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INDUSTRIAL ELECTRIFICATION

A HANDBOOK FOR ELECTRICAL ENGINEERS
EMPLOYED IN THE INSTALLATION, SUPERVISION
AND MAINTENANCE OF ELECTRICAL PLANT
IN INDUSTRIAL UNDERTAKINGS

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PREFACE

So far as the writer is aware, this book covers ground which has not previously been dealt with in any comprehensive book form. It is based on a number of years' experience in designing and maintaining electrical installations for large industrial plants, and it is hoped that it will succeed in filling a gap in technical literature which has existed for too long. It is realized, of course, that some of the material herein may seem to some readers to be somewhat controversial, but, on a subject which may perhaps have as many viewpoints as there are engineers dealing with it, it is felt that this book does at least afford a foundation upon which to build. No attempt has been made to give actual prices of electrical material, since these are largely unreal under immediate post-war conditions, but some typical price curves have been included which can easily be re-drawn to suit current prices and which should be of value.

Acknowledgment of particular items of information has been made in the bibliographies, but the facts have been drawn from many sources over a lengthy period and acknowledgment is here made to the many people whose work has contributed to the compilation of such information as is included in this book.

J. W. McQUILLEN

April, 1947

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CHAPTER I

THE INDUSTRIAL ELECTRICAL ENGINEER AND HIS JOB

THE duties and responsibilities of the present-day Industrial Electrical Engineer hold a very important and necessary place in the structure of modern industry and they are likely to increase in the future as the rate of industrial electrification increases and the sphere of his interest continues to expand. In a modern factory there is very little which does not concern the electrical engineer, however remotely. His job can, and frequently does, cover practically every aspect of electrical engineering from generation down to lighting, from high voltage or heavy current power circuits down to a few volts or milli-amps in a relay circuit and it is very necessary that he should be conversant to a greater or lesser degree with all these aspects. True he does not require to have the academic knowledge of specialists, but he must be able to assess the value of the work of these specialists and apply it to his own purpose. He must have a knowledge of economics to help his judgment in deciding which scheme to adopt where there is more than one alternative. He must also have a fair understanding of the mechanical side of engineering to enable him to select the most suitable equipment for his job and he should preferably be blessed with a good degree of ingenuity to help him to devise the many interlocks and gadgets which he is almost sure to be asked to provide.

Many Industrial Electrical Engineers are in a position of being the only electrical men in the factory, which state of affairs has both advantages and disadvantages. The engineer who finds himself in this position becomes the sole arbiter in any decisions he makes, since no one else is in a position to criticize his views, and he must satisfy himself that any schemes or propositions he puts forward are the best possible. He must be prepared to take a very firm stand in matters over which he disagrees or which affect the safety of workpeople since it is his responsibility to maintain the plant in a safe condition electrically. The disadvantage of the isolated engineer is that he lacks anyone with whom he can discuss his problems; and discussion is a fruitful source of solutions to problems and improvements to equipment. It is therefore hoped that this book may be of particular value to this type of engineer when he wishes to refresh his memory on some practical detail or when he feels the need of some other viewpoint on some particular problem. It is pointed out that no effort has been made in this book to deal in any detail with the generation side of industrial electrification, since this aspect has been well covered by other writers.

An Industrial Electrical Engineer should endeavour to maintain an open and inquiring mind as regards all matters electrical and should keep abreast of the latest developments with a view to incorporating new and improved equipment or methods in his installation. He should constantly keep his standards of installation work under review to make sure that out-of-date practices are not being perpetuated for no other reason than that they have been employed for many years past. This last point may appear to be somewhat unnecessary, but it is none the less important because it is very easy to assume that methods which have proved to be satisfactory in practice must be the best, whereas, with the proviso that there shall be no sacrifice of reliability, the best job is the most economical.

There is not a lot of statutory regulations and legislation for the Industrial Electrical Engineer to concern himself about, although certain regulations are in force in respect of specific industries such as mining and quarrying. His chief concern is with the Statutory Rules and Orders issued and made under the Factory and Workshop Acts to regulate conditions with respect to the generation, transformation, distribution, and use of electrical energy in factories and workshops. These regulations must be displayed prominently somewhere in the factory and also in each sub-station so that all concerned may be conversant with them and conduct their work in accordance with them, as is stipulated. The regulations commence with certain definitions some of which are now somewhat out of date and in need of revision, particularly the definition of low, medium, high and extra high pressure, which are given as below 250 volts, 250–650 volts, 650–3000 volts, and above 3000 volts respectively. This latter voltage would not usually be considered "extra high" under modern conditions and, in what has been written in this book, 440 volts has been included in the low voltage category. The regulations then pass to certain specific requirements for installations, buildings, and for operation of electrical equipment, most of which would probably be adopted by the engineer as a matter of course. The real sting is in a constantly recurring phrase "to prevent danger" in which the regulations depart from the specific and place the onus fairly and squarely on the shoulders of the electrical engineer for designing, installing, and maintaining a safe installation. His is the responsibility should any accident occur due to defective electrical work and he should constantly bear this in mind.

The Electricity Commission, a body set up under the Electricity Supply Act of 1919 to deal with the technical aspect of the Act, has drawn up a series of regulations relating to electricity supply for the purpose of "securing the safety of the public and for ensuring a proper and sufficient supply of electrical energy." Although these regulations do not apply to factory installations, the Industrial Electrical Engineer would do well to familiarize himself with them, particularly the overhead line section, since they indicate the official view of the minimum requirements for safety. This viewpoint is specifically mentioned by the Senior Electrical Inspector of Factories in an explanatory memorandum on the Electricity Regulations issued under the Factory and Workshop Act.

When we come to consider the internal installation for buildings, we find that no legal regulations are in force although it seems probable that, in the near future, some set of regulations approximating very closely to those issued by the Institution of Electrical Engineers will be made legal and binding. These regulations, of which the latest edition is the eleventh (revised) reprinted in May, 1945—a supplement was issued in 1946—are constantly under review to bring them up to date and they have a very useful function in electrical installation work as forming the basis for most specifications; they are indeed made obligatory by many fire insurance offices. The I.E.E. Regulations are fairly comprehensive and they set out in considerable detail the requirements for sound installation practice.

The electrical engineer should also be familiar with the various British Standard Specifications for electrical equipment published by the British Standards Institution and he should make full use of these when ordering material. Much useful information is incorporated in these Specifications and a recent innovation by the British Standards Institution in issuing Codes of Practice for various engineering operations will be found very helpful by engineers. Judicious standardization can cheapen production considerably and it is a process which should be encouraged as much as possible.

The foregoing can be considered as constituting some of the qualities which are necessary for making a complete electrical engineer. There are, of course, others, but it is perhaps a waste of time to remind electrical engineers, of their own virtues.

CHAPTER II

DISTRIBUTION NETWORK DESIGN AND INSTALLATION

WHEN an engineer sets out to design the electrical network for a factory site, he is undertaking the responsibility for a capital expenditure which quite often forms a large proportion of the total cost of the factory. The soundness of his judgment as reflected in the reliability of his network will affect the output of the factory, since the modern works is usually helpless without its electricity supply and the cost of a shut-down soon reaches a large figure.

The prime essentials of a good network are reliability and flexibility. Reliability can only be expected where good-class materials of proven ability are installed and where the rated performance of apparatus is within the limits of the worst possible fault conditions which may be imposed on it. Flexibility, by which is meant the ease with which extensions can be accommodated or the network modified at some future date to suit altered conditions, is not so easy to attain and the engineer must largely draw on his past experience to help him in this. As has already been implied, main distribution equipment is relatively expensive to install and it is also usually difficult to extend, so the distribution network should be designed in the initial stages to allow a reasonable margin of spare capacity.

At the outset of the job the engineer should accumulate as much information as he can about the factory. He must know the total estimated load, the loading of the various sections, the running time, whether full or only part time, the diversity which may be expected between different parts of the factory, and from all this he must estimate his maximum demand load. He is concerned with access conditions to the site so that his heavy material can be suitably delivered, he is concerned with the heating, lighting, and ventilation of buildings, all of which items build up a good-sized load, even the preparation of meals in the canteen affects him if this is to be done by electrical means. In short, there are very few aspects of the factory which do not concern him and he must be in a position to collect this information before he can commence to design his network.

Bulk Supply or Private Generation

One of the first questions to be settled is that of the source of electricity supply, and the engineer has a choice of three methods:

he can install his own generating plant, he can take a supply from the supply authority, or he can have a combination of both and install power plant to supply the base load whilst using the supply authority's network for his peak loads or vice versa. The problem of which to choose can only be answered after very careful assessment and comparison of the economics of the three systems.

It is unfortunately impossible to establish any sort of hard and fast rule which will solve the above problem for all cases, since the correct solution involves consideration of a number of circumstances, the combination of which is not likely to be the same for any two factories. Furthermore, it is outside the scope of this book to delve too deeply into the economics of any particular aspect of the problem, but we can consider what are the points which are going to have a bearing on the subject.

Having estimated the immediate and projected maximum demand and load factor figures, the engineer should then approach his local supply authority to ascertain what their tariff would be. The tariff quoted will usually be of the two-part nature, comprising a fixed charge per kilowatt of maximum demand and a running charge of so much per unit. There may or may not be a low power-factor penalty clause and there may or may not be a charge quoted for bringing a supply into the site under question, depending on whether or not the location of the site is convenient for the supply authority's network. If a charge is made for the service, then the annual charges on this sum can be added to the fixed charge in the tariff. The engineer can now work out what would be the cost per unit of his electricity if he took his supply from a supply authority.

The next step is to estimate what would be the cost of a power station to supply the load with, of course, a reasonable margin of spare capacity. The pre-war capital cost of industrial power stations was of the order of £12–£16 per kW capacity and, if this figure be adjusted to suit present-day advances, it is a relatively easy matter to estimate sufficiently accurately for our purposes the capital cost of a power station to supply the requisite load. The annual charges on this capital sum can now be arrived at to suit the current interest rates and depreciation and to these should be added such other annual costs as rates, insurance, staff salaries, and maintenance until we arrive at a figure representing the total annual cost of the power station. If we then divide this figure by the maximum demand of the load, we arrive at a figure which is comparable with the fixed charge in the supply authority's two-part tariff. So far as the running cost per unit is concerned, there is no reason to suppose that it would be any higher than that quoted by the supply authority, since their figure includes a margin for profit, and in all probability the running cost of generation by a private power station would be less than the figure quoted by the supply authority, even allowing for higher generation efficiency in large power stations which may be largely offset by transmission losses from the power station to the factory site. For the purposes of comparison we may safely work on the supply company's running cost and thus we are in a position to compare the unit costs for private generation or bulk supply. Admittedly this is a very rough comparison but, if the result has a very definite bias in either direction, then it has served its purpose; if the result indicates a border-line case, then further careful and more detailed investigation is necessary. To assist in the above comparison the itemized tables of generating costs for various-sized stations as published by the Electricity Commissioners will be of value.

Throughout the foregoing it has been assumed that the power station would be operated for the sole purpose of generating electricity and that the steam after passing through the turbines would be condensed and used again. If, however, steam in considerable quantity is required on the factory site for process or heating purposes, then an entirely different proposition can be presented. The argument in favour of private generation becomes very much stronger, since the process steam can be bled from extraction turbines or alternatively back-pressure sets can be used if the process steam is required at low pressure. By thus saving the heat which is normally lost in condensers, a very much more efficient heat cycle is obtained and the overall efficiency of the power station can be raised from 20–30 per cent to as high as 65–80 per cent with consequent reductions in the cost of electricity generated. If the demand for steam is such that it balances the electrical demand, then a very satisfactory state of affairs prevails and power plant can be installed to operate at the high efficiencies previously mentioned. If the electrical demand requires more steam raising than is required for process purposes, then either back-pressure generating sets up to the limit of the steam demand can be used and the balance of the electrical load taken from a public supply, or a mixed station can be designed incorporating back-pressure and condensing turbines.

If the load factor for the factory would be high, as in the case of a continuously running process, then a very good case can be made for installing generating plant, since the tariffs put forward by supply authorities usually offer no reward for high load factor despite the fact that their revenue must obviously be very much higher where the load factor is high than where it is low.

The factors mentioned in the preceding paragraphs as well as such other questions as the availability of an adequate supply of cooling water or the accessibility of the site for bringing in fuel supplies, all have a bearing on the problem of whether to use private generating plant or to take a bulk supply and, as it is apparent that these factors or the combination of them will vary with different factories, this is probably as far as we can pursue the subject.

System Voltage

Consideration must now be given to the question of the voltages to be selected for the distribution system. The deciding factors are the size of the load, the area covered by the factory, and the load distribution over the factory site. If the factory under consideration is small and compact and the electrical loading is only of the order of a few hundred kilowatts, then there would be no benefit in departing from low voltage. If, on the other hand, the load is of the order of 1000 kW and upwards and the factory area is extensive, then it is obvious that appreciable reductions can be made in distribution losses by adopting higher voltages, since the line losses for a given size of conductor vary inversely as the square of the voltage. Should the electricity supply be taken from a public authority, then, of course, the question of the supply voltage is outside the jurisdiction of the factory engineer and, if this supply is given at low voltage, then all choice in the question of system voltages is taken from him. The standardization of voltages throughout the country is likely to have beneficial effects on the electrical industry as a whole and, if he has any choice in the matter, the electrical engineer ought to accept the standard voltages which have been recommended and to adopt 415 volts, 3-phase, 50 cycles as his standard for low-voltage distribution.

In the case of a medium-sized factory with a load of a few thousand kilowatts, higher voltages will have to be adopted to distribute the load to various parts of the site and 3300 volts will normally be found to be the most suitable standard to select. This voltage may also be found convenient to adopt for large motors of 60 h.p. and upwards, particularly if slip-ring machines would have to be used if operated on the 400 volt system; 3300 volt motors are obtainable down to 60 h.p. and the substitution of a 3·3 kV squirrel-cage machine in place of a 400 volt slip-ring motor will often be an economic proposition.

For very large factories where large blocks of power have to be transmitted over fairly long distances it will often be found best to distribute at 11,000 volts, but voltages higher than this are not likely to be necessary.

Network Design

As has already been stated, the network must be designed to suit the factory lay-out; so the first step to take is to secure a site-plan of the factory under consideration. It is unlikely that any plan in the early stages of the factory design will be by any means final, but it will enable the electrical engineer to begin his work; and he must make due allowance for reasonable extension and alteration to the factory lay-out. The factory may consist of a number of separate buildings or it may take the form of one large building, but in either case it can be separated into various processes or parts of processes and the loading, both connected and running, should be marked on the plan in the appropriate areas. Differences in running times of the various sections should also be indicated to enable diversity to be taken into consideration. The distribution system should preferably be so arranged that each process building or each distinct section of the process has its own individual feeder cable or cables, so that any trouble on that particular section does not interfere with other parts of the factory.

Having estimated his total site loading, with due consideration to the factory lay-out, the engineer must now decide upon the location and number of sub-stations or distribution centres he will need. To do this satisfactorily he will have to bear in mind two deciding factors, viz. the limit of the capacity of his sub-stations and the limit of the length of his L.V. distributors. It is generally agreed that it is not good policy to make sub-stations too large and thus to put too many eggs in one basket. In general, it is suggested that the L.V. output capacity of a sub-station should be limited to between 2000 and 3000 kVA; exceptional circumstances will arise to make a departure from this ruling necessary, but for the majority of cases it will be found to be good practice. The total factory load can be split up into blocks of suitable size; with the above limit in mind and also allowing a reasonable margin for extension of load, the areas containing this load can be marked on the lay-out drawing.

With a certain amount of judicious juggling and transferring of load, it will normally be found possible to allocate a sub-station to a definite area of the factory which will contain possibly a number of complete plants or processes or a complete part of a process so that a tidy lay-out will be the result. This arrangement of allocating a sub-station to an integral part of a factory is well worth pursuing, even though it might entail a slight departure from the agreed standard capacity or the use of a greater number of sub-stations. The merit of this practice is the fairly obvious one that the loss of a sub-station would only affect the supply to a definite area and would probably allow other sections to proceed normally; whereas, if a plant is fed from more than one source, a failure of any of these sources is likely to shut down the plant.

If the load is well concentrated as it will be in most factories, then the above consideration of sub-station capacity will usually be the determining factor in the siting of sub-stations. If, however, the factory has a straggling lay-out and load is widely scattered, then feeders will be longer and the question of voltage drop must be considered. Here it would be timely to postulate two suggestions which the writer has found to work satisfactorily, that the permissible volts drop along an L.V. feeder be limited to 5 per cent and that the capacity of L.V. feeders be limited to 400 amps. The exceptional case will occasionally crop up to upset these suggestions, as in the case of some isolated building which can only reasonably be supplied from a particular sub-station but which is a long way from that sub-station, and in such a case a voltage drop of more than 5 per cent would probably have to be faced. The standard tappings on power transformers are ± 2½ per cent and ± 5 per cent, so that a 5 per cent drop along feeders can be compensated by altering the tap position on the transformer feeding it and the delivered voltage can thus be maintained within reasonable limits of its nominal value, a highly desirable state of affairs, since high voltage causes lamps to burn out more quickly and low voltage reduces the light output from lamps and also reduces motor output. The other suggestion to limit outgoing feeder capacity to 400 amps. has the advantage that this current can be carried by a 0·3 sq. in., 3- or 4-core, paper-insulated, lead-covered cable laid in the ground, thus obviating the use of heavy and unwieldy cables. It will usually also be found that a limit of 400 amps. fits in very nicely with the standard type of distribution gear on to which the cable will be feeding. Kelvin's Law can be applied, if desired, to determine the most economical section of cable to employ, but usually it will be found that this will be overruled by the matter of voltage drop. We can thus readily appreciate that the length of feeders is going to be limited by the above considerations and, as a consequence, the siting of sub-stations in scattered factory lay-outs is also going to be affected.

Having determined the number of sub-stations required to service the factory and the areas which they will feed, the chief question for the engineer is the exact location of the sub-stations. These should be fixed as near as possible to the centres of gravity of the load so that the length of feeder cables can be kept at a minimum. The only other point to be considered is that the stations should be easily accessible and not hemmed in by other buildings, so that the movement of heavy equipment into and out of the sub-station is not hampered in any way.

If the electricity supply for the factory is taken or generated at a voltage higher than 400, then it will be necessary to install transformers in the sub-stations to step-down the voltage for final distribution to the various plants or buildings. Standard-sized transformers should be installed, the size and number depending on the load to be supplied plus a reasonable margin of spare capacity for future extensions; thus, if a sub-station was required to supply a load of 900 kVA, a suitable arrangement would be to install three 500 kVA transformers, leaving one complete unit as spare. The question of spare capacity can only be properly considered in relation to the importance of the area being supplied and it may be considered in certain cases that to carry a transformer and its associated switchgear as spare is a condition which cannot be justified economically.

When the electricity supply is taken from a large supply authority or from a good-sized works power station, then the low-voltage distribution network must be so designed as to ensure that the possible short circuit mVA is kept within safe limits. It has been established that the worst short circuit conditions under which a man can reasonably hope to close a low-voltage switch against the consequent throw-off force is about 30 mVA and this has been accepted as the maximum rupturing capacity for most hand-operated low-voltage switchgear. In addition, the maximum rupturing capacity of most low-voltage, high-rupturing capacity fuses is 25 mVA so that, if we use this class of fuse as we almost certainly will, we must keep the short circuit capacity of our low-voltage system within the limit of 25 mVA. If we assume a reactance of 5 per cent for transformers, then it is apparent that the maximum capacity which can be connected to the network is 1250 kVA if the short circuit capacity on the high-voltage side of the transformers is sufficiently unlimited. This figure will also be the limit of the capacity of any individual transformer, although 1000 kVA is probably a better limit to adopt as representing a reasonable size of equipment. If the low-voltage load exceeds this figure, then the network must be suitably sectionalized to limit the load on any section to this maximum.

Having considered the number and capacity of the sub-stations required for feeding a factory site and having fixed their locations, we next must consider the manner in which to connect these sub-stations to the main supply so as to ensure the highest degree of continuity of supply under any conditions. To attain this high degree of availability of supply the practice of arranging to have alternative sources of supply in each sub-station is strongly recommended and its value cannot be too highly stressed. This practice should be adopted as far as possible throughout the network and should also be applied to the main incoming supplies into the network, whether from a public supply authority or from a private generating station. If a bulk supply is taken from a supply authority, then every endeavour should be made to ensure that the alternative incoming feeders are fed from separate and distinct sections of the supply authority's network and that, as far as possible, distinct, physical separation of the feeders is arranged so that, if the supply is brought in overhead, the two sets of cables are not carried on the same poles or, if brought in underground, the two cables are not laid side by side in the same trench. If the electrical engineer can secure all these measures, then he can rest content that he has taken all precautions within his power to ensure the constant availability of an electric supply into the factory; the matter of maintaining this availability of supply inside the factory is his own concern and depends upon the reliability and flexibility of his network.

If the factory load is of a size such as to warrant only one sub-station, then, obviously, all alternative sources of electricity supply will feed into this sub-station, but, if several sub-stations are necessary, then there are various means of providing the alternative supplies to these and the size of the load will usually determine which method to adopt. The choice will normally lie between a system of radial feeders from a central sub-station feeding to satellite sub-stations or a ring main feeding through all the sub-stations, or a combination of these two with a series of ring mains supplied from the main sub-station and feeding a number of satellites. All these schemes should be considered and the most economical adopted. It is reasonable to assume that if the factory load necessitates a number of sub-stations the main supply to the factory will be high voltage, 3·3 kV, 11 kV, or even higher, and the primary network comprising ring mains, radial feeders, and interconnexion will also be high voltage. High voltage and in particular high-rupturing capacity switchgear is expensive equipment and the system which involves the least number of high voltage switches consonant with equal flexibility and reliability is the best system to adopt. Where the short circuit kVA available in the high-voltage system is very large, the means of reducing this should be considered; such as the use of high-reactance transformers or the insertion of reactors in suitable places in the network. Considerable saving in capital expenditure can often be effected by the use of reactors, thus enabling lower rupturing capacity high-voltage switchgear than would otherwise have been necessary to be used, since the difference in cost between, say, 500 mVA switchgear and 100 mVA of equal voltage is very appreciable.

The various methods of feeding sub-stations are shown in Fig. 1. As has already been stated, the system to be adopted will usually be determined by the size of the load on the sub-stations. Thus, if the sub-station loadings are high, then the size of a ring main round these would be proportionately high and consequently expensive, so that radial feeders would probably be best under these conditions. With medium capacity sub-stations probably two or three could be connected together on to a ring main to give us the compromise arrangement, whilst with small sub-stations a ring main round them all would probably be the best.

Subject to its ability to stand up to short-circuit conditions, a ring main can be stepped down in size through the various sections, but it must be designed so that it can feed the full connected load either way with the ring opened at any point. The decision as to whether to operate the system with the ring main solid or open at some point will depend upon the protective system used and the severity of short-circuit conditions. To operate with a solid ring would entail the use of directional protection and/or correctly graded time-lag overload protection, with the risk of completely shutting down the ring due to mal-operation of a relay under fault conditions. In general, the writer feels that it is better to operate with the ring open and to use it to restore supplies to affected sub-stations after the occurrence of a fault and after the faulty section has been cleared. Operating in this way also reduces the short-circuit capacity available at the fault, with the resultant reduction of the severity of the duty imposed on all apparatus affected by the fault. However, it is for the engineer to decide for himself the best manner of operating a network.

If the radial system of feeding is adopted, with more than one feeder to a sub-station, then it is advisable to arrange for each feeder to supply its own portion of the load and to have the remote busbars suitably sectionalized by bus section switches. This is desirable to avoid shutting down the whole sub-station in the event of a fault on any incoming feeder, since under that condition, if the system was not sectionalized, all the other incoming feeders would feed into the fault. The latter undesirable state of affairs could be overcome by the use of directional protection, but probably the best remedy lies in sectionalization. One other point to bear in mind in connection with the condition of two or more feeders supplying a sub-station is the necessity of them being as nearly as possible the same length if they are to share the load equally, a point which it is easy to overlook.

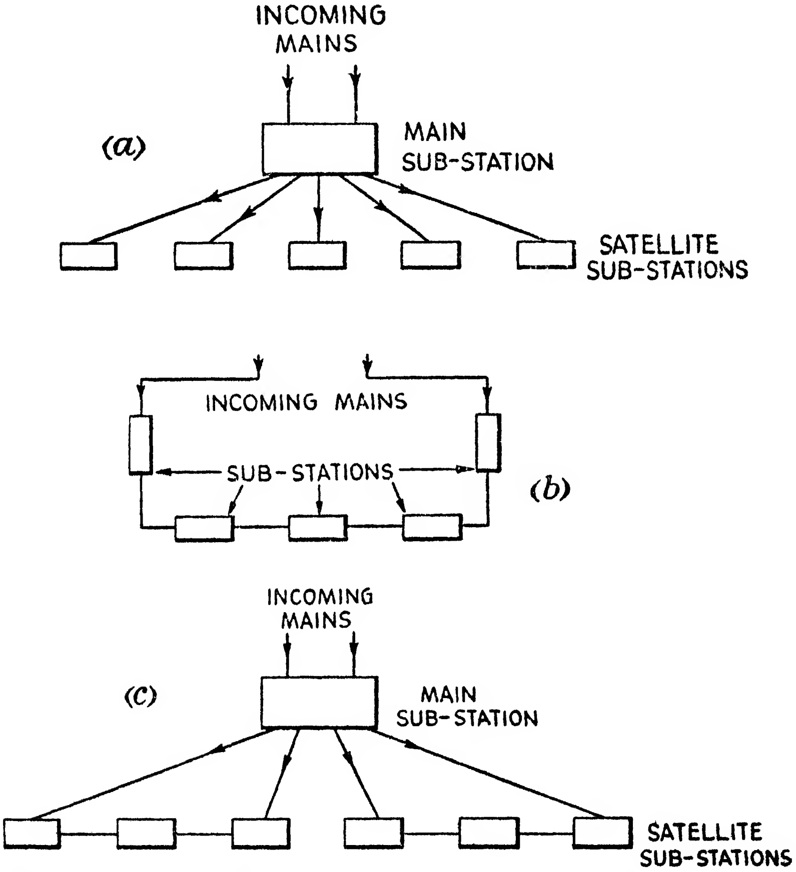


FIG. 1. USUAL SYSTEM OF FEEDING FACTORY SUB-STATIONS

(a) Radial System.
(b) Ring Main System.
(c) Combined Ring Main and Radial System.

The flexibility of a distribution system can often be improved by the judicious use of interconnectors between suitable points in the network. Superficially, this may only appear to be an extension of the ring main system, but actually the function of an interconnector is normally not the same as a ring main, since it should only be used in times of emergency to feed a sub-station which has lost the whole or part of its normal supply. Interconnectors represent idle capital and can be regarded as a form of insurance; consequently their use, however desirable, should be limited to places where the maintenance of the electricity supply is vital to the running of the factory. Before switching in an interconnector to run in parallel with a normal source of supply, it is well to consider how it will share the load, since the division will be inversely proportional to the impedance of the incoming feeders and, if the interconnector is long compared with the normal feeder, it will take a very small share of the load and may, in fact, be useless in this respect.

The foregoing should be sufficient to indicate the considerations which should be borne in mind when designing the network for a factory site.

