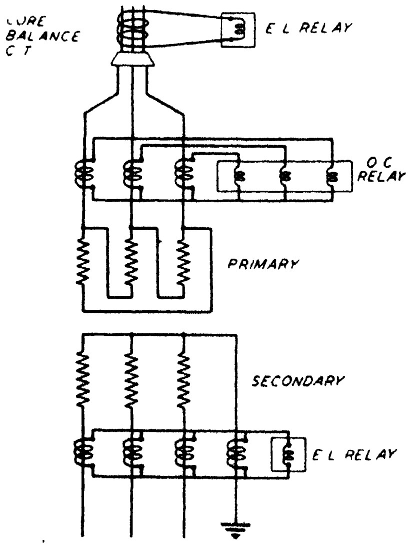


Fig. 164.—OVERCURRENT AND EARTH-LEAKAGE PROTECTION APPLIED TO POWER TRANSFORMER

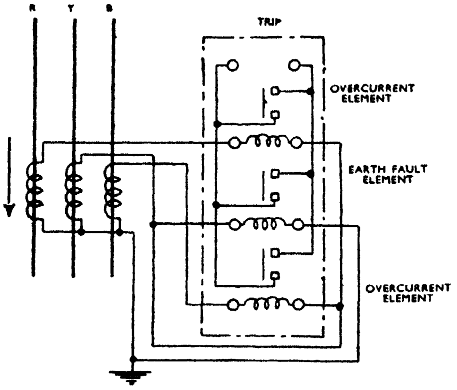


Fig. 165.—Three-pole relay connected for combined overcurrent and earth-fault protection

the conditions are sometimes such that to avoid the discrepancies resulting from the use of three C.T.'s connected on the residual principle, a core-balance transformer is used instead. This is shown diagrammatically in Fig. 164, applied to the protection of a transformer. The winding of the core-balance transformer is wound on an iron core which encircles the cable so that under normal conditions, although the magnetic field of the current in each phase induces a flux in the core, the sum of the three fluxes is zero, and no voltage is induced in the winding. When, however, an earth-fault current flows in the earth circuit this condition no longer obtains, and an induced voltage is applied to the relay terminals. Frequently, earth-fault relays connected for residual current are used in combination with relays for overcurrent protection ; the standard connections of the combination being shown in Fig. 165. To meet the limitations imposed by the small V.A. output of low primary current bushing type transformers, and for certain other applications, low-energy type overcurrent relays are used. The reduced volt-ampere consumption is mainly due to a modification in the iron circuit of the electro-magnets, and to a reduction in the travel of the disc, which is approximately two-thirds that of the standard type, resulting

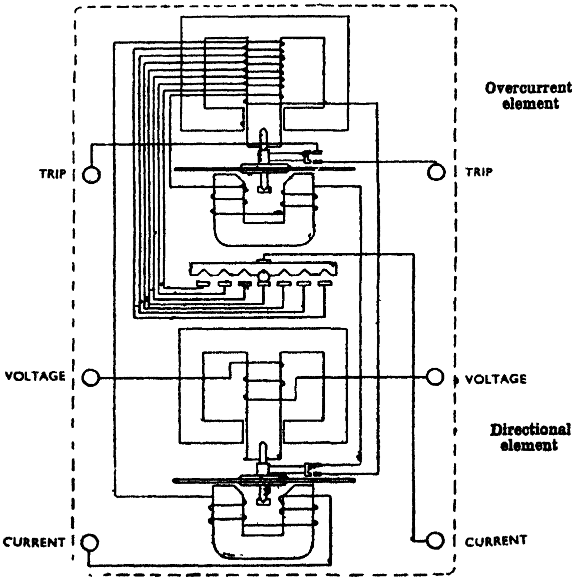


Fig. 166.—Internal connections of directional relay in a maximum operating time of 20 seconds instead of 30 seconds.

Directional Overcurrent Relays

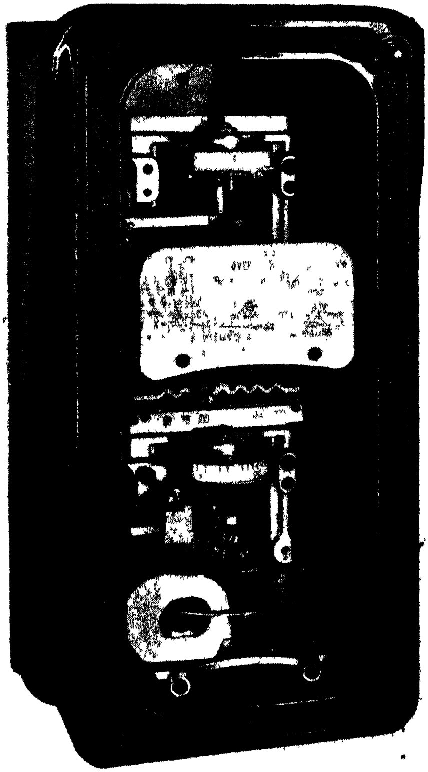


Fig. 167. Directional overcurrent relay type N.P.O. (*Metropolitan-Vickers.*)

Directional protection comes into the category of time-graded with the additional feature of discrimination with regard to the direction of flow of the fault current ; thus it is possible to obtain comparatively low fault settings. The directional overcurrent relays employed can be connected to provide discriminative automatic isolation of circuits in the event of faults to earth, and between phases, in a similar manner to the standard overcurrent relay, with the difference that the directional overcurrent relay will only operate with an overcurrent in the reverse direction to that normally obtaining. The relay is shown diagrammatically in Fig. 166, and is illustrated in Fig. 167. The latter is the latest form of the relay and differs from the arrangement shown in Fig. 166 in that the positions of the directional and overcurrent elements are reversed, i.e. in Fig. 167 the overcurrent element is at the bottom. This element is actually an improved form of the overcurrent relay shown in Fig. 156, which it supersedes. Thus, this particular type of directional overcurrent relay is a combination of two elements in one case, one a standard type of overcurrent relay, and the other a sensitive wattmeter type directional element whose contacts close with the power flow in one direction only and control the operation of the overcurrent element (see Fig. 166). The resultant combination of these two elements is a relay which will only operate to trip a circuit-breaker when three conditions, for each of which the relay is independently adjustable, are satisfied. These conditions are : (*a*) current in excess of the relay setting value ; (*b*) persistence of the excess for a predetermined time ; (*c*) the power must flow in a given direction.

As the construction of the overcurrent element is standard it is only necessary to note in Fig. 166 that the secondary winding of the upper electro-magnet is joined to the lower magnet winding in series with the contacts of the directional element. The satisfactory operation of these contacts is ensured by winding the secondary coil of the relay for a higher voltage and smaller current than the standard overcurrent relay.

The directional component is a sensitive wattmeter element consisting of voltage and current coils, and a metallic disc as in an ordinary watt-hour meter. In place of the usual train of gears a small lever is attached to the disc spindle which, when the disc is rotated in a clockwise direction, closes the contacts of the directional element. These complete the circuit of the lower operating magnet of the overcurrent element and allow that element to start operating. The overcurrent element cannot start to operate until the directional element has selected the direction of power flow, so that the full time for discrimination is always available.

When the rotation of the disc is counter-clockwise, the contacts are held apart so that operation of the overcurrent element cannot occur. Relays should always be connected into the circuit in such a way that the directional element disc moves clockwise, i.e. closes the contacts when the direction of power flow in the circuit is away from the busbars. This will mean in some cases that contacts will be closed with power flowing in a direction that is normal for the circuit concerned. Such cases occur in ring-main protection where the contacts of relays on outgoing feeders are normally closed, and those on incoming feeders are normally open. Circuit-breakers cannot, however, be tripped by either relay until the current has persisted for a definite period of time, determined by the time setting of the relay, at a value equal to, or greater

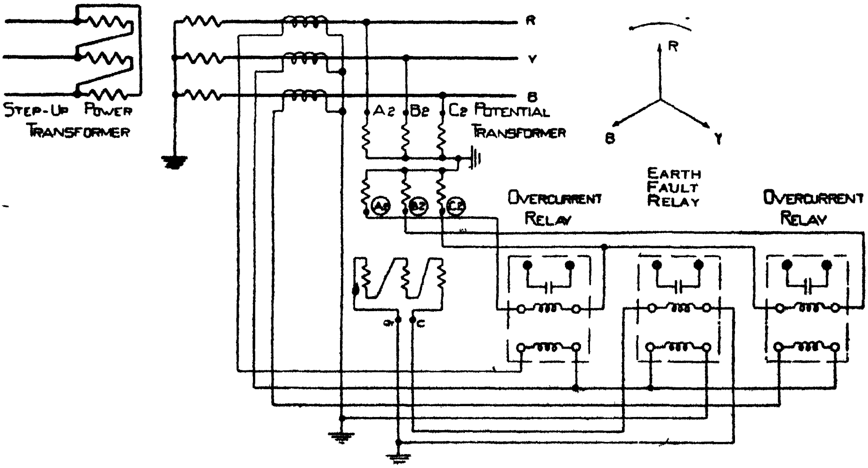


Fig. 168 —COMBINED DIRECTIONAL OVERCURRENT AND EARTH FAULT PROTECTION USING A VOLTAGE TRANSFORMER WITH A TERTIARY DELTA WINDING IN CONNECTION WITH THE EARTH-FAULT DIRECTIONAL ELEMENT OPERATING BY RESIDUAL VOLTAGE than, the overcurrent element current setting. Directional earth-fault protection is effected by the arrangement shown in Fig. 168.

An essential feature of the directional element is that it should operate definitely under all conditions of voltage and power factor. The relay shown in Fig. 167 is so designed that it will give correct discrimination as to direction so long as the voltage does not drop below 2 per cent. of its normal value.

The movement of the disc of the directional element is restricted to a small angle, so that the relay takes up its setting practically instantaneously.

Applications of Time-graded Protection.

Time-graded protection is used for various classes of circuits and equipments, different combinations of overcurrent, earth fault, and directional overcurrent relays being employed according to the nature of the system. Three typical arrangements are shown in Fig. 154. In these earth-fault relays are not included, but they are usually adopted and time-graded in a similar way to the overcurrent relays. With parallel circuits directional relays with comparatively low settings are required, otherwise, since fault current can flow in both directions, there will be a tendency for the overcurrent relays at the remote end of the system to trip circuit-breakers unnecessarily, by virtue of their low settings, which are essential for discrimination in a forward direction. From a consideration of the parallel system in Fig. 154 it will be apparent that a fault in any one zone will operate the overcurrent relays at the outgoing end, and the directional relays at the incoming end. Other relays may start to operate, but the difference in their operating times will ensure that they do not close their contacts before the relay at the opposite end of the circuit has tripped the circuit-breaker. The directional relays will, of course, only operate when the flow of power is in an opposite direction to that under normal conditions.

The discrimination with the ring-main system is effected in a similar manner, except that in this case higher current settings of the overcurrent element may be necessary since power may normally flow in either direction.

Overcurrent relays are not generally used to guard against normal overloads, but the inverse characteristic is of great utility in enabling more effective discrimination to be obtained with systems in which the maximum short-circuit current in the networks is widely different on account of links of fairly high impedance.

Under modern conditions the application of time-graded protection is generally limited to circuits electrically remote from a large transmission system, or for single stages of protection. With several stages of time-graded protection in series the minimum time-delay required at the supply end of the system to obtain effective discrimination is about 2 seconds, and this is not generally permissible. If a fault were allowed to persist for that length of time on a large system the result would be a widespread disturbance of supply, and the risk of further breakdowns. On large systems time-delay relays are mainly used for the protection of transformers and machines, and also as secondary " back-up " protection to cover any failure of the primary protection, which is usually of the instantaneous class.

High-speed Protective Systems

Since no protective system is actually instantaneous, schemes in which discrimination and stability are not obtained by time-grading, and successive stages of protective gear all operate in the minimum time practicable, are best described as " high-speed." To obtain high-speed clearance throughout the network it is essential that either all the relays have an equal time of operation with any value of fault current, or that the minimum operating times of all the relays be adjusted automatically so that those nearest to the fault close their contacts first irrespective of their position in the circuit. For the rapid clearance of faults the speed of the circuit-breaker is a very important factor, and special circuit-breakers are now available which can clear a short-circuit in 0·06 second ; but such speedy operation is not generally obtainable with the type of breaker demanded by economic considerations ; or is not actually necessary. Conventional oil circuit-breakers have been modified so as to decrease the tripping time ; and times of the order of 0·12 to 0·16 obtained. Arc control devices have materially assisted in this respect, together with other modifications such as stronger springs, lighter mechanisms, and forcing of the magnetic circuits of the tripping solenoids, which all assist in obtaining higher operating speed. Magnetic forcing is accomplished by increasing the tripping current, and in most cases high-speed auxiliary tripping relays are required to deal with these larger currents.

The time taken to clear a short-circuit includes that of the relay or relays to energise the trip coils of the circuit-breakers (see Table VI). If the fault must be cleared in, say, 0·25 second and the circuit-breaker takes 0·16 second, then the relays must operate in less than 0·09 second. In the same way a fault clearance time of 0·15 second with a breaker taking 0·08 second leaves 0·07 second for the relays. Since on certain protective schemes two or more relays may have to operate in sequence, the individual relays must be much quicker than this, and relays having an operating time of less than 0·02 second have been developed. Experience has shown that magnetic inertia is an important factor in the times taken to operate high-speed relays and to reduce this to the smallest practicable value it is necessary to force the magnetic circuit by increasing the ampere-turns. It is, however, impossible to eliminate entirely the time delay, and so-called high-speed relays have a certain time delay which varies inversely with the operating current, but not, of course, to such an extent as will produce an inverse time characteristic approaching that of time-graded relays. As the magnitude of the fault current can, in general, be taken as an indication of the disturbing effect of the short-circuit, the slower operation at lower current values is not a serious disadvantage. High-speed directional relays are designed to remain in the inoperative position during normal conditions by providing the relays with a voltage element which will develop a backward torque on the moving element. This torque is proportional to the square of the system voltage and will be sufficient to hold the relay against the torque developed by the wattmeter element during normal load, but will be insufficient to hold it during short-circuits when the voltage is low. One of the objections to very high-speed relaying was that it might cause the loss of healthy sections during transient conditions which accompany short-circuits on other parts of the network, but with modern stabilising methods this possibility has been reduced to a minimum. When all the relays of a system have approximately equal operating times, since there is no time-grading, other methods are adopted to ensure discrimination between successive stages ; these are : (*a*) differential or balance method, (*b*) locking method. Systems in which the relay operating times are automatically adjusted are virtually time-graded, the low operating times of the relay nearest to the fault being obtained by a (*c*) distance-measuring method.

Differential Protection

Protective systems employing the differential or balance method consist of equipment for comparing the current entering with that leaving the protected zone ; or for comparing the currents flowing in two parallel circuits.

With differential systems the relays respond only to the difference between currents which are normally equal, and operate in the minimum period of time practicable. The principle involved is that of maintaining either a voltage balance, or a current balance between the two ends of the circuit under normal conditions, and utilising any out-of-balance current resulting from a departure from normal to operate the protective relays. The difference between the two methods is illustrated in Fig. 169. For voltage balance the secondaries of two current transformers are connected in opposition, so that current only flows when there is any difference in the voltages e_1 and e_2 induced in the secondaries. For current balance the secondaries are connected in series, but not in opposition, so that a circulating current is a normal condition. Two points normally at the same potential are joined together, but this cross circuit will only carry current when the currents in the secondaries, i_1 and i_2, and therefore the primary currents are different.

The maintenance of a balanced condition in the C.T.'s of a differential protective system depends on there being the same value of current entering the circuit at one end as there is leaving it at the other. Thus, with certain exceptions, differential systems are applicable to straight-through circuits, such as feeders between two switching points, etc., and transformers; which, however, usually require special arrangements of relays, etc.

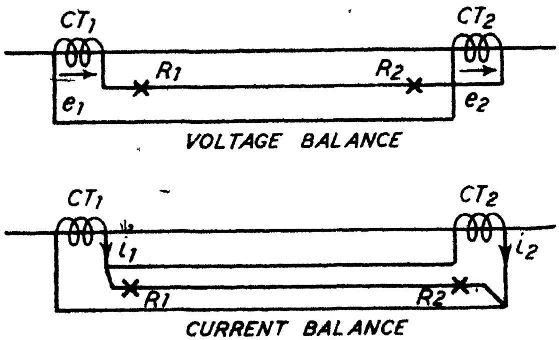


Fig. 169.—PRINCIPLES OF DIFFERENTIAL PROTECTION

In the case of a circuit supplied from one end only a fault on the protected section results in only the C.T.'s at that end being energised, thus producing the condition of unbalance required for relay operation. When the circuit can be supplied from both ends the polarity of the C.T.'s at the reverse current end will also be reversed, since current is flowing into the fault in both directions, thus operation will be ensured. Differential systems protect against any kind of fault, but in the case of limited earth faults, relay operation depends on a low current setting being obtainable if the circuit is to be disconnected when the fault is in its incipient stage.

The inherent defect of differential systems, which in the past led to instability on heavy through-faults, and often, inadvertent operation, lies in the fact that it is practically impossible to design ordinary current transformers so that they balance exactly, not only initially, but permanently. For this reason modern differential protective systems employ either distributed-air-gap C.T.'s or specially arranged relays and circuits, which are designed so that a restraint is applied to the relay under through-fault conditions, proportional to the current flowing, to oppose the out-of-balance current due to the C.T.'s, tending to operate the relay. With current transformers, in order that the induced voltage shall be proportional to the line current, it is essential that the magnetic circuit shall not reach saturation. This is effected in the distributed-air-gap C.T. by providing a number of air gaps in the iron core. By this means the voltage characteristic obtained is a straight line as it is independent of the quality and state of saturation of the core, which is, in fact, never saturated under service conditions. To secure initial matching, the transformers are balanced against a standard, and to ensure that there shall be no change of characteristics in service, they are enclosed within a magnetic shield which prevents neighbouring iron affecting the distribution of the flux.

Biased Relays

A satisfactory method of ensuring that high-speed differential protective gear will remain stable during through-fault transient conditions is to incorporate an electrical bias which increases with the magnitude of the through-fault current. This method is widely used with modern systems as it possesses the additional advantage of compensating for unavoidable variations in the normal characteristics of current transformers or any other temporary unbalance in circuits which may have to carry heavy through-fault currents.

With biased schemes induction disc or beam-type relays are used and controlled by two coils producing opposite torques on the moving element. Thus one coil restrains the moving element whilst the other tends to operate it so that by suitable arrangements of secondary connections, on through-faults, the restraining coil counteracts the effect of any current appearing in the operating coil, but when a fault occurs within the protected zone the protective system is so designed that the torque due to the operating coil is far greater than that of the restraining coil, and high-speed operation is ensured. A typical biased induction relay is shown in Fig. 174, and its application in Fig. 175. Another system employing biased induction relays is illustrated in Fig. 178. Beam-type relays consist of a moving beam element which is normally balanced on a pivot by a restraining coil at one end and an operating coil at the other (see Fig. 176 for a typical application). Biased relays are also used for high-speed earth-fault protection of machines and transformers by the residual current principle, as with this type of relay the inherent simplicity of this form of protection is retained without the relatively long time delays required with time-graded relays. In the protection of single feeders, the difference between the magnitude of the current entering a healthy feeder and that leaving the feeder may, due to line capacitance, become of consequence. This difference, though perhaps unimportant at normal frequencies, may cause incorrect operation of relays at the higher transient frequencies which arise during or immediately after short-circuits. To obviate incorrect operation from this cause, an electrical bias feature may be used, the torque due to which increases with frequency ; or relays tuned to respond to normal frequency only may be employed. If the differential scheme is of the opposed-voltage type as distinct from the circulating-current type, it is necessary to prevent operation due to charging current in the pilot wires. As the latter will not reach a dangerous magnitude unless the feeder is overloaded, the through-current bias feature will be effective in overcoming this difficulty.

Locking Systems

Protective systems obtaining discrimination by the locking method employ directional, overcurrent, and earth-fault elements in combination.

The relays are of a high-speed type, selective operation being attained by preventing the circuit-breakers, not associated with the faulty zone, from tripping on through-faults by a locking signal controlled by the directional relays. The locking signal is sent over a pilot, but the advantage of the system is that only a communication type of circuit is required, so that where this already exists and is used for, say, telephony, the pilot is automatically borrowed immediately a fault occurs, for the transmission of the locking signal. Another arrangement makes use of the main transmission lines by superimposing the signal on the high-voltage conductors. A high-frequency transmitter and receiver are installed at each end of the protected feeder, both being permanently in service and connected to the high-voltage lines through coupling condensers. The transmitters are controlled by the interlock relays so that the locking signal is only initiated under through-fault conditions. Tuned choke coils at each end of the feeder confine the signal currents to their particular section, a different frequency being used for each zone.

Distance Protection

Distance-measuring methods of protection are based on the time-graded principle, but the time delay is automatically adjusted so that it is, for each stage of protection, proportional to the distance between the relay and the fault. Thus, the more distant the relay the slower will be its operation. The distance is measured in terms of impedance or reactance, by voltage and current operated devices in combination. In the case of impedance systems the time delay of each relay is directly proportional to the voltage, and inversely proportional to the fault current at the point of its location. The voltage at each stage will depend on the position of the fault, there being a voltage gradient from the source of supply to the fault, where the voltage may be practically zero. Thus the time delay $t \propto E/I \propto Z \propto d$ where d is the distance of the fault from the relay. Although simple in principle, distance-measuring systems used in practice consist of complicated combinations of relays ; consequently they cannot be described without entering into lengthy detail which is mainly of interest to the specialist. This also applies to certain other forms of high-speed protection : for this reason only the simpler forms of protection are dealt with in the following pages.

