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TWO BOLINDERS TWO-CYCLE OIL ENGINES OPERATING AT BUTLER, N. J., LIGHT PLANT SINCE 1915

Courtesy of Bolinders Company, Inc., New York

DIESEL ELECTRIC PLANTS

A Practical Text on Characteristics of Diesel Engines, Principles of Diesel-Driven Generators, Governors, Voltage Regulators, Parallel Operation of Generators, Installation and Maintenance of Electric Equipment, Automatic Controls, Alarm Signals and Diesel Trains

BY

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ILLUSTRATED

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INTRODUCTION

DIESEL engines are extensively used for driving electric generators to produce cheap electric power, and a real need has developed for a book specially devoted to Diesel electric equipment. Many books have been published dealing with electric equipment by itself, and there are also several books on the subject of Diesel engines merely as engines. However, in Diesel electric plants the electric equipment is greatly influenced by the characteristics of the Diesel engine, and it is the purpose of this book to deal with the coordinated aspects of this specialized subject. The construction, operation, and maintenance features are specially stressed, and the book can be thoroughly understood without a college education.

An introduction describing the important characteristics of Diesel engines as prime-movers for electric generators, and citing a few of the economic aspects, is followed by a description of the types of generators suitable for Diesel engine drive.

Considerable space is devoted to voltage regulation, both D.C. and A.C., a subject of great importance in Diesel electric work, and one on which published information has heretofore been quite meagre. The operation of various types of voltage regulators is described, and information given as to the closeness of voltage control that can be expected.

Parallel operation of Diesel-driven generators is treated in a practical manner, starting with a brief explanation of the fundamental principles, and proceeding to methods of synchronizing, checking phase sequence, adjustment of field current, etc.

Men skilled in electricity frequently have only a hazy understanding of how a Diesel engine governor works, and how the governor performance affects the frequency and the load control. This subject and the operation of various types of engine governors is clearly described.

The section on Automatic Diesel Electric Plants describes in detail the methods used for full-automatic and semi-automatic operation of Diesel generating units, both singly and in multiple.

The routine procedure for putting in and out of service Diesel-driven generators and voltage regulators of various kinds is brought together in concise form.

Electric controls and alarms for the Diesel engine have come into extensive use. Considerable space is given to the purposes which these devices fulfill, how they are constructed and how they work.

Diesel streamline trains, as well as most Diesel locomotives and rail cars, employ electric transmissions. A chapter on this subject explains the fundamentals of these electric systems, including schematic diagrams and operating methods.

Installation and Maintenance of Electric Equipment cover the assembling of generators on Diesel engine shafts, general erection, operating care and adjustments, and trouble-shooting. The care and maintenance of voltage regulators is also covered.

This book should be helpful to the following groups: Students of electricity, of power plant design, and of operation and maintenance; operators and maintenance men of Diesel power plants and Diesel railway equipment; owners and superintendents of existing and proposed Diesel power plants; salesmen; and erectors.

ACKNOWLEDGMENTS

COMPANIES

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Safety Car Heating and Lighting Co., New York City
Woodward Governor Co., Rockford, Ill.
Leeds & Northrup Co., Philadelphia, Pa.

BOOKS AND MAGAZINES

Diesel Power, 192 Lexington Avenue, New York City
Diesel Engineering Handbook, Seventh Edition, 192 Lexington Ave., New York City
Southern Power Journal, Atlanta, Ga.
Standards of Diesel Engine Manufacturers' Assoc., 2 West 45th Street, New York
Industrial Power, St. Joseph, Mich.
Power, 330 West 42nd Street, New York City
Railway Age, 30 Church Street, New York City

INDIVIDUALS

A. I. Lipetz, Consulting Engineer, American Locomotive Co.

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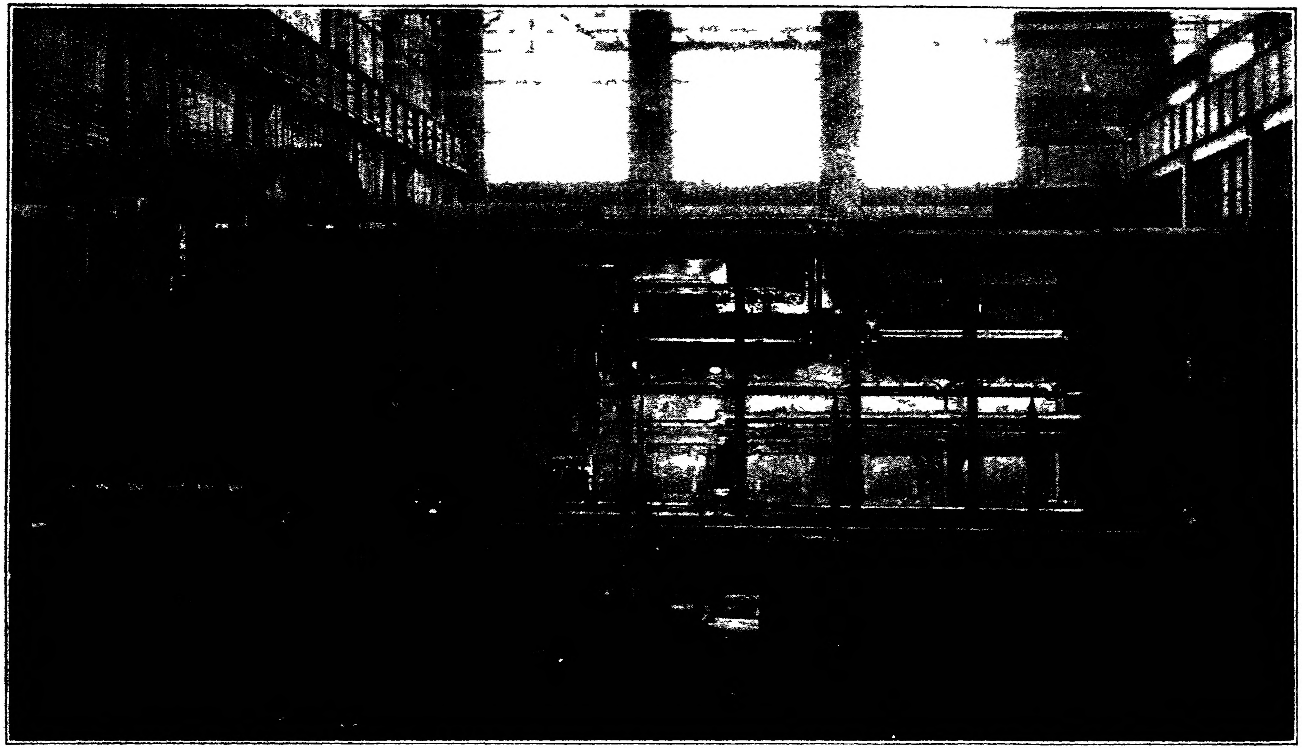


CAB OF DIESEL-ELECTRIC SWITCHING LOCOMOTIVE, WITH COVERS REMOVED TO SHOW ENGINE, GENERATOR, CONTROL AND BATTERY FOR NEW YORK, NEW HAVEN AND HARTFORD R R

Courtesy of General Electric Company

DIESEL ELECTRIC PLANTS

CHAPTER I

CHARACTERISTICS OF DIESEL ENGINES

Electric generators, being devices to transform mechanical energy into electrical energy, must be driven by machines that produce mechanical power, i.e., "prime-movers." The best known prime-movers are steam turbines, steam engines, and water turbines. The Diesel engine has now also become an accepted prime-mover in the small and medium size installations, and its characteristics are such that it is admirably fitted for driving electric generators, air compressors, centrifugal pumps, lineshafts, etc.

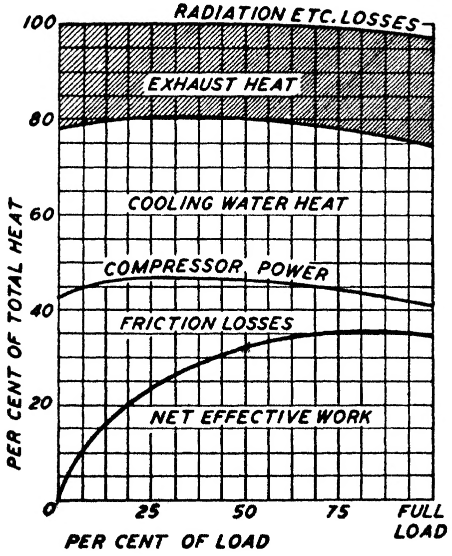


Fig. 1. Distribution of Heat Energy from Diesel Engines

Among these characteristics may be noted:

1. *High economy.* A Diesel engine converts into mechanical

energy at its shaft about 35 to 40 per cent of the heat energy of the fuel it consumes. This thermal efficiency far surpasses that of any other prime-mover in practical use. The Diesel's fuel consumption is between 1/3 and 1/2 pound of oil per brake horsepower-hour. The distribution of the heat energy, throughout the range of load, is shown for a typical engine in Fig. 1.

2. *Economy at light loads.* A Diesel engine maintains its high economy throughout the entire useful load range, the fuel consumption per horsepower at half load exceeding that at full load by only 10 per cent.

3. *Cheap fuel.* As compared with the gasoline engine, the Diesel uses a fuel costing only one-quarter as much.

4. *Economy in small sizes.* In great contrast with a steam plant, the small Diesel engine has practically as good an economy as the large one. This makes it possible to build an efficient power plant just large enough to meet present needs, and to enlarge it with additional units as the load grows; at all stages of growth the efficiency is high.

5. *Sustained economy with use.* Again in strong contrast with a steam plant, Diesel efficiency falls off very little with use. Steam plant efficiency depends upon maintaining clean boilers and upon incessant control of the furnace conditions. In the Diesel all of this is absent, and a clear exhaust is positive indication of high fuel efficiency.

6. *Independence of water supply.* An efficient steam plant requires great quantities of condensing water; the Diesel consumes very little water and can be successfully used in the most arid districts.

7. *Lightness and compactness.* The Diesel engine is a complete power plant in itself, can be made light in weight and takes up a small amount of space.

8. *Quick starting.* A cold Diesel engine plant can be started instantly and made to carry full load in a few minutes.

9. *Economy in labor.* No fire room force is required.

10. *Freedom from nuisance.* There are no ashes to be disposed of; no noisy and dusty coal handling equipment; no smoke; all noise can be easily eliminated.

Applications of Diesel Electric Equipment

These characteristics, severally, have caused Diesel engines to be used to drive electric generators for many diverse purposes, among which are:

(1) Electric central stations of small and medium size up to about 50,000 kilowatts.

(2) Stand-by power for hydro-electric systems.

(3) Private electric power plants for factories, mines, and large city buildings.

(4) Diesel electric propulsion for boats.

(5) Diesel electric propulsion for locomotives and rail-cars.

Cost of Diesel Electric Power

In stationary service the prime consideration concerning Diesel electric power is its cost as compared with the cost of electricity produced on the spot by other prime-movers or received by transmission from a distant source. Diesel power generally effects a greater saving in small plants than in large ones. Table I shows a comparison of total operating costs for a small Diesel electric plant compared with a steam electric plant of the same size. The power generated is 946,080 kilowatt-hours per year. The Diesel plant consists of three 72 kilowatt units. The steam plant is assumed to use 6 pounds of coal per kilowatt-hour. It will be noted that the total cost of power in the Diesel plant including fixed charges is 1.52¢ per kilowatt-hour as compared with 2.91¢ per kilowatt-hour for the steam plant. In a plant of this size it is seldom possible to purchase current from the utility company at less than 2½¢ per kilowatt-hour.

The cost of producing electric power with Diesel engines may be segregated into fuel, lubricating oil, upkeep, and attendance.

Fuel Cost. A Diesel engine driving an electric generator will produce from 7 to 13 kilowatt-hours per gallon of fuel oil consumed, depending upon load factor, generator efficiency and gravity of the fuel. Generally the fuel efficiency is better than 10 kilowatt-hours per gallon. Thus the fuel cost per kilowatt-hour, if fuel costs 5 cents per gallon, is less than one-half cent per kilowatt-hour. In some cases fuel is as cheap as 3 cents per gallon, giving a fuel cost per kilowatt-hour of less than 0.3 cent.

TABLE I

Comparison of Total Operating Cost of a Small Diesel Electric Plant with a Steam Plant of the Same Size

	Diesel Plant		Steam Plant	
	Total Cost	Cost per Kw-hr.	Total Cost	Cost per Kw-hr.
Fuel oil: 94,608 gals @ 5¢	$4,730 00	$ 0050		
Coal. 2,838 tons @ $5 00			$14,190 00	$ 0153
Lubricating oil	531 00	0005	200 00	0002
Attendance	5,000 00	0052	8,000 00	0085
Upkeep @ 2% on $25,000 00	500 00	0006	..	
Upkeep @ 3% on $30,000 00	. .		900 00	0009
Fixed charges:				
11 72% on $32,500 00	3,800 00	0039		
11 72% on $35,000 00			4,100 00	0042
Totals	$14,561 00	$ 0152	$27,390 00	$ 0291

Lubricating Oil Cost. The cost of lubricating oil for the Diesel engine cylinders, bearings, and other working parts approximates 0 05 cent per kilowatt-hour, though on some high-speed engines which consume more oil the cost may go to 0.15 cent per kilowatt-hour.

Upkeep Cost. The cost of keeping the engine and generator in condition, including repair parts, maintenance labor, and miscellaneous supplies such as cooling water, is generally between 0.1 and 0.15 cent per kilowatt-hour.

Attendance Cost. Diesel engines require comparatively little time of the attendant. The attendance cost is therefore low, because in a small plant only part of one man's time is needed, while in a larger plant the wages are divided into a large output. In fact, Diesel electric plants can and have been made completely automatic, even to starting and stopping the units, so that attendance is reduced to merely occasional inspections.

Total Cost. The entire operating cost of a Diesel electric unit will range from ⅔ to 1½ cents per kilowatt-hour, depending on size, load factor, and attendance. These costs are frequently much lower than comparative costs with other sources of power, and have been largely responsible for the great popularity of Diesel electric power.

Diesel Units in Electric Central Stations

In the United States, Diesel engines are not used by electric companies serving large, dense populations because the steam plant has a generating cost below that of a Diesel plant.

On the other hand, most power companies serve districts that are by no means densely populated. Transmission losses are heavy and make the application of smaller Diesel plants placed at strategic locations sound economics.

Other companies install Diesel units to carry a local load until the electric demand is sufficient to justify extension of the transmission line, whereupon the Diesel is moved to a newer and more thinly populated section.

Even where transmission lines exist, Diesel units tied in at the ends of long lines serve a useful function by improving voltage regulation and line stability, and by providing emergency reserve in case of line outage.

Diesel generating units have come into wide acceptance for municipally-owned electric plants because their generating costs, in the usual moderate size plant, are lower than those of steam plants. In 1935, there were 890 municipally-owned Diesel electric plants in the United States.

Stand-By Power for Hydro-Electric Systems

Many water-power developments are not self-sufficient, but require the use of stand-by plants to supply part of the load when the water flow is low. This is commonly done by means of steam plants, but in order that the steam plant may be ready to carry the load the boilers must be kept banked and a fire-room force kept on the payroll.

In the last few years, Diesel engines have come into use for this service primarily because they create no operating expenses when idle. No fuel is consumed, nor is any attention required. A Diesel plant can be started up from a completely idle and cold condition and be put on full load in less than five minutes. This contrasts strongly with a steam plant, whose banked fires require considerable time to develop full heat and whose turbines must be warmed slowly to prevent distortions that might cause stripping of the blades. A notable example of a Diesel auxiliary plant on a hydro system is the 7,500 kilowatt station built by the U. S. Government in the Canal Zone, to furnish stand-by service to the Gatun hydro-electric station, which normally supplies the power for operating the canal. In tests, one of these units was started and the full load of 2,500 kilowatts applied in 32 seconds.

Private Electric Power Plants for Factories, Mines, and Large City Buildings

Diesel electric plants of every size and type are in general use in industrial and commercial applications. As already explained, the main reason is the low cost of generation compared with other forms of power. Central station power usually costs little at the generating station, but the costs of transmission and distribution to the consumer often raise the price much higher than that of Diesel electric power generated on the spot with the consumer's own plant.

As compared to private steam plants, Diesel plants are generally found more economical except where the steam plant is large or where the exhaust steam can be saved and utilized for heating purposes.

Diesel Electric Propulsion for Boats

Diesel electric drives have come into extensive use for marine propulsion because they combine the fuel economy of the Diesel engine with the light weight, saving in space, flexibility in operation, and ease of control of electric transmission. The great flexibility and easy control are considered ideal for ferryboats, tugs, and dredges. In this system the Diesel engine is provided with an ordinary governor and runs a generator at constant speed. An electric motor drives the propeller and, in the case of dredges, motors are used to drive the cutter head, suction pump, etc. The entire control is handled directly from the pilot house by making changes in voltage and electrical connections. Thus, the engine load is changed from outside the engine-room, and the engineer has no manouvering signals to obey.

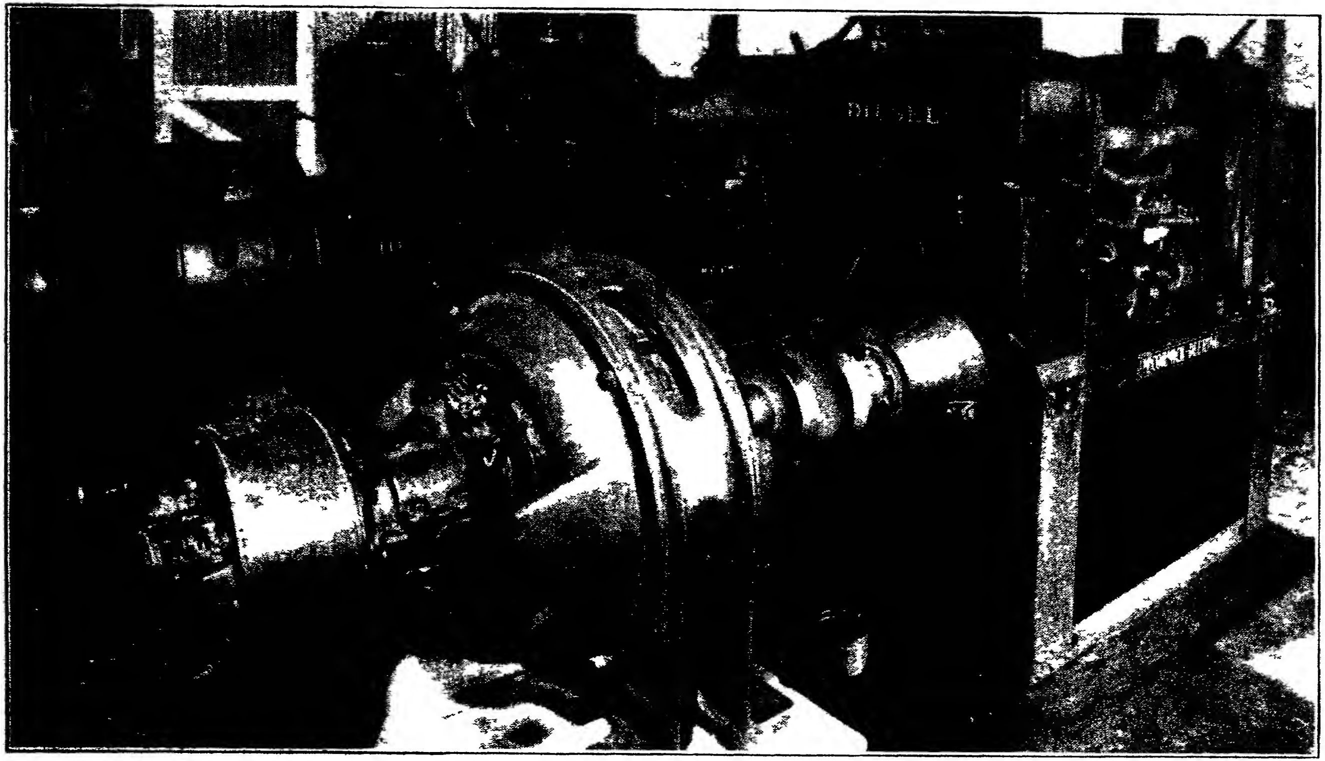
Diesel Electric Propulsion for Locomotives and Rail Cars

Here again electric transmission dovetails with the Diesel engine to give the advantages of light weight, fuel economy and ease of control. The railroads can now afford to operate trains in smaller units, at more frequent schedules, and at higher speeds, thus giving the traveler better service than before so as to meet the competition of the passenger automobile.

Diesel electric switching locomotives are widely used for reasons of fuel economy, high pulling power, and greater over-all serviceability than the steam locomotive.

VICE-PRESIDENT GALLAWAY OF THE B & O AND VICE-PRESIDENT KETTERING OF GENERAL MOTORS AT THE CONTROLS OF ONE OF THE B & O DIESEL LOCOMOTIVES

Courtesy of Baltimore & Ohio Railroad, Baltimore, Md.



THE DIESEL-ELECTRIC PLANT OF PENINSULAR DISTRIBUTING COMPANY, SULPHUR SPRINGS, FLORIDA

Three PD-40 Diesel engines are used The first one is driving a 37½ kw alternator with a direct-connected exciter. The two rear engines are used to drive by V Belts a single 75 kw Western Electric alternator with a belt driven exciter A clutch is used to disconnect the engine when starting

CHAPTER II

ALTERNATING-CURRENT AND DIRECT-CURRENT GENERATORS FOR DIESEL DRIVE

Although there are certain problems peculiar to the Diesel-engine-driven generator, the electrical characteristics do not differ fundamentally from generators driven by other types of prime movers. Standard voltages, temperature rises, speeds and other characteristics have been established. Machinery adhering to such standards should be purchased whenever possible. Special voltages, temperature ratings, etc., can be obtained, but these tend to increase the cost of the equipment. Generators for use with Diesel engines are rated at the load they are capable of carrying continuously without exceeding their temperature guarantees. Diesel engines are not in general designed for any continuous overload. This should be taken into account in selecting the generator size.

Alternating-Current Generators

Standard alternating-current generators are continuous rated at 50° C. rise on the armature, with no overload capacity. Ratings at 40° C. rise can be obtained at additional cost. Most alternating-current generators are arranged for 80 per cent lagging power factor, but if special conditions require a lower power factor, suitable machines can be furnished.

With respect to their general form and method of connecting to the Diesel engines which drive them, alternating-current generators may be classified into (a) engine type; (b) flywheel type; (c) coupled type; and (d) belted type.

Engine-Type Generators. This type of generator has no shaft, bearings or bedplate. The stator is mounted on soleplates on the foundation or on the engine bedplate. The rotor is pressed or clamped on the shaft of the engine. Usually the stator holds the alternating-current windings and the rotor carries the direct-current field. The rotor is mounted on the engine shaft or an extension thereof as closely as possible to the engine itself; the bearings are

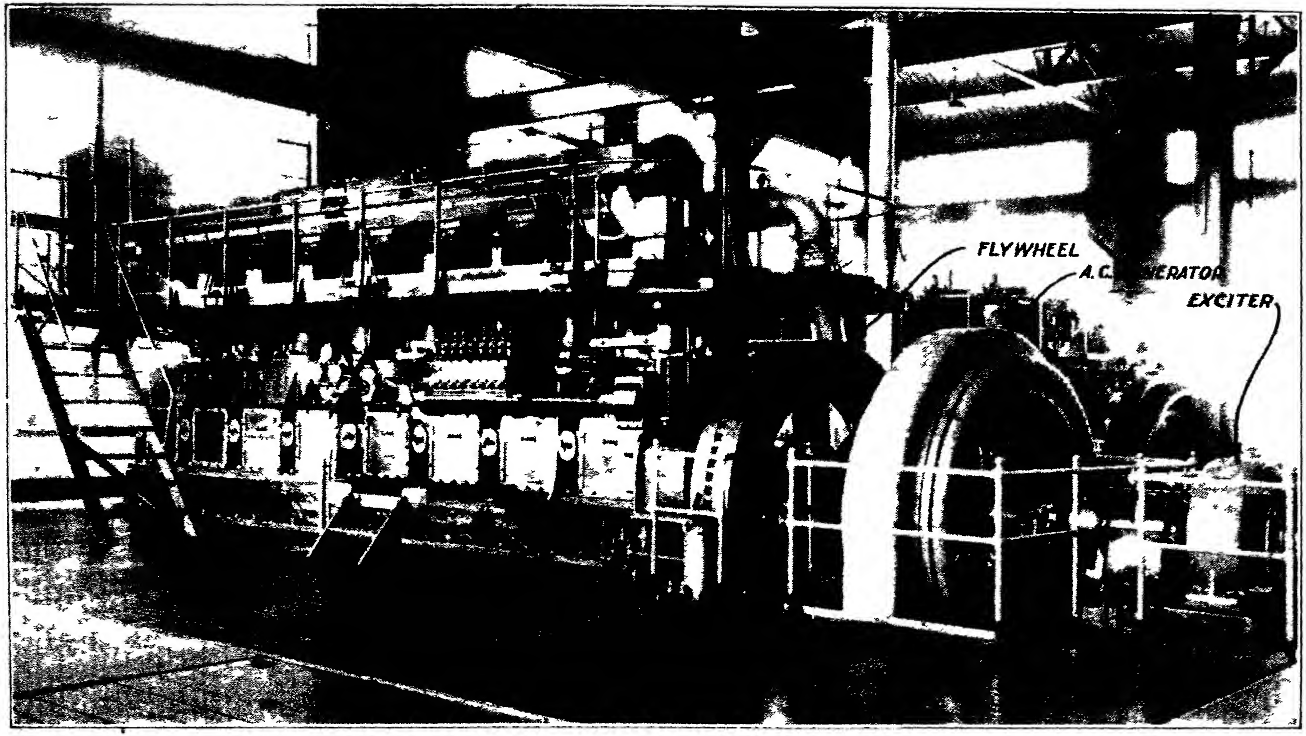


Fig 2 Diesel Driven 700 Kw , Engine Type A C Generator
Courtesy of Crocker-Wheeler Electric Manufacturing Co

furnished by the engine builder. This type is commonly used for speeds below 500 r.p.m. See Fig. 2.

Flywheel-Type Generators. The flywheel generator consists of a rotor with a heavy external rim which surrounds and rotates around the stator. The rotor carries the direct-current field, while the alternating-current windings are stationary. In other words, the flywheel type is like the engine type turned inside out. The flywheel type, Fig. 3, finds its application where space is at a premium, the flywheel effect of the heavy rotor making it possible to dispense with the flywheel of the engine itself.

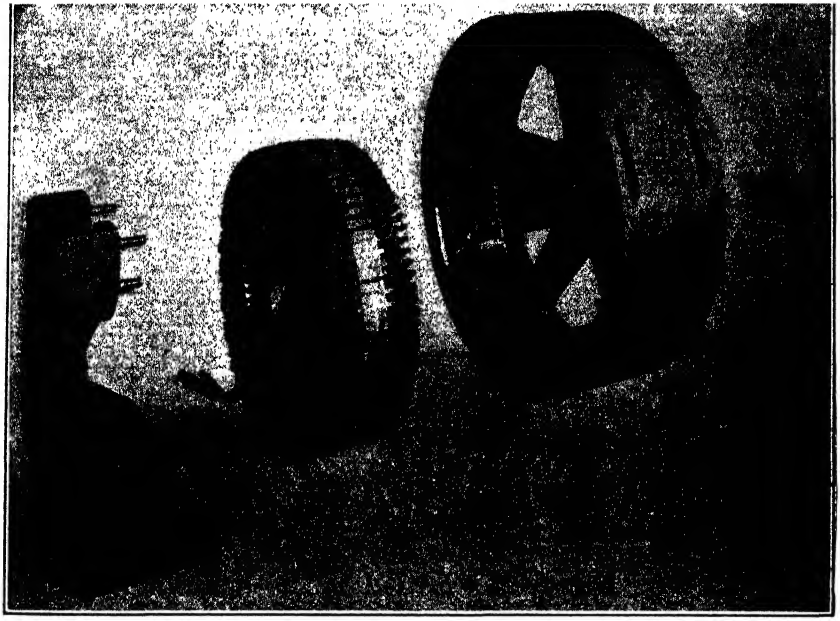


Fig. 3. Showing Bracket Support, Stator, Rotor, and Brush Holder Support in Order of Assembly
Courtesy of Ideal Electric and Manufacturing Co.

Coupled-Type Generators. The coupled-type generator has a bedplate, shaft, and bearings and, usually, a half coupling on the driving end as shown in Fig. 4. Coupled-type generators, with either one or two bearings, are generally used for speeds of 500 r.p.m. or more.

Belted Generators. These generators are made with two bearings and a shaft extension for a pulley in small sizes, and with three bearings with a pulley between two of the bearings for larger sizes as shown in Fig. 5. There are rails under the bedplate and a jacking device which permits movement of the bedplate along the rails so as to tighten the belt. Belted generators are less often used with Diesel engines than the types previously described.

Damper or Amortisseur Windings. Damper or amortisseur windings are generally specified for Diesel-driven generators, because they are necessary when such units are operated in parallel.

Damper windings consist of round bars of solid copper inserted through punched holes in the pole faces. The number of bars through each pole face varies according to the requirements, and the ends extend slightly beyond the body of the pole on each side. These projecting ends on each pole are short-circuited by connecting each bar to a flat copper strip. There is no inter-connection of these strips between poles, the damper winding of each pole being independent of any other poles.

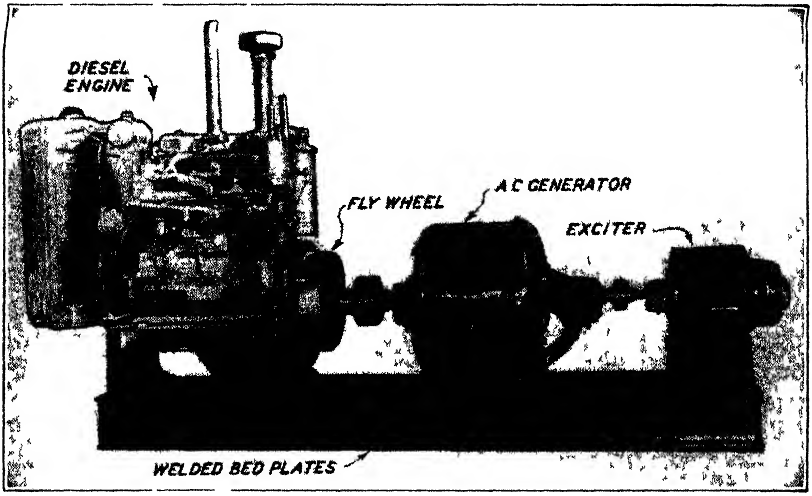


Fig 4. Diesel Driven 25 Kw, 720 R P M Coupled-Type A C. Generator
Courtesy of Crocker-Wheeler Electric Manufacturing Co.

Amortisseur windings are similar to damper windings except that the damper windings of each pole are joined by connecting strips to those of the adjacent poles.

Damper or amortisseur windings are used to prevent "hunting" in a generator, their effect being similar to the squirrel-cage winding of an induction motor in opposing rotation or pulsation of the magnetic field with respect to the winding. "Hunting" may be defined as the tendency of the rotor alternately to over-run and lag behind its normal position on account of load fluctuations or the non-uniform turning effort of the engine which drives the generator.

If a generator equipped with damper windings is paralleled with one or more other generators or with a distribution system, the tendency of the rotor to oscillate due to hunting causes the damper windings to cut across the flux lines set up by the rotor field poles and the rotating magnetic field of the armature which is synchronized with the other generators. The cutting of these flux lines induces a current in the damper windings that sets up a magnetic field of its own which reacts with the magnetic fields of the armature and rotor to create a torque which is always opposed to the oscillations of the rotor, thereby tending to hold the rotor in its normal load position with respect to the armature.

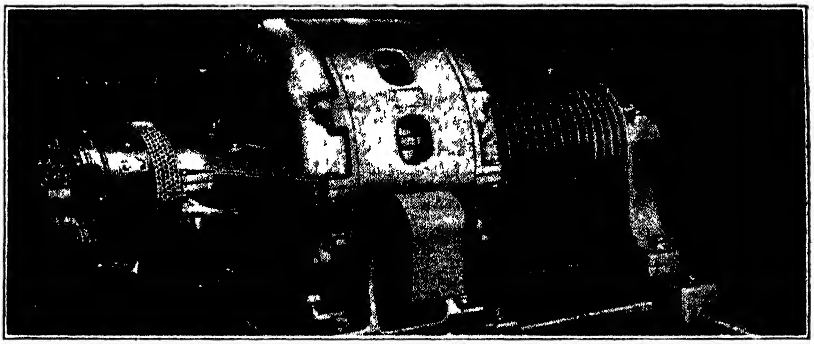


Fig. 5. Three-Bearing Generator with Direct-Connected Exciter
Courtesy of Allis-Chalmers Manufacturing Co.

Damper windings are without effect on generators used singly. This is because the rotating magnetic field of the armature is not synchronized with that of other generators, as in the case of parallel operation, and is free to follow the oscillations of the rotor flux. Consequently, there can be no flux lines for the damper windings to cut, no induced current in the dampers, hence no torque created to counteract the oscillations of the rotor. Nevertheless such generators are generally equipped with damper windings because of the possibility of future operation in parallel.

Standard Voltages. Unless there is good reason to the contrary, low speed engine-type alternating-current generators for Diesel engine drive are ordered for standard voltages of 240, 480, 600, 2,300 or 2,400 volts. For high speed (coupled-type) generators, 120 volts is also a standard rating.

Frequency. The usual frequency in the United States for municipal and industrial power plants is 60 cycles. However, there are a number of 50 cycle plants on the Pacific Coast, and 25 cycles is commonly used for railways.

Speeds. Standard pole grouping and corresponding 60-cycle speeds, to which the Diesel engine speed must be matched, are as follows:

High Speed Alternating-Current Generators

No. of poles	4	6	8	10	12	14
60-cycle speeds ...	1800	1200	900	720	600	514

Engine Type Alternating-Current Generators

No. of poles	16	18	20	22	24	26	28
60-cycle speeds	450	400	360	327	300	277	257
No. of poles	30	32	36	40	44	48	52
60-cycle speeds	240	225	200	180	164	150	138
No. of poles	56	60	66	72	80	90	......
60-cycle speeds	128	120	109	100	90	80	......

Standard KV-A Ratings. The standard National Electrical Manufacturers Association kv-a ratings are as follows:

31	219	750	1875	4375
44	250	875	2190	5000
64	312	1000	2500	5625
93	375	1125	2812	6250
125	438	1250	3125	7500
156	500	1563	3750	8750
187	625			

Exciters and Field Rheostats. The function of the exciter of an alternating-current generator is to generate direct current for energizing the field poles of the main generator. The voltage produced by an alternating-current generator is controlled by varying the strength of its field magnetism, which in turn depends upon the amount of direct current flowing through the windings on the polepieces. When the alternating-current voltage is controlled by hand, two rheostats are generally provided for regulating the excitation current—a small one in the field circuit of the exciter itself, which regulates the voltage of the direct current generated by the exciter, and a larger one in the field circuit of the alternating-current generator which, for any given exciter voltage, will control the excitation current. Since the current in the field circuit of the exciter is much less than that in the field circuit of the alternating-current generator, the rheostat losses are less when most of the regulation is done by varying the direct-current voltage. For this and other reasons, exciter voltage must be adjustable through a wide range, say 90 to 135 volts. Because of these requirements, the output of exciters is generally used only for the one function of field excitation.

The usual plan is for each alternating-current generator to have its individual exciter driven from the main engine. The exciter may be direct-driven, in which case it is mounted at the outer end of the main generator, or it may be driven by a V-belt or chain from the engine crankshaft extension.

In large Diesel plants with many units, excitation current is sometimes furnished by motor-generator sets, i.e., the direct current is produced by a generator driven by an alternating-current motor energized from the main buses. An emergency exciter driven by an engine is also installed in such cases in order to start the plant the first time and after a complete shut-down.

Ventilation. Small machines are usually constructed so that ventilating air is drawn in directly from the room and, after passing through the machine, is discharged back into the room. On larger machines the end bells are enclosed, and ventilating ducts are used to introduce and discharge the air.

Fans. Fans or blowers are attached to the rotors of most generators to assist in forcing ventilating air through the machines. Sometimes a completely assembled blower with inclined blades is used. In such cases it is important that the machine be run in such a direction that the edge of the blade nearest the shaft is in advance of the outer edge in the direction of rotation. Otherwise the amount of air delivered will be greatly reduced.

Bearings. Generator bearings may be either of the sleeve type or ball-bearings, the latter being confined generally to high-speed machines. Sleeve bearings are lubricated by means of oil rings.

Insulated Pedestals. Slight variations in the magnetic circuit of an alternating-current machine may tend to set up a current through the circuit formed by the shaft bearings and bedplate. If such a current is allowed to flow, it soon has a destructive effect upon the journals and bearings.

To avoid this trouble, one of the pedestals is insulated from the bedplate so as to prevent the flow of current. A sheet of insulation about 1/16 inch thick is placed between the bottom of the pedestal and the bedplate, and insulating tubes and washers are used around the bolts and dowels. However, many of the smaller machines have very little tendency to produce bearing currents and these may be operated safely without pedestal insulation.

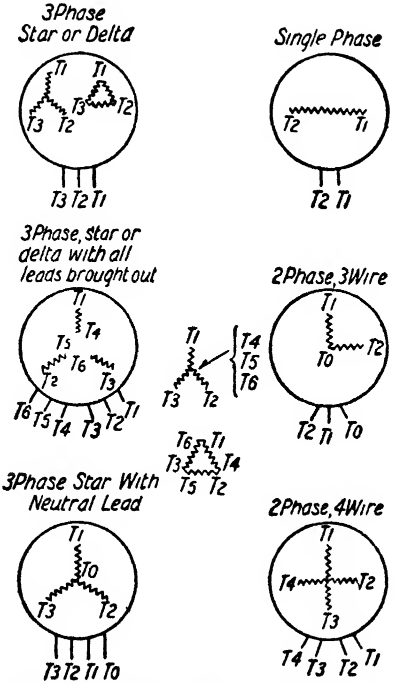


Fig. 6. Standard Arrangement of Leads for Various Windings

Courtesy of Westinghouse Electric and Mfg. Co.

Lead Arrangement and Phase Sequence. The arrangement of leads for various types of windings of Westinghouse generators is shown in Fig. 6. The leads are brought out normally at the bottom of the frame on the collector end of the machine and are equipped with terminals.

The phase sequence, or phase rotation as it is sometimes called, is in the order of T_1 T_2, etc., when the mechanical rotation is in a clockwise direction viewed from the collector end of the machine. When the rotation is counter-clockwise, viewed from the collector end, the phase sequence is in the reverse order.

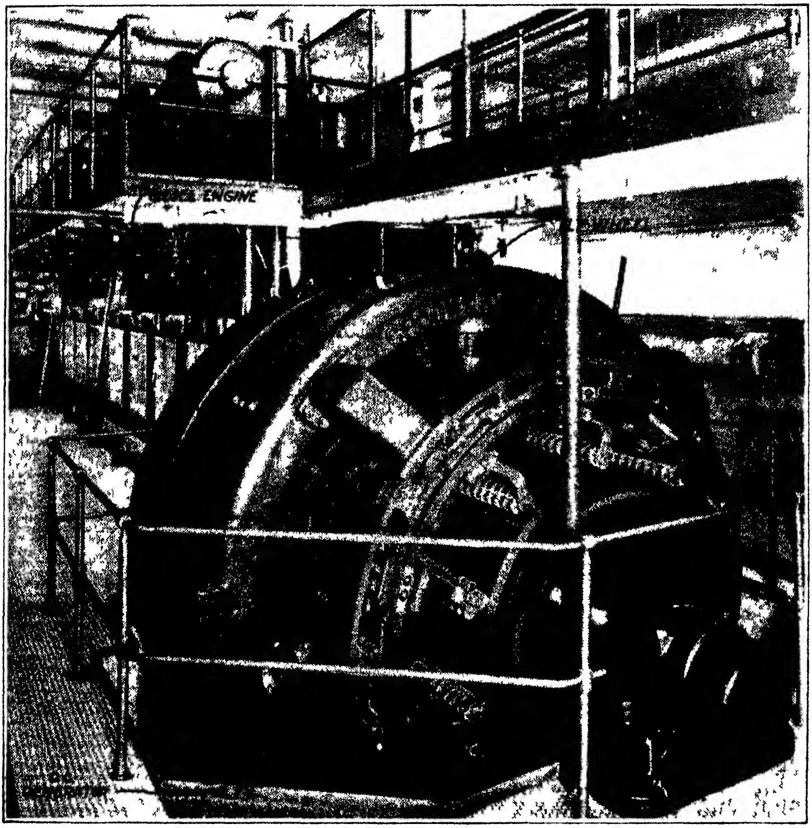


Fig. 7. Diesel-Driven 800 Kw., 225 R.P.M. Engine-Type D C. Generator
Courtesy of Crocker-Wheeler Electric Manufacturing Co.

Direct-Current Generators

Direct-current generators driven by Diesel engines are either the engine-type or the coupled-type, although the latter is sometimes arranged for belt connection.

The engine-type is without shaft or bearings, the rotating armature and commutator being mounted on either the engine crankshaft itself or on an extension of it as shown in Fig. 7. The generator frame or stator, which carries the field poles, is supported either on soleplates resting on the concrete block forming the engine foundation, or on an extension of the engine's bed-plate. Standard speeds for engine-type direct-current generators range from 450 r.p.m. down to 150 r.p.m., and correspond with alternating-current 60-cycle speeds.

The coupled-type generator is furnished with its own shaft and one or two bearings. It is designed for higher speeds than the engine-type, the standard speed range being from 500 r.p.m. up to 3600 r.p.m.

Standard voltages of direct-current machines are 125 volts two-wire; 250 volts, two-wire; and 125/250 volts, three-wire. Standard continuous full-load kilowatt ratings are based on a 40° C. temperature rise on the armature core and windings, and 55° C. on the commutator.

CHAPTER III

VOLTAGE REGULATION OF DIRECT-CURRENT GENERATORS

Action of Field Windings

Uniform generator voltage, regardless of changes in load, is required in most Diesel electric plants. In the case of direct current systems, it is a simple matter to maintain constant voltage, unless the load changes are severe and sudden. Compound-wound generators are used and the field poles are excited by two independent windings: (a) the shunt field circuit, which is connected across the main line, and (b) the series field circuit, through which is passed all of the current generated. See Fig. 8.