3-wire or 4-wire L.V. Distribution

Whilst on the subject of distribution it would perhaps be opportune to give some thought to the type of L.V. system to be adopted, whether 3-phase, 3-wire or 3-phase, 4-wire. It has already been recommended that the standard 415 volts, 3-phase, 50-cycle supply should be used and this would provide a single-phase supply of 240 volts if a 3-phase, 4-wire system were adopted. The principal use of this single-phase supply would, of course, be for lighting and any consideration of the use of this or some other voltage must be based upon its suitability for lighting circuits. The alternative to using 4-wire distribution would be to install transformers with 415 volt primaries and some other lower voltage secondaries with the object of gaining some advantage over using a 240 volt supply for lighting. There are points in favour of both, but the 3-phase, 4-wire system would seem to have the more advantages for the majority of cases. The chief advantages of this system are that it is very flexible, enabling almost unlimited extensions to be made to lighting and heating circuits, whereas with the other system strict limits are imposed by the capacity of the transformer installed; it gives a cheaper job, since it avoids the cost of many transformers (partly offset by the additional cost of the fourth core in the cable) and it makes possible the use of single-pole switches and distribution boards.

The disadvantages are the increased risk of shock due to the relatively high voltage of 240 volts to earth, the necessity of using high-rupturing capacity fuses throughout the system should their use be necessary at all, and the increased cost of lamps accompanied by reduced efficiency and life as compared with lower voltage lamps. If a good class installation is used, and provided that working conditions are reasonably good, little fear need be felt on account of the increased risk of shock mentioned above.

The advantages and disadvantages of the alternative system of using special transformers for lighting and similar purposes are very largely the converse of those put forward for the 3-phase, 4-wire system. For very wet and dirty situations it may be deemed advisable to use some voltage lower than 240 and probably the most satisfactory to use in this case would be 110 volts. This would give a higher safety factor, since the voltage to earth would be reduced to $\frac{110}{\sqrt{3}}$ or 63·5 volts and the risk of electric shock would be reduced as a consequence. The light output from equal wattage lamps is approximately 11 per cent higher for 110 volt lamps as compared with 240 volts, so that a saving could be effected in the number of lighting points in a building and in addition a more robust filament is used in lower voltage lamps, with the result that the lamps are not so susceptible to breakage due to vibration and so give a longer life. To offset these advantages there is the matter of increased cost of installation due to the additional cost of transformers, double-pole switches and distribution boards, the necessity of using larger section conductors to allow for the higher current and to compensate for increased volts drop and also the necessity of using a reduced loading per circuit, with the consequent need for more circuits and larger distribution boards.

Probably the greatest source of danger on lighting circuits is the use of portable handlamps and for these it is suggested that special low-voltage transformers having 25 volts secondaries be used. These are on the market fitted with socket outlets and of sufficient capacity to supply two handlamps, and their use is strongly recommended.

Methods of Internal Distribution

The method to be adopted for distributing electricity over a factory site will naturally depend on the type of factory concerned. If the factory comprises one large building or a series of connected buildings, then the best way would be to use insulated, multi-core cables clipped to the building walls or structure. If it comprises a number of separated buildings, then the supply of these can either be taken by underground cables, overhead lines or a combination of the two.

In general, where sites comprising a number of buildings are concerned, it can be stated that the most satisfactory and unobtrusive way of carrying the electricity supply to the various buildings and sub-stations is by the use of underground cables. To cheapen the job. walls of buildings can be used to hang cables on so that they would only then be run underground between buildings; or in the case of such places as chemical factories where pipe trenches or bridges are common these may be used to accommodate cables. The use of bare overhead conductors can be considered where the area to be supplied is particularly scattered and runs of, say, one mile and upwards have to be faced. In cases like this, overhead line construction costing about half that of an underground cable can be very attractive; but there are so many factors militating against the use of bare overhead conductors inside a factory that their use should only be contemplated in very exceptional cases.

The Factories Act does not definitely preclude the use of bare overhead lines in factories, but it does stipulate that, if they are used, they shall be "so placed and safeguarded as to prevent danger." This somewhat elastic requirement would seem to rule out the use of uninsulated overhead lines in any position where they may be touched by people carrying ladders or long pipes, all of which possibilities it is easy to visualize happening inside the average factory yard until, in the majority of cases, the only reasonable procedure to ensure safety is to use insulated cable and either bury it in the ground or run it on the side of buildings.

Apart from the fact that overhead line construction is cheaper than underground cables, it has the advantage of being easy to modify or extend and also any fault is usually fairly easy to locate by visual examination of the line. The advantages of using insulated cables buried in the ground or suspended from buildings would appear to outweigh those of using overhead lines since they are safer to factory personnel, not liable to damage by such things as mobile cranes, and completely unobtrusive, so giving a tidier appearance to the factory. The chief enemies of underground cable networks are mechanical excavators and workmen digging holes in the ground for sundry purposes, and every step should be taken to eliminate any sort of excuse for the depredations of these machines and people. Underground cable routes should be clearly marked by suitable cable markers and every bend or deviation should be easily discernible by the least intelligent of people; it is better to use too many markers than to offer any opportunity of their being overlooked, and it is best to install such markers as soon as possible after a cable is laid and whilst the cable route is still fresh in memory. The electrical engineer should also make sure that all the cable routes are carefully and accurately shown on a site lay-out drawing with sufficient dimensions to enable him to be able to locate any cable to within a few feet. Such other particulars as the position of joint boxes, the phasing of cables entering and leaving a joint box, cable sizes and types should also be carefully recorded. Information of this nature will be found to be invaluable at times of cable faults.

Underground cable routes should be carefully chosen and agreed upon by all interested parties to make sure that they do not sterilize land which may be required for future development. The shortest route is not always the best and the verges of roads often provide the best place for cables. Cables laid in the ground in factory yards should preferably be armoured to give protection against rough usage, since they are always liable to disturbance due to nearby excavation, and also to give them extra tensile strength so necessary in ground which is unconsolidated as it so frequently is on new sites. They should be run in trenches approximately 2 ft. 6 in. deep, covered with a few inches of well-riddled soil free from sharp flints or stones, and then covered with suitable cable tiles or creosoted planks before the trench is back-filled. Where roads or railways have to be crossed, the cables should be run in earthenware ducts or lengths of steel or cast-iron pipe so that the cable can be pulled out again at any future date without disturbing the road surface or rail track. In addition, where there is the probability of a fair degree of vibration in the ground, as for instance under rail tracks which carry a lot of heavy traffic, it is best to set the ducts or pipes in concrete. When pipes or ducts have to be laid across roads or rail tracks, it is customary to lay one or two spares in case they may be required at any future date, a practice which often pays handsome dividends, and particulars of the location, size, and number of such ducts should be indicated on the site cable lay-out drawing.

The use of paper-insulated, lead-covered cables for underground mains is now almost universal and, if due care is taken with jointing and making off, little trouble need be expected from a network built up from such cables except such troubles as would be experienced by any form of cable, as when it is damaged mechanically. Paper-insulated cables may be either plain lead-covered, single-wire armoured, double-wire armoured or steel-tape armoured, but all cables laid inside a factory yard should preferably be armoured as previously stated. Double-wire armouring would only be justified in exceptionally bad ground conditions, where the extra tensile strength is required for the cable to withstand the strain imposed by possible serious ground settlement; single-wire armouring is quite satisfactory for most purposes and is probably the most popular form, although it has little or no advantage over the cheaper steel-tape armouring beyond the fact that the steel-wire armouring can be finished off more neatly at cable terminations and has better conductivity. If ground conditions are likely to be corrosive, as when the cable runs through such stuff as chemical waste, then specially impregnated wrappings can be applied to the cable to prevent it from being attacked and the cable manufacturer should be informed of such ground conditions at the time of ordering the cable. If paper-insulated cables are run on building walls and this necessitates changes in the height at which the cables are run so that the insulating oil under the cable is put under pressure due to the head imposed on it, it is better to advise the cable manufacturer of this fact. He will then be able to provide a special type of cable which has little free oil or he will arrange for the cables to be drained of free oil before dispatching them from his works. Otherwise, if ordinary types of cable are used, the oil will almost invariably work its way through the compound in the sealing box and a very unsightly mess will be the result. It is recommended that cables made to the relevant British Standard Specifications be used throughout the factory, since these represent perfectly sound and reliable cables and it is difficult to appreciate any argument in favour of departing from these standards although, even to-day, certain engineers insist on their own special types.

In selecting a cable for a specific job the following points must be considered: it must, of course, be insulated to stand up to the voltage of the system on which it will be operating; it must be large enough to carry the requisite current without overheating; it must be large enough to carry the current over the necessary distance without excessive voltage drop; and it must be able to stand up to short-circuit conditions without suffering any damage. The current-carrying capacity of a cable is limited only by the safe operating temperature of that cable and this will be affected by the ambient temperature in which it operates, the heat-dissipating qualities of the medium surrounding it and the proximity of the other sources of heat such as other cables. Useful data relative to safe current ratings for paper-insulated cables for voltages up to 20 kV and made to British Standard Specifications are given in a book of tables published by the British Electrical and Allied Research Association. These tables give safe ratings for cables run in the various normal ways, i.e. buried in the ground, run in ducts, and run in air, and they also give correction factors to suit different types of ground and also different grouping and spacing of cables, an important point, since the current-carrying capacity of a group of cables is by no means the sum of that of each individual member unless they are adequately spaced. Having selected a cable of sufficient cross-sectional area to carry the requisite current without overheating, we can now easily check the ability of this cable to carry the current over the desired route without excessive voltage drop, and frequently it will be found that in the case of long routes it will be necessary to use a larger size of cable than the minimum required for current-carrying purposes. The question of the ability of the cable to stand up to short-circuit conditions is not of great importance in the case of low-voltage networks, since the relatively heavy currents involved necessitate the use of cables of a size which are well able to stand up to the worst short-circuit current possible, provided that the network is so designed as to limit the short-circuit capacity to 25 mVA as has been recommended. In high-voltage networks, however, where the short-circuit conditions are likely to be more rigorous, this question must be given consideration, since the effects of a number of cable burn-outs under system fault conditions can easily be extremely serious. The question of whether a cable will stand up to short-circuit conditions depends upon whether it can stand the heating effect of the short-circuit current for the maximum time in which the short circuit is likely to be maintained, which time will be governed by the relay time settings on the switchgear and the time taken for the switchgear to clear the fault. The assistance of the cable manufacturer should be sought in this matter, since the ability of a cable to withstand this additional heat is a function of the design of the cable and the supplier can usually furnish the purchaser with graphs depicting the maximum short-circuit current which the various sizes of his cable can withstand for various times, without sustaining damage to themselves. With the present-day tendency to increased interconnection of E.H.V. networks and with the concomitant increase in short-circuit capacity, this last-mentioned consideration is becoming of extreme importance and may quite easily be the deciding factor in the choice of high-voltage cable sizes. A typical curve showing the relation between short-circuit currents which different-sized cables can successfully withstand for various

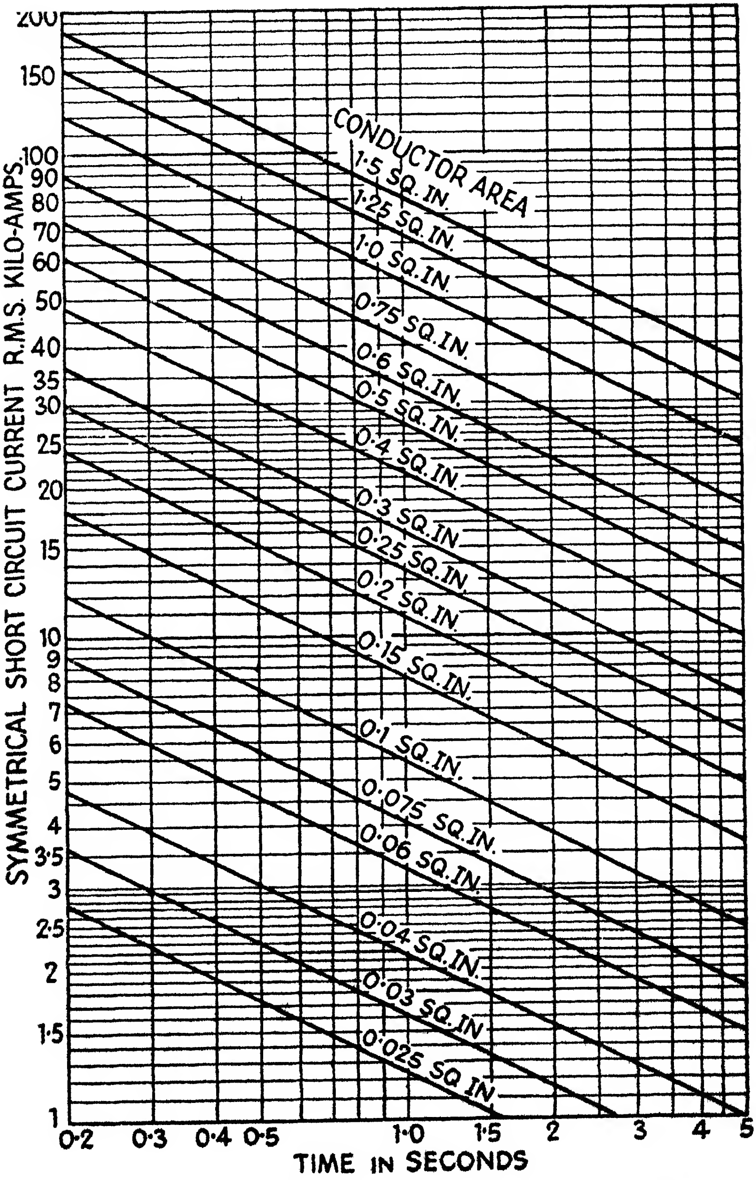


Fig. 2. Curves showing the Safe Short Circuit Current which can be Carried by P.I.L. C. S.W.A. Cables for Various Time Intervals

time intervals is shown in Fig. 2, but this information should be checked with a cable manufacturer for his own particular cables.

Much of what has been written can probably be amplified by consideration of the development of a distribution system for a typical industrial building. Fig. 3 shows the example to be considered, and whilst it is probably simpler than what would be met in practice, it should serve our present purpose. We will assume that the total connected electrical load amounts to 1300 kVA and that the estimated maximum demand load would be 1000 kVA which would include one 100 h.p. motor and that the residue would comprise lighting, heating, and a number of motors of less size than 50 h.p. The building is separated into four independent sections, A, B, C, and D as shown, in which the estimated maximum demand loads are 150 kVA, 250 kVA, 300 kVA, and 200 kVA respectively, plus the 100 h.p. motor in section A. It will be assumed that the factory is only in operation during the normal day working hours and that the load factor is so low as to make the proposition of private generation uneconomical. The local supply authority would be approached to give a supply to the site and, as it is unlikely that they would consider supplying a load of this capacity at low voltage, we will assume that they agree to supply the factory with energy at 3300 volts and that they will run two feeders into the factory from entirely separate sections of their network, so that the chances of having continuous availability of electricity at our site are thus favourable.

The amount of H.V. switchgear necessary should now be considered and the short-circuit kVA available at the site should be ascertained from the supply authority to enable the rupturing capacity of the H.V. gear to be determined. It will be assumed that the short-circuit kVA under fault conditions at the point of supply is low enough to permit the use of gear having a rupturing capacity of 50 mVA. This would make possible the use of relatively inexpensive switchgear and this in turn would probably make it an economic proposition to feed the 100 h.p. motor at 3300 volts. The number and size of transformers to be installed to supply the L.V. load should now be determined. Here it is suggested that the best arrangement, although obviously not the cheapest, would be to install three 500 kVA, 3300/400 volt transformers. This would enable the load to be carried easily by two transformers with a reasonable margin of spare capacity, whilst the third transformer acts as stand-by for use when either of the others is taken out of commission for servicing. Thus we arrive at an H.V. switchboard comprising two incoming feeder panels, three outgoing transformer panels, and one outgoing feeder panel to the 100 h.p. motor.

The 400 volt switchboard could conveniently be sectionalized by means of a bus section switch and arranged to have two transformers on one section and one transformer on the other. This switchboard would, therefore, comprise three incoming transformer panels, one bus section panel and four outgoing feeder panels. If we assume that the impedance of the transformers would be of the order of 6 per cent, then the short-circuit capacity on the L.V. system makes possible the use of H.R.C. switch and fuse units for the outgoing feeder panels; but oil circuit-breakers would be preferable for the incoming transformer panels for reasons which are given in the following chapter. A diagram of the sub-station arrangement at which we have arrived is given in Fig. 4.

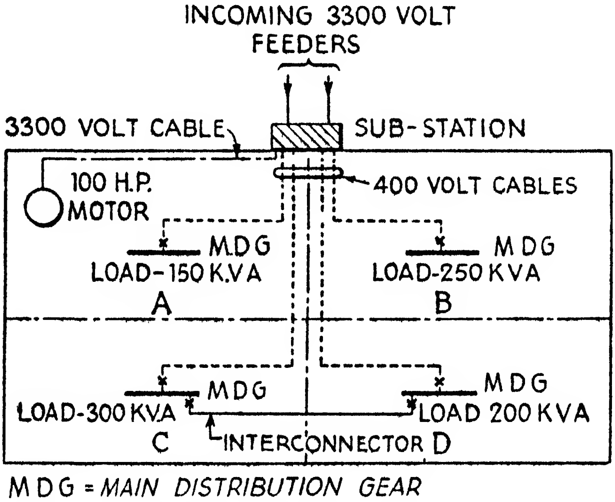


FIG. 3. LOAD DISTRIBUTION IN TYPICAL INDUSTRIAL BUILDING

Consideration can now be given to the location of the sub-station. Obviously the centre of load is in the centre of the building, but the people responsible for laying out a factory do not as a rule give up valuable space in the middle of a building for electrical purposes and we should probably find that we would be forced to adopt the next best thing which would be to locate the sub-station in the position indicated in Fig. 3.

L.V. feeder cables of suitable capacity would be run from the L.V. switchboard to each of the four distribution boards located as near as possible to the load centres of the four sections of the building. We will assume that the processes carried on in section C and D are vital to the continuous factory output, so that it is considered expedient to interconnect the distribution boards in these two sections. This would enable a supply to be maintained to both of these boards in the event of a fault on the main feeder cables to either of them. Thus we have completed the electrical distribution network for our typical industrial building. It is not suggested that all networks will be as easy to develop as this and probably several arrangements would have to be considered before the most satisfactory is arrived at.

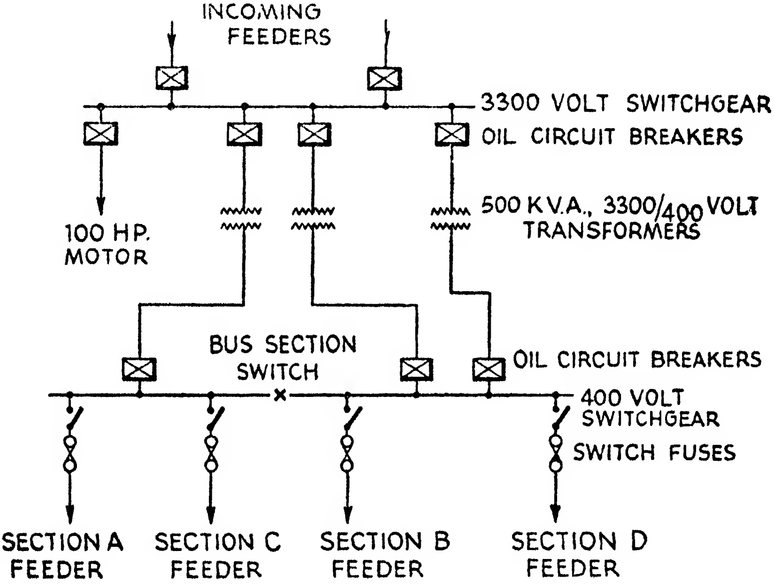


FIG. 4. DIAGRAM OF SUB-STATION EQUIPMENT FOR INDUSTRIAL BUILDING SHOWN IN FIG. 3

System Protection

Sufficient has now been written to indicate the most important factors which have a bearing on the lay-out and design of a good, sound factory network. Having reached this stage, the next point to be considered is how to ensure that this network will be reliable and discriminative in operation so that, if a fault does occur, then only that portion of the network immediately affected by the fault will be isolated automatically and the minimum of disturbance will be caused to other sections. This state of affairs can only be attained by the careful and effective introduction of suitable protective equipment into the system.

In general, it can be stated that the use of complicated and expensive protective equipment in factory networks is not warranted. Money laid out in this way shows no return and the simplest forms of protection, consistent, of course, with their suitability for the specific job, are all that is necessary for the comparatively short and low-capacity feeders and moderately sized equipment usually associated with the average factory. The cost of protecting a piece of apparatus or a cable should bear some relation to the value and importance of that apparatus or cable involved. Thus in the case of large transformers of great importance in the network it might be a reasonable proposition to install some form of "back-up" protection as well as the ordinary transformer protection, whereas in the case of smaller transformers this extra cost would probably be unjustifiable.

In making his choice of protection the electrical engineer should have a diagram of his network before him and he must then consider the effects of fault conditions in any section of that network in relation to other sections. His selection must be such that healthy sections will be maintained in commission whilst unhealthy sections will be disconnected as speedily as possible, so that the minimum of damage will be caused. The effects of a fault will be felt to a greater or lesser degree throughout that portion of the system which can feed into the fault and the engineer must select protective equipment which will be quite stable under fault conditions outside its zone of influence or, in other words, "through-fault" conditions, but which will operate reliably should a fault occur within the zone which it is required to protect.

It is not proposed to attempt to give the details and technicalities of the many protective systems which are available, as sufficient literature written by much more competent people than the writer is already in existence. It would, however, be opportune to make some suggestions as to the most suitable systems to adopt for the average industrial conditions. Possibly, the best way to do this would be to work through the different parts of a typical network and to make the appropriate suggestions for each. Commencing with the final low-voltage distributors in a network, it is suggested that straightforward overload protection is all that is necessary; in fact, the suggestion will be found in a later chapter that switch and fuse units incorporating high-rupturing capacity fuses will be found quite satisfactory for controlling low-voltage distributors. With regard to the setting at which the overload device should be set to operate or the minimum current at which the fuse should blow, it should be appreciated that overload protection on feeder cables is required to prevent damage to the cable and to isolate a particular cable under fault conditions on the feeder but not to protect running plant which is fed by the cable. This last point is mentioned because there is sometimes an inclination to try primarily to set the overload device to operate at some value slightly in excess of the normal current in the circuit, with the consequence that the overload device is somewhat sensitive and liable to operate under such conditions as heavy currents due to motors starting or due to some fault in a remote part of the installation supplied by the feeder. This consideration would emerge more particularly, for example, where possibly a 400 amp. cable has to be used to carry a 300 amp. load to keep voltage drop within reasonable limits and in such a case the protective apparatus should preferably be set to suit the capacity of the cable rather than the size of the load. If switch and fuse gear is not used for low-voltage distributors, then the choice will fall upon either oil-immersed or air-break switchgear and the relatively large currents, which have to be controlled, will normally make the use of current transformers necessary for operating the overload protective gear. This may take the form of A.C. trip coils shunted by suitable time limit fuses and energized direct from the current transformers, which arrangement is probably the most commonly adopted and is certainly the cheapest. Other arrangements for giving overload protection involve the use of relays energized by current transformers, so that when the current reaches a predetermined value the relays will close a set of contacts to energize a D.C. trip coil which trips out its associated circuit breaker. These relays may be either of the instantaneous operation type, in which case they would be shunted by time limit fuses, or they may be of the definite minimum inverse time limit pattern, in which the time taken for the relay to operate is inversely proportional to the operating current so that heavy currents or faults will cause the relay to operate more quickly than light currents; these relays also have a definite minimum time setting which is adjustable between limits. If relays are deemed to be necessary, then this latter type is recommended since it gives good control over operating time and enables grading of relays to be carried out, but more will be mentioned of this later. If current transformers are used for overload protection, then it is an easy matter to connect them so that earth leakage protection is also given and the engineer may feel happier with overload protection on two phases and, say, a 20 per cent earth leakage protection overall. This is a matter for personal preference although, with a metal-clad installation, any electrical fault is almost certain to develop into sufficient proportions to operate any overload device.

For the protection of power transformers a number of protective systems can be used and there is probably little to guide the engineer's choice to any particular system. The usual Merz-Price circulating current protection can be employed or any of a variety of proprietary systems which have been developed by the leading switchgear manufacturers, such as Translay or McColl protection, etc., but the majority, if not all, of these systems involve the use of pilot cores to connect between the current transformers on the high-voltage side of the main transformer and those on the low-voltage side. These current transformers would be located in the associated switchgear and, where the high- and low-voltage switchgear are in relatively close proximity as is often the case, there is no objection to the use of pilot cores from the point of view of expense or from the operational aspect, since the cores will normally carry circulating current. If, on the other hand, the high- and low-voltage switchgear are sufficiently far apart to make the previously mentioned points appreciable, then overload and earth leakage protection can be applied, provided that the earth leakage on the output side of the main transformer is of the restricted type, so that it is only operable by faults inside the protected area which includes the windings on the output side of the transformer and the associated cables as far as the output switch. It is easy to realize that the use of unrestricted earth leakage protection on the output side of a transformer would result in the protective relay operating or attempting to operate due to earth fault conditions anywhere on that section of the network fed by the transformer. For the input side of the transformer, overload and unrestricted earth leakage protection will protect the transformer windings satisfactorily. In what has just been written about restricted earth leakage protection, it has been assumed that the output side of the transformer to be protected would be star-connected and that the neutral point would be earthed, conditions which would apply to the majority of industrial networks. Where overload and earth leakage protection is adopted for protecting transformers, it is recommended that some suitable inter-tripping system be used to ensure that, in the event of the protective relays operating on either side of the transformer, then the switch on the other side will also trip out automatically. This is particularly important when several transformers are connected in parallel and where there would be the possibility of all transformers feeding into a fault on any one of them.

On large transformers which would normally be fitted with conservator tanks, the use of Buch-Holz Gas Relays is becoming increasingly popular as an additional safeguard over and above the protective gear mentioned in the previous paragraph. The Buch-Holz device consists of a gas chamber introduced into the pipe connecting the conservator with the main transformer tank. Inside the gas chamber are two floats to which are attached glass-sealed mercury switches; one float is arranged to tilt its mercury switch when sufficient gas accumulates inside the chamber to lower the oil level to a pre-determined level, whilst the other float is arranged directly in the path of the oil between the conservator and the main tank. The theory is briefly that any fault condition arising inside the transformer must result in breaking down some of the surrounding oil with the formation of gas; an incipient fault would result in the slow formation of gas which would accumulate in the gas chamber and eventually operate the first-mentioned float which in turn could operate an alarm-bell by means of the mercury switch attached to it; any major fault would result in the release of a relatively large volume of gas which would surge up to its easiest escape point, i.e. the conservator tank, and in so doing would operate the second float where the mercury switch could be arranged to trip out the respective switch controlling the supply to the transformer. This form of protection will be found quite satisfactory in service, once the transformer has settled down in commission and all the occluded air, which is normally found in new transformers, has been driven off.

The most suitable form of protection to apply to a feeder depends upon the nature of the duty which that feeder performs. If it is a single cable supplying a terminal sub-station, then plain overload protection will do all that is necessary and will provide the cheapest solution. If, on the other hand, the cable to be protected is one of a number of parallel feeders or part of a ring main system, then obviously some more elaborate protective equipment must be used to ensure that the cable is only cut-out of service automatically, due to a fault actually on that cable, but that it is maintained in commission at times of faults on other parts of the network. This can be done either by suitably graded overload and directional overload relays or by using one of the special feeder protections such as Merz-Price, Translay and others which will necessitate the use of pilot cables. In view of the fact that extremely long feeder cables are not normally encountered in factory networks and consequently the cost of running pilot cables would not be excessive, the use of one of the special feeder protection systems is recommended as likely to be the most reliable in service, since directional relays, whilst theoretically quite sound, are not always as reliable as could be desired.