Feeder Protection

Time-graded protection is often applied successfully to distribution network H.V. feeders, and simple lower-voltage systems generally ; but for important circuits some form of protection employing high-speed relays is adopted. Systems utilising special pilots have the advantages of simplicity and rapidity of operation with a high degree of stability. The one disadvantage is the cost of the pilot, for which reason long main

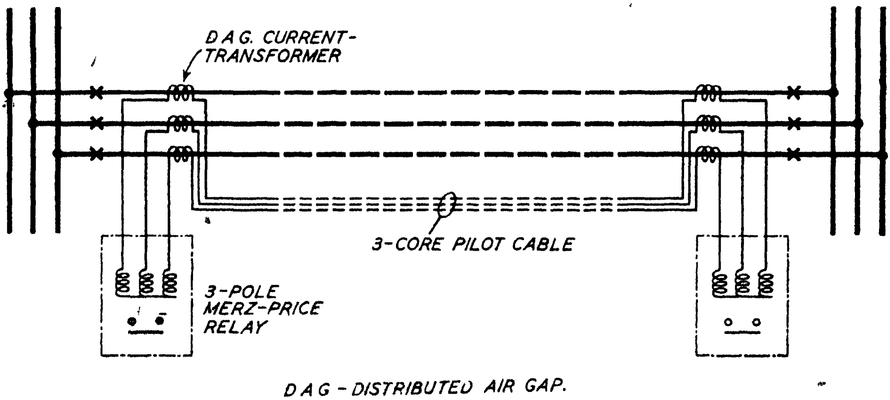


Fig. 170.- MERZ-PRICE FEEDER PROTECTION

transmission lines are generally protected by distance or interlock systems —mentioned above.

All protective schemes using special pilot cables are of the differential class.

The Merz-Price system operates on voltage balance ; a typical circuit is shown in Fig. 170. Three D.A.G. C.T.'s are installed at each end of the feeder, the secondaries being connected in opposition through a three-core pilot cable. Under normal conditions, and with through-faults the secondary voltages of the C.T.'s at the opposite ends of the feeder, balance, and no current circulates in the pilots, or in the relays. In the event of an internal fault the E.M.F.'s of the protective C.T.'s are no longer equal, current circulates in the pilots, and the relays at both ends operate to trip their associated circuit-breakers. The relays are of the electro-magnetic type and are instantaneous in action.

This system has been extensively employed and has proved very satisfactory on short feeders, and where the through currents are relatively small. However, for feeders of more than about 5 miles in length, or where the short-circuit currents are more than, say, 5,000 amps., the capacity currents which flow from core to core of the pilot cable become sufficiently high to cause incorrect operation of the relays under through fault conditions. The Beard-Hunter system (Fig. 171) which is basically the same as the Merz-Price, avoids the effect of capacity currents by the addition of a metallic screen around each core of the pilot cable. The capacity current, therefore, flows from the pilot core to the screen, and not through the relay. The system can be applied to feeders up to about 20 miles in length and where the through short-circuit currents do not exceed about 10,000 amps.

The Ferranti-Hawkins system of opposed voltage feeder protection

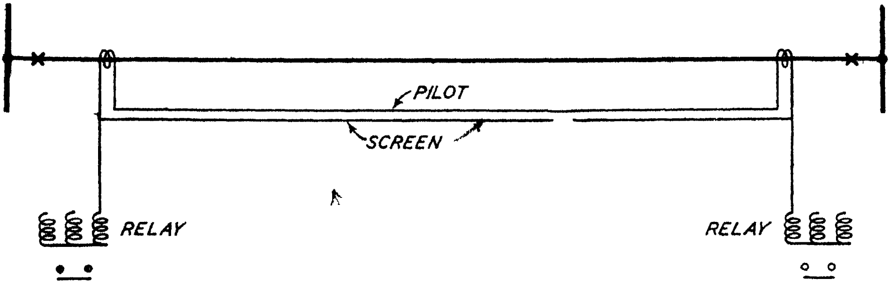


Fig. 171.—Beard Hunter Protection (Single-line Diagram)

employs core-balance C.T.'s (dealt with previously—see page 244). A diagram of connections for the gear is shown in Fig. 172, from which the operation will be apparent.

The self-compensating pilot wire feeder protective system (Fig. 173) developed by the British Thomson-Houston Company operates by circulating current. The risk of false operation due to capacity currents in unsheathed pilot wires has been overcome by means of a patented "pilot compensator," a simple static transforming device which can be applied to indoor or outdoor switchgear. Inadvertent relay operation due to high-frequency disturbances has been eliminated by the use of a relay insensitive to current of any frequency other than that approximating to the normal system frequency. This is achieved by using a vibrating reed relay which is tuned to the frequency required.

Under normal load conditions the voltage impressed on the pilot

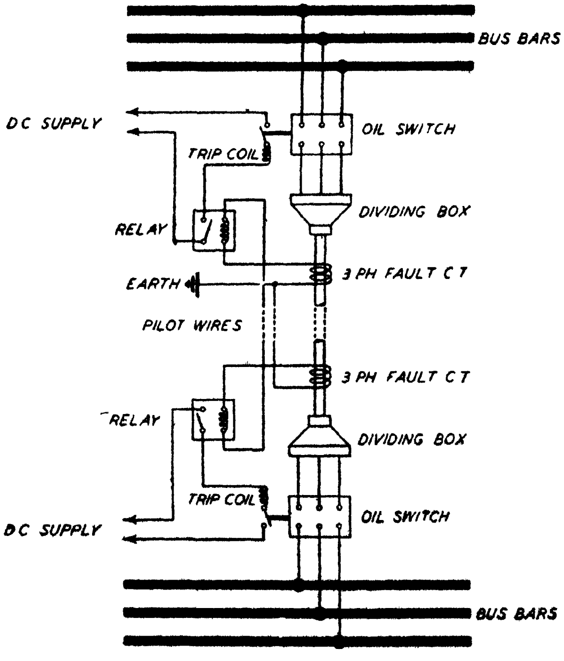


Fig. 172.—Connections of Ferranti-Hawkins Feeder Protective Gear wires used in the self-compensating system seldom exceeds 10 volts. Referring to the schematic diagram shown in Fig. 173, the operation of the system is as follows: At each end of the feeder, the secondary windings of the three C.T.'s, one to each phase, are connected to the conversion transformer of the pilot compensator. The single-phase current induced in the secondary of the conversion transformer at one end of the feeder is made to circulate, by means of the two outer pilot wires, with the single-phase current induced, in a similar manner, in the secondary circuit of the conversion transformer at the other end of the feeder.

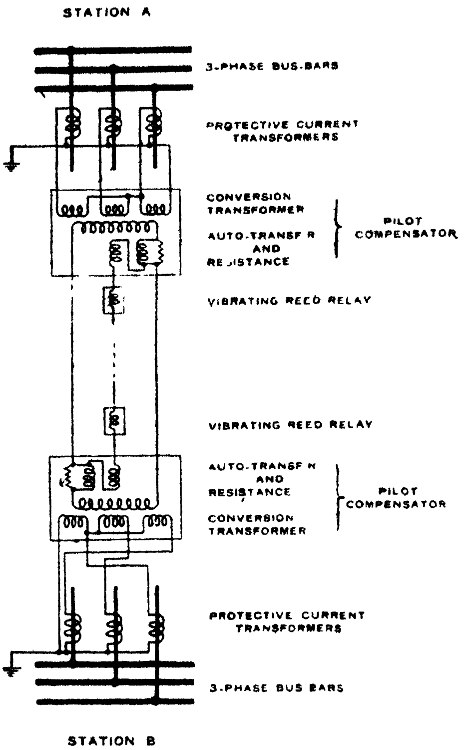


Fig. 173.—SCHEMATIC CONNECTION DIAGRAM OF B.T.H. SELF-COMPENSATING PILOT WIRE PROTECTION FOR A 3-PHASE A.C. FEEDER

The relays are connected one at each end of the centre pilot wire between equipotential points. Therefore, while the feeder is operating under healthy conditions, no current will flow in the centre pilot wire, and the relays will not be energised. Under normal healthy feeder conditions, a current of approximately 100 milliamperes flows in the circulating circuit formed by the outer pilot. If a fault occurs on the protected section of the feeder, the currents entering at one end will no longer be equal in magnitude to those leaving at the other end. This will disturb the balance of the circulating circuit formed by the two outer pilots, causing a current proportional to the difference between the incoming and the outgoing primary currents to flow in the centre pilot wire. When this current reaches a value corresponding to the setting of the relays the latter will operate and complete the tripping circuits of the O.C.B.'s concerned. The effect of capacity between unsheathed pilot wires is neutralised by means of two series resistances, equal in ohmic value, one at each end of the feeder.

The G.E.C.'s biased differential system for the protection of feeders uses the special relay shown in Fig. 174. By virtue of the differential

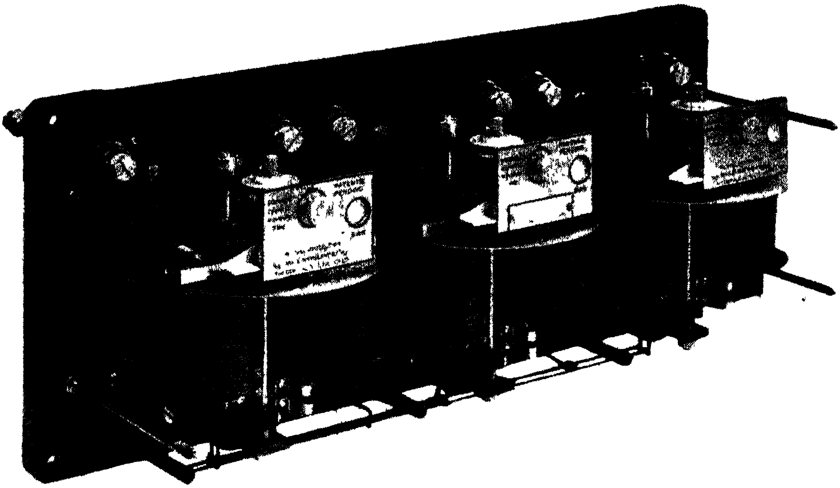


Fig. 174.– Biased induction relay. (*General Electric Co., Ltd.*)

connection of the coils, the fault current required to operate the relays increases in a fixed percentage with the load. The scheme is illustrated in single-phase form in Fig. 175. A " dummy " circuit is used at each end, containing the operating coil of the induction relay, together with a duplicate " resistor " having a resistance equal to half that of the single pilot wire. The pilot circuit is connected to the C.T.'s as an alternative path for the secondary current, and includes both restraining windings. All the relay coils have the same number of turns. The operating and restraining torques on the induction disc of the relay are derived from two separate electro-magnetic moving fields, which are produced by the relay operating and restraining coils respectively. The bias in favour of the restraining coil is obtained by suitably positioning the copper shading turns attached to each core limb, the bias usually being 25 per cent. for feeder protection.

It will, therefore, be seen that the pilot circuit, while having just twice the impedance of each dummy circuit (the return path for the pilot current being assumed to have no impedance), has two current transformers in series to drive the current through it, as compared with only one for each dummy circuit. Thus the secondary current from the transformers divides equally between the two circuits when the feeder is in a healthy condition, and, in consequence, the torques of the operating and restraining coils of each relay are identical. In the case of a feeder supplied from one end only, when a fault occurs the current in the C.T. circuit at the sending end will be greater than that in the C.T. circuit at the receiving end. There are again two paths open for the excess current, but

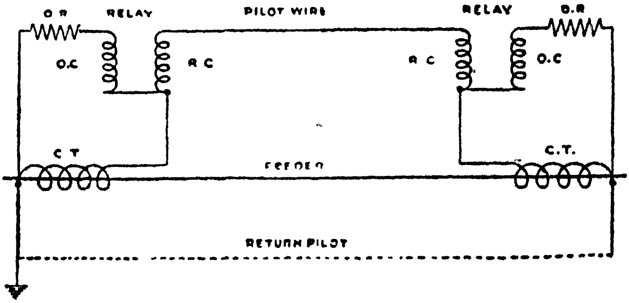


Fig. 175.—SINGLE-PHASE ARRANGEMENT OF BIASED DIFFERENTIAL SYSTEM

O.C. = Operating coil. R.C. = Restraining coil.
D.R. = Duplicate resistor.

that through the operating coil of the relay at the sending end has only one-third of the impedance of that through the restraining coil, which includes the two relay coils and the duplicate resistance at the receiving end. Three-quarters of the excess current, therefore, passes through the operating coil, and one-quarter through the restraining coil, and the relay tends to operate. As the torques of the operating and restraining coils can be assumed to be proportional to the square of the current, the torque of the operating coil is very nearly proportional to the load plus the fault current, and that of the restraining coil proportional to the load current only. The relay will trip when the fault current reaches 25 per cent. of the load current flowing at the time. When the feeder can be supplied from both ends the polarities of the C.T.'s will be in opposition so that the current through the restraining windings will be comparatively small, and both relays will operate.

The application of the Metropolitan-Vickers "Translay" system of feeder protection is also based on the use of a special type of biased relay. The scheme is generally similar to that which is adopted for the protection of power transformers, which is described in a later section.

Parallel Feeder Protection

The protection of feeders by differential methods in which the current entering the protected zone is compared with that leaving necessitates the use of a pilot cable running the whole length of the circuit. For long feeders this is a very expensive arrangement, and other schemes may be employed. Where there are duplicate feeders in parallel the pilots can be avoided by comparing the currents of both feeders at the same end. Under normal conditions the currents in the feeders are equal, but should a fault occur on one, this will no longer be the case, and the relays associated with the faulty circuit will operate due to the disturbance of the balanced conditions normally existing in the interconnected secondary circuits of the protective current transformers. At the sending end of the parallel feeders there will be only a difference in magnitude of the currents ;

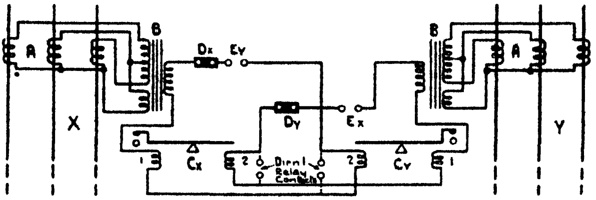


Fig. 176.—SCHEMATIC DIAGRAM SHOWING METHOD OF HIGH-SPEED PARALLEL FEEDER PROTECTION USING BEAM-TYPE RELAYS

A = Line-current transformers.
B = Auxiliary summation transformers.
C = Beam-type high-speed relays having operating coils 1 and restraint coils 2.
D = Contacts of high-speed auxiliary relays or tripping relays.
E = Auxiliary contacts on feeder circuit-breakers. (*Journal I.E.E.*)

but at the receiving end, since current is being fed into the fault by the healthy feeder, the currents will also be flowing in opposite directions. With one modern system of high-speed parallel feeder protection (Fig. 176), when both feeders are healthy, the relay associated with either is biased against operation by the summated load currents of the other, and both relays are inoperative. When a fault develops on one feeder the secondary current will cause its relay to operate and in addition will produce a larger restraint bias in the relay on the healthy feeder. As the magnitude of the currents may, when the fault is near the receiving end of the feeder, be practically the same, directional relays are used at the receiving ends. The directional relay of the faulty feeder closes its contacts to short-circuit the bias coil of the beam relay which then operates to trip the breaker at the receiving end, after which, as the feeders are no longer paralleled at both ends, the difference in the magnitude of the currents at the sending ends operates the relay of the faulty feeder. To prevent the healthy feeder tripping when the faulty feeder clears—since the interruption of the current will remove the restraining bias from the relay of the healthy feeder—a high-speed relay is energised in parallel with the trip coil of the faulty feeder circuit-breaker. The contacts of this relay interrupt the operating-coil circuit of the sound feeder relay until an auxiliary switch, also controlling this circuit, of the faulty feeder breaker opens.

Transformer Protection

The type of protection adopted for any transformer depends on its capacity, the importance of the service for which it is used, and its electrical position on the network. This will decide the possible short-circuit current; with low network impedance even the smallest transformers must be equipped with quick-acting efficient protective gear. Distribution transformers, which category includes all units with high-voltage primaries and low-voltage secondaries, are usually protected by some form of overcurrent protection in conjunction with circuit-breakers or fuses. For rural distribution both H.V. and L.V. fuses are used as an economical alternative to circuit-breakers. The instantaneous characteristic of a fuse above a certain current is an asset when only one stage of fuse protection is used, as, for instance, when transformers are "teed" off an H.V. feeder. With this arrangement the current to blow the fuse will be small compared with the overcurrent setting of the H.V. feeder relay, which precludes any possibility of a limited transformer fault tripping the feeder circuit-breaker. Oppositely, a low impedance fault on the H.V. side of the transformer will be practically equivalent to a fault on the feeder, producing instantaneous operation of the fuse. Actually a circuit-breaker with automatic protection would take about half a second to clear the same fault, and necessitate a longer time setting of the feeder relay than would be needed with H V. fuses.

For tripping the O.C.B. associated with the H.V. side of a distribution transformer the most elementary device is the direct-acting solenoid, used as a trip coil, energised from the current transformers. Delayed action is achieved either by dashpots, or time fuses. The L.V. side of the transformer is protected by fuses, or a circuit-breaker interlocked with the H.V. switch so that when this trips the L.V. side is disconnected from the network.

This may be effected by an auxiliary switch on the H.V. breaker, which closes, when the breaker trips, to energise a trip-coil on the L.V. breaker. Some form of inter-tripping is customary with all transformers, so that if either the primary or secondary breaker trips, the other is likewise tripped. With overcurrent protection the protective C.T.'s are connected in the leads to the primary winding, as it is obviously unnecessary to install separate overcurrent protection for the secondary as well, this being disconnected by means of the inter-tripping.

When several transformers are in parallel on the distribution network, a faulty unit will be cleared on the L.V. side by the excessive current flowing through the L.V. breaker into the fault. Should the fault and network conditions be such that the current value is too low to trip the L.V. breaker, but sufficient to operate the H.V. protective device, the secondary will be disconnected by the inter-tripping. With transformers in parallel, however, the breakers of the healthy units may also trip with fault currents above a certain value if the L.V. protection is not sufficiently discriminative. For instance, when there are only two transformers in parallel the healthy unit will supply all the fault current flowing into the defective unit via the L.V. network, which means that it also will trip out. In some circumstances this condition may be acceptable if the supply is relatively unimportant, but if really discriminative protection is required the L.V. protective device must have a definite and adjustable operating time, even with the maximum short-circuit current.

The value of the current flowing into a defective transformer is determined by the position of the fault. A fault across the H.V. terminals will produce the maximum current through the primary protective C.T.'s, but the current flowing into the fault through the L.V. network will, in the case of two transformers in parallel, be limited by the total impedance of the two units in series. Thus, if the L.V. protection has a definite minimum time of operation sufficiently long, the H.V. breaker will trip and clear the interlocked L.V. breaker by means of the intertripping and the breaker of the healthy unit will not be tripped. This condition can be achieved by using L.V. C.T.'s and some form of relay with a definite minimum time characteristic, but such an arrangement is, for transformers of low capacity, comparatively expensive. With a minimum of three transformers in parallel an attracted armature device with a compression-type dashpot will provide an ample margin between the fault clearance time of the defective unit, and that required to trip the L.V. breaker of each of the other units in parallel, since these share the total fault current between them. This will be appreciated by considering Fig. 155. Assuming three transformers in parallel, with a given fault current, this will be shared by the two healthy units, and from the curve corresponding to the dashpot setting the time-delay margin can be determined.

To obtain discriminative tripping of the breakers on the secondary side with only two transformers in parallel, directional protection is sometimes applied—especially to bulk supply units, i.e. those with both a high-voltage primary and secondary. A typical arrangement of relays and protective transformers is shown in Fig. 168. In this case it will be noted that directional earth-fault protection is also adopted, thus ensuring disconnection with any class of fault. The directional protection is, of course, installed on the secondary side of the unit, which in this case is the higher-voltage winding, as the transformer is stepping-up. The lower-voltage primary would be protected by some form of overcurrent and earth-fault gear, or might, if associated directly with an alternator, be included in the zone covered by the alternator protection.

Application of Earth-fault Protection

Since a large proportion of H.V. transformer faults are earth faults—or originate as such—earth-fault protection (not necessarily directional) is customary for the windings of transformers which are connected to earthed networks. An earth connection at the source is, of course, essential for protective gear operating by earth-leakage to function. For the purpose of earth-fault protection each transformer winding is independent, so that this can only be applied to both windings separately if the network to which the primary is connected is earthed at a supply point, and if the secondary winding itself is earthed. The earth-fault relay on the primary side will only operate in the event of a fault on the primary winding, and vice versa.

In the case of small transformers where protection is by means of solenoid trip coils directly energised from the C.T.'s, earth-fault protection is often effected by one of three trip coils which is wound for more sensitive operation, and is connected between the star points of the three C.T.'s and the two overcurrent coils. With earth-fault protection there is always a chance of reducing damage and disturbance to a minimum by disconnecting the transformer before the fault develops. One definite advantage is that earth faults on the primary will be cleared by the H.V. breaker tripping, the L.V. breaker being opened by the inter-tripping without any tendency to trip the breakers of the other units in parallel, since earth-fault protection is stable on through faults. This will not remove the possibility of phase faults tripping the healthy transformers, in the absence of discriminative overcurrent protection.

To obtain complete earth-fault protection the network, in the case of earth-fault protection of the primary winding, must be earthed at a point of supply (alternator or transformer) either solidly, or through a resistance or reactor of comparatively low value ; and in the case of the secondary winding this must itself be earthed in a similar way. With a high resistance to earth a large part of the windings is unprotected against earth faults. For example, with a resistance that passes only half full-load current with phase voltage across it, and relays which are set to operate at 15 per cent. of full-load current, only 70 per cent. of the winding is protected as, even a dead earth, at a point at which the potential to earth is less than 30 per cent. of the phase voltage, will not cause an earth current sufficiently large to operate the relays. The usual practice is to install an earthing resistance designed to pass full-load current with phase to neutral voltage. Solid earthing is used for extra high-voltage systems and in situations where the resistivity of the earth circuit is high ; in any case the resistance of the earth-plate alone may be from 1 to 4 ohms.