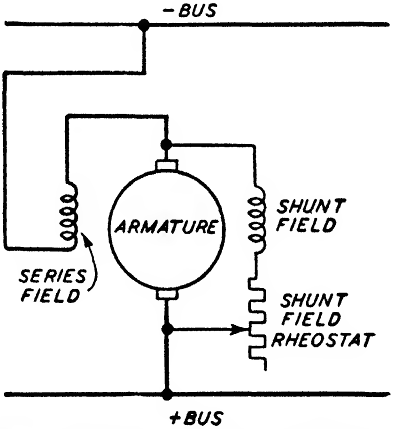


Fig. 8. Schematic Diagram of Compound-Wound Generator

Shunt Generators. The shunt field supplies sufficient magnetization for maintaining rated voltage at the generator terminals at no load, i.e., when no current is passing through the series field. However, this field excitation would be insufficient by itself to maintain rated voltage when the load increases and more current passes through the armature. The voltage would fall on account of the so-called "armature reaction" which weakens the effective field magnetism, and also because of the greater voltage loss (IR drop) in the armature windings. In the case of a shunt-wound generator, the field can be strengthened by cutting out resistance in the field rheostat and thus increasing the shunt field current. However, this requires the operator's attention if done manually, or an additional control device if handled automatically.

Compound Generators. The series field of a compound-wound generator supplies a simple and effective solution that is used in all cases except where the generator must be shunt-wound, as in the charging of storage batteries. When the load increases, the current through the series field windings becomes greater and the field magnetism automatically increases enough to hold up the voltage.

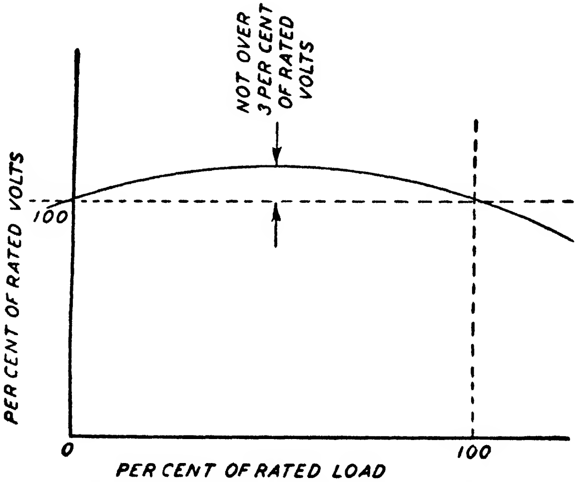


Fig. 9. Compounding Curve for D.C. Generator

Compound-wound generators are usually supplied "flat-compounded," i.e., they will give the same voltage at full load as at no load. In between these limits it is not feasible to make the field strength vary at exactly the correct rate to maintain perfectly uniform voltage, and the compounding curve will rise as shown in Fig. 9. However, in standard practice the compounding curve will not vary more than three per cent from the voltage at no load or full load.

Compound-wound generators may also be "over-compounded" by increasing the strength of the series fields, so that the voltage at full load will exceed that at no load. In this manner, voltage drop in the distribution line may be compensated for, and constant voltage maintained at the load itself instead of at the generator terminals. Over-compounded generators generally have the following characteristics:

Terminal Voltage

No Load	Full Load
120	125
240	250

Under these conditions the compounding curve may vary somewhat more than three per cent from a straight line between no load and full load.

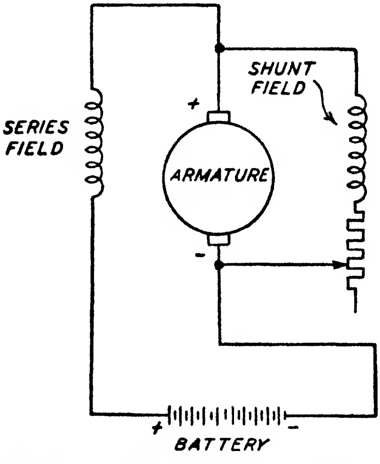


Fig. 10. Diagram of Compound-Wound Generator Connected to Storage Battery

Automatic Voltage Regulators

There are several applications of Diesel electric direct-current plants where compound-wound generators either cannot be used, or if used will not provide satisfactory voltage regulation.

Need for Regulators. Compound-wound generators, unless provided with special safeguards, are undesirable for charging storage batteries. The reason will become clear upon examination of Fig. 10 showing a compound-wound generator connected to a battery. After the battery has received charge for a time, its voltage will approach that of the generator. If now the speed of the Diesel engine driving the generator should decrease, the generator voltage may fall below that of the battery, whereupon current will flow in a reverse direction from the battery to the generator. The current will continue to flow through the shunt field in the same direction, thus maintaining the same polarity of the shunt field, but the series field will acquire a reverse polarity and will "buck" the shunt field. The net field strength is thus reduced and with it the generated voltage. This in turn causes the battery to deliver a heavier current to the generator which in turn strengthens the reverse effect of the series field. The action becomes rapidly cumulative until finally the series field overcomes the shunt field and reverses the generator's polarity. Because of the runaway hazard when compound-wound generators are used to charge storage batteries and because of other reasons such as easy control of the charging rate, shunt-wound generators are generally employed and are provided with some form of automatic regulator.

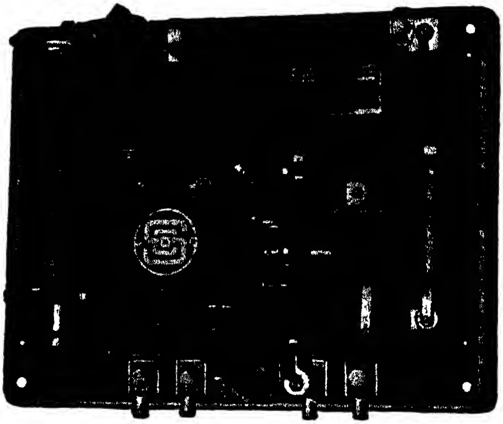


Fig. 11. Carbon-Pile Regulator
Courtesy of The Safety Car Heating and Lighting Co.

Carbon-Pile Regulators. Carbon-pile regulators are frequently used for regulating the generator voltage. In this type of regulator a variable carbon resistor takes the place of the conventional hand-operated field rheostat. The carbon resistor consists of a number of thin carbon disks and is operated electrically by a solenoid which varies the pressure on the carbon pile and thus adjusts its resistance.

The self-regulating carbon pile found its most extensive use in the railroad car-lighting field as a control for generator and lamp voltage, and for battery charge. Being simple and rugged, low in first cost and maintenance cost its use has now spread to other fields.

Regulating Generator Voltage. In Fig. 11 is shown a small carbon-pile regulator as built by The Safety Car Heating and Lighting Co. The carbon pile consists of two sets of disks 1⅞″ diameter and 1/64″ thick, with a capacity of 150 watts, and a resistance with the piles connected in parallel ranging from a minimum of 2 ohms to a maximum of 25. The pressure on the piles of disks depends upon the pull exerted by the solenoid, shown at the extreme left in Fig. 11. The pull of the solenoid varies with the current passing through the coil, which in turn depends upon the voltage of the circuit to which the solenoid is connected.

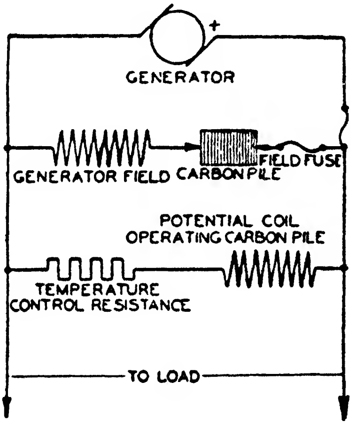


Fig. 12. Schematic Wiring Diagram of a Carbon-Pile Regulator
Courtesy of The Safety Car Heating and Lighting Co.

All parts of the regulator are mechanically balanced, the regulation being accomplished by springs. This gives constant and close regulation in spite of jars or movements incidental to service, and eliminates heavy liquid dashpots. The dashpots used are of the inverted air type with graphite plungers. It is claimed that these dashpots are constant in action winter and summer, regardless of temperature changes, and do not become clogged with the dust of service.

Variation in the regulated voltage due to heating of the voltage coil is limited to five per cent by inserting a zero-heat-coefficient resistance in series with the coil. Closer compensation can be had when necessary. Adjustment is provided so that any desired voltage may be obtained within the limits of the regulator. A schematic wiring diagram showing the application of a carbon-pile regulator for controlling generator voltages is shown in Fig. 12.

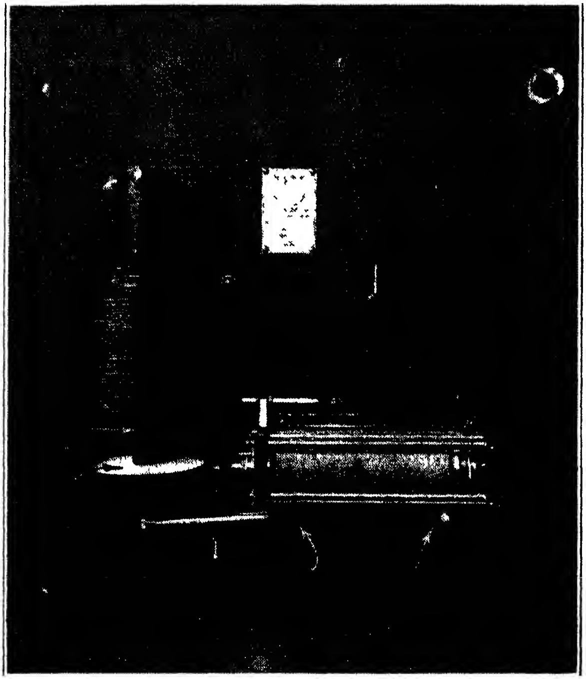


Fig. 13. Westinghouse Carbon-Pile Regulator for D.C. Generator

The generator in this case is controlled to give the proper voltage throughout changing speeds and loads by the amount of current supplied to the shunt field. This field current is controlled by the resistance of the carbon pile in series with the field. The resistance of this carbon pile is governed by the pressure exerted upon it by a lever which is operated by a plunger of the potential coil. If the voltage tends to rise above that for which the regulator is set to maintain, the voltage coil, through its lever, reduces the pressure on the carbon pile and holds the voltage to its proper value.

Fig. 13 shows a form of carbon-pile voltage regulator built by the Westinghouse Company for use on direct-current generators. It consists of two stacks of carbon disks *A* in series with the shunt field of the generator, each stack being approximately six inches long and two inches in diameter. The carbon disks are supported on glass tubing, which is capable of withstanding very high temperatures. Pressure is varied by the movement of the arm *B*, which is pivoted at *C*, with ground tool-steel pivots and bearings. Pressure is exerted on the disks by the spring *D*. Pressure is relieved by the upward travel of the magnetic core *E* and disk *F*. The coil *G* is connected across the source of supply, or at the point where it is desired to maintain constant voltage, through a suitable resistor. The carbon piles may be connected either in series, parallel, or singly. They may be located either in the exciter or generator field circuit.

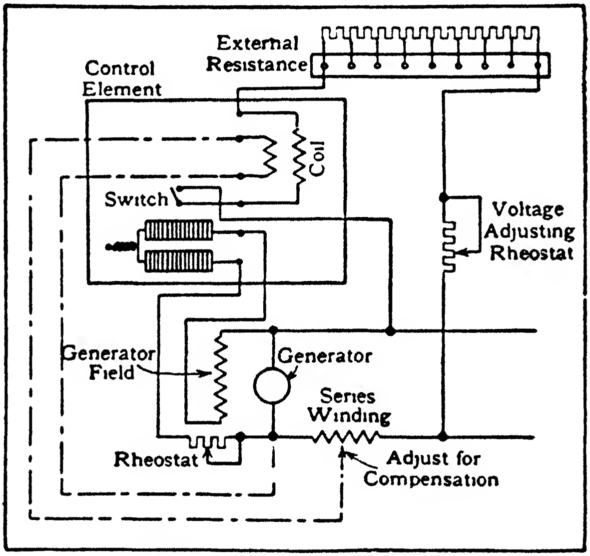


Fig. 14. Wiring Diagram of Westinghouse Carbon-Pile Regulator

The dashpot *H*, Fig. 13, which is of the air type, consists of a metal dashpot and graphite piston, connected to the core stem by means of a coiled spring. The spring connection provides anti-hunting and serves as a flexible coupling between piston and core stem, preventing any friction in the dashpot due to binding. An internal finish is applied to the dashpot to prevent corrosion, and the inverted position prevents dust from collecting inside to cause friction.

Limit spots are provided to prevent overtravel of the arm in both directions. This minimizes arcing between the disks, and prevents excessive voltage in case the coil circuit should be opened.

Carbon-pile regulators can also be used with compound-wound generators by using an extra, current-responsive, winding on the voltage coil. A typical wiring diagram is shown in Fig. 14. It will be noted that the extra winding is shunted across part of the series field winding.

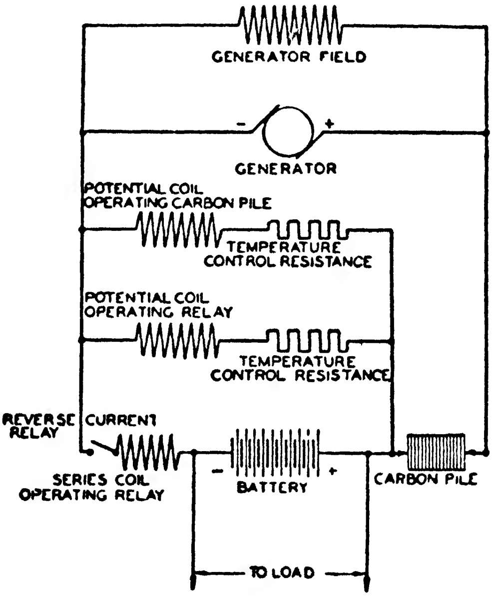


Fig. 15. Wiring Diagram of Carbon-Pile Regulator Controlling Battery Charge
Courtesy of The Safety Car Heating and Lighting Co.

Regulating Circuit Voltage. In certain Diesel electric systems used on locomotives and rail-cars the generator voltage varies through a wide range, this method being used to control the speed and torque of the traction motors. Storage batteries are generally used to furnish current when the Diesel engine is stopped. In order to supply uniform voltage for charging the batteries a simple form of automatic voltage regulator is used.

The application of a carbon-pile regulator to control a battery charge from a variable source of voltage is shown in Fig. 15. In this case, the carbon pile is connected in series with the battery, and is also equipped with a reverse current relay for disconnecting the battery from the generator when its voltage is below that of the battery. The charge in this case is controlled by the voltage only, although if desired, some current control can be used.

The potential coil is connected across the battery when the reverse current relay is closed, and if the generator voltage is higher than that which it is desired to maintain across the battery terminals the plunger of the solenoid will move, and thereby increase the resistance of the carbon pile until the desired potential is obtained.

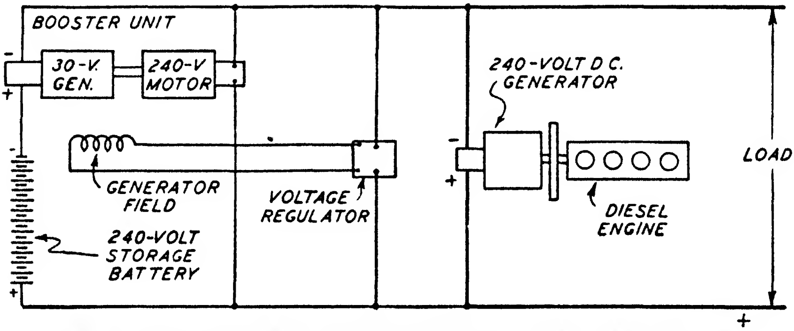


Fig. 16. Simplified Diagram of Controlled Booster System of Regulating D.C. Voltage

With a decrease in voltage at the battery, the opposite action takes place.

Effect of Sudden Load Changes. When a heavy increase in load is suddenly imposed upon an ordinary compound-wound generator, the magnetic lag (hysteresis) of the field poles prevents the series field building up its strength fast enough to offset the increased voltage drop at the generator terminals. Consequently, a momentary dip in voltage takes place until the stronger series field becomes effective. Such voltage dips are objectionable in private plants furnishing power and light to office buildings, apartment houses, etc., where a high quality of lighting service must be furnished despite sudden load changes due to the operation of elevators. Ordinarily the engine speed does not change suddenly, being prevented from doing so by the inertia of the flywheel and other rotating parts. The problem of voltage dip with sudden load changes is therefore an electrical one.

Eliminating Voltage Dip. One method of reducing or eliminating voltage dips of this kind is to use a storage battery floating on the line in parallel with the generator and the load. When the load is suddenly increased and the generator voltage falls, the battery takes over part of the additional load. Since the load on the generator does not greatly increase, its terminal voltage does not suffer the drop it otherwise would.

A further refinement of the storage battery plan is to use a controlled "booster" between the battery and the bus. This method, which is highly effective, is shown in simplified form in Fig. 16. In the system employed by C. F. Strong for automatic Diesel plants, the booster consists of a 30-volt generator driven by a 240-volt motor supplied directly from the main bus and in continuous operation. The field circuit of the generator is controlled by a voltage regulator in such manner that both the strength and the polarity of the booster field is determined by the main line voltage. Whenever a sudden load is imposed upon the generating unit and the voltage tends to drop, the voltage regulator increases the strength of the booster generator field in a positive direction, thus adding the

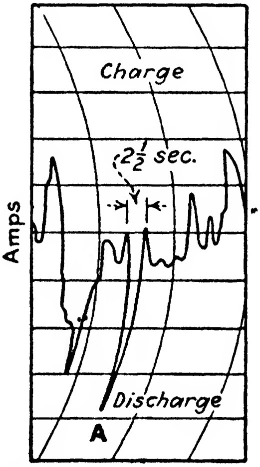


Fig. 17. Chart Showing Current Flow between Storage Battery and Main Bus

booster voltage to that of the storage battery. Since the combined voltage then greatly exceeds the bus bar potential, the battery immediately delivers to the bus practically all of the additional current required to maintain full voltage on the line. In other words, the boosting of the battery voltage causes the energy increment to be drawn from the battery instead of the engine-driven generator, and prevents the voltage dip that would otherwise occur.

On the other hand, whenever surplus generating energy is available, as when the load falls off suddenly, the polarity of the battery booster is reversed by the voltage regulator, causing the surplus energy to be absorbed by the battery instead of momentarily raising the line voltage. The voltage regulator is so adjusted that the battery remains fully charged while a continuous succession of short-time charges and discharges goes on.

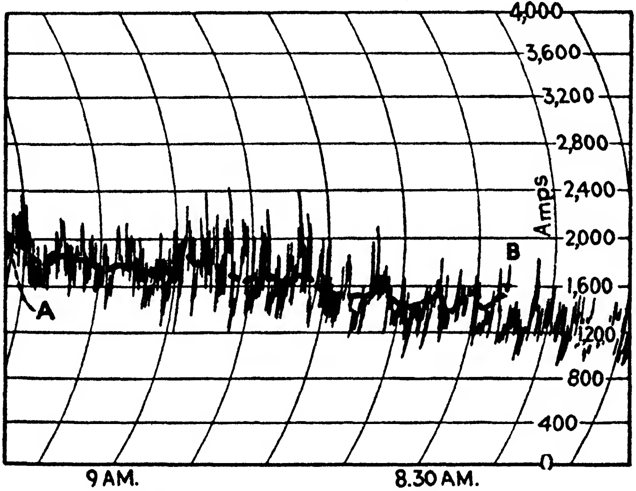
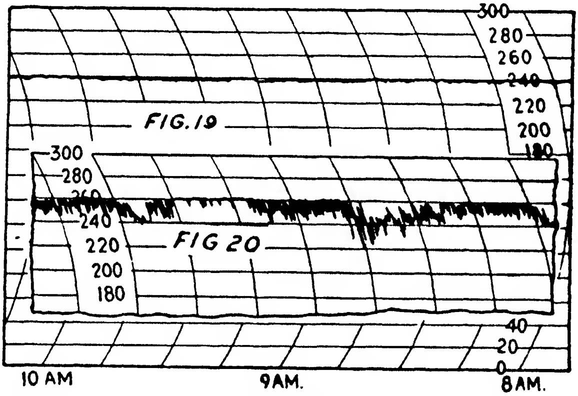


Fig. 18. Chart Showing Load Variations

The actual performance of this system of voltage control is shown in the accompanying graphs from a 720-kilowatt, 240-volt Diesel electric plant equipped with a 1,380 ampere-hour 240-volt battery and a 30-kilowatt, 30-volt booster. Fig. 17 is a high-speed chart of the current flow between the battery and the main bus. This shows a swing of 196 kilowatts at the point marked *A*, which is absorbed by the battery system in order to stabilize the voltage. The total period of this swing, from 0 to 196 kilowatts and back to 0 again, only occupied 2½ seconds. The balance of the curve, which is also given at a slower speed in Fig. 18, shows the alternating swings of charge and discharge on the battery.

On the chart shown in Fig. 18, line *A B* shows the averge load carried by the engines. The energy above this line is supplied by the battery and that below is absorbed. A graph of the line voltage, Fig. 19, clearly indicates the very close regulation secured and Fig. 20 shows a corresponding graph of the battery voltage caused by the booster in order to secure these results.

Vibrating-Type Regulators. Vibrating-type voltage regulators are sometimes used for direct-current generators supplying lighting and power loads where the power load is subject to sudden changes and would otherwise cause considerable flicker in the lights. They operate on the principle that when a regulating resistor is short-circuited a large voltage is available to bring the exciting current quickly to the desired value. The action consists of rapidly cutting in and out a resistance in the generator shunt-field circuit, which greatly improves the steadiness of the voltage by making the generator respond more quickly than if it depended upon the functioning of the series field of an unregulated generator or the action of most of the simpler forms of direct-current voltage regulators. However, where the load fluctuations are large, such as those caused by the starting of large elevator motors, even vibrating-type regulators will not entirely eliminate the flickering of the lights.



Figs. 19 and 20. Curves Showing Line and Battery Voltage

In the case of very small machines, the field resistance may be shunted directly by the main contacts of the control element. However, where the field current is large or where more than one generator is to be controlled by the same regulator, the field rheostats are shunted by the contacts of secondary relays that are controlled by the main control element.

Operation without Relays. A simple form of vibrating-type regulator, known as Westinghouse Type UV is shown in Fig. 21. It consists of stationary main and anti-hunting coils, a moving coil which is directly connected to the center shunting contact, and two stationary contacts. The three contacts are of graphite, and sticking and welding action are thus eliminated.

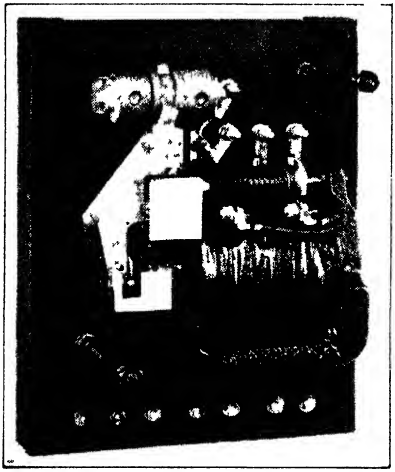


Fig. 21. Westinghouse Type UV Vibrating Regulator

The magnetic circuit consists of a soft iron casting, the core of the stationary coils extending into the moving coil, which is wound on a non-magnetic spool. A spring closes the right and center contacts, and the pull of the moving coil separates them. The right and center contacts shunt the field rheostat and on applications requiring wider ranges, the center and left contacts shunt the field through a resistor. A schematic diagram of the connections is given in Fig. 22. R_1 is the field rheostat, a part of which is shunted when contact C_1 is closed by the action of the spring when the line voltage falls and the attraction of the stationary and moving coils is thus weakened. R_2 (not always used), is a resistor which, when contact C_2 is closed by rising line voltage, shunts the generator field itself and thus broadens the range of the regulator. R_3 is a resistor in series with the stationary and moving coils, which reduces the effect of temperature and also can be used to adjust the voltage. The contacts are caused to vibrate continuously by the fact that when contact C_1 is opened by reason of an increase in current through the control coils, the coil current immediately falls because of the increased resistance of the circuit through R_4 and R_1, whereupon contact C_1 is again closed by the spring. The action, in principle, is similar to the interrupter used in an ordinary bell or buzzer. Condensers are generally used across the contacts to reduce sparking.

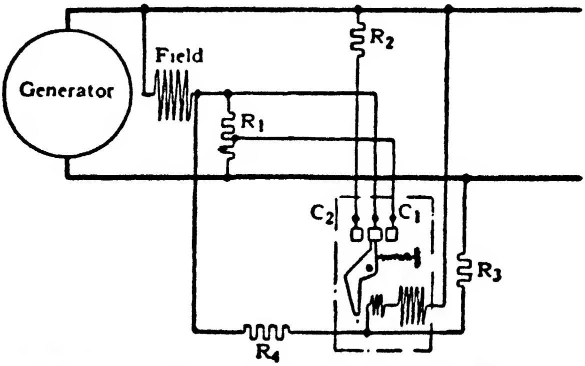


Fig. 22. Diagram of Connections of Westinghouse Type UV Regulator

While this type of vibrating-contact regulator is simple, sturdy, and comparatively inexpensive, the graphite contacts give a voltage value which slowly wanders about to a small extent. On some classes of work this is not objectionable. Because of its single contactor, this regulator cannot be used to control more than one generator at a time.

Operation with Relays. For large-size machines, for closer voltage control or for controlling paralleled generators from a single regulator, a more elaborate form of vibrating-contact regulator is used. This incorporates precious-metal main contacts on the control element and secondary shunting relays for the generator field rheostats. Generally up to three shunting relays can be controlled by the contacts of the main control element; if a greater number of relays must be controlled, a master relay is used, the contacts of which control the shunting relays.

Fig. 23 illustrates the Westinghouse form of direct-current voltage regulator with relays. The schematic wiring diagram, Fig. 24, shows the control element winding energized from the main bus. The shunting relays have two coils and each coil has two windings, the polarity of one winding bucking that of the other. The one winding is constantly energized from the main bus and tends to hold the relay contacts open. The other winding is only energized when the main or master relay contacts are closed. When it is energized, the pull of the other winding is neutralized, allowing the spring to close the contacts.

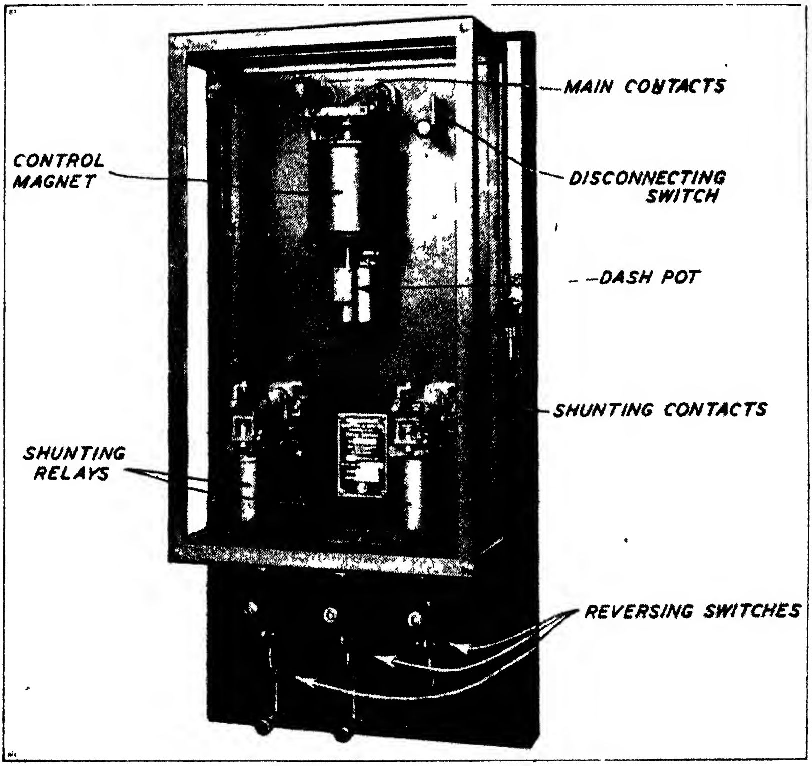


Fig. 23. Westinghouse Relay Type Voltage Regulator

Disregarding for the moment the effect of the antihunting or vibrating connection *a-b*, when the voltage on the main bus rises, the current in the main control coil is increased, causing the main contacts to open. This in turn opens one circuit of the shunting relay coils, which allows the other circuit to open the shunting relay contacts, thus inserting resistance in the field circuit of the machine. This causes the bus voltage to fall which in turn decreases the current in the main control coil, allowing the main contacts to close. When the main contacts close, the second circuit of the shunting relays is made, neutralizing the first and allowing the relay contacts to close. This short circuits the field rheostat which raises the bus voltage and the cycle is repeated. The purpose of the vibrating connection is to speed up the action by causing the main contacts to operate even before the regulator has had time to go through the whole cycle of voltage regulation just described. This is ac-

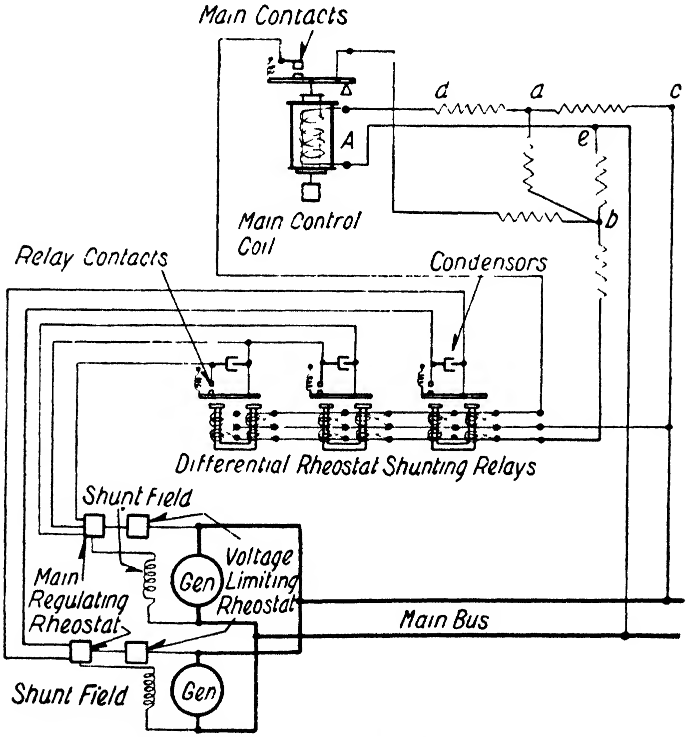
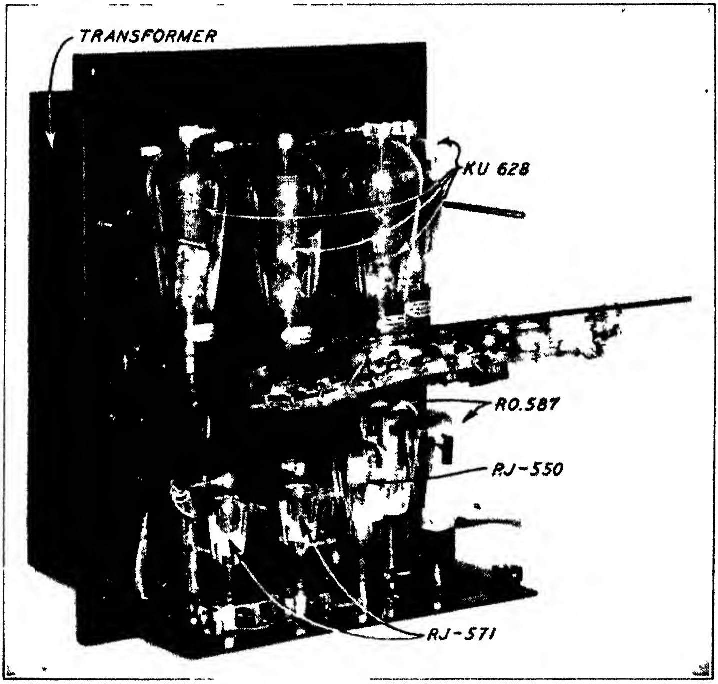
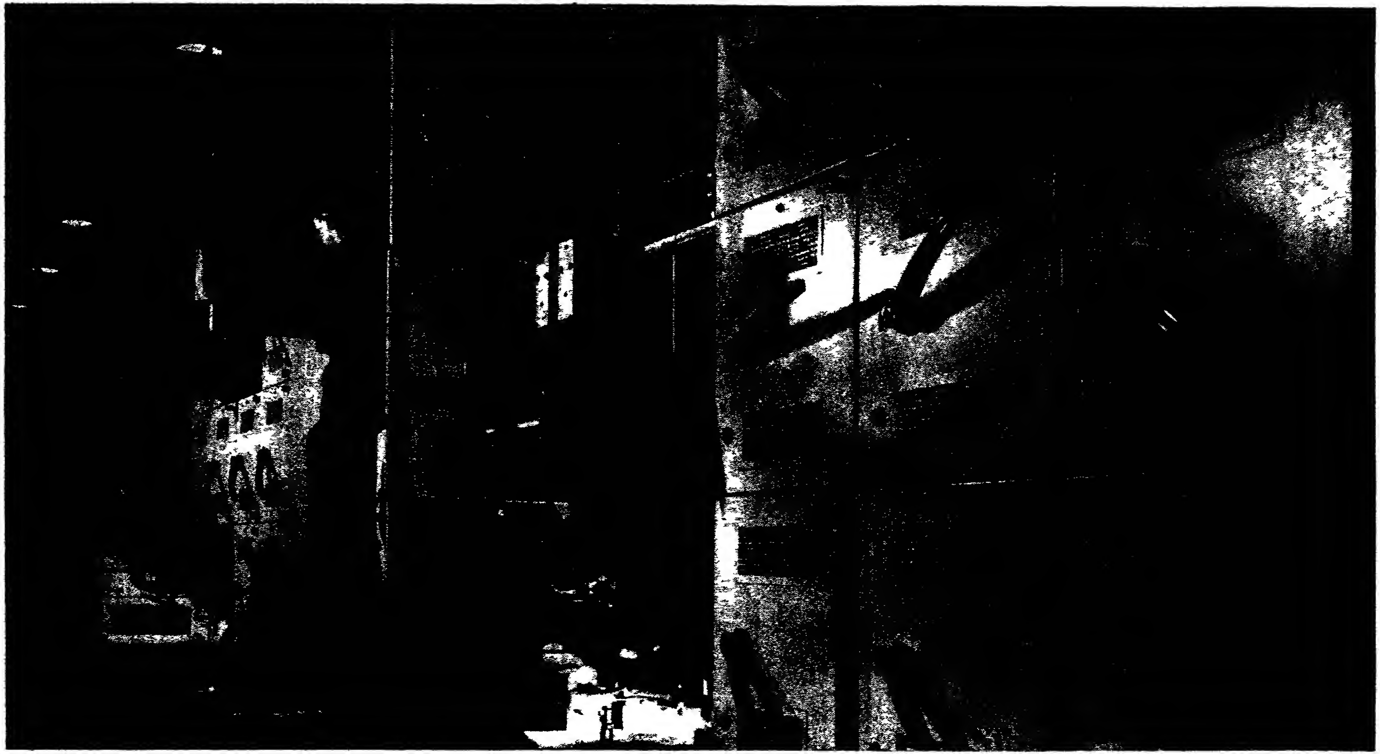


Fig. 24. Wiring Diagram of Westinghouse Relay Type Regulator

complished by the resistor between points *a* and *b*. The resistances between points *c-a-d-b* are so proportioned that when the main contacts close and the second circuit of the shunting relays is made, the current in the main control coil is increased, which tends to open the main contacts at once without waiting for a rise in bus voltage. This is due to the fact that when both relay circuits are made, the difference between the potential of point *a* and *b* is decreased thus decreasing the current in circuit *a-b* and increasing the current in the main control coil.



AN ELECTRONIC VOLTAGE REGULATOR
A group of industrial electronic tubes are used in the Westinghouse Type AT voltage regulator for alternating-current generators.



ASSEMBLING A MODERN SWITCHBOARD PANEL USED TO CONTROL ELECTRIC POWER IN ARSENALS, AIR BASES, PLANTS AND SHIPS

Courtesy of Westinghouse Electric and Mfg Co, East Pittsburgh, Pa

CHAPTER IV

VOLTAGE REGULATION OF ALTERNATING-CURRENT GENERATORS

The compounding principle, which in the case of direct-current generators is a simple and effective means of maintaining constant voltage at different loads, cannot be used for alternating-current machines. This is because the field coils must be magnetized with direct current, whereas only alternating current would be available for a series winding.

The inherent voltage regulation of alternating-current generators is quite poor. A standard 50° C. rise generator, 80 per cent power factor, when supplied with constant exciting current, will suffer a voltage drop of 40 per cent at its terminals when the load increases from no load to full load. Voltage variations of this magnitude are of course out of the question in most applications. Although the voltage could be controlled by manually operating the generator and exciter field rheostats and thus altering the amount of excitation current, such operation would not be feasible except in the rare cases of loads that are perfectly steady or that change seldom and at predetermined times.

Automatic voltage regulators are therefore required on most alternating-current installations. This problem has engaged the attention of inventors and designers for the last forty years and a wide variety of devices has been developed. While there are now in use many different forms of alternating-current voltage regulators, almost all of them control the current in either the alternator field or the exciter field by one of two methods or a combination of both. The *rheostatic type* controls the field current by varying in small steps the amount of resistance in the field circuit. The *vibrating-contact type,* known in some forms as the Tirrill type, continuously closes and opens a short-circuit around a regulating resistor in the excitation circuit, the effective excitation depending upon the proportion of the time the resistor is short-circuited. Combination rheostatic-vibrating types use a motor to move the field rheostat to a new position and also a vibrating contact to short-circuit the field rheostat during the interval while the field rheostat is assuming its new position.

Rheostatic-Type Voltage Regulators

Rheostatic-type voltage regulators vary widely in design, from simple types that are intended for less-exacting service to more complicated constructions suitable for quicker action and more accurate control. Some rheostatic-type regulators are described herewith.

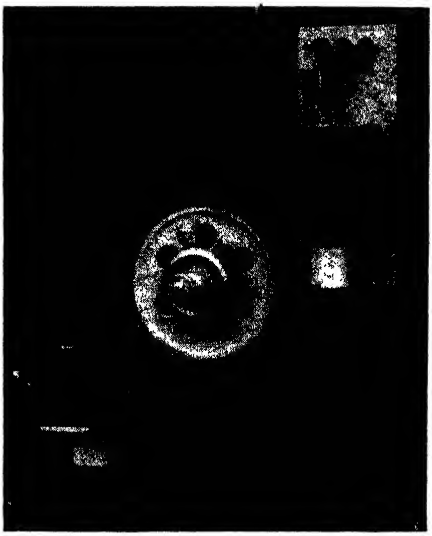


Fig. 25. Automatic Voltage Adjuster
Courtesy of R. E. S. Swam and Co.

Motor-Driven Rheostat Regulator. The Swam Automatic Voltage Adjuster, shown in Fig. 25, is designed for isolated electric plants and is simple, sturdy, and easily adjusted. The principle of operation is a field rheostat operated by a series motor which in turn is controlled by a special type of voltage relay in which contacts are made and broken with mercury switches.

The diagram of connections is shown in Fig. 26. The operation is simple, in that the armature floating in the field of the alternating-current potential coil always remains in the same position with the same voltage. Should the voltage rise, due to a reduction in load, the armature rises and trips a mercury switch which, in turn, connects the operating motor to its source of current, causing the motor to run clockwise, thus cutting in resistance on the exciter field. As soon as sufficient resistance is cut in, the voltage will return to normal and the mercury switch contact is broken. The motor then stops and awaits another change in voltage.

In order to obtain stable regulation, provision is made to adjust the speed of the operating motor so that the regulating resistance will be changed at the same rate as the speed of response of the exciter and generator. Thus the field rheostat is moved as quickly as possible, consistent with the avoidance of hunting or "over-regulation."

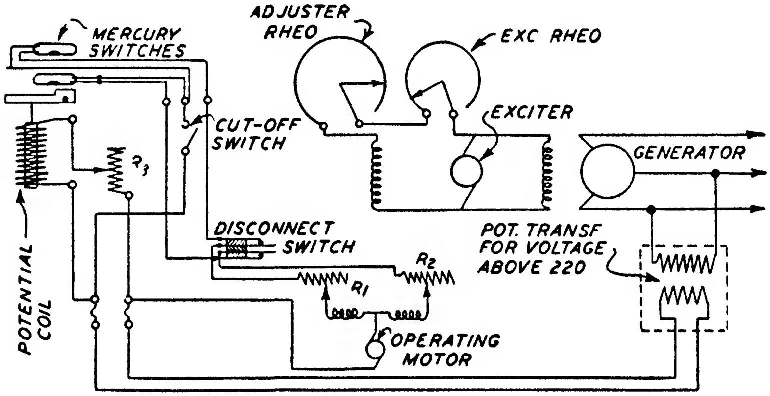


Fig. 26. Wiring Diagram of Swam Automatic Voltage Adjuster

The speed of the operating motor is adjusted by means of resistances R-1 and R-2 (Fig. 26), separate resistances being used so that the "Up" speed can be adjusted independently of the "Down" speed. The operating motor speed can be adjusted so that the rheostat is moved through its full range in from 45 seconds to two minutes.

A hand wheel on the front is connected with the gear wheel by means of a clutch, so that for quick starting hand control is provided. As soon as the plant is started up and the voltage brought up to about the right value by operating the hand wheel manually, the wheel is released and the operating motor immediately takes command; if the voltage has not been set exactly correct, the motor will correct it at once and keep it corrected until the plant is shut down.

The setting for the desired line voltage is made by means of a second resistor R-3 on the top of the panel connected to the potential coil.

The differential between the voltage above normal and that below normal is made by an adjustment of the angle of the mercury switches with respect to each other.

This adjuster may be used to control two alternating-current generators operating in parallel. In this case a single voltage relay is used to control two motor-driven field rheostats for the respective exciters, and the speed of each motor is independently adjustable. Circulating currents between the two alternating-current machines must be adjusted to a minimum value by hand control.

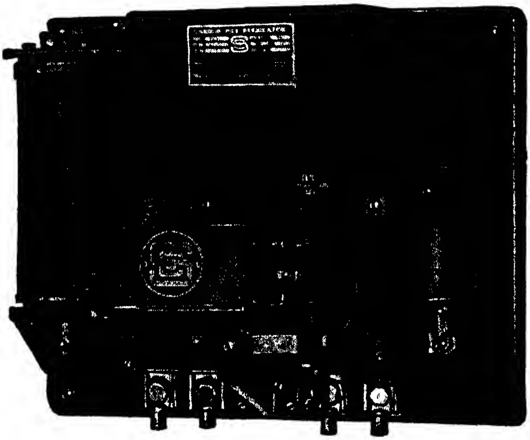


Fig. 27. Carbon-Pile Regulator for Small A.C. Generators
Courtesy of The Safety Car Heating and Lighting Co.

Carbon-Pile Regulators. Carbon-pile regulators for alternating-current generators, as in the case of those for direct-current generators previously described, depend on the principle that the resistance of a stack of carbon disks varies according to the pressure applied to the stack. The pressure is automatically varied by means of a potential coil acting through levers. This variable carbon resistor is used to alter the exciting current of the alternator and thus maintain the alternator voltage constant.