If generators form part of the network, then a number of well-known special generator protection systems are available for the engineer to make his choice from, and there is probably little to influence his selection in any special direction beyond the fact that the manufacturers of the switchgear concerned may have some proprietary system which they would prefer to install.

The question of busbar protection has been given considerable attention during recent years owing to the occurrence of one or two serious mishaps due to faults in these normally unprotected zones. A number of systems have been developed to deal with these faults, but it is suggested that the chance of a fault developing on busbars is so remote that this is a risk which can well be taken and that the installation of complicated systems to cover this possibility is not justified in industrial networks.

In the more important sections of the network, such as large transformers, generators, or heavy duty feeders, it may be considered desirable to install back-up protection over and above one of the systems previously mentioned, with a view to saving the network from serious damage should the primary protection fail to function properly. For this back-up duty the choice will almost invariably fall on overload protection, but care must be taken in setting the overload relays to ensure that they are correctly graded throughout the network, so that there is no chance of a fault shutting down sections of the network unnecessarily. The process of grading overload relays in a network simply consists of adjusting the operating times so that the relay or relays closest to the source of supply have the longest operating time and that each successive overload relay up to the most remote from the source of supply has an operating time sufficiently shorter than its predecessor, to allow it to operate and clear a fault before the contacts on the preceding relay can close. It is generally agreed that the minimum time interval to allow for suitable grading of overload relays is 0·5 sec. which covers the time between the closing of the relay contacts and the clearing of the fault plus any overswing due to inertia on the other back-up relays which of course would be trying to operate. If this grading time of 0·5 sec. is maintained throughout the network, then proper discrimination should be assured between all overload relays and only those relays immediately concerned with a fault should operate whilst the others remain stable.

With this object in view, the value of using definite minimum, inverse time limit relays for overload protection becomes more apparent, since the operating times on these are easily adjustable and the use of some additional form of time lag relay is thus obviated. These relays usually have a definite minimum operating time which is adjustable from 2·2 sec. downwards and an operating current adjustment by means of a movable plug from 50 per cent to 200 per cent of full load current in steps of 25 per cent. It is apparent that if the grading of a number of relays is to be carried out by adjustment of the minimum operating time only and if the time interval between successive relays is to be 0·5 sec., then the number of relays which can be graded in this way is limited to five and also those relays nearest to the source of supply, where the short-circuit current is going to be greatest, are going to have some long operating times. A useful method of grading relays which overcomes these difficulties is described in a paper by Messrs. Gallop and Bousfield which was read before the I.E.E. This method, which is described in greater detail in Appendix I, makes use of the inverse time limit characteristic of these relays to provide part of the discriminating time between relays and the residue is made up by adjustment of the time setting. By this means shorter time settings are made possible with the consequent speedier clearing of faults near to the source of supply where they are likely to be more serious and their effects more disastrous.

It is hoped that sufficient has been written to indicate the factors which must be taken into consideration in the design of an industrial network and that sufficient information has been given to enable a good network to be developed. Some parts of this chapter may appear to contain too many qualifications and conjectures, but it is not possible to lay down any definite line of attack in designing the electrical system for a factory since the number of variables to be considered will differ probably with each factory. When it is possible to solve all electrical problems by definite rules, then will be the time when the experience and training of the electrical engineer has lost much of its value and his job will have ceased to merit the designation of profession.

Chapter III

SUB-STATION DESIGN AND EQUIPMENT

Sub-stations and their ancillary gear are expensive items of plant, and the electrical engineer must give much careful consideration to the lay-out and type of equipment which he proposes to install and the nature of the load which the sub-station will have to carry. He should avoid elaboration as far as possible and cut out unnecessary frills, but he must also realize that if sub-station gear does not function properly then the supply to a large part or possibly the whole of the factory may be cut off. The loss of production during a shut-down of part or the whole factory can soon offset the cost of a sub-station and the engineer will win no medals for cutting down the first cost of his installation at the expense of the reliability of his equipment. Modern electrical equipment is very reliable and, provided that equipment of good repute and known ability is installed and is well maintained, little trouble need be expected in sub-stations.

Switchgear—H.V. and E.H.V.

H.V. and E.H.V. switchgear is available in a number of different forms and the supporters of any type can always produce arguments in defence of their own particular favourite and against the others, but on balance it is difficult to put forward a conclusive argument in favour of any type, cubicle or metalclad, horizontal or vertical isolation, truck type or otherwise, compound-filled or oil-filled. The writer's personal preference lies in the direction of metalclad, horizontal isolation, compound-filled gear, but he would not care to be dogmatic over this matter. The prime essential is that the gear should be able to perform its duty satisfactorily, which is to make or break the circuit under normal and abnormal conditions without risk to operators or interference with adjacent equipment and to this end it is strongly recommended that only gear which has been proved under test should be installed. A number of short-circuit testing stations are now in operation in this country and any manufacturer can have his products tested and certified at these stations.

The present-day tendency is to limit the use of oil for cooling and arc-extinguishing to a minimum, since it introduces fire hazards of its own which may render the after-effects of a switch failure more damaging than the original explosion. To this end, "oil-poor" switchgear has been developed in which only a small volume of oil is used to surround the arc and, more recently, the air-blast switch has emerged from the designer's hands as a marketable product. This latter type of gear has many attractive properties and, if the price is competitive, it should find much use in industrial sub-stations. The number of fires caused by the failure of oil-immersed switchgear is very small and it would be difficult to justify extra expenditure for installing air-blast instead of oil-immersed switchgear solely on the grounds of reduced fire hazard. Nevertheless it must be admitted that it is basically illogical to use an inflammable material to extinguish an arc and any means of eliminating this state of affairs are well worth consideration. At the moment it looks probable that, for some years at least, the use of air-blast switchgear will be limited to voltages of 11 kV and upwards and then only in the higher rupturing-capacity class. The chief drawback about this type of gear is the possible failure of compressed air supply; but this should not present a very real risk in industrial sub-stations which are normally visited quite frequently or where it is a simple matter to rig up some form of alarm device to draw attention to the fact that the air supply has failed. The main attractions are—

(*a*) the elimination of oil with the consequent reduction of fire risk;

(*b*) cleanliness and ease of maintenance; since any maintenance work on oil circuit breakers almost inevitably results in oil spillage.

One of the early points to be settled with regard to switchgear is the busbar arrangement. It is very tempting to install duplicate busbars wherever possible, as a spare set of busbars can be very convenient in times of emergency or for testing newly installed plant, but the use of this refinement can usually only be justified in the case of large sub-stations. In the vast majority of cases a single set of busbars is all that is necessary. It is, however, often convenient in sub-stations where there is more than one source of supply to sectionalize the busbars to bring the incoming feeders on to different sections. Thus, if the section switches are normally kept open, a fault can be restricted to one section of the board only.

The common practice with regard to switch operation has developed along sound lines and it is now laid down in B.S.S. No. 116–1937 that the use of hand-closing mechanism for H.V. and E.H.V. switchgear should be limited to gear having a rated rupturing capacity of not exceeding 150 mVA. This is, of course, due to the fact that, in the event of a man endeavouring to close a breaker on a fault, it must be possible for him to close the switch without any hesitation in order to eliminate any prolonged arcing in the switch tank and, since the electromagnetic throw-off force increases in proportion to the square of the fault current, it is obviously necessary to restrict the use of hand-closing gear to sizes where the average man could overcome the repulsive force resulting from a short circuit. The most common alternatives to hand closing are spring closing and solenoid closing. The former has been applied on breakers up to 750 mVA, but the writer would not advocate its use above 250 mVA and for sizes of gear greater than this he strongly recommends remote control with the operator at some distance away and, whilst spring closing can certainly be arranged for remote operation by means of a long lanyard, this arrangement does not always present itself as an engineering job. Spring closing is very satisfactory and strongly to be recommended for the medium capacities of gear, since it eliminates the use of a costly and bulky battery, but for the larger sizes of gear solenoid operation appears to be the most satisfactory method yet evolved. The standard voltages for switch-closing batteries are 110 volts and 230 volts with the former the more popular and it will be found that, if the battery is kept on constant trickle charge, it will have a very long life and require little maintenance. For tripping, the use of a D.C. battery-operated trip is most common, with the selected voltage usually ranging between 12–30 volts, but preferably the higher end of the range where dust and dirt on contacts with consequent high resistance is not so mal-effective; A.C. tripping is also feasible in certain cases with the A.C. trip coils shunted by time limit fuses and energized directly from the current transformers, but this is only a practical proposition where the normal full load current is reasonably large and where the rupturing capacity of the breaker is small enough to permit the use of wound type current transformers, since the high V.A. necessary to operate an A.C. trip coil necessitates a large number of ampere-turns on the current transformer and the guidance of the switchgear manufacturer must be sought in this matter.

When purchasing E.H.V. switchgear the engineer will find himself faced with quite a wide range of possible suppliers, all of whose products have been tested and can be relied upon to carry out their duty as switches satisfactorily. He will normally also find that there is little difference in the price of the various makes of gear and it is thus upon the operational merits or demerits that he must base his choice. By this it is meant that he must view the gear from the aspect of being called upon to operate it himself; he must consider the accessibility of the gear from a maintenance standpoint (economy of space is not always a good selling feature when maintenance is considered), the adequacy of interlocks, soundness of mechanical features, and general appearance of the gear. He would be well advised to inspect the particular gear in operation, if possible, or at least in the maker's works and to spend some time familiarizing himself with it, since drawings do not always give a true picture of what they try to portray. One or two common weaknesses in design of switchgear may be opportunely mentioned here, viz.—

(1) Most manufacturers seem to be obsessed with the idea that the correct position for relays, watt-hour meters, etc., is as near to the floor as possible where they are very difficult to see or read, where they are likely to pick up the most dust or water during floor cleaning, and where they are in the best position to be knocked or kicked accidentally.

(2) When a number of secondary connections have to be carried from the fixed to the moving portion of the switch, the most satisfactory way to do this is by means of long, permanently connected leads in flexible tubing and not by means of plug contacts which are a very possible source of trouble due to bad contact and which, in addition, necessitate introducing some form of "jumper" contact for testing purposes when the switch is racked out.

(3) Cable boxes are often far too near the ground and very deep trenches are thus required to obtain a reasonable bend on the cable as it leaves the box.

Switchgear—L.V. and M.V.

Much of what has been said in the preceding paragraphs relative to H.V. and E.H.V. gear is equally applicable to L.V. and M.V. gear. Here again there is a strong tendency to move away from oil-immersed switchgear and in this case the tendency is towards air-break gear as distinct from air-blast. Most manufacturers now have air-break gear available in ratings up to rupturing capacities of 25 mVA and voltages of 0·44 kV or 3·3 kV.

A strong case, however, can be made out for the use of switch and fuse gear for main distribution switch boards in industrial networks. If, as has been advocated earlier in this book, the network is so arranged that the maximum short circuit is limited to 25 mVA, then fuses capable of successfully clearing short circuits up to this value are readily obtainable. The amount of load breaking which a sub-station switch is called upon to do is usually very small and so, if a non-automatic switch capable of breaking all currents up to its normal rating is backed up by fuses capable of breaking the circuit under any possible fault condition, we have a very satisfactory method of controlling a circuit. A number of manufacturers can supply such gear, but probably the most convenient to use is that which is built up of standard units and is thus easily extended. Certainly, for outgoing feeders to various parts of the factory, this arrangement will give satisfactory service; but probably incoming panels would be best in the form of automatic circuit-breakers, since these will frequently be heavy current panels and outside the range of available fuses. In addition, automatic incoming circuit breakers would enable some form of protection to be incorporated (viz. earth leakage) other than the straightforward short-circuit protection afforded by fuses. Thus we arrive at the arrangement of a composite switchboard comprising switch and fuse units for the outgoing panels and automatic air break circuit-breakers for the incoming panels. This would give a compact, clean, cheap and reliable arrangement. It may be argued that valuable time would be wasted in replacing blown fuses in the event of a fault; but, provided that suitable spares are carried, this need not be a lengthy procedure and it is certainly capable of being carried out whilst the cause of the trouble is being located.

The vast majority of L.V. switches are of the hand-operated type and it is only in very exceptional cases that remote operation would be applied. For automatic tripping A.C. trip coils energized direct from current transformers and shunted by time limit fuses are most frequently used, since the relatively heavy currents associated with L.V. switchgear make the design of suitable current transformers a simple matter. If the selected protective system, however, necessitates the use of relays, then D.C. trip coils will be used.

Instruments for Switchgear

The following may be of use as a guide to the selection of instruments for switchgear—

(*a*) *H.V. SWITCHGEAR*

Incoming Panels: Ammeter, voltmeter, wattmeter, and power-factor meter.

Outgoing Panels: Ammeter and wattmeter in special cases.

(*b*) *L.V. SWITCHGEAR*

Incoming Panels: Ammeter and voltmeter.

Outgoing Panels: Ammeter.

Ammeter switches to enable the current in any phase to be

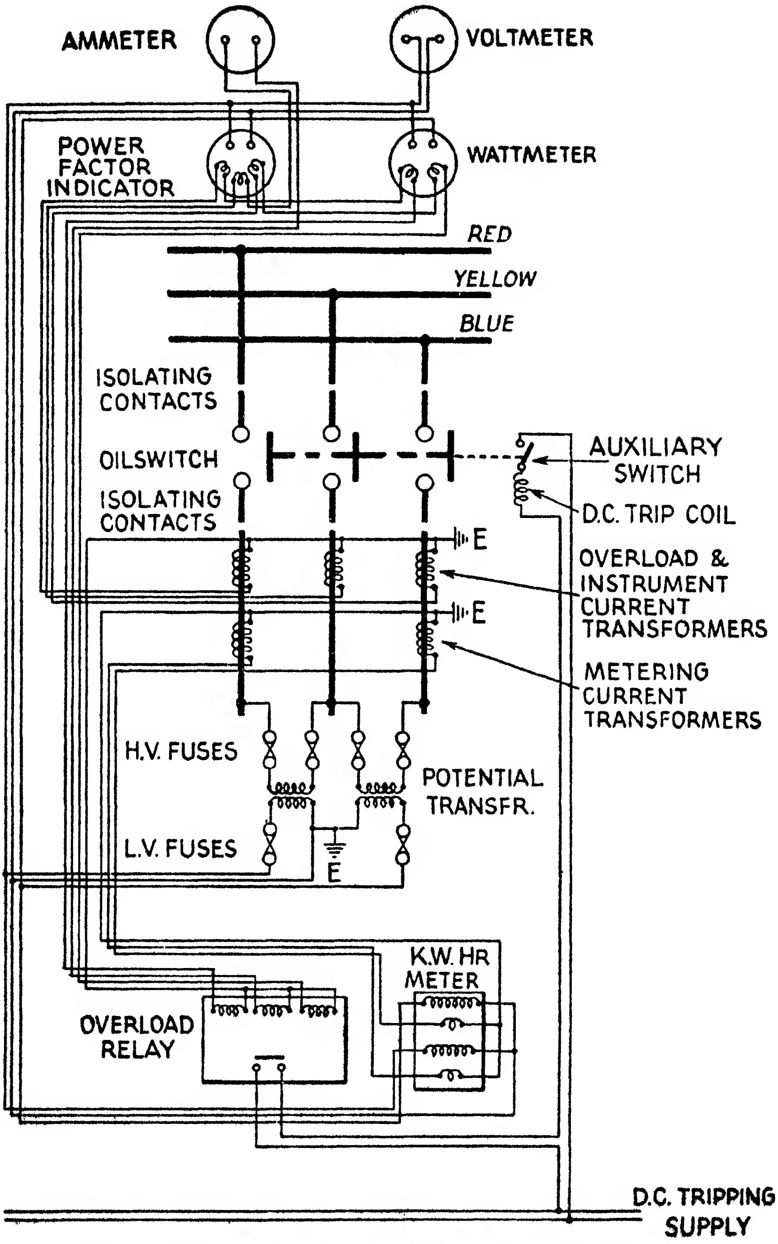


FIG. 5. DIAGRAM OF SECONDARY WIRING FOR H.V. INCOMING FEEDER SWITCH

indicated, are useful on 3-phase, 4-wire switchboards. Integrating meters, of course, will be installed where it is necessary to meter the load. Wiring diagrams for typical H.V. incoming and L.V. outgoing feeder panels are shown in Figs. 5 and 6 respectively.

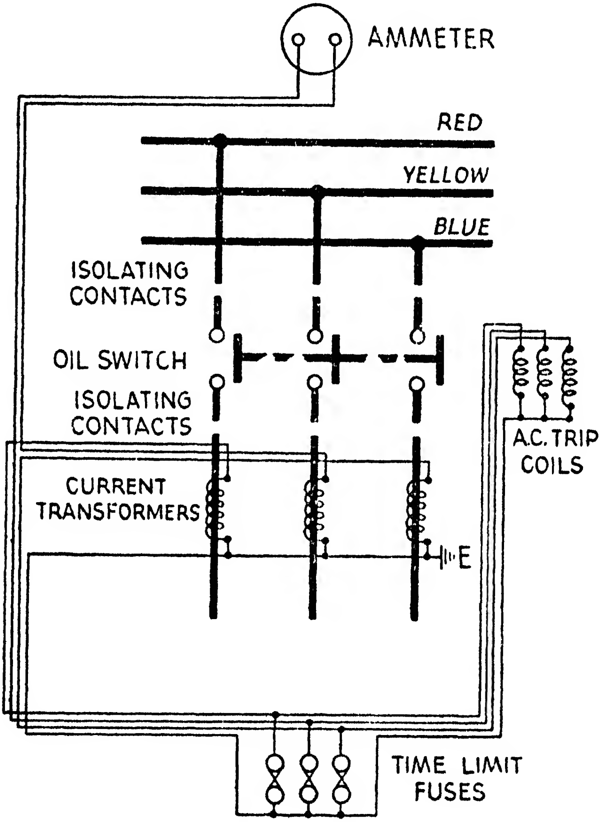


FIG. 6. DIAGRAM OF SECONDARY WIRING FOR L.V. OUTGOING FEEDER SWITCH

Transformers

The electrical performance figures and prices of modern transformers have been standardized to such an extent that there is little to guide the engineer in making a choice of supplier, beyond his previous experience of the products of the various manufacturers under consideration and the quality of the service which can be expected from them. The physical dimensions of equal capacity transformers vary between different manufacturers and in certain circumstances this may have some bearing on the selection made.

One of the prime necessities for keeping oil-immersed transformers in good trim is adequate ventilation to avoid overheating; excessive heat greatly accelerates the production of sludge and acid in the oil and these are the principal causes of trouble in transformers. Acid attacks insulation and sludge impairs the heat dissipation, so raising the temperature still farther, creating more sludge and acid; and so the process is cumulative until the transformer finally breaks down. With this end in view, it is probably better to use outdoor type transformers for sub-station work with a light roof over them to enable maintenance work to be carried out under cover and with suitable division walls between them to localize any trouble. If, however, indoor type transformers are used they should each be installed in their own fire-proof cubicles and special attention must be paid to the ventilation of the cubicles to ensure that the cooling air sweeps right across the transformer; this is best arranged by having the air inlet at the bottom-front of the cubicle and the outlet at the top-back. It might be opportune at this juncture to give the following formula for calculating the amount of cooling air required—

$$Q = \frac{1740 \text{ kW}}{T_2 - T_1}$$

where Q = quantity of cooling air in cub. ft./min.
kW = kilowatts loss in transformer.
$T_2 - T_1$ = temperature rise of air in ° C.

Thus, if we assume a maximum temperature rise of 50° C., the quantity of cooling air per kW loss will be $\frac{1740}{50} = 35$ cub. ft./min.

As has been stated, oil deterioration is promoted by heat, but it is also assisted by the presence of the two main metallic constituents of transformer, viz. iron and copper, which act as catalysts in the oxidation of oil; and the use of bare copper and iron under oil should be eliminated as far as possible. Copper connectors should be taped and the interiors of transformer tanks should be shot-blasted to get rid of scale and then coated with a suitable protective varnish.

The fitting of conservator tanks to all transformers of any appreciable size is a practice to be strongly commended, since these serve the dual purpose of maintaining the oil level in the tank and also helping to keep the oil in good condition. Increasing attention is being paid to the growth of acidity in transformer oils whilst in service and it is generally acknowledged that transformers fitted with conservator tanks are not so prone to this trouble. This is probably due to the fact that in a conservator tank a smaller surface area of oil is exposed to the atmosphere and consequently less oxidation takes place. Further, since the early products of oxidation of oil are organic acid gases which dissolve in any moisture to give rise to acid conditions, it is easy to see how beneficial a conservator tank can be in this respect. An additional precaution in this direction is the use of silica-gel or calcium chloride breathers to dry the air being inhaled by the transformers, and the small extra cost of these is well worth while.

Other fitments which should be included are indicating thermometer, oil level gauges, drain cocks, lifting lugs, and diagram plates. A small detail which can be of great value during the installation period is the provision of "barring" holes round the circumference of the wheels to enable the transformer to be manœuvred into position more easily, an operation which is not always easy in the restricted space of some cubicles.

The provision of tap-changing gear is almost standard practice in these days, the standard and the most common taps being ± 2½ per cent and ± 5 per cent which should cover all normal requirements. In the majority of cases tap changing is carried out "off load" as it is only in the case of very large transformers that the use of expensive "on-load" tap-changing gear can be justified except in very special circumstances. The most satisfactory arrangement of off-load tap changing is to have a switch inside the transformer tank which is operated by a rod carried through the tank wall and finishing in a handle which may be locked in any definite tap position but which cannot be left in an intermediate position.

Probably the most popular grade of oil used for transformers is class "B0" for indoor transformers or "B30" for outdoor transformers as specified in B.S.S. No. 148—1933, and these will be found to cause no anxiety under normal conditions in spite of the fact that they have greater sludging tendencies than Class "A" oils. This latter, more highly refined and more expensive class is more liable to acidity than class "B," and for this reason its use should be restricted to situations where there is an abnormally high ambient temperature. In brief, the possibility of more sludge with Class "B" oil is much less disturbing than the probability of more acidity with Class "A."

On large transformers of upwards of, say, 1000 kVA capacity the installation of a Buch-Holz gas relay is worth serious consideration. The function of this relay has been described in the previous chapter.

When purchasing transformers consideration should be given to the kind of duty they will be called upon to perform, since appreciable saving can be effected by matching the load at which maximum efficiency is obtained to the average load on the transformer. The losses in a transformer can be split into two sorts, iron losses and copper losses, the former being a steady loss as long as the transformer is energized and the latter varying in proportion to the square of the load current. It is fair to assume that the sum total of these losses has been reduced in modern design to an almost irreducible minimum, consonant with a reasonable size of transformer and without the discovery of a new, more efficient grade of core iron; but it is convenient that either loss can be increased or decreased at the expense of the other. As is well known, the maximum efficiency of the transformer occurs when the iron loss is equal to the copper loss and thus the best efficiency can be arranged by the designer to suit the estimated loading conditions. Thus, if a transformer is used for supplying a 24-hour per day load which varies little over the period and is near to the rated output of the transformer, the maximum efficiency should be arranged to occur at 100 per cent load. If, on the other hand, the transformer only supplies a heavy load during the day and a light load at night, the best efficiency would be better arranged to occur at about 60 per cent load. The factor to be estimated, which incidentally is not quite load factor as commonly assumed, is obtained by the ratio—

$$\frac{\text{Average estimated daily load in kW hrs.} \times 100}{\text{Rated output of transformer in kWs} \times 24}$$

and this will give the optimum load at which maximum efficiency should be arranged.

Miscellaneous Equipment

Into this category fall such incidental but nevertheless important items as tripping and closing batteries, heaters, and telephones.

For tripping and closing switchgear, two types of battery are normally used, viz. the alkaline and the acid types, and there is really little to choose between them from a performance point of view although the acid battery is much less expensive. Provided they are kept constantly on trickle charge and given occasional attention, both types of battery will be found to give many years of trouble-free service. For large batteries of the lead acid type it will be found better to use sealed top cells as distinct from open top, since these former give less trouble due to evaporation of the electrolyte and less trouble due to acid fumes. A neat arrangement of battery and trickle charger mounted in a sheet steel cabinet is on the market and is eminently suitable for tripping service.

The heating and ventilating arrangements for sub-stations usually comprise some form of tubular heater, with roof ventilators and side wall louvred ventilators to promote air circulation. In unattended sub-stations the heating apparatus will most likely be switched on in the autumn and off in the spring. This arrangement is no doubt effective in the majority of cases, but a little further investigation will often show that it is not the most economical. The first thing to be realized is that the object of installing heating equipment in an unattended sub-station is not to raise the temperature for comfort purposes but to raise the air temperature, so that it can absorb more moisture and avoid this being deposited on the electrical apparatus. In other words, it is moisture which has to be combated and not cold. In attended stations the statutory working temperature for the comfort of attendants will normally take care of condensation worries. With the foregoing in mind, it follows logically that the humidity of the atmosphere inside the sub-station is the criterion of whether the heater should be switched on or not. If the air temperature can be kept reasonably above the dew point and, provided that there is a fair degree of air circulation to avoid stagnant pockets, there should be little chance of condensation on electrical gear. An effective way of doing this would be the use of electric unit-heaters with fans and controlled by a humidistat to cut in the heaters when the humidity reaches some value of between 80 and 90 per cent. It has been demonstrated that very considerable savings can be made by adopting some such method of ventilation. More on this subject can be read in a paper by Messrs. Favell and Connon which was read before the I.E.E. and in which they give details of how they applied this ventilation system to certain sub-stations and how very appreciable savings were thus effected.

With regard to telephones it can only be stated that these are very necessary in sub-stations. In the normal course of events they will have little usage, but in the case of emergency when time is money they soon justify their installation.

Fire Protection

Expense incurred by the provision of protective devices to minimize fire hazards in a sub-station should be considered as a form of insurance premium inasmuch as it is hoped that they will never be used; but, if they should be, then they are extremely useful. With this consideration in mind the engineer would do well to temper his enthusiasm for counter-fire measures with a certain amount of discretion, since it is easy to conceive all sorts of possible eventualities; but it is really only for the probabilities that he should prepare and the ability to distinguish between the possible and probable is one of the features of a good engineer.

Certain practices in common use can be agreed upon as being logical and reasonable. The practice of segregating fire hazards is a good one; so that a failure of one section of the plant followed by a fire would not affect other sections. This practice usually follows the lines of separation walls between outdoor transformers or separate cubicles for indoor transformers, whilst different voltage switchboards will be mounted in separate compartments. Also in the case of bus section switches in switchboards of fairly high-rupturing capacity, say 250 mVA and upwards, it is common to enclose them in a fire-proof cubicle so that a fire occurring on one section of the board will not affect the other sections. Other simple and inexpensive precautions, which are well worth doing, are taping cables from the floor up to the cable gland with asbestos tape or using special asbestos sleeves which are obtainable and building low curbs round the cables where they emerge from cable trenches to prevent them from being damaged by burning oil flowing over the floor. Open cable trenches should not be encouraged, but these should be filled with sand or shingle and skimmed over with a thin crust of concrete. Examples of these are shown in Fig. 7.