A system of earth leakage and overcurrent protection is often used for large transformers, sensitive relays being used and careful attention given to the relay settings. Fig. 164 shows a typical arrangement for a delta-star unit. The primary is protected by three overcurrent elements (which will operate on secondary phase faults as well), and an earth-fault relay which will only be energised when there is current leakage to earth from the primary. To protect against earth leakage from the secondary winding another relay is connected as shown. This is different from the arrangement shown in Fig. 163 in that there is a fourth C.T. in the earthed neutral. This is necessary to ensure stability of the protective system when an earth fault occurs on the network supplied from the transformer ; without it the fault current returning through the earth circuit would produce an out-of-balance current in the relay as the sum of the three C.T.'s currents would not then be zero. With the four C.T. arrangement the sum of the currents is always zero except when a fault occurs within the zone of the secondary winding.

Circulating Current Gear

Circulating current protective gear gives a very high degree of protection, as with this class both light fault settings and rapid operation are obtained. The form of circuit used is shown in Fig. 177, a standard connection. To take advantage of the low potentials arising when the fault current is low a sensitive relay is necessary, but at the same time, owing to the fact that when a transformer is switched-in the magnetising current may, for a number of cycles, attain values comparable with or in excess of full-load current, some means may be provided to make the relay insensitive during the switching-in period. " Kick-fuses " shunting the relays have been used, these being cut-out of circuit after the switching-in, either by hand or by an auxiliary relay arranged to operate after a suitable interval of time : but the present tendency is to employ a low-energy type overcurrent relay with a time setting long enough to prevent the trip contacts closing before the switching transient has subsided.

Apart from switching transients instantaneous relays also tend to operate with voltage fluctuations due to disturbances on the system, and heavy overcurrents in the transformer resulting from through-faults, which are likely to produce unbalancing in the C.T. secondary circuits. With an overcurrent relay inadvertent operation can be prevented by providing a time setting which will allow the circuit-breaker on the network to clear a fault outside the protective zone of the transformer before the relay of the latter closes its contacts.

With the combination of C.T.'s and relay shown in Fig. 177, to protect against excessive current on through-faults or faults in the zone not covered by the circulating current protection, that is in the connections to the circuit-breakers and the busbars, fuses inserted in the pilot wires blow at the particular overcurrent value required. This does not affect the differential protection normally, but when the fuses blow the current balance is upset and the relay functions as an overcurrent relay with the appropriate time delay, being energised from the primary C.T.'s only. For the protection of a transformer with star-delta windings the protective C.T.'s will be connected delta-star to allow for the phase difference between the primary and secondary currents. Delta-star main connections will necessitate star-delta C.T. connections ; the latter being

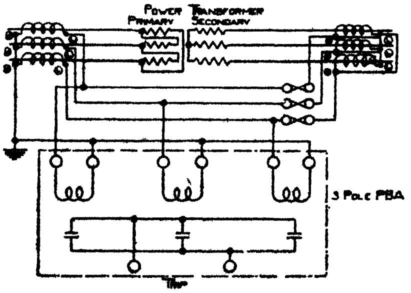


Fig. 177.—CIRCULATING CURRENT TRANSFORMER PROTECTION USING A LOW-ENERGY THREE-POLE RELAY always opposite to the power transformer connections. The C.T. ratios are such that the circulating currents are equal ; and are the same as the ratio of the currents in the power transformer, allowing for the difference in the method of connection. When this form of circulating protection is used for transformers fitted with tap-changing gear one set of protective C.T.'s must also be tapped so that it is possible to change their ratio to correspond with the change in the power transformer ratio. To avoid this complication other methods have been devised which retain all the advantages of the circulating current method of protection. Some methods are similar in principle to those employed for the protection of feeders, stability being achieved by utilising a biased form of induction relay which is restrained by any normal out-of balance current flowing through the circuit.

“ Translay ” System

The “ Translay ” balanced protective system is a typical example of the application of biased relays, which can be modified so as to be effective both for feeder protection, and for power transformers with on-load tap-changing gear, without tapped C T.'s being required. Another feature of the “ Translay ” relay is that it has an inverse time characteristic whereby operation can be delayed to prevent the contacts closing during switching-in, this characteristic being adjustable to suit individual power transformers. At heavy fault currents the operating time is reduced to 0·25 second at full setting and proportionally lower times at lower settings.

A typical “ Translay ” scheme is shown in Fig. 178. In its main features the relay used resembles an induction watt-hour meter of orthodox design, but differs in that it has no voltage winding, this being replaced by a current winding (11 in Fig. 178) connected to the line C.T. In Fig. 178 this winding of the top element of each relay is connected to the two outer phases, and the winding of the bottom element of the same relay is connected to the middle phase. The winding 11 acts as primary to a small secondary winding 12 on the same limb of the electro-magnet, the two windings thus forming a small transformer. The secondary winding is in series with the winding 13 on the lower electro-magnet, and the two windings are also connected in series with the pilot wires, as shown in the figure.

Any current induced in winding 12 circulates through winding 13 by way of the pilot wires, and the flux thus produced in magnet 16, being in quadrature with the leakage flux from magnet 15, a moving magnetic field is set up which interacts with eddy currents induced in the disc (not shown) thereby producing a torque in this tending to rotate it to close the trip contacts. Under healthy conditions the line C.T.'s at opposite ends of the transformer supply equal currents in the windings 11 and 11A, which induce equal E.M.F.'s in the windings 12 and 12A respectively ;

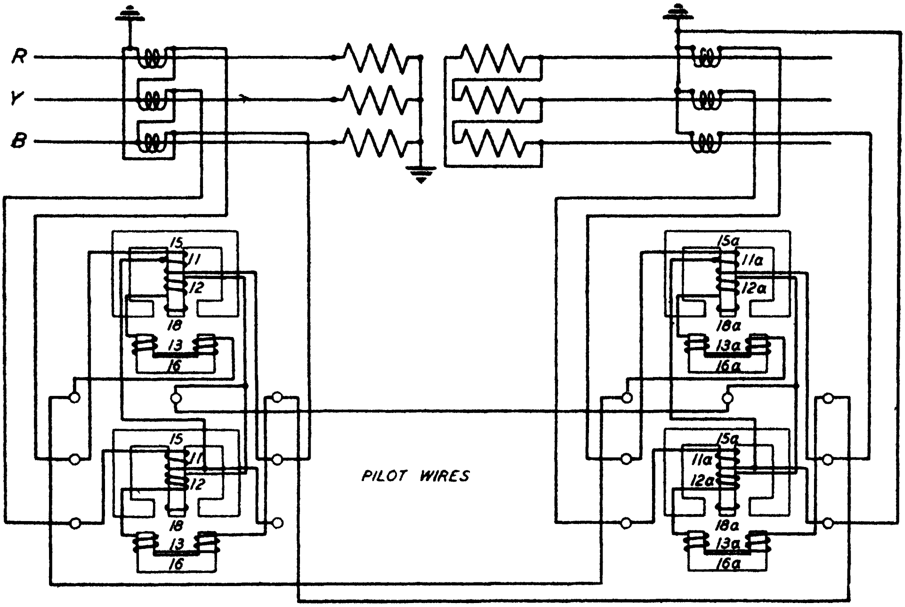


Fig. 178.—Circuit diagram of "Translay" balanced protection

but as these E.M.F.'s are of opposite polarity no current flows through coils 13 and 13A except that due to normal conditions of unbalance of the C.T.'s, and of the power transformer, which is reflected in the former. To compensate for this, copper loops 18 and 18A are provided which, besides counteracting the lack of balance between C.T.'s, are also arranged to give the relay a bias to counteract the effect of any changes in transformation ratio due to tap-changing.

Under normal conditions any current circulating in coils 13 and 13A, due to the partially unbalanced state of the circuit, is of no significance, but when a heavy load or through-fault current causes the induction in the magnet to be high, an appreciable forward torque is exerted on the relay disc. In these circumstances the current induced in loops 18 and 18A causes a backward torque to be exerted on the disc, thus counteracting the tendency towards forward operation. When a fault occurs in the transformer the E.M.F.'s induced in coils 12 and 12A are no longer equal and opposite, and a much greater current circulates round windings 13 and 13A via the pilot wires. The de-magnetising effect of the current in coils 12 and 12A is correspondingly large and the loop 18 and 18A is then influenced by a much-reduced flux, and the counter torque is proportionally less. Briefly the effect is that, under fault conditions, the operating torque in the elements of both relays is equal, since the same value of current circulates through windings 13 and 13A, but the counter torque, due to the current in windings 11 and 11A affecting the loops 18 and 18A, will depend upon the position and the nature of the fault in the transformer. Thus, one element at least of either relay will operate under any fault condition. Each relay is provided with double circuit trip contacts to trip simultaneously the circuit-breakers on both sides of the transformer.

Buchholz Transformer Protector

Most transformer protective devices depend for their operation on the existence of abnormal current or temperature conditions. The Buchholz Protector (Fig. 179) is a device operating on the principle that every kind of fault in a transformer results in a more or less violent generation of vapours or gases. With this device it is claimed that faults can be detected in their incipient stages, thus reducing the damage caused and effecting a valuable saving in the time taken for repair. As the device is sensitive to the presence of gas to such a degree, in certain cases, the alarm given may actually be the means of preventing development of the conditions leading to a fault ; such as a reduction in the oil level due to leaks, or the ingress of air owing to defects in the oil-circulating system. An approximate diagnosis of the trouble may be obtained from the colour of the gas observed through the inspection window. Generally, the Buchholz Protector is fitted only to transformers with conservators, although it can be applied to other types. Various sizes are used to suit any particular transformer.

The protector shown in Fig. 180 comprises a cast housing containing two hinged floats, each fitted with a mercury switch. Normally the housing is full of oil and the floats rotate on their hinges until they engage their respective stops. With a slight or incipient fault arising in the transformer small gas bubbles are generated which, in passing upwards from the transformer, are trapped in the housing of the protector, the effect being that the oil

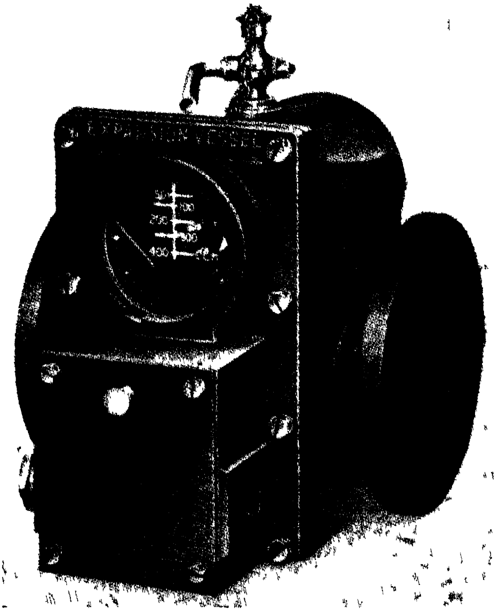


Fig. 179.—BUCHHOLZ PROTECTOR (*Metropolitan-Vickers Electrical Co., Ltd.*)

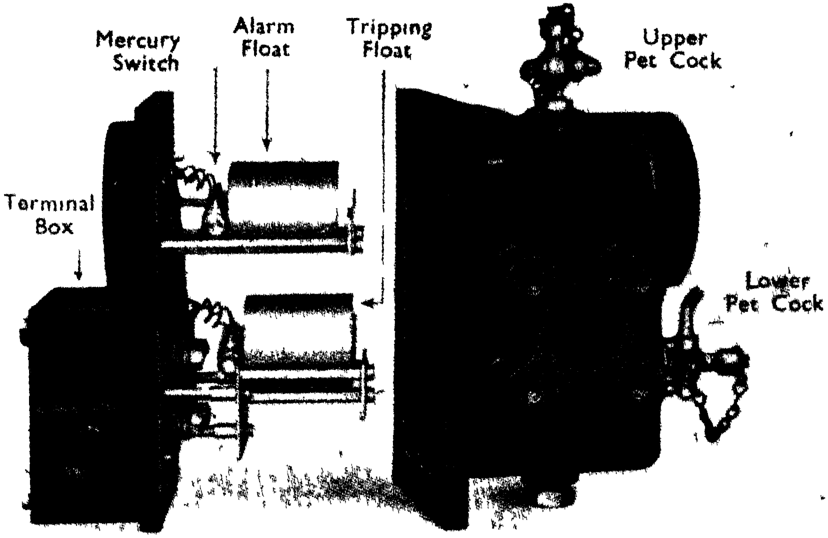


Fig. 180.—Buchholz protector showing internal construction
(*Metropolitan-Vickers Electrical Co., Ltd.*)

level falls since the gas pressure will prevent oil flowing from the conservator. The upper float follows the oil level and rotates to close the alarm circuit by means of the mercury switch. In the event of a serious transformer fault the gas generation is more violent and the oil displaced by the gas bubbles rushes through the connecting pipe to the conservator. The lower float will then rotate to close the tripping contact. Certain types of Buchholz Protector have a shield mounted round the lower float to deflect the larger part of the oil flowing during severe faults. A hole in the centre of the shield permits a sufficient proportion of the oil to impinge on the float under fault conditions.

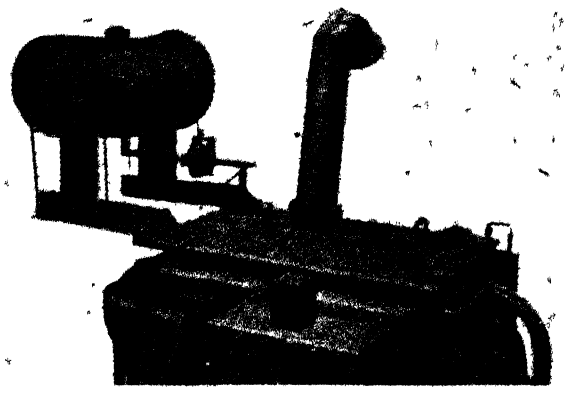


Fig. 181.—Transformer fitted with a Buchholz Protector. (*Metropolitan-Vickers Electrical Co., Ltd.*)

A petcock is fitted to the top of the protector to permit the release of the collected gases, and on the type shown in Figs. 179 and 180 another petcock, fitted to the lower part of the housing, is connected internally to a short length of piping directed against the lower float. This arrangement enables the continuity of the electrical circuits to be tested by connecting the petcock to a compressed air supply. A slow release of air will operate the alarm float while a quick release will operate the tripping float.

For transformers up to 1,000 kVA. capacity a single float protector may be used. The float is so arranged in its housing that it is responsive to either gas collection or oil surges, and the mercury switch may be used for either an alarm or tripping circuit.

Busbar Zone Protection

The zones covered by the feeder and unit protective systems do not, with most substation layouts, include the busbars, the circuit-breakers and the connections between these, since the protective current transformers are located on the line side of the breakers for safety and convenience. In consequence, any fault in the busbar zone must, in the absence of special protection, be cleared by the disconnection of all the circuits feeding into the fault. If overcurrent relays are installed either as first line protection, or back-up, a bus zone fault can be cleared locally by the operation of these ; otherwise the fault may have to be cleared by the tripping of breakers elsewhere on the system. Such an arrangement is likely to lead to serious dislocation of supply, and even the time delay of overcurrent relays operating locally may be too long to be permissible as a general method of clearing bus zone faults on extensive interconnected systems, and some form of high-speed protective system may be installed for this purpose.

Criticism has been made of busbar protective schemes on the ground that these may cause inadvertent total shutdowns and are not, therefore, worth while, as busbar faults are relatively rare. As an alternative to automatic protection, schemes have been devised in which only an indication of the existence of a bus zone fault is given, and breakers are tripped by hand to clear the appropriate section of the switchgear. The objection to this would appear to be the inherent time lag of any fault clearance system which includes a human element. Even although the fault current may be considerably limited by the resistance of the defective insulation, arcing sustained for a few seconds may lead to extensive damage and start fires. Nowadays many bus zone protective systems are giving satisfactory service, being designed for either the rapid disconnection of all the circuits feeding into the fault so that the substation is isolated completely from the rest of the system ; or for high-speed selective tripping with the object of isolating one section of the substation only. With the latter scheme sectionalising breakers and/or duplicate busbars and busbar coupling breakers are required.

Small substations are not usually equipped with busbar protection, reliance being placed upon the protective devices associated with the connected circuits to trip out these and thereby make the busbars dead. In this case the station is, of course, shut down entirely, and since busbar faults are rare the expense of discriminating busbar protective gear is not warranted. For important minor substations in which the switchgear is of the distribution metalclad class, and the layout fairly simple, leakage-to-frame bus zone protection is an effective method of ensuring instantaneous tripping of all the circuits in the event of a bus zone fault to earth. With this scheme the whole of the switchgear metalwork is insulated from all other metalwork by suitably insulating the standards, and by using insulated cable glands. In addition, all control cables, conduits, etc., associated with the gear are provided with insulated glands or joints to prevent fault current flowing to earth along the sheaths or tubing. The switchgear metalwork is bonded together and connected to earth through a current transformer, so that in the event of a leakage to frame, the fault current can only flow to earth along the bonding bar, and must, therefore, pass through the C.T. at the earthed end of the bonding bar. The secondary of the C.T. is connected to a relay which makes one pair of contacts in a tripping relay circuit, and another pair in an alarm circuit. In series with the first pair of contacts is another pair which are controlled by a check relay energised from a core-balance C.T. on an incoming feeder. Thus before the tripping relay will operate both relays must be energised, which will, of course, be the case in the event of a bus zone fault. By using these two forms of protection in conjunction a very high degree of stability is ensured.

With major substations linking important H.V. networks the disconnection of all incoming and outgoing circuits to clear a busbar fault will result in widespread dislocation of supply. To avoid this the present tendency is towards the installation of protective gear which, while perfectly stable on circuit faults, operates on busbar faults to disconnect a section of the switchgear only so that some, at least, of the circuits are kept in service. Busbar protective schemes are, in general, fairly complicated, by virtue of the number of circuits involved and the need to obtain a high degree of stability on external faults. Modern systems are based on some combination of differential and earth-fault protection, and employ a variety of relays, auxiliary switches, transformers, etc.

The principle of operation is, very roughly, that when the busbars are healthy the current flowing into them is the same as the current flowing out, but should an earth fault develop this condition no longer obtains. Most busbar faults originate as earth faults, in fact, some designs of metalclad gear are adopted to ensure this, consequently many bus zone protective systems incorporate special current transformers connected on the residual current principle, in conjunction with relays and circuits for comparing the incoming and outgoing

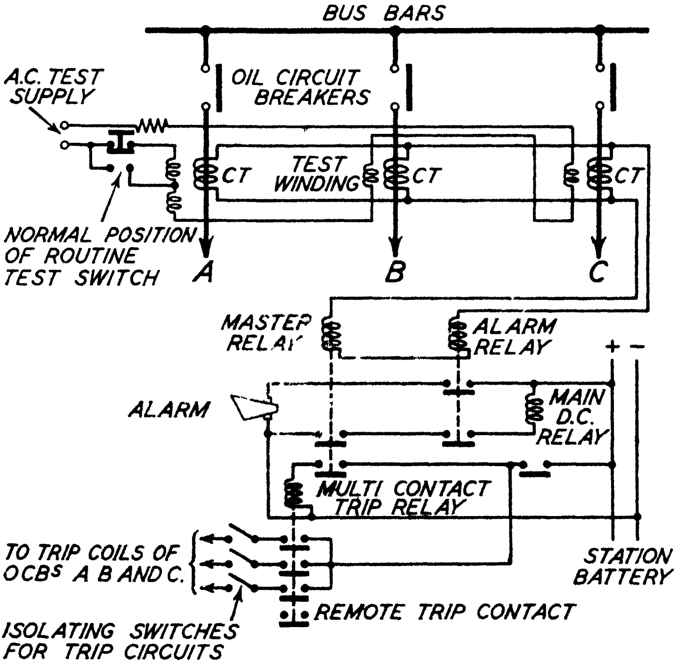


Fig. 182.—SCHEMATIC DIAGRAM OF CONNECTIONS OF THE SELF-CHECK INSTANTANEOUS SYSTEM OF BUSBAR PROTECTION APPLIED TO A SINGLE BUSBAR

currents. When an earth fault occurs in the bus zone the incoming and outgoing currents differ by the amperes which flow back to the source, or sources, of supply through the earth ; and as the busbar protective current transformers of all the connected circuits are paralleled, the secondary current resulting from the unbalance due to an earth fault in the bus zone will be available for the operation of the protective relays.

A system based on the principles of residual current and current balance is shown schematically, as a single line diagram, in Fig. 182. A novel feature of this system—from which its name is derived—is the self-check arrangement which gives an alarm if a defect develops that might make the protective gear unstable. For this purpose testing windings are provided in the current transformers through which a small current is made to circulate in such a way as to assimilate a through-fault. If the protective gear is in order, no current appears in the relay circuit, otherwise a small current flows which, although insufficient to operate the master tripping relay, actuates a sensitive alarm relay.

The particular system illustrated is designed for the rapid disconnection of all the circuits. When selective tripping is required sectionalising and/or coupling breakers are necessary, and the protective gear must be

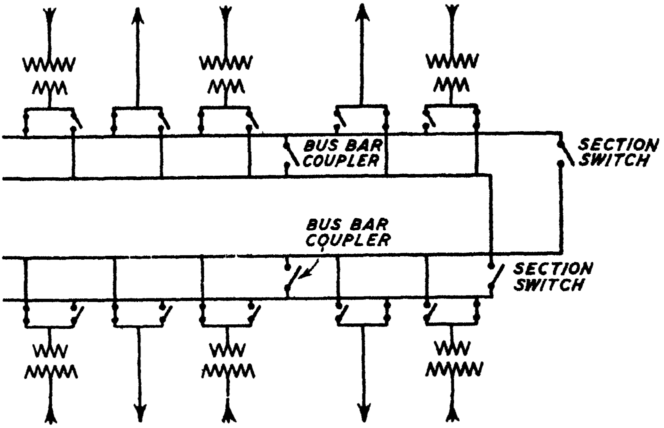


Fig. 183.—ELECTRICAL SECTIONALISING
The transformer and feeder circuit breakers are not shown

so arranged that the first operation when a bus zone fault occurs is the tripping of these breakers ; after which each section becomes in effect an individually protected zone so that, as the secondary protective circuits are also automatically sectionalised, only those main circuits associated with the faulty section are tripped.