"Three Per Cent" Carbon-Pile Regulators. In Fig. 27 is shown a carbon-pile regulator of The Safety Car Heating and Lighting Co. design, which is suitable for alternating-current generators up to about 50 kilovolt amperes. The pull of the solenoid shown on the

extreme left varies with the current passing through the coil, which in turn depends upon the generator voltage. Variations in the pull of the solenoid produce similar variations in the pressure on the carbon pile by means of a leverage system. It will be seen, therefore, that a variation of line voltage causes a change of resistance in the carbon pile and this change is such as to cause a correction of the generator voltage by varying the field.

As the moving parts of the regulator are mechanically balanced, these parts are free to move easily but are not affected by vibration.

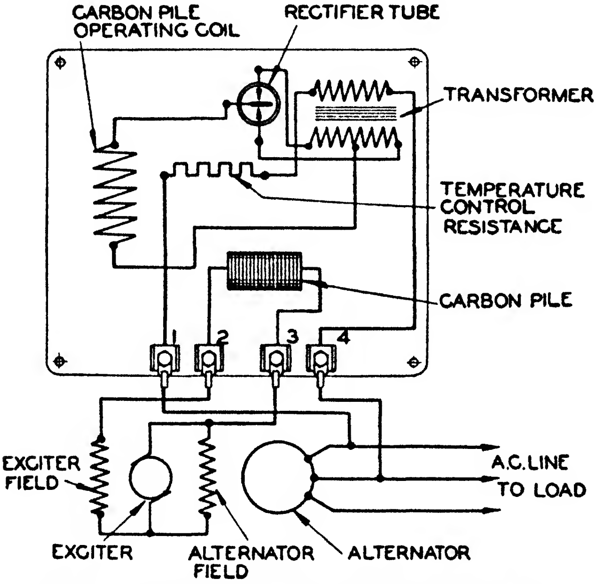


Fig. 28. Wiring Diagram of Regulator Shown in Fig. 27

A change of voltage is followed by a very prompt response of the regulator. Overshooting of the moving arm is minimized by an adjustable air dashpot shown at the right in Fig. 27.

An adjustment is provided so that any desired generator voltage may be obtained within the limits of the generator.

The regulator may be connected in the exciter field as shown in Fig. 28, or in some cases in the generator field as on smaller size generators. On alternating-current generators an electronic tube rectifier is interposed between the solenoid and the generator terminals to change the alternating current to direct current, which provides a smooth, even pull on the solenoid plunger. When the generator voltage is higher than 120 volts, a small step-down transformer is interposed between the generator terminals and the regulator, so that there are never any dangerously high voltages on the regulator. This regulator maintains the voltage within three per cent or better.

As the regulator coil or solenoid heats up, the voltage gradually increases because of the change in resistance of the winding. This effect is reduced by using a temperature control resistance, Fig. 28, whereby the voltage increase is kept down to 5 per cent or less.

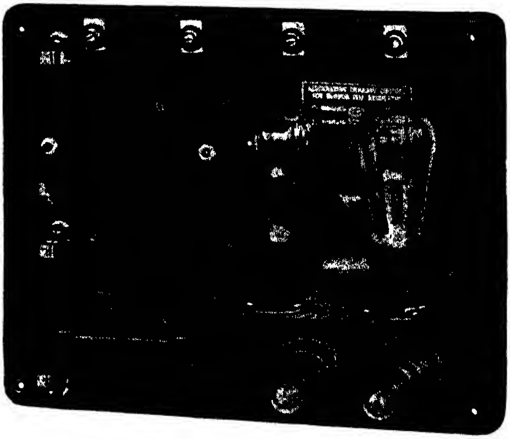


Fig. 29. Control Panel for Obtaining Close Regulation
Courtesy of The Safety Car Heating and Lighting Co.

"One Per Cent" Carbon-Pile Regulators. For closer regulation the "three per cent" regulator just described is provided with an additional control panel shown in Fig. 29 instead of the simple rectifier tube. This control rectifies the current supplied to the coil and so amplifies the changes in coil current produced by departures from normal voltage, that regulation is provided within plus or minus one per cent of normal. The wiring diagram is given in Fig. 30. The regulator control panel incorporates a balanced bridge net-work of resistances and two grid-controlled rectifier tubes. A slight variation of voltage across the net-work changes the voltages on the grids of the rectifier tubes, causing a comparatively large change of current in the outputs of these electronic tubes which, in turn, feed the solenoid of the carbon pile panel.

Automatic Voltage Adjuster. A simple form of rheostatic voltage regulator, intended for use where accuracy requirements are not exacting, has recently been developed by the General Electric Co. It is designated as Automatic Voltage Adjuster Type G-4 and is illustrated in Fig. 31. The voltage adjuster consists of a voltage-sensitive element of the movable-core solenoid type, which directly operates, through levers, a wide-range, quick-acting rheostat. The rheostat is connected in the exciter shunt field circuit, and any change in voltage is corrected by direct action of the solenoid on the field rheostat. The solenoid is excited through a fixed resistor from the generator armature potential. An air dashpot provides antihunting action.

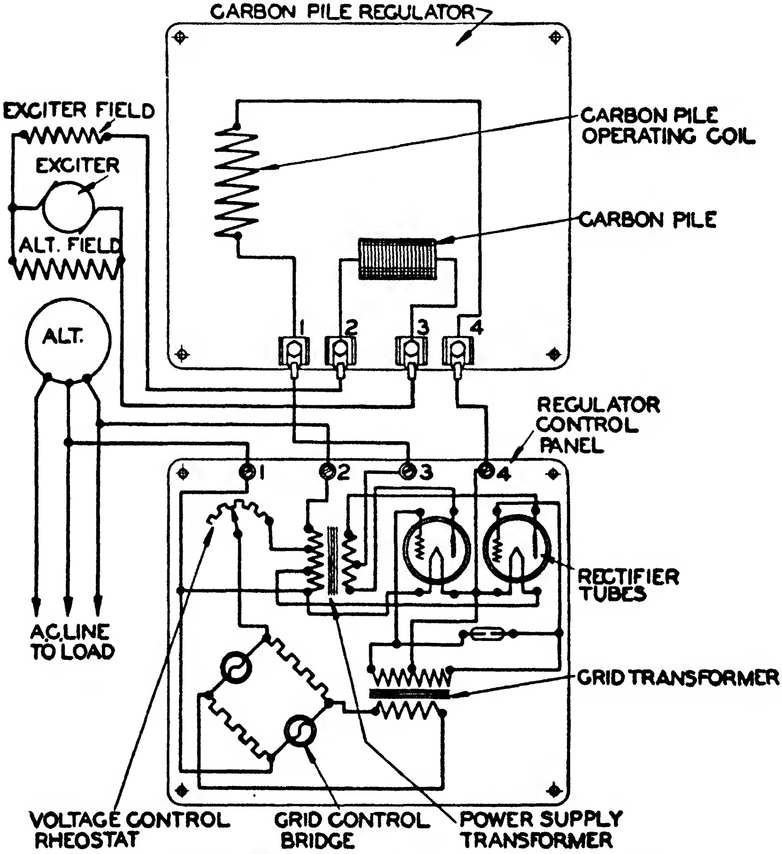


Fig. 30. Wiring Diagram of Control Panel and Carbon-Pile Regulator
Courtesy of The Safety Car Heating and Lighting Co.

The unique feature of the adjuster is the rheostat element, details of which are shown in Fig. 32. The element is mounted near the top of the regulator panel and is insulated from the panel with sheet mica. It consists of two vertical stacks of special resistance materials, the resistance of the stacks varying with position. Each stack consists of a series of thin rectangular resistance plates separated by thin sheet-metal spacers. Each resistance plate has a silver button insert passing through one end of the plate. The resistance plates are of graphite or carbon composition.

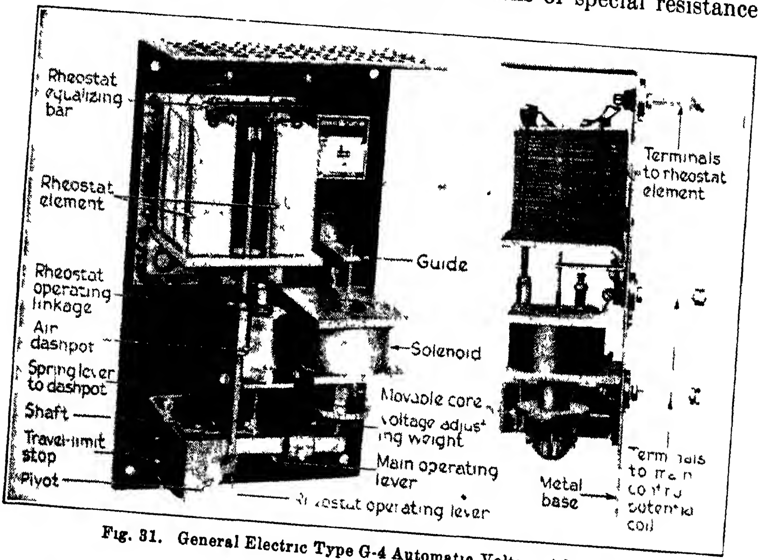


Fig. 31. General Electric Type G-4 Automatic Voltage Adjuster

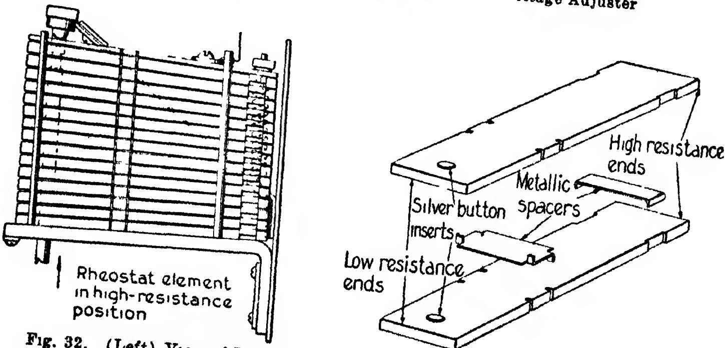


Fig. 32. (Left) View of Rheostat (Right) Carbon Plates with Metallic Spacers
Courtesy of General Electric Company

These parts are so arranged that when a slight pressure is applied to the top of the outer end of the stacks, the stacks tilt slightly forward, separating the resistance plates at the back ends, and causing the front ends with the silver inserts to come together one at a time. This forms a low resistance silver-conductor path through the rheostat element.

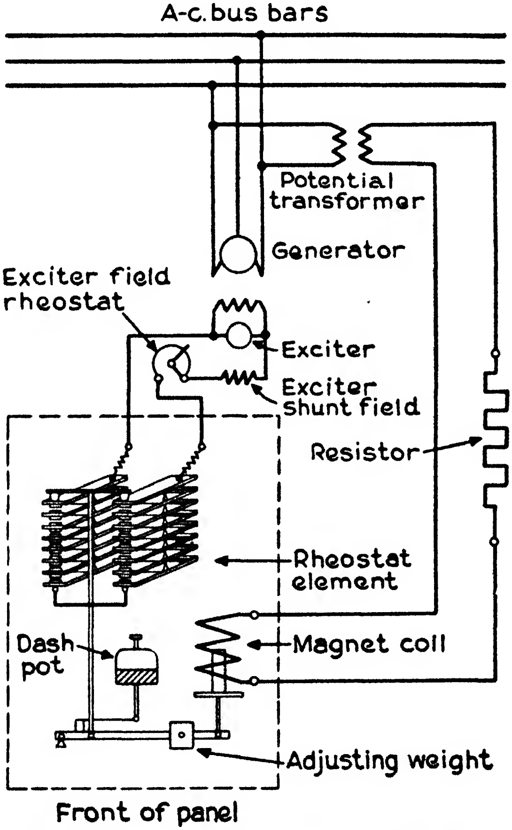


Fig. 33. Wiring Diagram of General Electric G-4 Voltage Adjuster

If the pressure is released from the front end of the stacks, the rheostat element tilts back and the circuit through the silver inserts is gradually broken, so that the field current must flow through the graphite or carbon plates and interleaved metal spacers. This causes the full resistance of the elements gradually to be brought into the circuit.

The basic difference between this rheostat and the carbon-pile compression type of rheostat is that the change in resistance is effected entirely by a tilting motion of the stacks, rocking from a metal-to-carbon contact to a silver-to-silver contact, instead of by a change in pressure on the stacks. This tilting action requires only very slight motion and pressure from the operating device, which permits the use of a direct-acting mechanism and high accuracy in the regulator. The silver inserts provide a means for short-circuiting the entire rheostat in the low-resistance position, allowing operation of exciters up to their maximum voltage. There are no noticeable steps in the resistance change, a smooth transition being obtained from maximum to minimum resistance. This permits accurate adjustment of field currents to proper value by the regulator.

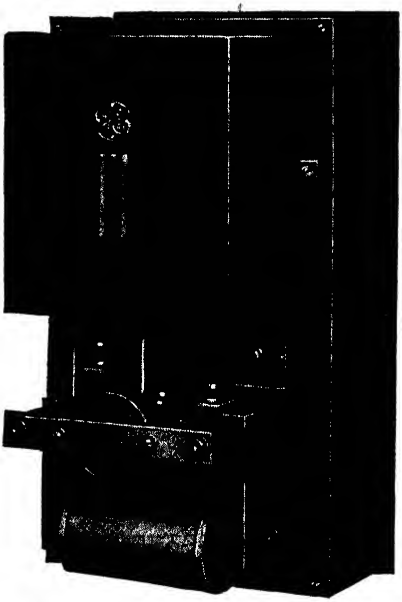


Fig. 34. General Electric Type GDA Voltage Regulator with Cover

Operation. This type of voltage adjuster operates on principles similar to the simple forms of voltage regulators previously described. The regulator is normally at rest and operates only when a change in excitation is required. Its wiring diagram is shown in Fig. 33.

Adjustment of generator voltage is provided for by the voltage adjusting weight shown in Fig. 31. Moving the weight toward the solenoid causes the adjuster to hold a higher generator voltage and vice versa.

This voltage adjuster may also be used to control the voltage of direct-current generators by varying the resistance of the shunt-field circuit.

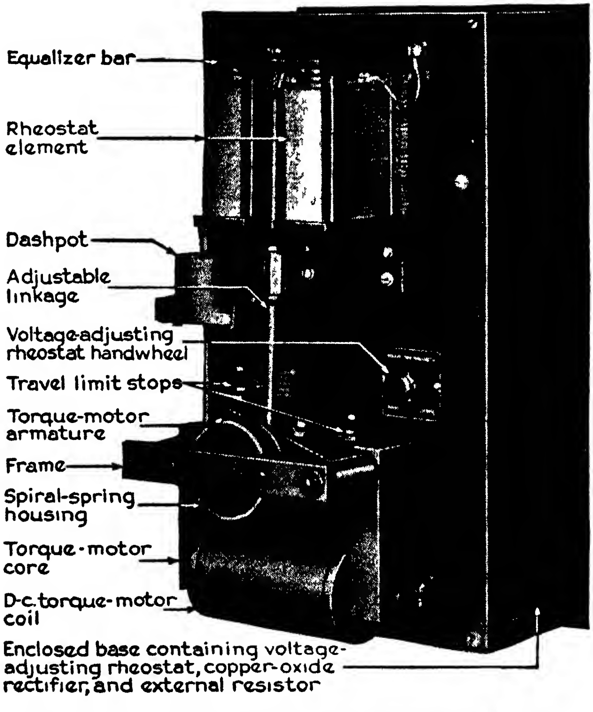


Fig. 35. General Electric Type GDA Voltage Regulator with Cover Removed

Direct-Acting Voltage Regulator. A more refined type of regulator than the "voltage adjuster" just described, but employing the same form of rheostat element, has recently been brought out by the General Electric Co. under the name of "Direct-Acting Generator-Voltage Regulator Type GDA." It is illustrated in Fig. 34 and the uncovered mechanism is shown in Fig. 35.

This regulator operates by automatically varying the resistance in the shunt-field circuit of the exciter. It is simple in construction, operation, and adjustment. It has no vibrating contacts, and operates only when a change in excitation is required.

Construction and Design. The regulator consists of a voltage-sensitive element of the torque-motor type, which is balanced against a spiral spring. It directly operates a rheostat element consisting of a vertical stack of tilting carbon or graphite plates, shown in Fig. 32. The rheostat element is connected in the exciter shunt-field circuit, and any change in voltage on the alternating-current machine is corrected by the direct action of the torque motor on the rheostat element. The torque motor is a direct-current device and is excited through a small copper-oxide rectifier from the alternating-current potential. The characteristics of the torque motor and spring are such that voltage is held constant for all conditions of load, temperature, and frequency. Anti-hunting action is provided by a spring-connected air dashpot.

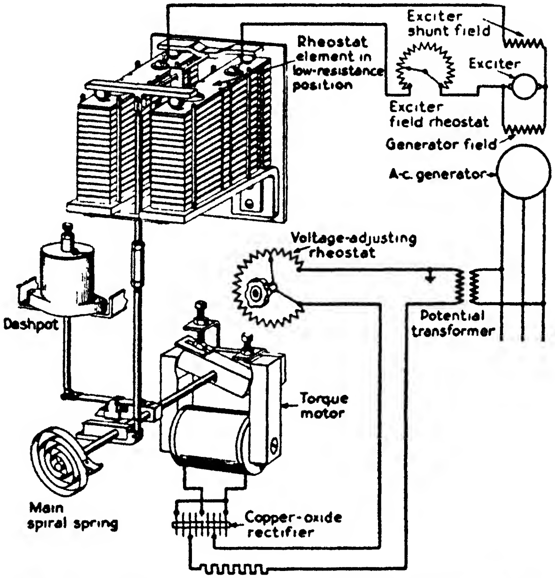


Fig. 36. Schematic Diagram of a Direct-Acting Voltage Regulator

Courtesy of General Electric Company

The fact that very little pressure is required on the rheostat element permits the use of a very sensitive voltage-control device. If high pressure were required, a large torque motor with inherently high inertia and consequently slow operation would be necessary.

Operation. The connections and method of operation are shown diagrammatically in Fig. 36. The regulator operates on the principle that any change in alternating-current voltage causes the armature of the voltage-sensitive torque motor, which is normally balanced, to move against a spring and assume a new position. The armature directly operates the rheostat element in the proper direction and amount to correct excitation conditions of the alternating-current machine and restore the original voltage.

The regulator is normally at rest and operates only when a change in excitation is required. Operation consists of a slight motion of the torque-motor armature either with or against the main spring, which moves the lever and linkage operating the rheostat element. This tilts the rheostat stacks slightly, one way or the other, changing the resistance to correct excitation. All of the resistance may be inserted or removed within a few cycles, or the resistance varied slowly, in an infinite number of steps, depending on the required excitation change. This permits smooth voltage control over the entire range of operation.

Parallel Operation. This regulator, like all other simple regulators that do not use secondary relays controlled by a master coil, can be used to control only one exciter. In the case of parallel operation of generators, a separate voltage regulator is used to control each exciter, and the exciters are operated nonparallel. In other words, each generating unit is independent of the others except for the final junction of the generator outputs at the bus-bars.

Independent regulation of alternating-current generators has one important advantage in that it can easily be arranged to equalize the power factors of the several generators and thus cause each machine to carry its share of the reactive kilovolt-amperes. When paralleled generators are operating under improper control, it is quite possible to have the engine governors so set that each machine is carrying its correct share of the load, but to have one generator overexcited and the others underexcited. In this case the overexcited generator may carry all of the reactive kilovolt-amperes and thus be overloaded even though the voltage at the bus-bars be normal.

To effect automatic control of the reactive current as well as the voltage, the regulators are connected as shown in Fig. 37. The connections are the same as for non-parallel operation (Fig. 36) except for the addition of a current transformer and compensating rheostat for each regulator. The current transformer is connected in the middle phase with the potential transformer across the two outside phases. The phase relations are then such that the regulator will

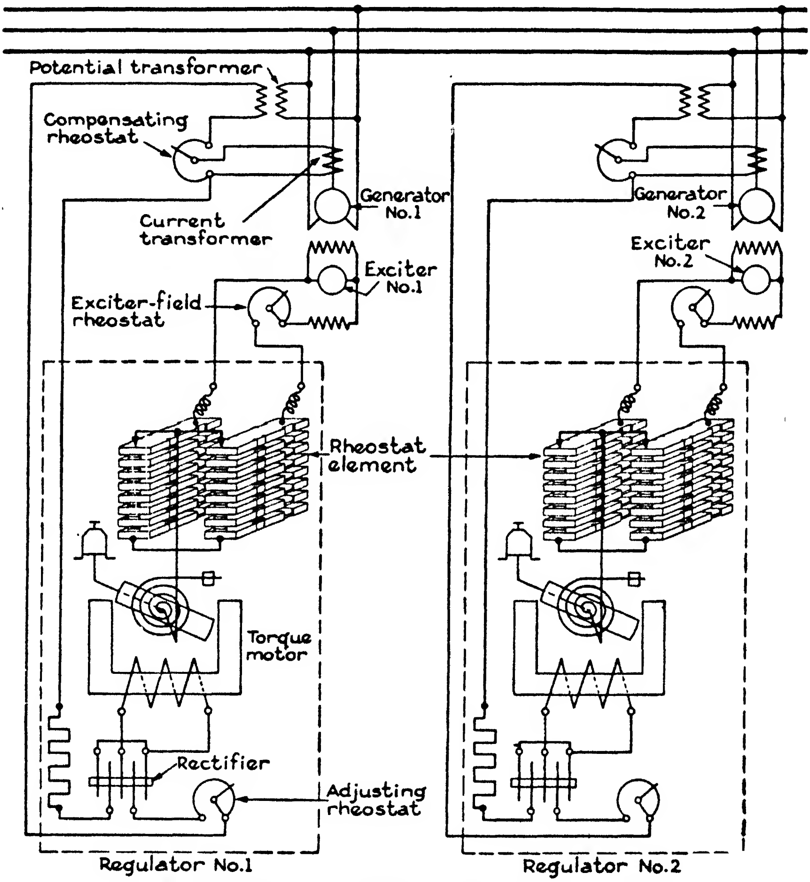


Fig. 37. Connection Diagram of Two General Electric GDA Regulators

reduce excitation when its generator produces more reactive current, and vice versa. This action tends to divide reactive kilovolt-amperes between machines in proportion to their ratings and enables the regulators to properly control generators operating in parallel. For the usual range of power-factor, there is not sufficient droop in the voltage caused by the compensation to be noticeable.

Excitation Systems for Paralleled A.C. Generators

The alternating-current voltage regulators previously described are designed to control only a single generator. On the other hand, the more elaborate types of regulators about to be set forth, can if desired, be arranged to control the voltage of several generators operating in parallel.

The various ways in which voltage regulators can be used to control paralleled generators depend upon the type of excitation system employed. The three usual types of excitation systems used in Diesel electric plants and the corresponding methods of regulator control are as follows:—

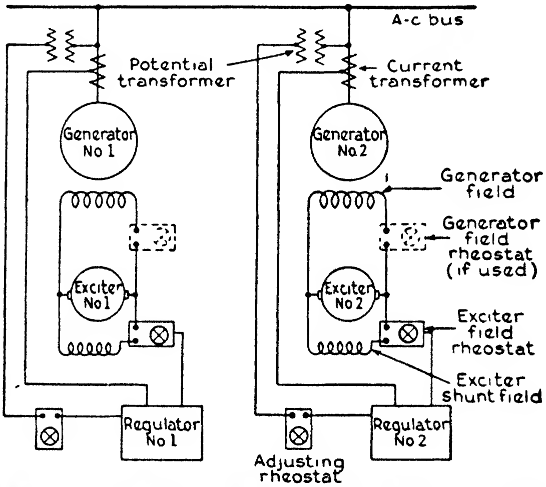


Fig. 38. Diagram Showing Individual Regulators for Two Generators Operating in Parallel

Unit Exciters with Individual Regulators. The unit system consists of an individual exciter and regulator for each alternating-current machine. The exciters are operated nonparallel as shown schematically in Fig. 38. With this method, the voltage of each alternating-current machine is automatically and independently controlled by its own regulator, and the division of reactive kilovolt-amperes among machines is automatically controlled by alternating-current compensation of the regulator from a current transformer and a compensating coil. With this system, there is no problem of load division among exciters, as each operates independently.

Unit Exciters with Common Regulator. Each alternating-current machine field is excited from an individual exciter (operated non-parallel), and all are controlled from a single regulator. A diagram of this scheme is given in Fig. 39.

If the regulator is of the vibrating type, each exciter is controlled by a separate relay which shunts that exciter's field rheostat, and all the relays are controlled simultaneously from the single regulator control element.

If the regulator is of the rheostat type, each exciter is controlled by a separate rheostat in the exciter field circuit, and all the rheostats are operated simultaneously from the single regulator control element.

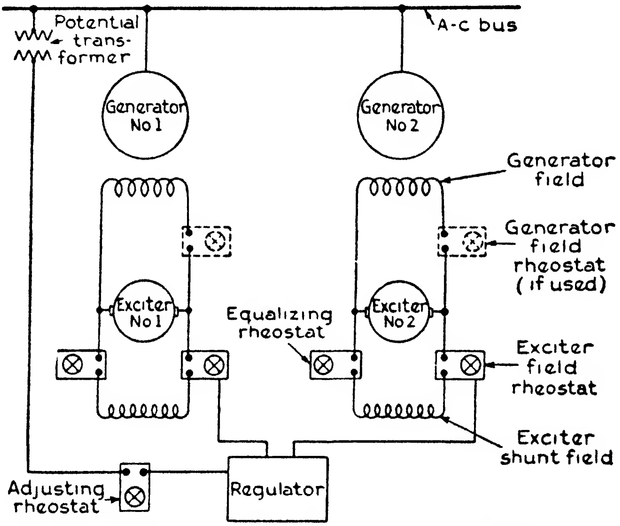


Fig. 39 Diagram of a Single Regulator Controlling Two A.C. Generators Operating in Parallel

With this method the regulator provides completely automatic control of alternating-current voltage, but division of reactive kilovolt-amperes among alternating-current machines and load division among exciters require manual control. Manual control consists of adjustment of the exciter-equalizing rheostats, the main generator-field rheostats, or both rheostats combined.

Common Exciter Bus and a Common Regulator. The alternating-current machine fields are excited in parallel from a variable-voltage exciter bus supplied by one or more exciters. All of the alternating-current machines are controlled from one regulator, with the appropriate number of relays or rheostats applied to each exciter-field circuit. This scheme is shown diagrammatically in Fig. 40.

The alternating-current bus voltage is under full-automatic control of the regulator. The division of reactive kilovolt-amperes among alternating-current machines in parallel is controlled manually by adjustment of the main generator field rheostats. Division of load among exciters operating in parallel is controlled manually by adjustment of the exciter-field-equalizing rheostats, as shown in Fig. 40.

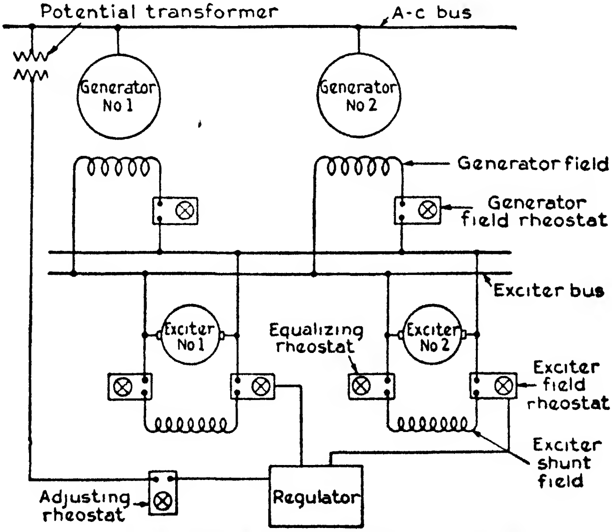


Fig. 40. Diagram of a Single Regulator Controlling Two Paralleled Exciters

The unit system of excitation with individual regulators has many advantages, such as completely automatic control of reactive kilovolt-amperes as well as voltage, lower rheostat losses, increased generator efficiency, simplified synchronizing and elimination of exciter paralleling difficulties. On the other hand, the cost of individual regulators for each machine, especially in small size plants, is usually considerably greater than that of a single regulator capable of controlling all the machines.

Rocking Contact Type Voltage Regulators

This type of rheostatic voltage regulator, built by Allis-Chalmers Mfg. Co. from Brown Boveri design, embodies several distinctive features. The regulator is suitable for use in Diesel generating stations where accurate voltage control is required in the face of sudden load variations. The distinctive features are: (a) the use of rocking contacts on the rheostat elements, which greatly reduce friction; (b) control device acting on the principle of an induction motor; and (c) an elastic recall device, consisting of a spring and a magnetic damper, whereby the regulator momentarily "over-regulates" so as to obtain quick action and then immediately assumes a stable position.

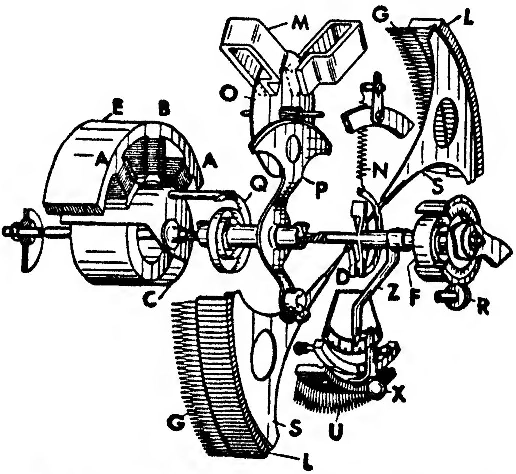


Fig. 41. Brown Boveri Type of Rheostatic Voltage Regulator

The mechanism of this regulator is shown in Fig. 41. The control device is in substance an induction motor used to produce torque instead of rotation. What corresponds to the rotor of an induction motor is the thin hollow drum of aluminum *C* mounted on a spindle. The torque produced in the drum by the current in the split-phase winding of the stator *E* is counterbalanced by springs. A sufficiently high resistance is connected in series with the stator winding to prevent variations in temperature and small variations in frequency having any marked effect on the constancy of the voltage which the regulator is set to maintain.

The field rheostat with contact device is an integral part of the regulator. The stationary contacts *L* to which the resistance coils *G* are connected are arranged concentrically with the rotor spindle in two or four rows, depending upon the size of the regulator. The inner side of these contacts, facing the spindle, is provided with a V-shaped groove that serves as a guide for the moving contacts *S*. The latter have the shape of a sector, with a curved strip of silver or carbon as contact surface. The weight of each sector is carried by springs, which is shown in the illustration, Fig. 42. Each sector is operated by moving its inner end in a tangential direction, this being done by means of a leaf spring *D* connected to the rotor spindle. This causes the sectors *S* to roll in the groove of the stationary contacts *L*, putting in or cutting out resistance. The latter is connected in series with the shunt field of the exciter, as shown in Fig. 43.

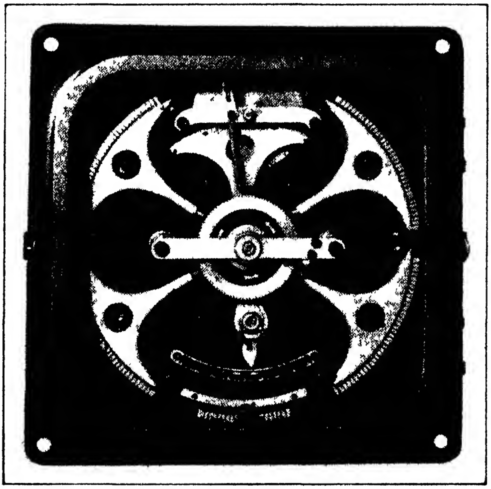


Fig. 42. Rocking Contact Type Regulator
Courtesy of Allis-Chalmers Manufacturing Co.

This design of the field rheostat entirely eliminates gliding friction and replaces it by rolling friction which is so small that it can almost be neglected. All moving parts are made of aluminum. Therefore the inertia is small, and as only small displacements are required to cover the whole regulating range, the moving system responds very quickly to changes in voltage.

Because of the light weight and quick action of this regulator, the least drop in voltage causes the rotor to turn quickly into the extreme right-hand position and thus give maximum excitation. This over-regulation, if limited to a fraction of a second, is highly desirable since it helps to overcome quickly the magnetic lag in the exciter and the generator field. However, the over-regulation must be stopped before the voltage is fully restored, otherwise the regulator would be unstable and would continually "hunt" from one extreme position to the other. This is accomplished by means of an elastic recall device, which consists of an aluminum disk *O*, Fig. 43, rotating between two permanent magnets *m*. The disk is geared to the rack of an aluminum sector *P*, which can turn concentrically with the rotor spindle and is fastened to the aluminum drum *C* by means of a flexible spiral spring *q*, acting as a recall spring. If a change in voltage occurs, the eddy currents induced in the disk *O* tend to resist quick response of the moving system. However, thanks to the flexible coupling, the drum, which directly controls the contact sectors *S*, will immediately take up a position in which the torque of the various springs and the electrical torque are again balanced. The coupling spring between the drum and the disk is made weak enough to allow powerful over-regulation and yet maintain perfect stability.

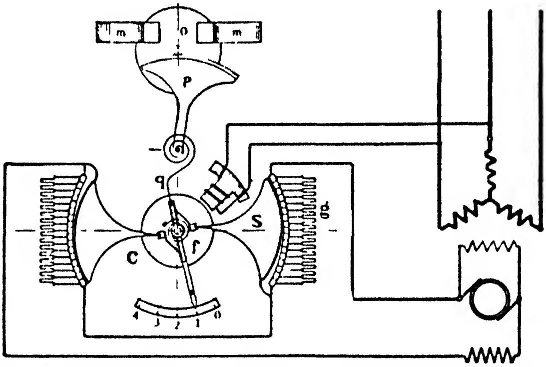


Fig 43. Wiring Diagram of Rocking Contact Type Regulator

Method of Operation. Referring to Fig. 43, if the generator is fully loaded the contact segments will take up a position similar to the one shown in which a great part of the resistance is short-circuited. This position does not change as long as the voltage remains constant. A drop in load tends to raise the voltage, but the smallest increase is immediately followed by an increase of the electrical torque so that the system becomes unbalanced. As a result the sectors are displaced to the left till the mechanical torque, now increased by the torque of the recall spring *q*, again equals the electrical torque. The resistance inserted in the field circuit by the displacement of the sectors is much in excess of what would be necessary to adjust the excitation to the new load condition. In this way the inherent inertia of the magnetic field is rapidly overcome and the voltage restored to normal. This causes the sectors to go back to the right, but since the tension of the recall spring has been reduced (because of the following up of the aluminum disk, to which its other end is connected through the geared quadrant) they come to rest in the position which corresponds to the correct excitation.

Parallel Operation. Since there are two independent rheostats in the two-sector type regulator, it can simultaneously control two exciters. Similarly, the four-sector type can control a maximum of four exciters. However, when more than one machine is controlled by one regulator, only the voltage can be controlled automatically, and the wattless energy must be distributed among the parallel operating alternators by hand adjustment of the alternator rheostats. When using one regulator for several exciters, it is essential that the field current and magnetic characteristics of the exciters do not differ too much from each other.

When paralleled generators are controlled by separate regulators, the latter are provided with cross current compensation by means of current transformers, and the reactive kilovolt-ampere is automatically distributed in proper proportion.

Vibrating Type Voltage Regulators

Vibrating-contact voltage regulators are widely used to control alternating-current generators, and are especially adapted to central station, municipal, and industrial Diesel generating plants of moderate capacity, as well as to Diesel power plants for office and apartment buildings. They operate by varying the strength of the exciter field, which in turn varies the generator excitation and thus the alternating-current voltage.

The outstanding feature of vibrating regulators, some forms of which are known as Tirrill regulators, is their ability to "over-regulate" momentarily when the voltage changes, and in this manner to reduce the inherent time lag of the generator and exciter. This over-regulation is achieved by periodically short-circuiting a regulating resistor in the exciter field circuit and thus quickly effecting a large increase in the exciting current. Obviously the over-regulation must be only momentary as otherwise the alternating-current voltage would change too much in the other direction. This would cause the regulator to act again but in reverse, and would set up a continuous "hunting" action which of course would be highly objectionable.

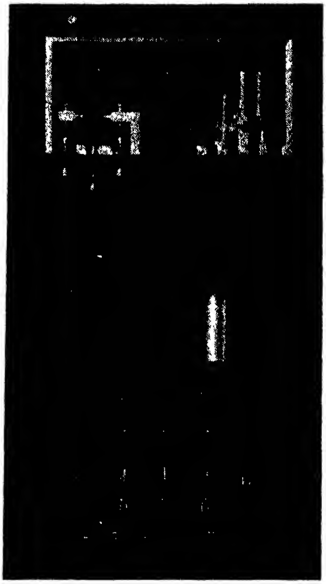


Fig. 44. Simplex Voltage Regulator
Courtesy of The Simplex Corporation

The function of the vibrating contacts in the vibrating regulator is to prevent this hunting action by stopping the over-regulation a fraction of a second after it starts, thus giving the alternating-current generator voltage a chance to respond before the regulator

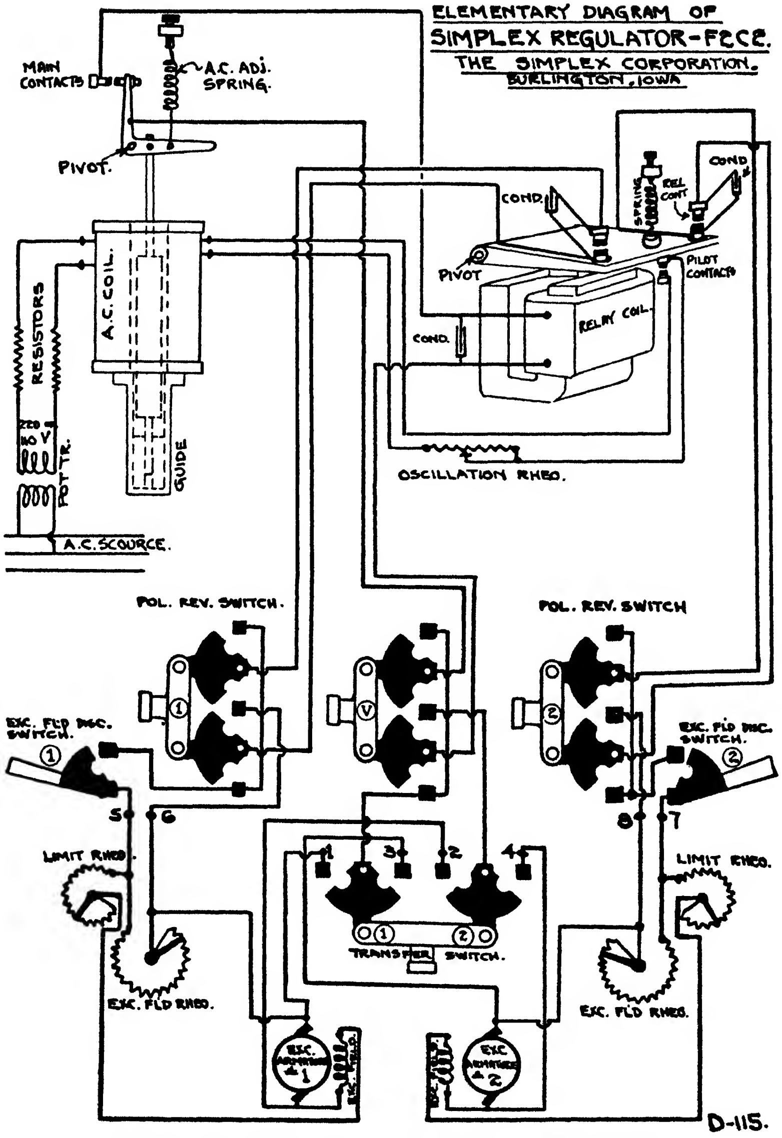


Fig. 45. Elementary Diagram of Simplex Voltage Regulator

applies further vigorous measures. Different methods of producing the vibrating action are employed in the various commercial forms of vibrating regulators.

Simplex Voltage Regulator. This regulator, manufactured by The Simplex Corporation, is shown in Fig. 44 in the form used for controlling two generating units operating in parallel. The vibrating action is produced by a secondary winding on the main alternating-current control coil, which winding is periodically short-circuited by contacts operated by a relay. The elementary diagram, Fig. 45, illustrates the method of operation with two paralleled generators with individual nonparalleled exciters.

The alternating-current coil responds to the changes in alternating-current voltage and opens or closes the main contacts. Closing the contacts causes direct current from one of the exciters to flow through the relay coil which attracts its armature, opening the two relay contacts and closing the pilot contact. The relay contacts are used to shunt the exciter field rheostats, while the pilot contact closes a circuit through the oscillation rheostat and the secondary winding on the alternating-current coil previously mentioned.

Operation. When the alternating-current voltage falls, the A.C. coil drops its core and opens the main contacts, de-energizing the relay coil and permitting the spring on the relay coil armature to close the relay contacts and open the pilot contact. The closing of the relay contacts short-circuits the exciter field rheostats and thus increases the alternating-current voltage. At the same time, however, the opening of the pilot contact opens the circuit of the auxiliary winding of the A.C. coil, which acts as the secondary of a transformer of which the alternating-current voltage winding is the primary. The effect of opening the circuit of the secondary winding is to increase the pull of the solenoid. This recloses the main contacts, re-energizes the relay and opens the exciter field rheostat shunting the relay contacts, thus preventing the alternating-current voltage from rising too rapidly.

These movements follow each other rapidly and repeatedly, thus setting up a continuous vibration of both the main and the relay contacts. The frequency of vibration is adjustable by means of the oscillation rheostat from about 50 to 1000 vibrations per minute. In this manner voltage corrections are made rapidly by changing the time of contact engagement, i.e., the ratio of the time the contacts are closed to the total time.

The function of the polarity reversing switches 1 and 2 is to reverse the direction of current through the relay contacts and thus minimize the tendency for one contact to build up. Reversing switch *V* similarly reverses the polarity across the main contacts. The transfer switch serves to select the exciter from which the regulator relay coil receives its operating energy.

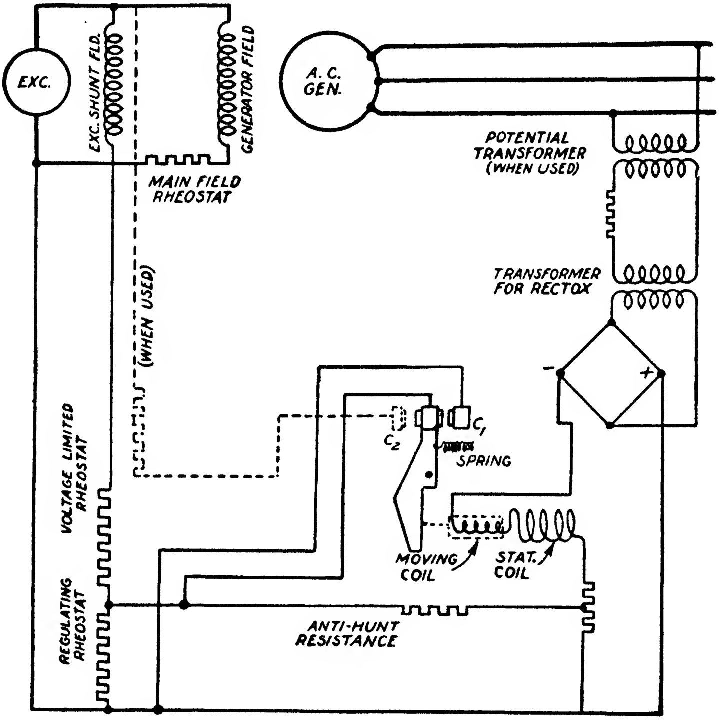


Fig. 46. Schematic Diagram of Westinghouse Type UV Regulator for A.C. Generators

When a single regulator is used to control two or more generators operating in parallel, it automatically regulates the joint alternating-current voltage, but manual adjustment of the field rheostats is necessary to distribute the reactive current among the several generators.