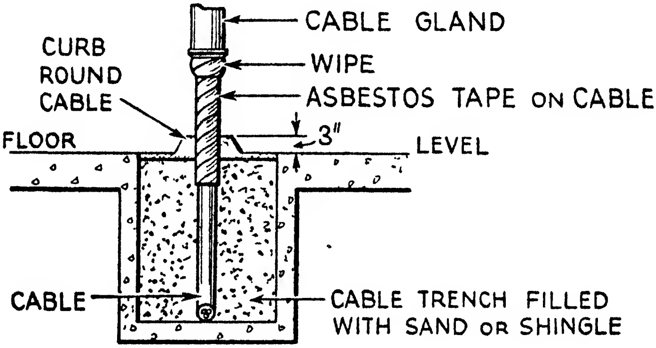


FIG. 7. SECTION THROUGH CABLE TRENCH SHOWING FIRE PROTECTION

Where there is a risk of a large quantity of oil being liberated by the failure of electrical gear, as in the case of a transformer, or switch tank bursting, some drainage system should be installed to drain the oil quickly away to a special sump where it can be quenched if it is alight. A satisfactory arrangement of such a sump is shown in Fig. 8, in which it will be seen that the burning oil spills over a 1 ft. thick bed of pebbles where it is cooled and quenched by seeping through the pebbles and accumulates in the bottom of the sump whence it can be pumped out at leisure. The pebbles should be medium sized, varying from the size of a hen's egg to about the size that would pass through a 4 in. mesh and they should be well rounded, so that they form a bed that will offer the maximum area of cooling surface whilst offering the least obstruction to the passage of oil. It will be noticed that the pebbles are carried on an expanded metal or some such screen which rests on suitable supports and underneath this is the storage space for the quenched oil. Obviously the size of the sump will be related to the volume of oil which may be liberated. Several variations of this arrangement are in use, but this particular one will be found to be quite effective.

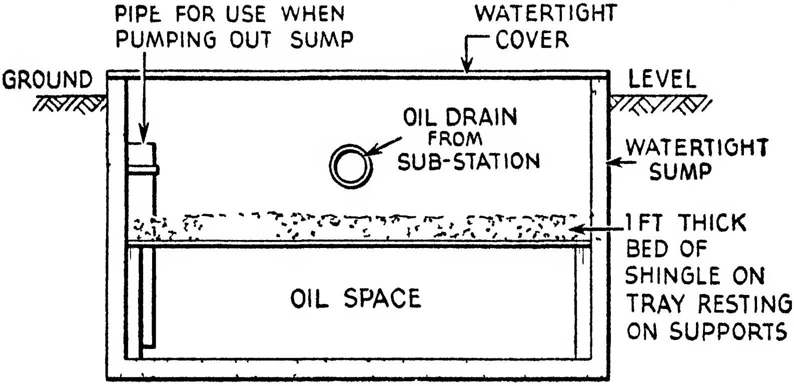


Fig. 8. Arrangement of Oil Sump

For actually extinguishing fires in sub-stations a number of automatic systems are available which involve the use of the common fire-extinguishing media, such as carbon tetrachloride, methyl bromide, carbon dioxide and water. The most desirable for electrical purposes is probably carbon dioxide, since it has no obnoxious after-effects either in the way of poisonous gases or of adverse effects on electrical equipment. The carbon dioxide gas is stored in liquid form in cylinders which are automatically released by means of trip devices actuated by falling weights, which in turn are released by the melting of fusible links in the event of fire. Carbon dioxide cylinders and the trip mechanism should be located in a separate chamber so that any fire in the sub-station cannot damage them and render them inoperative. When a fire occurs and the fusible links which are located at the most vulnerable points operate, then the gas escapes through a number of suitably placed nozzles to flood the chamber where the fire is. This type of installation is very reliable and relatively inexpensive.

Water, whilst being a very good extinguisher for most purposes, is not suitable, except under certain conditions of use, for electrical fires involving oil. The chief objections are that water is an electrical conductor and also that it tends to spread oil fires by floating the burning oil on the surface. The most successful way of using water for electrical fires is in the form of a very fine spray which is non-conducting and which mulsifies any oil it comes in contact with and renders it non-inflammable. Under these conditions it is very effective and proprietary systems are available embodying these principles; but they are relatively expensive and their use can usually be justified in the case of very large sub-stations only.

It is difficult to suggest any figure which should be the limit of what should be spent on fire protection, but something of the order of 5 per cent of the total value of the equipment being protected would seem to be a reasonable figure. It will be realized that the present-day tendency to reduce, or eliminate entirely, oil from switchgear is going to simplify matters considerably and reduce expenditure on fire protection.

Earthing

Before considering details of earthing, it is well to establish the reasons for the procedure. The three main functions are to reduce the risk of injury by electric shock to persons and animals, to reduce the risk of damage to electrical apparatus by enabling certain types of protective gear to be employed and, thirdly, to cheapen and simplify the construction of electrical apparatus. In the case of low- and medium-voltage apparatus the first of these factors predominates, the second is largely incidental and the third hardly applies. With high- and extra-high-voltage apparatus the first factor is scarcely relevant, the second factor is perhaps the most important and advantage is taken of the third in the design of certain pieces of apparatus.

The reduction of risk of electric shock is apparent since, in the case of a 3-phase, 400 volt, A.C. system with an earthed neutral, the maximum voltage to earth is 230 and the effects of shock at this voltage are not so likely to be fatal as a shock at 400 volts which would be more probable with an unearthed neutral system. On higher voltage systems the argument is not so applicable since the results of a shock are likely to be fatal in any case.

With regard to the value of earthing in connection with the reduction of risk of damage to electrical gear in the event of an insulation failure, the advantage is that it enables quick-acting, earth leakage protection to be used which can be adjusted to operate at relatively low values which would not be possible otherwise. Thus it is possible for an earth fault to be cleared in its incipient stages before it has built up to such a value as would damage the electrical gear beyond repair.

On a 3-phase, A.C. system with an earthed neutral the maximum voltage to earth is the phase voltage or $\frac{\text{line voltage}}{\sqrt{3}}$ and, consequently, the quantity of insulation to be provided need only be proportioned to this, whereas, with an insulated neutral, all conductors must be insulated to suit the full line voltage. Advantage is taken of this in cable and overhead line design and also in the case of high-voltage windings in transformers and alternators where the quantity of insulation is graded from a maximum at the end of the winding remote from the star point to a minimum at the star point. Thus it is possible to make appreciable savings in first cost of high-voltage equipment without sacrifice of reliability. In the case of low-voltage equipment the saving would not be appreciable and usually advantage is taken of the increased factor of safety rather than attempt to grade insulation.

On the question of whether to earth transformer and generator neutrals solidly or through a resistance there is some variance of opinion, but it is the writer's view that, in the majority of cases and certainly in the vast majority of industrial networks, the use of earthing resistances is not necessary. The argument put forward in their favour is that they reduce earth fault current and so reduce the stress on electrical gear under fault conditions. Whilst this is undoubtedly correct, it must be realized that the worst form of electrical fault which gear must withstand is not an earth fault but a dead short between phases and, if this were to take place near to the machine or transformer terminals, then the limiting factor would be the impedance of the machine or transformer. Thus, if we consider a transformer whose impedance is 5 per cent, a dead short across the transformer terminals would result in a short-circuit current of 20 × full load, whereas an earth fault would be less than this due to the resistance of the earth connections in addition to the transformer impedance. The resistance of the earth is likely to be considerably higher than the transformer impedance and so there would appear to be little point in adding further resistance, since the electrical gear must in any case be designed to withstand more onerous conditions than earth fault.

The size of the earth conductor should be related, of course, to the possible fault current and should be of ample cross-section to carry this current without over-heating or without excessive voltage drop along its length. Joints should preferably be sweated and riveted, but a bolted link just before the conductor leaves the sub-station will be found very convenient for future testing of the earth plate or pipe; if two or more earth connections are made, then a link can be inserted in each connection to enable any to be isolated for test purposes. Apart from the final connection to the earth plate or pipe, all joints should be made above ground so that there is no risk of a hidden disconnection underground to nullify the value of the earth electrode. Also it is recommended that the final portion of the conductor, from just before it enters the ground until it terminates at the earth electrode, be insulated to avoid stray potential gradients on the surface of the ground which may be a source of danger to human beings or, more particularly, animals.

It is very easy to theorize on the merits of securing a low value of resistance for the earth electrode, but it is not always so easy in practice to attain such an ideal. The easiest and best way of ensuring a good earth is to bond on to a large, buried, cast-iron water main and it is fortunate, since we are considering industrial electrification, that these desirable objects are frequently in sufficiently close proximity to sub-stations to permit of their use for earthing. It is always as well to have an additional buried electrode in parallel with the water main in case of interference or alteration to that main by parties who are not so interested in the maintenance of its electrical earthing function.

As has been stated, it is often found to be very difficult to get a low earth resistance when using a buried electrode, since it is determined by the type of ground in which the electrode is buried and also the type and size of electrode used. The best type of ground for this purpose is wet ground or ground containing a fair proportion of moisture-holding constituents such as ashes and cinders. From this best type of land we range through clay and loamy soil; clay and loam mixed with sand, gravel, and stones; damp sand; dry sand; gravel and stones; with the resistivity of the different types increasing until the last is twenty to forty times the resistivity of the best. An effective way of reducing the resistivity of the ground surrounding the electrode is by treating it with common salt, even a very small proportion of which can lower the electrode resistance by as much as 80 per cent, but this is not a practice to be strongly commended and should only be used as a last resort. On the other hand, it is not essential to have water-logged conditions to have a low resistance, and beyond a moisture content of 15–20 per cent there is little decrease of resistance.

Soil Resistivity Ohms/Cm³	Duration of Fault as Determined by Setting of Protective Gear									
	1 secs.	2 secs.	3 secs.	4 secs.	5 secs.	10 secs.	15 secs.	20 secs.	25 secs.	30 secs.
1,000	2·7	3·9	4·7	5·5	6·1	8·7	10·6	12·2	13·7	15·0
2,000	3·9	5·5	6·7	7·7	8·7	12·2	15·0	17·3	19·3	21·2
3,000	4·7	6·7	8·2	9·5	10·6	15·0	18·4	21·2	23·7	26·0
4,000	5·5	7·8	9·5	11·0	12·3	17·3	21·2	24·5	27·4	30·0
5,000	6·1	8·7	10·6	12·2	13·7	19·3	23·7	27·4	30·6	33·5
7,000	7·5	10·6	13·0	15·0	16·8	23·7	29·1	33·5	37·5	41·1
10,000	8·7	12·2	15·0	17·3	19·4	27·4	33·5	38·7	43·3	47·4
15,000	10·6	15·0	18·4	21·2	23·7	33·5	41·1	47·4	53·0	58·0
25,000	13·7	19·4	23·7	27·4	30·6	43·3	53·0	61·2	68·5	75·0

Fig. 9. Length of ⅝-in. Dia. Driven Copper Earth Rod per 100 amps. of Fault Current

Another point to be borne in mind is that the resistivity of the surface ground will vary with seasonal changes in weather and electrodes should always be buried at a sufficient depth to avoid this. It can usually be taken for granted that reasonably stable conditions will be obtained at depths of 2 ft. and more, and no electrode should be buried at a less depth than this but preferably at a depth of 6–8 ft.

When we consider the actual form of electrode to be used, then we are faced with a number of possible choices which may take the form of driven rods, driven pipes, buried pipes, or buried plates. It is axiomatic that a low earth electrode resistance can only be obtained if a large surface area of the electrode is in intimate contact with the surrounding earth. With this in mind, it would seem that an electrode which is driven into the earth would probably be in more intimate contact with the ground than one for which a pit has been dug and then the earth back-filled after sinking the electrode. Of course, in certain types of ground it is impossible to drive rods or pipes to any distance; but generally speaking this is the best method of sinking an earth electrode.

For driven electrodes either galvanized steel pipe of about 1 in. diameter or bare copper rod of about ¾ in. diameter may be used and will usually be found to be satisfactory if driven to a depth of 6–8 ft. If, however, a sufficiently low resistance is not obtained after having driven the rod or pipe to this depth, it is frequently more effective to drive deeper than to drive more electrodes and use them in parallel since very good conducting layers of earth are often found at greater depths. A convenient tool for driving electrodes of these sizes is a pneumatic or electric hammer which enables quite high rates of driving to be maintained and is not so injurious to the electrode head as when an ordinary hammer is used.

The number of electrodes required must of course depend upon the fault current which may have to be passed and the time interval for which this current may be maintained. The current-carrying capacity of an electrode is not a finite quantity but it will depend upon the type of ground into which the electrode is driven. When fault current is passing there will be heat generated and if this heat is excessive, then the earth surrounding the electrode will be dried rapidly with the consequence that the resistance of the electrode increases and very undesirable consequences may ensue. Recommendations for ratings of driven copper rods were given by Mr. P. W. Cave in a paper read before the Association of Mining, Electrical and Mechanical Engineers in which he gave a table showing lengths of ⅝ in. diameter copper rods which are required for every 100 amps. of fault current flowing for various times of from 1 to 30 seconds and when driven in soils of varying resistivity. This table is shown in Fig. 9 and may be of assistance in designing earth electrodes; the resistivity of the soil in question should, of course, be determined by test. It must be appreciated that the actual resistance of an earth electrode comprises the resistance of a body of earth surrounding the electrode and it reaches some finite value at a certain radius from the electrode. Thus when a number of electrodes are connected in parallel they should be separated by a distance of at least 6 ft. so that their spheres of influence do not overlap.

If the use of a plate type electrode is decided upon in preference to rod or pipe, then this should preferably be of cast iron or copper about 3 ft. 6 in. × 3 ft. 6 in. and should be buried on its edge at a depth of about 6 ft. The value of surrounding it with coke breeze is doubtful, since this may introduce corrosion problems which otherwise would not be present.

If dissimilar metals come into contact underground anywhere on the earthing system, then the joint should be suitably waterproofed to prevent the ingress of water as there would be the probability of electrolytic action under these conditions which might easily negative the value of an expensive earthing system.

The foregoing notes on earthing may be somewhat incomprehensive, but to deal with the subject fully would require a separate book. It is hoped, nevertheless, that sufficient has been written to enable the reader to appreciate the problems involved and to give him some line on how to solve them.

Lay-out and Building

A sub-station is, of course, essentially a functional building, but there is no reason, if a certain amount of care is taken in its design and lay-out, why it should not be aesthetically pleasing without a lot of unnecessary money being spent on it. Sub-stations are usually the only buildings on a works site in the arrangement of which the electrical engineer has any jurisdiction, and it is up to him to ensure that they enhance the prestige of his profession. The building details are outside his control; but the lay-out is strictly his own affair.

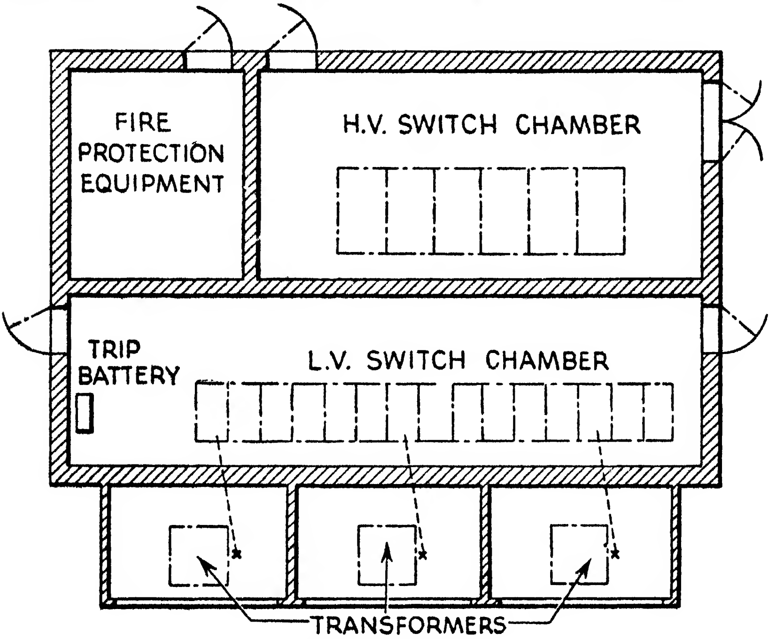
The Regulations for the use of electrical energy in premises covered by the Factory and Workshop Act lay down that sub-stations shall be substantially built and this should be sufficient authority for the electrical engineer to insist upon a good standard of building. It is a reasonable stipulation to make, since the after-effects of a failure of electrical equipment often take the form of a quite violent explosion and this should not be liable to cause the disintegration of the sub-station building. It is also specified that sub-stations shall be adequately ventilated and kept dry, desiderata which have already been touched on earlier in this chapter.

The value of windows in a sub-station is doubtful. They would certainly form a kind of relief valve in the event of an explosion and would presumably blow out to relieve the pressure on the building fabric; but the chances of their being used in this respect are very remote, whereas they have the permanent offsetting disadvantage of causing unnecessarily high heat loss from the building. This point about the heat loss is quite important, since frequent fluctuations of the sub-station internal temperatures are likely to cause condensation on the electrical gear, and, furthermore, the better the heat-retaining properties of the building the cheaper will be the cost of maintaining the requisite temperature inside the station. Thus flimsy roofs, walls, doors, and windows are unwelcome features in sub-station design.

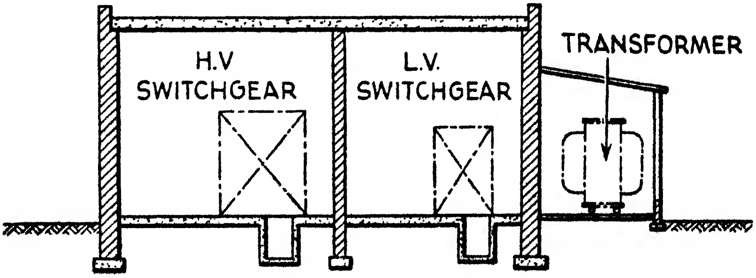
The Regulations are not specific when they deal with the question of the location of access doors in sub-stations and the onus is put on the engineer to ensure the adequacy of numbers and suitability of position of doors from the point of view of safety. When electrical switchgear is located in a long narrow chamber as it frequently is and, more particularly, when oil-immersed gear is used, then access doors should be provided at each end of the chamber to ensure that an operator in the event of an explosion is not cut off by a fire between him and the door. These doors must open outwards and should preferably be fitted with a "panic bar" or some similar locking device which can be easily and quickly operated in the case of emergency.

Dust is one of the great enemies of electrical gear, particularly relays and meters which have delicate movements, and everything possible should be done to avoid the use of materials which create dust. Concrete is a bad offender in this respect and all inside concrete surfaces should be suitably painted; brickwork should be similarly treated. Floors may be tiled, an expensive procedure which is attractive when properly carried out but liable to cause much trouble due to tiles lifting if carelessly carried out, they may be treated with one of the many flooring compounds on the market or, alternatively, a satisfactory surface can be obtained with a carefully finished concrete floor painted with a special hard-finishing paint which is marketed expressly for the purpose. Finally the sub-station should be of fire-proof construction which precludes the use of ordinary wooden doors and necessitates the protection of any exposed steelwork building members.

It is obviously impossible to give an example of a standard lay-out of a sub-station, since the arrangement will depend upon the type and quantity of electrical equipment to be housed in the building. One or two examples of good lay-outs can, however, be given and these may serve as a guide for different assemblies of gear. It is wrong to try to economize too much in space, and careful consideration should be given to the possibility of future extensions, and provision should be made for reasonable extension. Switch chambers must be of sufficient size to allow enough walking way when a switch is withdrawn; a point which it is easy to overlook but difficult to remedy. If two or more transformers are connected to a switchboard and these transformers are expected to operate in parallel and share the load equally, then it is necessary for the lengths of cable between the transformer switches and the transformers to be equal. That this is necessary will be appreciated when it is realized that the transformers will share the load in inverse proportion to the cable



PLAN VIEW



SECTIONAL ELEVATION

FIG. 10. TYPICAL ARRANGEMENT OF MEDIUM CAPACITY SUB-STATION

impedance plus transformer impedance. This latter point may seem to be somewhat obvious, but it is often the obvious which is overlooked and the writer admits to having fallen for this himself.

Fig. 10 shows an arrangement for a medium-capacity sub-station comprising 11 kV or 6·6 kV switchgear, 400 volt switchgear and three transformers of capacity 500–1000 kVA. The H.V. and L.V. switchgear are housed in separate chambers each with two access doors, one of which in the H.V. switchroom is a double door to facilitate the entry of the more bulky H.V. gear. The H.V. and L.V. gear is hand or spring closed and a common tripping battery and trickle charger are provided in the L.V. switchroom. The transformers are of the outdoor type and are housed in open-ended cubicles with a light corrugated sheet roof over them to give a certain amount of protection against rain and sun but arranged not to impede the ventilation of the cubicles. A low curb is provided at the open end of the cubicles to retain any spilled oil, and oil drains would be arranged in each cubicle as well as in each switchroom to drain away any oil to a sump where it would be extinguished in case of fire. A small room is provided to house any automatic fire-fighting equipment or anything else such as local distribution boards which it may be required to install in the sub-station. It will be noted that the transformer cables to the L.T. switchboard are of equal length and these could be run in suitable trenches to join into the main cable trench running underneath the whole length of the L.T. switchboard. The cables from the H.T. switchboard could be run in suitable earthenware ducts laid in the ground during the building period.

For larger capacity and higher voltage sub-stations the basement type of building on the lines of that shown in Fig. 11 is becoming increasingly popular. This arrangement is very suitable for housing 33 kV and upwards switchgear and it greatly facilitates the running of cables. High-voltage cables are very large and require a large bending radius to accommodate them under the switchgear, and it is plain that a very deep trench would be required, so we proceed from a cable trench to a cable basement which enables the cables to be neatly racked. Separate sections of the basement are allowed for main and control cables so that any trouble on the main cables will not affect control cables and so render the protection inoperative. It will be seen that a control room has been included in the lay-out, as the size of the gear would demand that it be remote controlled. This room could accommodate all relays, meters, and control switches and would also be a satisfactory place to locate the battery charger. The battery, which would be of large capacity for closing and tripping operation, would be housed in a separate room, whilst the third chamber could be used for the fire protection equipment. Accommodation has not been provided for transformers but, if these were required, they could be arranged on similar lines to those shown in the medium-capacity station. A crane will almost certainly be necessary to handle the parts of the high-voltage switchgear and in any case it would be a tremendous asset during erection of the gear. A further basement under the control room would probably be found extremely useful as a storage space for odd lengths of cable, transformer oil (provided the basement is dry) and the usual odds and ends which are infrequently required but for which storage space is often difficult to find.

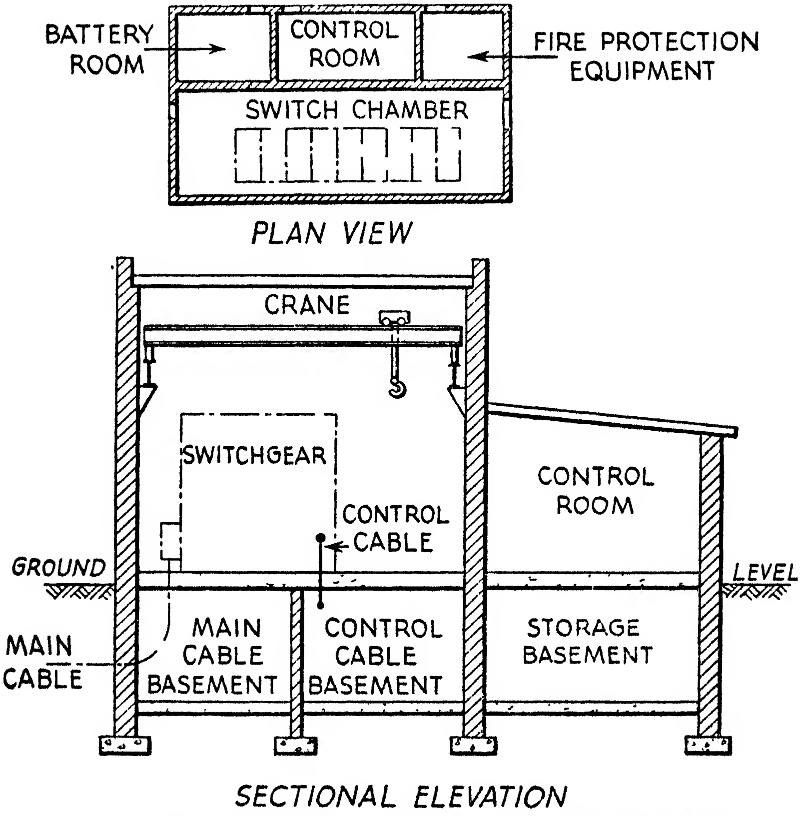


FIG. 11. TYPICAL ARRANGEMENT OF LARGE CAPACITY SUB-STATION

CHAPTER IV

ELECTRICAL INSTALLATIONS FOR INDUSTRIAL BUILDINGS

WHEN an engineer is called upon to design the electrical installation for an industrial building, the first thing to be done is to gather as much information as possible regarding the nature of the work to be carried out in the building and the atmospheric conditions which will pertain. The more information he can gather, the better will he be able to design the most suitable installation. He is vitally concerned with any explosive or corrosive gases or liquids which may be used in the process; any considerable quantity of dust or fluff in the atmosphere concerns him and any excessively moist or hot conditions must be provided against. He must get some idea of the running conditions of the plant to enable him to assess the probable diversity, so that his main supply cable sizes can be determined and he must also know of any special lighting requirements. In short, time spent in discussing the plant with the plant designer, and accumulating information as to the process to be carried out, is time well spent.

Distribution Gear

The electrical distribution system inside a plant is the "nerve" centre from which all electrical apparatus takes its supply of energy and the choice of system will largely be determined by the plant lay-out and the disposition of power-consuming apparatus. A good system must be electrically and mechanically sound, it must be flexible in that it should be able to cope with reasonable extensions without too drastic modifications, and it must be economical. The decision as to what constitutes a reasonable extension to the plant can only be taken as a result of previous experience with plant design, and to strike a happy medium between lavishness and parsimony in spare capacity is the test of a good engineer.

The first requisite is a lay-out drawing, showing the location and horse-power of all motors which have to be fed from the system. Should any of the motors be of large size, say 200 h.p. and upwards, the possibility of feeding these from the E.H.V. network of the factory should be considered, since L.V. machines and control gear of such size are expensive items and it may be found that E.H.V. will enable cheaper and simpler types of equipment to be employed, such as squirrel-cage motors instead of slip-ring machines, which would almost certainly be necessary if fed from the L.V. network. Of course, if the E.H.V. network is such that switchgear of 100 mVA and upwards is necessary, then the high cost of such gear will often rule out the use of E.H.V. motors.

For an L.V. distribution system the choice normally lies between a "load-centre" system or a "tee-off" system depending upon the lay-out of the plant. If the motor drives are laid out in regular rows as is commonly found in machine shops or assembly shops, then the "tee-off" system will usually be found to be the more economical, but the plant lay-out most commonly found in practice usually means that the "load centre" system will be used and this is described first.

"Load Centre" Distribution System

The "load centre" system simply consists of determining the centre of gravity or heaviest concentration of load in the plant and situating the main distribution gear at, or as near as possible to, this point with the heavy feeder cables running to it. These feeder cables will normally be L.V., but the Americans have gone a step farther by marketing what they call "load-centre" units which in effect comprise a complete sub-station including kiosk, H.V. switch, transformer, and L.V. distribution gear; these units are fed through an H.V. ring main and are located inside the plant as near as possible to the centre of the load.