The foregoing account of bus zone protection is, of course, very general; in practice the disposition of the main circuits, the interconnections with other stations, etc., influence the type and arrangement of the apparatus. An essential characteristic of this class of protection is absolute stability on through-faults, to ensure which biased relays, locking methods, and combinations of relays of different types are used. In the latter case two distinct protective schemes may be installed, both sensitive to faults in the bus zone, but each selected by reason of inherent stability under particular through-fault conditions so that generally, although inadvertent operation of one protective system may occur, it is highly improbable that both will be effected with any type of through-fault. Thus by connecting the trip circuits of each system's relays in series, tripping of breakers will only be initiated by a fault in the bus zone since inadvertent operation of one system only will not complete the trip circuit. In certain classes of substation where busbar protection is not used the busbars may be sectionalised to reduce the number of circuits paralleled to a minimum, and, thereby, the maximum value of the fault current. With the system layout shown in Fig. 183 a busbar fault is cleared by the tripping of the transformer breakers connected to the section involved.

The disadvantage of such a scheme is that a transformer fault may also make a whole section dead ; but unless the maximum degree of continuity of supply is essential the period of interruption need not be

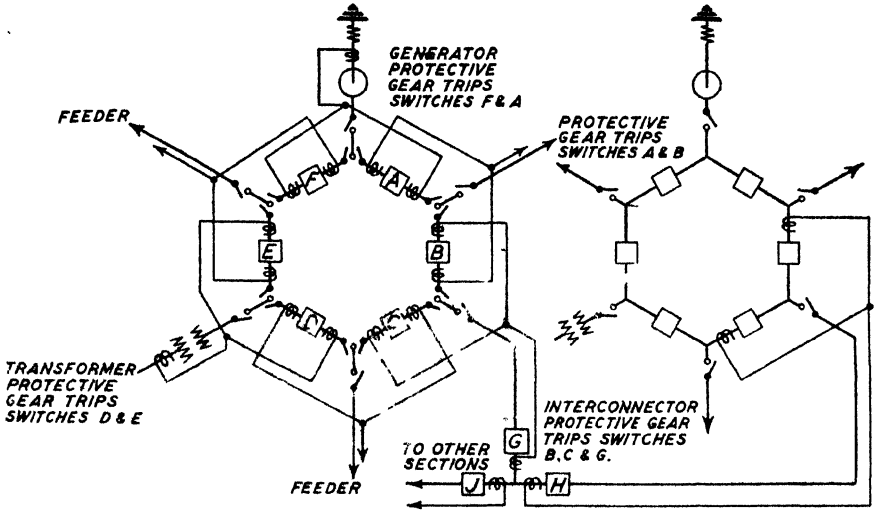


Fig. 184.—Mesh connection of station circuits to eliminate busbars
A to J are automatic O.C.B.'s.

excessive. Generally the other three sections will be undisturbed, and it will be possible to restore supply on the dead section by closing the appropriate breakers. The busbar protection problem has been solved in some cases, e.g. certain Grid substations, by dispensing with busbars altogether and grouping the circuits in miniature ring-mains. This arrangement, known as the mesh connection, is shown in Fig. 184, applied to a generating station—although it can also represent two interconnected substations. The circuit-breakers are connected in the ring-main, and it is necessary for two to trip to disconnect any circuit automatically.

A.C. Protection of Conversion Equipment

The protection of both rotating convertors and rectifiers is usually effected on the H.V. side by overcurrent and earth-fault relays. In the case of rotating machines interlocking may be provided so that: (*a*) unless the unit is arranged for D.C. starting it must not be possible to close the D.C. breaker until the A.C. breaker has been closed. (*b*) Whenever the A.C. breaker is opened it must automatically trip the D.C. breaker (if this has not been done) to prevent the machine from motoring on the D.C. supply.

A special feature of some rectifier equipments is the surge protection against the transient overvoltages which may be produced by the arc, and appear across the secondary windings of the main transformer. To limit the surge voltage to a safe value some form of surge divertor—often a spark gap and resistor in series—is connected across each secondary winding.

D.C. Protection

Equipment for the protection of D.C. machines and circuits is simple compared with that for alternating current. Frequently overcurrent protection suffices ; fuses or circuit-breakers fitted with overcurrent trips being used for the purpose. High-speed breakers are extensively adopted for machines, and for feeders, supplying D.C. systems which are liable to severe short-circuits.

When machines operate in parallel some form of reverse current protection is usually employed to trip the D.C. breakers in the event of excessive current being fed into the machine from the D.C. system as the result of low voltage, relative to that of the other machines feeding the same system ; or the loss of the A.C. supply. Machines in the same station are as far as possible equally loaded and operation of the reverse current protection does not normally occur if the load is steady ; but this is not always the case. For instance, the load on a traction substation may vary from zero to several thousand amperes in a few seconds, or vice versa ; and slightly differing machine characteristics may cause excessive current to flow into a machine during a period of negligible load. Unless the breakers are tripped there is a danger of flashover as the machine is motoring with commutation adjusted for heavy forward load. Since traction substations operate in parallel, to avoid reverse currents of a dangerous magnitude due to the difference in voltage of machines a considerable distance apart, sensitive reverse current protection is essential.

Reverse current protection will also clear internal machine faults from the D.C. busbars more quickly than the overcurrent protection, as low current settings are possible, and may thus prevent the disconnection of other machines, particularly when the conditions are such that the fault would produce current values above the overcurrent settings. Protective selectivity on most D.C. systems is usually obtained by stages of current settings and not time settings.

Reverse-current devices may be integral with the breaker, or take the form of a separate relay. With the first type a current reversal neutralises the flux of a holding coil keeping the breaker in the closed position, or actuates an armature attached to the tripping latch. The first tripping method depends on the creation of a flux, by the reverse current, opposing the holding coil flux ; but with the second method operation of the device depends upon the sum of two magnetic fluxes. One of these is due to a series coil and is variable both as regards direction and magnitude, and the other is due to a potential coil ; its magnitude varies with voltage, but the current, and the flux, are always in the same direction. Normally the two fluxes are in opposition so that the armature is not attracted, but with a current reversal there is a resultant flux available for actuating the armature and thereby tripping the breaker.

The relay type of reverse current device consists of a pivoted coil controlled by a magnetic field. In one type the coil is energised from a potential circuit, and is rotated by interaction with a field obtained from an iron core surrounding a current-carrying conductor, such as a circuit-breaker stud. With normal current flow the coil moves in a direction opposite to that required to close the trip contacts, but when the current reverses the latter trip the breaker by short-circuiting a low-voltage release, or energising a shunt trip coil. The most sensitive form of reverse relay is the type which is essentially a moving coil ammeter with a current coil connected across a shunt ; and a permanent magnet field. Tripping is effected by the closing of a fixed adjustable contact, and a contact on the moving element.

In addition to, or instead of, reverse current protection a centrifugally operated overspeed device may be fitted to the machine shaft to prevent an excessive and rapid increase of speed should the A.C. supply fail and D.C. still be available from the busbars to motor the machine. The overspeed device closes its contacts to trip the D.C. breakers. Low-voltage releases can be used to trip the D.C. breakers in the event of an A.C. supply failure, but generally for important installations their liability to inadvertent operation during momentary disturbances does not recommend their employment.

D.C. Protection of Rectifiers

With rectifiers protection against normal current reversal is not required, as this is not possible ; but in the event of a backfire a rectifier must be disconnected with all speed. In some cases, and generally for small-capacity units, anode fuses have been found to give effective protection against the effects of a backfire. They are now so designed that they do not fuse under ordinary forward short-circuit conditions, but only in the event of a backfire. Various types of H.R.C. fuses are used, but their length is increased—as compared with those for purely A.C. interruption—so as to render them capable of dealing with any D.C. component in the backfire current.

Large rectifiers are usually equipped with high-speed reverse breakers and, sometimes, grid control for the suppression of backfire current. Breakers with operating speeds down to 0·012 second are used, and these provide a most effective means of protecting the rectifier from major damage, whether the potential source of damage be short-circuits, backfires, surges, or even lightning disturbances on the D.C. system—in the case of traction units.

Instrument Transformers

Relays and meters used for normal operating purposes are usually energised from the secondaries of very small-capacity transformers since it is not practicable to connect them directly in the main circuits. By means of instrument transformers high voltages and heavy currents are reduced to values which are convenient for the operation of instruments and protective gear.

There is a fixed ratio between the primary and secondary turns so that the secondary values are generally representative of the primary values, but not exactly so, since the actual transformation ratio differs from the turns ratio according to the load on the instrument transformer. In the case of a current transformer the ratio between the primary and secondary currents should preferably remain constant throughout the working range of the apparatus it serves, but this ratio could only be maintained if there were no voltage-drop in the secondary circuit.

When apparatus is connected to the secondary the voltage induced is proportional to the impedance of the secondary circuit, and the current flowing through it. The flux producing this voltage is derived from the primary current, and since a component of this is required for magnetising the core, and is not reproduced in the secondary, the primary and secondary ampere-turns differ by the amount of the magnetising ampere-turns. As the magnetising ampere-turns are not a linear function of the flux density a simple relationship between these ampere-turns and the secondary burden (the volt-ampere load connected to the secondary) does not exist ; consequently variations in both the magnitude and power factor of the current in the primary cause variations of the resistance and reactance drops in the transformer, and the no-load current, which result in the current ratio differing from the turns ratio in both magnitude and phase.

Since the primary current in a current transformer is independent of the secondary circuit if this is open-circuited, the primary current becomes the magnetising current, the flux reaches a very high value, and an excessive and even dangerous voltage may be induced in the secondary. This is because with no current flowing in the secondary no back E.M.F. is produced to oppose the induced E.M.F. The voltage of an open-circuited current transformer may be sufficient to break down the insulation or be a potential source of danger to human life ; and the excessive flux may cause deterioration of the core-iron.

Whenever the secondary burden is disconnected the winding should first be short-circuited, in which case the primary current becomes the short-circuit current. The voltage induced in the secondary is then very low as it is simply the short-circuit impedance voltage. A voltage, or potential, transformer is similar in principle to a power unit. With a load connected to the secondary the actual transformation ratio differs from the ratio of primary to secondary turns due to the internal losses in the transformer, whilst there is also a difference in phase between the primary and secondary voltages. In practice instrument transformers

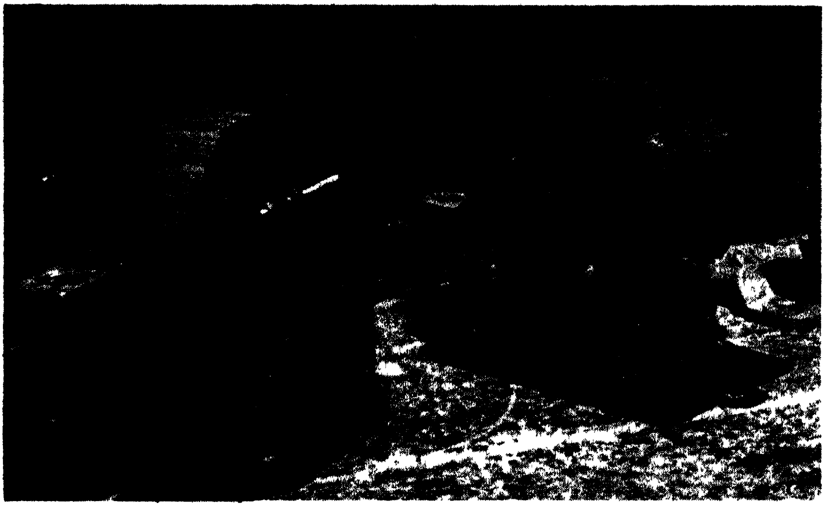


Fig. 185. – WOUND-TYPE CURRENT TRANSFORMERS

are designed, with regard to accuracy of ratio and phase-angle, in accordance with the class of service for which they are intended.

Current Transformer Types

Open, wound-primary type current transformers are generally used up to 500 amperes and 11 kV. for certain classes of indoor switchgear in situations where the atmospheric conditions are favourable. Fig. 185 shows wound-type current transformers.

Oil- or compound-filled wound-primary types are employed for the same range of current and voltage on open-type switchgear in locations where the atmosphere is too humid or corrosive to permit the use of the dry type. The type is also used on outdoor switchgear for all operating voltages where wound primary transformers are required. Single-turn or bar primary-type current transformers are constructed in several forms, each distinguished by varying details; but in every case the primary current passes along a

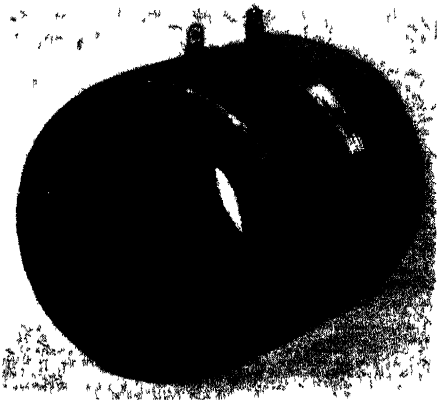


Fig. 186. –RING-TYPE C.T. WITH NICKEL-IRON CORE straight insulated conductor, around which an iron core, carrying the secondary winding, is fixed. Fig. 186 shows a typical wound core which encircles a main conductor. Bar primary current transformers are invariably used on heavy-current circuits, and very frequently for currents below 500 amperes when they can be mounted on high-voltage switchgear bushings.

Another form of bar primary current transformer comprises a core and secondary winding of rectangular shape for mounting over a conductor of rectangular cross-section. Owing to the nature of the primary conductor, bar primary current transformers are particularly well suited for withstanding the thermal and dynamic effects of system short-circuit currents, consequently this type is widely used on systems subject to the heaviest short-circuit currents possible in practice.

The short-circuit capacity of a current transformer is of vital importance, as in the past inadequate capacity has on a number of occasions resulted in failures arising from the occurrence of faults on the system which have overstressed current transformers associated with healthy sections.

Wound-primary current transformers having a small number of turns are inherently more secure against short-circuit effects than those having a larger number of turns, the degree of security decreasing progressively as the number of turns increases. The type with former-wound primary and secondary, insulated with wrappings of tape and impregnated, can be robustly constructed to withstand the electro-magnetic forces due to overcurrents ; but the type employing main insulation of porcelain in tubular form with a pulled-through winding is relatively weak.

Types of Voltage Transformer

The dry type of voltage transformer is generally only employed where the voltage does not exceed 3,300, because of the liability to insulation failures in damp situations, vulnerability to accidental damage, and rapid rise in temperature of the windings under overload conditions.

Compound-filled units are sometimes used on certain types of metal-clad switchgear as they afford security from damp, mechanical damage or, often, open sparking in the case of failure ; but generally voltage transformers of an oil-filled type are used for 3,300 volts and upwards. One advantage of oil filling is that the condition of the oil can be checked and the quality restored, if necessary, by treatment in a purifying plant. For this purpose high-voltage outdoor transformers may be fitted with two valves to enable oil to be circulated through a purifier without taking the unit out of service. Another advantage of oil filling is the comparatively low rate of temperature rise of the windings in the event of excessive overload, such as would be caused by a fault on the secondary wiring not high enough to blow the secondary fuses.

Voltage transformers are invariably connected to the H.V. circuit through fuses ; but owing to the high short-circuit impedance the current in the primary winding may, however, be insufficient for satisfactory fuse operation, even if the secondary is short-circuited. The primary fuses are, therefore, more in the nature of protection for the system against the consequences of a transformer breakdown rather than to protect the transformer itself. A fuse wire fine enough to blow at low current values, and thereby afford protection to the transformer, would be fragile and liable to corrosion from the effects of corona. Secondary fuses protect against faults in the secondary wiring or connected apparatus. Some types of primary fuses available for voltage transformer circuit protection are not capable of interrupting the current, which would flow on the occurrence of a primary short-circuit, and a wire-wound limiting resistance is connected in series with the fuse to limit the current to a value within its breaking capacity. Alternatively high-resistance fuses may be employed which limit inherently the maximum value of the current to be interrupted.

With indoor gear the fuses are usually mounted in the transformer tank under oil, in a position accessible for renewal through a hinged cover, or so arranged that they can be withdrawn through the H.V. insulators. In this case the withdrawable unit may be made up of a fuse at the lower end, normally oil-immersed, and a limiting resistance ; the whole assembly forming the H.V. connection to the primary winding. For outdoor gear liquid fuses are used, both they and the limiting resistances being mounted on the structure independent of the voltage transformer.

With metalclad and some forms of cubicle switchgear isolation of the voltage transformer is effected by withdrawing it from the socket contacts. At 33 kV. and higher voltages the arc drawn out by slow isolation will produce undesirable high-frequency oscillations which may break down the winding insulation. To avoid this some form of quick-break device is provided to interrupt the magnetising current ; such as an external lever which withdraws the fuses from the fixed fuse contacts and so opens the circuit under oil.

Connections of Voltage Transformers

To obtain a three-phase supply a three-phase unit may be used, or three, or two single-phase units. Up to 11 kV. single-phase transformers are generally constructed with fully insulated windings and with both primary terminals insulated for the line voltage. For 22 kV. and upwards, when one end of the primary winding will be permanently earthed, voltage transformers are usually fitted with only one primary bushing. The earthed end of the winding is less heavily insulated from earth and is connected to a low-voltage bushing. This effects a considerable saving in cost, which is relatively greater the higher the voltage.

The star/star connection on a three-limb core is almost universally adopted for three-phase voltage transformers since it gives the cheapest and most compact arrangement, and is quite satisfactory for all normal requirements. When single-phase units are used for a three-phase supply it is undesirable to connect them in star on the primary side unless the H.V. neutral can be connected to the star point of the transformer connections. If this cannot be arranged, the secondary voltage of each transformer will contain a pronounced third harmonic, and the phase-to-neutral voltage is useless for most purposes.

With a star/star connection of single-phase transformers a tertiary winding is employed on each transformer, these being connected in delta to provide a circuit in which the third harmonic magnetising current can circulate, and so avoid distortion. Certain forms of protective gear, e.g. directional earth-fault, make use of a voltage proportional to, and in phase with, the displacement of the transformer neutral from its normal condition. For this purpose it is essential to earth the H.V. neutral of the voltage transformer in order that the primary phase-to-neutral voltages may always be the line-to-earth voltages which are to be reproduced.

Special Types of Voltage Transformer

Above about 66 kV. the cost of directly connected voltage transformers is very high; consequently in some circumstances special arrangements are used to obtain low voltages proportional to the voltages of the main circuits.

The compensated voltage transformer is an arrangement whereby use is made of a power transformer connected to the higher-voltage system. A voltage transformer of the usual type is connected to the lower-voltage side of the power unit and so connected that the secondary voltage derived therefrom will be in phase with the voltage of the higher-voltage system; but due to the voltage-drop in the power transformer between no-load and full load the magnitude of the secondary voltage will not be constant. To compensate for this variation current transformers are connected in either the primary or secondary circuit of the power transformer for supplying current to compensating reactors so designed that the voltage induced in them is proportional to the voltage-drop in the power transformer.

The compensating reactors are connected to the secondary winding of the voltage transformer so that the voltage induced in them is compounded with the normal secondary voltage of the voltage transformer. As this voltage is proportional to the actual voltage at the secondary terminals of the power unit, and, therefore, varies with the load on the unit, and since the value of the compensating voltage is suitably proportioned to the load, the resultant voltage at the secondary terminals of the voltage transformer is proportional to the voltage applied to the higher-voltage terminals of the power transformer irrespective of the load on that unit.

The capacitor voltage transformer is based on the principle that the voltage-drops across condensers in series vary inversely as their capacities. High-voltage multiple-unit porcelain insulators and condenser-type bushings form such a series of condensers, and in other types of bushing an equivalent arrangement can be obtained by inserting a metal foil plate near the outer surface of the dielectric. This plate, one of the foils in a condenser bushing, or an insulator cap in a porcelain string may be employed as the high-voltage electrode of a condenser to which a connection can be made to the high-voltage side of a voltage transformer.

The potential between the tap point and the earthed mounting flange may be of the order of 4,000–10,000 volts so that it is necessary to provide a voltage transformer to step-down this voltage for instrument operation. A variable reactor and condenser are provided in the secondary circuit to permit adjustment of voltage and phase angle to suit the actual working burden. At the present stage of development the use of the capacitor voltage transformer is restricted to synchronising, voltage indication, and in some cases, certain relay operations. The tapped condenser does not reduce appreciably the insulation value of the bushing, and does not necessitate any additional apparatus, such as fuses, connected to the high-voltage system, although a spark gap is required between the tapping point and earth in order to limit to a safe value the voltage in the bottom section of the condenser.

Chapter XVI

FIRE PROTECTION

ELECTRICAL equipment has always been subject in some degree to the twin risks of fire and explosion. The tendencies of the past years towards intensive interconnection and large-capacity units have made available enormous quantities of fault energy which have to be dissipated by the circuit-breakers; in consequence, although failures to interrupt successfully are, with modern equipment, rare, the results are likely to be far more serious. For this reason fire protection equipment is important and essential even if it is never used; and modern practice endeavours to ensure that fire protection, in the form of extinguishing equipment, will not have to be used by careful attention to preventive safeguards. These include, of course, the prevention and rapid automatic isolation of electrical faults—already discussed in previous chapters—and the elimination of factors likely to cause fire and explosion as the result of electrical failure.

Causes of Fire

The majority of fires in electrical stations originate from uncontrolled arcing in the presence of some inflammable medium; and the necessity for sensitive high-speed fault protection is apparent. Protective systems employing relays which require a comparatively high value of fault current for operation may permit arcing for dangerously long periods, so that the conditions favourable to fire and explosion are created—by the action of the arc on any oil, compound, etc., present—before the fault resistance diminishes to a value low enough to allow a sufficient flow of current for relay operation. Arcing earth faults are especially dangerous as they are liable to set up excessive transient voltage conditions initiating faults elsewhere in addition to being a likely cause of fire locally. When comparatively long fault clearance times are unavoidable earthing resistances must be designed to carry the maximum earth fault current for an adequate period of time.

In the absence of sensitive bus zone protection a possible source of danger exists in earthing resistances of inadequate capacity which burn out under certain fault conditions, thus making the system an insulated one. With the loss of the neutral earthing, system oscillations occur which, together with persistent arcing of the original fault, cause risk of consequential faults.