Westinghouse Type UV. The general principles of the simple form of vibrating regulator originally developed by the Westinghouse company for direct-current generators and known as Type UV have already been mentioned. This type of regulator has been adapted for controlling alternating-current generators by adding a rectox rectifier. In this way the control element is actuated by direct current whose voltage is proportional to that of the alternating-current line.

Operation. Referring to the schematic diagram, Fig. 46, a drop in alternating-current voltage reduces the direct-current voltage produced by the rectox rectifier and weakens the attraction of the stationary and moving coils, causing contacts C1 to close. This shunts the exciter field regulating rheostat and so increases the exciter voltage. But as soon as contacts C1 close, the current through the control element increases because the resistance of this circuit is reduced on account of the additional path through the antihunting resistance and the contacts C1. The increased attraction of the coils opens contacts C1 and the process repeats itself indefinitely, thus causing a continuous vibration of the contacts.

Fig. 47 Westinghouse Type A Voltage Regulator Panel

Westinghouse Type A. This is an old and well-known type of vibrating regulator for alternating-current generators. The vibration is produced by a separate vibrating relay whose contacts cause an interrupting action. The regulator illustrated in Fig. 47 is capable of controlling two exciters. The two upper large coils are the main control magnet and the vibrating magnet, both of which operate the main contacts. Of the three smaller coils below, one is the vibrating magnet relay and the others are the exciter rheostat-shunting relays.

Operation. Referring to Fig. 48, which is a schematic diagram of a regulator with only one rheostat-shunting relay, the main control and vibrating magnets are energized from the alternating-current bus. The cores of both magnets are attracted upward and, in conjunction with the spring and counterweights, actuate the main contacts into and out of engagement. The main contacts, in turn, control the shunting relay or relays.

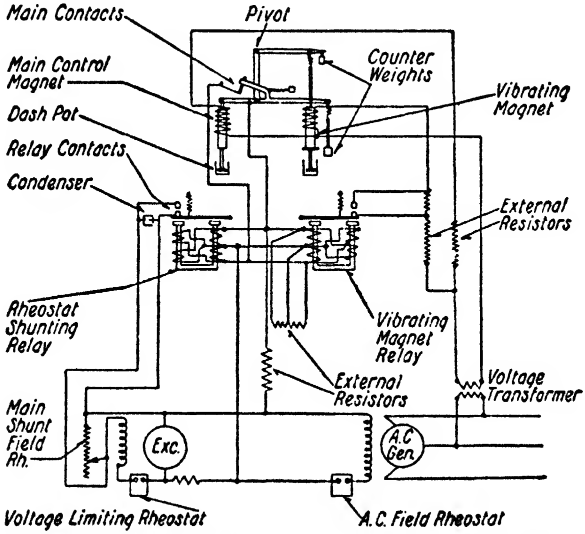


Fig. 48. Schematic Diagram of Westinghouse Type AB Regulator

The shunting contacts alternately open and close across the exciter field rheostat and the effective resistance of the rheostat is determined by the time of contact engagement. For any effective resistance, there is a corresponding exciter voltage and, therefore, alternator voltage.

The vibration is set up by the vibrating magnet relay which is connected so that the closure of its contacts shunts a small portion of the resistance in series with the vibrating magnet, thus increasing its pull and opening the main contacts. The opening of the main contacts opens all relay contacts and inserts the full resistance in the vibrating magnet circuit, weakening the pull and again closing the main contacts. Thus, a continuous vibration is set up.

The rheostat-shunting relays and also the vibrating magnet relay are of the differential type, each coil consisting of two windings, one energized continuously and the other intermittently through the action of the main contacts. When one winding is energized, the armature is attracted to the fixed cores against the tension of a spring, thus opening the contacts. When the differential winding is energized by the closing of the main contacts, it opposes and neutralizes the effect of the first winding thus allowing the spring to close the contacts. As a result, the contacts of the differential relay are made to vibrate in unison with the main contacts.

Where the number of relays required exceeds the capacity of the main contacts (the usual limit being three, one vibrating and two shunting), a master relay is used which makes it possible to actuate as many as eight shunting relays from a single control element. The master relay is also of the differential type similar to the vibrating and shunting relays.

All relays are energized by direct current obtained from one of the exciters, as selected by means of transfer switches.

Reversing switches are connected in the leads from the various relay contacts. Their purpose is to reverse the polarity across the contacts and thus minimize any tendency for one contact to build up. The single-pole disconnecting switches below the reversing switches are connected only in the shunting-contact leads and serve to disconnect the regulator from the machine which it is controlling.

The distinctive features of this type of vibrating regulator are as follows:

(1) Quick action.

(2) Ability to force the field to the limit and hold it there indefinitely if necessary.

(3) Multiple-unit control making it possible to control a number of units simultaneously from a single regulator.

(4) Individual shunting relays, making it possible to provide for unanticipated future machines by the addition of extra relays, within the limits of the regulator.

The rated sensitivity of this regulator is within plus or minus 0.5 per cent.

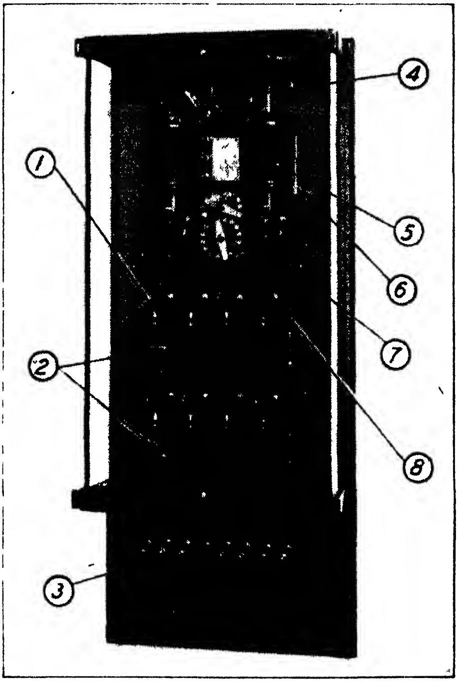


Fig. 49. Westinghouse Vibrating-Type Voltage Regulator

① Relay contacts are of two kinds as follows: For V and X relays an especially durable contact material is used. For shunting relays, because of the greater wear and more frequent renewal required, silver is the standard material but tungsten is available in special cases where preferred.

② The number of shunting (S) relays depends on the number and size of machines controlled. One vibrating (V) relay required to force and maintain vibration in a manner dependent only on the regulated A.C. voltage. When more than three shunting relays are required on one regulator, one or more master (X) relays are used. These are connected between the main contacts and the shunting relays to relieve the main contacts of unnecessarily heavy duty.

③ Reversing switches are provided for periodically reversing the polarity of M, X and S contacts, thus prolonging the time between maintenance periods.

④ Main contacts (M) operated by the control coils which maintain a continuous vibrating action part time open and part time closed. This vibrating action energizes the relays and causes them to vibrate continuously.

⑤ Coils of control element are energized from the bus voltage through a potential transformer.

⑥ Regulating counterweights by which the regulated voltage may be adjusted at installation to a value between the taps on the external resistor as required.

⑦ Dashpots with ports adjustable by needle valves. These dashpots permit installation adjustment so that the damping characteristics of the control element match the machine and load characteristics.

⑧ The compensating dial switch with which the control element is biased for cross-current or line-drop compensation as required by the particular installation.

The various parts of this regulator, with their functions indicated, are shown in Fig. 49.

General Electric Type TA. Like the Westinghouse Type A, this is also a well-known type of regulator for alternating-current generators, operating on the principle of rapidly opening and closing a shunt circuit across the exciter field rheostat. The vibration, however, is produced in a different manner. The main contacts "float," i.e., *both* contacts are movable, one being controlled by the direct-current exciter voltage and the other by the alternating-current generator voltage.

A view of this regulator, with the various components indicated, is given in Fig. 50. The form shown contains a single shunting relay and is suitable for controlling one exciter. Fig. 51 is an elementary diagram of the connections.

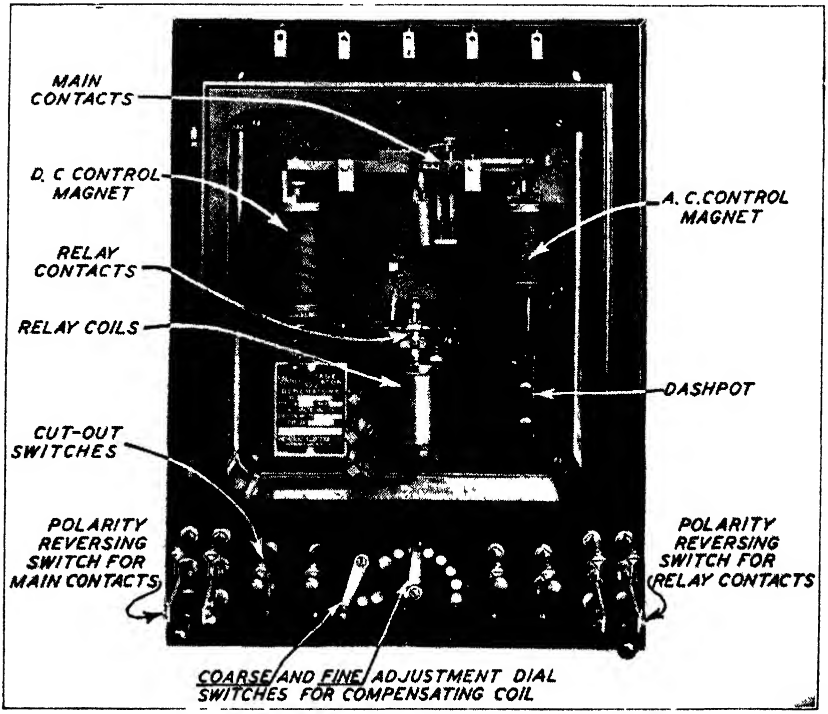


Fig. 50. General Electric Type TA Voltage Regulator

Operation. The regulator consists fundamentally of two parts, a direct-current control system and an alternating-current control system which cooperate in determining the position and movement of the main (floating) contacts. The direct-current control system is simply a direct-current regulator having a main control magnet and relay magnet connected across the exciter mains, the contacts of the relay being arranged to shunt the exciter field rheostat. This operation maintains not a constant but a varying exciter voltage, the value varying in accordance with the demands of the alternating-current control magnet which is connected to the alternating-current bus, the latter magnet being the alternating-current portion of the regulator.

The direct-current control magnet is responsive to exciter voltage and attracts downward a movable core attached to a pivoted lever, at the other end of which is a flexible contact. This is one of the floating main contacts. A differentially wound relay magnet is also connected to the exciter bus, one winding being permanently connected to the bus, while the other is arranged to be opened and closed by the floating main contacts. The relay contacts are connected across the exciter field rheostat.

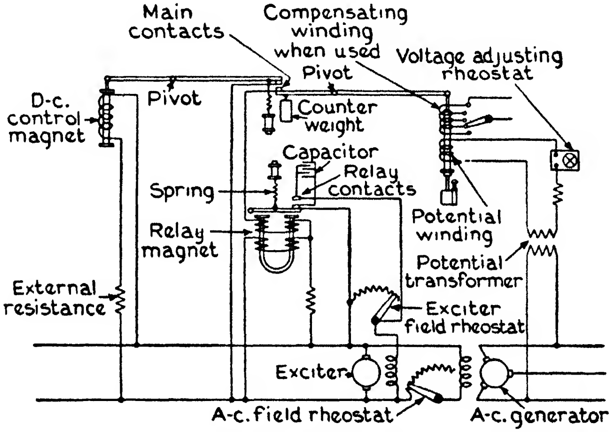


Fig. 51. Elementary Diagram of General Electric Type TA Voltage Regulator

The potential winding of the alternating-current control magnet is connected across the generator bus through a potential transformer. This magnet is of the ordinary solenoid type, having a laminated iron core which is attracted upward by the magnetizing force. The core is attached to a pivoted lever, at the opposite end of which is mounted the lower main contact.

It will be seen from the foregoing that the exciter voltage is controlled by the rapid opening and closing of the relay contacts. The value of the voltage depends upon the position of the alternating-current magnet core and lever arm, which is in turn dependent upon the value of the alternating voltage being held.

At any constant load, speed, and power-factor, the alternating-current magnet core does not actually move, the regulator acting as a direct-current regulator maintaining the proper exciter voltage to give the correct alternating voltage. Should the power-factor change, or should a heavy load be thrown upon the alternator, the previous exciter voltage will not give the correct alternating voltage. Therefore the alternating-current core will drop slightly. This forces the lower main contact against the upper main contacts, which in turn closes the relay contacts. This, as previously explained, causes the exciter voltage to increase. The travel of the alternating-current magnet core will continue until the exciter voltage has reached a value corresponding to that required to give normal alternating voltage under the new conditions. The direct-current side of the regulator will then operate and maintain the exciter voltage of the regulator at this higher value in order to hold again the proper alternating voltage. In case the load drops on the alternating-current generator, the reverse action takes place and the regulator maintains a lower exciter voltage, in order to give the correct alternating voltage.

This regulator can also be arranged to control more than one exciter, the principle of operation being the same except that several shunting relays are used instead of one. The regulator appearance is then as shown in Fig. 52.

Combination Rheostatic-Vibrating Voltage Regulators

Automatic control of voltage on large alternating-current machines frequently involves field currents and rheostat capacities beyond the practical range of application of either the direct-acting rheostatic or vibrating-contact types of regulators. The indirect-acting rheostatic type regulator, which uses a combination of rheostat movement and vibrating contacts, is especially adapted to large central station installations where large, slow-speed exciters are used or where the rate of response to change in voltage on the field of the generator is slow. This type of regulator is adapted to three-phase instead of single-phase response and avoids the operating difficulties encountered with the continuously vibrating contacts of vibrating regulators when used for heavy field currents. In this regulator no motion occurs until there is a change in voltage. Then a combination of vibrating relay contact action and rheostatic regulation corrects conditions until the rheostat reaches the correct position for the new load condition.

The indirect-acting regulator with its accompanying high-speed relays and motor-operated exciter field rheostat is relatively expensive, and its use is usually limited to the control of large and important machines. Two forms of this type of regulator are briefly described herewith.

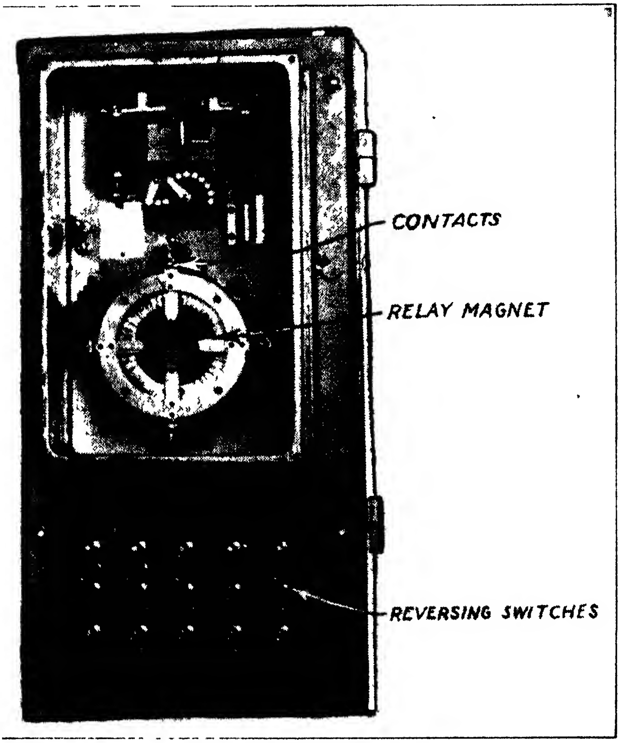


Fig. 52. General Electric Type TA Voltage Regulator for Controlling Several Generators

General Electric. The main components of this regulator, known as Indirect-Acting Type GFA-4 are a main control element shown in Fig. 53, with a motor-operated exciter field rheostat, and a relay panel with high-speed relays. The voltage-sensitive part of the main control element, which is the heart of the regulator, is a polyphase torque motor responsive to the average voltage of all

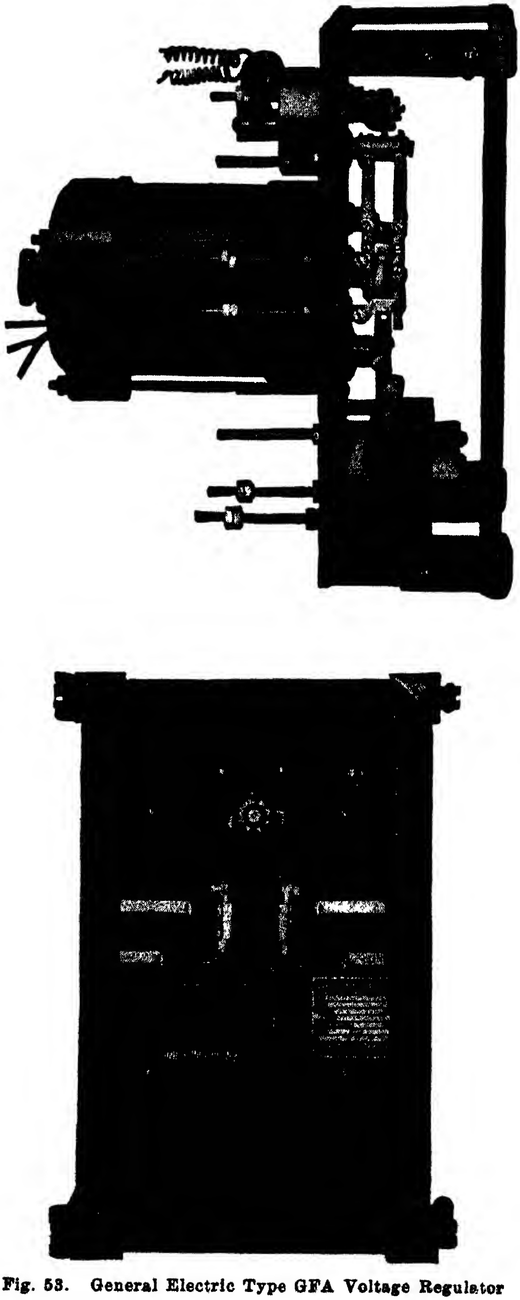


Fig. 53. General Electric Type GFA Voltage Regulator

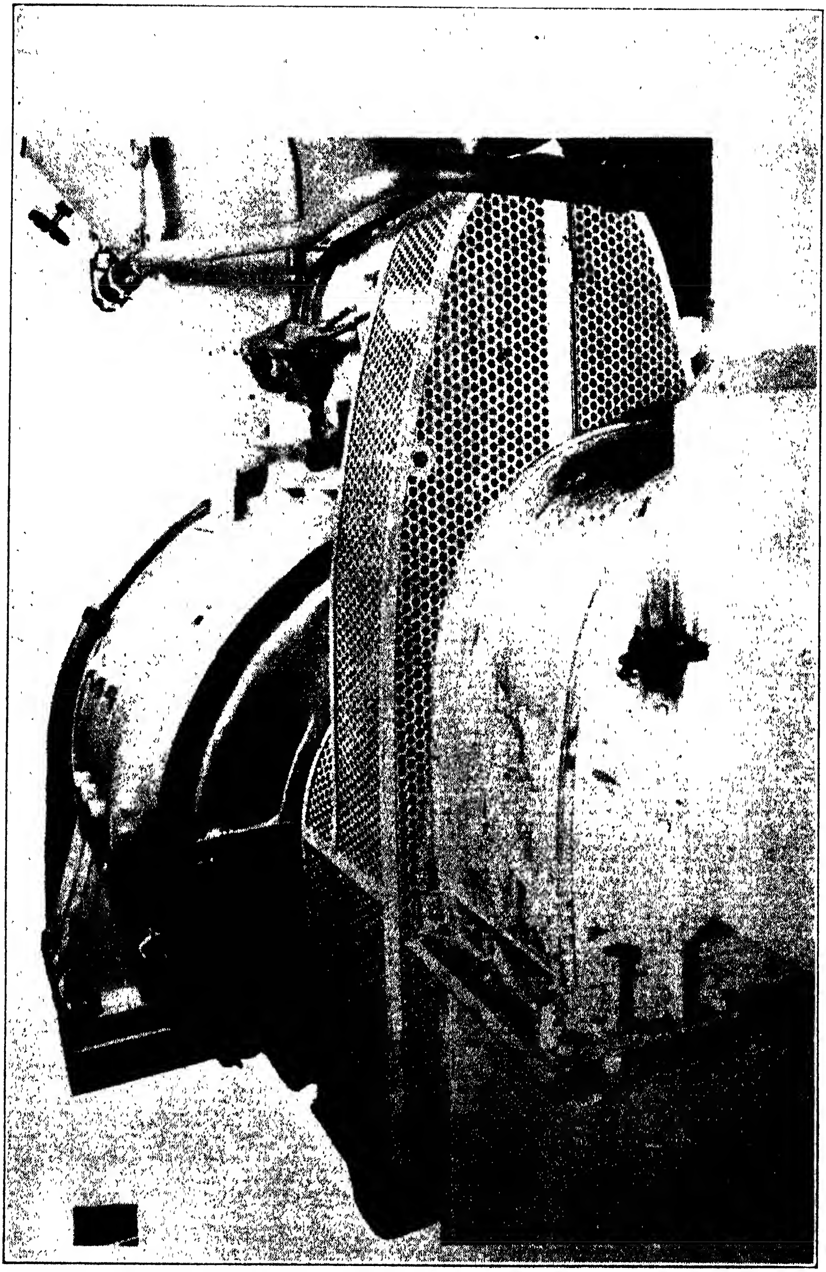
three phases. A rotating cam contact wheel is used which gives the desired intermittent contact action without depending upon the direct-current interrupter action employed in vibrating regulators.

Two sets of contacts provide for separate operation of the exciter field rheostat for small changes, and of the high-speed accelerating relays for large changes. For small changes of voltage the first set of contacts function by moving the motor-operated field rheostat to a new position, but as the engagement of the contacts is interrupted by the rotating cam, the rheostat is moved in short steps allowing sufficient time for the alternating-current voltage to be corrected between steps. The greater the voltage change, the longer the time of engagement and the faster the motion of the field rheostat. If the voltage change is large enough, the second set of contacts come into action. These operate the accelerating relays which cut in or out *all* of the regulating resistance. The regulator acts fast when the maximum rate of voltage correction is needed, the time required to close the accelerating contacts and to operate the accelerating relays being only 3 cycles or 1/20 of a second. When the voltage is steady, the regulator contacts do not close at all. In this regulator the control is effected through varying the resistance in the exciter field circuit and therefore the exciter armature voltage is non-uniform. An individual regulator is required for each alternating-current machine to be controlled, and each alternating-current machine must have its own individual exciter.

Westinghouse. The Westinghouse company also builds a combination type of regulator known as Exciter-Rheostatic Types AW and AJ. This operates almost identically like the General Electric type just described, except that the antihunting arrangement which prevents overshooting of the regulated voltage is electrical instead of mechanical.

The rheostat is notched step-by-step to its correct position when normal alternating voltage has been closely approached or when the load change is very slight. However, this does not appreciably affect the rate at which voltage restorations are made, since the notching process does not start until the alternating voltage has been restored to within a few per cent of its normal value.

Under steady load conditions the regulator is in a state of rest, operating only when the necessity arises.



CLOSE-UP VIEW OF ELECTRIC GENERATOR AND BELT-DRIVEN EXCITER (ABOVE) WHICH PRODUCES THE CURRENT FOR THE ELECTRIC DRIVING MOTORS ON A DIESEL ELECTRIC LOCOMOTIVE

Courtesy of Baltimore And Ohio Railroad, Baltimore, Md.

CHAPTER V

PARALLEL OPERATION

Two or more electric generators are said to be operating in parallel when the machines are electrically connected, or in other words, when they are delivering current to the same set of bus-bars. Parallel operation permits wide flexibility in loading of generators and effects many economies. Most Diesel electric plants containing more than one unit are arranged for parallel operation.

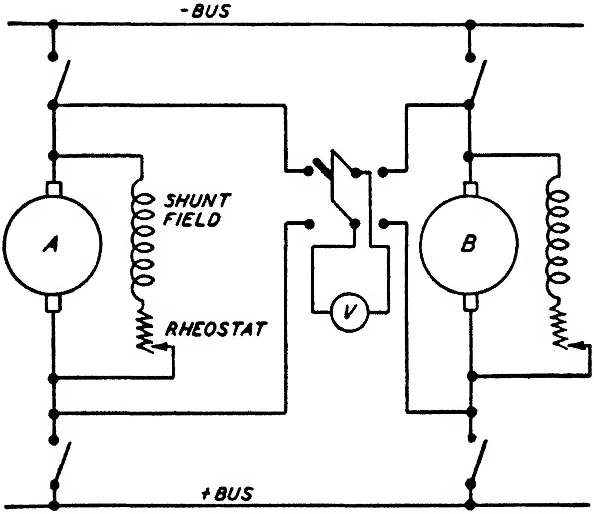


Fig. 54. Diagram of Connections for Parallel Operation of Two Shunt Generators

Direct-Current Generators

Shunt-Wound Generators. A simple example of paralleling direct-current machines is shown in Fig. 54, which illustrates the case of two shunt-wound generators *A* and *B*. The voltmeter *V*, by means of a double-throw switch, can be made to indicate the terminal voltage of either machine *A* or *B*. Assume generator *A* is in service and connected to the buses, its main switches being closed.

To parallel generator *B* with generator *A*, *B* is brought up to speed and its field rheostat is adjusted until the terminal voltage of *B* is the same as that of *A*. *B*'s main switches are then closed, putting *B* in parallel with *A*. However *A* will still carry all of the load and *B* will run idle until the voltage of *B* is further increased by means of its field rheostat, whereupon *B* can be given any desired part of the load. Since the voltage of shunt-wound generators drops off with increase of load it is evident that when a certain load is divided between the generators in a certain ratio, that ratio will be automatically maintained as long as the load remains the same. If for example, because of a momentary speed change, generator *A* should start to take more than its share of the load, the terminal voltage of *A* would start to fall and would cause *A* to relinquish the additional load at once.

If the shunt-wound machines have similar voltage characteristics, i.e., if the same increase in load will cause the same drop in voltage on both machines, they will divide the load in the same ratio regardless of variations in the total load. If their voltage characteristics are not the same, some regulation of the field rheostats may be required when a change in load takes place.

Compound-Wound Generators. The paralleling of compound-wound generators is not as simple as that of shunt-wound machines, because of the effect of the series fields. The latter have a marked effect on the voltage characteristics, tending to cause the terminal voltage to rise with increase of load, instead of falling as in the case of shunt-wound machines. Thus, if compound-wound generators were to be connected in the simple manner of shunt-wound, the division of load would be unstable. If one machine should start to take more than its share of the load, its series field would be strengthened and its terminal voltage would increase. This in turn would cause the same generator to assume still more of the load, whereupon its voltage would increase further. The effect would be rapidly cumulative and would finally result in the one machine not only carrying all of the load but also operating the other generators as motors. For this reason it is necessary to use an "equalizer connection" with all compound-wound generators operating in parallel.

The purpose of the equalizer connection is to place the series fields in parallel so that any tendency of one armature to increase or decrease its load will automatically increase or decrease the load on the other armature. The equalizer connection should be of low resistance and should be located as shown in Fig. 55. Since the current flowing through each series coil is proportional to the resistance and is independent of the load on any machine, an increase of voltage on one machine builds up the voltage of the other at the same time, so that the first machine cannot take all the load, but will continue to share it in proper proportion with the other generators.

Compound-wound generators should first be adjusted to operate stably in parallel as shunt generators, that is, without the series field, by proper brush setting. After that, the series fields may be adjusted by resistances or shunts so that the same full load voltage is obtained on all machines and the load will divide properly at all intermediate loads.

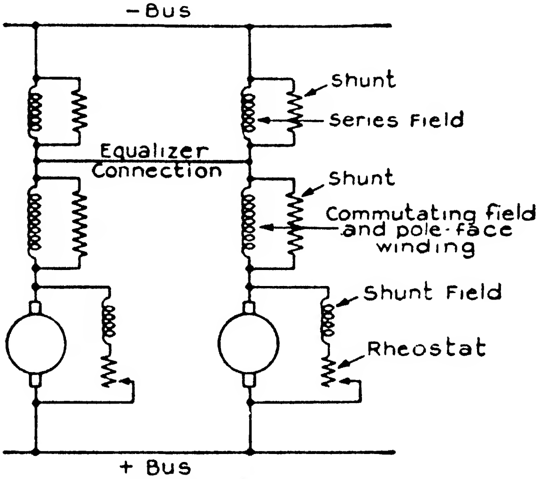


Fig. 55. Connections for Parallel Operation of Two Compound-Wound Generators
Courtesy of General Electric Company

To obtain proper division of load between generators, the voltage characteristics when plotted against per cent load should be the same or very nearly so. In determining the voltage characteristics, the change in speed of the Diesel engine with load should be taken into consideration.

The shape of the voltage characteristic is dependent upon the type of generator, design, and adjustment. The amount of droop in the case of shunt generators can be changed somewhat by shifting the brushes or changing the strength of the commutating pole. However, the range of adjustment by these methods is limited by commutation. The voltage regulation of a compound generator may be changed by varying the strength of the series field.

From the point of view of good parallel operation, it is much better to have all generators flat compounded or even with a voltage characteristic that droops slightly with load.

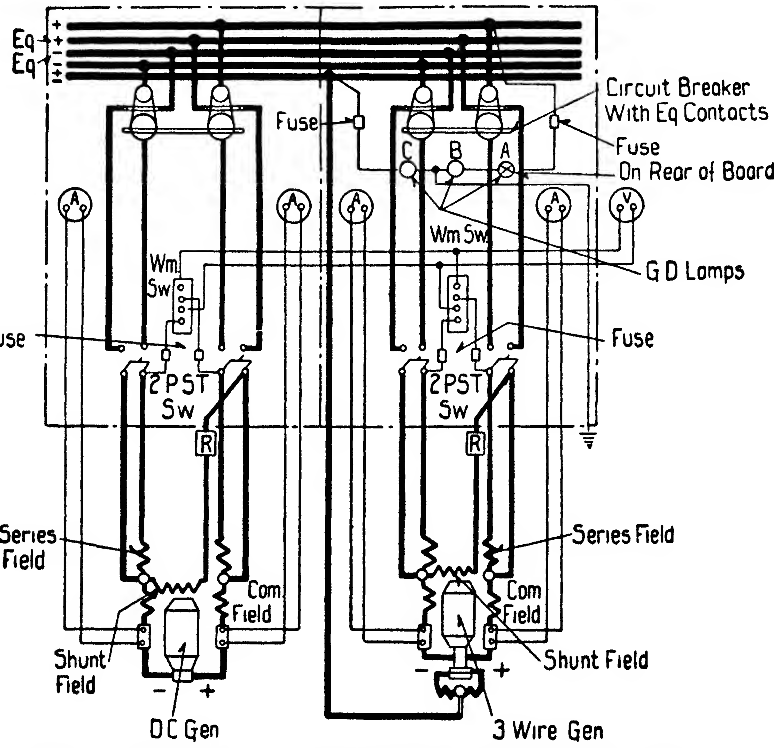


Fig. 56. Diagram of Connections for Paralleling a Three-Wire 125-250-Volt D.C. Generator with a Two-Wire 240-Volt Generator

Courtesy of Westinghouse Electric and Mfg. Co.

Actual connection diagrams for generators operating in parallel are more elaborate than the simplified diagrams in Figs. 54 and 55. The Westinghouse plan for connecting a 3-wire commutating pole 125-250-volt compound-wound generator with a 2-wire 240-volt generator is shown in Fig. 56.

Alternating-Current Generators

The process of paralleling alternating-current generators involves more steps than the paralleling of direct-current machines. In the case of direct current, the equalization of voltage between the incoming machine and the line is the important factor. In the case of alternating current, however, it is not only necessary to bring the generators to the same voltage but they must be of the same frequency, and most important of all—exactly in phase. In the case of alternating-current machinery, the process of paralleling is generally termed "synchronizing" because of the dominating importance of the two currents being in phase or in step with each other just before the main switches are closed.

The importance of the phase relation becomes obvious if it is recalled that in a 60-cycle, 240-volt circuit the instantaneous voltage swings from 340 volts positive to 340 volts negative and back to 340 volts positive every sixtieth of a second. Consequently, even though the frequency of an incoming generator is the same as that of the line, it is possible to make the unfortunate mistake of closing the main switch or circuit breaker at a moment when say, Phase A of the incoming machine is at the highest point of its positive voltage swing, but Phase A of the bus is at its greatest negative voltage. The resulting effect will be equivalent to a sudden short-circuit of double the normal voltage, and the instantaneous current may under certain conditions rise high enough to damage seriously the generators, transformers, and circuit breakers.

The earliest commercial method of indicating synchronism, and the simplest, is the lamp method. It is still frequently used, and even where a more refined device known as a "synchronoscope" (described later) is employed, synchronizing lamps are generally installed as well. The principle employed is illustrated in Fig. 57, representing two single-phase generators, of which *A* is being started in order to synchronize it with *B* which is already in service and connected to the bus. Since the generator speeds, and therefore their frequencies, differ, their electromotive forces will periodically change from a condition of phase coincidence to one of phase opposition, and likewise the flow of current through the lamps will vary from a minimum to a maximum.

When the electromotive forces of the two machines are exactly equal and in phase, the current through the lamps is zero. As the difference in phase increases, the lamps light up and increase to a maximum brilliancy when corresponding phases are in exact opposition. From this condition the lamps will decrease in brilliancy until completely dark, indicating that the machines are again in phase. The rate of pulsation of the lamps depends upon the difference in frequency, i.e., upon the relative speeds of the machines.

When the fluctuations of the lamps become very slow, about one in two or three seconds, the frequencies of the two machines are almost the same; the switch may now be closed when the lamps are dark, since at this time the electromotive forces of the two machines are equal. The machines are now operating in parallel and will continue to do so under all ordinary conditions, being held in synchronism by powerful electrical forces.

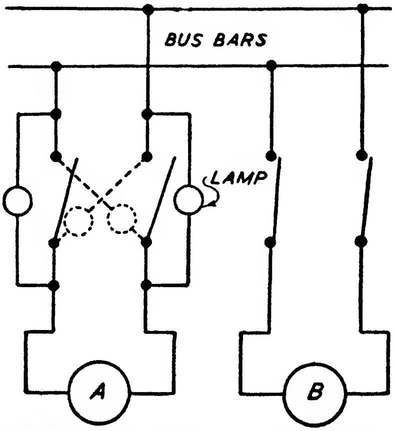


Fig. 57. Lamp Method of Synchronizing Single-Phase Generators

Synchronizing in the foregoing manner is termed "dark synchronizing." It is also possible to use "bright synchronizing," in which case the lamps are connected diagonally across the line switch as shown by the dotted connection of Fig. 57. Here synchronism is indicated when the lamps are brightest.

Bright synchronizing is not in general use. The lamps glow through a wide range of voltage and it is rather difficult to ascertain the exact moment of synchronism by watching for the maximum brilliancy. Where bright synchronizing is used, carbon filament lamps are to be preferred. These have a negative resistance coefficient, and their hot resistance is about half the cold resistance. Consequently, changes in voltage when the lamps are bright are more noticeable.

For a corresponding reason, when using dark synchronizing, which is the common method, tungsten filament lamps are better. They have a positive resistance coefficient and their cold resistance is only about one-twelfth that when hot. Consequently, they glow down to low voltages and only go out completely when the voltage is close to zero.

The one objection to dark synchronizing is that there is a chance of one of the lamps burning out at the critical moment and thus giving a false indication. However, this possibility can be guarded against by using two independent sets of synchronizing lamps together, or by checking with the indications of the synchronoscope if there be one.

When the voltage of the system is too high for direct use on the lamps, it is usual to place voltage transformers between the main circuits and the synchronizing lamps, as shown in Fig. 58. This figure also shows the connections for two independent sets of lamps.

If the connections of either the primary or secondary of either transformer should be reversed from those shown in the diagram, the indications of the lamps would be reversed, i.e., when the generators are in phase, the lamps would burn at maximum brilliancy and vice versa.

In order to make certain that the lamps will be dark instead of bright when the machines are in phase, disconnect the main leads of the first generator at the generator and throw in the main switches of both generators with full voltage on the second generator. Since both machine circuits are then connected to one machine, the lamp indication will be the same as when the main or paralleling switches are open and both machines are in phase. If the lamps burn brightly, the connections of one of the voltage transformer primaries or one of the secondaries should be reversed.

Phase Sequence. In the case of polyphase machines, it is not only necessary that one phase be in synchronism with one phase of another generator but the sequence of maximum values of voltage in the several phases must be the same The phase sequence must therefore be checked. The necessary connections for two three-phase generators are shown in Fig. 58.

Connect the generators temporarily to their switches, but with the switches open, so that the phases of *D* will be in parallel with those of *E*. Connect synchronizing apparatus in any two phases. Test out the synchronizing connections with machine *D* running at normal speed and voltage, the leads disconnected from *E* at the generator and the paralleling switches closed. Having changed the synchronizing connections, if necessary, so that both sets of lamps will be dark when indicating synchronism, open the paralleling switches, re-connect the leads of machine *E* and bring it up to normal speed and voltage. Then observe the two sets of synchronizing lamps. If their pulsations come together, i.e., if both sets are dark and both are bright at the same time, the phase rotation of the two generators is the same, and the connections are correct for paralleling the generators when the lamps are dark. If, however,

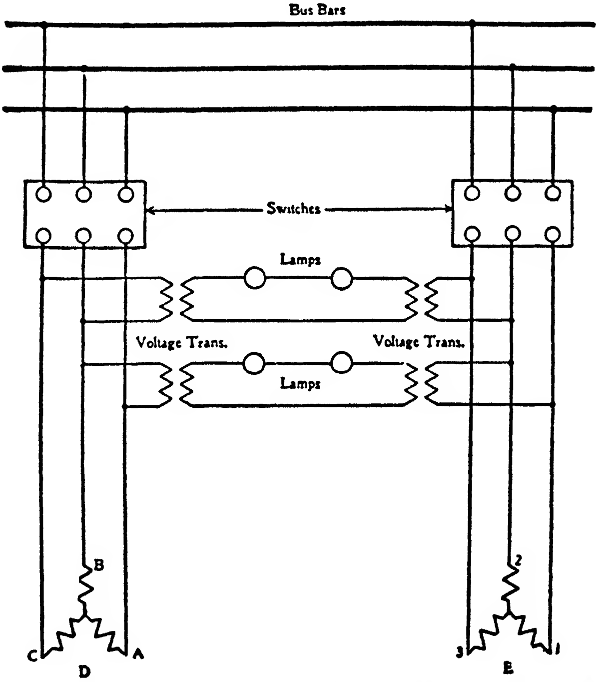


Fig. 58. Connections for Synchronizing Three-Phase Generators
Courtesy of Westinghouse Electric and Mfg. Co.

the pulsations of the lamps alternate, i.e., if one is dark when the other is bright, reverse any two leads of one machine and test out the synchronizing connections again, changing them if necessary so that they are the same when indicating synchronism. The lamps will now be found to pulsate together and the generators may be thrown in parallel at the proper indication. Phase sequence thereafter need be checked only if some change is made in the wiring.

Synchronoscope. A synchronoscope, Fig. 59, is an instrument that indicates the difference in phase between two electromotive forces at every instant. By its aid the operator can see whether the incoming machine is running fast or slow, what the difference in speed is, and the exact instant when it is in synchronism. These conditions cannot be observed with certainty by the use of lamps alone.

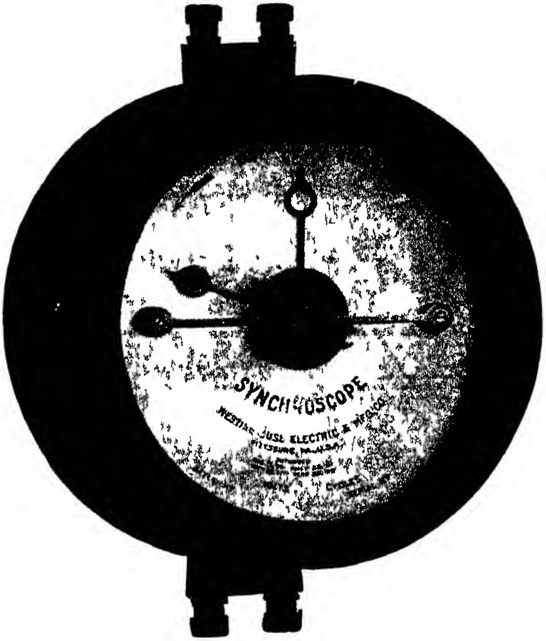


Fig 59. Westinghouse Synchronoscope

The synchronoscope has a pointer which shows the phase angle between the incoming and running machines. This angle is always equal to the angle between the pointer and the vertical position marked on the dial of the instrument. When the frequencies of the two machines are equal, the pointer stops at some position on the scale and when the machines are in phase, the pointer coincides with the marker at the top of the scale.

In order to check the synchronoscope connections, proceed in the same manner as previously described for determining whether lamps will be bright or dark for a given synchronizing connection.

The principle upon which a synchronoscope works consists of impressing the rotating fields from the running and the incoming machines upon a stator winding. An iron vane armature, free to rotate upon a shaft, then takes up a position dependent upon the resultant value of the two fields, and this position or phase angle is indicated by a pointer attached to the armature shaft. Synchronoscopes are not intended for continuous service; as soon as the machines have been paralleled, the synchronoscope switch should be opened to prevent overheating of the instrument and its resistor.

Automatic Synchronizing. Fully-automatic devices have been developed which will synchronize and parallel an incoming generator with the line, and which work safely, accurately and speedily. The operator need only start the engine, put it under governor control and adjust the voltage, whereupon the synchronizer will do the rest. These devices are rather expensive and are therefore adapted only to large Diesel plants. They may also be used in fully-automatic alternating-current Diesel electric plants.