Having fixed the approximate position of the main distribution gear, the next thing is to decide upon the nature of the gear to be used and here again past experience must be called upon, but the general considerations which govern the choice may be given and a typical example of a distribution system will be given later.

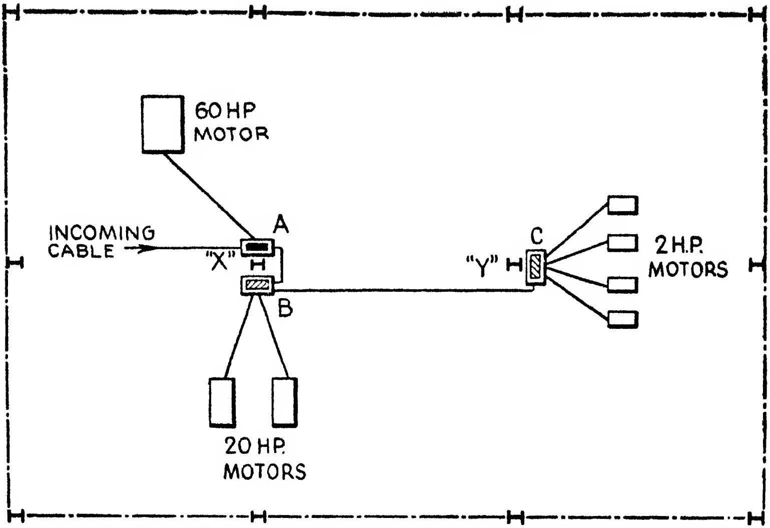
The load must first of all be split up into a number of sections which should preferably be of equal or nearly equal capacity to fit in with the size of fuse-ways in a distribution board. It may not always be possible to subdivide the load into more or less equal sections, but this should be the aim, so that sub-distribution boards can in their turn be located at the load centres of the sections; and so the process continues until suitably sized distribution boards are reached for finally supplying the smaller motors. Large motors will, of course, be fed from intermediate boards and will very often decide the size of fuse-way to be adopted. The sizes of fuse-ways most commonly in use are 15 amp., 30 amp., 60 amp., and 120 amp. or values approximating to these, and these should be the loadings to which the distribution system should be designed. Distribution boards containing larger sizes of fuse are, of course, obtainable but they are somewhat unwieldy and it is suggested that, when fuses of larger capacity than 120 amp. are required, consideration should be given to the use of unit type distribution gear of the Reyrolle "H.H." type or the B.T.-H. type, which comprise a metal-clad busbar chamber to which the incoming and outgoing feeders are connected by means of switches, switch-fuses, or oil circuit breakers, if desired, for the incoming feeders. This type of gear is easily extendable and is admirably arranged for the main distribution board for large installations where the load may be of the order of several hundred kVA.

The development of a typical "load-centre" distribution system will perhaps be best appreciated by reference to Fig. 12, which traces out the various steps in the procedure. From this it is clear that the "load-centre" is in the vicinity of stanchion *X*, and this is the best position for the main distribution gear. The obvious place for the distribution board for the 2 h.p. drives is on stanchion *Y*, and so the process continues. Probably, in practice, the plant lay-out would not be so convenient, but this simple lay-out will serve to illustrate the method of developing a "load-centre" distribution system.

The chief merits of this system are that it is economical in copper and it is flexible, provided that it is well planned to leave a reasonable number of spare ways on the distribution boards.

"Tee-off" Distribution System

As previously mentioned, this system is best suited to plants where the machines are arranged in regular rows and where the motors do not vary much in horse-power (say a range of 0–10 h.p.). The lay-out is quite straightforward and consists of running a set of overhead busbars along each row of machines and teeing off these bars at each motor position. Each set of busbars, which is of ample cross-section to permit of increase to the number and size of motors being fed, is supplied from its own way on the main distribution board, which is suitably located to reduce the length of feeders to the busbars to a minimum. The busbars may take the form of copper or aluminium bars run in metallic ducts or, alternatively, an ordinary multi-core cable may be run and tee-boxes inserted at intervals. If air-insulated bars in ducts are used, then it is usual to have socket boxes at regular intervals, with connectors on to the busbars so that plug boxes can be inserted where required to feed the motors. Fuses are usually incorporated in the tee-boxes to protect the small wiring to the motors. A number of proprietary systems of this type are marketed and



PLANT LAYOUT SHOWING DISPOSITION OF MOTORS

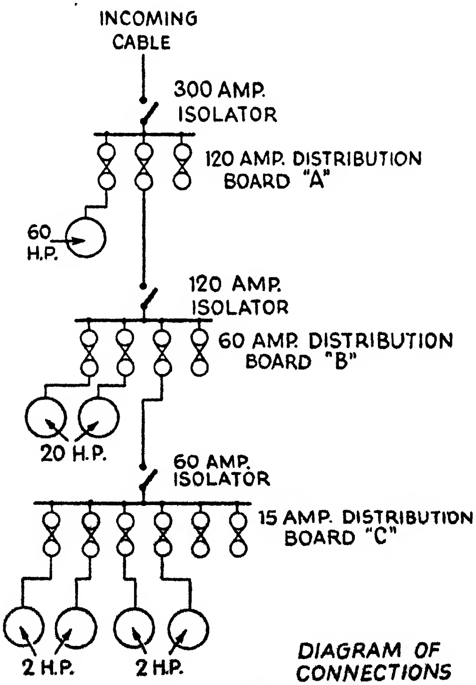


DIAGRAM OF CONNECTIONS

Fig. 12. Typical "Load-Centre" Distribution System

they have many advantages for the type of plant lay-out described. They are flexible, easy to install and maintain, and neat in appearance.

Choice of Equipment

Having assessed the merits of the above systems with respect to the immediate plant lay-out and having made his choice, the engineer is next faced with the problem of clothing the skeleton or, in other words, (deciding on the type of switchgear, distribution gear, motors, control gear, and wiring to be used. His decisions must, of course, be governed by economics, but other things besides "first-cost" come into the picture and it is frequently better economics to install more expensive equipment which will give more reliable service and require less maintenance than to purchase equipment on the grounds of initial cheapness. The operating conditions of the plant will have to be considered and allowed for, since dirty or corrosive conditions require special attention. It is obviously impossible to lay down hard and fast rules governing the selection of equipment, but the following points may be of assistance in making the choice.

Isolating Switches

Every distribution board should have its own isolating switch which will be double pole, triple pole, or triple pole and neutral according to the system. There are many makes of switch available and many different prices. The main points to look for are—

(*a*) Good contacts.

(*b*) A good, positive operating mechanism.

(*c*) Sufficient wiring space.

(*d*) Robust enclosure—some otherwise good switches have weak handles or weak hinges on the covers.

(*e*) Suitability of the enclosure to stand up to atmospheric conditions and to prevent the ingress of dust or moisture.

Distribution Boards

Here also there is a wide field to choose from and the final choice should be decided by—

(*a*) Good contact—some of the cheaper makes suffer from "sloppy" contact.

(*b*) Sufficient space for wiring.

(*c*) Ease of wiring.

(*d*) Robust enclosure.

(*e*) Suitability to stand up to atmospheric conditions.

Fuses

The choice of fuses lies between re-wireable and cartridge types. The latter type is more expensive, but is much to be preferred

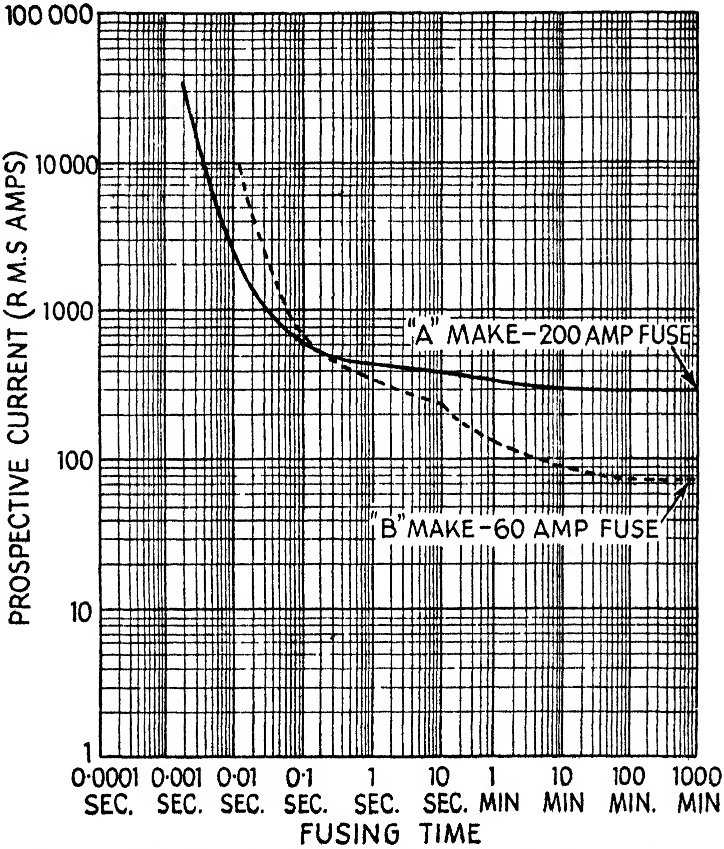


Fig. 13. Comparison of Fusing Characteristics for Different Size Fuses of Different Manufacture

and is indeed essential on most systems on the basis of rupturing capacity which usually exceeds the capabilities of the open or semi-enclosed, re-wireable type of fuse.

A number of different makes of high-rupturing capacity (H.R.C.) cartridge fuses are available, most of which are quite reliable and capable of handling short circuits up to 25 mVA; some, however, whilst quite capable of handling large short circuits, have weaknesses in the lower end of the range when the fault is limited by circuit conditions to something in the nature of an overload, as for instance a motor stalling, and fuses have been known to explode instead of clearing the fault. Whilst it is not the purpose of the writer to extol the merits of any particular make of apparatus, in his experience one of the most satisfactory H.R.C. fuses is that made by Messrs. Parmiter, Hope & Sugden, Ltd., which can deal with overloads and short circuits equally well. Whichever type of fuse be decided upon by the engineer, it cannot be too strongly emphasized that he should stick to one, and one maker only throughout his system. It is unfortunate that very little standardization exists in the field of fuses; each different make has different characteristics, different dimensions, and different tags and, in fact, certain manufacturers make different types of the same rating of fuse so that the position is somewhat chaotic. The chief drawback about mixing different makes in the system is that discrimination may be upset due to the different characteristic curves and the main fuse may blow before a sub-fuse. This will be apparent on reference to the curves in Fig. 13 which give the characteristics for two different makes of fuse, one a 60 amp. size and the other 200 amp. Here it will be seen that for low values of fault current the fuses will discriminate satisfactorily, but for high values the 200 amp. size will blow before the 60 amp.

In selecting the size of fuse for a circuit feeding squirrel-cage induction motors, it must be remembered that the starting current of such motors is often of the order of 7 × full load current. The fuse must be large enough to stand this heavy current and thus it loses much of its value as a protection against overloads and becomes mainly a short circuit protection.

Wiring

The engineer is faced with a number of different methods of wiring which, generally speaking, will give an equally satisfactory installation and the problem of which system to use can usually be determined on economic grounds. It is a problem which is well worth careful consideration, since a big proportion of installation cost may be bound up in cabling; very often the type to be used is determined by the standard practice of the factory which may not have kept pace with changes in cost and types of cable available, with the result that an installation is put in which, while quite sound, costs much more than it should. Perhaps a brief description and assessment of the pros and cons of the various common systems would be opportune at this juncture.

V.I.R. Cables on Porcelain Cleats

This is a wiring system which has little in its favour beyond cheapness of material. It is expensive to install and it is very unsightly. It is very liable to mechanical damage and has to be suitably protected where it passes through walls and floors and where it is within 5 ft. 6 in. of the ground. Unless an "all insulated" installation is used, a separate earth wire must be run to pick up all metal enclosures and fittings. In brief, this system has little to commend it and it should find no place in a good-class installation.

V.I.R. Cables in Conduit

A well laid-out conduit installation gives probably the neatest arrangement of any. It is the cheapest installation for industrial lighting and, even for power wiring for small motors where the wires can be drawn into ¾ in. conduit, it compares favourably with other systems. For most situations heavy gauge, welded, black enamelled conduit will be found quite satisfactory; solid drawn heavy gauge conduit is of course necessary for flame-proof installations; whilst, for very damp situations or outside work, it will be found advisable to use galvanized conduit. If spacing saddles are used and the conduit is painted as soon as possible after erection, it will be found that the installation gives many years of trouble-free service. A properly erected conduit system, where care has been taken to ensure that screw threads are clean and that tubes are screwed the requisite distance into fittings, should give no trouble with regard to electrical continuity, and no separate earth wire should be necessary. In damp situations a certain amount of condensation may take place inside the conduits, but this can usually be taken care of by the use of drain plugs.

Other types of conduit such as close joint and light gauge tubing are not satisfactory for industrial work. A copper conduit system has been developed which has all the merits of a steel conduit system plus the added benefits of greater immunity from normal corrosion and excellent electrical continuity. This system, however, has the drawback of suffering from rather severe price variations due to fluctuations in the copper market which is very much less stable than the steel market.

Generally speaking, a conduit installation is very satisfactory mechanically, electrically, and aesthetically, and up to ¾ in.–1 in. conduit it is cheaper than other systems. When the conduit size must be increased above about 1 in. diameter, then the increased labour cost of screwing and bending reacts unfavourably against it.

Multi-core Cable

Probably multi-core cable is the most common method of power wiring and, if it is carefully installed, it gives a neat, reliable installation. Several different types of cable are available, but the choice normally lies between V.I.R., paper-, cambric-, and mineral-insulated cables and the following information may help in making the selection.

1. *V.I.R. MULTI-CORE CABLE*

V.I.R. insulated and single-wire armoured cable will be found suitable for most installations, although it may be found necessary to have it lead sheathed in certain situations such as chemical plants where chemicals which are rubber solvents may be present. It is non-hygroscopic and hence requires no special sealing to prevent the ingress of moisture. It has a lower current rating than paper or cambric cables, and in the larger sizes above 0·1 sq. in. it becomes rather bulky and expensive to handle.

Some of the rubber substitutes such as polyvinyl chloride are more chemically inert and hence less liable to attack than V.I.R. and they may quite easily oust pure rubber from the cable market if the cost of production can be suitably lowered.

2. *PAPER-INSULATED CABLES*

Paper insulation being hygroscopic, these cables are always lead sheathed but quite commonly are installed without any armouring. The writer is of the opinion, however, that a good case can usually be made out for using armouring on cables which are to be installed in industrial plants. They are always liable to mechanical damage by articles dropping on them and almost invariably when a piece of apparatus has to be moved the electric cables will be found to be in the way and will have to be disturbed. Also it is found that the greater care which has to be exercised in installing unarmoured cables and the resulting increased labour costs often outweigh the saving made by omitting armouring.

Paper cables will be found to be cheaper than V.I.R. cables and they also have a higher current rating. The only drawback is the fact that they have to be sealed at the ends to prevent moisture from getting in, an expensive procedure which can easily offset the saving in price of the cable unless the run is a long one. It should not, however, be outside the capabilities of the cable suppliers to devise a cable termination for paper cables which avoids the use of sealing boxes and which will be suitable for use in most industrial situations which are reasonably dry. If such a cable termination could be developed, it would be found that paper-insulated, lead-covered and single-wire armoured cable offered a very attractive proposition both electrically and economically throughout the whole range of cable sizes.

3. *CAMBRIC-INSULATED CABLE*

Cambric-insulated cable has similar characteristics to paper-insulated cable and has the same current rating. It is more expensive than paper cable but is less hygroscopic with the consequence that compound sealing is not necessary. A satisfactory seal can be made with cambric tape or some form of sleeving, providing the tails and the crutch are well varnished before and after application of the tape or sleeving.

4. *MINERAL-INSULATED CABLE*

This type of cable has been developed in recent years in this country and is proving itself to be highly satisfactory. The cores are laid in a mineral insulation, and the whole is enclosed in a thin copper sheath. This cable is heat resisting and is also very strong mechanically, being able to withstand rough handling and hard knocks. It is slightly hygroscopic and special sealing glands have been developed for use with this cable. It is fairly flexible and easy to handle, and once the technique of using it has been acquired, it can be installed at a cost which is competitive with a V.I.R. multi-core installation. An installation using this type of cable can be made very neat and unobtrusive. At the present time this multi-core cable is only made in the smaller sizes and, where these sizes are suitable, it is a very attractive proposition.

The foregoing will give the reader some idea of the merits and demerits of the various wiring systems in common use. On reference to the graphs in Fig. 14 he will get some idea of how the prices vary. Obviously, exact prices cannot be given, since these fluctuate from time to time; but these curves are strictly comparable. They represent the cost of cable only and do not include the cost of erection and termination. Similar curves can be constructed at any particular time to suit the current price of cable; then, with a knowledge of erection and termination costs, the most economical type of cable can be selected. It will usually be found that on short runs of 100 ft. and less and on the smaller sizes of cable, it is uneconomical to use paper-insulated cable if compound sealing is necessary. / Go on

Motors

As a rule the electrical engineer has little to do with deciding the horse-power and speed of motors, since these are usually determined by the mechanical aspect of the drive. It is an unfortunate state of affairs, however, since frequently a little

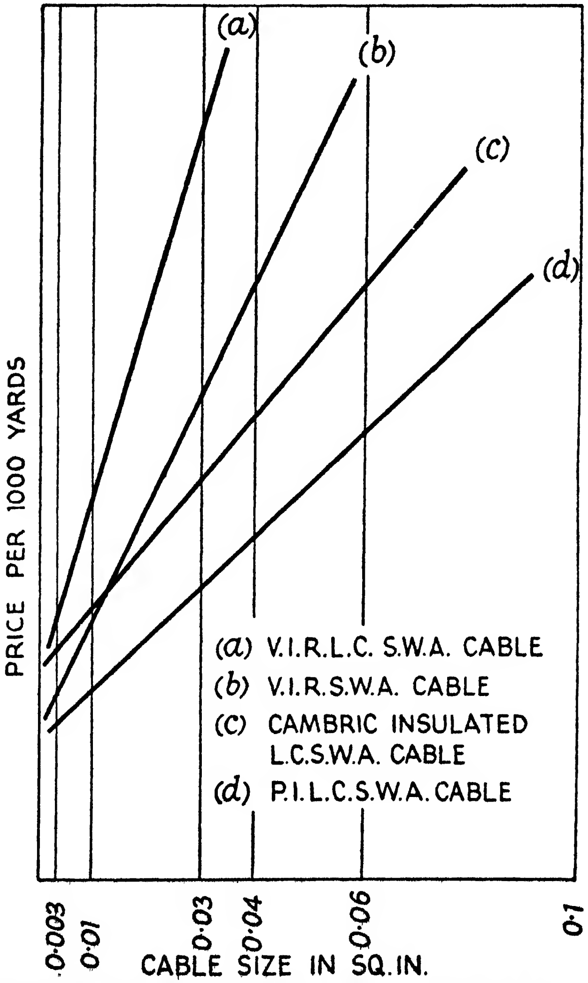


FIG. 14. COMPARISON OF PRICES FOR DIFFERENT TYPES OF L.T. CABLE

more consideration of the electrical side of the business would enable a lot of money to be saved both in initial and running cost.

It is a tendency of mechanical engineers to estimate the horsepower required by a drive, allowing the usual margin for error and then to "add a bit on for luck." This practice is much to be deprecated, since the electrical engineer is then saddled with motors which are too big and too expensive for their duty and which as a consequence operate at lower efficiency and power-factor than could otherwise be obtained. It should be realized that all continuously rated motors are rated to give their full output continuously and that most machines have limited overload capacity to handle abnormal peaks of short duration, so that there is no justification, other than uncertainty of the mechanical design, for "over-motoring." The electrical engineer's restraining influence at this stage of the design would be effective. He should also, if possible, exert his influence with regard to motor speeds. A reference to Fig. 15 will show how the price of motors is affected by speed and how an appreciable saving in initial cost of an installation can be effected by installing high-speed motors. A certain amount of caution must be used in this respect, however, since very high-speed motors such as 3000 r.p.m. introduce troubles of their own; they are more prone to bearing trouble and they are sometimes difficult to start owing to the longer time they take

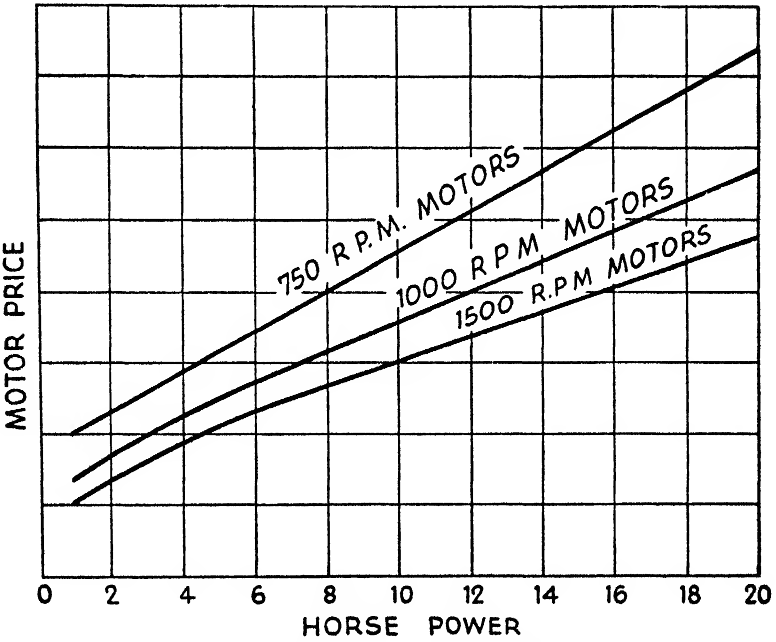


FIG. 15. CURVES SHOWING HOW MOTOR SPEEDS AFFECT PRICES

to run up to speed and the consequent longer period of high starting current causing overload trips to operate. The most satisfactory speeds to aim at are 1500 r.p.m. or 1000 r.p.m. synchronous with possibly a tendency towards slower speeds for larger motors.

A further point to be considered in fixing horse-power of motors is the question of interchangeability. It is good practice to standardize on a single make of motor, so that machines of the same horse-power and type will be interchangeable in the case of emergency. It may also be expedient to install motors of slightly higher output than is essential for the drive so that they will line up with other drives, as for example two drives requiring 7 h.p. and 8 h.p. respectively, when it would be advisable to install 8 h.p. motors in each case so that they will be interchangeable. This may involve a certain sacrifice in electrical performance in some cases, but the value of having identical motors inside a plant which can be drawn on in case of breakdown far outweighs the small losses involved.

In deciding upon a make of motor for standardization an engineer must draw upon his past experience of motor manufacturers with respect to the reliability or otherwise of their products, and the standard of service which they give. Details for consideration are efficiency and power-factor, temperature rise (since some firms' motors run notoriously hot, denoting high losses), terminal box position (in the writer's opinion the best position for the terminal box is on the top of the motor, as it can then be turned in any of four directions for cable entry), ample size of terminals, adequacy of wiring space, and type of insulation. Many makes of motors are on the market, and the engineer should consider carefully before making his decision, since motors vary considerably in performance and reliability.

The speed and horse-power of the motors being settled, the next point for consideration is the type of winding, e.g. squirrel-cage or wound motor. There is a regrettable and unjustifiable tendency on the part of some supply authorities to limit the size of squirrel-cage motors which may be switched direct-on-line to about 3 or 5 h.p.; star/delta starting is permitted up to 10 or 15 h.p., and above this wound rotor machines with resistance starters must be used. This attitude is regrettable, since it pushes up the cost of the installation unnecessarily, due to wound rotor motors and starters being very much more expensive than simple squirrel-cage motors with direct-to-line starters. It is unjustifiable for two main reasons—

(a) The peak current which is obtained when using the star/delta method of starting is frequently much higher than when switching direct-to-line (this point will be amplified later), and there is thus no justification in stipulating star/delta starting.

(*b*) The starting current for a wound rotor machine will probably be of the order of 2 × full load current. Thus if a 50 h.p., 400 volt, 3-phase, 50 cycles slip-ring motor is being started up, the current may be approximately 130 amps. If we assume that the starting current of a squirrel-cage motor switched direct-on-line to be 7 × full load current, then it is surely consistent to permit squirrel-cage motors whose full load current is $\frac{130}{7}$ or 18·6 amps. (12 h.p.) to be switched direct-to-line. In other words the thing to restrict is the starting current and not to limit types of winding to certain horse-powers.

Fortunately, most industrial plants of any size take an E.H.V. supply and have their own step-down transformers, so that they are in a position to fix any limits on starting current to suit their own transformer capacity. A reasonable limit for starting current would be 33⅓–50 per cent of the full load current of the transformer feeding the system as, with a transformer whose reactance was 6 per cent, this would only result in a voltage drop of 2–3 per cent which would not cause any undue disturbance on the network. A further proviso is that the starting current of motors at the end of long L.V. feeder should be still further restricted, as voltage drop along the feeder may be excessive during the starting period and the motor may not develop sufficient torque to start the load. If these premises are accepted, then it will be seen that quite large squirrel-cage motors can be switched direct-to-line without disturbing the system, e.g. if the network is fed through 750 kVA, 440 volt transformer whose reactance is 6 per cent, then the maximum starting current for motors should be 330–500 amps. which permits ordinary squirrel-cage motors of 50–70 h.p. to be switched direct-to-line. For larger motors, a special high reactance type of machine is available which limits the starting current to approximately 4 × full load current so that in the above-mentioned example high reactance squirrel-cage motors of up to approximately 100 h.p. could be switched direct-to-line. These high reactance motors have a slightly poorer electrical characteristic than the ordinary type, but it will be realized that a considerable capital saving can be effected by eliminating slip-ring motors with their associated starters.

It is the opinion of the writer that there are very few, if any, drives which cannot be taken by a squirrel-cage motor, and, generally speaking, the only reason for using slip-ring motors should be to limit starting current. In the majority of cases, e.g. centrifugal pumps, fans, line shaft, conveyors, etc., which only require a small starting torque and which pick up load as the speed increases, the ordinary squirrel-cage motor developing 100–125 per cent full load torque at starting is ideal. For other drives, such as reciprocating pumps, fly-presses, guillotines, etc., which require a high torque at starting, high torque squirrel-cage motors are available which can be designed to give anything up to pull-out torque at starting. Squirrel-cage motors are much to be recommended in preference to slip-ring motors which are not so mechanically robust and where slip-rings and brushgear require periodic attention.

Figs. 16 and 17 will be of interest as illustrating the characteristics of an ordinary squirrel-cage motor applied to a centrifugal pump drive and a high torque squirrel-cage motor applied to a reciprocating pump and starting against load. From these it is apparent that a reciprocating pump drive which is required to start up against load, is outside the starting capabilities of an ordinary squirrel-cage motor but is quite easily started by a high torque machine. Similarly, if an engineer can obtain particulars of the starting characteristics of any drive for which he is required to furnish a motor, he will almost invariably find that his requirements can be met by a squirrel-cage motor of some description.