Apart from arcing earth faults there is a fire risk from ineffective protection of low- and medium-voltage circuits against persistent earth leakage. Such continuous leakage is guarded against by supply authorities in their substations, but the danger is not always fully appreciated by those responsible for the operation of small industrial substations; especially where a manufacturing process involves inflammable conditions. The danger arises in the first place if the circuit protection is not sensitive to the earth leakage current which flows through conduit and bonding to the earth connection. Should the current exceed a certain value a conduit earthing bond may fuse and start a fire; or this may be delayed until the leakage current returning through chance contacts sets up local heating or sparking in the presence of inflammable substances.

To avoid the danger of persistent earth leakage sensitive protection is used and systematic measurements made of earth continuity resistance to ensure that, in the event of earth leakage, sufficient current can flow to operate the circuit protective devices. (For a detailed discussion of persistent earth leakage see "Electrical Accidents and their Causes, 1938," H.M. Stationery Office.)

Careful inspection and maintenance of oil circuit-breakers should be a sufficient safeguard against failures due to imperfect adjustments, poor oil quality, etc.; but in practice despite the obvious necessity for such attention accidents still occur occasionally as the result of negligence.

An interesting oil circuit-breaker failure on record relates to an internal explosion caused by a cleaning rag wedged between contacts of one phase. The breaker, of the cubicle type, was a busbar coupler short-circuited by a busbar selector on another circuit. During switching operations sustained arcing between the contacts separated by the rag occurred, causing the switch to explode. In passing it should be mentioned that the careless disposition of cleaning rags may make fire extinguishing more difficult. During tests carried out by the British Electrical and Allied Industries Research Association ("Fire Fighting Equipment for Electrical Installations," *Journal I.E.E.*, vol. 85, p. 719) it was found impossible to extinguish a fire which persisted on a piece of rag left in the nest of transformer cooling tubes, after a fire-extinguishing equipment of the fixed remote-controlled type had operated, except by hand. There was no doubt as to the effectiveness of the equipment for successfully extinguishing fires arising from the risks which it was designed to cover; the test simply served to emphasise the necessity for ensuring that no combustible material of this sort is left in such a position as will encourage re-ignition of oil fires.

Tap-change gear has on occasion been responsible for causing explosion and fire. Apparently when contactors operate under oil the arcing produces natural "cracking" which may result in the gradual deposit of carbon particles on horizontal insulating surfaces, thus affecting the insulating properties of the material used, with consequent liability to tracking and eventual failure.

Routine oil testing and filtering are important in avoiding oil risks, but it should be remembered that filtering is itself a dangerous operation in circumstances where there is a possibility of the oil vapour being ignited. In one case when an explosion occurred while a transformer tank was being filled it was suggested that ignition of oil vapour by static electricity was responsible. The transformer had been isolated from all sources of electrical power for four days previous to the explosion and the windings earthed.

Dividing boxes are sometimes a source of trouble, and it has been pointed out that whilst a dividing box failure elsewhere may only have a localised effect, attachment to a transformer containing a large bulk of oil involves a greater risk and indicates the need for extreme care in the avoidance of possible defects.

Avoidance of Oil Fires

Insulating oil is always a potential source of danger. High-voltage, large-capacity plant has resulted in the concentration of huge quantities of oil in buildings, some of which, planned many years ago when 6 kV. was considered a really high voltage, now house plant up to 66 kV. and of several times the original capacity. Nowadays the tendency is towards the reduction of the quantity of oil used in circuit-breakers by improved designs ; and at the lower voltages, the use of air breakers whenever practicable. In the case of transformers a non-inflammable dielectric medium may be used in special circumstances, but in general oil is still favoured.

Air-cooled transformers are sometimes installed to avoid the oil risks, and with these it is essential that the windings be kept free from accumulated dirt to prevent overheating and the risk of fire.

Fire Sectioning

In modern substations individual sections of plant are frequently separated physically by fire-resisting partitions. Circuit-breakers used for busbar coupling or sectionalising may, in important stations, be separately enclosed, and physical separation extended to such components as main and control cables with the object of making each section of the plant self-contained as far as is practicable without uneconomic multiplication of such components as tripping batteries and operating boards.

Brick and concrete structures are used for the dual purpose of fire sectioning and the limitation of explosive effects. With regard to the latter both small non-sectioned substations and fire-sectioning structures in large stations should be designed so that at least one wall parallel to the gear contains enough windows or doors to act as relief vents for the intense pressures which may be set up by explosive failures of electrical gear, and thus secure the safety of the main structure.

In stations designed before the necessity for protection against fire

Fig 187 —SHOWING THE APPLICATION OF FIRE PROTECTION PANELLING TO A METALCLAD SWITCHGEAR INSTALLATION (*Durasteel Roofs, Ltd*)

risks was fully appreciated, it is often impossible to adopt brick or concrete fire sectioning on account of the relative congestion of the equipment. This condition may also apply to new stations in which the maximum of plant has to be installed in a limited space. For these situations some form of fire sectioning is frequently obtained by using a fireproof material occupying a minimum of space but giving ample security. Such a material is Durasteel " 3DF2 " fire protection panelling, which is a composite flat sheeting consisting of two light-gauge steel facing sheets securely keyed by a patent process to a highly compressed asbestos-composition core. The application of the panelling to a metalclad switchgear installation originally designed without fire sectioning is illustrated in Fig. 187. By this arrangement the inherent protection against fire risks obtained with metalclad gear is further improved without impracticable alterations to plant layout. Fig. 188 shows box-type fire barriers of Durasteel panelling sectioning a bank of transformers. The panelling is extensively used for the complete enclosure of vulnerable and important equipment such as control panels and fire-extinguishing apparatus.

Outdoor substations with switchgear and transformer units widely

Fig. 188 –TRANSFORMERS PROTECTED BY SECTIONALISING PARTITIONS. (*Durasteel Roofs, Ltd.*)

spaced may not require any specific fire sectioning, but where adequate spacing is not possible walls may be used. Outdoor metalclad gear possesses excellent fire-resisting properties, but having close spacing of units fire sectioning may be similar to that of indoor layouts. Ground area permitting, wide spacing of metalclad gear may be adopted to avoid the use of walls. Often, as the result of a transformer or circuit-breaker failure, a large quantity of burning oil is released, and to be of real value fire sections should completely prevent the passage of this oil from one part of the plant to another. For this purpose sills of a minimum height of 6 in. are used across doorways, cableways, ventilating openings and the like. The sills should be capable of holding all the oil available in each section.

Oil Drainage

Where it is not practicable to segregate each unit or section of the plant in separate enclosures some other means are usually adopted to retain free oil. The minimum provision should be dwarf walls around each transformer or section of switchgear, at a sufficient distance to ensure that escaping oil will not be thrown outside the area enclosed by the walls.

Preferably there should be a well or sump beneath each unit filled with screened rubble or pebbles for the oil to drain into. The material used in the wells should be of such a nature and large enough not to impede the passage of oil. Sand should not be used and pebbles should be at least ½ in. diameter. The ideal arrangement is for the drains from the wells to pass to pits, filled with pebbles graded from 1 in. to 2 in., outside the building, and located in a position remote from any exit or entrance. With outdoor units a screened ballast surround is frequently used—in the absence of high retaining walls—to catch escaping oil and to act as a fire quencher. It has the further advantage of limiting the fire to a definite area, thus facilitating its extinction by fixed equipment covering the area.

Fireproof Construction of Buildings

Many substations installed in recent years are located in buildings which are designed to be fireproof to a high degree by the use of fireproof doors, steelwork, etc. In the case of small unattended substations, although it may not be economic or practicable to arrange the layout of the plant so that each section of the equipment is segregated, the enclosure as a whole is usually sufficiently fireproof to prevent the spreading of the fire outside the substation. Where substations are chambers located in large buildings special precautions are necessary, especially in the case of cinema and similar substations when it is important to localise a fire. This class of substation should be arranged so that the plant is well below the lowest floor level of the main building to ensure the retention of any burning oil in a position where it can be rapidly extinguished by an automatic fixed fire equipment, the provision of which is imperative when the station is normally unattended or inaccessible to the occupants of the main building. When the fire risk has to be eliminated as far as possible the use of transformers filled with a non-inflammable medium is advisable.

Protection of Cables

The primary aim with regard to fire protection is to restrict the fire to as small a section of the plant as possible, this being achieved by the metallic enclosure of components, and physical fire sectioning. A secondary consideration is that the equipment actually located in the fire area should suffer as little damage as possible, so as to facilitate the re-commissioning of the plant. This is secured by metallic enclosure, and the installation of effective fire-extinguishing apparatus.

Armoured cables are inherently fire-resisting to a high degree. This was demonstrated by a series of experiments (" Electric Cables and Fire Risks : Recent Developments and Investigations," *Journal I.E.E.*, vol. 87, p. 521) which drew attention to the extraordinary fire-protective qualities of armour wire, which renders the exterior wrappings and their impregnating compound substantially fire-resisting, and also protects the interior of the cable. The behaviour of the cables under the various tests applied indicate that relatively long exposure to an external flame—which implies an already existing severe fire—is necessary to ignite the wrappings ; and it appears that if the source of the flames is local the cable will not, in general, convey flame away from the area of application. With a more severe and general conflagration the cable might well become ignited and convey flame, but the conditions envisaged would be such that any additional flame resulting from the cable would probably be relatively unimportant. In one test it was noted that the application of a hot external flame for about fifteen seconds was necessary to ignite the compound on the wrappings of a standard C.M.A. cable, so that it seems reasonable to conclude that such wrappings would not become ignited as the result of a transient flame due, for instance, to an explosion resulting from an electrical failure.

Further experiments with various compounds led to the general conclusion that, while wrappings treated with petroleum pitch compound were appreciably more fire-resisting than might have been expected, wrappings can for practical purposes be made non-ignitible by the use of fire-resisting paint compounds. These are not so resistant to the passage of water as are the standard petroleum-pitch type used specifically to give protection against corrosion. Consequently, the use of fire-resisting compounds in place of the present standard type makes the armouring wires more liable to corrosion from acid waters, etc., which fact should be considered in relation to the conditions obtaining.

Recently, cables have been introduced having both fire-resisting outer coverings and dielectric, which are identical with the standard rubber-insulated type as regards flexibility, method of installation, and overall dimensions. So far development has been restricted to the sizes and types of cable normally used in ordinary wiring work, i.e. braided and compounded or metal sheathed, but attention is being given to other types.

In some stations special precautions are taken to prevent fire damage to cables, each

Fig. 189.—A TYPICAL INSTALLATION USING MOULDED ASBESTOS IN SECTIONAL FORM. (*Newall's Insulation Co.*)

cable or group being protected by enclosure in a suitable arrangement of heat-resisting material. A material used frequently is moulded asbestos, which is applied in various ways with due regard to the technical problems involved ; one of which is that the thermal resistivity of the protective covering should be low enough to avoid any critical internal heating of the cable which will decrease, in effect, the current rating to a serious extent. The thermal resistivity of moulded asbestos is of the order of 700 thermal ohms, a value which may decrease the rating of the enclosed cables by about 20 per cent. ; although much depends on the grouping of the cables in the ground. If they are sufficiently close for proximity heating to occur, this will offset the effect of the moulded asbestos protection on the lengths of cable which normally separate when they are taken to the switchgear.

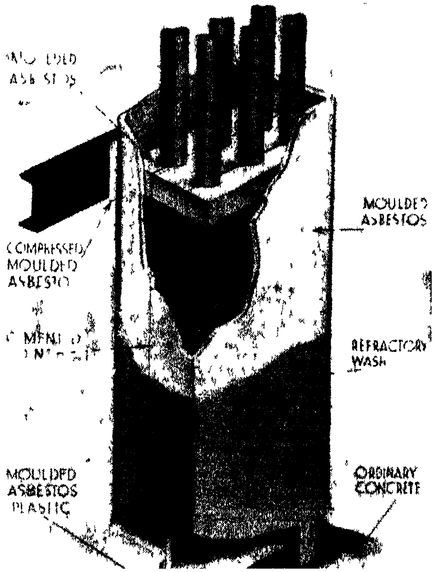


Fig. 190.—TREATMENT OF GROUP OF SMALL CABLES. (*Newall's Insulation Co.*)

The effectiveness of moulded asbestos was demonstrated by a test in which four different forms of the material protecting lead-covered cables, and one unprotected lead-covered cable, were exposed to a fire. After nearly one hour's heating up to a maximum temperature of about 1,100° F. the highest recorded temperature on a protected cable sheath was 176° F. ; but the lead covering of the unprotected cable melted and the cable fired after 45 seconds.

Moulded asbestos is applied in a variety of ways, typical examples being shown in Figs. 189, 190, 191, and 192.

The material is supplied in sections two of which are fitted around the cable and jointed with special fire-resisting cement. An alternative method of fixing, which allows the removal of sections when required, is to bind the sections with nickel chromium wire. To fit round bends the sections are cut into segments and suitably mitred. In general, cables passing through floors, and liable to be exposed to burning oil, should be protected up to a height of at least 18 in. above floor level. The floor should be sealed to prevent the passage of oil—as shown in Figs. 191 and 192. In addition to the usual cable clamps above floor level cables should be clamped immediately below floor level to prevent them slipping into the basement or cable tunnel should they be burnt away from their dividing boxes.

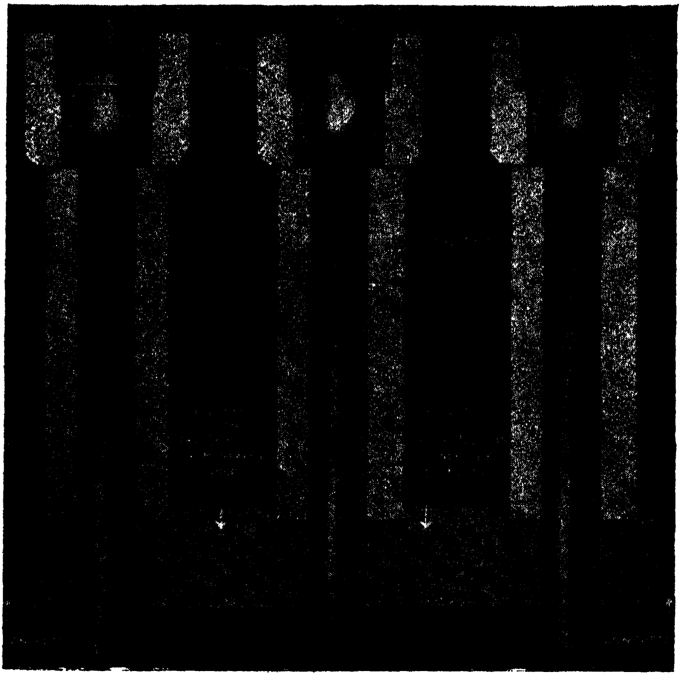


Fig. 191.—PROTECTION OF CABLE GLANDS AND CABLES PASSING THROUGH FLOOR. (*Newall's Insulation Co.*)

Fire Extinguishing Methods and Media

Despite all preventive safeguards the danger of an outbreak of fire, although remote, is always present, and most substations are equipped with some form of fire-extinguishing apparatus. Fires may be extinguished by one, or both, of two methods : first, by cooling down to below the point of combustion ; and second, by smothering, thereby cutting off or diluting the supply of air which supplies the oxygen supporting combustion. The first method is generally the most effective for the extinction of freely burning materials of carbonaceous nature—such as wood, paper, fabrics, etc. Fires in substations will not—at least in the initial stages—be such as can be extinguished solely by this method. Generally, the second method will be most effective for the highly inflammable liquids, semi-liquids, and solids that melt and flow when heated, which constitute the major risks in electrical stations, as such substances only burn on the surface : actually it is the vapour given off that burns, the liquid underneath remains relatively cool in the initial stages of the fire. Extinguishing media effective in smothering the outbreak are, therefore, largely used. Some media do, of course, possess both smothering and cooling properties in varying proportion.

The extinguishing media used for covering electrical risks are : carbon tetrachloride, methyl bromide, carbon dioxide ; foam, generated either mechanically or chemically ; and water, used in emulsion-forming water-jet installations, and in the ordinary way as back-up protection. The first three are non-conductive and are therefore especially suitable for protecting equipment which cannot be made completely dead immediately, or when it is essential to avoid switching-out healthy units. Thus they are ideal for switchgear risks.

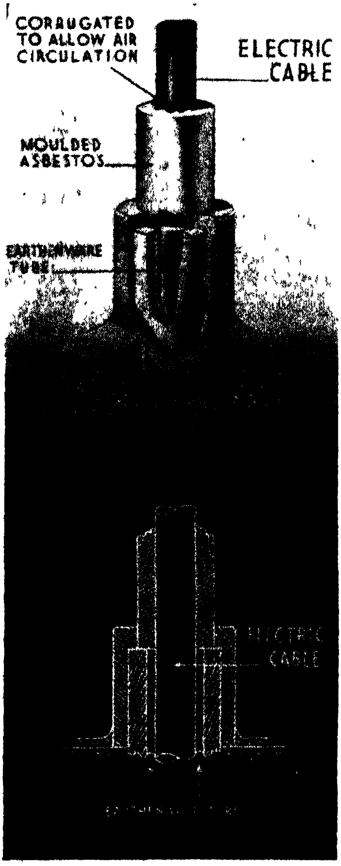


Fig. 192.—CONSTRUCTIONAL DETAILS OF FLOOR SEALING. (*Newall's Insulation Co.*)

Gaseous Media

Although with carbon tetrachloride, methyl bromide, and CO_2 fire extinction is effected primarily by the presence of gaseous vapour heavier than air, all three are stored in liquid form, and are vaporised on being released to atmosphere. With carbon tetrachloride the change of state is comparatively slow at normal temperatures, but when it reaches about 77° C., by reason of being discharged on to a fire, it is rapidly converted into a dry cohering gaseous vapour 4½ times as heavy as air. The volume of vapour generated is 233 times that of the liquid used. The vapour blankets the fire by diluting or displacing the air in the immediate vicinity, thereby excluding the oxygen necessary to combustion. Whilst this medium is an effective smothering agent it is also suitable for the extinction of freely burning materials if brought into action in the incipient stage of the fire.

Commercial carbon tetrachloride contains water and other impurities likely to cause corrosion and have some solvent effect on insulation ; but the special forms developed—such as Pyrene liquid—are almost entirely non-damaging. The liquid remains effective indefinitely and it is non-conductive, which property has been demonstated—in the case of the Pyrene liquid—by the extinction of an arc in a 120 kV. circuit with a hand extinguisher.

Methyl bromide is a stable, colourless, and volatile liquid with a boiling-point of 4·5° C. Upon release to atmosphere it rapidly evaporates to a fire extinguishing gas 3¼ times heavier than air. It is contained in sealed copper or steel cylinders, with nitrogen added to increase the pressure to about 50 lb. per sq. in. In special instances higher pressures may be used. A jet of methyl bromide has a very intensive cooling effect : the low boiling-point coupled with a rather high latent heat of evaporation, and the wide range of temperatures involved, cause an almost instantaneous absorption of heat. Methyl bromide has also a comparatively low diffusion coefficient and is, therefore, less easily affected by air currents.

Carbon dioxide is contained in high-pressure cylinders with specially designed closure valves. Under pressure in the cylinder CO_2 is in liquid form, but when discharged to atmosphere expands to a gas 450 times its liquid capacity. A 50-lb. cylinder will produce approximately 450 cubic feet of gas whose weight is about 1½ times that of air. Modern practice calls for the discharge of a 50-lb. cylinder in not more than a minute. The sudden expansion from liquid at high pressure to gas at atmospheric pressure naturally results in a severe temperature drop at the point where expansion takes place. Should this expansion occur within either the cylinder or the pipe leading to the discharge nozzles, the resulting temperature drop would be sufficient to freeze some of the CO_2 and block up the outlet. To prevent this appliances are designed to discharge the CO_2 in a liquid form until it actually reaches the discharge horn. It passes into the atmosphere at an extremely low temperature—so low, in fact, that the discharge is largely in the form of finely divided CO_2 "snow" (see Fig. 193(*b*)) at a temperature of − 110° F.—and has a definite cooling effect. Table VII shows technical data relating to the gaseous extinguishing media.

TABLE VII.—GASEOUS FIRE EXTINGUISHING MEDIA TECHNICAL DATA

Property	*Methyl Bromide*	*Carbon Tetrachloride*	*Carbon Dioxide*
Structure	CH_3Br	$C\,Cl_4$	CO_2
Molecular weight (O = 16·0)	94·9	153·8	44·0
Specific gravity (water = 1)	1·73	1·63	0·77
Vapour density air = 1·0 at N.T.P.	3·27	5·31	1·52
Boiling-point at 760 mm.	4·5° C.	76·7° C.	− 78° C.
Melting-point	− 93° C.	− 30° C.	—
Specific heat of liquid at 0° C. cals/gram.	0·12	0·185	0·20
Latent heat of vaporisation cal/gram. at B.P.	62	46	90
Vapour pressure at 60° F. lb. per sq. in.	20·0	1·75	810
Gas generation, cubic feet per lb. at N.T.P.	3·7	2·3	8·0
Inhibitory factor per cent. in dry air	3·0	15·0	19–29
Diffusion coefficient grms./$cm.^2$/sec./air	0·097	·076	0·142
Normal pressure in cylinders, lb. per sq. in. at 60° F.	50	80	810

The quantity of a particular gas required for a given fire risk depends largely on its inhibitory factor, i.e. the percentage necessary to procure extinction in dry air (see Table VII). In practice, however, a low inhibitory factor is not necessarily the only consideration.

