ELECTRIC-RAILWAY SYSTEMS

METHODS OF SUPPLYING CURRENT

1. Electricity is now generally conceded to be the most economical power for the operation of street railways. It has shown itself superior to horses, compressed air, or cable, both as regards flexibility and cheapness of operation. Cable roads may be advantageous in some very hilly localities; but for ordinary traffic, most of the cable roads installed some years ago have been converted into electric lines. Compressed air has been used in a few cases, notably in mining work, but for general purposes electricity has the field practically to itself.

2. So far, electric cars have been operated by direct current almost exclusively; that is, the current supplied to the cars is direct though the current supplied from the station may be alternating. On roads where a considerable amount of power has to be transmitted a long distance, alternating current is used in order that the transmission may be carried out economically at high line pressure, but even under such circumstances the general practice has been to step-down the alternating current and transform it to direct current before supplying it to the cars. On roads where the distance of transmission is not very long, direct current may be supplied from the station and the use of alternating current is unnecessary; if boosters are used, as described later, the radius of direct-current supply can be extended considerably.

The direct-current series motor is admirably adapted for traction work, and alternating current has not been used to

For notice of copyright, see page immediately following the title page

any extent on the cars for the reason that heretofore no alternating-current motor that could compete on all points with the direct-current motor has been available. A number of roads are operating in Europe on which polyphase induction motors are used, but the induction motor has never been used to any extent in America because it presents a number of disadvantages. It is essentially a constant-speed motor and is not well adapted for work where a variable speed, large starting torque, and decreasing torque with increasing speed are desired. Again, three-phase motors necessitate at least two trolley wires. However, it has long been recognized that the use of alternating-current motors on cars would simplify and cheapen the construction of roads on which alternating current must be used for the transmission of power. Rotary converters are dispensed with and it becomes possible to use a much higher pressure between the trolley wire and the rail. Within the last few years, a great deal of experimenting has been done on the use of single-phase motors for traction work, and it is probable that this type of motor will be largely used for interurban roads. A single-phase motor requires only one trolley wire, and the motors so far developed have speed and torque characteristics very similar to those of the direct-current series motor. It is safe to say, therefore, that in many future installations alternating current will be supplied to the cars and rotary-converter substations dispensed with on those roads where the conditions are such that direct current cannot be used economically for the transmission from the station.

VOLTAGE

3. The voltage at which current is supplied to the cars has in the past been limited principally by the conditions for sparkless commutation on the motors and also by considerations of safety. It is difficult to build direct-current motors that will operate without sparking or flashing under the severe conditions incidental to electric traction, if the pressure is over 650 volts. Also, in places where the trolley wire is

exposed, as in public streets or along public highways, the pressure should not be much over 500 volts on account of the danger to life. Thus, the general practice has been to use from 500 to 550 volts for city traffic and 600 to 650 volts for interurban traffic. Under conditions of heavy load, the pressure may be very much lower than these figures because of the large line drop. On interurban lines operating on a private right of way, there is no reason why a pressure higher than 650 volts could not be used between the trolley wire and track, provided that motors could be made to operate satisfactorily on the higher pressure. Experiments have shown that there is no special difficulty in collecting current at high pressure from an overhead trolley, though, of course, the wire has to be insulated better than is usual for ordinary 500-volt work. On the Berlin-Zossen experimental three-phase road, a trolley pressure of 10,000 volts was used without difficulty. With alternating-current motors, the current can be supplied at high pressure and stepped-down by means of a transformer carried on the car. The use of alternating-current motors will therefore in all probability be accompanied by trolley-wire pressures much higher than those customary with direct current, and a corresponding saving in the amount of copper required to supply current to the cars will be effected. The use of high trolley pressures will, of course, be confined to roads operating in places where the trolley wire will not be a source of danger.

METHODS OF CURRENT COLLECTION

4. Several methods are available for supplying current to the cars, but the one to be used in any given case is generally fixed by local conditions. The usual methods are given below in the order of the extent of their application.

1. By means of an overhead conductor or pair of conductors connected to the car by an under-running contact; this is known as the *overhead-trolley system*.

2. By means of contact or conductor rails run alongside of, or between, the car rails, contact being made with the

car by means of sliding shoes; this is usually called the *third-rail system*.

3. By means of underground conductors run in a conduit and connected with the car by means of a contact plow passing up through a slot; this is called the *open-conduit system*, or *slot system*.

4. By means of electromagnetic switching devices that make connection between the car and a conductor situated underground; this is usually called the *electromagnetic*, or *surface-contact, system*.

5. By means of storage batteries carried on the car; in this case no conductors between the power station and cars are necessary.