One such device built by Allis-Chalmers and known as a Synchro-Operator is shown in Fig. 60. It functions by operating automatic frequency matching contacts which control a speed adjusting motor on the engine governor so as to obtain the correct speed for synchronizing. It then measures the phase angle between the incoming generator and the line, and at the proper time it closes the synchronizing contacts which operate the circuit-breakers and connect the machine to the line. It even allows for the lag in the circuit-breakers by closing the synchronizing contacts at a phase angle slightly in advance of true synchronism.

After the machine is paralleled, it is of course necessary for the operator to adjust the governor so that the machine takes its share of the load.

The same synchronizer may be used to parallel several units, only an additional auxiliary relay being needed for each unit.

Frequency-Matching. A simple method of bringing the incoming machine to the same frequency as the bus, preparatory to throwing in parallel, is to provide the Diesel engine governor with a "speed-matcher." This consists of two special three-phase squirrel cage induction motors and a differential gear mechanism. The horizontal shaft of the differential gear mechanism acts through suitable gearing on the adjusting spring of the governor. One motor

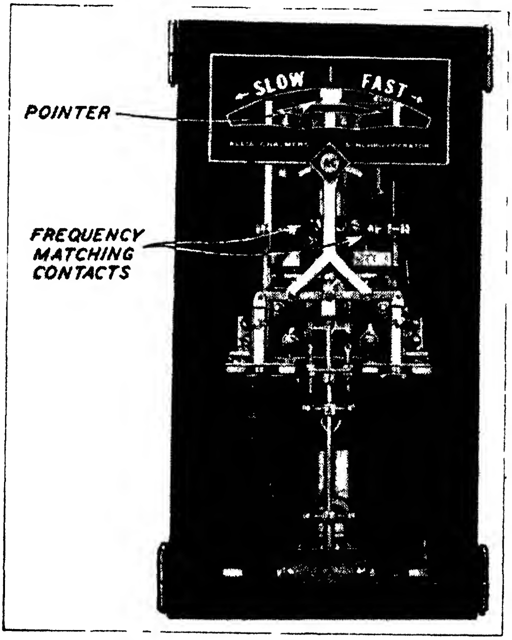


Fig. 60. An Automatic Synchronizer
Courtesy of Allis-Chalmers Manufacturing Co.

is connected to the bus and the other to the incoming machine, the first tending to increase the engine speed and the second to reduce it. The speed-matcher may be put into operation either by a manual switch or by a relay of an automatic synchronizer. Since the motors act in opposition to each other, any difference in speed between the unit and the bus (and consequently the two motors) will cause the horizontal shaft of the differential gear mechanism to adjust the tension of the adjusting spring of the governor to bring the speeds parallel as nearly as possible. When the frequency of the unit and bus are practically alike, both motors will be operating at the same speed and the shaft of the differential mechanism will cease operation and remain stationary.

Adjustment of Field Current. A generator operated in parallel with one or more other generators may have its excitation varied through a fairly wide range while delivering the same kilowatt output at rated voltage. A change in field current under these conditions changes the power factor of the generator. The field current may be set at its rated full load value for all loads or it may be varied depending upon the need for reactive kilovolt-ampere to the system and thus relieves the other generators of part of their burden. No change in kilowatt output can be effected by variation of the field current. This can be accomplished only by changing the setting of the engine governor.

The field current should be adjusted so that each generator (if the units are of equal size) produces the same amperes as well as the same kilowatts. This would show that they are operating at the same power factor.

Operation with field current lower than the value which gives 100 per cent power factor should usually be avoided since this imposes additional load in reactive kilovolt-ampere on the other generators. In addition it reduces the ability of the machine to stay in step with the system and may result in its being pulled out during periods of heavy load.

Satisfactory Parallel Operation. The requirements for successful parallel operation are as follows:

(1) The speed regulation of the Diesel engines should be alike. That is, the per cent drop in speed for a given per cent increase in load, should be the same on all units. The drop in speed from no load to full load may be only 2 per cent or less but if it is the same on all units which are in parallel, the total load will divide between them in proportion to their ratings.

(2) The governors of the Diesel engines should be free from hunting and should bring the machines to a steady speed without delay. Any oscillation of the governors will result in a transfer of load back and forth between machines and a fluctuation of the voltages.

(3) The generators should be equipped with damper or amortisseur windings. These increase the synchronizing forces, reduce the

fluctuations in rotor speed due to the engine firing impulses, and thus limit the cross-currents.

(4) The total flywheel effect of each unit should be such that:

(a) During parallel operation the maximum periodic displacement of the rotor in either direction from the position of uniform rotation should not exceed 3½ electrical degrees.

(b) The natural frequency of oscillation of the unit should differ at least 20 per cent from the frequency of any forced impulse of any of the engines operating in parallel.

Small high-speed Diesel engines generally have ample flywheel effect to meet these conditions, but care is needed in the case of slow-speed engines, particularly those with few cylinders.

The critical frequencies to be avoided are as follows:

(a) For a four-cycle engine: particularly one-half the revolutions of the engine crank but also the revolutions of the crank.

(b) For a two-cycle engine: particularly the revolutions of the engine crank, but also two times the revolutions of the crank.

For any given unit the natural frequency at which the rotor tends to oscillate can be changed by changing the flywheel effect, as shown by the following relation:

$$F=\frac{266{,}500}{\text{r. p. m.}}\sqrt{\frac{P_s x f}{WR^2}}$$

where F=natural frequency in periods or beats per minute

r.p.m. =revolutions per minute

P_s =kw. output when the rotor is continuously displaced from the no-load position by one electrical degree. This is a constant furnished by the generator manufacturer

f =frequency of generator in cycles per second

WR^2 =flywheel effect in lb-ft.^{2}

Example. For a 60-cycle, 150-r.p.m., direct-coupled generator having a value of P_s =33.5, and driven by a four-cycle engine, the natural frequency must not lie between 60 and 90 periods per minute, or between 120 and 180 periods per minute. That is, the total WR^2 (flywheel and generator) must not lie between 1,760,000 and 790,000 lb-ft.^{2}, or between 440,000 and 196,000 lb-ft.^{2}

MUNICIPAL POWER PLANT AT GOWRIE, IOWA

The two 225 HP Diesel engines are direct connected to 150 kw alternators The exciters are belt driven

Courtesy of Worthington Pump and Machinery Corporation

CHAPTER VI

ENGINE GOVERNORS—FREQUENCY AND LOAD CONTROL

The Diesel engine, when used for driving an electric generator, must be a constant-speed machine, i.e., its speed must remain within a few per cent of normal, regardless of load variations within its working range. This regulation of speed is accomplished automatically by a device known as a "governor," which is always standard equipment on Diesel engines intended for electric generating work. The governor regulates the delivery of fuel into the engine cylinders in accordance with changes in load so as to maintain the speed substantially constant. Actually the change in load must change the speed slightly in order to actuate the governor, and different types of governors vary as to the amount of speed change necessary to actuate them.

Mechanical Governors

In its simplest form, the governor consists of a pair of weights rotated off-center, their centrifugal force being opposed and balanced by a spring. For any given speed, the governor weights will take a definite position a certain distance from the axis. By means of a collar, the radial movement of the governor weights to and from the axis is transmitted to the regulating mechanism of the engine fuel injection pump.

Referring to Fig. 61 which shows the design of a simple but effective governor with its accompanying fuel injection pump, the governor weights *B* revolve about the axis of the vertical spindle which is geared to the engine itself. Centrifugal force tends to throw the weights outward and depress the sleeve, but is resisted by the main governor springs *A*. When the engine load is constant, the speed is also constant and the governor sleeve neither rises or falls. Should the load increase, the engine speed, and therefore the governor speed, will commence to fall, because the fuel injection pump is not feeding sufficient fuel to the cylinders to develop the increased power needed. The drop in speed, although quite slight, is sufficient to reduce the centrifugal force of the governor weights; this causes the main springs *A* to raise the sleeve until a new balance is obtained between the centrifugal force and the spring force. The upward movement of the sleeve is communicated by means of a collar and swivel *D* to lever *E*, which in turn moves the regulating mechanism of the fuel pump to a new position where the required amount of additional fuel is injected into the cylinders. Springs *F* are auxiliary or speed-adjusting springs.

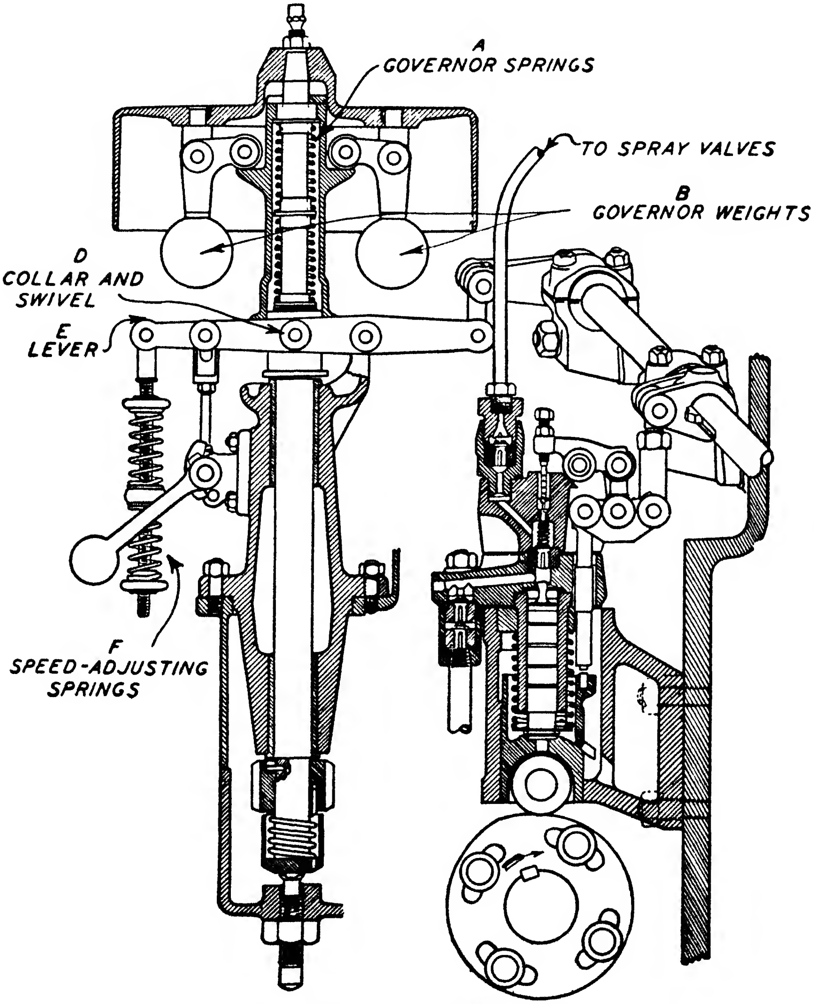


Fig. 61. De LaVergne Type of Governor and Fuel Pump

Definitions of Terms. The meanings of several terms commonly used in describing the characteristics of governor action are as follows:

Speed Droop. Speed droop is the decrease in steady speed of an engine caused by an increase in load from a no load condition to full-rated load, without change in the adjustment of the governor. This decrease in speed is expressed as a per cent of normal rated speed:

Speed droop in per cent

$$= \frac{(\text{no load speed} - \text{full load speed}) \times 100}{\text{no load speed}}$$

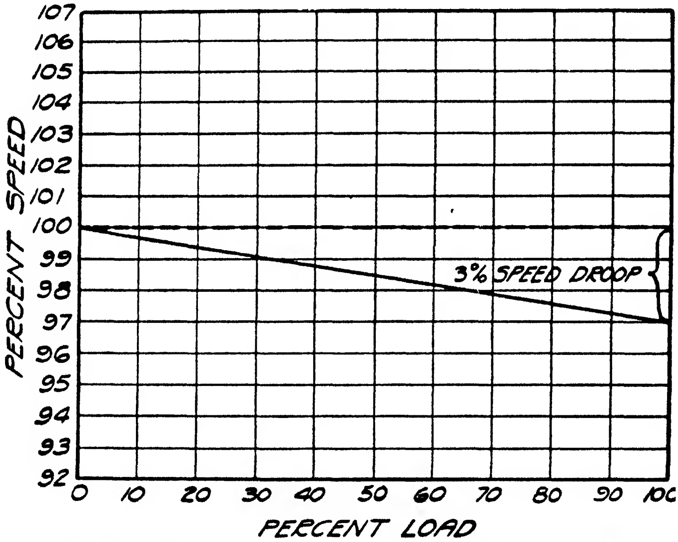


Fig. 62. Chart Showing Change in Speed as Load Increases
Courtesy of Woodward Governor Co.

Speed droop is illustrated in Fig. 62 which is a speed and load chart for a Diesel engine governor with 3 per cent speed droop. The speed decreases 3 per cent when the load increases from zero to full load. When half load is thrown on, the speed will reduce one-half of 3 per cent or 1½ per cent, etc.

The simple governor described above operates with speed droop, and it is, in fact, an inherent feature of most governors.

Isochronism. A governor which regulates engine speed so that there is zero speed droop, is termed isochronous.

Momentary Speed Changes. Momentary or transient changes of engine speed caused by sudden, as opposed to gradual, changes in load (also termed instantaneous speed changes) are expressed as the per cent increase or decrease of speed as referred to normal speed.

Sensitiveness. The per cent of speed change required to produce a corrective movement of the fuel control mechanism is called the sensitiveness of a governor.

Some Diesel engine manufacturers offer two different types of governors for their engines, (a) standard, or (b) electric-type. The former is intended for mechanical drives such as direct-connected compressors, pumps or line-shafts, while the latter is a more sensitive and powerful device for closer speed regulation. Even so, there is a wide variation in the demands upon electric-type governors depending upon the nature of the service. The easiest electric service from the governing standpoint is a single generating unit supplying a load that is steady or that changes only gradually. Here the governor has plenty of time to act and the main requirement is that it have sufficient power to operate the fuel pump regulating linkage to maintain a reasonably constant speed. If the load is subject to rapid variations, the governor must have more power or sensitiveness in order to respond quickly to the load changes.

Governing for Parallel Operation

Direct-Current Generators. When two or more Diesel engines are driving direct-current generators, the governing requirements become slightly more severe, inasmuch as the distribution of the load between the units is proportional to their generated voltage, which in turn depends upon their speed. Thus if two units with different speed droops are adjusted for the same voltage at no load, the unit with the greater speed droop will take less than its share of the load when the load comes on. Consequently, for satisfactory division of the load between the machines at all outputs, the engine governors should have the same, or nearly the same, speed and load characteristics.

Alternating-Current Generators. The governors of Diesel engines driving alternating-current generators must fulfill much more severe requirements than in the case of the direct-current machines. This is because the amount of load taken by a paralleled alternating-current generator depends directly upon the position of the engine governor, *not* upon the generated voltage. Consequently, governors for this service must be readily adjustable while in motion so that the rate of fuel injection (and the engine speed when the unit is operating unparalleled) may be changed gradually and accurately. The speed-adjuster is used, before paralleling, to match the frequency of the incoming machine with that of the line so that it may be synchronized and paralleled. Also, after paralleling, the speed-adjuster must be moved in the direction to increase speed, in order to transfer the desired amount of load to the incoming machine.

Speed-Adjusters. In simple forms of governors, the method of adjusting the engine speed is to adjust the tension either of the main governor springs which oppose the centrifugal weights, or of an exterior, auxiliary spring which acts upon the governor collar and thus supplements the effect of the main springs. The latter method is used in the governor shown in Fig. 61, *F* being the auxiliary springs. For example, with the engine running unparalleled at any given load, if the spring tension acting against the weights is increased, the weights will be momentarily drawn in toward the axis, the governor sleeve will rise, the engine will receive more fuel and will accelerate until the governor again stabilizes but at a higher speed.

Adjustable governors for Diesel engines driving alternating-current generators are generally provided with a range of adjustment of about 5 per cent above and below rated speed.

The actual adjustment of the governor springs may be performed in two ways: (a) directly at the engine by manually turning a hand wheel or lever, and (b) by remote control from the switchboard through switches or relays which control the current supplied to a motor mounted on the engine governor and connected, generally through worm gear drive, to the spring-adjuster.

Direct control is used for nonparalleled machines, alternating-current and direct-current, also for paralleled direct-current machines, because in these cases there is no need of making speed adjustments from the switchboard. Remote control is, however, frequently used for alternating-current machines running in parallel because it permits one man to stand at the switchboard and control the whole operation of synchronizing. He is able to watch the synchronoscope, adjust the speed of the incoming machine in small steps as required, and close the circuit-breaker when synchronism is obtained. Remote control also enables one man to adjust the load distribution between two or more machines without leaving the switchboard.

Speed Droop. Speed droop of the Diesel engine governors, which is the percentage reduction in engine speed at full load compared to no load, is vitally important in the satisfactory operation of alternating-current machines in parallel because it determines the re-distribution of the load among the several machines whenever a change occurs in the load as a whole.

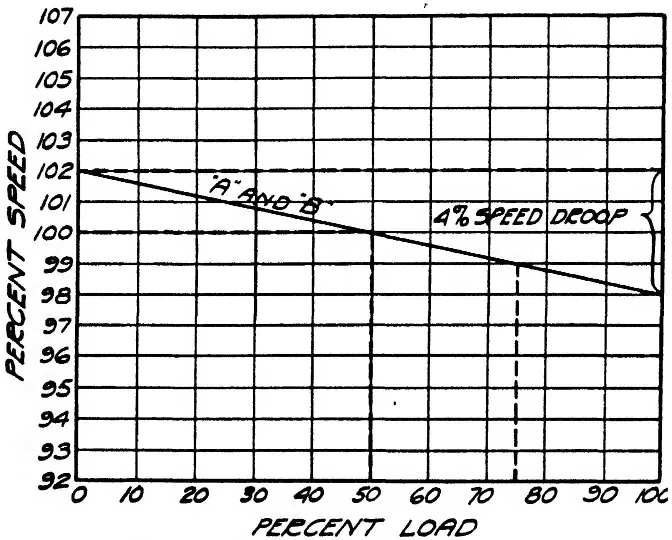


Fig. 63. Chart Showing Equal Speed Droops
Courtesy of Woodward Governor Co.

Take, for example, two Diesel engines *A* and *B* whose governors both have 4 per cent speed droop (from 102 per cent speed at no load to 98 per cent at full load), as shown in Fig. 63. Then each engine will follow the same speed-load line and, therefore, at all times divide the total load equally between themselves. Thus, if they are each carrying half load at 100 per cent speed and the load increases to 75 per cent of full load, the speed of both will reduce to 99 per cent, as shown. If the load reduces to zero, the speed will rise to 2 per cent above normal. They will remain in exact parallel. The amount of speed droop required to produce proper parallel operation depends upon the particular governors but is usually 3 per cent to 6 per cent with simple types of governors.

Now take an example where the speed droops of two paralleled units are unequal. Referring to Fig. 64, assume Diesel units *A* and *B* to have a capacity of 100 kilowatts each. The governor of *A* has a speed droop of 4 per cent while that of *B* has only 2 per cent. Assume that they have been adjusted so that each unit is carrying 50 kilowatts at 100 per cent speed. If now a load of 75 kilowatts is added, both engines will naturally slow down until their governors take new positions that will feed the engines with the additional fuel required. The new speed of each engine will of course be the same, since their generators are paralleled. Inspection of Fig. 64 shows that the new speed will be *X-1,* or 99 per cent; unit *A* will carry a load of 75 kilowatts as per *X*, while *B* will carry 100 kilowatts and thus become fully loaded. Note that *B,* which has a speed droop only half that of *A*, takes twice as much of the added load as *A*. Conversely if the units are half loaded at 100 per cent speed and a 75 kilowatts load is dropped, *B* will drop 50 kilowatts and be completely unloaded and *A* will drop 25 kilowatts and be 25 per cent loaded, as per *Y*. The resultant speed will be 101 per cent, as per *Y-1.*

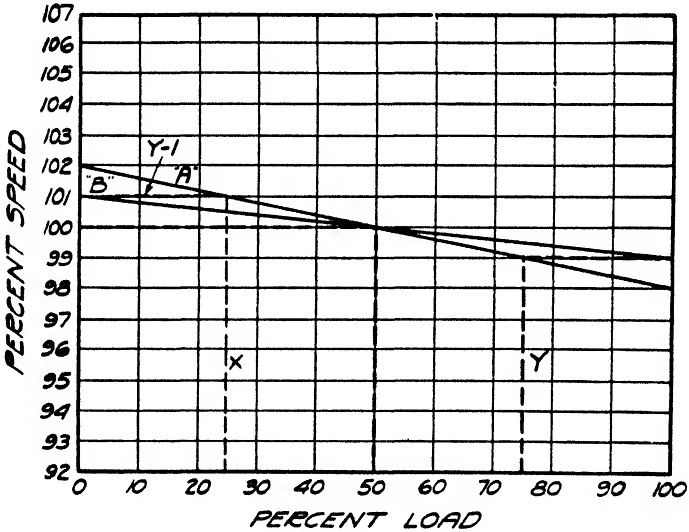


Fig. 64. Chart Showing Result of Paralleling Units with Unequal Speed Droops

Courtesy of Woodward Governor Co.

From the foregoing, it is clear why in actual plants it is sometimes found that one of the units has a tendency to "hog" the load. This could be prevented if its governor characteristics could be altered so as to increase the speed droop; such a fundamental change is, however, impracticable in most cases because it would be necessary to change the construction of the governor.

Frequency Control. Speed droop is an inherent characteristic of simple governors, and even if satisfactory division of load is secured by using governors with equal speed droop, the frequency will vary with the amount of load unless the governors are adjusted by hand every time the load changes. The correct *average* frequency can be measured by using a synchronous clock and comparing its indications with those of a high-grade standard clock or with those of another synchronous clock operated from an independent electric system of known accuracy. In plants requiring constant frequency and having variable loads, hand adjustment becomes burdensome if not impracticable.

Speed control has assumed increasing importance in modern industry during recent years. The nature of the product in various industries, such as textile, flour and paper mills, printing plants, etc., requires practically constant speed to secure a uniform standard of manufacture. Motion picture production and projection, radio broadcasting, electric clocks, etc., are all inherently dependent for satisfactory results on constant frequency. Other plants require extremely close voltage regulation, and constant speed is a very important contribution.

Hydraulic Governors

These reasons have justified the development and application of highly refined types of Diesel engine governors that operate by hydraulic means and are able to control the speed and frequency with far more accuracy than the simpler types of governors. The speed droop of some of these hydraulic governors can be adjusted easily and can even be reduced to zero. In this case the governors maintain perfectly uniform frequency independent of the load and are called "isochronous."

The conditions that determine the amount of engine speed deviation from normal for a certain percentage load change are as follows:

(1) The time required to correct the rate of fuel injection to correspond with the new load.
(2) The amount of flywheel effect in the engine and generator.
(3) The time required for the engine to respond to the change in rate of fuel injection.

Theoretically, if it were possible to detect the instant of and magnitude of the load change and instantly and accurately correct the rate of fuel injection and the Diesel engine would respond instantly, the speed would never change regardless of the size, and the number of load changes. That, however, is impossible due to practical limitations. Therefore there will be a certain amount of time elapsing between the instant of load change, the correction of the rate of fuel injection and the response of the engine. The flywheel effect, in absorbing or supplying energy, will for a brief period (depending upon the amount of flywheel effect) act to hold the speed constant—but only for a very brief period. The less time lost, then, between the instant of load change and the instant of fuel injection correction, the less will be the speed change for a certain amount of flywheel effect. This indicates the importance of time as a factor in governor performance. Some hydraulic-type governors combine sensitive indication with powerful control to such a degree that their sensitivity is better than 1/100 of 1 per cent, that is, the governor responds to a speed change of less than that amount, and furthermore is capable of shifting the fuel pump mechanism from full load position to no load position or vice versa in less than one quarter of a second.

Woodward Hydraulic Governor. An isochronous governor of this type, built by the Woodward Governor Co., and known as Type IC, is shown in schematic form in Fig. 65. It consists principally of a control unit, a power unit, and an oil pressure unit.

The *control unit* consists of a sensitive governor head, positively driven from the engine shaft, the function of which is to indicate to the power mechanism the instant of and magnitude of every change in engine speed; a compensating device that checks the power mechanism when the fuel supply to the engine cylinders has been changed the correct amount for the change in load; a load indicator; a load limit to permit limiting the amount of load the unit is to carry; an adjustment to permit the introduction of speed droop when and in the amount desired; and an adjustment for varying the speed of the unit for synchronizing.

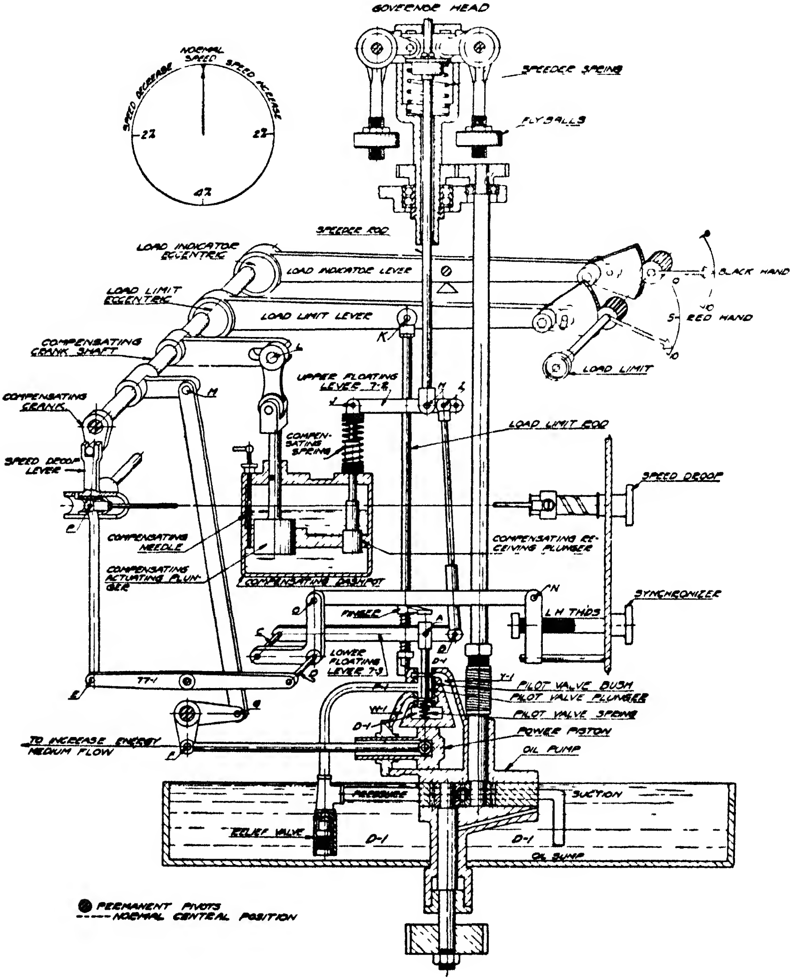


Fig. 65. Woodward Type IC Hydraulic Governor

The *power unit* consists of a pilot valve, servo-motor and mechanical linkage. The pilot valve is mechanically connected by means of floating levers and rods with the governor head and hydraulically with the servo-motor. This valve is of the sleeve type and is so finely balanced that it requires but an infinitesimal amount of power from the governor head flyballs to operate it. The servo-motor is an oil cylinder with a close fitting piston that connects by means of the piston rod with the mechanical linkage. The mechanical linkage varies for different types and makes of engines but in each case forms a mechanical connection between the servo-motor and the engine fuel control mechanism.

The *oil pressure unit* consists of a rotary gear type pump, positively driven from the engine shaft, a spring loaded relief valve, and a sump tank to contain the necessary governor oil and so constructed as to form the base of the governor. The pump operates continually and is completely immersed in oil. The spring loaded relief valve maintains constant and instantly available oil pressure, which is the actual force employed by the pilot valve to control the servo-motor and, consequently, the engine fuel control mechanism.

Isochronous action is obtained by the action of the compensating device which, after the governor has responded to a change in load, quickly restores the pilot valve to its original position and brings the engine speed back to its former value without changing the amount of fuel injection. An adjustment is provided on this compensating device so that, if desired, the engine speed may be permitted to change slightly when a change of load occurs; in this way the governor may be given any desired speed droop from zero to about 5 per cent. Where several units operating in parallel are equipped with Woodward hydraulic governors, and it is desired that they shall share the load in fixed proportions throughout the whole load range, it is necessary to adjust the governors for speed droops of about ½ per cent or 1 per cent (identical amounts, of course, being used for each governor). The frequency will thus vary with the load, but not as much as with mechanical governors with inherently larger speed droop. (If the several governors were adjusted for zero speed droop, i.e., isochronism, the load distribution between the units would be unstable and impracticable.)

Parallel Operation at Constant Frequency. An isochronous governor and one or more governors employing speed droop can be operated in parallel *if the engine with the isochronous governor has sufficient capacity to take all load changes.* The advantage of such a plan is that constant frequency can be maintained in a whole power plant by using only one isochronous governor.

The manner of operation is shown in Fig. 66. Assume engines *A* and *B* operating in parallel and adjusted so that each engine has 50 per cent of rated load. If more load is added, *A* will keep the speed up to normal and take all the added load, while *B* will remain at its initial 50 per cent loading because the speed has not permanently changed. In other words, *A* may go from no load to full load and *B* will remain at its initial load. If the load changes are rapid, *B* as well as *A* will start after the load providing the governors are of equal sensitivity, but *B* will always return to the same loading while *A* will always finally assume the entire load change. The resultant speed will always be 100 per cent.

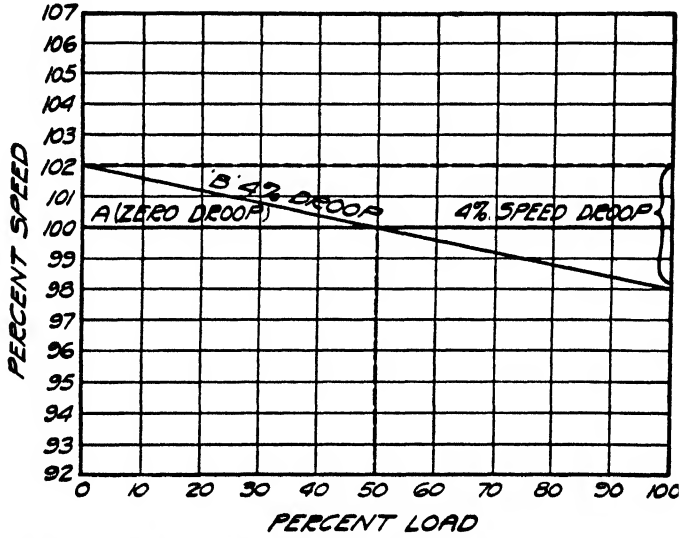


Fig. 66. Curve Showing Load Taken by Two Generators, One Governor Being Isochronous

Courtesy of Woodward Governor Co.

The accuracy of this form of frequency control is indicated by the willingness of one governor manufacturer to guarantee to maintain time over 24 hours with a time error of less than ten seconds without any manual adjustment. Actual tests showed an error of less than three seconds.

Electric Frequency Controllers

Electrical methods of controlling frequency have been developed which supplement the Diesel engine governors and automatically maintain constant frequency in a multiple-unit plant while distributing the load among the several units so that all participate equally in the regulation. This is not possible with mechanical or hydraulic governors alone. On the other hand, it must be borne in mind that an electric frequency controller is a device that measures the frequency at intervals, generally two seconds, and then operates not on the fuel injection systems of the engines themselves, but merely on the adjusting springs of the engine governors. For this reason the electric frequency controller cannot be expected to supplant or improve the action of the engine governor in its functions of sensitive response to speed (load) changes, and quick, positive control of the engine fuel injection system. All the electric frequency controller can do is to regulate the frequency and the distribution of load over periods of two seconds or more; for shorter periods, the task falls on the engine governors, fuel control mechanisms, and flywheels.

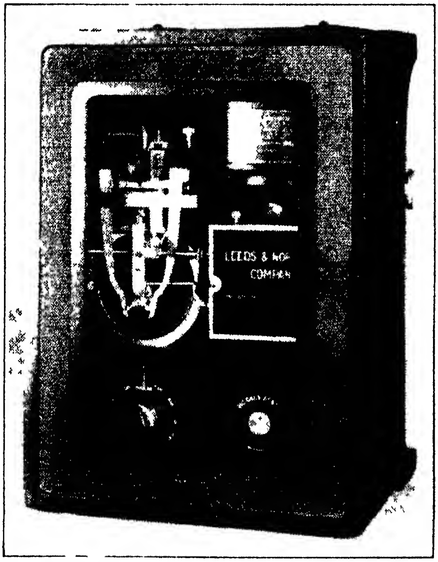


Fig. 67. Leeds and Northrup Electric Frequency Controller

The heart of an electric frequency controller, Fig. 67, is the frequency-sensitive bridge, or impedance bridge, the circuit of which, as used by the Leeds and Northrup Company, is shown in Fig. 68. Of the four arms of the bridge, two consist of non-inductive resistances, *D* and *E*, while the other two consist of combinations of non-inductive resistances and condensers. Of the latter two, one contains resistance *A* in parallel with condenser *C*, while the other contains resistance *B* in series with condenser C_1. The balance point of such a bridge is extremely sensitive to changes in frequency and, therefore, the circuit makes possible a sensitive frequency measuring instrument.

The arrangement constitutes a balanced or null bridge in which changes in line voltage or changes in sensitivity of the galvanometer cannot affect the accuracy. The only contacts in the bridge are in the galvanometer circuit where variation in contact resistance can cause no error.

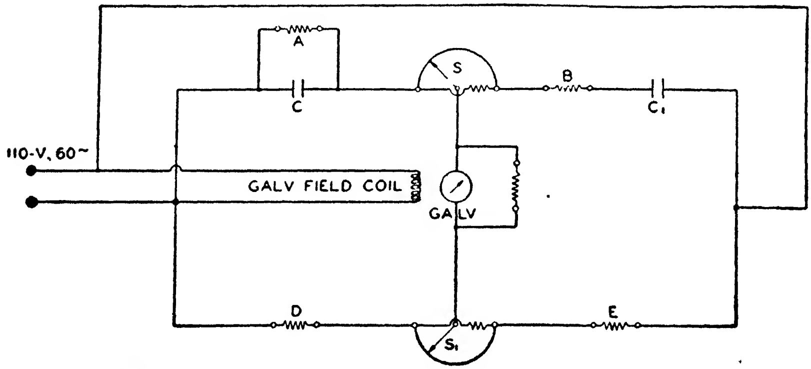


Fig. 68. Diagram of Leeds and Northrup Frequency Controller

The two moving contacts *S* and S_1 are mechanically connected and move together. One of these moves over a compensating resistance which makes the balance point independent of the phase of the current in the field coil.

The operating mechanism, for the simple case of controlling a single generating unit, is shown schematically in Fig. 69. When the frequency varies from the control setting, the controller galvanometer, which is simply a detector of current unbalance, is deflected in a direction depending upon the unbalance current through the bridge. The direction of this current is in turn determined by whether the frequency is high or low. The deflection of the galvanometer pointer is picked up by the controller mechanism, and closes contacts which operate the governor-synchronizing motor, changing the tension on the governor spring, thereby changing the amount of fuel injection.

This controller is called a "proportional-step frequency controller" because of the design of the cams and contact mechanism whereby the duration of the impulse sent to the governor-adjusting motor is directly proportional to the amount of deviation of the frequency from the control setting. This means that the greater the deviation from the control setting, the greater the correcting impulse, and as the frequency approaches the control point, the correcting impulse is correspondingly decreased. This feature accomplishes two things—first, it brings the frequency back to normal much more rapidly than an impulse of unvarying duration, and second, it pre-

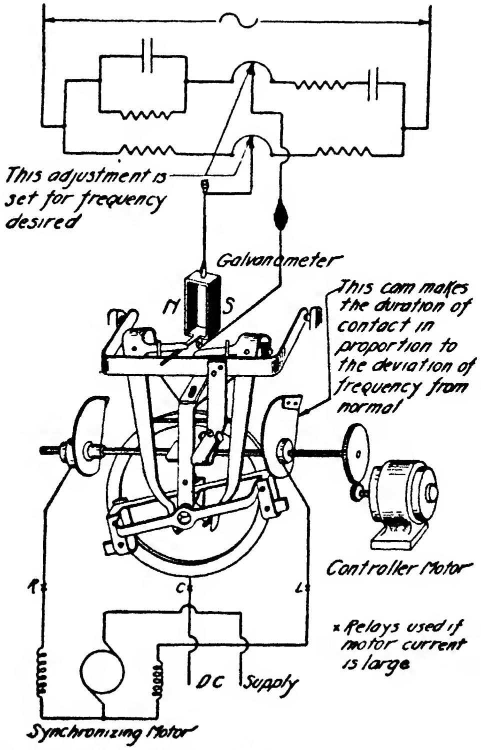


Fig. 69. Diagram of Leeds and Northrup Frequency Controller Showing Connections to a Single Generator

vents overtravel or hunting. The frequency controller is sensitive to variations in the order of 0.01 of a cycle.

Multiple-Unit Frequency and Load Control. In a plant containing two or more units operating in parallel, a separate electric frequency controller may be applied to each unit, together with load-indicating devices, whereby any one unit in the plant may be selected to operate on flat frequency control (equivalent to isochronism in an engine governor), and the other controllers used to distribute the load automatically among the remaining units in proportion to their capacities. The schematic diagram of the Leeds & Northrup system is shown in Fig. 70. Unit No. 1 is on flat frequency control, the galvanometer of its controller being connected in the frequency bridge, and unit No. 2 is connected for proportionate load control.

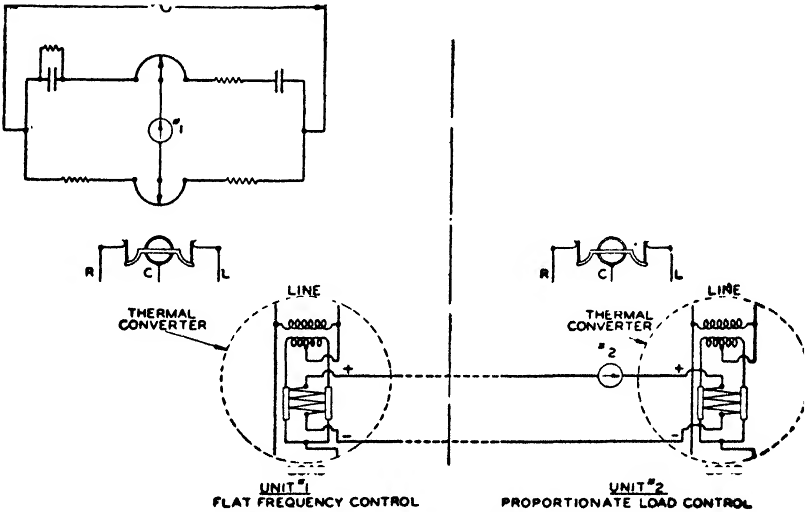


Fig. 70. Leeds and Northrup Multiple-Unit Frequency Control

A Lincoln thermal converter is placed on each unit, and operates like a wattmeter except that instead of indicating the load, it produces a low voltage direct-current potential which is proportional to watts. This potential form unit No. 1, which is regulating the frequency, is opposed through the galvanometer of unit No. 2 to the potential of a similar thermal converter located on unit No. 2. If, under normal conditions, the load on unit No. 1 is equal to the load on unit No. 2, or in the proper predetermined fixed ratio, these potentials will be equal and the galvanometer on unit No. 2 will indicate a balance.

If, on the other hand, the load on unit No. 1 should increase (either because of the action of its frequency controller or because of an increase in total plant load) and should become greater than the load on unit No. 2, the potential produced by its thermal converter will be greater than that produced by the thermal converter on unit No. 2, and the galvanometer on unit No. 2 will indicate this unbalance. This deflection of the galvanometer will cause the mechanism in controller No. 2 to operate to increase the load on that unit until the potential produced by its thermal converter is exactly equal to that produced by the thermal converter on unit No. 1, or in other words until the load on the two units is equal.

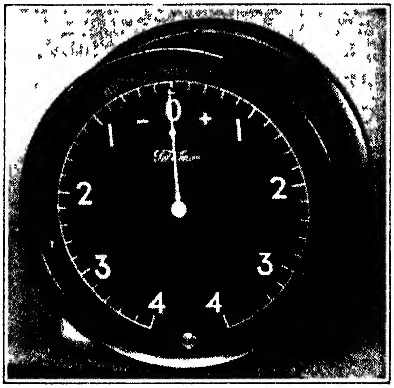


Fig. 71. Time Deviation Indicator from True Frequency
Courtesy of Leeds and Northrup Company

In similar manner, when additional units are placed under load control, the potentials of their thermal converters are opposed through their galvanometers to the potential produced by the converter on the master unit, as is shown for unit No. 2. Therefore, it is apparent that as unit No. 1, in controlling frequency, picks up or drops off load, the controllers on the remaining units will cause them to pick up or drop off in the same manner, with the result that the load changes will be divided among all units in the plant.

By this arrangement the load distribution is automatically maintained so that there is no tendency for an unbalance of the load among units in the station regardless of differences in their individual governor characteristics, and at all times all units under control share equally in the frequency regulation.

Automatic Control of Integrated Frequency. Even with frequency checked and corrected every two seconds, small discrepancies may gradually accumulate and produce an error in the time shown by synchronous clocks. This can, of course, be corrected by hand-regulation. However, by adding certain accessories to those described above, such deviations from true time can be automatically corrected before they become noticeable by slightly increasing or decreasing the frequency for a short time. The comparison is made by a "time deviation indicator," one form of which is shown in Fig. 71. This device receives accurate time impulses from a high-grade pendulum clock, as well as synchronous time from the system which it is controlling. The dial of the indicator shows the difference, up to 4 seconds fast or slow, at any instant between synchronous time and pendulum time. The indicator also operates a biasing slidewire which raises or lowers the balance point of the impedance bridge in the frequency controller, so that the latter raises or lowers the frequency slightly to the extent necessary to correct the synchronous time.

CHAPTER VII

AUTOMATIC DIESEL ELECTRIC PLANTS

The high cost of continuous attendance in Diesel plants of small and moderate size has acted as a strong incentive to the design and use of automatically operated plants.

In the usual Diesel power plant, the attendants' duties are comparatively few. The engines must be started and stopped. The lubrication and water supply must be maintained in order to assure uninterrupted service and to prevent the engines being damaged by overheating of the bearings, pistons, cylinders, or cylinder heads. Obviously the fuel supply must also be maintained. Wear and tear must be noted, whether it be the gradual result of normal operation or the sudden effect of some derangement. In electric plants it is necessary to regulate the voltage. The foregoing are the most important matters with which the attendant is concerned; there are others, but if those mentioned are looked after, the rest are easy.

Experience has shown that it is perfectly practicable to provide automatic or semi-automatic controls in the Diesel plant to take the place of most of the personal supervision. The attendant need not be stationed in the engine room and may be assigned to productive work. In completely automatic plants only occasional inspection and maintenance is necessary.

Not only does such an arrangement greatly reduce the power plant payroll expense, but it also leads to improved operating conditions. Automatic controls have several advantages over human superintendence. They act promptly as soon as the need for action arises, while with manual guidance a delay is inevitable until the operator's attention has been attracted and he manipulates the necessary controls. This is emphasized where frequent changes in conditions occur.