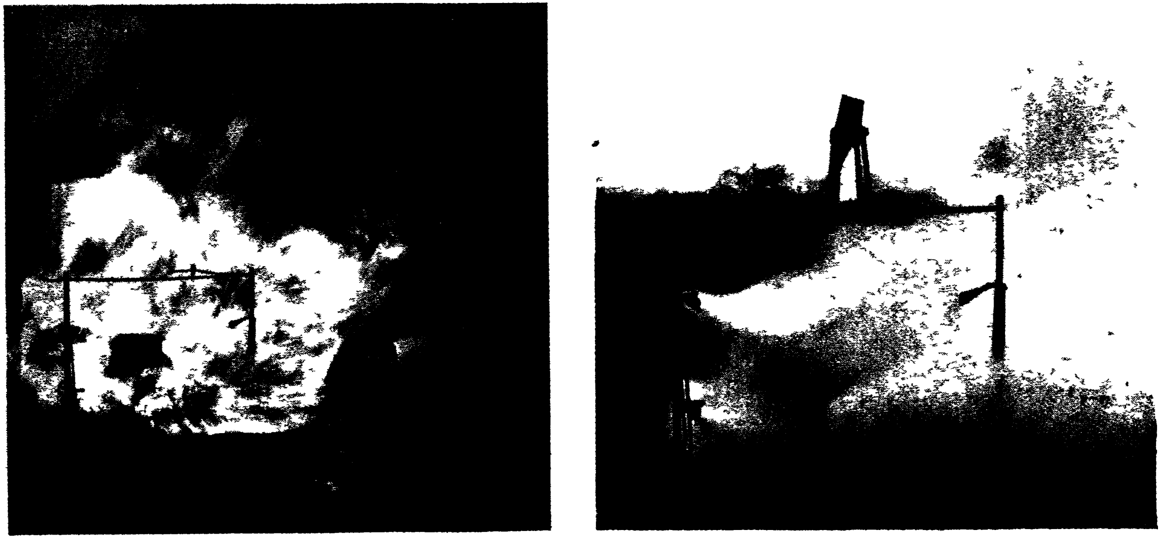
Application of Extinguishing Gases

Both carbon tetrachloride and methyl bromide are released from the containers in liquid form, consequently extinction may be assisted to a certain extent (when the jet is directed at the seat of the fire) by the actual striking of the jet tending to knock the fire out. However, the more effective cause of extinction is the actual displacement of the oxygen in the vicinity of the fire by the heavier gas resulting from the evaporation of the liquid. This method of applying the liquid medium by " direct-impingement " is adopted for certain fixed extinguishing equipments, and for portable appliances : but with CO_2 it is not possible on account of the physical characteristics of this medium.

The second method of applying the gaseous media is by " concentration." In this case a compartment is flooded with a sufficient percentage of gas to render the atmosphere as a whole incapable of supporting combustion. The percentage of gas required in dry air for an effective concentration depends upon to what extent the compartment is free from convection currents and draughts , and the coefficient of diffusion of the gas. To keep the percentage of gas released into a compartment to an effective minimum the ingress of fresh air may be greatly diminished at the moment of discharge by suitable apparatus arranged to automatically close all ventilation openings, or switch-off fans simultaneously with the operation of the extinguishing equipment.

In certain situations, such as open switchgear galleries in a main substation, it is not always possible to control the ventilation, and the concentration method is not applicable since this depends for its effectiveness on a minimum of ventilation. To cover this type of risk the general practice is to use more gas than is theoretically necessary in still air, and by a careful disposition of the nozzles " drown " the affected plant in gas for a period long enough to secure extinction. So successful has this drowning method proved that its effective application to an extreme case —a fierce oil fire in the open air—has been conclusively demonstrated by repeated tests. Figs. 193(*a*) and 193(*b*) are photographs taken during one test, and they reveal that, despite the unfavourable wind conditions prevailing at the time, rapid extinction of the class of fire illustrated can be effected by drowning if the installation is carefully planned, and a sufficient quantity of gas is discharged. The medium used for the extinction was CO_2 which is visible in Fig. 193(*b*) as a cloud of finely divided " snow." The shielded nozzles—or discharge horns—should also be noted. Methyl bromide is also used—on the direct-impingement principle—for exterior hazards, and certain interior hazards located in substations where the concentration method is inapplicable. Probably the success of gaseous fire extinction depends as much upon the installation itself as on the medium used—if not even more so.

The gaseous extinguishing media are toxic, and may therefore consti-



(a) (b)

Fig. 193.—(*a*) SHOWS A 75 KVA. TRANSFORMER CONTAINING 50 GALLONS OF OIL ON FIRE DUE TO HEATING THE OIL TO ITS FLASH POINT. AFTER THE FIRE HAD BEEN ALLOWED TO PERSIST FOR TWENTY MINUTES CO_2 WAS DISCHARGED FOR TWENTY SECONDS, WITH THE RESULT SHOWN IN (*b*) (*The Walter Kidde Company, Limited.*)

tute a danger to personnel using hand appliances inside a badly ventilated chamber or a confined space, or present in the vicinity of a fixed installation at the moment when it is brought into operation either by accident, or as the result of a fire occurring. The potential danger of each medium must be considered in relation to the amount or concentration likely to be present at a given fire. On this basis the relative toxicity of the three media depends on the quantity of each that has to be discharged for equal results. The inhibitory factor of a gas is the percentage necessary in dry air to procure extinction, and that of methyl bromide has the lowest value, consequently although it is, for equal weights, far more toxic than CO_2, there may be little difference between the relative toxicities with the concentrations of each required to effect extinction. In actual fire extinguishing the toxic effect of the products of decomposition have also to be considered, in which case carbon tetrachloride may have some ten times the toxicity index of methyl bromide under certain conditions.

After gaseous media have been discharged into a closed space thorough ventilation is essential. If immediate attention to plant involved in the fire is necessary, personnel should wear breathing apparatus consisting of a mask supplied with air from a portable cylinder. Such apparatus is, in any case, advisable for fire-fighting since large volumes of smoke and fumes may be present.

Foam

There are two basic types of foam for fire extinction, known as "chemical" foam, and "mechanical"—or "air"—foam respectively. A chemical foam is produced by the agency of interacting chemicals, whereas a mechanical foam depends upon physical action for its production.

Chemical foam consists of minute bubbles inflated with CO_2 gas generated by the reaction of acid and alkali constituents of a chemical charge. The gas generated provides sufficient pressure for the expulsion as well as the expansion of the foam.

The bubbles of mechanically produced foam usually contain air instead of CO_2. No chemical action is involved, the foam-making agent being an inert liquid which is automatically drawn into the stream of water passing through a special branch pipe, and expanded into foam by means of the air also drawn into the appliance. The foam jet depends for its propulsion upon the pressure of water from a pump or hydrant. For oil fires foam is particularly suitable as it can be applied to smother the burning liquid : it floats on, and spreads freely over, the surface, thereby excluding the oxygen necessary to combustion and completely blanketing the flames.

Foam withstands great heat, and prevents re-ignition of surfaces already covered since it has a definite cooling action. Although inflammable liquids constitute the main risks efficiently covered by foam fire extinguishing, the foam produced is of such a nature that it adheres to solid surfaces, thus forming a fire-resisting covering which definitely checks the spreading of the fire by protecting the surrounding structure or materials. For the best results the foam must be of the correct viscosity. Foam is conductive and should not be applied by hand-operated appliances to live gear ; although this may be permissible when it is supplied from a fixed installation remote controlled, and effectively earthed.

Water

The application of a solid water jet to an oil fire is useless as the water being heavier than oil sinks through to the bottom, and also splashes the burning surface liquid in all directions, thereby spreading the flames. The only method of successfully employing water is in the form of a high-pressure spray from specially designed discharge nozzles by means of which the issuing jet of water is spread out into a cone of spray of high velocity and momentum. The impact of the spray on a burning oil surface changes this into a non-burning emulsion, which consists of an immense number of minute oil globules each surrounded by a film of water, with a thin sheet of water at the surface.

Major substations are usually equipped with water hydrants and hose ; but in the initial stages of an electrical fire water should not be used since it is sufficiently conductive to be dangerous in the presence of live gear. This is an important consideration when a fire involves only one unit, or a small section of the plant, and it is desired to avoid shutting-down adjacent units or sections. The use of water in these circumstances may cause insulation failures in healthy units, or at least put them temporarily out of commission.

In the event of a general conflagration developing water may have to be applied. Although water is a conductor there is little risk in the use of a broken jet on live gear up to 600 volts. At higher voltages there is a risk unless the branch is a considerable distance from the live apparatus. As the result of tests carried out in 1933 in the presence of members of the Institution of Fire Engineers and the technical staff of the C.E.B. it was concluded that no special precautions need be taken when working at 40 ft. or more from a 132 kV. line with nozzles having a diameter of ⅝ in. or less. For nozzles having a diameter of ¾ in. or more the distance should be at least 60 ft. Thus, it is clear that water may only be used when there is a clear knowledge that the conditions are favourable, and suitable precautions are taken.

The use of soda-acid portable extinguishers in substations should also be avoided since the jet is highly conductive. These extinguishers generally use a charge of sulphuric acid, contained in a bottle inside the main body of the extinguisher, which is filled with a solution of bicarbonate of soda. By inverting the extinguisher or, in another type, striking a plunger, the acid is released from the bottle and flows into the soda bicarbonate solution. The resulting chemical reaction produces CO_2, sodium sulphate, and water ; the CO_2 providing a pressure to throw a

30-ft. to 35-ft. jet of water containing sulphate of soda. Although the sulphate of soda retards combustion it does not take any appreciable part in the extinguishing of the fire, so that the extinguisher is simply a convenient means of obtaining a water jet.

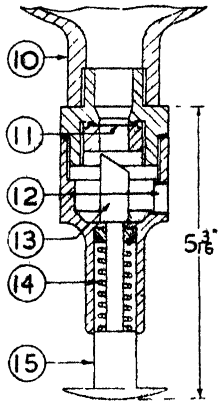


Fig. 194 SEAL-PIERCING PLUNGER MECHANISM
(*The National Fire Protection Co., Ltd.*)

Gaseous Extinguishing Equipment

The gaseous extinguishing media are used in hand appliances, portable, transportable, or fixed containers to which are attached hose lengths; or permanently fixed systems operated by manual or automatic control. The capacity of each equipment installed will, of course, depend on the nature of the risk it is intended to cover.

Carbon tetrachloride is, in general, only used for hand or portable extinguishers consisting of a double-action pump giving a continuous jet; or the contents of the extinguisher may be expelled by pressure. It is not usually employed for fixed installations covering electrical fire risks.

Methyl bromide is used in both portable appliances and fixed equipments—the simplest form being a hand extinguisher of the total discharge type; i.e. the entire content of the cylinder has to be released once the seal is pierced. A typical seal-piercing plunger mechanisn is shown in Fig. 194. The actuating plunger consists of a brass body (15) enclosing the piercing mechanism (13). When this is forced upwards the copper sealing disc (11) is partly cut through and then folded back. As the plunger returns to its original position the contents are discharged through the orifice (12) into which is screwed either a jet—in the case of a portable appliance—or the connection to a pipeline, when the equipment is of the fixed type. Similar types of piercing mechanisms are also used for CO_2 cylinders. Fig. 195 shows another type of extinguisher head, for portable methyl bromide containers, which enables the discharge to be controlled. The withdrawal of a safety pin releases

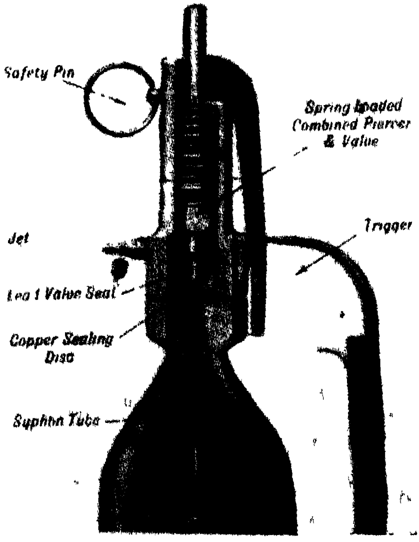


Fig. 195.– "ESSEX" EXTINGUISHER HEAD
(*The National Fire Protection Co., Ltd.*)

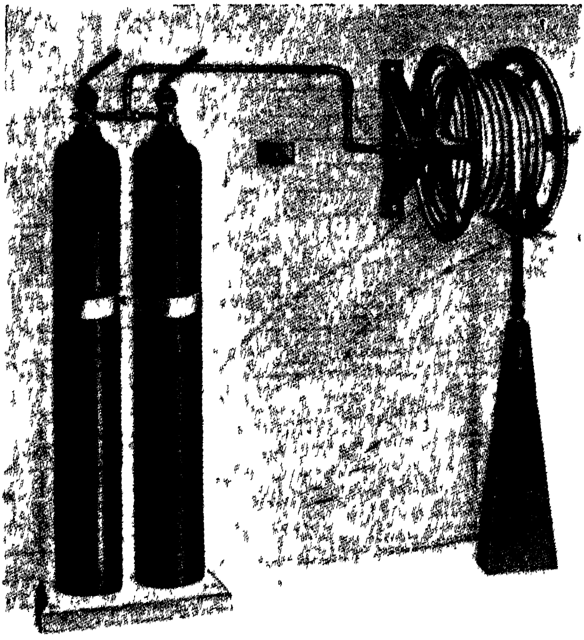


Fig. 196.—Hose reel CO_2 equipment (*Pyrene Co., Ltd.*)

a spring-loaded combined piercer and valve. After the sealing disc is pierced the valve is operated by the trigger to control the discharge. The siphon tube should also be noted. Other types of extinguishers, without sealing discs, are controlled by screw-down valves.

CO_2 is also used in a variety of portable appliances and fixed equipments A useful form of equipment is the CO_2 hose reel installation, an example of which is shown in Fig. 196. The cylinders are discharged by pulling down the levers shown to pierce the sealing discs, and opening the valve on the discharge horn. Apart from their value as primary protection in situations where fixed installations are not applicable, hose reels are often employed as back-up protection to cover any failure of a fixed equipment to extinguish odd spots of fire which may persist after the initial outbreak has been dealt with.

Fixed installations are generally used to cover certain types of unattended substations, and major attended substations where it is essential that a fire should be rapidly extinguished. Automatic control is used in the first case, and automatic or remote manual control in the second, or a combination of both, so that, for instance, the equipment can be operated manually if the fire-detecting devices actuating the automatic control do not function before the outbreak is observed.

With gaseous media any capacity of the equipment can be obtained by manifolding together the appropriate number of standard cylinders.

Gas Installations for Minor Substations

For small substations a single-cylinder installation often suffices. Fig. 197 shows diagrammatically a CO_2 equipment of this type. Automatic operation is secured by the heat-sensitive fusible link which melts at a predetermined temperature, thereby allowing the weight to actuate the cutter valve.

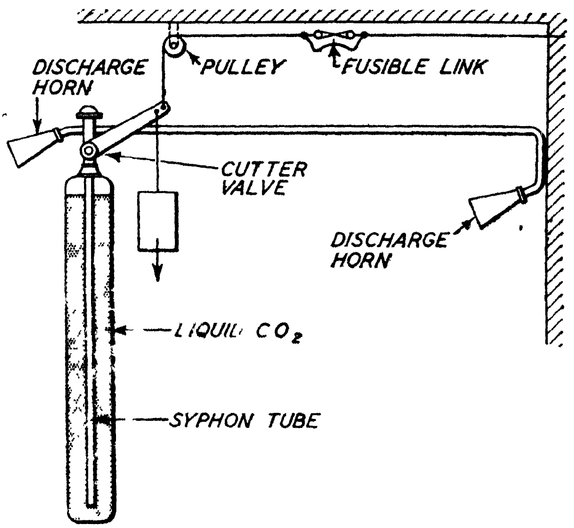


Fig. 197. Diagrammatic arrangement of CO_2 apparatus

Several forms of fusible link are in use, the simplest consisting of a special alloy strip bridged by a loop of wire (Fig. 197). Another type of link, shown in Fig 198 (2), is housed in a brass cover (1). The link itself consists of a special alloy joining the two slotted brass components which are attached to the ends of the flexible steel wires forming the release line. The tension strain of the wire is normally taken by short brass rods which hold the alloy strip in position. Standard links of the type illustrated are designed to melt at 150 and 175° F. respectively ; but links melting at other temperature values are also used.

Some systems employ heat-sensitive quartz bulbs containing a special liquid. In normal circumstances the bulb acts as a member of a mechanical link and serves to keep the whole link in a state of equilibrium against the pull of the weight tensioning the line. At a predetermined temperature the rapid expansion of the liquid shatters the bulb, and the link collapses, thus allowing the weight to operate the cutter valve levers. The number of links used depends on the area covered by the extinguishing equipment. A typical fusible link line is shown in Fig. 199, which also illustrates the layout of CO_2 discharge horns and pipelines.

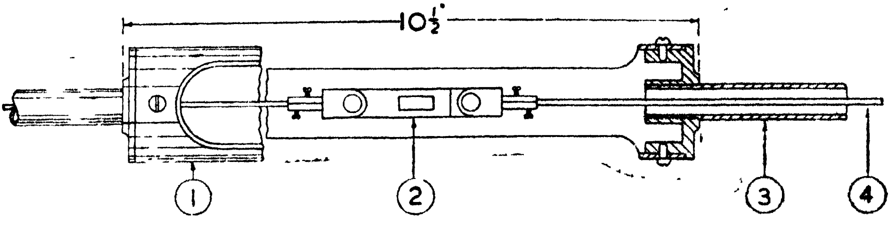


Fig. 198.—Heat-sensitive fusible link. (*The National Fire Protection Co., Ltd.*)

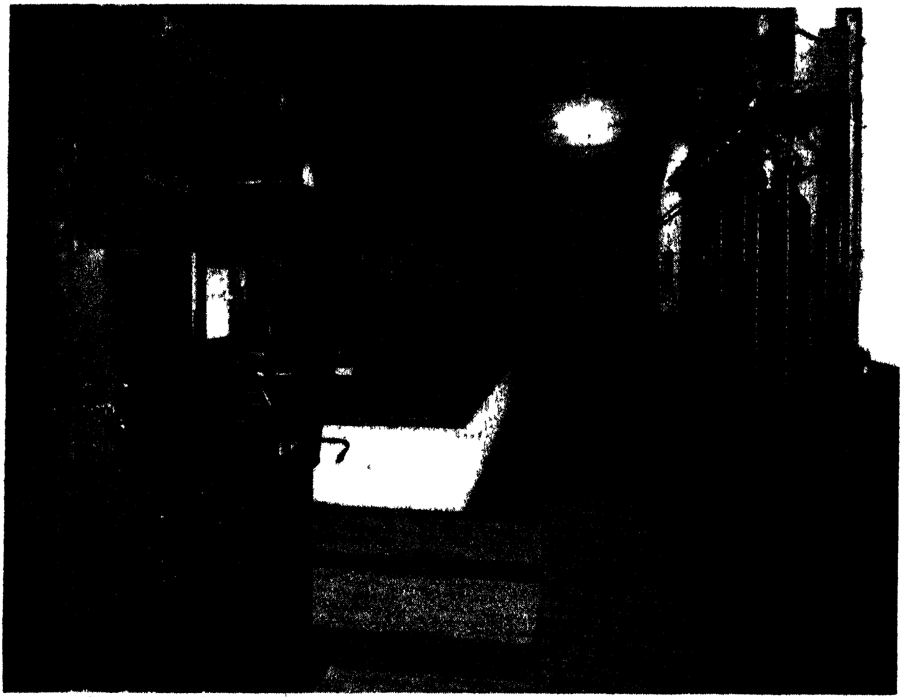


Fig. 199.—CO_2 GAS EXTINGUISHING INSTALLATION WITH FUSIBLE LINK LINES (*The Pyrene Co., Ltd.*)

In general, both CO_2 and methyl bromide installations are operated on similar mechanical principles. Distinctive differences in design of detail are partly due to the particular physical characteristics of each medium. A three-cylinder methyl bromide equipment is shown in Fig. 200. The seal-piercing mechanism is of the type illustrated in Fig. 194, and at the top of each supporting bracket an angle piece carries a centrally pivoted lever whose lower end engages a catch attached to a weight. The lever is for the purpose of releasing the weight. Normally it is held in position against spring tension by the taut wires of the automatic fusible link operating system. Between the top portion and the levers actuating the seal-piercing plungers is a pair of cadmium-plated rods upon which the operating weight with its bushes and ball bearings is assembled. The weight is normally suspended by the catch engaged by the weight-releasing lever, but when the link line relaxes the weight is free to fall and, by impact, force the piercer spindles upwards to discharge the cylinders.

At the bottom of the unit in Fig. 200 a switch operated by the lever mechanism is built integrally with the bracket. This may be used for the actuation of alarms, or the breaking of ventilating fan and other circuits. Another feature is the safety control to render the gear inoperative,

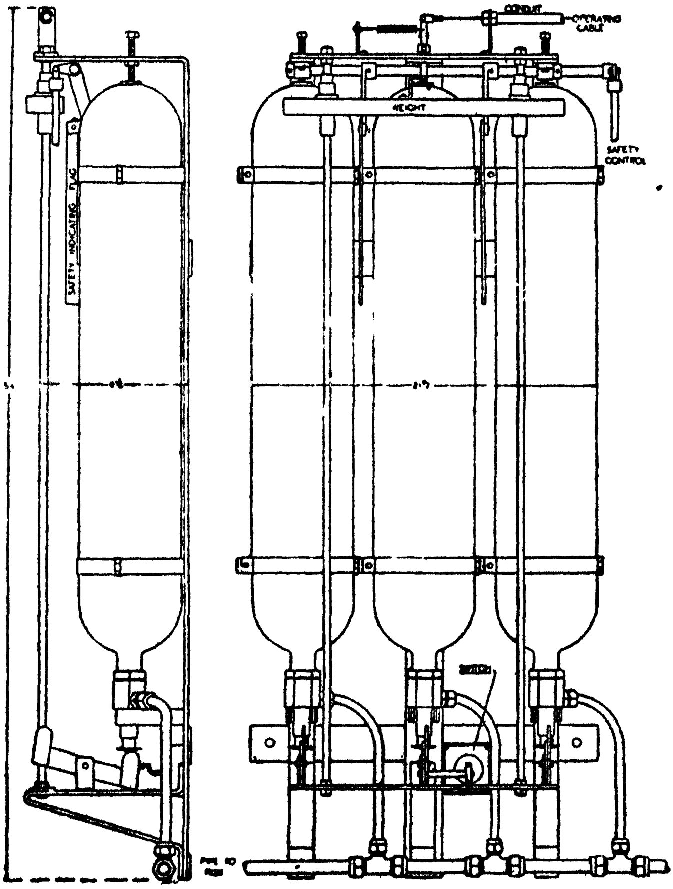


Fig. 200.—METHYL BROMIDE AUTOMATIC UNIT. (*The National Fire Protection Co., Ltd.*)

thereby avoiding accidental operation when personnel are working in a protected compartment.