Now, the only outstanding question to be settled is that of the motor enclosure, and here the choice will be between protected and totally enclosed machines. This is a choice which is fairly easy to make, since for the vast majority of cases a screen protected motor is quite suitable. In explosive areas, of course, totally enclosed flame-proof motors must be installed and out-of-doors, also, totally enclosed, weather-proof motors will be required; but apart from these and a few other exceptional cases, such as lime works, cement works, boiler houses, etc., where dust is liable to accumulate inside motors, ordinary screen-protected motors will be found to give reliable service. If the location of the motors is very damp, then drip-proof enclosure can usually be obtained by the simple expedient of fitting small cowls over the air inlet and outlet openings and, if the motors are liable to regular hosing down as in dairies and food factories, hose-proof enclosure can be obtained by fitting specially deep cowls to prevent the ingress of water. It should be borne in mind that totally enclosed motors cost approximately 50 per cent more than their screen protected counterparts, they have poorer electrical characteristics, and are not rated to carry any sustained overload. In addition they have

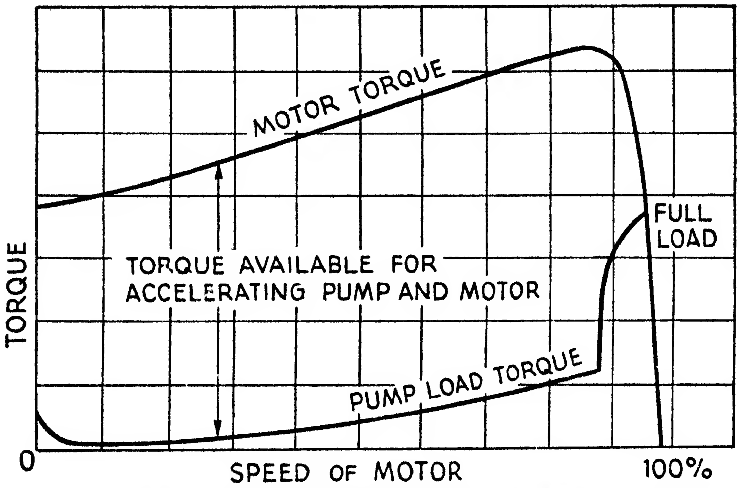


FIG. 16. COMPARISON OF ORDINARY SQUIRREL-CAGE MOTOR TORQUE AND CENTRIFUGAL PUMP LOAD TORQUE

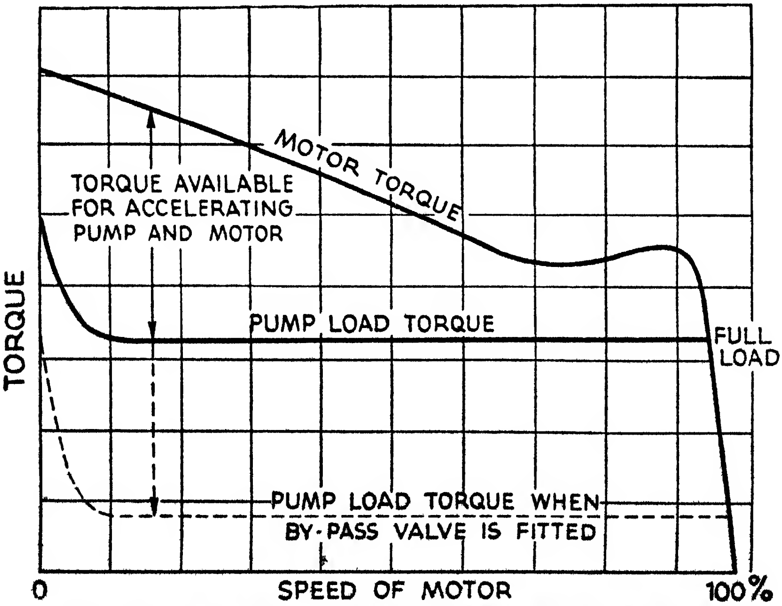


FIG. 17. COMPARISON OF HIGH TORQUE SQUIRREL-CAGE MOTOR TORQUE AND RECIPROCATING PUMP LOAD TORQUE

the inherent weakness of being susceptible to breathing which can give rise to considerable trouble if the place where they are installed is subject to appreciable temperature variation. If a totally enclosed motor is standing idle and the ambient temperature drops, then air is drawn into the motor carcase; this air will possibly have water vapour occluded which will condense inside the motor and form a pool at the bottom of the machine unless provision has been made for draining off. The writer has had experience of several motors failing in service due to this accumulation of moisture which can only be ascribed to breathing. Thus it will be obvious that any tendency to install totally enclosed motors unnecessarily should be restrained.

If, in spite of what has been advocated in favour of using squirrel-cage motors wherever possible, the engineer finds himself forced to use slip-ring machines for certain drives, then what has been written relative to the enclosure of squirrel-cage motors is equally applicable to the slip-ring variety. It is also possible to purchase a hybrid form of enclosure which takes the shape of protected enclosure for the main carcase of the machine but with the addition of flame-proof enclosure for the slip-ring assembly. The exact function of this latter type of enclosure is not apparent, since the adoption of flame-proof enclosure is not a matter for compromise, and, if it is necessary for the slip-rings, then it should be equally essential for the rest of the motor. It used to be standard practice to fit brush-lifting and short-circuiting gear to all slip-ring motors to save wear and tear of brushes, but this practice is falling out of favour somewhat. By far the greatest amount of brush wear is caused by the disintegration of brush faces when current is passing between the brushes and the slip-rings and, to eliminate this wear, it is recommended that short-circuiting gear should always be fitted but that brush-lifting gear is not necessary, since the purely frictional wear is negligible. In addition to short-circuiting gear it is suggested that the small extra cost of installing continuously rated (as distinct from short time rated) slip-rings and brushgear is well worth while; this will avoid any trouble due to operators forgetting to short-circuit the slip-rings and so to cause overheating if short time rated brushgear was fitted. Provided that slip-rings are cleaned periodically, that correct brush tensions are maintained, and that brushes are checked for wear, then little trouble need be expected from slip-ring gear.

The electrical engineer will sometimes find himself faced with a request to install a variable speed drive and here, for his own peace of mind, if he has to maintain the job and particularly if the machines are to be used in corrosive atmospheres, he should make certain that a variable speed drive is really essential and cannot be avoided by some mechanical means. Motors which give an infinite variety of speeds over a given range are, of course, well known and in fairly common use, but they are expensive and require a fair degree of maintenance, probably no more than an average D.C. motor but still considerably more than a fixed speed A.C. machine. In addition, they are sometimes difficult to protect since on slow speeds at the bottom of the range or on high speeds at the top end of the range, very high currents may flow in certain parts of the circuit without there being any actual mechanical overload on the motor; thus it is difficult to set the overload trips at a value relative to the mechanical load, which will also protect the motor winding. Two main types of A.C. variable speed motor are on the market—the Schrage types with movable brushgear to adjust speed and the Stator-fed type with fixed brushgear but with an induction regulator for speed variation. There is little to choose between the two machines in the way of electrical performance; possibly the machine with the fixed brushgear gives slightly better commutation and longer brush life than the other type, but it has off-setting disadvantage in that it requires a separate regulator and takes up more space. There is also very little difference in the cost of the machines although for certain horse-powers and speeds one type of machine may show an advantage over the other, depending upon the outputs allocated to particular frame sizes. An infinite variation speed over a range of 3 : 1 is obtainable with these machines and whilst greater ranges are possible the machines tend to become bulky and to have poorer electrical performances. Very often it will be found that an infinite variation of speed is not required but that a fixed number of speeds is needed, and a gear-box will probably give all the variety that is necessary.

If only a small speed variation is required and if the horsepower of the motor is not too large, say 10–15 h.p., then it may be expedient to use a wound rotor machine with a rotor regulator to vary the speed. This, of course, is an inefficient method of speed variation, since the losses are proportional to the slip of the motor and the further the motor speed departs from synchronism the more energy has to be dissipated in the form of heat in the rotor regulator.

Finally, if motors have to run in an atmosphere which may be corrosive, as in many chemical works, then the motors should be suitably impregnated to prevent the windings from being attacked. This costs very little extra but is well worth trying.

Motor Starters

A motor starter is a very important piece of apparatus and may have some very arduous duties to perform in the case of certain drives which involve frequent starting and stopping. Should a starter fail to function correctly in the event of overload, then the cost of the damage which may ensue to the driven machinery will usually outweigh many times the cost of the starter; thus it is bad policy to look for economy in motor starters and to install gear which is not robust and up to its job.

The function of a motor starter is to control a motor and to trip it out in the event of an overload which may damage the motor if sustained unduly. It is not a circuit-breaker and should not be expected to deal with short circuits or wiring faults. If the short-circuit capacity of the network exceeds about 2000–3000 kVA, then the starter should always be backed up by a suitable fuse or circuit-breaker to interrupt the circuit before the starter attempts to open in the event of a short circuit as distinct from an overload. It must be remembered, however, that the starting current of the squirrel-cage motors switched direct-on-line may exceed 7 × full load current and the starter must be capable of dealing with this high current.

It is laid down in the I.E.E. Regulations that starters for motors exceeding half horse-power shall be fitted with under-volt coils to trip out on a supply failure and to prevent re-starting automatically on the resumption of the supply. Exceptions to this ruling are, of course, such drives as are automatically controlled by pressure or temperature controls or float switches and which are cutting in and out continuously in the normal performance of their duty. It is also recommended that for each motor circuit means be provided for isolating the supply from the motor and starter during maintenance periods and for this it is probably best to incorporate an isolator in the motor starter which can preferably be locked in the "Off" position, so that whoever may be working on the motor or mechanical drive can lock off the isolator and retain the key in his own possession. This isolator should also be in a separate compartment in the starter so that, when it is in the "Off" position, all accessible parts of the starter are dead and any maintenance can be carried out in safety.

Two main classes of starter are available, viz. oil-immersed and air-break, and the choice will be made according to the inclination of the engineer. In general, there is little to be gained by using oil-immersed gear unless there is a likelihood of corrosive atmosphere which would attack the contacts. Air-break gear is more readily accessible for maintenance purposes and is cleaner in use since oil is always liable to be spilled during the filling or maintenance process. Oil-immersed starters are available in either the hand-operated or automatic contactor type, whereas air-break starters are almost invariably of the latter type. Here again it is a matter for the individual preference of the engineer, since there are points in favour of both types. Hand-operated starters are generally more robust and positive in their action and in this respect are frequently better than the contactor type which sometimes vibrate and chatter in an alarming fashion if the magnet faces are dirty or rough. The contactor type of starter has the advantage of being easily adapted for remote control from any number of positions and can also be arranged to start up any number of motors in sequence automatically, a condition which is of considerable value in plants where the process is of a progressive nature and apparatus is required to come into operation stage by stage. Hand-operated starters can, of course, be arranged to incorporate "Stop" push buttons in series with the under-volt coil and can thus comply with Home Office requirements of having some means of stopping a motor close by the driven machine if the starter is remote from the motor.

An ammeter or, better still, a wattmeter calibrated in horse-power, is a good investment and should be incorporated in the starter as an almost invariable rule so that the load taken by the drive can be constantly checked. If a single-phasing preventing device can be incorporated in the starter, then this is also well worth any small extra cost, since single-phasing is a fairly common source of trouble with polyphase motors and might be caused by some state of affairs extraneous to the starter such as one fuse blowing on a 3-phase supply.

For overload protection some manufacturers standardize on magnetic and some on thermal trips, whilst at least one manufacturer has an ingenious combination of the two. On a balance there is no outstanding merit to make the selection of any particular type automatic. The main points are that the overload trip should be absolutely reliable and accurately calibrated. Magnetic trips will, of course, attempt to operate immediately the current exceeds the value to which the trip is set and some form of adjustable time lag is a necessary adjunct to a magnetic trip to give the motor starter stability during transient overloads and also to hold the starter in during starting up periods when the motor is taking a heavy current. Thermal overloads have certain attractive theoretical properties which unfortunately are not always realized in practice. The condition which causes damage to motors is not so much excessive current as excessive heating caused by the heavy current and, if an overload trip can be operated by the thermal effect of the current, then this is apparently the best form of trip. In other words, if an overload trip can be devised to cut off the supply to a motor when the motor reaches a dangerous temperature, then this is the trip to use. However, with the overload trips incorporated in the starter this could only be achieved if the trip had exactly similar heat-dissipating qualities to the motor and provided the trip worked in the same ambient temperature as the motor. The former is obviously difficult to achieve unless each trip is carefully calibrated to match its own particular motor, a procedure which is not practicable: the other point is worth bearing in mind and any starter which is fitted with thermal trips should be located in the immediate vicinity of the motor. Thermal overload trips have an inherent time lag which is inversely proportional to the current and no form of mechanical time lag should be necessary.

For squirrel-cage motors three types of starter are used, viz.: direct-to-line, auto-transformer, and star/delta. The most common and cheapest type and, as suggested earlier, the one which ought to be used as much as possible is the direct-to-line starter where the full supply voltage is switched straight on to the motor. Auto-transformer starters are expensive and heavy and are not now used to any large extent; the starting tap on the transformer may be adjusted to suit the starting torque required by the drive and the starting current is reduced in proportion to the applied voltage. If star/delta starters are used with the object of limiting current peaks during the starting period, it is quite probable that this object will not be attained and, in fact, it is possible to get worse peaks with a star/delta starter than with a starter which switches the motor direct on to the supply. This is due to the fact that, during the change-over period from star connection to delta, when the motor is actually disconnected from the supply, the magnetic field of the motor does not collapse immediately; there is thus a residual voltage in the stator which might be out of phase with the supply voltage with the result that, when the motor is reconnected to the supply in delta connection, a heavy transient current flows which is likely to exceed in amplitude the peak which would have been obtained had the motor been switched direct-on-line. Thus very strong arguments can be put forward for the use of direct-to-line starters as often as possible.

If slip-ring motors have to be used, then suitable stator and rotor starters must be installed. These comprise a stator switch, complete with overload trips and under-volt feature for connecting the supply to the stator, and a rotor rheostat which must be all in circuit when the supply is switched on and which is cut out in stages to bring up the motor speed. The stator switch may be air-break or oil-break, hand-operated or contactor type and the arguments given previously hold good.

The rotor rheostat, which will usually be either of the wire wound or metallic grid type, may be either air- or oil-cooled and may be cut out in stages automatically by means of a series of contacts operated by a timing device or alternatively it can be cut out by hand operation, the latter method being the cheaper. For large motors of several hundred horse-power output it will be found necessary to use a liquid type of rheostat on account of the large amount of energy which must be dissipated in the form of heat during the starting up period and which can best be handled by a liquid type of starter. Whichever type of rotor rheostat is adopted the following points should be borne in mind—

(*a*) Suitable interlocks should be incorporated to ensure that the motor cannot be started up unless the rheostat is all in circuit and unless the brush-lifting and/or short-circuiting gear on the motor, if fitted, is in the correct position.

(*b*) The rating of the starter is determined by the nature of the duty it has to perform and the frequency of starting should always be specified on ordering since, if a motor is required to be started fairly frequently, a rheostat must be used which can dissipate the extra heat which will be generated.

(*c*) The starting torque which will be developed by the motor is a function of the rotor resistance and particulars of the torque required to start the drive should always be passed on to the starter manufacturer, to enable him to supply a suitable resistance.

(*d*) Details of the rotor current and voltage should also be furnished to the starter manufacturer—it is an unfortunate state of affairs that these data vary considerably between different motor manufacturers for the same sizes of motors and thus a rotor starter bought for, say, a 50 h.p. motor of a certain make is very unlikely to be suitable for a 50 h.p. motor of a different make.

Power-factor Correction

Much can be done in the design stages of the installation to avoid low power-factor by ensuring that motors are not too large for the duty they have to perform. A well-designed system should operate at a power-factor of 0·8–0·85 which should give the engineer little cause to worry. Any attempt to improve the system power-factor above these limits resolves itself into a question of balancing the annual cost of power-factor improvement equipment against the amount which would be saved per annum by reducing the wattless current of the network. It is generally agreed that it is uneconomical to try to improve the power-factor above 0·95 and whether the optimum may be set lower than this depends upon the tariff at which energy is bought and the current cost of power-factor improvement equipment.

Apart from the aspect of saving expense on energy bill it may be expedient to improve the power-factor on a particular section of the network to enable feeders to carry an increased load or to reduce voltage drop along a feeder.

Theoretically, the best place to attack low power-factor is at the source; this would entail the installation of condensers to each motor or other apparatus and would involve an unnecessarily high capital outlay if the apparatus was only in use intermittently. Power-factor improvement of a single machine is usually only attempted in the case of large machines and, generally, the condensers or other equipment are installed in sub-stations or switch houses where the benefits of diversity are apparent and a smaller total capacity of corrective equipment is necessary.

The most common method of improving the power-factor of a system is to install a delta-connected bank of static condensers but, if there happens to be some large motor on the system which runs continuously, then it will be found expedient to use a synchronous or synchronous-induction motor on this drive which can be over-excited and run at a leading power-factor to improve the system power-factor. On very large induction motors a saving can usually be made on running cost by using some form of phase advancer.

It is not possible to lay down any rulings with regard to power-factor correction, since conditions vary according to the installation under consideration and the energy tariff, so that each must be separately assessed under its own prevailing conditions before any decision can be arrived at. It is a comparatively simple procedure to weigh up the merits of power-factor improvement and it must be sufficient for the purposes of this book to indicate the various methods of attaining it.

Lighting

/ Much greater attention has been paid during recent times to the question of industrial lighting, and modern conceptions of good and adequate levels of illumination would have seemed quite fantastic a few years ago. Sufficient experience has been gained to demonstrate that the output of factory workers is definitely affected by the lighting conditions under which they have to work and, where adequate levels of lighting are maintained to enable work to be carried out without any undue eye strain, the output will be at a higher level than where insufficient light is provided. It is quite likely that the maintenance of high levels of illumination will become obligatory in the near future and that the lighting load will form a good proportion of the factory load, so that the electrical engineer will do well to consider which will be the best method of obtaining the requisite degree of illumination.

Purpose of Building to be Illuminated	Average Foot Candles Recommended	Range (Foot Candles)
Drawing Office	35	25–50
General Office	12	10–15
Assembling Shop—		
Rough Work	8	6–10
Medium Work	12	10–15
Fine Work	20	15–25
Extra Fine Work	35	25–50
Machine Shop—		
Rough Bench and Machine Work	8	6–10
Medium Bench and Machine Work	12	10–15
Fine Bench and Machine Work	20	15–25
Extra Fine Bench and Machine Work	35	25–50
Store—		
Heavy	3	2–4
Light	5	4–6

FIG. 18. SOME TYPICAL RECOMMENDED ILLUMINATION VALUES FOR INDUSTRIAL BUILDINGS
(Extracted from the I.E.S. Table of Recommendations.)

The question of what constitutes adequate illumination will vary according to the nature of the work to be carried out, and a table of recommended lighting intensities for many different purposes has been drawn up by the Illuminating Engineering Society and it is suggested that these standards be adopted. Some typical lighting intensities recommended by the Illuminating Engineering Society are given in the table in Fig. 18. A wealth of technical literature is available to assist the electrical engineer in designing his lighting installation and the writer does not propose to attempt to duplicate this information, but rather to pass on some hints and advice which may be useful.

(At the present time the tendency is towards the adoption of gas discharge lamps as the light source and it is quite probable that metal filament lamps with their relatively low efficiency and short life will soon be superseded. The high quality of the light obtained from fluorescent lamps and their freedom from glare and excess heat would seem to indicate that this will be the particular type of gas discharge lamp which will find most popularity in spite of the fact that installation costs must inevitably be higher than for metal filament lamps, due to the additional gear necessary such as chokes, condensers, and starting switches. In designing his installation, the engineer should consider this form of lighting and it will often be found that the reduced number of lighting points necessary, due to the higher efficiency of gas discharge or fluorescent lamps, will more than offset the higher initial cost as compared with metal filament lamps). One unwelcome feature of gas discharge and fluorescent lighting is the stroboscopic effect which it produces and which can be irritating or even dangerous, when this form of lighting is used for illuminating moving machinery. In large buildings this effect can be almost completely eliminated by using a 3-phase supply for the lighting and by arranging adjacent lighting fittings to be connected to different phases. In the case of fluorescent lamps a special circuit has been developed whereby the lamps are connected in pairs, but only one lamp of the pair is provided with a power-factor correction condenser; by this means the flickering of the two lamps is thrown out of phase and the stroboscopic effect is thus very appreciably reduced. Another method of lighting buildings, more particularly high buildings, is to use floodlights, and there would seem to be great scope for the use of non-glare floodlights inside buildings. By this means a relatively few well-placed, high-powered floodlights mounted in accessible positions will be found to be much more convenient for servicing than the usual large number of the normal type of lighting fitting. Floodlights are also very effective for yard lighting provided that they can be mounted in such a way as to avoid glare.

(Road lighting inside a factory follows normal street lighting practice except that it may be convenient to mount the lighting fittings on factory buildings or it may be possible to use floodlights. It is suggested that the best practice is to arrange road lights on entirely separate circuits from internal lighting and to control them by either time switches or some form of remote control system.)

Having calculated the theoretical ideal lay-out of lighting points, the designer should convince himself of the accessibility of these. If lighting fittings are located in inaccessible positions, then the time taken to install new lamps can easily give rise to exorbitant costs of re-lamping and it might be sounder economics to use more lower powered lights in accessible positions than to install the theoretical minimum of high-powered lights.

The number of lighting points on a fuse-way should be restricted to a reasonable number depending upon the size of lamps used. Also the lights on a fuse-way should be scattered about the building so that, in the event of a fuse blowing or a circuit having to be made dead to allow re-lamping to be carried out, it is not necessary for a section of the building to be in complete darkness, with the consequent suspension of any process which may be proceeding in that section of the plant.

There is a big difference in the wiring space available in different makes of lighting fitting and frequently there is insufficient space to permit the looping of wires to be carried out on the terminals in the fitting. Certain makes of fitting also are inadequately ventilated and high temperatures build up in the caps, with the result that V.I.R. wiring soon perishes and has to be replaced by some form of heat-resisting cable. Engineers should look for these faults in lighting fittings and should avoid using any which show tendencies in these directions.

Earthing

The object of earthing metallic enclosures of electrical conductors is primarily to prevent the building up of dangerous potentials on these enclosures due to faulty insulation of the conductors, and to provide a low resistance path to earth to discharge any such unwanted voltage, and also to operate the protective device to isolate the faulty circuit. With this object in view, it will be appreciated that earthing is not a matter to be treated lightly, but that the securing of a good system should be regarded as important as securing good insulation since the safety of personnel is involved in this matter.

The I.E.E. Regulations are fairly explicit and comprehensive in giving a guide as to what constitutes good earthing. Here it is laid down that the maximum resistance of the earth continuity path from the connection with the earth electrode to any point on the installation being protected shall be 1·0 ohm. The cross-sectional area of any copper earthing lead is also specified as being not less than 0·0045 sq. in. and, in general, not less than one-half that of the largest of the conductors to be protected, provided that no conductor larger than 0·1 sq. in. cross-sectional area need be used; the equivalent cross-sectional areas for non-copper conductors would, of course, be used. In the average installation these conditions are not very difficult to achieve, and usually in steel-frame buildings earth resistances of considerably less than 1·0 ohm will be common, since the metallic enclosure to be protected will be in fairly intimate contact with earthed metal at a large number of points.

It is not generally necessary to run separate earth conductors for each circuit, since the conductivity of steel conduit or cable sheaths and armouring is usually quite adequate to comply with the above requirements. If in a particular instance it is found that the resistance of the earth path exceeds the 1·0 ohm value, then it is a simple matter to provide a special earth connexion for that circuit; but such cases are not numerous. In the case of multi-core cables the lead sheath, if any, should be securely bonded to the armouring and the armouring should be bonded to and across any breaks in its continuity as when a cable is broken through a starter on its way to a motor. When the cables or conduits converge to a distribution board, they can then be strapped together by a suitable copper strap and an earth strip can be taken from this point to a buried water main or some specially sunk electrode, either buried plate or pipe or driven rod, but preferably to a buried water main.

It is not suggested that a multiplicity of sizes of earth conductor be adopted to meet the 50 per cent conductivity rule mentioned before, but that certain standard sizes be used. The main point to ensure in an earthing system is that good contact is obtained and maintained between earth clamps and metal to be protected, that contact faces are carefully cleaned to free them from rust and paint, and also that any joints in the earth conductor itself are of low resistance and preferably sweated.

For the earth electrode it is possible to use the steel frame of a building, provided that it is ascertained that the steel frame is itself effectively earthed, and savings in earth conductor may be obtained by taking advantage of this dispensation; but it is the writer's opinion that the best electrode to use whenever possible is a buried iron or steel water main.

Situations may arise where it is extremely difficult to obtain a low earth resistance due to ground formation or some other reason, and in such circumstances the use of leakage trips should be considered. These are circuit-breakers introduced into the main conductors and which have incorporated in them a trip coil which is set to operate at a potential of 40 volts across it. This trip coil is connected between the metallic enclosure which has to be protected and the surrounding earth or nearby metalwork, so that any dangerous voltage building up on the metallic enclosure would operate the trip coil and disconnect the circuit from the supply.

Testing Installations

Before any electrical installation is made alive and put into commission, it should be carefully tested and the results of the tests should be recorded for future reference so that any deterioration in the installation can be checked by future testing. The insulation resistance between conductors and to earth should be measured by means of an insulation tester. The resistance of the earth continuity path should also be measured to ensure that it does not exceed the maximum permitted value of 1·0 ohm. Finally the installation should be carefully examined to make sure that it is properly finished off; such things as conduit box lids have a habit of being left off and odd cable or conduit clips are sometimes overlooked. When everything is in order, then the supply can be switched on and motors can be checked for direction of rotation before leaving the installation in commission.

CHAPTER V

FLAME-PROOF INSTALLATIONS FOR HAZARDOUS AREAS

IT is well known that the materials used in certain industries can, if they are present in the atmosphere in correct proportions, give rise to very serious explosions should the mixture be ignited by any means. Many gases and certain fine dusts can set up these dangerous conditions, and it is quite possible for the explosive mixture to be ignited by some faulty electrical condition or even some normal electrical operation such as switching. The decision as to whether an explosion or fire risk is present in a factory is not primarily the responsibility of the electrical engineer, but he should be familiar with the materials which are likely to set up hazardous conditions, so that he can express his own opinion on the subject and take the precaution of installing suitable electrical equipment to eliminate the risk of an explosion caused by his installation. No statutory obligation is laid on the engineer to use certified flame-proof equipment in dangerous areas, but it is obviously in his interest to do so in order to have as safe an installation as possible as is required of him by the Factory Act.

The requirements for obtaining a flame-proof installation for an industrial plant do not, as yet, appear to have been set out in any clear and concise manner so far as the writer has been able to find. British Standard No. 229—1946 gives a specification for the flame-proof enclosure of electrical apparatus, but this is not comprehensive, and it is to be hoped that before long a standard code of practice for flame-proof electrical installations will be available as it is probable that some installations are not as safe as they should be.

The best principle to follow with regard to installing electrical equipment in hazardous areas is to avoid doing so as far as possible. This may appear to beg the question, but nevertheless it is sound practice and very often, as the result of suitable co-operation with the plant designer in the initial stages of the design, it will be found possible to keep all electrical gear outside those areas where there is the possibility of an explosive atmosphere. Motors can be located outside the danger area and can be arranged to drive through walls by extension of the shaft of the driven machine through a gas-tight gland in the wall; lighting fittings can be mounted outside buildings but arranged to shine through special windows and so illuminate the building; this form of lighting can be very effective and in addition to being safe it makes the renewal of lamps very much easier. Installations of this type will probably entail longer cable runs, but the additional cost of these is quite likely to be more than counter-balanced by the fact that ordinary industrial types of equipment can be used, costing something of the order of half as much as their flame-proof counterparts. This form of installation, besides being less likely to cause an explosion, has the additional advantage that maintenance and the carrying out of extensions is much simplified and divorced from the explosion risk. It must always be borne in mind that, whilst it is quite possible to design and install electrical equipment suitable for use in dangerous areas, it is an entirely different proposition to maintain the flame-proof nature of the installation; screws have a habit of disappearing from gear which is accessible to irresponsible personnel, conduits may be damaged or joints disturbed by careless handling of ladders, and frequently the risk of corrosion is ever present; any of these conditions can negative the flame-proof value of an installation which may have cost a large sum of money to install.