It will aid in understanding the various methods of railway power distribution to consider, very briefly, the main features involved in each method. The details will be taken up later in connection with line and track construction.

OVERHEAD-TROLLEY SYSTEM

5. The **overhead-trolley system** is more widely used than any of the others. For lines in towns or cities, when a road is run along a public right of way and where the live working conductor must be placed so that there will be no danger of accidental contact with it, the overhead-trolley system is the cheapest both as regards first cost and cost of maintenance.

Fig. 1 shows a simple trolley system supplied from a direct-current generator. The positive terminal of the generator connects, through the switchboard, to the overhead-trolley wire; the negative terminal connects to the rail, and the path of the current is indicated by the arrows. The current is carried to the moving car by means of the under-running trolley wheel. This arrangement, simple as it may seem, was not arrived at without considerable experimenting. In the early electric roads two trolley wires were used, and the track was not employed as one side of the circuit. This scheme is still used in a few

places, notably in Cincinnati. Also, on the first roads installed, the trolley wheel ran on top of the wire; but this method of collecting the current was soon superseded by the under-running trolley.

It should also be noted that the cars are operated in parallel. This is true of all systems of distribution where current is supplied to the cars from an outside source. All street-railway systems are, therefore, operated at approximately constant potential; i.e., constant or nearly constant pressure is maintained between the trolley wire and the track. Wherever connection is made from the trolley to the track through the motors, a current flows and the car is propelled.

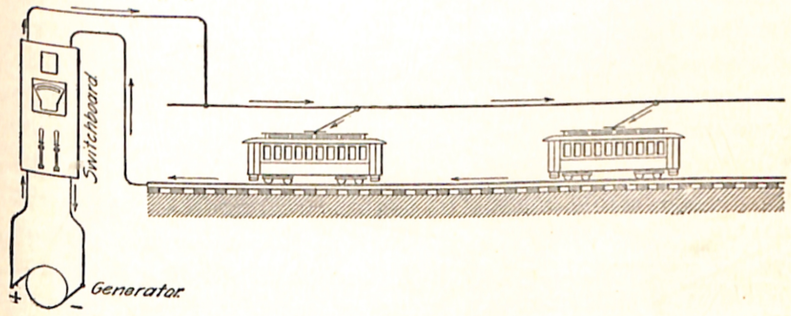


FIG. 1

Each car is independent of the others and takes an amount of current proportional to the power required to drive it.

The arrangement shown in Fig. 1 admits of many modifications. For example, except on very small roads, the trolley wire is not sufficiently large to carry the current necessary; so **feeders**, or heavy cables, are run to the station instead of carrying back the trolley wire itself. Also, in some cases, return cables are used in connection with the track. The overhead-trolley method is, at present, the only one that is available for the supply of current at high trolley pressures, the insulation provided by the other methods not being sufficient, to say nothing of danger from shock.

THIRD-RAIL SYSTEM

6. The **third-rail system** is, in principle, the same as the overhead trolley. The trolley wire is replaced by a third rail mounted on insulators to one side of the track, or between the tracks on double-track roads, and slightly above the other rails. Current is supplied to the car by means of shoes that slide on the contact rail and the current returns through the track rails, as in the overhead system. In a few special cases, two conductor rails have been used, the track not being employed to carry the return current.

Fig. 2 shows the arrangement of collecting shoe for an ordinary third-rail equipment. The third rail *a a* is of the standard **T** pattern and is supported on insulators *b* resting on every fifth tie, which is extended for this purpose. The cast-iron shoe *c* is suspended from links, so that it is free to move up and down through a limited range, and the whole collecting device is attached to a wooden beam *d* carried by the truck. Cable *e* leads to the controlling devices on the car and connection is made to the shoe by means of bare flexible copper cable or braid *f*, the links not being depended on to carry the current. In some cases, a copper fuse is placed at *g* to cut off the current in case of short circuits.

The third rail is much used for roads where the traffic is heavy and when the presence of the contact rail does not interfere with other traffic. It is the outcome of a demand for a construction more substantial than the overhead trolley and better adapted to high-speed work and the collection of large currents. The contact rail provides a working conductor of large cross-section and long stretches of track can be supplied with current without any feeder other than the third rail.