The extinguisher units are manifolded together by a copper pipe system which is usually extended to form a ring main arranged and graded in diameter to secure the best distribution of methyl bromide throughout the protected area. Within this pipeline are fitted a suitable number of discharge heads positioned and proportioned to obtain the optimum discharge.

Various arrangements of the operating mechanisms of CO_2 equipments are in use ; in that shown in Fig. 197 the cutter valve lever is held in a position of equilibrium by the free end of the fusible link line—attached to the end of the lever—and a weight suspended from an adjacent point.

The lever is so positioned that it rotates to cut out the sealing disc when the link line relaxes. Direct operation of the cutter valve levers is generally only practicable with one or two cylinder installations where the layout of the line is simple and straightforward.

When it can be adopted, the arrangement often enables the cylinders to be located at suitable points in the protected space as near as possible to the risk, thus shortening and simplifying the pipelines. In fact, distribution lines are not in some cases required as the nozzles (or nozzle) can be fitted to a short length of pipe directly connected to the cylinder gas outlet. This applies in particular to compartments in which gas is used for concentration extinction—as distinct from drowning. Since the method consists of flooding the space with a sufficient percentage of gas to make the atmosphere inert the nozzles need not be of the directional shielded type as the points of discharge are not critical—within limits.

When a bank of cylinders has to be discharged simultaneously the usual practice is to gang the lever weights in some way and operate the arrangement by a specially designed release, which is itself operated by the weight tensioning the link line.

Fig. 201.—CO_2 INSTALLATION WITH DISTRIBUTING VALVES. (*The Walter Kidde Co., Ltd.*)

Gas Equipments for Major Stations

In large substations it is uneconomic and unnecessary to install a separate bank of gas cylinders for each section or compartment. A usual practice is to have a central battery of cylinders from which pipelines, each fitted with a valve manually or automatically operated, are taken to different sections of the plant. The storage capacity is more than sufficient to allow for two separate discharges to cover the worst conditions in the largest section of the plant likely to be involved at one time. A typical scheme is to divide the battery into two banks, one of which is controlled automatically by heat-sensitive devices, or manually, for the initial discharge ; the other being manually controlled and held in reserve to cover any failure to extinguish the fire by the first discharge. More than one battery may be installed when it is not practicable to centralise all the cylinders outside the protected area.

Fig. 201 shows a CO_2 battery installation fitted with both automatically and manually operated distributing valves. The battery is divided into two banks, the cutter valve levers of the cylinders of each bank being ganged for simultaneous discharge by coupling the levers together with short lengths of cable and screw connectors.

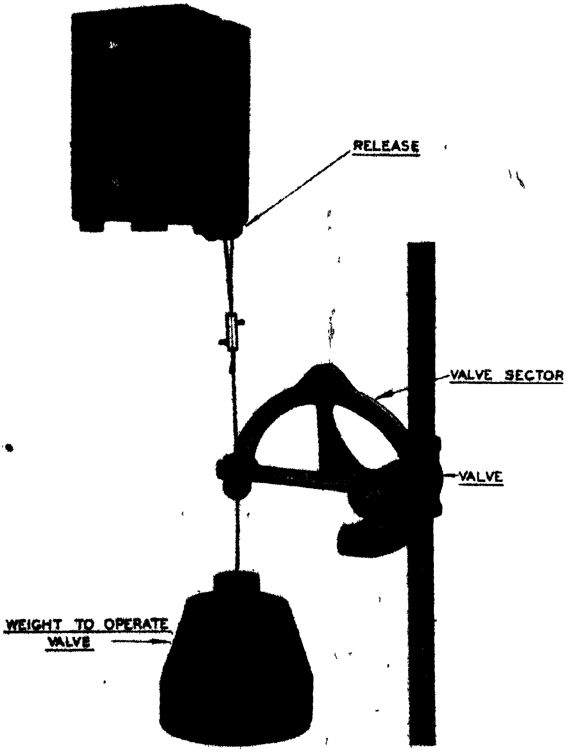


Fig. 202.—CO_2 DISTRIBUTING VALVE AND ELECTRIC RELEASE. (*The Walter Kidde Co., Ltd.*)

An important component of the central battery class of equipment is the distributing valve controlling each pipeline. Valves are designed to open rapidly to avoid any hindrance to the passage of the liquid gas, as the effect of a valve partially open when the gas discharge commences is to allow expansion of the medium to occur in the pipeline. Such expansion is detrimental to the rapid release of the medium to atmosphere (especially with CO_2) as there is a severe temperature drop at the point where expansion takes place. Should this expansion occur within the pipeline through a partially open valve some of the medium may freeze, prevent the valve opening, and block up the restricted passage through the valve. The cylinders are fitted with cutter valves designed to give full bore opening almost instantaneously, and a siphon tube to carry the medium through the cylinder outlet, and into the pipeline in the liquid, not the gaseous state. In order to ensure that the same condition obtains with the distributing valves, the control system must open these either before, or at the same time as, the cutter valves operate. Fig. 202 shows a distributing valve specially designed and constructed to meet the characteristics of CO_2. The release allows the weight to fall when the automatic detecting device functions, or a manual control is operated. The release illustrated is actuated electrically by the completion of a circuit energising a solenoid.

Electrical Control

In large substations an electrical control system may be installed for the operation of the fire-extinguishing equipment. Automatic control may be effected by flame- or heat-sensitive switches, or bi-metallic thermostats. Where exceptionally rapid fire detection is necessary a control device actuated by the rate of rise of the air temperature adjacent to the risk may be used. With electrically controlled systems the mechanism

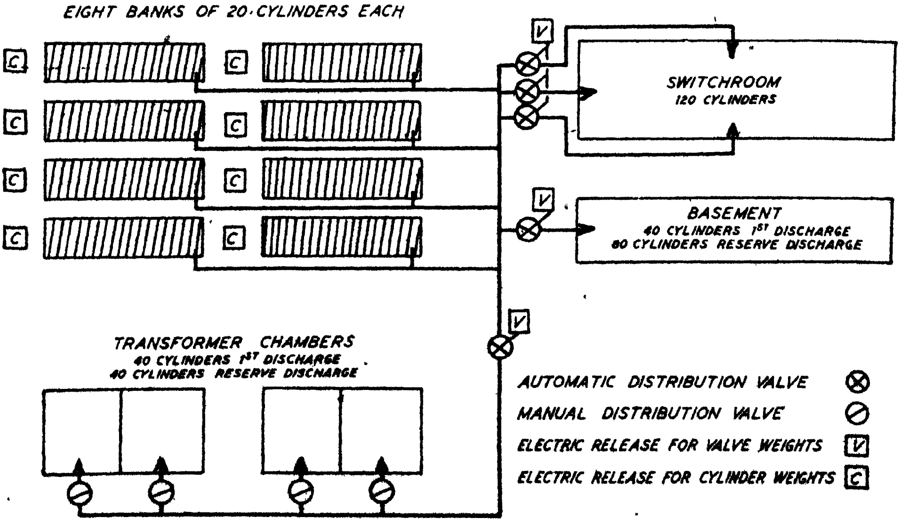


Fig. 203.—Typical arrangement of 160 cylinder battery for operating the cutter valve levers is also actuated by an electric release, which is energised simultaneously with the distributing valve release.

A typical arrangement of a large CO_2 battery is shown in Fig. 203. With this layout the battery is divided into eight sections for convenience of control and the cylinders are manifolded in groups so as to enable 40, 80, 120, or 160 to be discharged into the distribution system together. The grouping permits each compartment to be protected by the number of cylinders required to adequately cover the risk—as indicated in the diagram.

The switchroom is supplied through three pipelines, each fitted with an automatic weight-operated valve. All three valves are opened together by a common electric release for tripping the valve weights. The basement is supplied through a single pipeline and valve ; and the transformer chambers through a common pipeline with a branch line to each. Manually operated valves are used to select any particular transformer chamber after the main valve has been operated by the remote control located in a suitable position. In the case of the transformer chambers and the basement, the arrangement provides for a reserve supply of gas to these risks. Any combination of the eight cylinder banks is available by connecting up the electric releases in the appropriate manner.

Pressure Gang-release Units

In Fig. 204 an alternative method of discharging large banks of CO_2 cylinders, by pressure gang-release units, is shown. To the right of the main battery are three pilot cylinders of the type in which the cutter valve levers are held in equilibrium by a weight and a flexible cable attached to the release. When the release is actuated—in this instance by the electrical control system—the copper sealing discs of the pilot cylinders are pierced, and high-pressure liquid CO_2 is admitted to pistons working in the long tubular cylinders shown between the pilot and main gas cylinders in Fig. 204. Each of the three pistons is attached, by means of a flexible cable, to the ganged cutter valve levers of one of three banks of cylinders ; which in this case are all discharged simultaneously. After the piston has reached the endof its stroke the $CO_2$from the pilot cylinders, used to operate it, passes by way of a connecting pipe into the manifold, and is discharged into the fire area—thus full use is made of all the gas available. Fig. 204A shows the type of cylinder head used for the battery in Fig. 204. At the extreme left of this battery are three cylinders forming an auxiliary bank which is controlled by its own release, the cutter valve levers being actuated by directly attached weights. This bank, although separately controlled, discharges into the main pipeline system for supplying hose reels, or fixed discharge horns covering a relatively small hazard.

For the selective discharge of a large battery operated by pressure

Fig. 204.—CO_2 BATTERY OPERATED BY GANG RELEASE UNITS. (*The Walter Kidde Co., Ltd.*)

gang-releases the arrangement will be similar to that shown in Fig. 205; and, assuming that the layout of the gas distribution system is identical with that in Fig. 203, in this case the control switches will energise the corresponding electric releases for tripping the distributing-valve weights simultaneously with the master cylinder electric releases. From the diagram it will be clear that the number of cylinders discharged will depend on which master cylinder releases are energised at the same time. With the particular layout shown it is possible to discharge 40, 80, 120, or 160 cylinders together by means of three pairs of master cylinders supplying the pressure gang-release units.

Fig. 204A.—CUTTER VALVE LEVER CONTROL.
(*The Walter Kidde Co., Ltd.*)

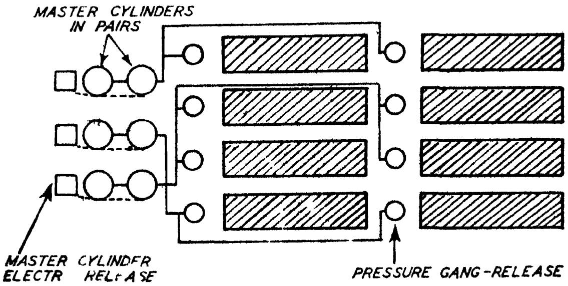


Fig 205 Typical arrangement of gang release units

As it is important that there should always be an ample supply of CO_2 in the master cylinders their weight is checked at frequent intervals. In some installations the master cylinders are mounted as a unit on a scale balance, so that should the weight of the combination drop by more than a certain amount contacts close to energise an alarm.

Methyl Bromide Installations

Fig 206 shows a large methyl bromide installation suitable for the protection of a large substation in conjunction with selective distributing valves. The equipment illustrated is of the falling-weight link-line type, the simplicity of which is desirable for obtaining certainty of action. This is the advantageous feature of all mechanically operated installations, which are used whenever practicable as electrically operated systems

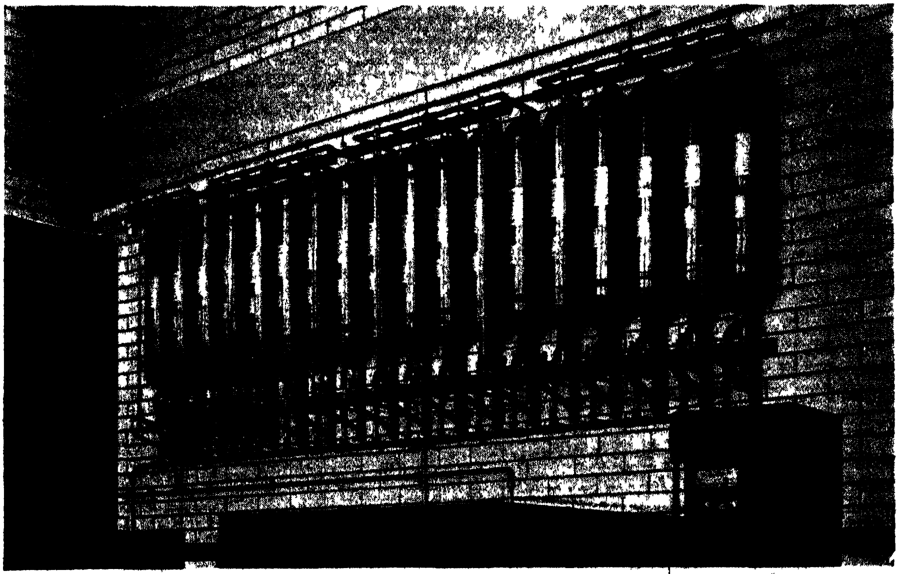


Fig. 206.—Typical methyl bromide installation. (*The National Fire Protection Co., Ltd.*)

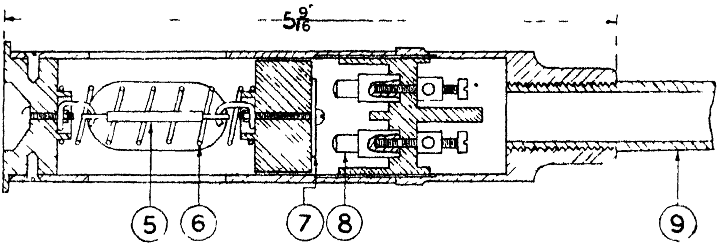


Fig. 207.—FLAME-SENSITIVE ELECTRIC SWITCH. (*The National Fire Protection Co., Ltd.*)

require a storage battery for their operation. With some substation layouts, however, a fusible link-line system would be so complicated as to be impracticable, and an electrical scheme is preferable, since with the class of substation concerned a storage battery is usually available.

The "Essex" methyl bromide equipment, when electrically operated, incorporates certain features of particular interest. One of these is a flame-sensitive electric switch, Fig. 207. A link (5) of gun-cotton, or other inflammable material, or alternatively a composite link of fusible metal, holds an insulated plate (7) under spring tension. The destruction of the link allows the spring (6) to force the plate against the spring-loaded contacts (8) and thus complete the circuit. With this type of flame-detecting device a solenoid may be used to operate the weight retaining lever of a unit generally similar to that shown in Fig. 200, in which case the solenoid armature trips the lever, and the weight descends to the bottom levers actuating the piercer spindles.

An alternative method of operation is by means of the cartridge breech mechanism shown in Fig. 208. Affixed to the lower portion of the unit bracket (18) is a strong body in which are accommodated spring connectors (21) held in close contact with the terminals of a small detonator (20), above which is fitted a movable piston (16). Upon completion of the circuit a small wire fuses in the detonator, and the piston is forced upwards taking with it the plunger of the seal-piercing mechanism. Excess pressure is vented through a small hole (17).

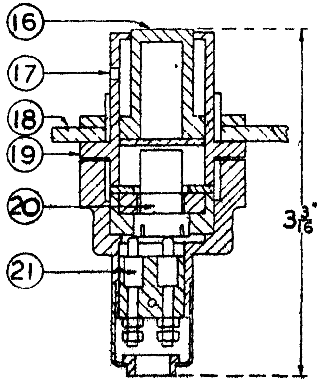


Fig. 208.—CARTRIDGE MECHANISM TO OPERATE PLUNGER (*The National Fire Protection Co., Ltd.*)

Ventilation Control

Although control of ventilation is not essential if an adequate quantity of gas is discharged to compensate for wastage (especially when the drowning method is employed), wherever practicable fans are switched-out and ventilators, etc., closed simultaneously with the operation of the extinguishing equipment. Pivot-type windows and shutters in a protected space may be closed by means of pressure trips, which are installed in the distributing pipeline and operated by the pressure of the gas discharge. Shutters are sometimes fitted which are normally held open by a taut wire, which is either released by a pressure trip, or is kept taut by attachment to the link-line system and released when a fusible link functions, in both cases the shutters being closed by their own weight. Complicated arrangements are not usually justified as they produce an elaboration of equipment which can be avoided by increasing the quantity of gas discharged.

When methyl bromide is applied by means of jets directly impinging on the seat of the fire, suitably placed screens enable the medium to be used economically to the best advantage, especially where there are strong draughts—such as would be caused by rotating machines. This class of plant in attended substations is not usually protected by a fixed installation, reliance being placed upon portable extinguishers. Machines located in compartments of reasonable volume can be protected by the concentration or drowning methods if the ventilation is controlled.

Safety Controls

All gas equipments are provided with means of preventing operation of the discharge mechanism whilst personnel are working in the protected space if this is at all confined. It is also desirable that the safety device should be arranged for remote control from outside the space so that, in the event of an outbreak while the equipment is temporarily out of service, it can be brought into action after the personnel have left. In the ordinary way a safety catch need do no more than prevent the cutter valve lever weights from falling by holding the operating mechanism after it has been released. Thus the remote control for the safety catch will not operate the installation unless the fire-detecting device has already functioned, consequently in many cases a remote operating control is fitted, distinct from the safety catch control—if used.

Although with gas installations the danger of harmful effect to personnel is always present, with methyl bromide and CO_2 it is far less than has been commonly supposed in the past—with the gas concentrations required for most electrical risks. However, it is as well to envisage the worst possible conditions which may arise when considering the precautionary measures to be adopted in connection with gas equipments, especially in situations where the station exits are not readily accessible.

The discharge of CO_2 into a space is attended with considerable noise which provides a useful warning of what is happening, so that in situations where there is nothing to hinder the movements of personnel the effect of an accidental discharge is not likely to be dangerous. Even in confined spaces the danger to personnel from sudden conflagrations, and the resulting smoke and fumes, may be far greater than that arising from a temporary immersion in a gas concentration required for rapid effective extinction ; so that in some circumstances it may be advisable not to put the extinguishing equipment out of action.

Maintenance of Equipment

To enable work—such as testing of manual controls and releases—to be carried out, gas installations are usually arranged so that the cutter valve levers can be rendered immovable, independently of the rest of the equipment, and full cylinders removed without danger of accidental discharge. This is necessary when cylinders have to be weighed periodically to check for leakage. Although there is little likelihood of leakage occurring a usual practice is to weigh all cylinders six months after installation and, if correct, follow this by weighing once a year.

In general, gas is the medium usually adopted for fire protection by a fixed installation in small and unattended substations, but in large stations both foam and atomised water equipments are also used.

Foam Generators

Portable chemical foam extinguishers are frequently used to cover small risks. This type is brought into operation by simply turning them upside down, or laying them lengthwise as the case may be, and, with some units, opening the mixing valve. These actions mix the two solutions the effect of which is to generate sufficient pressure to expel a stream of very fine foam bubbles from the jet. The capacity of the portable type is obviously limited, and a further development is the foam-generating fixed equipment which uses water, and a single dry powder charge, for making foam by the action of water jets impinging on to the charge in a container.

Water from the mains supply, or a pump drawing from a tank, is admitted through an inlet valve from which it is conducted to specially designed nozzles inside the generator. These nozzles are fitted obliquely near the top of the charge, and the water is driven into the foam powder with considerable force. The effect of the jets on the powder is to form a solution, and carbon dioxide is generated, the result being the formation of a freely flowing foam which is projected by the pressure set up within the generator. The foam is delivered through rubber-lined hose—for manual application—fixed pipes, or both, and is distributed on to the fire either by large-bore branchpipes, pouring tubes, or special discharge heads—according to the precise nature of the risk involved.

A continuous supply of foam can be made available by using a pair of generators, recharging of one being carried out while foam is actually discharging from the other. The method of operation is extremely simple and consists of opening and shutting valves in a certain sequence to start, or recharge, a generator. A single equipment can be used to cover a number of electrical units by installing separate feed pipes and control valves.

The Foam-making Branchpipe

Mechanical foam is a modern form generated by a device which consists of a specially constructed branchpipe coupled up to an ordinary standard hose length. The appliance delivers foam at an unprecedented rate by combining air from the atmosphere, water, and foam-making compound in such a way as to produce an immediate conversion.

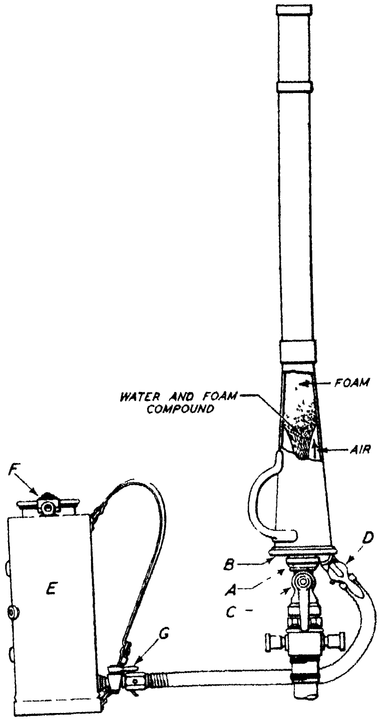


Fig. 209. Foam-making branchpipe (*Pyrene Co., Ltd.*)

A knapsack-type branchpipe is shown in Fig. 209. The waterhead *A* incorporates an ejector for drawing in the foam compound; water and compound being discharged into the foam-making branchpipe at a rate which ensures the correct degree of atomisation. The piston effect produced in the branchpipe draws in air through the space *B* provided around the waterhead. This air is combined with the water and compound streams, and the energy of these streams is used to complete the formation of foam. The main water pipe is provided with a cock *C*, and there is also a cock *D* for controlling the foam compound supply to vary the consistency of the foam being delivered. The knapsack tank *E*, which is used as a container for the foam compound, is fitted with a quick release cover *F*, which permits rapid replenishment. The cock *G* on this tank enables the compound supply to be turned on and off as required. The arrangement of the controls enables the branchpipe to be used for foam of the required consistency, or water only.