Semi-Automatic Diesel Plants

A semi-automatic Diesel plant is one in which the starting and stopping of the engine or engines is done by an attendant, while automatic controls and safeguards are on watch at all times during operation.

Starting. The starting of a Diesel engine requires several operations. Ordinarily, the engine must be barred to the starting position; the lubricating system primed; the water supply opened; the starting air turned on; and the fuel admitted, after which the starting air must be turned off and the engine given its load. (Of course where engines are started electrically, the electric starter must be operated instead of the starting air.) In plants where engines are started only once or twice a day, it will not be worth while to arrange for automatic starting since not much of a man's time is required to go through these several operations. Furthermore, when an engine is started only infrequently, the opportunity should be used to give it an inspection before setting it in motion.

Lubricating System. An engine is no more reliable than its lubricating system. Any failure in lubrication will not only cause an immediate shut down, but it is also likely to result in considerable damage in the form of wiped bearings or scored pistons. Modern Diesel engines almost invariably employ pressure or force-feed systems arranged to deliver oil to all important parts. Hence, human attention is required not for actually supplying the oil, but merely for checking the correct functioning of the pressure system.

It is a simple matter to safeguard the lubricating oil pressure. A double oil circulating system can be arranged using two pumps, one driven directly by the engine, the other by electric motor. The two pumps operate in parallel, delivering to the same oil supply header. Either pump will maintain sufficient pressure if the other fails.

With duplicate pumps a loss of pressure due to pump failure is extremely unlikely. However, a broken pipe connection might cause the pressure to drop. This can easily be guarded against by installing an electric contactor which will sound a gong or klaxon when the pressure drops to a predetermined figure.

Should the warning be unheeded or the attendant be unable to remedy the trouble before the oil pressure is entirely lost, an automatic device will shut down the engine before any damage is done. A simple method of accomplishing this is to have a small piston or metal bellows receive the lubricating oil pressure, preferably from the far end of the header. When the pressure drops too low, the motion of the piston or bellows stops the engine fuel pumps. Where further safeguards would be justified, pyrometers can be inserted in the main bearings and arranged to sound an alarm when the temperature rises too high.

Water Circulating System. In many Diesel plants the water for the cylinder and cylinder head jackets is delivered by gravity from an overhead tank. This ensures a continuation of the water supply for a certain length of time should the circulating pump fail. It also facilitates cooling off the engine after it has been shut down and provides a temporary supply of water while the engine is being started the next time.

The overhead tank system can easily be equipped with as many safeguards as may be desired for self-controlled operation. With a recirculating system the pump capacity should always exceed the maximum requirements of the engine so the overhead tank will be full and overflowing at all times.

In plants that are not continuously attended, an alarm system can be readily applied that will make a suitable signal when, for any reason, the overflow ceases from the supply tank and the water level starts to fall. Should the signal be disregarded and the water level continue to fall, a float valve in this tank connected to the city mains will open and maintain the supply to the engine. Meanwhile the alarm will keep sounding until the attendant has rectified the derangement in the regular pumping system.

In some plants the jacket water is contained in a closed system comprising radiators or heat-exchangers, and a continuous recirculation is maintained by pumps. In such systems there is little danger of loss of water, but the possibility of excessive jacket temperature must be guarded against. Simple thermostatic devices are available for automatic control of the volume of flow to maintain a constant water discharge temperature regardless of the amount of load. In addition, a thermostatic contact device may be applied to the water outlet which will give an alarm when the temperature rises too high.

Fuel System. In one respect the maintenance of the fuel supply is not as vital as the lubrication and water, because a lack of fuel will merely result in a shut down without doing any damage to the engine. All stationary engines are equipped with governors to maintain constant speed by controlling the amount of fuel to suit the load. These governors are built into the engines and are exceedingly reliable. However, if it is desired to safeguard against the possibility of a runaway engine, an overspeed stop may be installed which, in case of excessive speed from any cause, will stop the engine either by shutting off the fuel pumps or by holding the exhaust valves open.

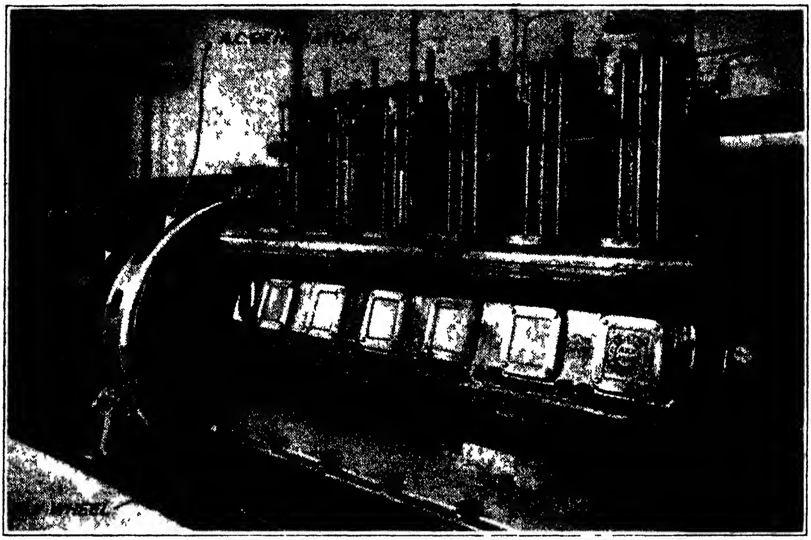


Fig 72. Semi-Automatic Diesel Electric Plant

Electrical System. In Diesel electric plants of the automatic type, the electrical system is of course provided with all the usual electrical controls and safeguards such as automatic voltage regulators, circuit breakers, and fuses.

If the lubrication and water supply is assured by the measures just described, only occasional visits are necessary to inspect the general performance of the engine, as it is not likely that any sudden derangement will occur which will require immediate attention. In fact the inspection of such plants may be made according to a predetermined schedule so the various engine parts receive the amount of care which experience has shown they require.

A semi-automatic Diesel electric plant of 160-kilowatt capacity, designed by the author in accordance with the foregoing principles, is shown in Fig. 72. This plant supplies the entire electrical requirements of a structural iron works. The engine room is situated next to the tool room of the factory, and the power plant was so designed that a tool room machinist, regularly occupied near the intervening doorway, could also take care of the power equipment without losing more than 1½ hours per day from his productive work.

The machinist starts and stops the engine at the beginning and end of the working day and also at the noon period. This takes so little time that it would not pay to install automatic devices for the purpose.

Fully-Automatic Diesel Plants

For a plant to be fully-automatic it is necessary that the engine or engines start up and connect their generators to the line one by one as the load requires it, and that they disconnect and shut down when the load demand falls off. While in operation, they must of course be fully controlled and safeguarded as in the case of semi-automatic plants.

Applicability. Among suitable applications for automatic Diesel power plants may be mentioned the following:

(1) Light and power service for large city buildings, such as office and loft buildings, institutions, department stores, hotels, clubs, and apartment houses.

(2) Development of outlying sections by electric public utilities where the load at present is too light to justify the construction of transmission and distribution lines.

(3) Reinforcement of heavily loaded transmission lines.

(4) In combination with steam power plants, where there is need for low-pressure steam for heating or process work and where Diesel engines can be effectively used to improve the heat balance and reduce overall costs. In such plants the Diesel engines can be arranged to start automatically as soon as the process-steam demand falls off and causes a rise in the steam engine back pressure.

(5) Suburban and country estates where central-station service may be unavailable, costly, or unreliable.

(6) Stand-by plants. In some industries, such as rayon, a power outage causes great losses because it interrupts important continuous processes. An automatic Diesel plant may be used

which will start instantly when the outside power service is interrupted. The laws of many states require that coal mines be provided with auxiliary power in case of emergency.

(7) Railroad water-pumping stations, which are often located in sections isolated from public-utility lines.

Single-Unit Plants. It is comparatively simple to arrange for automatically starting and stopping a single Diesel electric unit. One of the first fully-automatic Diesel plants to be built contains a single 25-kilowatt unit. A storage battery forms part of the outfit, and whenever the electric demand exceeds the rating of the battery, the Diesel generating unit is automatically started with battery current. It then continues to run at full load, not only supplying the electric demand but also charging the storage battery. When the demand drops below the capacity of the battery and the latter has been given a full charge, the Diesel unit is automatically shut down. Electrical means are provided for disconnecting the generator from the battery and sounding a klaxon horn if, for any reason, the engine does not start within two minutes after the attempt is made.

Stand-By Plants. In this service the Diesel generating equipment is used as stand-by to an outside source of power and does not operate as long as the outside source is available. In case of failure of the outside power supply, the Diesel unit starts automatically and carries the load until the outside service is restored.

Details of the switching mechanism for this service may vary to considerable extent, but in general the following is needed:

(1) A relay to operate one set of contacts when line conditions are normal, and another set when the outside power supply fails.

(2) Automatic starting mechanism for generating units to be set in action by the relay upon failure of the outside source of power.

(3) An automatically operated transfer switch for transfer of the load from the outside source of power to the generating units after the latter are brought up to speed.

(4) Upon resumption of normal conditions on the line, the relay (1) closes contacts for this condition and causes the switch mechanism to stop the generating unit, and switch (3) throws the load back to the outside source.

Multiple-Unit Plants for High-Grade Service. An independent, fully-automatic Diesel electric plant for supplying a city building generally comprises several units and must render a superior class of service. The essential requirements are as follows: (1) Units must be started and stopped one by one in accordance with the line load; (2) the engine supply services must be thoroughly safeguarded; (3) in case of trouble with any unit it must be shut down, and another put in service; (4) perfect voltage regulation must be maintained under all conditions, including load surges, starting operations, or difficulties.

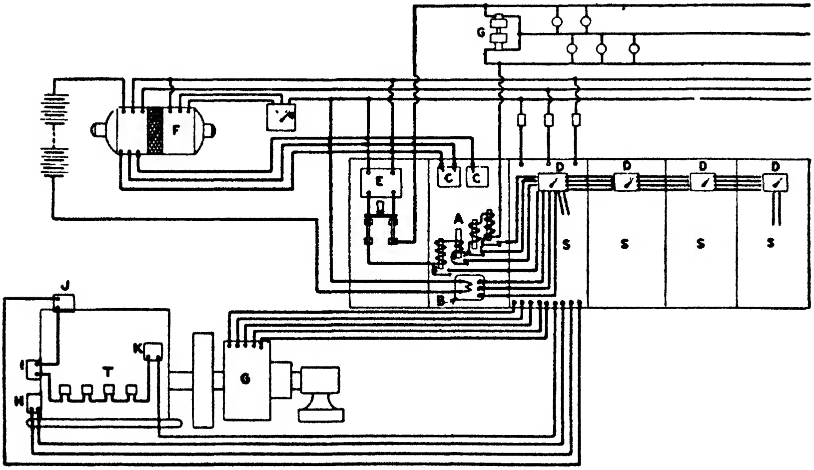


Fig. 73. Diagram of Strong's Multiple Unit Control

A—Relays
B—Amperehour meter
C—Booster control
D—Control for rotation of starting order
E—Watthour meter
F—Motor-driven booster
G—Generator
H—Compression relief
I—Oil pressure control
J—Water temperature control
K—Fuel oil pressure control
P—Exhaust pyrometer
S—Control panel
T—Bearing temperature control

Strong's System for D.C. Plants. Several fully-automatic multiple-unit Diesel electric plants have been installed in city buildings in accordance with the patents and designs of C. F. Strong. A storage battery is used, which performs several important functions: It supplies energy for starting the Diesels, provides a reservoir of quickly controlled energy to supply sudden current demands without loss of voltage, and provides an emergency reserve of power. A schematic diagram giving the essential features of the Strong automatic system for a four-unit plant is shown in Fig. 73.

The control panel of the switchboard is provided with a number of spring-loaded relays in series with the line, one for each engine. The relays are adjusted so that with an increase of load on the building feeder lines they act and cause the engines to be started.

These switchboard relays are set so that so long as the amount of current flowing to the building lines does not exceed a certain value only one engine is kept in operation. But just as soon as the current increases beyond the capacity of the first engine a second unit is started; when the load goes beyond the capacity of the two units, the third engine is started and when the full load rating of the three engines is exceeded, the fourth engine is started. As the load decreases, the engines are stopped in sequence so that the operating units have an economical load factor. As long as an engine is idle, the exhaust valves are held open by a spring opposing a solenoid, thereby preventing the cylinders having any compression. Likewise, the governor mechanism controlling the by-pass valves of the fuel pumps is held open by a spring of the governor solenoid in such a position that the fuel pump by-pass valves are open, preventing the injection of fuel into the engine cylinders.

When the load requires the starting of an engine, the generator is caused to act as a motor from current supplied by the battery, bringing the engine up to about half speed. When half speed is reached, the solenoid operating the compression relief mechanism is energized and full compression is thrown on the engine.

If the lubricating oil pressure is up to normal and if the bearing and cooling water safeguards are in the "safe" position, the solenoid controlling the fuel pumps is energized, releasing the fuel pump to the control of the engine governor and causing it to deliver fuel to the injectors. The engine then fires and accelerates to normal speed.

When the voltage of the incoming generator equals that of the bus, the main and equalizer switches are closed, whereupon the generator comes on the line and, by reason of its compound fields, automatically takes on its share of the load.

The engine starting contactors are provided with dashpots so that a unit will not be started until the increased load holds for a certain period. Also there is a difference between the start and stop settings of the load relays. In this way unnecessarily frequent starting and stopping is avoided.

Stopping of the engine is caused by de-energizing the engine fuel and compression relief solenoids. The springs already mentioned then cause engine compression to be relieved and fuel oil supply to be cut off. Low lubricating oil pressure or excessive temperatures of water or bearings breaks the circuit to the fuel solenoid, thereby stopping the engine.

The electrical controls are very sensitive and are able at all times to disconnect the generating unit from the line if it fails to develop its correct voltage or develops mechanical or operative trouble. Infrequent, but possible, troubles, such as a dragging piston, hot bearing, failure of cooling water supply or loss of oil pressure, cause the defective unit to be stopped and the spare unit to be substituted. A trouble indicating circuit is arranged to operate a signal when the spare unit is forced in operation.

Continuity of service is carefully safeguarded. Each generating unit, its controls, and fuel supply, are completely separate from the other units, the only common points being the fuel oil storage tank at one end of the engine room and the common bus bars at the switchboard. Each generating unit is controlled by its own automatic switching panel on the switchboard and this panel with its switching mechanism, can be disconnected from the bus bars and the rest of the system. This makes it possible to repair the switching mechanism for any generating unit without interfering in any way with the operation of the plant.

A vital part of the Strong system is the method of using a storage battery and booster to absorb severe fluctuations of load, thus keeping the voltage steady and preventing flicker in the lighting system.

The battery service requirements are not severe, as it is never called upon to take a long discharge except in emergency. Graphic records of the energy interchange between battery and bus show a continuous succession of small charges and discharges, and have led battery engineers to conclude that the battery life should exceed nine years.

Figs. 74 and 75 show the generating-units and switchboard respectively of a fully-automatic plant of this kind, installed in a New York City office building. This plant contains four 270 horsepower, 6-cylinder Diesel engines operating at 375 r.p.m., each engine being directly connected to a 180-kilowatt 250-volt direct-current generator. A storage battery of 116 cells and 1,380 ampere-hour capacity operates in parallel with the generator through a 30-kilowatt motor-driven booster.

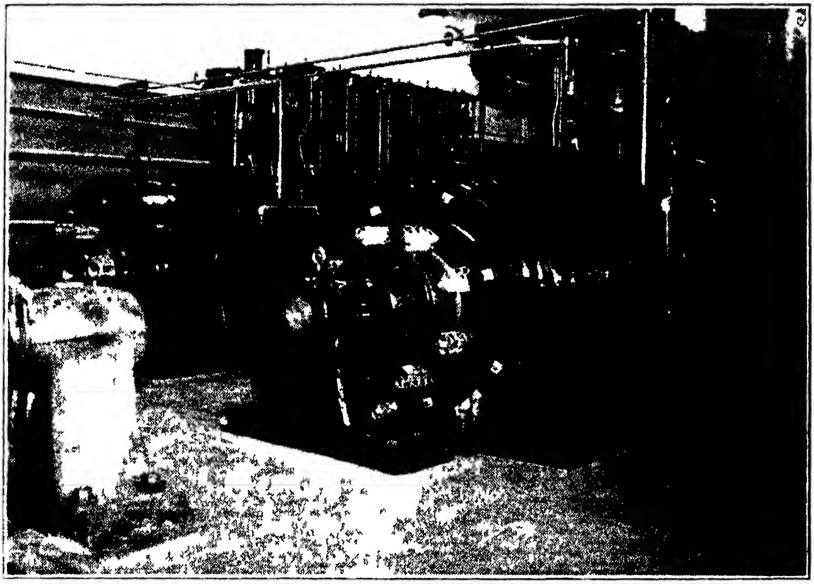


Fig. 74. A Portion of the Automatic Diesel Electric Plant Located at Number One Park Avenue, New York City

Strong's System for A.C. Plants. For automatic operating of alternating-current Diesel plants, Mr. Strong's system is similar to that of direct-current plants. In place of the battery booster, however, a motor generator set is used. A direct-current machine is operated across the batteries and is direct-connected to an alternating-current synchronous machine operating on the alternating-current line. Fig. 76 shows a schematic diagram. *C* represents the switchboard. Synchronizing is accomplished without the use of special automatic synchronizing apparatus by suitable design of the alternating-current synchronous converter *D* and

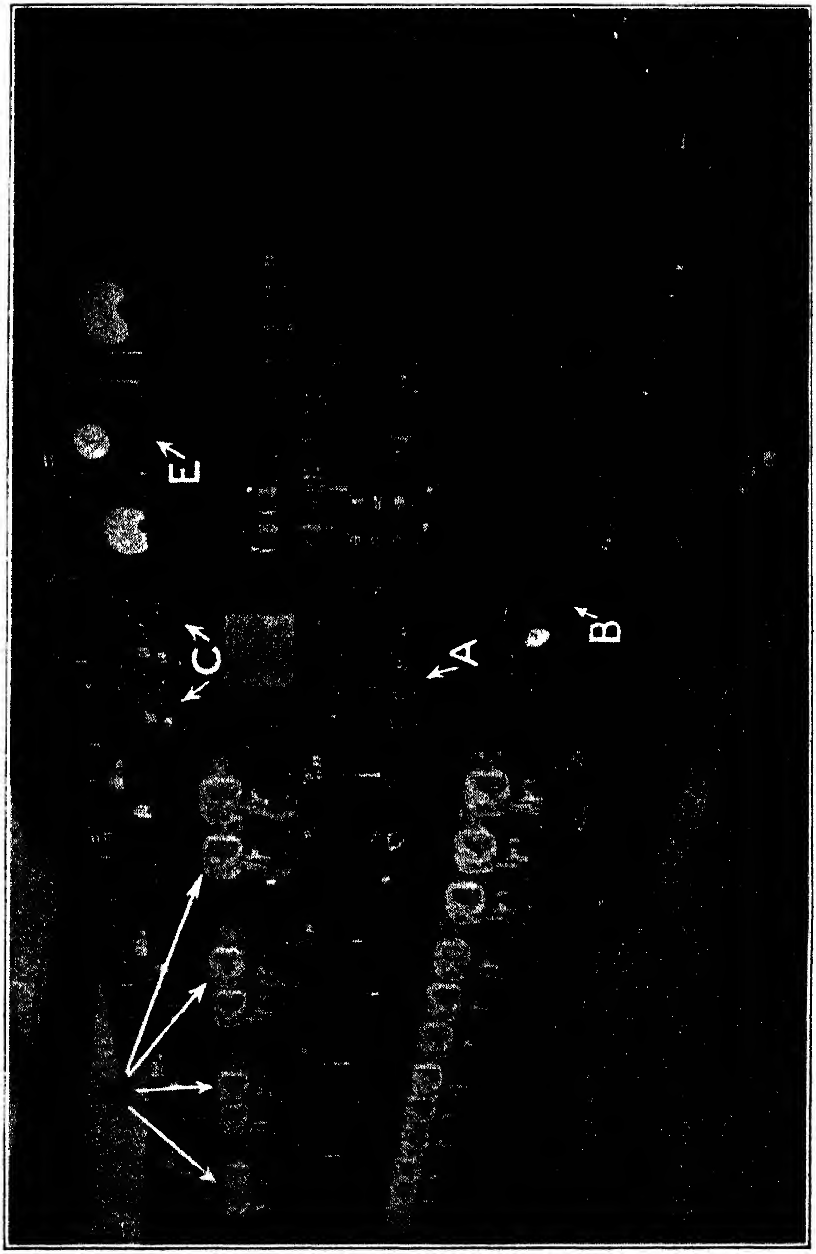


Fig. 75. Switchboard at Number One Park Avenue Plant, New York City
(See Fig. 73 for explanation of letters.)

the synchronous generators *B*. Machine *A* acts as a motor and drives *D* as a generator to supply additional alternating-current energy when a sudden increase in load occurs. Vice versa when the load dips suddenly, machine *D* acts as a synchronous motor, drives *A* as a generator and puts the surplus energy into the storage battery.

General Electric System. The system offered by the General Electric Co. for fully-automatic multiple-unit Diesel electric plants comprises the following functions:

The *starting indication* or impulse to start the first unit in a station may be given by means of (1) a push button or its equivalent, installed locally or at some remote point; (2) in response to power failure of the normal source of supply as indicated by an undervoltage relay; or (3) in response to load demand. In Diesel generating stations, load responsive starting of the first set is usually confined to stations which have a power battery operating in parallel with the generator for carrying light loads and the engine set is started on heavy load demands.

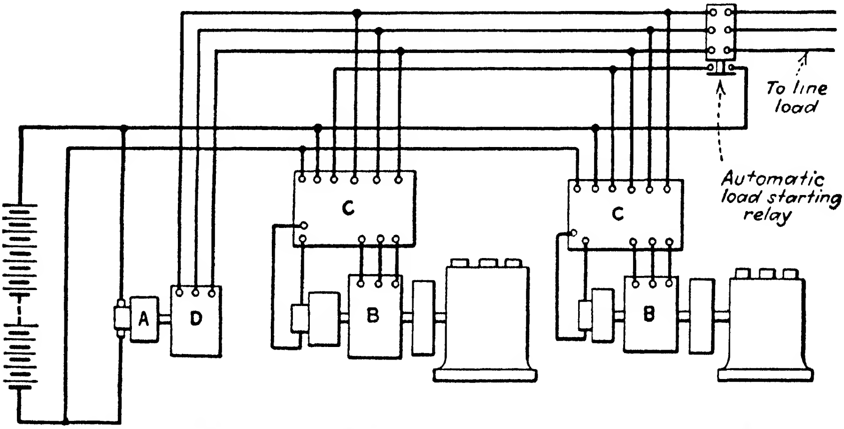


Fig. 76. Diagram of Strong's System for Parallel Operation of Alternators

The undervoltage relays which indicate failure of the normal power supply may be made instantaneous, if desired, but it is preferable to introduce a time delay of perhaps 2 seconds before starting the engine, in order to make sure that power has actually failed rather than dipped momentarily.

As soon as the starting indication is given, the automatic equipment performs the necessary operations to crank the unit, turn on cooling water, open fuel valve or turn fuel pump cams and other operations required by the particular installation.

In order to insure positive firing at the start, it is usual practice to bring the engine up to 20 per cent speed during the *cranking period.* This may be accomplished by using several different methods, some of which are as follows:

(1) Compressed air. If the engine has a sufficient number of cylinders to insure positive starting without barring, compressed air starting is commonly used (alternating-current or direct-current stations).

(2) Main direct-current generator acting as motor connected to station power battery through starting resistor (direct-current stations only).

(3) Main direct-current generator acting as motor connected to special low voltage starting battery. The recommended minimum voltage is 15 to 20 per cent of generator voltage. Suitable battery charging equipment should be installed.

(4) Exciter acting as motor connected to special low-voltage starting battery (alternating-current stations only).

(5) Standard automotive starting device with low-voltage starting battery. The automotive types of starting devices are used primarily in connection with the smaller engines. Some states have laws prohibiting the use of automotive starting devices in connection with emergency power stations (alternating-current or direct-current stations).

Direct-current generators or exciters when they are to be used as cranking motors are provided with a special series field, which is reversed or disconnected after the starting operation is completed.

As soon as firing speed has been attained and the engine begins to run under its own power, it is necessary to discontinue the cranking operation. This may be accomplished by means of a speed switch attached to the engine shaft or to the governor, or, in the case of machines taking power from storage batteries, it can be accomplished by means of a relay, which indicates the drop in current drawn from the batteries as the engine begins to fire.

In alternating-current installations, the main generator field contactor closes as soon as the exciter voltage has built up sufficiently to close it.

Automatic control equipment for direct-current stations includes the necessary relays to insure that the generator voltage is up to the proper value and is of correct polarity before the machine is connected to the bus. Reverse power protection is also provided in case of parallel operation with other generators or a battery.

Speed matching and synchronizing equipment must be included in the control equipment for alternating-current stations, so that the generators can be synchronized before they are connected to the bus. One master synchronizing equipment plus some auxiliary devices will serve for a multiplicity of generators.

After the first set in the station is started, subsequent units may be started by means of a push button, or in response to load demand. A selector switch is usually provided so that any one of the sets in the station can be made to start in the desired sequence as unit 1, 2, 3, and so on.

For ordinary installations flat compound wound direct-current generators without voltage regulators are satisfactory. However, if very close regulation is required, a voltage regulator should be used with either shunt or compound wound machines.

Alternating-current generators must have some kind of voltage regulator.

CHAPTER VIII

ELECTRIC STARTING OF DIESEL ENGINES

In order to start a Diesel engine, it is necessary to set it in motion and bring it up to a certain speed before admitting fuel to the cylinders. The starting or "cranking" speed required to insure firing of the injected fuel depends upon many factors, such as air and engine temperature, size of cylinders, and design of the combustion chamber and fuel injection system. A cranking speed of the order of 20 per cent of normal speed is ordinarily required.

Although large and moderate size engines are generally started by admitting compressed air to their cylinders through suitable valves, electric starting is used to start engines of this size when installed in automatic plants, the current being obtained from the full-voltage storage battery that is employed in such plants for other reasons. In automatic plants, the Diesel engine may be arranged for electric starting by using its generator as a motor if a direct-current plant, or its exciter if an alternating-current plant.

Electric starting is also frequently used for small, high-speed Diesel engines. A separate starting motor is used which is connected to the engine through a clutch or Bendix drive and operated from a low-voltage starting battery. The battery is generally charged from a small engine-driven generator provided with a voltage regulator or a like method of current control. The whole arrangement is similar in principle to that in general use for automobile engine starting systems.

As a general rule, Diesel engines require considerably more power for starting than the equivalent size of gasoline engines because of heavier construction, higher compression, and the necessity of very much higher engine cranking speed to reduce heat loss during compression. To supply this higher torque requirement, large motors capable of withstanding currents of 1,000 to 1,500 amperes for time periods of 30 seconds or more, are necessary. Likewise, to furnish high engine cranking speed, the motor must operate with an applied voltage of from 16 to 26 volts. depending upon the engine size and the required minimum cranking speed. In other words, these starting motors, approximately 6 inches in diameter and 12 inches in length, must develop a maximum of 35 horsepower. Compared to a regular 115-volt industrial electric motor with a diameter of about 24 inches and a length of 24 inches, these small starting motors perform a heavy task, although they will do so only for a short time.

Fig. 77 shows the characteristics of a typical starting motor installation, with a gear ratio of 10 to 1 between starting motor and engine crankshaft. One curve shows the engine cranking torque developed at various current flows. A set of two curves gives the horsepower developed at 24 volts and at 14 volts on the starting motor. Finally, a set of curves shows the engine cranking speed produced at various currents and voltages. For example, for an engine cranking torque of 800 ft.-lb., 1,150 amperes are required. If the engine must be cranked at a speed of at least 150 r.p.m. in order to start firing, 22 volts must be applied, whereas for 120 r.p.m. 18.4 volts are required. It is also apparent that as the torque requirement increases, so must the applied voltage be increased to obtain the same engine cranking speed. At low temperatures the starting torque may be several times that at ordinary room temperatures.

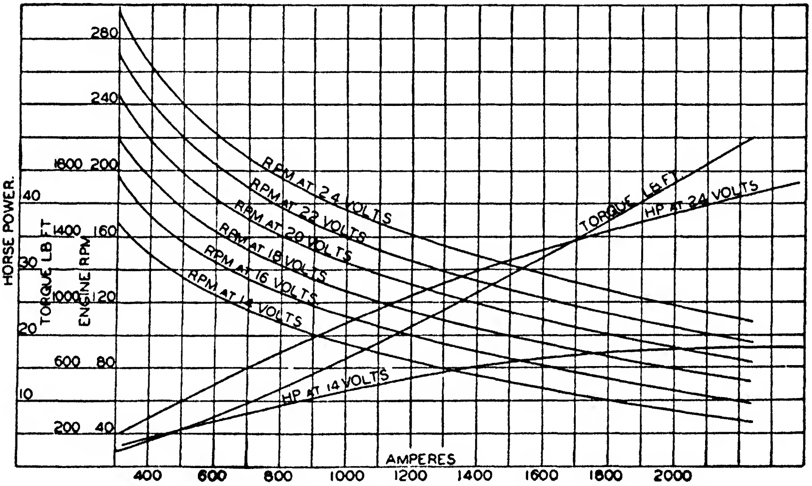


Fig. 77. Curve Showing Torque, Horsepower, and Speed of a Starting Motor

CHAPTER IX

STARTING AND STOPPING GENERATORS AND VOLTAGE REGULATORS

The following outlines are intended to suggest the routine procedure for putting electrical equipment in and out of service. Details will vary with different plants.

Alternating-Current Generators

STARTING (Generator Operating Singly)

1. See that all switches connecting the generator to any load are open.
2. Cut in all of the field resistance.
3. Start the engine and bring it up to speed.
4. Reduce the field resistance until normal voltage is obtained.
5. Close the oil circuit breaker or main switch.
6. Apply the load gradually.

STARTING (Generator Operating in Parallel)

1. See that all switches connecting the incoming generator to any load are open.
2. Cut in all field resistance.
3. Start Diesel engine and bring it up to speed under hand control.
4. Close the field switch and gradually cut out the field resistance until the voltage of the incoming generator is equal to that of the bus.
5. Vary the speed of the incoming generator until the voltage of the generator and bus are in phase (synchronized).
6. With voltage of generator and bus equal and in phase, close the oil circuit breaker or main switch.
7. Adjust the input to the generator by means of the engine governor to make the generator take its share of the load.

When starting up after a temporary shut down, it is unnecessary to wait for the unit to come to rest; as soon as the switches are open begin the regular order of starting operations.

STOPPING

1. Adjust the input to the generator by means of the engine governor until the wattmeter indicates a light load.
2. Cut in the field resistance until the ammeter indicates a low value of current.
3. Trip the oil circuit breaker or open the main switch.
4. When the unit comes to rest open the field switch.

Direct-Current Generators

STARTING (Generator Operating Singly)

1. See that all switches connecting the generator to any load are open.
2. Cut in all of the field resistance.
3. Start the engine and bring it up to speed.
4. Gradually cut out the field resistance until normal voltage is obtained.
5. Close the line switch.

STARTING (Generator Operating in Parallel)

1. See that all switches connecting the generator to any load are open.
2. Cut in all field resistance.
3. Start the engine and bring it up to speed.
4. Close the equalizer switch. Closing the equalizer switch before closing the shunt field circuit will insure the generator picking up on the right polarity. Check polarity.
5. Close the field switch.
6. Gradually cut out the field resistance until the voltage of the generator is equal to that of the other generator.
7. When the voltages of the two generators are of the same value, close the line switches.
8. Adjust the voltage of the incoming generator to make it take its share of the load.

Do not parallel generator without closing the equalizer switches.

Do not close any switch slowly.

Do not close the circuit breaker with the main switch closed.

Do not close the circuit breaker after a heavy short circuit without plugging the voltmeter to the generator to make sure that the polarity is not reversed.

In starting up after an accidental shut down, it is unnecessary to wait for the generator to come to rest. As soon as the switches are open begin the regular order of starting operations.

STOPPING

1. Cut in the field resistance until the ammeter indicates a very light load.
2. Trip the circuit breaker or open the main switch.
3. Stop the engine.
4. Open the field switch.

Never break a field circuit suddenly, as the inductive discharge voltage is always many times higher than the operating voltage, and may puncture the insulation of the field. A discharge resistance should be used connected to a special field switch, which is ordinarily supplied with a large machine.

Do not open a switch on a circuit carrying a large amount of current. Trip the circuit breaker first, then open the main switch.

See that all switches, circuit breakers, etc., are open when the machine is not operating.

Always close the circuit breaker first; then close the switch.

Voltage Regulators

Single-Unit Plants. When a voltage regulator controls a single Diesel electric generating unit, the unit can be shut down without changing over to hand regulation or varying the setting of the field rheostats. Therefore, when the generator is again started, the field rheostats have the correct setting for normal operating condition, the excitation will adjust itself and will, as the speed increases, automatically come under control of the voltage regulator. This applies to all kinds of quick-acting regulators, whether they be of the rheostatic or vibrating types.

Because of its slower action, the simple form of voltage adjuster depending entirely upon a motor-driven field rheostat to change the excitation, requires a different procedure. The method of shutting down this voltage adjuster is as follows:

(1) Remove load.

(2) Throw cut-off switch of voltage adjuster to "OFF" position, thus disconnecting the driving motor.

(3) Stop Diesel engine.

The reason for disconnecting the adjuster before shutting down is to prevent it from trying to raise the voltage as the line voltage dies down, and thus leave the adjuster in the wrong position for starting.

The starting procedure with this type of voltage adjuster is as follows:

(1) Start the Diesel engine and bring it up to speed.

(2) Adjust voltage to normal by means of hand-wheel on exciter field rheostat.

(3) Throw cut-off switch of voltage adjuster to "ON" position, thus energizing the driving motor.

Paralleled Units. *A. Individual Regulators for Each Generator*—When each alternating-current machine and direct-connected exciter has its own regulator, it is usually unnecessary to take the regulator out of control when shutting down the unit. Reduce load by governor control and reduce wattless current with the voltage adjusting rheostat until the machine line breaker can be opened. When synchronizing, the regulator then automatically takes care of the voltage for the operator, as the speed is varied for synchronizing.

To take the regulator out of control while the generating unit itself remains in service (say, for maintenance work on the regulator), slowly turn the main regulating rheostat towards "OUT" or high voltage until all contacts stay permanently open, then open all disconnect switches. The reverse operation places the regulator in control again.

B. Common Regulator with Parallel Exciters. The Westinghouse method of putting an exciter on the bus requires a voltage limiting rheostat for each exciter. With the regulator in service on a generator and exciter, the sequence of operation for paralleling another exciter is as follows:

(a) The main regulating rheostat of the incoming exciter should be turned to its marked position and the voltage limiting rheostat turned "all in."

(b) Close the disconnect switches on the regulator corresponding to this exciter. This puts the regulator into service on the incoming exciter before it is put in parallel with the running exciter.

(c) Turn out the voltage limiting rheostat to make the voltage of this exciter equal to the voltage of the operating exciter, or bus, and when the two have been made equal, the exciter main switch can be closed.

(d) The proper load can now be taken on this exciter by adjusting its voltage limiting rheostat.

Disconnecting an Exciter. When two or more exciters are in service on the regulator, to disconnect one, the load should first be reduced to a low value by turning in the voltage limiting rheostat of that exciter, after which open the main switch to the exciter busbars. Then open the disconnecting switches on the regulator corresponding to this exciter.

C. Common Regulator, Non-Parallel Exciters. The regulator itself is the same as that used with parallel exciters except that transfer switches are provided for the purpose of transferring the relay circuit of the regulator to any running exciter for a source of energy.

Referring to the Westinghouse design, there are from two to five quick-throw transfer switches at the bottom of the regulator, numbered consecutively. The wiring of these switches is such that if the relay circuit is to be energized from the exciter connected to No. 1 transfer switch, all the other switches must be thrown down, and No. 1 thrown to its up position.

If it should now be desired to transfer the relay circuit to the exciter connected to No. 2 transfer switch, this would be obtained by throwing No. 2 quickly to its up position, after which switch No. 1 should be thrown down. For simplification, these switches should be kept in their downward position, except the switch corresponding to the exciter from which the relays are being energized, which should be thrown up.

Paralleling Units. The procedure for putting a second generating unit into service on the regulator is as follows:

The generator to be paralleled should first have its field rheostat, if any, turned to the "all out" or to the marked position. Then, the exciter for the incoming set should have its voltage limiting rheostat turned "all in" and the main regulating rheostat turned to its marked position. The single-pole disconnecting switch or switches at the bottom of the regulator, 1, 2, 3, etc., as required for this exciter, should be closed. The regulator would now be intermittently shunting the exciter field rheostat of the incoming unit. The alternating-current voltage of this generator can now readily be made equal to the voltage of the operating unit, by varying the voltage limiting rheostat in its exciter field circuit.

When the voltage is made correct in this way, the generator can be synchronized, as usual, after which the voltage limiting rheostat should be turned slowly to its marked position and the load properly divided, as usual, by the speed of the prime movers. Should there be excessive wattless current between the generators, this can be reduced and the actual reactive load divided proportionally among units by varying the voltage limiting rheostats.

CHAPTER X

ELECTRICAL CONTROLS AND ALARMS FOR THE DIESEL ENGINE

Automatic devices, electrically operated, have come into extensive use in Diesel engine plants for controlling and safeguarding the operation of the engine itself. These devices have the following advantages:

(1) They reduce the amount of attention required from the operating engineer, permitting him to devote his time to vital matters rather than to unnecessary routine observations.

(2) They improve the operating conditions by keeping the temperatures, pressures, etc., steadier than they would be under manual control.

(3) Automatic alarms protect the engine better in case of engine derangement because they act immediately.

Automatic devices are used in two general ways:

(1) To control the normal operation of the engine.

(2) To act in case of derangement, either by signaling an alarm or by shutting down the engine. In general, an alarm is sufficient, because if the engineer is notified promptly and acts at once, he can either rectify the trouble and keep the engine in service, or he can stop the engine by hand if he finds he cannot correct it quickly. However, where continuity of service is not important, or where the engineer may not be always accessible, the automatic device may be arranged to stop the engine directly.

Conditions vary widely in different Diesel plants. In the larger ones, attendants are continuously on duty in the engine room, and in case of derangement only a warning signal is necessary. On the other hand, many small Diesel plants receive only the occasional inspection of an attendant who may have other duties far remote from the engine room. In such cases more elaborate precautions are justified.

Items which may be controlled or safeguarded are as follows:

1. Jacket Water Temperature. All Diesel engines, except aircooled aviation engines, must be kept cool by a continuous and adequate flow of water through the jackets surrounding their cylinders and cylinder heads in order to carry off that part of the heat of combustion which enters the metal walls and would otherwise heat them to a destructive temperature. The amount of heat to be carried off increases with the load on the engine. Consequently, if the water flow is adjusted to give a satisfactory jacket temperature at a light load, it is necessary to increase the flow when the load increases. The simplest and most common method of automatically adjusting the water flow to suit the load is a mechanically operated thermostatic regulator, the thermostatic bellows being placed in the jacket water discharge pipe and operating a valve in the water inlet pipe. See Fig. 78. Such a device will maintain the discharge water temperature within close limits regardless of the amount of load on the engine or the temperature of the incoming water.

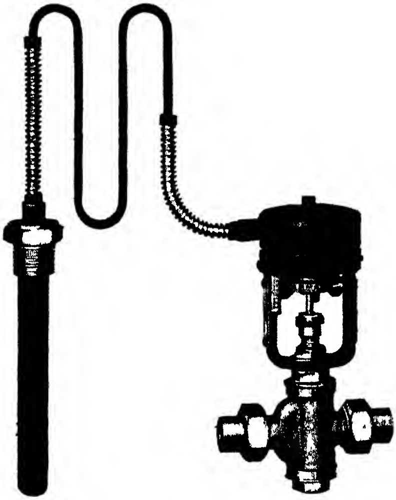


Fig. 78. Temperature Regulator for Cooling Water
Courtesy of Fulton Sylphon Co.

The thermostatic valve, however, will become ineffective if the water supply is shut off, as might occur through failure of the water pump or the inadvertent closing of a valve. To meet this contingency, a jacket water alarm is frequently employed. This consists of a thermostatic element placed in the water discharge pipe, which is adjusted to close an electric contact when the water temperature rises to some predetermined limit. The electric circuit thus closed may be used to give an alarm signal by bell, horn or lights, or to stop the engine.

2. **Lubricating Oil Pressure.** Most modern Diesel engines have force-feed lubrication, that is, all important wearing surfaces are supplied with lubricating oil through a system of pipes and passages which is under pressure from a pump. The oil pressure in such a system is, of course, highest next to the pump and lowest at the most remote point. It is of the greatest importance that the normal pressure should be maintained at all times, as otherwise serious damage would soon result, such as bearings melting or pistons seizing.

If the lubricating pump should fail to supply the usual quantity of oil, or if a pipe should spring a leak, the derangement will first become apparent at the far end of the system, where the pressure will at once commence to fall. This is the place, therefore, to install an alarm or shut-down device that is operated by the pressure of the oil in the lubricating system. The device is set to operate at a pressure slightly below the normal pressure but still above the danger point, so that the engineer will have time to remedy the trouble or shut down the engine before actual damage occurs.

3. **Engine Speed.** Diesel engines driving electric generators are constant-speed machines, and employ a governor to keep the speed uniform irrespective of changes in load. However, it is conceivable that something might happen to the governor which would put it out of action. For instance, the governor driving gears might strip or shear, so that the governor would cease rotating, whereupon it would cause the engine fuel pumps to inject the maximum quantity of fuel into the cylinders. Because of the excessive rate of fuel injection, the engine would rapidly accelerate, and if not stopped in time, would run away and reach a dangerous speed.

Such accidents are so rare that generally no special precautions are taken. However, when it is considered necessary, they can be guarded against by installing an overspeed alarm or stop. This is generally a device operating on the principle of centrifugal force, like a governor or tachometer, and arranged to close an electric contact when a certain speed is reached.

If a tachometer device is installed for overspeed protection, it is generally a simple matter to add an underspeed contact so that an abnormal change in speed in either direction will shut down the engine. The underspeed protection is useful in case of some engine trouble which might cause it to slow down and labor. This might result, for instance, from an overtight piston or bearing. The heavy load would cause the engine to slow down, but it might continue to keep running for some time and aggravate the trouble. The underspeed device prevents this.

4. **Bearing Temperature.** Thermostatic elements can be fitted into the main bearings, i.e., the bearings in which the crankshaft revolves, and may be arranged to close electric contacts when excessive bearing temperatures are reached for any reason. Such devices, however, are seldom used, as they are generally considered unnecessary if an alarm device is used to signal a reduction in the lubricating oil pressure.