If, in spite of what has been said, the electrical engineer finds himself obliged to locate his equipment inside a hazardous area, he must ensure that his installation is as safe as it is possible to be and that it complies with the various British Standard Specifications which have been issued for particular electrical apparatus. All motors, starters, switches, lighting fittings, conduit fittings, etc., should be properly certified as being suitable for use under the conditions which will obtain in his factory and all this equipment should be assembled in the approved manner; there is no room for slipshod work in a flame-proof installation. It may be possible in certain circumstances to make use of the intrinsic safety of a special circuit to avoid explosion risk, by which is meant the inherent inability of the circuit to set up a spark of sufficient intensity to ignite the explosive mixture, but more about this will be written later.

For purposes of classification and certification, the various explosive gases have been divided into groups according to their explosive properties and also according to the industries in which these gases are most commonly used. The following grouping has been adopted—

GROUP I—which covers the coal-mining industry and is mainly concerned with methane or firedamp hazards;

GROUP II—which covers petroleum and cellulose paint industries, and which is sometimes classed as the pentane group. This group covers petroleum and acetone vapours and most of the risks encountered in chemical works.

Group III—which covers the coal gas industry and includes coal gas and coke oven gas.

Group IV—which includes hydrogen, acetylene, and carbon bisulphide. These gases are considered to be particularly dangerous and it is recommended that no electrical apparatus be installed where they may be present.

Sub-divisions are also made for Groups I and II to cover oil-immersed apparatus, since the gases evolved due to cracking of oil under electrical fault conditions—viz. hydrogen and acetylene, make special treatment necessary for this type of equipment.

The definition of a flame-proof enclosure for electrical apparatus is given in B.S.S. No. 229—1946 as "one which will withstand without injury any explosion of inflammable gas that may occur within it under practical conditions of operation within the rating of the apparatus (and recognized overloads, if any, associated therewith) and will prevent the transmission of flame such as will ignite the inflammable gas which may be present in the surrounding atmosphere." Typical pressures which are attained by the explosion of gases in the three groups are: *Group I*—Methane: 102 lb./sq. in. above atmosphere. *Group II*—Pentane: 127 lb./sq. in. above atmosphere. *Group III*—Coal Gas: 113 lb./sq. in. above atmosphere. It will thus be realized that any flame-proof enclosure must of necessity be very robust and this is further emphasized by its need to withstand, without damage, such rough handling as may come its way when it is installed in places such as mines. Since it is obvious that the enclosure cannot take the form of a solid envelope but must have joints to give access to the electrical apparatus and to enable connections to be made, it follows that limits must be set for the gaps between the flanges forming these joints, since a joint may pass a flame in the event of an explosion taking place inside the enclosure. The maximum permissible gaps for joints for use in the main groups of gases have been determined by experiment and are specified in B.S.S. No. 229—1946 as—

	(*a*)	(*b*)	(*c*)
Group I	0·02 in.	0·02 in.	0·006 in.
Group II	0·016 in.	0·016 in.	0·006 in. (for certain gases only)
Group III	0·008 in.	0·016 in.	—

Column (*a*) refers to gaps between joint faces and to clearances for operation rods and spindles.

Column (*b*) refers to shaft glands for motors and generators other than labyrinth glands.

Column (*c*) refers to gaps between joint faces and clearances for operating rods and spindles for oil-immersed apparatus.

It must be realized that these are maxima and must never be exceeded, although smaller gaps are permissible. To ensure that these limits are never exceeded, metal to metal joints are stipulated and any form of packing or jointing material is not permitted owing to the risk of deterioration of the packing, with the consequent excessive gaps between flanges; it is the responsibility of the user of the apparatus to ensure the maintenance of these limits.

For the purpose of testing and certifying apparatus for use in hazardous areas a testing station was set up by the Mines Department of the Board of Trade in 1931 at Buxton, which place lends its name to the commonly used term "Buxton Certificate" as applied to the official certificate issued when a piece of apparatus is approved for use in certain conditions. Any new development in the way of flame-proof electrical gear can be submitted to this testing station where drawings and specifications are inspected and, if necessary, the apparatus is subjected to rigorous tests to prove its safety for use in explosive atmospheres. If the authorities are satisfied that the apparatus complies with requirements and passes its test satisfactorily, then they issue a certificate for that particular item of apparatus and other items made to exactly the same specification. This certificate states which gas group or groups the apparatus may be used in, and no extension of this limitation is permissible. No modification can now be made to this apparatus without submitting details of the proposed modification to the testing authority for further approval; non-compliance with this would invalidate the flame-proof certificate. Having received approval of the particular piece of electrical gear, the manufacturer can now market it as certified as being a flame-proof enclosure and can mark it with the official mark comprising a crown with the letters "FLP" therein. The apparatus should also be marked with the number of the covering certificate and also the group number of the gases or vapours covered by the certificate. It will be realized that certification is made as the result of a type test and that the responsibility for ensuring that all equipment manufactured subsequent to the approval of the prototype rests with the manufacturer; also that the responsibility for maintaining this equipment in the same condition as when submitted for test rests with the user after he has purchased it. The user's responsibility would, of course, inevitably be passed on to the electrical engineer.

The requirements for a flame-proof enclosure as set out in B.S.S. No. 229—1946 and other British Standard Specifications have mainly been decided as the result of experiment, and their object is firstly to ensure that no flame set up as the result of an explosion inside the enclosure can pass outside the enclosure and ignite the surrounding atmosphere, and secondly to ensure as far as possible that the safety of the enclosure is not nullified by unauthorized interference. With the first object in view limits have been set for the width of flanges, joint faces, and glands for shafts or operating spindles to make sure that a flame set up inside the enclosure would be cooled and quenched by the joint faces before it reached the outside atmosphere, provided that the maximum permissible gaps are not exceeded. These limits have been fixed at 1 in. for enclosures having a volume of more than 100 cub. in. and $\frac{3}{4}$ in. for smaller enclosures; the presence of bolt holes can be ignored in measuring the width of a flange, provided that the edge of the hole is at least $\frac{3}{8}$ in. from the inside edge of the flange. These limits also apply to screwed joints in flame-proof enclosures such as joints in conduit runs, and in this case the dimension must be measured across the top of the threads, thus making the use of specially long conduit couplers, since the normal conduit coupler is only approximately $1\frac{3}{8}$ in. long.

A further requirement for flame-proof apparatus is that the conductors, bringing the supply to that particular piece of equipment, must not pass directly through the wall of the flame-proof enclosure but must connect to suitable bushed terminals which pass through the wall and form an integral part of the apparatus as shown in Fig. 19. The line side of the terminals must be enclosed in a flame-proof box and the conductors, whether run in conduit or in the form of multi-core cable, must be terminated in an approved manner; thus if multi-core cable is used the cable end box must be compound sealed; or, if conduit is used, then it must be screwed for at least 1 in. An alternative means of connecting the supply conductors to the apparatus is to use a flame-proof plug and socket with the base of the socket portion forming a flame-proof joint with the wall of the enclosure.

Whilst on the subject of cable termination, it may be timely to make some suggestion as to the type of termination to adopt with a view to making future modifications to the installation a simple job. It is suggested that the use of compression glands, embodying compressible lead sleeves or lead wool and avoiding the necessity of wiped joints, will be found very convenient, as this eliminates the use of a blow-lamp which may be possible during the construction stages of an installation, but which might entail shutting down a plant should any alteration be required after the plant has been commissioned. Similarly, the use of a cold pouring, hard setting, sealing compound might be found advantageous although the ordinary type of compound can always be heated outside a dangerous area and carried inside to fill up a sealing box.

The care and maintenance of flame-proof apparatus calls for special attention and should not be left to the inexpert, but should be given into the care of persons duly trained and authorized to maintain such gear and who are fully aware of the risks involved and the necessity for maintaining the installation in a safe condition. To assist in this respect the heads of screws and bolts securing the parts of the enclosure should be shrouded, thus making the use of special spanners and tools necessary for dismantling the gear and so discouraging unauthorized interference. It is also advisable to interlock parts of switches and similar equipment to ensure that the apparatus is properly and completely assembled before it can be operated.

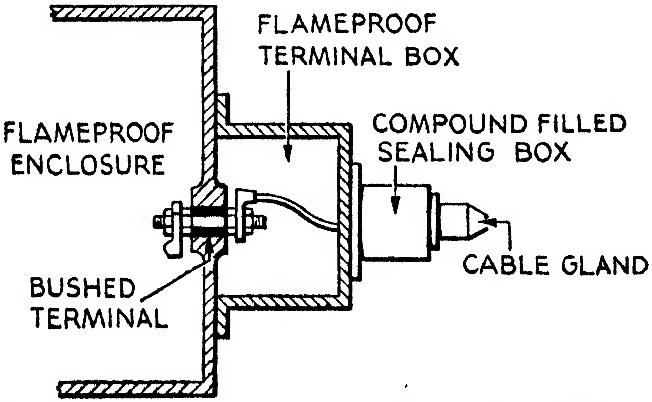


FIG. 19. ARRANGEMENT OF BUSHED TERMINALS FOR CONNECTING SUPPLY TO FLAME-PROOF GEAR

The foregoing covers the principal requirements of individual pieces of flame-proof electrical gear, but the question now arises as to what means should be adopted for connecting it up. The choice of system is not very restricted and most standard forms of wiring practice may be used with the exception of probably only cleat wiring. The chief requirements are that the installation be robust and not liable to mechanical damage; it must be gas-tight and must be easily maintained in a safe condition. The choice will normally lie between V.I.R. conductors in conduit, multi-core cables with rubber, paper, or cambric insulation, and multi-core cables with a mineral insulation, and the salient features of these types of flame-proof installation can now be given.

(*a*) V.I.R. Conductors in Conduit

This gives a very good job although it is somewhat expensive. Solid drawn, heavy gauge conduit only must be used, and all boxes, bends, couplings, etc., must be of the certified flame-proof type. Care must be taken that the conduit does not allow inflammable gases to pass along it and so spread the risk of explosion to parts of the plant where it would normally be non-existent. To overcome this risk it is necessary to fit barrier or sealing couplings in the run of the conduit immediately it leaves a hazardous area and enters a safe area. These couplings are illustrated in Fig. 20 and, when filled with compound, form a gas-tight barrier inside the conduit. If the cubic volume of the conduit installation is likely to exceed 100 cub. in., then the threaded portion of conduit and fittings should be at least 1 in. long.

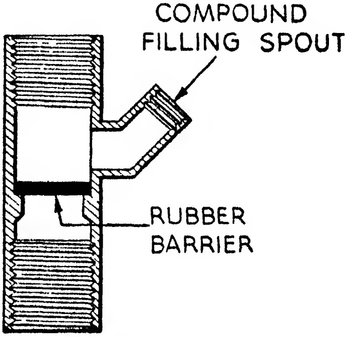


FIG. 20. ARRANGEMENT OF CONDUIT SEALING COUPLING (SECTIONAL VIEW)

(*b*) Rubber-, Paper-, or Cambric-insulated Cables

These should be lead-sheathed and armoured to give the mechanical protection so necessary in this type of installation.

No special technique is required to install these types of cable and a very sound installation is obtained which will probably cost less than a conduit installation.

(*c*) Mineral Insulated Cables

These are very suitable for flame-proof installations by nature of their inherent non-inflammable character. They are smaller in size than their equivalents in other types of cable and are therefore less obtrusive and less likely to be damaged. Special types of gland must be used with flame-proof conduit boxes.

The cost of an installation using this type of cable will usually be comparable with a class (*b*) installation.

The final selection as to the type of cable employed will, of course, be decided by the economics of the case which will vary according to the nature of the plant, but any of the above-mentioned types will be a sound and reliable installation.

The first essential in designing a flame-proof installation is to determine the nature of the risk involved and the group of the particular gas or gases giving rise to the risk. The tables in Appendix II give details of some of the materials which can give rise to explosive conditions and also give provisional grouping in certain cases, but it must be emphasized that an official ruling from H.M. Factory Inspectors should be obtained where any doubt exists as to the group to which a gas or explosive dust belongs.

The electrical apparatus can then be purchased as certified for operating in the particular group of gases required. Motors, starters, and switchgear are marketed with certificates for operating in Group I and Group II gases, but not for Group III, since the very small clearances permissible for this group cannot be guaranteed with confidence for moving parts such as are met in these types of apparatus. Lighting fittings certified for Groups I and II gases and provisionally certified for Group III are obtainable, but the larger sizes are not available for Group III risks.

As an alternative to flame-proof motors it may be found expedient in certain instances to use ordinary totally enclosed machines and to feed air, nitrogen, or some inert gas under pressure, through the motor. By this means the atmosphere containing the explosive gases is prevented from getting inside the motor and the risk of explosion is obviated, but some automatic device would be necessary to cut off the electrical supply to the motor in the event of a failure in the supply of the inert gas. Care must also be taken in such a case to ensure that all parts of the motor, including the terminal box, are purged by the inert gas.

Motor starters and switchgear may be hand-operated or push-button operated, oil-immersed or air-break according to the nature of the plant in which they are to be installed. Where there is the possibility of corrosion it will generally be found advisable to use oil-immersed gear but, otherwise, air-break gear will be found satisfactory and frequently less expensive than oil-immersed gear. A very good case can usually be made out for the use of ordinary, industrial type, contactor starters and installing these in some safe part of the building, whilst flame-proof push buttons are located near the motor drive to control the starter. On the smaller size of motors, below approximately 10 h.p., it will usually be found that this latter scheme is the most economical, since the difference in price between an ordinary and a flame-proof motor starter may easily more than offset the cost of increased lengths of control cable between flame-proof push buttons and the industrial type starter; it also has the added advantage that maintenance on the starter is made easier.

Distribution gear should be located in a safe part of the plant or, if necessary, in a separate switch house or weather-proof enclosure outside the building since, were it situated in the dangerous area, it would be necessary to isolate an entire distribution board before work could be carried out on any particular circuit, with the possible consequence of shutting down a number of motors for the sake of working on one only. This means that distribution boards will not be positioned at load centres, and that cable runs will be consequently longer, but these facts must be faced in this type of installation. Any non-flame-proof apparatus should be located at a safe distance—say not less than 20 ft.—away from any possible source of explosive atmosphere.

In addition to the use of a flame-proof installation, there is another means of ensuring safe working conditions for electrical equipment in explosive atmospheres, and this is to design the electrical apparatus and the circuits feeding the apparatus so that they are intrinsically safe. The definition of the term "intrinsically safe" as accepted for the British Standard Glossary for terms used in electrical engineering is as follows—

(*a*) applied to a circuit to denote that any sparking that may occur therein in normal working is incapable of causing an explosion of the prescribed inflammable gas or vapour;

(*b*) applied to apparatus to denote that it is so constructed that, when connected and used under prescribed conditions, any sparking that may occur therein is incapable of causing an explosion of the prescribed inflammable gas or vapour.

Thus it is apparent that the securing of intrinsic safety must be approached from two aspects; the circuit conditions must be designed so that the voltage and current are limited to reduce the incendivity or "fatness" of a spark to safe limits, and the apparatus must be designed to ensure that it cannot give rise to dangerous sparking.

Sufficient research on this subject has not yet been carried out to enable group certification to be applied as in the case of flame-proof equipment, or to enable specifications to be drawn up to ensure intrinsic safety. At the present, each circuit and its associated apparatus can be tested and certified only for operation in very definite conditions and in specific atmospheres. The voltage of the circuit is limited to something under 30 volts and the current is similarly restricted either by inherent resistance as in the case of D.C. circuits supplied from dry or Leclanché batteries, or by added resistance as in the case of transformer fed circuits. By these means the circuit can be rendered intrinsically safe.

With regard to the apparatus, the main thing to ensure is that dangerous sparking cannot be caused by inductive voltages when the circuit is interrupted. There are several ways of discharging induced voltages in coils, such as connecting a high resistance, a condenser, or a half-wave rectifier in parallel with the coil, or by winding a low resistance, short-circuited secondary on the coil, and the most suitable arrangement would depend on the circuit under consideration and whether it was fed from a D.C. or an A.C. supply.

Owing to the severe limitations on voltage and current in intrinsically safe circuits and apparatus, it is not suggested that this arrangement is likely to have a very wide application in industrial installations, but it may be very useful for signalling purposes or for operating relays in automatically controlled processes where the use of standard flame-proof equipment would not be possible.

Static Electricity

The building up of static electrical charges on objects is quite a well-known phenomenon and it usually devolves upon the electrical engineer to take suitable counter-measures against it, although the causes are usually outside his jurisdiction. The most common cause of static is friction and it is quite possible for high potentials to be built up on objects until the spark resulting from the discharge of these can be dangerous, particularly where explosive atmospheres may be present. It is fortunate that in this country we have a fairly humid atmosphere under average conditions and the building up of static charges is not so probable, since the moisture film which forms on objects provides a suitable low resistance path for the charge to leak away; it is possible, however, that operating conditions in certain processes may demand a very dry atmosphere and in this case static electricity would be more pronounced.

The friction which causes the static charges to be built up may take place between solid objects, such as between a leather belt and its pulley or between liquids and gases flowing through pipes if these liquids and gases be non-conductors. Obviously, such charges could not accumulate on apparatus which was in contact with the earth, since the charge would under those circumstances leak away to earth, and it follows from this that the best way to avoid static electricity is to ensure that such places as it is likely to occur are efficiently earthed. This can be done in the case of leather belts or conveyors by arranging an earthed, metallic comb to rest on the belt after it runs off the pulleys, the comb being, of course, as wide as the belt. Vessels and pipes containing liquids such as petrol, benzene, alcohol, etc., or gases such as dry steam, hydrogen, etc., which are likely to give rise to static charges, will usually be earthed through their supporting framework, but a separate earthing conductor should be used if any doubt exists as to the efficiency of the framework as an earth conductor. Metallic pipe runs should be inspected and tested if necessary to ensure that continuity is complete, as sight glasses, etc., are sometimes introduced which break the electrical conductivity of the pipe run, and in such cases it will be necessary to introduce a special bonding link across the break in the conductivity. In general, it will be found that continuity is effectively maintained at flanged joints in pipework by means of the flange bolts, but if the flanges and bolts should be badly corroded or should they have been painted, then it will be necessary to clean the flange faces and the under side of bolt heads and nuts to ensure good electrical contact; the use of serrated lockwashers to bite into the flanges and the bolts when the latter are tightened may be deemed advisable to secure good contact; but this is in the nature of a refinement.

As has been stated, the electrical engineer's chief concern over static electricity is in areas where explosive atmospheres may exist and it is in such areas that such special precautions as have been described would be taken. A further step which is recommended is that the use of leather or fabric belt drives be avoided completely in such areas and that recourse be made to chain drives, mechanical geared or direct coupled drives. Apart from the risk of static charges, cases have been recorded where fabric or leather belts have actually caught fire due to frictional heating, and the consequences of such an occurrence in an explosive atmosphere can be well imagined.

CHAPTER VI

MAINTENANCE OF ELECTRICAL EQUIPMENT

THE duties of electrical engineers attached to industrial concerns may be broadly divided into two categories—installing plant and maintaining it. In large companies these duties are sometimes split and allocated to separate engineers, whilst in other cases both devolve upon the same man. The interests of these two functions are not necessarily complementary, although they certainly should be, but this much can be said, that the installation engineer who has also had the experience of maintaining electrical equipment is more likely to make a sound installation than the one who has not. When an installation engineer is contemplating the purchase of a piece of apparatus, he too frequently regards it purely from a functional aspect so that, providing it will perform its electrical duties correctly, it is satisfactory. The maintenance engineer, however, would look beyond its electrical duties, and regard it as a piece of apparatus which would have to be dismantled and overhauled by some unfortunate individual (possibly himself) in the future, and he will assess the equipment from this additional aspect. In the event of a breakdown—when time is money—then inaccessibility of electrical gear is fatal, and far too much electrical equipment suffers from this weakness.

It is the duty of the maintenance engineer to ensure, so far as lies within his control, that a supply of electricity for the factory is always available, and that all electrical equipment is maintained in a sound, safe, and serviceable condition; usually this means that it is his responsibility to ensure that the factory can maintain production. Much of his work is done behind the scenes with probably little to show for it beyond a steady output from the factory, and it is one of the misfortunes of his calling that the more efficiently he carries out his work, the less attention he attracts to himself and, frequently, the less appreciation he gains for his service. The writer has come to the conclusion that an occasional electrical failure often indirectly does a lot of good, but he is not prepared to advocate that any engineer should follow a deliberate policy of occasionally shutting down his factory in the hope of winning further recognition.

The prime essentials for maintaining electrical equipment in good order are regularity of inspection, adequacy of records, sufficiency of spares to enable running repairs to be carried out and, in addition, a fair amount of intelligent anticipation on the part of the engineer to pick out possible sources of trouble, and to take the necessary precautions. Regularity of inspection will figure prominently in what is written in this chapter, but it is appreciated that it is not always possible to carry out these inspections at the suggested intervals, particularly in the case of electrical gear installed in continuously running process plants, and the engineer will have to seize such opportunities as arise to overhaul and inspect his equipment, but nevertheless the suggestions can be regarded as a target to be aimed at. The necessity of keeping concise records of inspections cannot be too highly

		Transformer Serial No.:
Capacity: kVA.	Ratio:	Tappings:
Maker:	Maker's Serial No.:	Type:
Class of Oil		Location
Quantity of Oil		
Weight of Oil		
Total Weight of Transformer		
Weight of Core and Windings		

FRONT

		OIL TESTS		
Date	Moisture	Acidity	Break Down	Remarks

BACK

FIG. 21. SUGGESTED ARRANGEMENT OF TRANSFORMER CARD

stressed, since the past history of a piece of apparatus can often supply the reason for its failure and be a means of avoiding future recurrence of the trouble. Certain parts of electrical gear, such as contacts in motor starters and brushes in motors, can be regarded as consumable during the normal operation of the apparatus, and replacements would be carried in stock as a matter of course; certain other parts such as operating coils for contactors and bearings for motors are liable to fail in service, and the engineer should ensure that he has sufficient spares, especially for any apparatus which may be vital to the running of the factory. With regard to the intelligent anticipation of trouble, this is something which is only acquired by experience. and cannot be written in books.

To assist him in maintenance work and in locating faults, the electrical engineer will require certain instruments, and the following are suggested as being the bare essentials—

Multi-range ammeter.
Multi-range voltmeter.
Insulation tester and ohmmeter.
Tong type ammeter.
Tachometer.

The ammeter and voltmeter can conveniently be combined in the one instrument, and some excellent universal test meters are now available, enabling voltage, current and resistance measurements to be read on the one instrument. In addition to the above, some form of resistance bridge equipment will be found useful, as would also a phase sequence indicator. For large factories, where a number of integrating meters are installed, some form of check meter is well worth while to check the accuracy of the meters, whilst if a lot of oil-immersed equipment is installed, particularly E.H.V. equipment, some form of portable oil filter and high-voltage oil test set will be found to be indispensable if the oil is to be maintained in good condition. No doubt other equipment will be found necessary and useful in certain cases, but the above-mentioned will be found adequate for most purposes.

Electrical equipment is very reliable, and does not normally require a great deal of maintenance, and the following recommendations are put forward as being suitable for the common items of electrical apparatus operating under average conditions.

Oil-immersed Transformers

Given fair operating conditions within their normal rated load, and sufficient ventilation to avoid excess temperature, oil-immersed transformers will be found to give many years of trouble-free service. If calcium chloride or silica gel oil breathers are fitted, these should be examined regularly, say monthly, and re-activated when necessary. Samples of transformer oil should be taken annually, and tested for sludge formation, acidity, and breakdown value. A visual examination of the oil will indicate excessive sludge formation, whilst the acidity test laid down in B.S.S. No. 148—1933 can easily be applied by the works chemist. For the breakdown test some form of pressure test apparatus is necessary, and several firms market suitable equipment. A small sample of the oil should also be boiled in a test tube, when any moisture in the oil would make its presence obvious by a loud crackling noise.

It is recommended that some form of card record system be adopted to record the history of each transformer. The transformers can be given serial numbers, and a separate card can be drawn up for each equipment. On one side of the card can be set out such relevant data as is desired, whilst the other side can carry the history of the annual tests, so that any progressive deterioration in the condition of the transformer oil is readily discernible. The set-up of a card which has been found satisfactory is shown in Fig. 21, but the most important thing is that the progressive history of the oil condition should be easily noted in order that steps can be taken to deal with any rapid deterioration of the oil.

If there are any signs of moisture or excessive sludge present in the oil, then it should be filtered to remove them. Several types of portable oil filters are on the market, but the writer's personal preference leans towards those types which do not involve the use of filter paper which may introduce loose fibres into the oil.

Increasing attention is being paid to the formation of acid in oils, since it has an adverse effect on transformer winding insulation, and on the windings themselves. A useful report on the care and treatment of transformer oil to reduce acidity, by D. V. Onslow, has been published by B.E.A.I.R.A., in which it is recommended that the oil should be suitably treated if the acid value exceeds 0·5 mg KOH/g, and under no circumstances should the oil be used if its acidity exceeds 1·5. Figures as high as this should not be reached with proper running conditions and ventilation for the transformers but, if they are reached, then it is recommended that the oil be drained off and returned to the oil suppliers for treatment.

With regard to pressure testing of oil little need be said except to stress its importance, particularly where the oil is being used in E.H.V. gear. The specified test for insulating oil as laid down in B.S.S. No. 148—1933 is to subject a sample to a pressure of 30 kV for a period of one minute, to which the oil must stand up satisfactorily.

If Buch-Holz gas relays are fitted on the transformers, then these should be examined periodically to see whether there is any accumulation of gas in the gas chamber. When transformers are first commissioned, it will usually be found that a certain amount of trapped air will accumulate in the Buch-Holz relay, and it will take probably some days to be driven off, but after the transformers have settled down, any accumulation of gas should be tested. This can be done by bubbling the gas through a small bottle containing a 5 per cent solution of silver nitrate which will turn cloudy, due to the formation of silver acetylide should any acetylene be present in the gas, acetylene being one of the products of the decomposition of oil under fault conditions.

The oil level in transformers should be checked periodically, although any leaks are almost bound to be self-evident. If explosion diaphragms are fitted, these should also be inspected, and if any signs of cracking are evident the diaphragms should be replaced, as otherwise the transformer would be able to breathe damp air, and so by-pass the breather.

On the subject of oil filtering and also pressure testing, the writer is of the opinion that it is better to use portable filters and pressure-testing gear, and to handle the oil actually on the job, rather than have to transport it to some central filtering apparatus. In other words, it is better to take the gear to the oil than the oil to the gear, since under suitable weather conditions oil can easily deteriorate during transit between a central filtering apparatus and the spot where it is required. This also applies to the treatment of oil for switchgear.

Switchgear

The suggestions made under this heading will be applicable to both oil- and air-break switchgear if the remarks dealing with oil are disregarded when considering air-break gear.