Foam-making branchpipes are used in various sizes delivering up to 2,000 gallons of foam per minute.

For the production of mechanical foam, water must be available at a pressure sufficient to throw the jet to the distance required; but when used in a building a long jet is not essential so that in this case a reasonably low pressure may be used with efficient results. The foam-making branchpipe has also been adapted for fixed installations. For supplying large-capacity branchpipe installations the foam-making compound is usually contained in a tank, located at a convenient point, from which it is withdrawn by inductors. The portable "inline" inductor (Fig. 210) is simply a specially designed by-pass, with a connection to the compound tank, which utilises part of the energy being supplied to the branchpipe to draw in the compound. The "multiple" inductor shown in Fig. 211 enables one or more foam-making branchpipes to be used in conjunction with any fire pump.

Foam-making equipments are sometimes arranged for automatic operation. In the case of a foam generator using impinging water jets an automatic installation is brought into action by a suitable mechanism opening the valve on the water supply. For this purpose the hydraulic method is probably the most widely used; the water pressure being made to open a differential valve which is normally kept closed by some form of pressure balance which can be upset by the operation of a sprinkler detector, pneumatic or electrical release, actuated by the usual heat- or flame-sensitive devices.

Fixed foam-making branchpipe installations can also be arranged for automatic operation; although, in general, remote manual control is satisfactory for the substations in which it is practicable to install foam-making equipments. For back-up protection in large attended stations the foam-making branchpipe is of particular utility.

Emulsion-forming Water-jet Equipment

Fire extinguishing by emulsion-forming water-jets or, in short, atomised water, is usually restricted to major substations where very large quantities of oil are involved, and a reliable water supply is available.

Atomised water installations are actually a development of sprinklers. The main pipe system supplies branchpipes to groups of projectors covering the protected plant. In some installations the main pipe system is normally filled with water under pressure, and the supply to each group of projectors is controlled by a valve which is kept closed by a device incorporating a heat-sensitive liquid-filled bulb until such time as an outbreak of fire shatters the bulb—as the result of an appropriate increase in temperature—when the automatic opening of the valve releases water to the projectors.

Since the emulsification of the burning oil depends on the water being discharged at considerable pressure a pump is started automatically, immediately the discharge commences, to maintain the requisite pressure in the system. The pump motor switch is closed by gravity due to the momentary drop in the pressure which normally keeps the switch in the open position. By dividing the total number of projectors required to cover a large unit into several groups, each controlled by a separate valve, in the event of a small localised fire only those projectors covering the affected zone will be brought into action, thus avoiding the unnecessary discharge of water. If the fire is of a general character involving the whole

Fig. 210.—Inline inductor inserted in delivery hose line
(*Pyrene Co., Ltd.*)

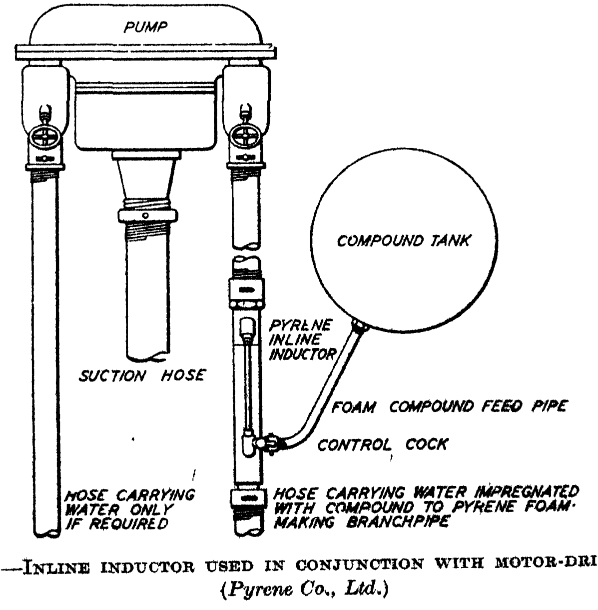


Fig. 211.—Inline inductor used in conjunction with motor-driven pump
(*Pyrene Co., Ltd.*)

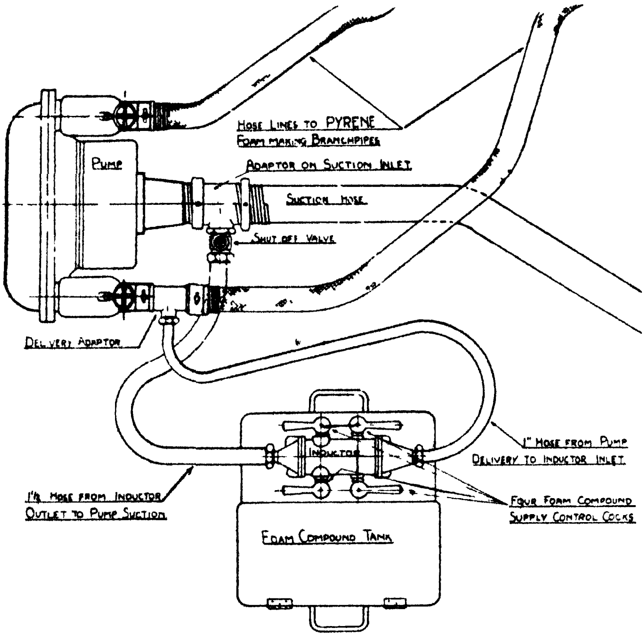


Fig. 212.—Combined four-jet inductor and foam-making compound tank
(*Pyrene Co., Ltd.*)

of the protected unit or section all the projectors will be brought into action.

Outdoor Installations

In locations where freezing is possible, as is the case with installations covering outdoor units, the outdoor pipe system is normally charged with air at low pressure. When a fire occurs a differential valve, normally kept closed by the opposition of air and water pressures, opens automatically with the release of the air in the pipe system and admits water to the projectors.

Many outdoor installations employ pilot detectors fitted to a pipe system maintained under air pressure, and independent of the pipe system, serving the projectors, which is normally kept dry. The pilot detectors are mounted in suitable positions to ensure immediate operation of at least one in the event of a fire, so that the air pressure in the pipeline connected to the air chamber of the differential valve falls rapidly and the valve opens to admit water to the projectors. With this arrangement a fire of a local nature will bring all the projectors into action ; but in the case of outdoor electrical units no harmful effects will, of course, result from the water discharge.

For the extinction of small oil fires, which do not warrant the discharge of a fixed equipment, special branchpipes delivering an atomised water spray are generally available in substations where this form of fire protection is employed.

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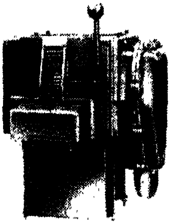

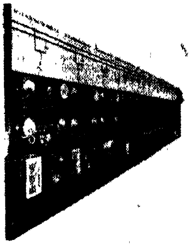

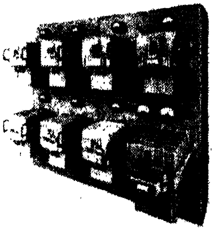

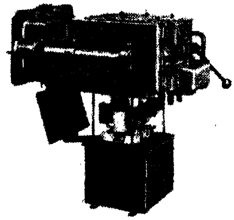

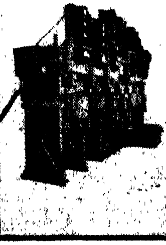

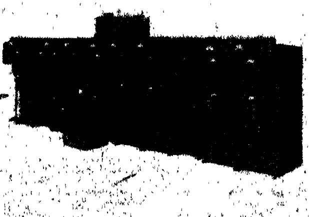

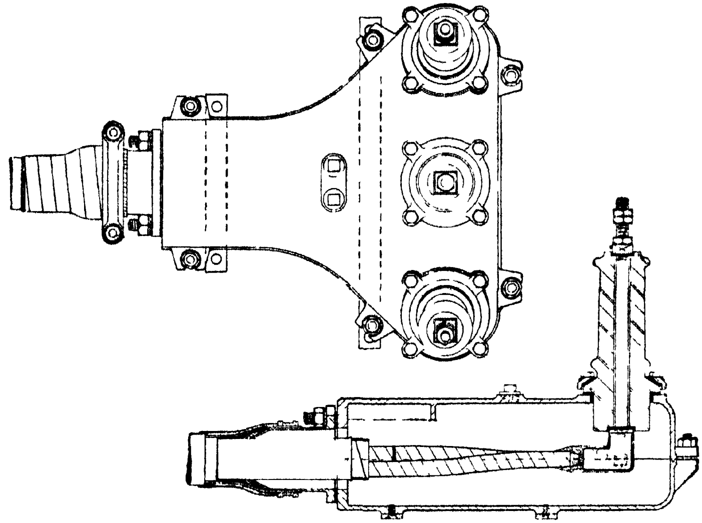

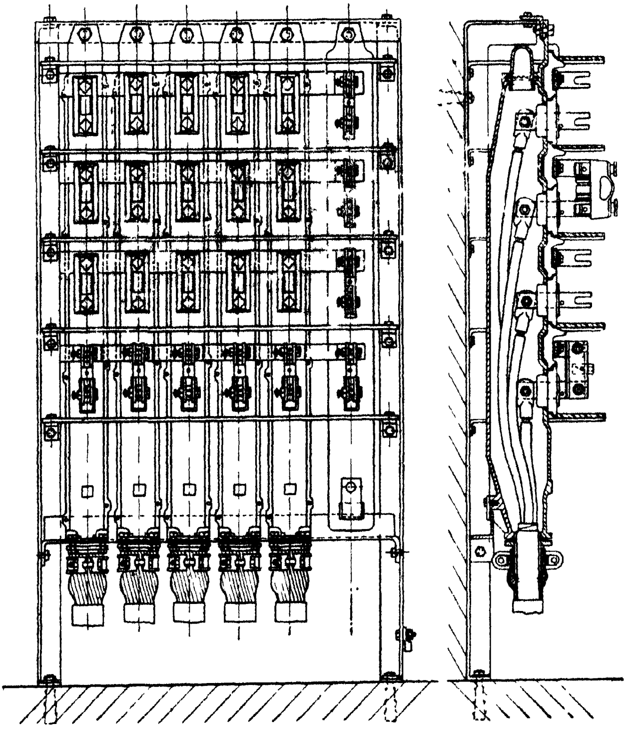

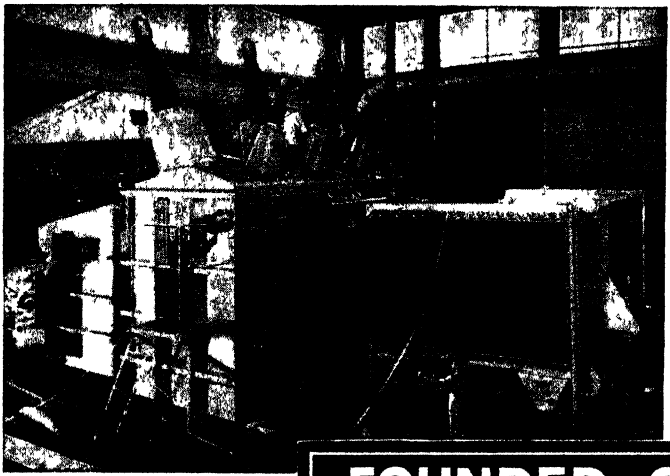

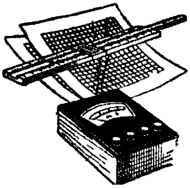

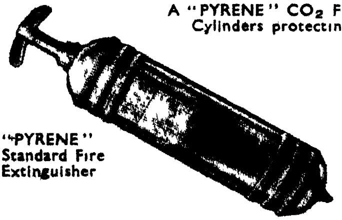

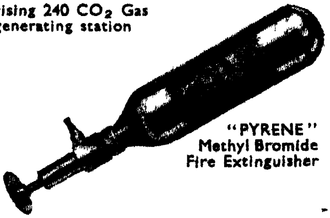

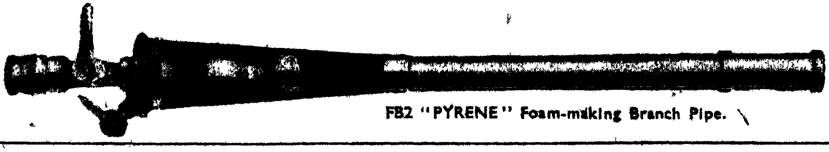

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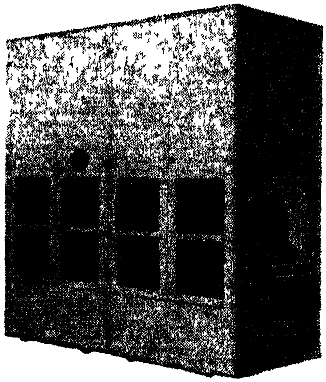

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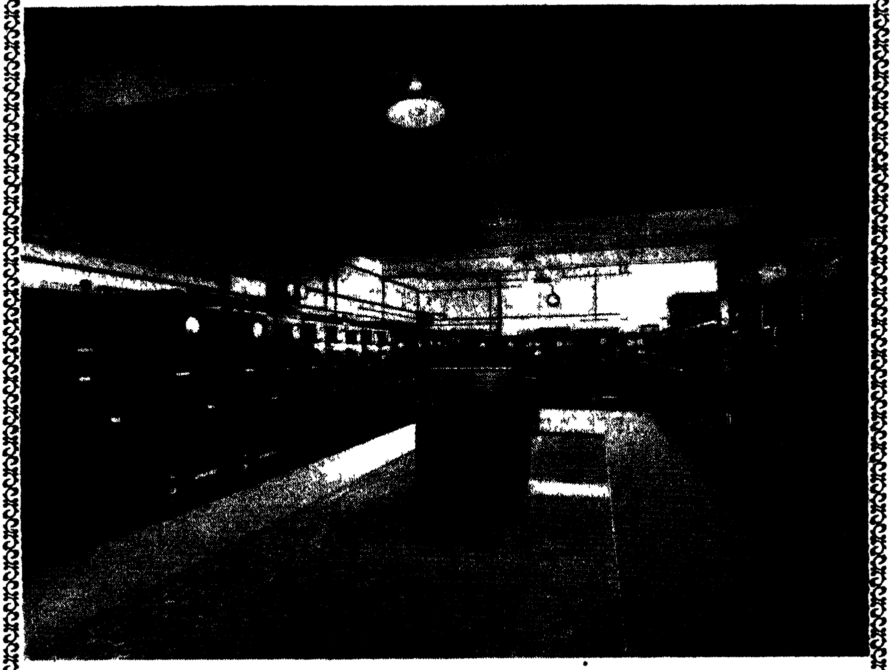


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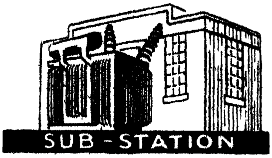
GLASS-BULB TYPE
STEEL-TANK PUMPLESS AIR-COOLED TYPE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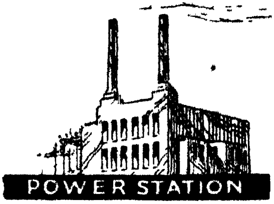
SWITCH STATION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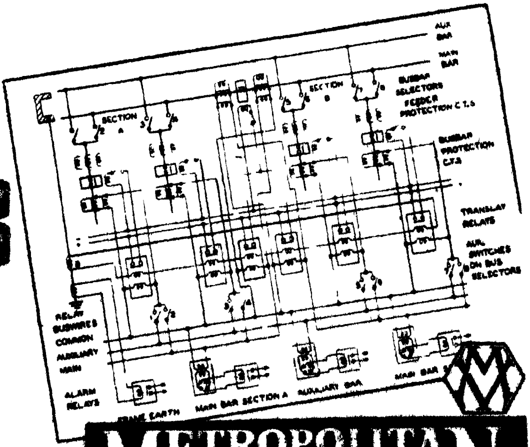
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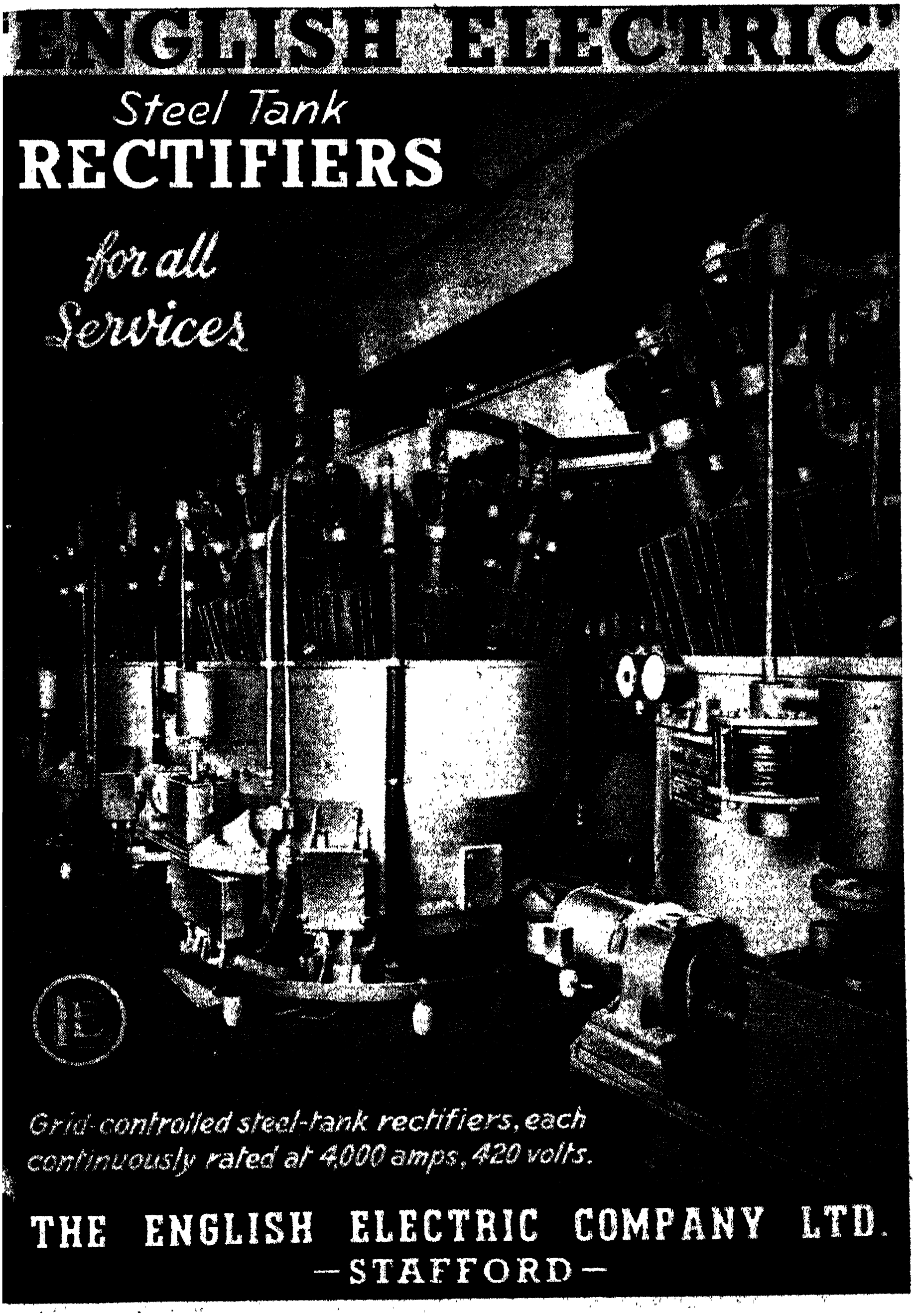
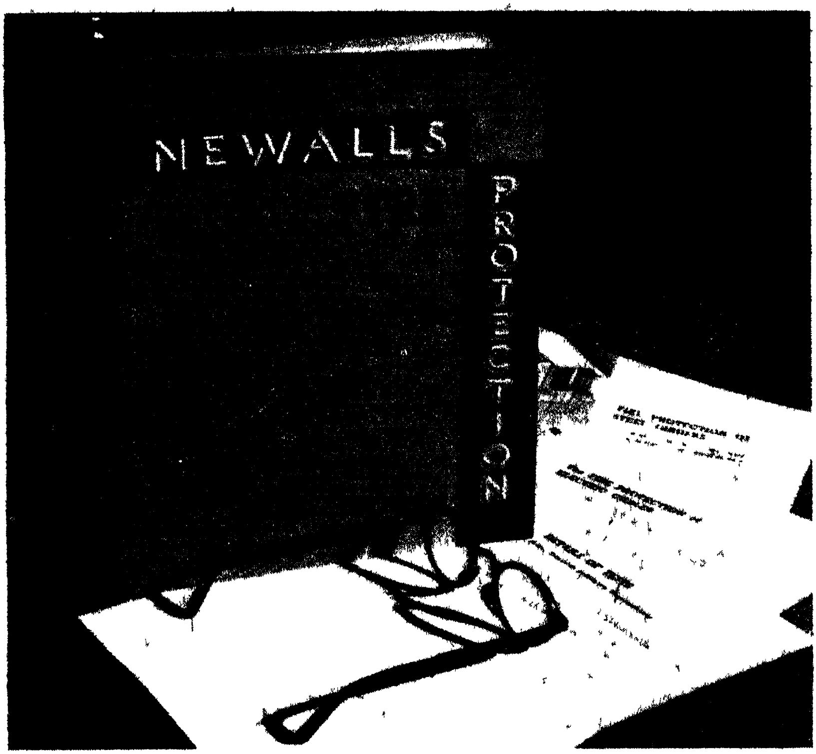
MAIN BAR
SECTION A
SECTION B
BUSBAR SELECTORS
FEEDER PROTECTION C.T.S
BUSBAR PROTECTION C.T.S
TRANSLAY RELAYS
AUX. SWITCHES ON BUS SELECTORS
RELAY BUSWIRES
COMMON
AUXILIARY
MAIN
ALARM RELAYS
FRAME EARTH
MAIN BAR SECTION A
AUXILIARY BAR
MAIN BAR

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