5. **Exhaust Temperature.** The temperature of the exhaust gases discharged from each cylinder of a Diesel engine is commonly measured in order to indicate the combustion conditions in that cylinder. If, in a multi-cylinder engine, the exhaust temperatures of each cylinder are equal or nearly so, it is a fair assumption that each cylinder is doing its share of the work. On the other hand, if one cylinder shows a higher exhaust temperature than any of the others, it may be receiving more fuel and doing more than its share of the work. A high temperature might also result from a leaky exhaust valve or from delayed fuel injection.

Exhaust temperatures are generally measured electrically by means of thermocouples fitted into the exhaust ports and connected by leads to a millivoltmeter calibrated to read temperature directly. The latter is called a "pyrometer." Exhaust pyrometers are used for visual indication; automatic alarms are rarely employed because of the considerable cost and complication.

6. **Overload.** The Diesel engine is a heat machine in which part of the heat energy of the fuel is converted into mechanical energy; the remainder passes into the hot exhaust gases and into the metal walls surrounding the combustion chamber. The latter, in turn, are kept from overheating by the water passing through the jackets surrounding the cylinder and cylinder head.

The power capacity of a Diesel engine depends upon several unrelated factors: (a) the amount of fuel and air that can be introduced into the cylinder; (b) the strength of the parts to endure the mechanical stresses; and (c) the ability of the parts to withstand the effects of high temperatures. Factors (a) and (b) determine the maximum capacity of the engine for short-time overloads, which do not last long enough for the temperatures of the parts to rise abnormally. Factor (c), however, determines the safe power rating of the engine in continuous service. No matter how much power an engine can develop momentarily, it is necessary for the sake of reliability and low maintenance to limit its *steady* load to the point where the internal temperatures remain within safe bounds. Otherwise the pistons and piston rings will lose their lubrication, the exhaust valves will soften and pit, and heat strains will cause distortions and cracks in pistons and cylinder heads.

It is obvious, therefore, that automatic overload protection for a Diesel engine driving a generator should be so designed that it will permit the engine to develop a short-time overload, such as might be caused by the starting inrush of a large motor, but will give warning when the engine is developing a steady load in excess of its safe rating. This sort of protection can be accomplished by a time-element power relay, which is essentially a contact-making wattmeter. This is connected in the main output circuit of the Diesel-driven generator, and so set that it will make contact when the electric output has exceeded the normal safe load for a predetermined length of time.

Another suitable method of providing overload protection is to use a power-demand limitator, which is a device originally designed for the purpose of keeping down the demand charge on bills for electric power purchased from a utility company. This device also acts on the principle of a wattmeter, and when the load has exceeded the set amount for a certain length of time, it operates relays which disconnect part of the load. If desired, it can be arranged merely to give a signal.

7. Exhaust-Pipe Shut-Off. Although in most plants individual exhaust pipes are used for each engine, it is sometimes convenient to join the exhaust pipes into a common header in the engine room. In such cases shut-off valves must be placed in the individual exhaust lines. These valves must be shut when an engine is stopped, in order to prevent the exhaust gases of the running engines coming back into the idle engine. This prevents corrosion of the internal surfaces of the idle engine; it also prevents the exhaust gases blowing back into the engine room when an engine is dismantled for overhaul.

In manually-operated plants, ordinary gate valves are used for this purpose. In automatic plants, however, it is necessary to arrange for the shut-off valve to close automatically when an engine is stopped and to open when the engine is started again. This is accomplished in a simple manner by a swing-check valve operated by a solenoid, the latter being connected in the same circuit used to put the engine fuel pumps into action. Thus, when the engine is started, the solenoid opens the swing-check valve, being assisted by the pressure of the exhaust gases of that engine. Similarly, when the engine is stopped (by opening the circuit which controls the fuel pumps), the exhaust pipe solenoid is de-energized, permitting the check valve to swing closed under the pull of a spring assisted by the back-pressure of the exhaust of the running engines.

Thermostatic and Pressurestatic Contact Makers

Industrial Types. There are available many types of control switches used in domestic and industrial fields of application for controlling temperatures and pressures of liquids. Such switches can be used on Diesel engines to close electric alarm circuits in case of excessive temperatures of jacket water or bearings, or in case of insufficient lubricating oil pressure. In general, these switches are operated by a bellows element which is either actuated directly by the controlled pressure or by a volatile liquid in the case of temperature control. They are usually provided with two adjustments, one for the operating point, i.e., the temperature or pressure at which the contacts close, and the other for the differential, i.e., the amount of change in temperature or pressure required to open the contacts again. Care should be taken in setting these adjustments; in Diesel engine service a small differential is generally desirable.

Fig. 79 shows a typical pressure control switch, as made by the Detroit Lubricator Co. This switch utilizes a permanent magnet at the contacts to provide a quick make and break and prevent excessive arcing.

Similar switches are also available which employ mercury tubes in which the contacts are sealed. Contacts are closed and opened by tilting the mercury tube. Fig. 80 shows the American Radiator Company design. These switches should preferably be installed where they are free from vibration, in other words, not on the engine itself.

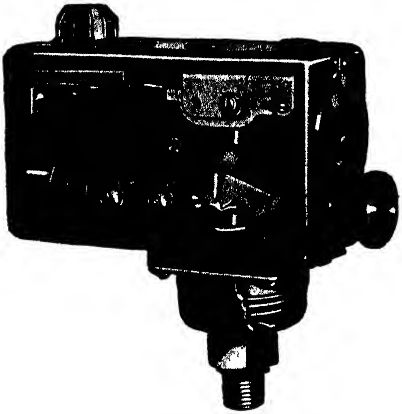


Fig. 79. Pressure Control Switch with Cover Removed
Courtesy of Detroit Lubricator Co.

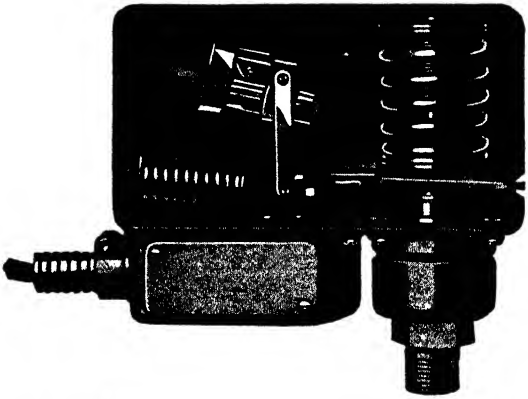


Fig. 80. Mercoid Pressure Control with Cover Removed
Courtesy of American Radiator Co.

Viking Type. Contact makers for pressure and temperature specially made for use on Diesel engines have been developed by Viking Instruments, Inc. They are designed to be shock and vibration proof, and may be installed directly on the engine itself and in any position without affecting their accuracy or life. The thermostatic contact maker is shown in Fig. 81. It consists of a closed system comprising a bellows and a bulb containing a volatile liquid. As the temperature rises, the vapor pressure increases, extending the bellows which, at a predetermined temperature operates a mechanical snap switch. The construction of the switch is such that it remains in position until the operating lever reaches a certain point, whereupon the contacts open with a snap. The contacts snap open with the same speed regardless of the rate of the temperature or pressure change. The housings of these contact makers are constructed to exclude moisture, fumes, and dust, and to prevent tampering or unintentional changes of adjustment after installation.

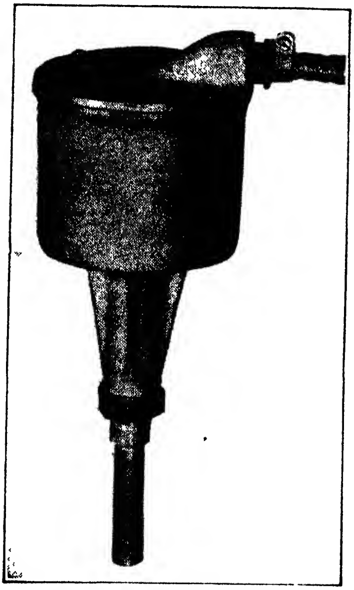


Fig. 81. Viking Thermostatic Contact Maker

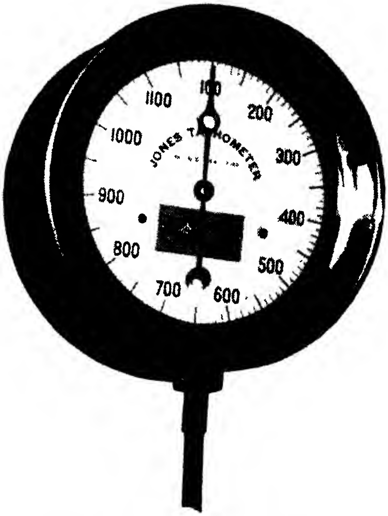


Fig. 82. Viking Safety Control Unit

Overspeed and Underspeed Contact Makers

A Diesel engine can be protected against all contingencies that might produce an abnormal speed of say 15 per cent above or below normal, by means of the safety control shown in Fig. 82. This consists of a Viking overspeed and underspeed contact maker, mounted inside the case of the instrument, which is connected to the shaft of the Diesel engine by an ordinary flexible tachometer cable. The contact makers are mechanical snap switches of the same design as those used in the thermostatic and pressurestatic contact makers previously described, and are operated from the speed responsive or governor shaft of a standard tachometer mechanism. The same mechanism actuates a pointer over the dial, thus giving continuous visual indication of the speed.

Pogue Overspeed Contact Maker. Another form of overspeed device, designed by George M. Pogue, consists of a mercury tube with contacts mounted on a vertical spindle driven by the Diesel engine. The tube is set at an angle of 60 degrees with the vertical axis of revolution, and when the predetermined excessive speed is reached, centrifugal force throws the mercury into the outer end of the tube, submerging a pair of electric contacts. The contacts are wired to slip-rings at the base of the device, the brushes of which are connected to the alarm circuit.

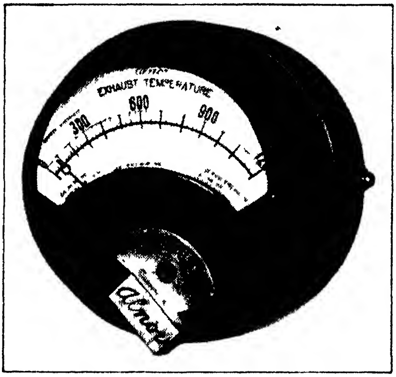


Fig. 83. Exhaust Temperature Pyrometer
Courtesy of Illinois Testing Laboratories, Inc.

Exhaust Pyrometers

Fig. 83 shows a small pyrometer in common use, and Fig. 84 three typical forms of thermocouples, as manufactured by the Illinois Testing Laboratories. Exhaust pyrometers operate on the well-known thermo-electric principle. The heat-responsive element consists of two wires of dissimilar metals welded together at one end, the welded end being protected by a casing and inserted into the exhaust passage of the engine. When heated, the thermocouple generates an electromotive force which can be measured in millivolts and which is directly proportional to the temperature. The pyrometer is a millivoltmeter whose scale is graduated in temperature units, usually 0-1000° F. for two-cycle engines and 0-1200° F. for four-cycle engines. Where ruggedness and ability to withstand vibration are required, the coils of these instruments are made of fairly low resistance.

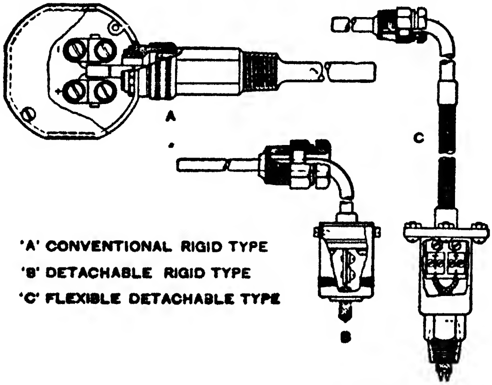


Fig. 84. Showing Three Typical Forms of Thermocouples

A pyrometer for a multicylinder engine is provided with a selector switch whereby readings may be quickly taken from the several thermocouples in the individual cylinders.

Two kinds of wire can be used to connect the thermocouples to the pyrometer, ordinary copper wire, or duplex alloy wires of the same two metals as are used in the thermocouples themselves. A pyrometer really measures the *difference* in temperature between the "hot-end" and the "cold-end" of the thermocouple, the cold-end being the point where the dissimilar metals are joined to the copper circuit. If ordinary copper wires are used to connect the thermocouples to the pyrometer, the cold-end is the point of attachment of the copper wires at the thermocouple terminals. On the other hand, if alloy connecting wires are used, the cold-end is extended to the pyrometer itself.

In order to take account of the cold-end temperature, pyrometers are provided with an adjustment so that the instrument needle may be set at the actual cold-end temperature when the pyrometer is disconnected from the thermocouple. For instance, if copper connecting wires are used and the temperature of the thermocouple terminals is found to be 90° F., then the pyrometer pointer should be set to read 90° F. when the selector switch is in the "off" position. On the other hand, if alloy connecting wires are used, the pyrometer in "off" position should read the temperature of the terminals at the pyrometer itself.

The actual temperature of the exhaust gases is not as important as the comparison of temperatures of the several cylinders. Hence an error in setting the cold-end temperature is not as serious as a difference in the cold-end temperatures of the various thermocouples. Consequently, where there are differences in temperature among the several thermocouple terminals, and where accurately comparative readings are desired, duplex alloy connecting wire should be used in order to bring all the cold-ends to a common point. Such temperature differences may result from differences in the amount of heat radiated from the engine itself.

However, with engines having water-jacketed exhaust manifolds, the temperature differences at the thermocouple terminals are generally quite small, and this is particularly the case where the flexible, detachable type of thermocouple is used. Here the terminals are about 24 inches distant from the exhaust pipe and their temperature is usually only slightly higher than that of the room. Under such conditions copper connecting wire may be satisfactorily used.

When alloy connecting wire is used for the sake of greater accuracy, the wires from each thermocouple must be nearly the same length, or a pyrometer of high internal resistance must be used, because alloy wire has nearly 20 times the resistance of the copper wire. Take, for example, a pyrometer that has an internal resistance of 25 ohms and the connecting wire for the several thermocouples varies from 50 feet for the shortest to 100 feet for the longest. With No. 14 gauge duplex copper wire, the resistance of which is approximately ½ ohm per hundred feet, the difference in external resistance between the longest and shortest connecting wire is but ¼ ohm. Assuming that the meter is calibrated for an average of

75 feet of copper wire, the error with either the shortest or the longest connecting wire then would amount to a ratio of ⅛ to 25 or ½ of 1 per cent, which at 500° F. would be approximately 2½° F. This slight difference would not be readily readable on a 1000° F. scale.

Compare this with alloy wire which has a resistance of 9.5 ohms per hundred feet for the 14 gauge duplex or double conductor wire. With conditions as above outlined, the difference from the mean value would amount to 2⅜ ohms which, compared to the internal resistance of the meter, is about 10 per cent, or about 50° F. at 500° F.

It is evident, therefore, that when alloy wire is used with a low resistance pyrometer, the pyrometer must be calibrated for a definite length of alloy wire and each connecting lead must be approximately the same length, otherwise the resistance error with the alloy wire will exceed the cold-end temperature error with copper wire. When all the leads are short, the resistance error becomes negligible. Also, with pyrometers of higher internal resistance, the resistance error becomes less in the same ratio as the resistance of the pyrometer increases. For instance, if a 500 ohm pyrometer had been used in the preceding example, the resistance error with alloy wire would have been only ½ of one per cent.

Overload Protective Devices

Fig. 85 is a Westinghouse Type CW Power Relay. This device is designed to close a set of contacts when a given amount of power flows in a given direction through its coils for a predetermined length of time. Fundamentally, it consists of an electromagnet carrying both potential and current coils, and a moving element in the form of an aluminum disk, to which is connected a restraining spiral spring and one of the contacts.

The combined effect of fluxes, produced by the currents flowing in the two sets of coils, serves to produce a torque tending to rotate the disk. The control spring exerts a countertorque and holds the contact open until sufficient power is flowing to produce enough torque to overcome the torque of the spring and thus cause the disk to rotate, closing the contacts.

The speed with which the relay will close its contacts depends upon the amount of power flowing. With just sufficient current flowing in the coils to produce enough torque to overcome that of the control spring, the disk will very slowly close the contacts. This speed increases as the current flowing in the coils increases and thus the larger the overload, the quicker the contacts will close.

The time of operation is also dependent upon the distance through which the disk must turn before the contacts are closed, which distance is directly proportional to the setting of the time-index lever. Such a relay may, for instance, be set to close contact when 30 per cent overload has been carried for ten seconds.

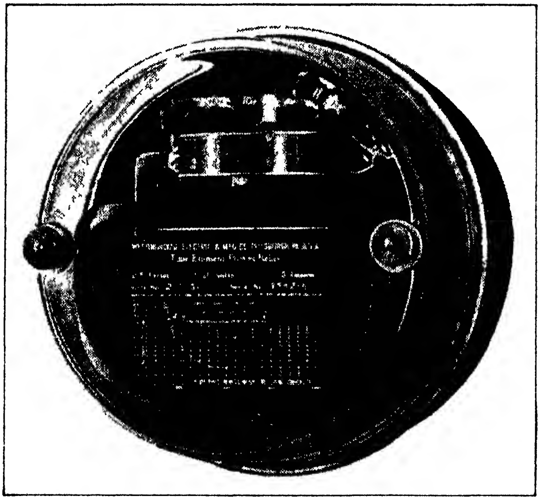


Fig. 85. Westinghouse Type CW Power Relay

Alarm Signals

Warning signals may be of the visual or audible type. If visual they usually consist of electric lights which glow when the alarm contact is made. Generally, however, the alarm signal is given audibly, and lights are used merely to indicate which function is out of order. Audible signals may be given by klaxon, siren or gong. A klaxon or howler, such as that shown in Fig. 86, produces a distinctive note which can be readily heard above engine room or shop noise. For installations where the operator may be at a considerable distance from the engine in the event of trouble, a powerful weatherproof siren, as shown in Fig. 87, may be mounted outside the building. Such a siren may be heard over distances up to three-quarters of a mile.

Engine Shutdown Devices

Diesel engines may be shut down in several ways, (a) by stopping the fuel supply to the injection pumps, (b) by stopping the action of the injection pumps themselves; (c) by holding the exhaust valves open; (d) by shutting off the air supply.

Stopping Fuel Supply to Injection Pumps. This can easily be accomplished automatically by using a solenoid valve, such as shown in Fig. 88, in the fuel supply line close to the injection pumps. The solenoid, of course, is energized from the alarm system. This is, however, not the best way of stopping an engine, for two reasons. First, the engine will continue to fire for an appreciable time on the fuel between the solenoid valve and the injection pump valves; second, when the injection pumps run short of fuel, air will get into the fuel system of most engines and will probably cause uneven firing when the engine is started again.

Fig. 86. A Warning Howler

Courtesy of Viking Instruments, Inc.

Fig. 87. A Weatherproof Siren

Courtesy of Viking Instruments, Inc.

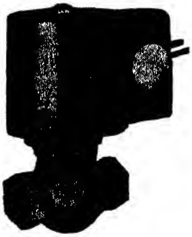


Fig. 88. A Solenoid Operated Valve

Courtesy of Viking Instruments, Inc.

Stopping Action of Injection Pumps. This is the method most commonly used to stop engines quickly. It acts without delay, and the fuel pumps cannot become air-bound. The shut-down device may be a spring released by an electrically-controlled latch, or it may be a solenoid. In either case, it is arranged to overcome the spring of the engine governor and move the fuel pump regulating mechanism into the shut-off position.

Holding Exhaust Valves Open. This is an excellent way of stopping a Diesel engine because the cylinders must have compression in order to ignite the fuel charges. Holding the exhaust valves open immediately stops compression and consequently firing ceases at once. This method has the advantage of being able to stop an engine even if it is receiving excessive fuel, as might occur because of some derangement of the fuel pump or governor, or because (in the case of some two-cycle engines) crankcase lubricating oil was being drawn up through the air inlet ports and burned in the cylinders.

However, this system is not generally used, because the devices for holding the exhaust valves open are of such design that they must be specially made and applied to the engine at the factory.

Shutting Off Air Supply. A Diesel engine will stop if it does not receive oxygen wherewith to burn the fuel. It is upon this principle that shut-down devices have been designed which close a valve in the air-intake line. The valve is of the butterfly type and is closed by a weighted lever which is normally held in the open position by a latch which can be released electrically. The main disadvantage of this method is its rather high cost. Also, it is not easy to keep the shut-off valve tight enough to prevent the powerful vacuum produced by the engine pulling in enough air to keep the engine running for some time.

Layout of Alarm Systems

In view of the wide diversity of conditions in various Diesel plants, an alarm system for any one plant should be specially designed to fit the requirements of that plant. A few examples of typical installations are given herewith.

Simple System for a Small Plant. Fig. 89 shows the wiring diagram of a simple alarm system used in a factory containing a small Diesel electric plant with a single engine. The engine is protected against excessive jacket water temperature by a thermostatic contact maker, and against insufficient lubricating oil pressure by a pressurestatic contact maker. The alarm is given by a klaxon horn, and signal panels in the engine room and in the factory indicate the nature of the trouble by illuminating red lights "W" for water or red lights "L" for lubricating oil. Each signal panel is also provided with a green pilot light "P" which burns continuously while the signal system is in service.

It will be noted that the signal system is operated at low voltage through a transformer energized from the main power circuit, and is automatically put into service as soon as the Diesel unit is started and the main power switch closed. The signal cut-out switch is kept closed at all times except when it is necessary to do maintenance work on the alarm system.

Simple Shutdown System. The Viking safety control shown in Fig. 90 is designed for engines which do not have operators in constant attendance, where it is desired to stop the engine immediately in case of trouble with the jacket water or lubricating oil. It consists of a thermostatic contact maker for mounting in the circulating water discharge; a pressurestatic contact maker for connection to the lubricating oil system; a circulating water temperature gauge and a lubricating oil pressure gauge mounted in a single housing together with a trouble-source indicator. Terminals are provided to connect to an audible alarm and to an automatic engine shutdown device.

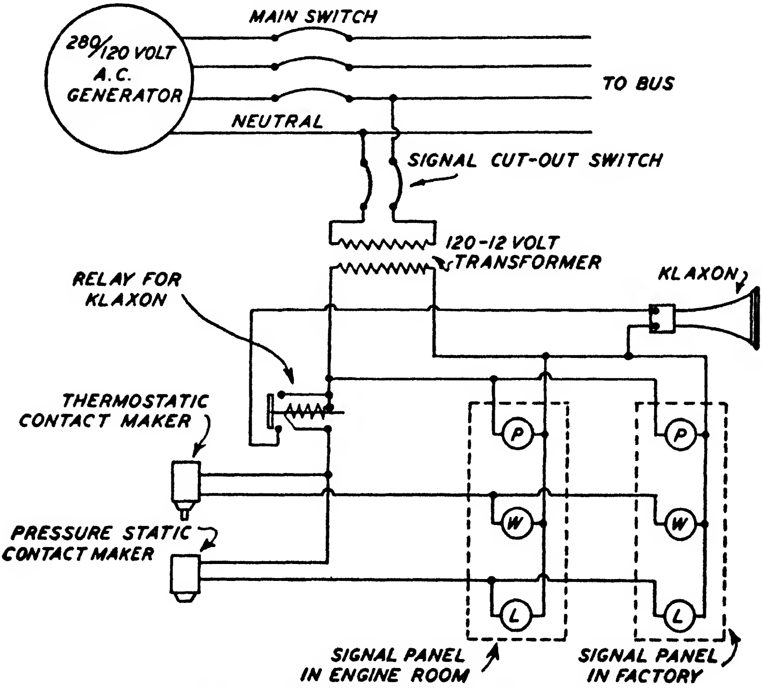


Fig. 89. Layout of Simple Alarm Systems

During normal engine operation, the pressure and temperature gauges provide a continuous indication of conditions in the circulating water and lubricating oil systems, and the red pointer of the trouble-source indicator remains in the center position. The alarm and shutdown circuits are de-energized. Should the circulating water temperature rise above a safe limit, the safety control takes charge instantly, energizing the alarm and shutdown circuits. At the same time the red pointer of the trouble-source indicator is thrown to the side, indicating jacket water trouble. Similar action occurs in the case of insufficient lubricating oil pressure.

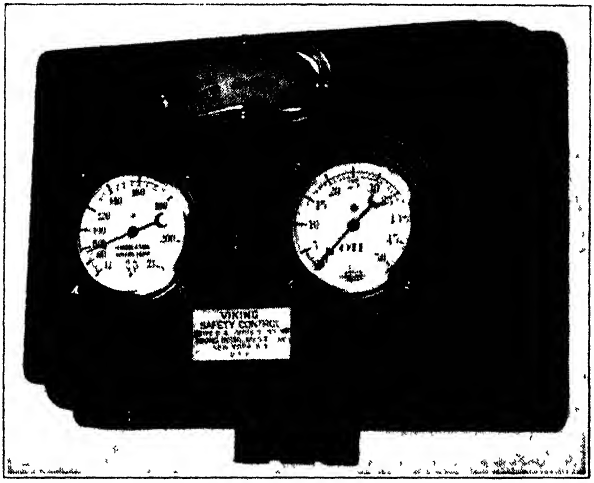


Fig. 90. The Viking Safety Control Unit

Signal-Stop System. The two 800 kilowatt Diesel generating units in the New York department store of R. H. Macy & Company are protected by an elaborate and complete alarm and shutdown system designed by George D. Pogue. The system warns of trouble by sounding a klaxon, indicates what the trouble is, and automatically stops the affected engine if the trouble is not corrected after a predetermined number of minutes, which can be set at from zero to ten. The two panels of this signal stop system are shown at the right in Fig. 91; the exhaust gas pyrometer is mounted on the column in the center, and a glimpse of one of the engines is given at the left.

The derangements guarded against are as follows:

(1) Loss of pressure on lubricating oil system.
(2) Loss of pressure of cooling water supply to power cylinders.
(3) Loss of pressure of cooling water supply to injection air compressors
(4) Loss of pressure of injection air.
(5) Excessive speed.

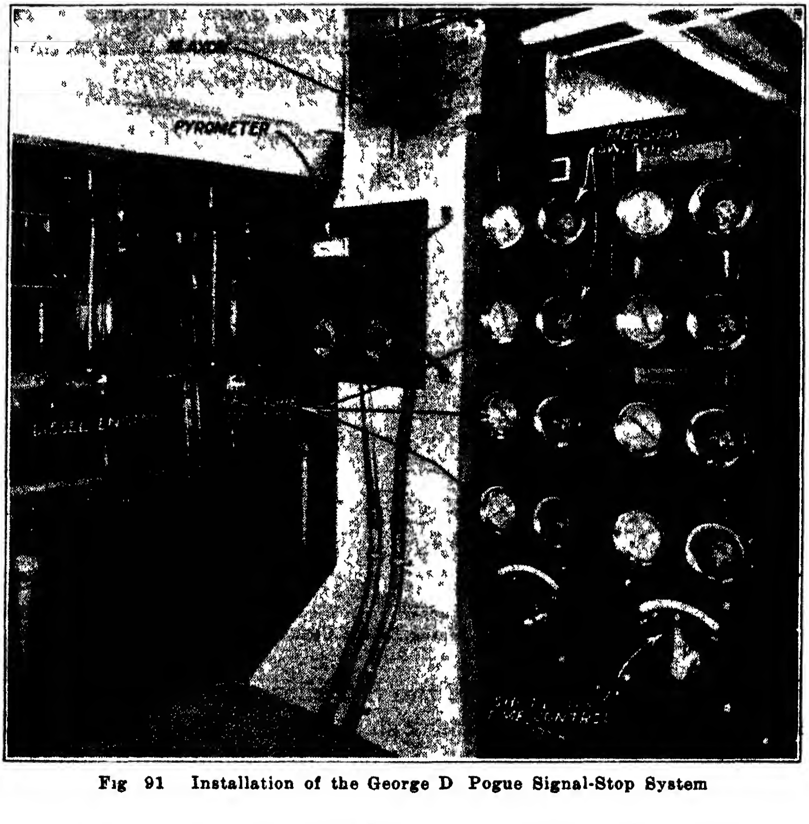


Fig 91 Installation of the George D Pogue Signal-Stop System

The first four items, being matters of pressure, are guarded by mercury switches which close circuits when operated by pressure gauges of the Bourdon type. The overspeed contact maker is the Pogue inclined mercury tube design as previously described.

The shutdown device consists of a large valve in the air intake pipe of each engine, which is normally open, but may be closed by gravity by releasing a solenoid-operated latch.

All the four pressurestatic contact makers for a given engine are mounted on a single vertical panel alongside of the usual indicating pressure gauges. On each panel are also mounted four corresponding ground glass signs which ordinarily show blank, but which are lit up with red letters spelling out the words "Lubricating Oil" or "Cooling Water," as the case may be, whenever the pressure falls low enough to tilt the mercury tube and to close the circuit. A glass case containing a movable pointer capable of moving over a scale graduated in bold letters from 0 to 10 minutes is fastened to the lower part of the panel, while a klaxon horn of the industrial howler type is fastened to the wall nearby.

The movable pointer can be moved at one fixed rate of speed only by a small electrical motor, and when it reaches the zero end of the scale it closes the circuit to the solenoid which releases the air shut-off valve and stops the engine.

The stop-valve solenoid can be energized in either of two ways: overspeeding of the engine or the movement of the time-delay pointer to the zero position. If it is actuated by the latter method, the engineer is first warned both audibly and visibly and given a certain time to correct the trouble, the amount of such time depending on the position between 0 and 10 minutes at which the pointer is initially set. However, if the stop solenoid is actuated by the overspeed rotating mercury tube, this action takes place directly without time lag, as the condition is generally too dangerous to justify anything but immediate stoppage.

Self-Checking Alarm System. A unique scheme which gives continuous evidence that the entire alarm system is in operating condition is illustrated diagrammatically in Figs. 92 and 93. It consists of a thermostatic contact maker, for installation in the circulating water discharge line; a pressurestatic contact maker, for connection in the lubricating oil system; a warning howler for sounding an audible alarm; a visual indicator for immediate identification of the affected system; a connection box, for collecting the wiring of the system in a convenient central location; and an automatic throttle switch, which energizes the safety control system automatically when the engine is started up and de-energizes it automatically when the engine is shut down, thus eliminating the obvious disadvantages of manual operation. The contact makers are of the double-throw type.

Referring to the schematic diagram, Fig. 92, and the circuit diagram, Fig. 93, the system operates as follows:

When the engine is shut down, the automatic throttle switch is in the open position, and the safety control system is completely de-energized. Thus, all lights of the visual indicator are out and the warning howler is silent. As the engine is started up, the automatic throttle switch is moved to the closed position, energizing the safety control system. Current then passes through the "pilot" light (center light of visual indicator). Note that the "pilot" light is in series with the warning howler, therefore current passes through warning howler continuously, but it does not operate under normal

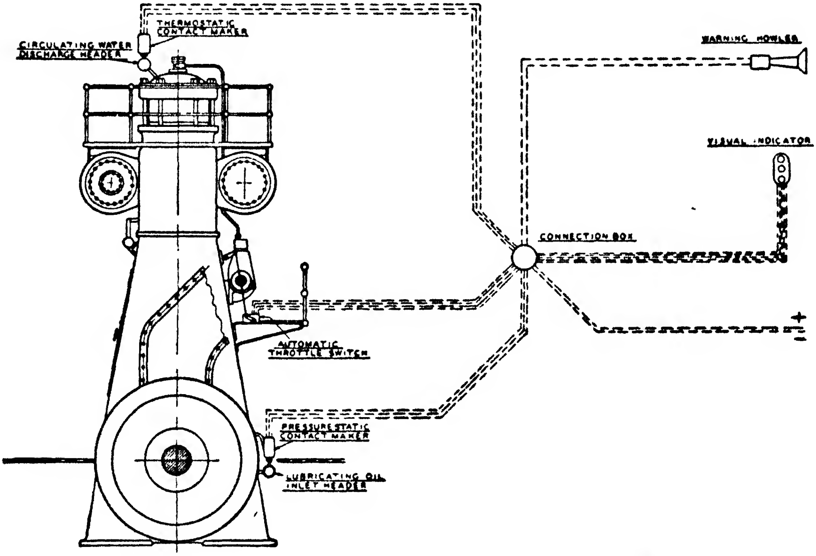


Fig. 92. Schematic Diagram of a Self-Checking Alarm System
Courtesy of Viking Instruments, Inc.

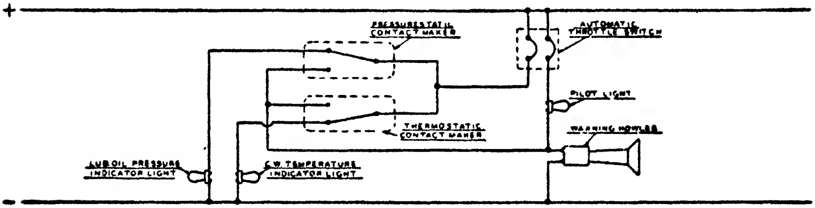


Fig. 93. Circuit Diagram of a Self-Checking Alarm System
Courtesy of Viking Instruments, Inc.

conditions because of high resistance of the "pilot" light. Provided the circulating water temperature and the lubricating oil pressure are normal, both contact makers will be in the "normal" position, and current will pass through the "lubricating oil pressure" light (top light of visual indicator), and through the "circulating water temperature" light (bottom light of visual indicator).

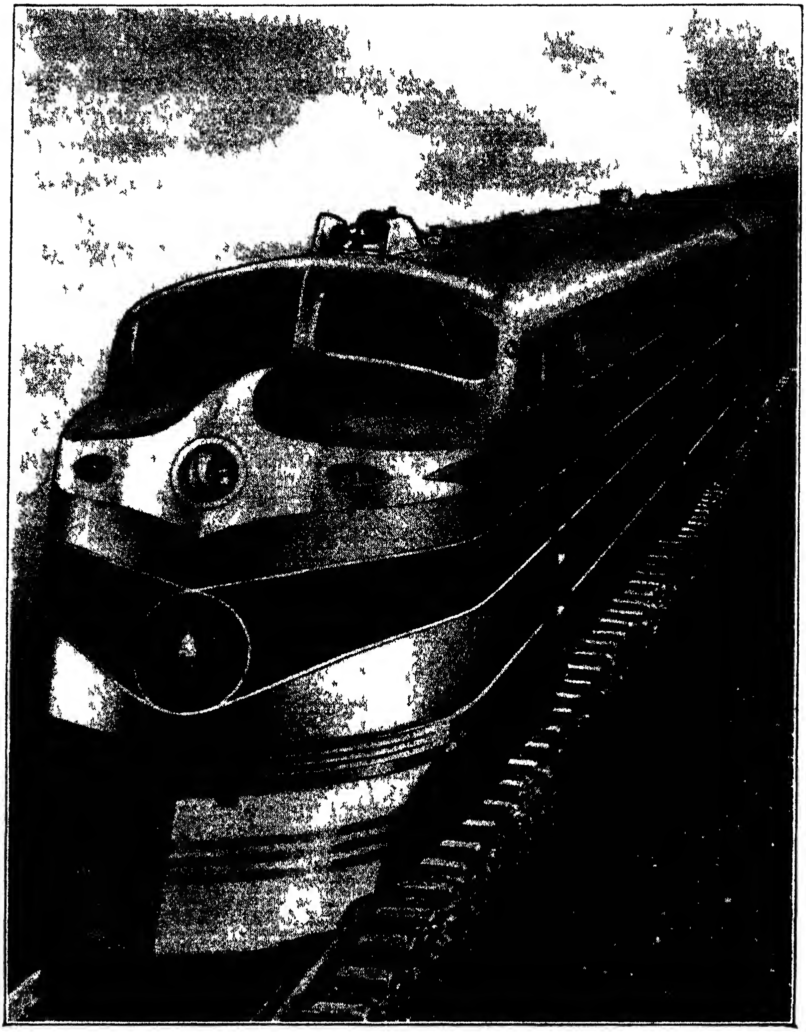
Thus, when the engine is running under normal conditions, all lights of the visual indicator will be on and the warning howler will be silent.

Should the lubricating oil pressure drop below the operating point of the pressurestatic contact maker, the contact maker switch will be thrown to the "alarm" position. This action of the switch throws the warning howler directly across the line, causing it to sound the alarm. Simultaneously, both the "pilot" light and the "lubricating oil pressure" lights will go out. Therefore, as the warning howler sounds the alarm, a glance at the visual indicator shows the "lubricating·oil pressure" light out and establishes instantly the source of trouble.

The warning howler will continue to operate, and the two lights of the visual indicator will remain out until the lubricating oil pressure returns to normal. If the engine is shut down, the safety control system will, of course, be de-energized.

A similar operation follows an excessive rise in the circulating water temperature. In this case, the "pilot" light and the "circulating water temperature" lights go out as the warning howler sounds the alarm, the "lubricating oil pressure" light remaining on.

It will be noted that this alarm system is self-checking at all times when the engine is in service, since all lights are *on* when conditions are normal.



ONE OF THE SIX 3,600-HP. DIESEL LOCOMOTIVES USED TO PULL THE CAPITOL LIMITED, NATIONAL LIMITED, ROYAL BLUE, AND COLUMBIAN TRAINS

Courtesy of Baltimore And Ohio Railroad, Baltimore, Md.

CHAPTER XI

DIESEL LOCOMOTIVES AND TRAINS

The inflexibility of the Diesel engine as compared to the steam engine makes it impracticable to couple the Diesel engine shaft directly to the driving wheels of a locomotive or rail-car. The Diesel engine cannot start under load; in fact, it developes no torque (i.e. pulling power) at standstill. Furthermore, the torque when the engine is running is strictly limited to a little more than that for which the engine is rated, whereas, the steam engine can be made to produce many times its rated torque when necessary by temporarily sacrificing efficiency. Since railroad operation demands maximum pulling power when a train is being started and accelerated, it is necessary to use some form of power transmission between the Diesel engine and the wheels. In this way the Diesel engine may be run at full speed while the train is being started, and its full power may be applied to the wheels through what is equivalent to low gear, thus giving large tractive effort at low speed.

Mechanical transmissions and clutches similar to those used on automobiles were naturally the first to be considered for Diesel locomotives and rail-cars, but they were found to be satisfactory only for small powers such as are used in industrial switching locomotives. The difficulties became more serious as the engine power increased, so that mechanical transmission is generally considered unsuitable for full-size railroad work.

Hydraulic and pneumatic transmissions have also been used to some extent but have not yet been accepted as having emerged from the experimental stage.

At the present time, the electrical system of transmission is, by far, the more widely used and thoroughly developed for Diesel locomotives weighing 30 tons or more. In this system one or more Diesel engines drive electric generators, and the electric energy produced operates traction motors on the driving wheels. The Diesel electric and the steam locomotive have in common a handle for controlling locomotive or train speed, a controller handle for selecting forward and reverse movement and the conventional air brake handle. A steam operator not familiar with the Diesel electric is sometimes called upon to operate it and, not being acquainted with its characteristics and limitations, naturally expects a deal of mystery in its action. Nevertheless, the Diesel electric, as operated by the steam personnel, has done extremely well and in general is being universally welcomed by both the railroads and operators.

The advantages claimed for electric drive are that it is easy to operate; gives great pulling power and superior overall performance on grades; is easy on the engine; and produces a locomotive of high reliability and availability. The electric drive is a variable-speed transmission with an infinite number of smooth speed changes, and with the right speed automatically selected by the transmission itself rather than through the questionable judgment of the engine-driver. The electric transmission provides a perfectly elastic cushion between the wheels and the Diesel engine. The first Diesel electric locomotive built in the United States was a 300 brake horsepower switching locomotive which was put in service in 1925; there are now more than 150 locomotives and 35 rail-cars in operation in the United States and Canada with Diesel electric drive. Power has increased greatly, up to 3,600 brake horsepower in four engines.

Ward-Leonard Variable Speed System

The Ward-Leonard system of variable speed transmission has been in use for many years in numerous applications in science and industry, and is the progenitor of the electric-drive systems employed in many modern Diesel electric locomotives. In this system a wide speed range for the motors is obtained by using a variable voltage generator to vary the voltage applied to the motor terminals. The generator voltage is adjusted by changing its excitation. The diagram shown in Fig. 94, as used for Diesel engine drive, comprises a direct-current generator, an exciter, and one or more motors. The exciter, which is a constant voltage machine, supplies field current to both the generator and the motor.

To obtain slow speed, the generator field excitation is reduced by means of the field rheostat, thus reducing the voltage E that is applied to the motor. As the field excitation of the generator is increased, the voltage E rises and so does the speed of the motor.

The motor can readily be reversed by reversing the generator excitation. Thus the entire control is effected by means of a small field rheostat and a small reversing switch. The operation is very smooth and because of the small electrical losses the efficiency of the transmission is comparatively high. The simple system described, however, has certain disadvantages for Diesel railway drive, inasmuch as the engine itself runs at full speed even when the motor speed is low. This causes unnecessary wear and tear, and also reduces the engine efficiency on account of operating at fractional loading. To overcome these disadvantages and to increase the pull of the locomotive or railcar, i e. the torque of the propulsion motors, during the starting period, more elaborate systems of transmission and control have been devised.

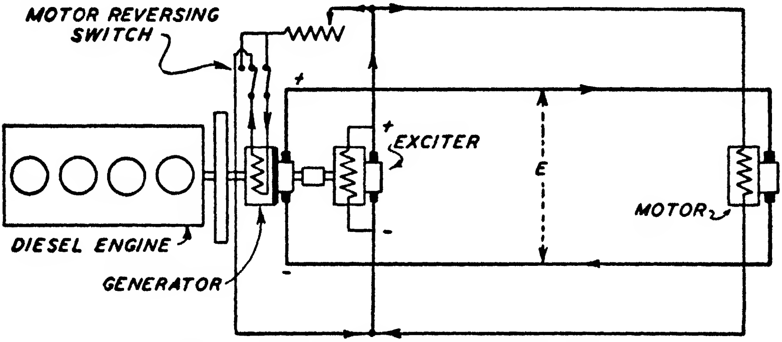


Fig. 94. Ward-Leonard Variable Speed Control

First Diesel Electric Locomotive

The first Diesel electric locomotive in this country (1925) was a 0-4-4-0 machine containing a 300 brake horsepower Ingersoll-Rand Diesel engine operating at 600 r.p.m. and direct-connected to a 200 kilowatt, 600 volt, differentially compound-wound, direct-current generator. This switching locomotive was the forerunner of a large number of similar machines. There were four geared motors, one for each axle, mounted on the trucks. The motors were series wound, with commutating poles. For speeds below five miles per hour, the motors were coupled in series, for higher speeds in parallel. The output of the generator was automatically adjusted to suit the varying resistances of the train. This was obtained by inserting a differential series field in the output circuit, thus modifying the excitation of the generator so as to give the proper proportion of amperage for the tractive effort and of voltage for speed. No rheostats were used in the power circuit for speed control. The position of the control handle determined only whether the motors were connected in series or in parallel, and acted on the Diesel engine throttle to control the power generated by the engine. In other words, the engineer brought the engine up to speed with the throttle, independently of the speed of the train itself. The full power of the engine was then applied to starting and accelerating the train. At first, when the train speed was low and maximum tractive effort was required, the generator produced maximum current and low voltage. As the train accelerated, less tractive effort was needed and the current was reduced, which automatically increased the generated voltage and thus increased the speed of the driving motors. This system of automatic proportioning of a given amount of power into tractive effort and speed is known as the Lemp system, after its inventor Hermann Lemp, and is now much used, as described later.