The duties of main switchgear under normal conditions are unspectacular, and it is easy to be lulled into a sense of false security by gear in commission which, to all outward appearances, seems quite healthy but which actually may be useless for clearing fault conditions due to the mechanism sticking, a run-down battery or a faulty relay. It is only by routine maintenance that any degree of confidence can be attained.

Location	Duty	Voltage
Maker	Type	Maker's Serial No.

Protection	Rupturing Capacity

Current Transformers	
Purpose	Ratio

Instruments		
Type	Scale	Serial No.

Maintenance Record			
Date	Remarks	Date	Remarks

Fig. 22. Suggested Arrangement of Switch Card

Apart from routine inspection and maintenance, it is very strongly recommended that the first opportunity should be seized to overhaul any switch which opens under fault conditions. If the fault has been of any degree of severity, then the oil will almost certainly be carbonized and will require to be filtered or replaced; contacts also will be burned and should be replaced or cleaned up.

The chief enemies of switchgear are rust and dust which can render mechanism inoperative and prevent the gear from functioning correctly. To combat these, it follows that gear should be installed in clean, dry places and, if in addition it is given an annual overhaul, little fear need be felt of unsatisfactory operation.

A card system will be found very useful for recording information and details of inspections; each switch should have its own card, one side bearing such information as size, rupturing capacity, current transformer data and particulars of relay settings, whilst the other side could bear a dated record of overhauls. The arrangement of card shown in Fig. 22 will be found suitable.

It is suggested that each switch should be overhauled completely at least once per year, and more often if it has frequent and heavy duty to perform. The switch tank should be lowered, and the oil should be pressure tested to ascertain its breakdown value. If there is any sign of excessive carbonization of the oil, it should be filtered. Switch contacts should be cleaned and checked for alignment, insulators should be examined and cleaned if necessary, taking care of course to use suitable dusters which are not likely to leave loose fibres and fluff behind. The operating mechanism should be tested and oiled, and any interlocks should be checked. Main plug and socket connections should be carefully cleaned, and lightly smeared with vaseline. Secondary wiring should be examined, and any slack connections tightened or dirty contacts cleaned.

In addition to the above, which really amounts to a mechanical overhaul, if relays are fitted these should be cleaned and checked for operation. Small hand bellows will be found useful for blowing out such things as relays and instruments, whilst any more obstinate obstructions can usually be removed by means of a feather which is not likely to damage the delicate mechanism. The most satisfactory way of checking the operation of relays is by means of injecting a suitable current into the main primary connections of the current transformer by means of a transformer, but the apparatus for doing this is somewhat expensive, and could probably only be justified in the case of very large factories where many relays have to be checked. Although the primary injection method is advocated as the ideal to be used wherever possible, the next best method of checking relays is to open the secondary circuit and inject the requisite current to operate the relays. The secondary current is usually very much less than the primary, and the injection equipment is accordingly cheaper; it is, in fact, quite an easy job to rig up a satisfactory equipment using a low-voltage secondary transformer, with a suitable rheostat in series to vary the current, and an ammeter to measure the current flowing. The relay movement should be inspected to make sure that it is quite free and, if it is of the inverse time lag type, the time taken to operate should be checked against the various settings indicated on the relay.

Any tripping or closing batteries should be inspected about every three months to ensure that the electrolyte is in good condition, and the battery fully charged. If the battery is kept on constant trickle charge, then little maintenance will be found necessary beyond this periodic check.

Motors and Starters

Here again it is suggested that a card system will be found extremely useful, particularly in the case of motors; and a typical motor card is shown in Fig. 23. In addition to routine maintenance records, any repairs to the motor should be briefly outlined on the card, so that the history of the motor can be seen at a glance. By this means, contributory causes to motor troubles, which are external to the machine, can often be diagnosed and corrected. Thus, if it is found that bearings have to be frequently replaced on a particular machine, it would probably indicate some faulty lining-up between the motor and its drive, or some out-of-balance in the driven machine.

Modern motors are extremely reliable pieces of apparatus, and do not require a lot of routine maintenance if they are installed in good atmospheric conditions, and are not overloaded excessively. For all motors an annual overhaul should be all that is necessary, but slip-ring or commutator machines will require more frequent inspection to check up on the condition of the brushes, slip-rings or commutators. During the annual overhaul, the insulation resistance should be measured and recorded, and also the air gaps, and any dirt, fluff or moisture inside the machine should be removed. The windings should be painted with a suitable insulating varnish if necessary, and the bearings should be washed out with paraffin, examined and renewed if there are any apparent signs of wear, or repacked with suitable lubricant. For the vast majority of motors this annual cleaning and repacking with grease is all that is necessary for ball or roller bearings; the grease gun enthusiast should be severely kept in check, as he frequently does more harm than good with his grease gun and packs the motor up with grease until it eventually burns out due to overheating.

When purchasing motors, the engineer should obtain from the

Motor Serial No.................

H.P.	Speed	R.P.M.	Volts	Phase	Cycles
Maker			Maker's Serial No.		Type
Enclosure			Frame Size		

Drive End Bearing		Non-drive End Bearing		Out Board Bearing	
Type	Maker	Type	Maker	Type	Maker

Brushes			Location	
No. per Set	Type	Maker	Plant	Drive
Similar Motors:				

FRONT

Maintenance and Repair Work			
Date	Description	Date	Description

BACK

FIG. 23. SUGGESTED ARRANGEMENT OF MOTOR CARD

manufacturer full details of bearings and brushes used in the motors. These details should be entered on the respective motor cards and a sufficient quantity of spares should be ordered to cover running repairs to important drives. For those motors which are vital to the running of the plant or factory, it is well worth while carrying complete spare machines in stock, as the cost of a spare motor can usually be very quickly offset by the cost of time and production lost due to the failure of an important drive. If the practice of standardizing motors is followed as suggested in an earlier chapter, then the number of spares to be carried will not be excessive.

Also, at the time of purchasing motors, the engineer should secure copies of test certificates for each motor. These should be examined and, if satisfactory, they can then be marked with the internal serial number which is to be allocated to the particular motor, and which will be marked on the motor and its card. Thus everything relative to any motor bears the same reference and can be easily located.

At the same time as the motor receives its annual overhaul, its starter should be inspected. Little should be necessary in the way of maintenance for starters, beyond cleaning of contacts or fitting new ones if required, changing oil, cleaning magnet faces in contactors, and generally cleaning the apparatus. It is not suggested that a card system is necessary for starters.

A useful practice in connection with motor starters is to mark a red line on the ammeter to indicate the full load current of the motor. Any overloading can then be easily noticed and steps taken to correct it.

General Maintenance

For satisfactory maintenance and speedy repairs at times of breakdown of the electrical system in a factory, it is essential that records should be complete and up to date. Drawings should be immediately available showing accurately the position of any underground cables, and bearing as much information as possible relating to cable sizes, position of joint boxes and how the phase colours or numbers connect up inside joint boxes. A diagram of the network is also necessary to assist in switching operations. In addition, lay-outs and diagrams for the installations inside plants and buildings should be kept up to date to facilitate extensions, and to assist repair work in times of trouble; such drawings should be readily accessible to maintenance electricians.

It is assumed that the electrical installation generally will be inspected fairly frequently by the engineer during the course of his tours round the works, and many incipient troubles come to light during such tours. Bearing or brush trouble in motors can often be spotted and rectified during casual inspection, and hot switches or fuse-board troubles sometimes reveal themselves if the engineer makes his inspection something more than a visual one.

Flame-proof installations call for a much more detailed inspection owing to the greater hazards involved. Covers on switches, motors, lighting and conduit fittings should be carefully examined to ensure that all screws are intact, cables and conduits should be watched for any signs of deterioration or bad usage which is likely to open joints, and it is suggested that covers on motors and starters be opened periodically, say every three months, to make sure that the flanges are in good condition, and not rusting or giving rise to excessive gaps. Lighting fittings should be inspected for cracked or broken well glasses.

Some of what has been written in this chapter may be regarded as being too ambitious or idealistic, and not capable of being practised in an industrial works, but, with suitable co-operation from all concerned, it will be found reasonably practicable. In the case of continuously running plants, periodic shut-downs are in the interest of the mechanical as well as the electrical engineers, and it is surely sound sense to have a pre-arranged shut-down to enable maintenance work to be carried out than to have an unwanted and inconvenient shut-down due to lack of maintenance.

Location and Correction of Electrical Faults

It is not proposed to attempt to enumerate and suggest remedies for the various electrical faults which can occur, but rather to suggest a line of attack to adopt when dealing with fault conditions, with the object of expediting their correction. The most important thing to do after the occurrence of a fault is to note the effects, and to try to get a true story of what was the state of affairs before, during, and after the fault. It is surprising how difficult it is to collect this information from witnesses because, even after making due allowance for the usually short space of time during which the events occur, there seems to be an inherent reluctance for men to offer lucid and correct statements of what took place; their first inclination seems to be to evolve some statement which will clearly exonerate them of all possible connection with the occurrence, and their statements, whilst frequently palpably incorrect, can often draw serious "red herrings" across the track of the cause of the trouble. Hence, it follows that the electrical engineer is fortunately situated if he can persuade his staff to give a true picture of events after a fault has developed, and to make them realize that less blame will accrue to them if they are at all responsible for the fault than they would otherwise incur by deliberately offering misleading statements. Every effect has a cause, and by careful consideration of the effects of a fault, a correct diagnosis of its cause can usually be arrived at. Too frequently is time wasted by attempting to rush at the job of correcting fault conditions and, unless the reason for the trouble is immediately obvious, it is much better to give the matter serious consideration before adopting any particular course of action.

A common failing among electricians is what appears to be an innate fear of wiring diagrams, when they are called to repair a piece of apparatus which includes a certain amount of secondary wiring. Instead of working to a diagram they will disconnect wires at random, and then try to reconnect them as they were originally, but the total effect is frequently to leave the apparatus in a hopeless tangle which will necessitate stripping down most of the small wiring, and reconnecting it again. This may appear to be a libellous statement, and if any electrician should read this and resent it. then to him the writer offers apologies, but nevertheless the fact is indisputable. The electrical engineer should make sure that wiring diagrams—in as simple a form as possible—are available for his maintenance electricians, and that these men are fully acquainted with the diagrams, and understand them, even if the engineer has to explain them himself. By intelligent use of diagrams the cause of otherwise unexplainable events often becomes apparent.

The above generalizations are perhaps as far as this subject can reasonably be pursued, but if they are accepted and, provided that suitable test instruments are available, then much valuable time can be saved in locating and correcting such electrical faults as are commonly encountered in industrial installations.

APPENDIX I

GRADING OF DEFINITE MINIMUM INVERSE TIME LIMIT RELAYS

THE modern definite minimum inverse time limit relay takes its description from the fact that its operating time depends upon two features, the first being the length of travel of the relay movement necessary to close the contact which forms the definite minimum portion of the time and which is adjustable by variation of the length of travel; the second feature is an inherent property of the design which renders the operating time inversely proportional to the current in the relay coil. A typical characteristic curve for a relay of this type is shown in Fig. 24, which gives the relation between the operating current and the operating time for a maximum time setting value which is equivalent to a minimum operating time of 2·2 sec. in this case. From this curve

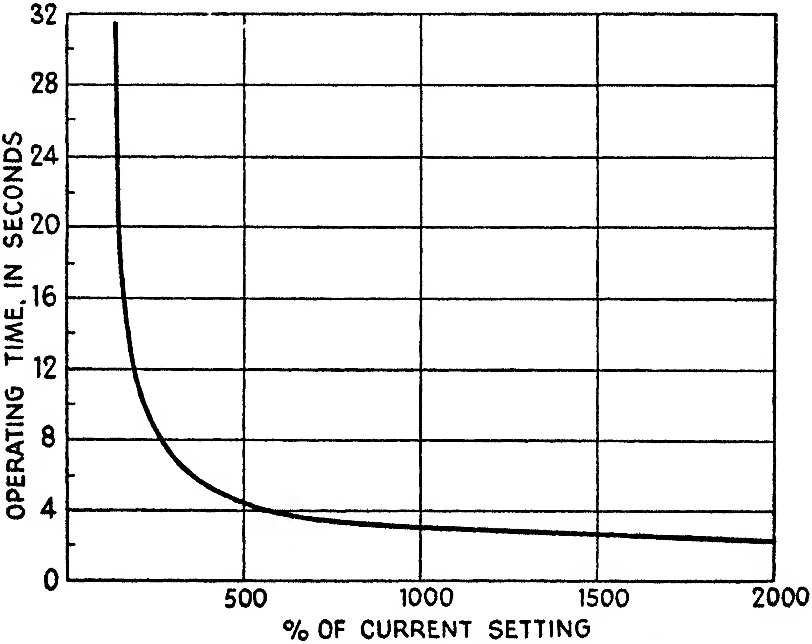


FIG. 24. CHARACTERISTIC TIME-CURRENT CURVE FOR DEFINITE MINIMUM INVERSE TIME LIMIT RELAY

it is apparent that the relay will be inoperative for values of operating current less than 100 per cent of the setting value, but at currents slightly in excess of this the relay will begin to creep although taking a long time to operate. For the particular relay under consideration the current at which the movement just begins to creep is 130 per cent of the setting value, so that if we are dealing with a 5 amp. relay set at 100 per cent then this relay would commence to operate with a current of about 6·5 amps., but this figure should be checked from the characteristic curve of the type of relay being used. The current at which the relay begins to creep is usually termed the "pick-up" current. As the relay current increases beyond the pick-up value, the operating time decreases until it reaches a minimum at about 16 × the setting value at which point the relay becomes saturated and any further addition to the operating current will not affect the operating time. It is thus obvious that adjustment of the operating time of the relay can be obtained by variation of the operating current between the limits of pick-up current and saturation current, and this variation can often be achieved by suitable selection of the current setting plug position. Two variable adjustments are incorporated in these relays, a time setting adjustment which varies the length of travel of the relay, and a current setting plug which, in effect, alters the ratio of the current transformer; thus, if a 5 amp. secondary transformer is used and the current plug is set at 100 per cent, then 5 amps. plus the pick-up correction will cause the relay to operate, or if the current plug is set at 150 per cent, then 7·5 amps. plus the pick-up correction would operate the relay. The method of grading relays as outlined by Messrs. Gallop and Bousfield in their I.E.E. paper makes use of both these adjustments, instead of merely grading by means of the time-setting adjustment, and by this method much shorter operating times are obtained.

In the application of this grading method use is made of a factor which is termed the "Plug Setting Multiplier" and which is simply the ratio

$$\frac{\text{Fault current in relay}}{\text{Relay full load current}} \quad \text{or}$$

$$\frac{\text{Fault current in primary of current transformer} \times 100}{\text{Current transformer full load primary current} \times \text{Relay current setting}}$$

It can be shown that, for similar types of relay, provided that this Plug Setting Multiplier for any relay is always equal or greater than that for the preceding relay in the grading sequence, then there is no chance of any wrong discrimination between the relays no matter what may be the operating current. If this proviso is not maintained, there is the risk of wrong discrimination with low values of fault current.

To grade a series of relays, it is necessary to know the ratio of the current transformers which will be energizing the relays and also the short circuit currents for faults anywhere on the system. These should best be set out in tabular form as shown in Fig. 26. The settings for the relay most distant from the supply point are considered first, and this is given the lowest possible time setting and also the lowest possible current setting consistent, of course, with its stability and its correct functioning as a back-up relay, so that any protective system it may be backing-up should always tend to operate first. The Plug Setting Multiplier for this relay should now be calculated and listed in the appropriate column in the table. The preceding relay in the sequence can now be considered and the current setting for this should be selected to fulfil two requirements; it must operate in its minimum time for a fault between it and the most distant relay—i.e. it must be saturated or as nearly saturated as possible—and it must have a Plug Setting Multiplier, equal to or less than the most distant relay to ensure correct discrimination throughout the range of operating currents. There will usually be a number of possible settings which would satisfy these conditions, but the lowest possible current setting should be adopted as this would give the highest possible Plug Setting Multiplier. If the system conditions are such that the fault currents and current transformer ratios result, in the event of a fault at the remote end of the network, in the remote relay being saturated but the preceding relay being unsaturated, then it can be seen on reference to Fig. 24 that there will be a difference in the operating times of the two relays provided that the time settings are the same and the remote relay will operate quicker than the other. If the fault currents have been tabulated for faults anywhere on the network as has been suggested, then it is an easy matter to read off the characteristic curve what the operating time would be for full-time setting and to determine to what the time setting should be adjusted in order to give the time grading interval of 0·5 sec. which, as has been stated earlier in this book, is the desirable difference to maintain between the operating times for successive relays in order to ensure correct discrimination. This process should be continued for all the relays in the sequence when it will be found that the operating times for relays close to the source of supply are very much shorter than they would otherwise have been, if the grading had been carried out by adjustment of the time setting only.

Perhaps the above can be made clearer by a brief description of an actual application of this method of grading to a network. A diagram of part of a system in which it was necessary to grade a sequence of overload relays is shown in Fig. 25. It will be seen to comprise 33 kV and 11 kV switchgear with overload relays acting as back-up protection at the points marked A, B, C, D, E, and F, and it is thus necessary to grade these relays in sequence commencing with relay A at the most remote point. The maximum short-circuit currents and also the short-circuit currents in other parts of the network for faults at the positions 1, 2, 3, 4, 5, and 6, were now calculated and the values were listed in tabular form as in Tables 1 and 2 in Fig. 26. The current transformer ratios are listed in Table 1, and from these and the maximum possible short-circuit currents it is now possible to calculate the maximum permissible current setting of the relay to ensure that it will be saturated under conditions of a fault on the network just beyond the relay position; it is assumed that anything in excess of 16 × full load current would saturate the relay. Any relay setting equal to or lower than this last-mentioned value would cause the relay to operate in its minimum time for fault conditions as just described, and this state of affairs should be aimed at in all relay settings although it is not always possible to attain.

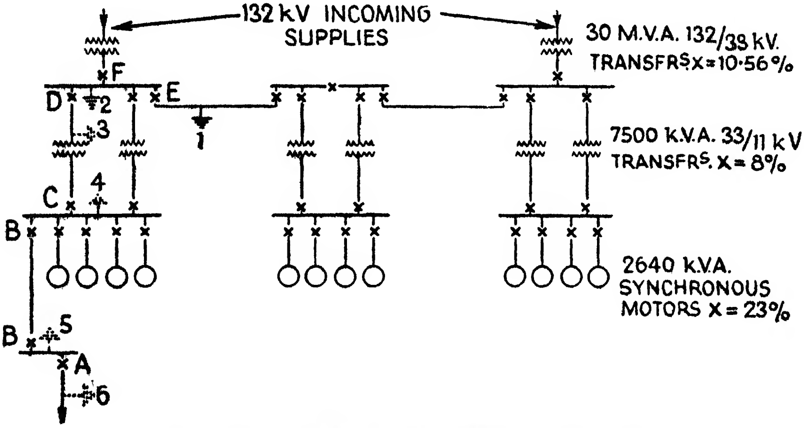


FIG. 25. DIAGRAM OF 33 kV AND kV NETWORK

TABLE I

Relay Position	Curr. Transf'r Ratio	Max. possible Short Circuit		Max. Current to Saturate Relay at 100% Setting	Max. Plug Setting to Saturate Relay	Recommended Plug Setting	Recommended Time Setting
		M.V.A.	Amps.				
A	150/5	234	12260	2400	200%	100%	·05
B	400/5	234	12260	6400	150%	100%	·28
C	400/5	94	4925	6400	75%	100%	·40
D	150/5	279	4880	2400	200%	100%	·4
E	350/5	316	5330	5600	75%	100%	·59
F	500/5	243	4250	8000	50%	150%	·50

TABLE II

(P.S.M. = Plug Setting Multiplier)

	Fault at 6			Fault at 5			Fault at 4			Fault at 3			Fault at 2			Fault at 1		
Relay Position	Amps.	P.S.M.	Op't'g Time	Amps.	P.S.M.	Op't'g Time	Amps.	P.S.M.	Op't'g Time	Amps.	P.S.M.	Op't'g Time	Amps.	P.S.M.	Op't'g Time	Amps.	P.S.M.	Op't'g Time
A	12260	81·6	·11	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
B	12260	30·6	·61	12260	30·6	·61	—	—	—	—	—	—	—	—	—	—	—	—
C	4925	12·3	1·1	4925	12·3	1·1	4925	12·3	1·1	—	—	—	—	—	—	—	—	—
D	1640	10·9	1·1	1640	10·9	1·1	1640	10·9	1·1	4880	32·5	·88	—	—	—	—	—	—
E	2780	7·95	1·9	2780	7·95	1·9	2780	7·95	1·9	5530	15·8	1·4	5530	15·8	1·4	—	—	—
F	1850	2·47	3·9	1850	2·47	3·9	1850	2·47	3·9	4250	5·7	1·95	4250	5·7	1·95	4250	5·7	1·95

Fig. 26. Tables showing Recommended Relay Settings and Actual Operating Times for Various Fault Conditions

The relay A, being the most remote from the supply source, would be given its settings first. The time setting would be given its minimum value of 0·05 and, although it will be seen that the current setting could be as high as 200 per cent to secure saturation, a current setting of 100 per cent would be satisfactory as giving stability under local conditions, and also giving the maximum Plug Setting Multiplier of 81·6. The operating time for this relay under conditions of a fault at 6 would be $0{\cdot}05 \times 2{\cdot}2 = 0{\cdot}11$ sec.

Relay B can now be considered and it is required that this relay, under fault conditions at position 6, should have an operating time of $0{\cdot}11 + 0{\cdot}5 = 0{\cdot}61$ sec. to give correct discrimination. It will be seen that the network conditions are such that the fault current due to a fault at 6 besides saturating relay A would also saturate relay B, and so the discriminating time must be obtained by adjustment of the time setting which should consequently be set at $\frac{0{\cdot}61}{2{\cdot}2} = 0{\cdot}28$. The current setting can also be 100 per cent in this case which would give a Plug Setting Multiplier of 30·6.

For relay C it will be seen that the maximum current plug setting which would saturate the relay under fault conditions would be 75 per cent; but the minimum possible stable setting would be 100 per cent which gives a Plug Setting Multiplier of 12·3. On reference to Fig. 24 it will be seen that, for the maximum time setting, this relay would operate in 2·8 sec. under short-circuit conditions, whereas an operating time of $0{\cdot}61 + 0{\cdot}5 = 1{\cdot}1$ sec. is required. Thus a time setting of $\frac{1{\cdot}1}{2{\cdot}8} = 0{\cdot}393$ or 0·4 approx. can be used. It will be appreciated at this point that a time setting of $\frac{1{\cdot}1}{2{\cdot}2} = 0{\cdot}5$ would be necessary if the grading was being carried out by adjustment of the time setting only.

The above process is carried on throughout the network until provisional settings have been determined to suit conditions of a fault at position 6, and the appropriate columns in Table II will be completed. The same procedure should be followed to suit faults at the other positions indicated, and it may be found that some of the provisional settings will need to be revised to suit other fault conditions, but in the end a final set of relay settings, which will give correct discrimination for all fault conditions, will be arrived at. The benefit of setting these calculations out in tabular form is that it is then an easy matter to run one's eye down a column and to check up that all the Plug Setting Multipliers decrease correctly from the most distant relay to that nearest the supply source, and that the correct grading time interval of at least 0·5 sec. is maintained throughout the sequence of relays under all conditions.

It will be readily appreciated that it would not be possible to grade as many relays as this by adjustment of the time setting device only and also that, by adopting this grading method, much shorter operating times are secured for relays close to the supply point where the short circuit conditions will be most severe.

APPENDIX II

PROVISIONAL GROUPING OF EXPLOSIVE GASES MOST COMMONLY USED IN INDUSTRY

Gas Group	Provisional Grouping of Gases having similar explosive characteristics
I Methane	Methyl Chloride, Hydrogen Cyanide.
II Pentane	Acetone, Methyl Ethyl Ketone, Ethane, Propane, Butane, Hexane, Heptane, Octane, Benzene (Benzol), Toluene (Toluol), Xylene, Cyclo-Hexane, Methyl-Cyclohexane, Methyl Alcohol, Ethyl Alcohol, Propyl Alcohol, Butyl Alcohol, Amyl Alcohol, Acetaldehyde, Methyl Methacrylate, Methyl Formate, Ethyl Formate, Methyl Acetate, Ethyl Acetate, Propyl Acetate, Butyl Acetate, Amyl Acetate, Ethyl Butyrate, Butyl Butyrate, Cellulose Lacquer Spray, Petrol, Methylated Spirits, Naphthalene, Paraffin, Blast Furnace Gas, Ethyl Chloride.
III Town Gas	Carbon Monoxide, Diethyl Ether, Ethylene, Water Gas.

The above groupings are provisional only and are based on the similarity of the explosive properties of the gases. Where any doubt exists as to the official classification of any particular gas, then an official ruling should be obtained from H.M. Inspector of Factories.

The classification shown on page 112 is taken from Form 829, "Memorandum on Dust Explosions in Factories, 1930," issued by the Factory Department, the classification being—

Class "A." Dusts which ignite and propagate flame readily, the source of heat required for ignition being comparatively small —e.g. a lighted match.

Class "B." Dusts which are readily ignited but which, for the propagation of flame, require a source of heat (*a*) of large size and high temperature, such as an electric arc, or (*b*) of long duration, such as the flame of a Bunsen burner.

Class "C." Dusts which do not appear to be capable of propagating a flame under any conditions likely to occur in a factory (*a*) because they do not readily form a cloud in air; (*b*) because they are contaminated with a large quantity of incombustible material; or (*c*) because the materials of which they are composed do not burn rapidly or produce inert gas.

Classification of Dusts from the Point of View of Explosion Hazards

Class "A"	Class "B"	Class "C"
Sugar	Copal Gum	Organic Ammonia
Dextrine (Calcined Farina)	Leather	Tobacco
Starch	"Dead Cork"	Spice Milling
Cocoa	Coco-nut Oil Milling	Bone Meal
Rice, Meal, and Sugar Refuse	Rice Milling	Lamp Black
Cork	Saw Dust	Sack Cleaning
Soya Bean	Castor Oil Meal	Retort Carbon
Wood Flour	Myrabolum and Valonia Nuts	Grain Cleaning
Malt	Paper Tube Works Dust	Tapioca
Oat Husk	Yellow Meal	"Hooking Frame" dust
Grain (Flour Mill)	Heycol 10817 CA (Dye)	Era Chrome Brown
Syrolit	Oil Cake	Era Chrome Green
Distillery Meal	Offal Grinding (Bran)	Gumgatto (Coarse)
Spice Room (Cattle Food)	Grist Milling	Drug Grinding
Locust Bean Kernel	Horn Meal	Cotton Seed
Locust Meal	Mustard	Cotton Seed and Soya Bean
Parboiled Rice Meal	Genatosan	Charcoal
Cellulose Acetate	Shoddy	Foundry Blacking
Liquorice Root	Shellac Composition	Brush Carbon
Maize	Gluten Feed	Stale Coke
Tea		Plumbago
Compound Cake		Bone Charcoal
Grain (Grain Storage)		Mineral and Ivory Black
Rape Seed		Rag Paper Works Dust
Cornflour		Alizarine Yellow "G"
Flour (Flour Mill)		Anachrome Brown
Chicory		
Briquette		
Gramophone Record		
Pitch		
Ebonite		
Erinoid		
Gumgatto (Fine)		
Mimosa Bark		
Cascara Sagrada		
Gentian Root		
Balloon Dust		

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