Fundamentals of Modern Electric Transmissions

Essentially, the electric transmission system consists of a generator coupled to the engine, the necessary number of traction motors for applying power to the driving axles, and a control system for regulating the flow of electrical energy from the generator to the motors, for reversing the direction of movement, and for insuring an adequate supply of power for the operation of locomotive auxiliaries.

Generator. The generator armature is usually coupled directly to the engine crankshaft as shown in Fig. 95. Nearly all recent generators have been of the single-bearing type, with one end of the armature shaft supported by the engine crankshaft. It has also been found expedient to mount an auxiliary generator on the main generator frame at the outer end, with its armature mounted on an extension of the generator shaft. This auxiliary generator then supplies current to the main generator's field, for the operation of air compressors, for charging the battery and for similar purposes.

The most satisfactory system of transmission is obtained by the use of direct current. The generator is of the variable voltage type and the traction motors are always of the series type. The method of control of the voltage characteristics of the generator to secure the maximum effectiveness in power application has differed on locomotives of different manufacture, but in each case the aim is to transmit as much of the full engine horsepower to the traction motors as possible. To accomplish this it is necessary to reduce the electrical losses in both the motors and the generator to the extreme, and to make sure that the voltage is kept as high as possible dependent upon the current demands of the traction motors.

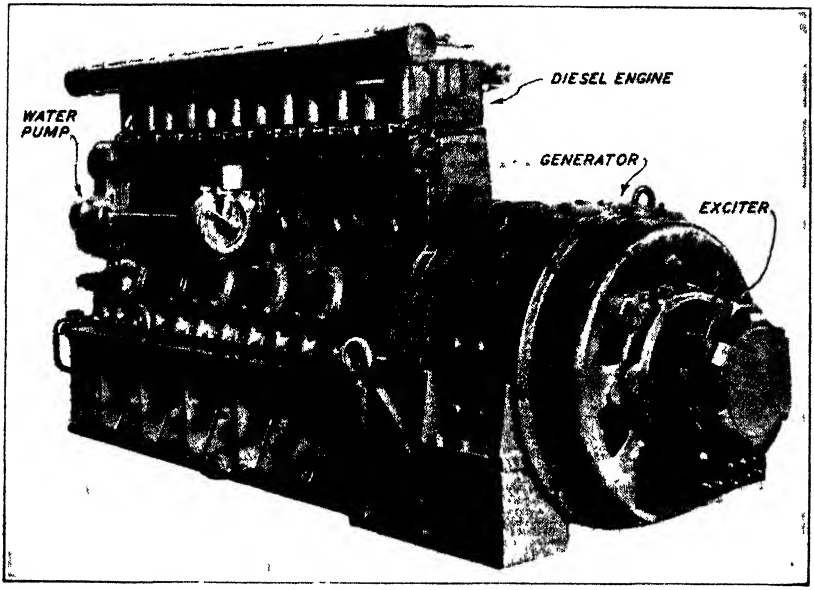


Fig. 95. A 400-Horsepower Diesel Engine Driving an Electric Generator on a Locomotive
Courtesy of Westinghouse Electric and Mfg. Co.

Since the circuits are independent of any fixed voltage system, the designer usually selects that voltage which results in maximum economy of materials and gives the lowest losses. In general, a satisfactory maximum voltage varies from 600 to 750.

Traction Motors. Traction motors may either be built for operation on this voltage or may be connected two in series and designed for half voltage.

The size of motors used for any locomotive depends to a great extent upon its weight, which determines the maximum tractive effort required and the type of service, and is nearly independent of the capacity of the power plant installed. The generator is then applied to suit the engine speed and the voltage and ampere characteristics of the motors.

Control System. On account of the variable power requirements of railway traction, the Diesel engine is usually arranged for operation at various speeds. Control of engine speed is accomplished by (a) a variable speed governor, in which the tension of the governor spring is varied, or (b) a control handle acting on the fuel pumps and regulating the amount of fuel injected into the engine.

It is the function of the electric equipment to transmit the engine power, whatever it may be at any time, to the driving wheels in such manner that the best combination of tractive effort and speed is obtained, and that the least power is wasted in losses.

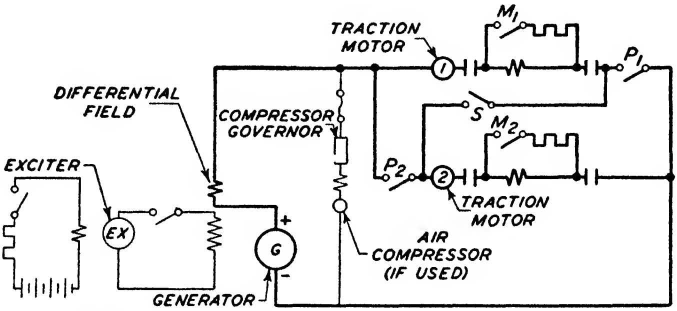


Fig. 96. Diagram of a General Electric Locomotive Control

General Electric Drive System. A schematic diagram of the electric transmission employed by the General Electric Co. with the Lemp system of automatic control is given in Fig. 96. It will be noted that the generator has two fields, one a constant shunt field supplied by a separate exciter, the other a differential series field. The effect of the latter is to *reduce* the excitation and therefore the generated voltage when the current output increases. This is just the opposite to the effect of the series field of an ordinary compound-wound generator. The result of the opposed fields is a generator characteristic having the amperage and voltage relations shown in Fig. 97.

Two traction motor combinations are used. In the first combination the motors are connected in series, and in the second combination in parallel. Referring to Fig. 96, the contactor S is closed for the first motor combination and only contactors P-1 and P-2 are closed for the second combination. In order to develop a high torque, the motors demand a large current from the generator. To make an economical design, the current demand from the generator is reduced to a minimum in the first motor combination by connecting the motors in series, when contactor S is closed. After the locomotive or train is started and speeds up, the torque demand of the motors decreases, which in turn decreases the current demand from the generator. With a decrease in generator current, an increase in generator potential is automatically obtained, as will be seen from Fig. 97, which results in an increase in the speed of the locomotive.

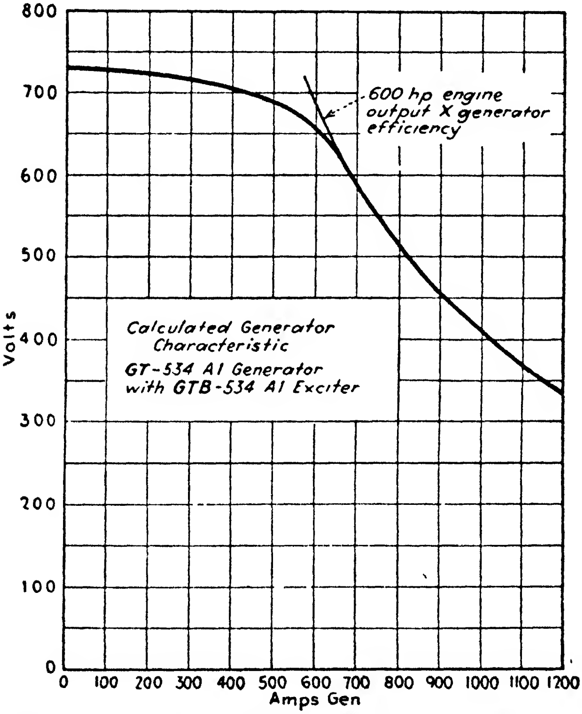


Fig. 97. Curve Showing Relation of Generator Voltage, and Current

Courtesy of General Electric Company

In the first motor combination, in which the motors are in series across the generator, the voltage across each motor will be one-half that of the generator. At a pre-determined speed, it is the usual practice to transfer the motors from the first to the second combination in which the motors are connected in parallel. Each motor then has full voltage across the terminals. The locomotive speed is approximately the same just before, during, and after the transfer. During this time the torque demand remains the same, so that each motor continues to draw approximately the same current.

Since the motors are connected in parallel after the transfer, the current demand from the generator is then twice as much after as before, or in other words, at least a part of the cycle is repeated over the generator characteristic, but with the motors running at higher speed.

Further increase in motor speed is obtained by shunting (and weakening) the motor fields by means of resistors and switches M1 and M2, Fig. 96. The current demand for a given motor torque is greater with reduced field than for full field, resulting in operation over a part of the generator characteristic a third time when the motor fields are shunted.

The electrical equipment is designed to perform the above functions under control of the operator through the engine throttle handle and the controller handle, which are used to start and run the locomotive. The running speed of the locomotive is determined by the speed and output of the engine. The motor combinations are selected by the different operating positions of the controller handle. There are three positions of the controller handle for both the forward and reverse connections, and one "off" position. These operating positions give the first and second motor combinations and, finally, the field shunting of the traction motor.

The engine throttle, which is usually operated manually, controls the fuel input to the engine. After the engines have been started, the operator puts the controller handle in the first operating position, in the desired direction of movement of the train, and then opens the engine throttle. This speeds up the engine and automatically applies power to the traction motors.

As the throttle is opened, the speed of the engine increases and the generator increases its output until at full engine speed the generator is delivering its full load.

After the train has reached a pre-determined speed, the controller handle can be moved from the first to the second operating position, and later from the second to the third, usually with the engine throttle open. Provision is now frequently made in the control so that the operator in starting the locomotive can place the controller handle in the last operating position and the different motor combinations will then be obtained automatically.

Electrical Auxiliaries. The electrical auxiliaries of a locomotive usually consist of fan motors for cooling the engine radiators, motor-driven air compressors for furnishing compressed air for the air brakes, motor-driven fans for ventilating the traction motors and some source of power for charging the storage battery. In general, the control of these auxiliaries is a major problem, because they must function properly when operated from a variable-voltage source. With recent improvements in the electrical equipment, it is now possible to obtain a constant-voltage source with normal variations in engine speed from idling to full speed.

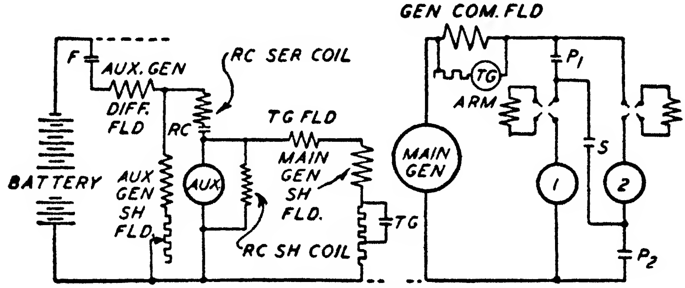


Fig. 98. Westinghouse Diesel Electric Car Control

Westinghouse Electric Drive System. Fig. 98 is a schematic diagram of this system. This differs essentially from the General Electric system in that here the control of the generator output is accomplished by regulation of the auxiliary exciter instead of by windings on the main generator. Also an electropneumatic governor operator is used to vary the Diesel engine speed. The exciter is provided with a differential field which varies the generator field current and consequently its voltage so as to maintain constant engine power output over a wide range of tractive effort and speed. This prevents overloading of the Diesel engine and also permits full speed operation of the engine at reduced engine torque in case the engine loses part of its power because of some derangement. This system permits maintaining a constant voltage on the auxiliary generator for operation of the electrical auxiliaries, while the main generator voltage is varied to suit the locomotive road requirements. A single lever controls all power operations of the locomotive.

Comparative Performance of Diesel Electric and Steam Locomotives

Enough Diesel electric switching locomotives are now in operation for a considerable amount of statistical information to be available. The American Electric Railway Association and the American Railway Association have gathered actual operating data from all possible sources and have tabulated it in committee reports. These reports include steam locomotive operating statistics for comparison with Diesel locomotive figures. The general conclusions which may be deduced from this data are summarized as follows:

(1) Diesel fuel cost per 100 ton-hours is approximately 25 per cent of steam fuel cost with oil at 5 cents per gallon and coal at $3.00 per ton.

(2) One gallon of fuel oil produces, in switching service, the equivalent of 140 pounds of coal.

(3) Diesel engine lubrication approximates $8.76 per 100 ton-hours of locomotive switching service.

(4) "Other Lubrication" cost for Diesel locomotives is 35 per cent of steam locomotive lubrication cost.

(5) The total cost of fuel, engine lubrication, locomotive lubrication, and "other expenses" for Diesel locomotives is 33 per cent of that of the corresponding steam locomotive costs.

(6) One-man operation is practicable and economically correct.

(7) Diesel locomotive repair costs for industrial switching service are lower than are indicated for trunk line railroads and are considerably lower than steam locomotive repair costs.

Diesel Streamline Trains

The electrical transmission used in modern Diesel streamline trains is illustrated by that employed in the New Haven "Comet." There are two identical power plants, one at each end of the train.

Each consists of a 400 horsepower, 900 r.p.m. Diesel engine driving a main and an auxiliary generator which supply power for the operation of traction motors and auxiliary apparatus throughout the train. The current generated by the main generator is governed by the torque-control system and is transmitted through switching and control devices to operate the axle-hung traction motors which are geared to the driving axles. There are two traction motors on each power truck.

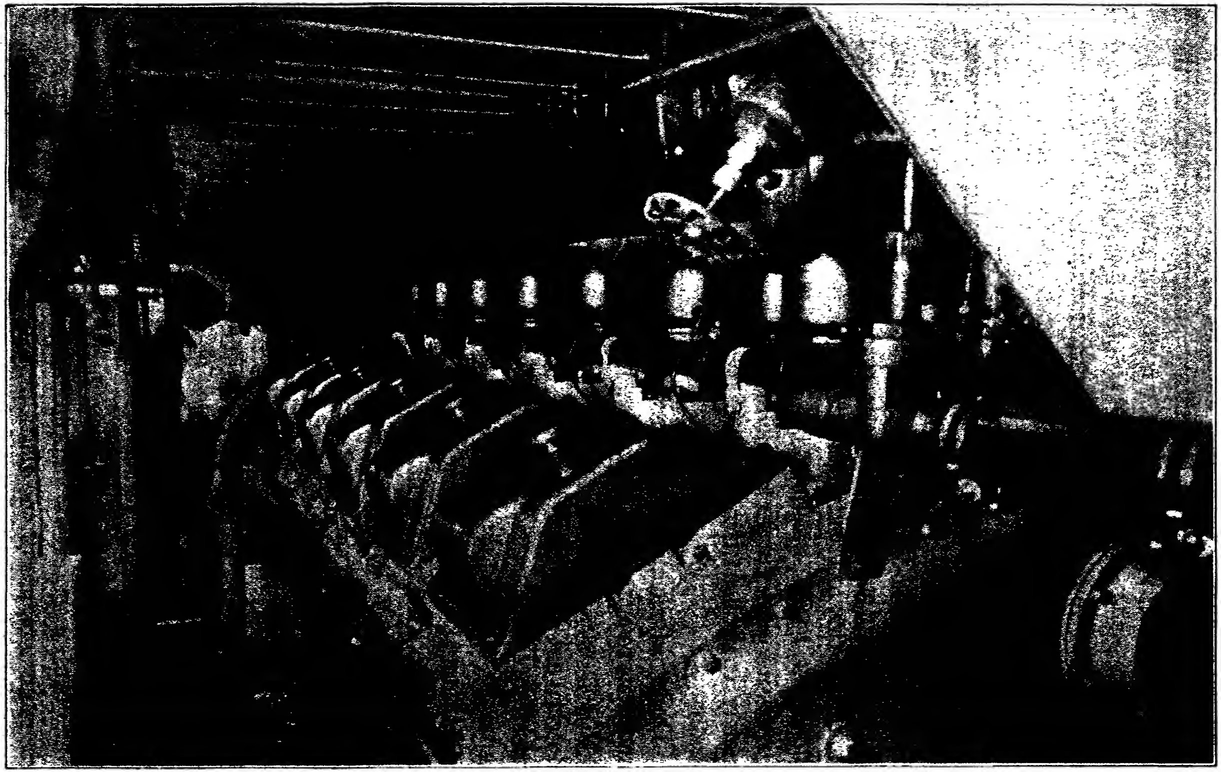
The main generator, which bears a nominal rating of 500 volts, is operated as a motor to start the Diesel engine when connected to the storage battery through its series-starting field. The starting circuits are controlled by magnetic contactors which are operated from the starting push buttons in the engine room for initial starting (cold engine, no air pressure, etc.). To restart the engine after short layovers, if air pressure is available, the starting contactors may be remotely controlled from either of the two compartments of the operator.

During idling, the main generator is used through the starting connections to charge the battery and, at the same time, to operate the air compressor and radiator-blower motor. As the throttle lever is notched out and the engine speeds up, the auxiliary load is transferred from the main generator to the auxiliary generator so that air-compressor operation and battery charging are obtained virtually at all times. The auxiliary generator is rated at 140 volts. Low-voltage motors are used to drive the air compressor, so that full air capacity is available with the engine idling.

The control circuits are energized from the battery, being independent of the engine speed.

The 110-volt lighting circuits are connected across the battery and auxiliary generator through carbon-pile regulators and the lights are controlled from "no-fuse" switch stations.

The speed and direction of motion of the train are controlled by the master controller, through the operation of various switching devices which are grouped together in control cabinets. The starting and control contactors, and those employed in the auxiliary apparatus circuits, are of the electromagnetic type, while the power switches and reverser in the traction-motor circuit are of the electro-pneumatic type.



INTERIOR VIEW OF DIESEL LOCOMOTIVE SHOWING ENGINE AND ELECTRIC GENERATOR

Courtesy of Baltimore And Ohio Railroad, Baltimore, Md.

CHAPTER XII

INSTALLATION AND MAINTENANCE OF GENERATORS AND VOLTAGE REGULATORS

Assembling Rotor on Engine Shaft

Solid Rotors. The hub and rim of engine type rotors are generally solid, instead of being split and the halves bolted together, like flywheels. The hubs of direct-current armatures are always solid.

It is customary to ship the engine shaft to the manufacturer of the generator to have a solid-type rotor pressed on the shaft, but if this procedure is not followed, the work can be readily done in the field. The two usual methods are (a) force the engine shaft in the generator rotor by pressure, and (b) expand the generator bore by heat.

Since adequate facilities are not generally available in the field to "press-on" rotors, the heat expansion method is usually practiced. The following suggestions will be found useful:

Before fitting any type of spider on the shaft, remove all protecting coats of paint and oil with kerosene or other solvent. If rust is present on the journal or the part of the shaft that rests in the bearing, it must be removed. The rust may be removed with a piece of emery cloth, but the shaft should then be polished with a fine oil stone. Do not mar or scratch the shaft, as any roughness will cut the bearings causing them to run hot.

Methods of applying heat depend to a large extent on the facilities available. Whatever means of applying heat is used, it is important that the temperature of the spider be raised gradually, and that the heat be uniformly applied so that objectionable stresses do not occur in any part of the structure. The best results can ordinarily be obtained by enclosing the entire spider in a temporary housing. Sometimes it may be necessary to cover only the hub. When electric or steam heat is used, a tarpaulin will often be satisfactory. Experience has shown that the proper degree of expansion can be obtained by heating the rotor to a total temperature of 150°C. (302°F.)

If poles and coils are mounted on a spider, the enclosure should be made to confine only the rotor center. Poles and coils should be kept outside of the enclosure.

After the rotor has been located on the engine shaft, the whole mass should be allowed to cool gradually to avoid any serious contraction stresses.

Split Rotors. When the rotor of an alternating-current generator cannot be shipped mounted on the engine shaft and when mounting of a solid rotor in the field would be difficult, the rotor may be designed with a split spider. The usual design is to fasten the hub with bolts and the rim with links. The links are tightened and the two edges of the rim are drawn together with steel wedges, driven in from both the inside and outside of the rim. A steel plate holds the wedges in place on the inside, while the pole is bolted over them on the outside.

When assembling any type of spider, first place the key in the shaft key-way. The two halves of the completely split spider may then be placed in position around the shaft. Tightening the bolts at the hub will bring the edges of the rim together and the links or bolts may then be inserted and tightened.

After the spider is in place on the shaft, the collector ring bolts at the split should be tightened. The two halves must fit together exactly and, if they do not, they should be lined up by slight tapping with a rawhide mallet or wooden block. After exact alignment is obtained, tighten the bolts at the split uniformly. Notice whether or not the collector rings run true when the rotor is turned. An eccentricity of five or six thousandths of an inch is quite acceptable on low speed machines. If the eccentricity is greater than this, the nuts on the collector studs should be slightly loosened and the rings tapped lightly into position. An indicator gauge will be found convenient for measuring the eccentricity.

Erection of Generators

Coupled Type. If the generator is of the coupled, self-contained type, erection is comparatively simple. The Diesel engine is usually set before the generator, and after the engine has been levelled by wedges the assembled generator is aligned to it.

Alignment may best be checked by backing off the coupling bolts slightly and turning the machine over by hand or with the crane. The coupling halves will separate if the two shafts are out of line, the space between the halves indicating the direction in which the alignment must be adjusted. In this connection it must be remembered that the shoulder between the halves of the coupling carries the weight, the bolts do the driving and must not be used to draw the two halves of the coupling together unless the faces are perfectly parallel. Great care must be used in this checking as large shafts may be broken from crystallization after a few weeks' operation, when out of alignment, although there are no indications of undue vibration or heating of the bearings.

Flexible couplings are not intended to take care of considerable error in alignment. Flexible couplings should be aligned originally with as great care as is used with solid couplings. If good initial alignment is obtained, the couplings will have greater capacity to take care of subsequent operating misalignment, and the life and satisfactory operation of the flexible couplings will be greatly enhanced. Any specification of definite limits is difficult.

Certain small, high-speed Diesel generating units are shipped from the factory completely assembled and aligned upon a cast-iron or structural steel base. In this case erection of course offers no difficulties, and it is merely necessary to set the unit level.

Engine Type. Engine-type generators are usually mounted upon the same concrete block as the engine itself. Soleplates are used under the generator frame to provide adequate support and to facilitate alignment. The erecting procedure is as follows:

(1) Set and level the soleplates, allowing for the height of the adjusting liners.

(2) Place the frame upon the soleplates. If the frame is of the split type, as in the case of some direct-current machines, set only the lower half.

(3) Lower shaft and rotor into the bearings. If the frame is one-piece, this will also necessitate some endwise shifting.

(4) Adjust the frame in position, shifting it axially until the center of the laminations is directly opposite the center of the rotor or armature.

(5) Tighten the soleplate bolts and grout the soleplates to the foundation.

Adjustment of the Air-Gap and End-Play

In setting up any machine in which the bearings are independent of the frame, great care must be exercised in adjustment of the air-gap between the armature core and the pole faces, as any inequality in the gap will cause unnecessary friction and heating of the bearings and unequal heating of the armature iron. During these adjustments, gauge the air-gap at different points from each side of the machine. Gauges for this purpose should extend to the center of the core. They may be made from thickness or "feeler" gauge stock that can be procured in various micrometer thicknesses and any suitable length.

It is also necessary to check the end-play or "float." In case the axial position is not shown, particular care should be used to see that the rotor punchings are centered axially with respect to the frame punchings. After a check has been made to see that the radial air gap is uniform at both ends, the frame should be bolted down but not dowelled. When the machine is started up, the end play should be checked and the frame moved axially until the rotor floats freely both with and without the field excited. When the end play is satisfactory, the frame should be dowelled.

Drying Out Windings

Moisture in electric machines affects the insulation resistance of the windings and should be removed before the machine is placed in operation. It is usually found that machines which have not been exposed to rain or unusual dampness will not require drying out.

Alternating-Current Machines. Alternating-current machines may be dried out by passing alternating or direct current through the windings, by operation at low voltage, or by use of external heat.

When drying out by use of alternating or direct current, use 60 to 100 per cent of the normal current stamped on the nameplate. The current should be adjusted so that the temperature of the windings does not exceed 85°C. by resistance or embedded temperature detector (65°C. by thermometer) in less than two hours, preferably in not less than six hours. The drying out should be continued at this temperature until the insulation resistance becomes constant.

The following methods of drying out may be used:

Direct-Current Method. Connect the direct-current supply to two of the three leads of the winding at a time, until the entire winding has been dried out. The resistance of the winding to be dried out should be determined in order to obtain the direct-current voltage needed to give the proper current.

Alternating-Current Method. Drive the machine at normal speed with all phases of the armature winding short-circuited. The field excitation should be just sufficient to give an armature current which will give the temperatures mentioned above, but not more than 110 per cent of normal armature current.

Operation at Low Voltage. In case a low or variable alternating-current voltage is available, the machine may be operated at 25 to 35 per cent rated voltage with the stator current adjusted to normal value or less by field control. The terminal voltage may be raised slowly as the drying progresses, or the machine may be operated at low voltage until the drying is completed and then placed in operation at normal voltage.

Use of External Heat. In many cases, it is impracticable to dry the windings by heat generated within the machine and external heat must be used. A tarpaulin should be used to cover the machine and some source of heat, preferably electric heaters, placed within the enclosure. An oven may also be used or a number of coils of steam pipe, enclosed with the machine in a box. Openings in the top and bottom of the box should be provided to give ventilation, the moisture being carried off by the hot air. The temperature should not exceed 85°C. (188°F.).

Direct-Current Machines. The armatures of these types of machines should be dried out by the use of external heat as described for alternating-current machines. Field windings may be dried out by the use of direct current. The armature windings of direct-current generators may be dried out by operating them with the armature short-circuited at the machine terminals through an ammeter. The series field should be cut out, the shunt field separately excited, and the brushes shifted slightly in the direction of rotation so there will be no danger of operation as a series generator with excessive armature current. The commutating field should be in the circuit and the armature current limited to a value that will not produce injurious commutation and in no case exceed normal value. Current should never be passed through a direct-current armature when stationary as there is danger of locally overheating the commutator and risers.

Insulation Resistance

As a guide to determine whether sufficient moisture is present to require drying out insulation, resistance measurements can be used. However, judgment should be exercised in using the values of resistance obtained. Quoting from A.I.E.E. Standards, the insulation resistance of machinery is of doubtful significance as compared with the dielectric strength. It is subject to wide variation with temperature, humidity, and cleanliness of parts. When the insulation resistance falls below prescribed values, it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying the machine. Insulation resistance of machines in service should be checked periodically to determine possible deterioration of the windings.

This measurement gives an indication of the condition of the insulation particularly with regard to moisture and dirt. The actual value of resistance varies greatly in different machines depending on the size and voltage. The chief value of the measurement therefore, is in the relative values of resistance of the same machine taken at various times. During a drying out run, for example, the insulation resistance rises as the winding dries out although it may fall appreciably at first. When measurements are made at regular intervals, with the machine at the same temperature, as part of the maintenance routine, it is thus possible to detect an abnormal condition of the insulation and take steps to remedy it before a failure occurs.

The insulation resistance is usually measured with an instrument called a "megger." In case a megger is not available, the test may be made as follows:

A direct-current voltmeter and a source of constant potential of 125 to 500 volts direct current are used. Before using power from any circuit for this test, determine whether the supply circuit is grounded by connecting to ground first one side and then the other through a single lamp for 125 volts or a bank of four lamps in series for 500 volts; if either side causes the lamps to light, the circuit is grounded. The ungrounded side should be connected in series with a voltmeter to the windings of the machine and the grounded side to the frame of the machine being tested. (See Fig. 99.) The circuits should be protected with a fuse having a capacity of 5 to 10 amperes. An incandescent lamp may be substituted for the fuse if more convenient.

With the testing circuit line switch open, read the voltage of the testing circuit. Then close the line switch and read the voltmeter connected between the ungrounded side of the line and the windings of the machine. The insulation resistance of the windings is then calculated from the following formula:

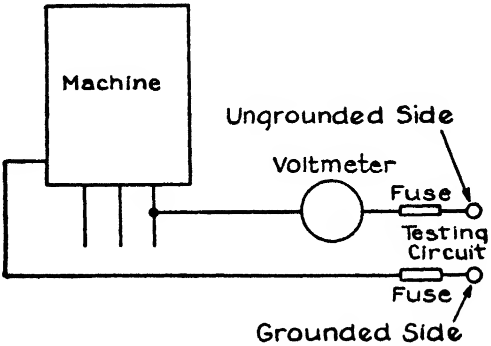


Fig. 99. Connection for Testing Insulation Resistance
Courtesy of General Electric Company

$$R = \frac{r\,(V - v)}{v\,(1{,}000{,}000)}$$

in which

V = voltage of the line
v = voltage reading with insulation in series with voltmeter
r = resistance of voltmeter in ohms (generally marked on label inside the instrument cover)
R = resistance of insulation in megohms (1 million ohms)

Voltmeters having a resistance of one megohm are now made for this purpose so that, if one of these instruments is used, the calculation is somewhat simplified since $r = 1{,}000{,}000$ and the above formula becomes

$$R = \frac{V}{v} - 1$$

In accordance with the Standardization Rules of the American Institute of Electrical Engineers, the insulation resistance in megohms at approximately 75°C. when the machine is clean and dry should be not less than

$$\frac{\text{Rated voltage}}{\text{Rated kv-a.} + 1000}$$

The insulation resistance of the rotor of synchronous motors and generators at 75°C. should not be less than one megohm.

Care of Generators

Cleaning. The interior and exterior of the machine should be kept free from dirt, oil, and water. The machine should be cleaned as often as operating conditions make necessary. Compressed air is an effective means of cleaning the interior parts. The collector rings, commutator, brushes, and brush rigging should be wiped carefully.

Oil. See that the oil wells are filled with a good grade of lubricating oil nearly to the top of the overflow of the oil filler, or to the center of the gauge. After the machine has operated the first week, draw off the oil, wash out the bearings with fresh oil or kerosene, and refill with new oil. Before replacing the drainage plugs, dip them in a mixture of red lead and shellac to prevent leakage. The oil should be replaced about once in six months or oftener, depending on such conditions as cleanliness, severity or continuity of service, etc., and the bearings cleansed periodically with kerosene. In order to avoid incorrect oil level, do not fill the oil wells when the machine is running, and do not allow the bearings to leak oil and throw it on the windings and commutator.

The oil rings should be watched to see that they revolve and carry a sufficient quantity of oil for proper lubrication.

Only the best grade of oil, having a viscosity of from 200 to 220 seconds, Saybolt, at 100°F., should be used. It is false economy to use cheap inferior oil.

Commutators. When a machine is first put in service, it should be run light for at least 24 hours with normal brush pressure and then an additional 24 hours at not over half load in order to give the commutator surface and brushes a good polish. During this period and the first few weeks of subsequent operation, the commutator surface should be frequently wiped off with dry canvas in order to remove all carbon deposits. Do not use waste or other linting materials. In some cases it may be necessary to use a very fine grade of sandpaper to remove the carbon deposit.

The commutator should maintain a polished surface. Blackening of all the bars indicates poor adjustment of the commutating field, or incorrect brush pressure; blackening of groups of bars at regular intervals may be due to the same cause or to poor brush contact; blackening at irregular intervals indicates a rough or eccentric commutator. Noisy brushes are due to a rough commutator or too much clearance between commutator and brushholders. Do not use lubricant of any kind on commutators.

In many cases where a commutator is rough but concentric, it is possible to stone it smooth with sandstone and finish with sandpaper, instead of turning it down. When the commutator is too rough to be stoned down by hand, the stone may be held in a tool post in a pair of ways, but better results will be had by using a revolving wheel grinder. In some cases it may be necessary to use a cutting tool. While doing such work, provision must be made to prevent dust or chips reaching the interior of the machine. When the commutator is true, it should be smoothed and polished with very fine sandpaper, and the slots between segments cleaned; if the mica appears to be flush with the bars, groove it below the surface at least 1/32 inch, using a grooving machine or a piece of hack-saw blade.

Collector Rings. Collector rings and brushes should be given the same careful attention given commutators in order to obtain and maintain good polished surfaces. The brushes should be staggered across the ring to minimize grooving and should not extend beyond the edges of the rings to prevent the formation of brush slivers.

One of the most common sources of trouble with synchronous machines is sparking at the collector rings. Much of this trouble is due to the lack of proper care. The collector rings are one of the most important parts of the machine, and they should be frequently inspected.

Any black spots that appear on the surface of the collector should be removed by rubbing lightly with fine sandpaper the first time that the machine is shut down. It is very important that this be done because, while these spots are not serious in themselves, they will lead to pitting of the rings and the necessity of regrinding. However, no harm is done to the rings, if the condition is corrected at once.

The brushes used should be light in weight, with a fairly high current capacity and should contain a slight amount of abrasive material.

Air Gap. Measure the air-gap clearance with a gauge periodically to detect any appreciable bearing wear.

Bolts. All bolts should be inspected occasionally to see that they are tight, particular attention being given to the bolts used to clamp any insulation. Do not disturb commutator clamping bolts.

Adjustment of Brushes and Brush Rigging

Direct-Current Generators. To obtain proper brush spacing, set up the studs with brushholders in place, and wrap the commutator with a long strip of paper covering its whole circumference. Mark the lapping point of this paper. Remove the paper. Spread it out on a flat surface and divide the space between the marked "lapping points" into as many equal divisions as there are brush studs. Replace the paper around the commutator and adjust the brush studs until the toes of the brushes of the different studs just touch these marks.

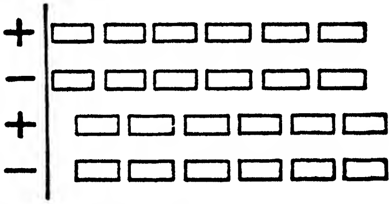


Fig. 100. Showing Correct Method of Staggering Brushes
Courtesy of General Electric Company

All brushholders should be the same distance from the commutator, not over ⅛ inch, and the toes of all brushes on one stud should line with the edge of one segment. If a stud is out of line in either of these directions, file or shim the insulating collars to correct it.

Stagger the brushes so that they will not follow in each other's tracks on the commutator and thus prevent the formation of grooves on the commutator surface. The brushes should be staggered in pairs as shown in Fig. 100.

When the brushes have been properly set, sand them to fit, with medium or fine sandpaper—do not use emery or carborundum. A good brush fit is essential. Clean away the carbon dust, as it may cause trouble if allowed to collect on the windings.

Alternating-Current Generators. To insure uniform wear of the collector rings, adjust the brushholders on the studs so that the brushes will be staggered across the width of the collector rings. See that the brushes move freely in the holders and at the same time make firm, even contact with the collector rings. Poor contact will cause sparking.

To obtain a final brush fit, so that the curvature of the brush conforms to the curvature of the ring, use sandpaper with the sanded side up, drawing it in the direction of rotation on the ring surface. Lift the brush when moving the paper back to its original position. Keep the ends of the sandpaper close to the collector ring to avoid rounding the edges of the brush. Treat each brush separately in like manner. Do not use emery or carborundum paper. See that the pigtails do not interfere with the rigging.

Generator Troubles

Frequent careful inspection of generators during operation is essential in order to detect any troubles which may in time result in a serious failure. A broad outline of the troubles which should be looked for, and their causes, are given below. These troubles should be corrected as soon as discovered.

Mechanical

Hot bearings: worn-out or dirty oil, insufficient oil, sticking of oil rings, rough journal, poorly fitted bearing, misalignment, excessive end thrust.

Oil leaks: too much oil in bearing, incorrect grade of oil.

Vibration: misalignment, improper foundation, misalignment due to settling of foundation, uneven air gap, sprung shaft.

Electrical

Hot bearings: shaft current.

Vibration: short-circuited field coil, unbalanced stator currents in case of alternating-current machines.

Overheating of any member: excessive current, open phase or unbalanced alternating-current resulting in single-phase components of current, improper ventilation or insufficient air, excessive ambient temperature, unequal air gap, short-circuited windings, reversed field coil, dirty condition.

Unbalanced currents: wrong connections, unequal resistance or reactance in parallel circuits, incorrect meters.

Improper voltage: wrong transformer taps, excessive line reactance or resistance, incorrect meters, short-circuited field coil.

Poor commutation: improper adjustment, vibration, incorrect brushes, rough commutator, oil-soaked mica, short-circuited segments, excessive load, poor brush fit.

Improper parallel operation: See Chapter V on "Parallel Operation."

Failure of insulation: wrong voltage, induced voltages due to opening field circuits too quickly, dirty insulation, oil-soaked insulation, excessive temperature, excessive vibration, mechanical damage, excessive moisture or water, voltage surges produced by lightning, switching, etc.

Low insulation resistance: dirty insulation, excessive moisture.

Low Voltage—A. C. Generators

The following causes may prevent alternating-current generators from developing their normal voltage:

(1) The speed of the generator may be below normal.

(2) The switchboard instruments may be incorrect, and the voltage may be higher than that indicated, or the current may be greater than is shown by the readings.

(3) The voltage of the exciter may be low because:

- (a) Its speed is below normal.
- (b) Its series field is reversed.
- (c) Part of its shunt field is reversed or short-circuited.
- (d) Its brushes may be incorrectly set.

(4) Part of the field rheostat or other unnecessary resistance may be in the field circuit.

(5) The power-factor of the load may be abnormally low.

Low Voltage—D. C. Generators

The following causes may prevent direct-current generators from developing their normal electromotive force.

(1) The speed of the generator may be below normal.

(2) The switchboard instruments may be incorrect and the

voltage may be higher than that indicated or the current may be greater than is shown by the readings.

(3) The series field may be reversed, or part of the shunt field reversed or short-circuited.

(4) The brushes may be incorrectly set.

(5) A part of the field rheostat or other unnecessary resistance may be in the field circuit.

Reversing Polarity—D. C. Generators

To change the polarity, if a generator keeps the same rotation, it is necessary to reverse the residual magnetism, which is done by exciting the shunt field momentarily in the opposite direction from some outside source.

Excitation Troubles—D. C. Generators

When starting up, a generator may fail to excite itself. This may occur even when the generator operated perfectly during the preceding run. It will generally be found that this trouble is caused by a loose connection or break in the field circuit, by poor contact at the brushes due to a dirty commutator or perhaps to a fault in the rheostat, or incorrect position of brushes. Examine all connections; try a temporarily increased pressure on the brushes; look for a broken or burnt-out resistance coil in the rheostat.

A very simple means for getting a compound-wound machine to pick up is to short-circuit it through a fuse having approximately the current capacity of the generator. If sufficient current to melt this fuse is not generated, it is evident that there is something wrong with the armature, either a short-circuit or an open circuit. If, however, the fuse has blown, make one more attempt to get the machine to excite itself. If it does not pick up, it is evident that something is wrong with the shunt winding or connections.

Sparking at Brushes—D. C. Generators

Sparking at the brushes may be due to any of the following causes:

(a) Commutating-pole field air gap may not be correct.

(b) The generator may be overloaded.

(c) The brushes may not be set exactly on neutral.

(d) The brushes may be wedged in the holders or have reached the end of their travel.

(e) The brushes may not be fitted to the circumference of the commutator.

(f) The brushes may not bear on the commutator with sufficient pressure.

(g) The brushes may be burned on the ends.

(h) The commutator may be rough; if so it should be smoothed off.

(i) A commutator bar may be loose, or may project above the others.

(j) The commutator may be dirty, oily or worn out.

(k) The carbon brushes may be of an unsuitable grade.

(l) The brushes may not be equally spaced around the periphery of the commutator.

(m) Some brushes may have extra pressure and may be taking more than their share of the current.

(n) High mica.

(o) Vibration of the brushes.

(p) Incorrect brush angle.

The commutator should run smoothly and true, with a dark, glossy surface.

Heating of Field Coils—D. C. Generators

Heating of field coils may develop from any of the following causes:

(a) Too low speed.

(b) Too high voltage.

(c) Too great forward or backward lead of brushes.

(d) Partial short-circuit of one coil.

(e) Overload.

Heating of Armature

Heating of direct-current armature may develop from any of the following causes:

(a) Too great a load.

(b) A partial short-circuit of two coils heating the two particular coils affected.

(c) Short-circuits or grounds on armature or commutator.

Heating of Commutator

Heating of commutator may develop from any of the following causes:

(a) Overload.
(b) Sparking at the brushes.
(c) Too high brush pressure.
(d) Lack of lubrication on commutator.
(e) Improper grade of brushes.

Maintenance of Voltage Regulators

The maintenance required by a vibrating type voltage regulator, such as the Westinghouse, may be briefly summarized as follows:

(1) Keep the main contacts clean by stoning off with the finest carborundum stone, keeping one ball-shaped.

(2) Keep both dashpots CLEAN and CLEAR at the window. When re-filling, wipe thoroughly clean and dry. Handle distilled water in its own vessel used for no other purpose.

(3) Keep extra relay contacts on hand and replace weekly, if necessary. When one set is removed, file off flat and use again at the next replacement. Keep contact gap about equal to the thickness of the upper-contact mounting-spring.

(4) If relay contacts build up, reduce condenser capacity. Keep armature-stop clean.

(5) Every shift should throw all reversing switches as soon as going on duty.

The general care which should be given is as follows:

Cleanliness. The case on the control element should be kept closed, and cleaned inside and out when necessary. The interior parts of the regulator should be cleaned carefully by dusting with a half-inch camel's-hair brush.

Floating Lever. The floating lever of the control element should never operate more than $\frac{1}{16}$ inch above or below the central position as determined by the centering post. Adjust the position of this lever by the vibrating-magnet spring.

Main Contacts. The main contacts should be inspected once each month. The contact surface should be bright and lustrous and slightly uneven. If cavities, projections, or dark spots appear accompanied by unsatisfactory operation, these contacts should be removed and ground. This should be done on a small fine-grained carborundum stone. Do not use a dirty or oily stone for this purpose. The spring-mounted contact should be ground flat and the screw-mounted contact should be ball-shaped.

Relay Contacts. The rheostat shunting relay contacts should wear a bright, mottled surface. Blackening at the outer edge of this contact is a normal condition of a good contact. A bright, mottled surface though somewhat uneven forms a better contact than a newly-fitted surface. Contacts should be kept approximately .014 inch apart. The gap should never be allowed to exceed 1/32 inch. If the contact surfaces become very uneven, they should be refitted. This is best done by filing with a fine file until the surfaces are flat and true. Contacts should be replaced in the relays so that one registers squarely over the other, and then securely fastened. These contacts will spark for a time after being newly fitted. Loose contacts will cause unstable operation and increase the tendency to arc over.

Pivots and Bearings. All pivots and bearings should be adjusted so that there is only enough play to prevent binding. A slight amount of play is absolutely necessary for the free operation of the levers.

Dashpots. The water level in the dashpots should never be allowed to fall below the window, or more than ⅛ inch below the lower arrow, if one is shown. The dashpots should be removed, emptied, and thoroughly cleaned with gasoline and wiped bright and dry with clean, new rags every six months or more frequently if there is any indication of deposits from the water used.

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