7. A No. 000 trolley wire has a cross-section of .132 square inch; a 70-pound rail has a cross-section of about 7 square inches. Taking the conductivity of the conductor rail as one-tenth that of copper, the rail will be equivalent to .7 square inch of copper, or 5.3 times the cross-section of the trolley wire. If especially soft steel were used for the

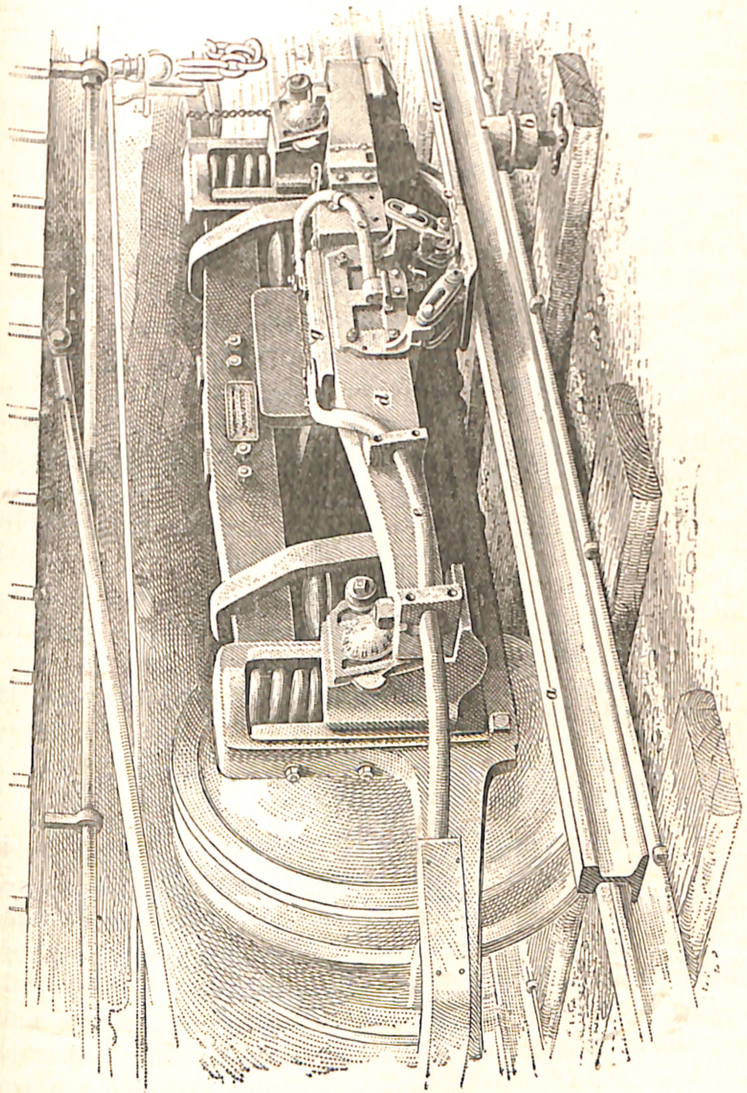


FIG. 2

third rail, the resistance might not exceed 7 to 8 times that of copper; but even with steel not especially made for high conductivity, a 60- or 70-pound rail will provide a much larger carrying capacity than a trolley wire of the size ordinarily installed. The third-rail construction is generally considered more expensive than the overhead trolley, but as a matter of fact it is cheaper when the comparison is made on a basis of equal current-carrying capacity.

8. This system is not without its disadvantages, and by some engineers it is thought that it will eventually give way to some kind of overhead construction more substantial than the ordinary trolley wire, or to some well-developed surface-contact system. There is unquestionably an element of danger in the exposed third rail even when the road is elevated, underground, or run on a private right of way carefully fenced in. The exposed live rail is in the way when track repairs are being made, though the trackmen soon become accustomed to it and accidents are surprisingly few. It is also very difficult to use it in yards and terminals, the numerous crossings of the tracks making the work very complicated and dangerous. On this account, on some third-rail roads the cars are equipped with overhead trolleys and all switching in the yards and at terminals is carried out by the overhead system.

OPEN-CONDUIT SYSTEM

9. The **open-conduit system,** because of the great expense of installation, is used only in a few large cities where the traffic is heavy enough to warrant the expense and where the city authorities do not permit the stringing of overhead-trolley wires and feeders. Current is supplied from two conductor rails placed in a conduit between the track rails. This conduit is closed at the top with the exception of a slot about $\frac{5}{8}$ inch wide, through which a plow suspended from the car passes. Two cast-iron shoes, carried by the plow, press sidewise against the conductor rails, and cables lead from the shoes to the motors on the

car. Fig. 3 illustrates the main features and Fig. 4 shows the arrangement of the plow in relation to the conductor rails. The conduit is made sufficiently deep so that mud and water will not interfere with the conductor rails, and at regular intervals sewer connections are provided. The two contact shoes s, s are pressed sidewise against the conductor rails a, a by flat springs b, b. Shoes s, s connect to cables c, c, which lead to the motors and controlling devices on the

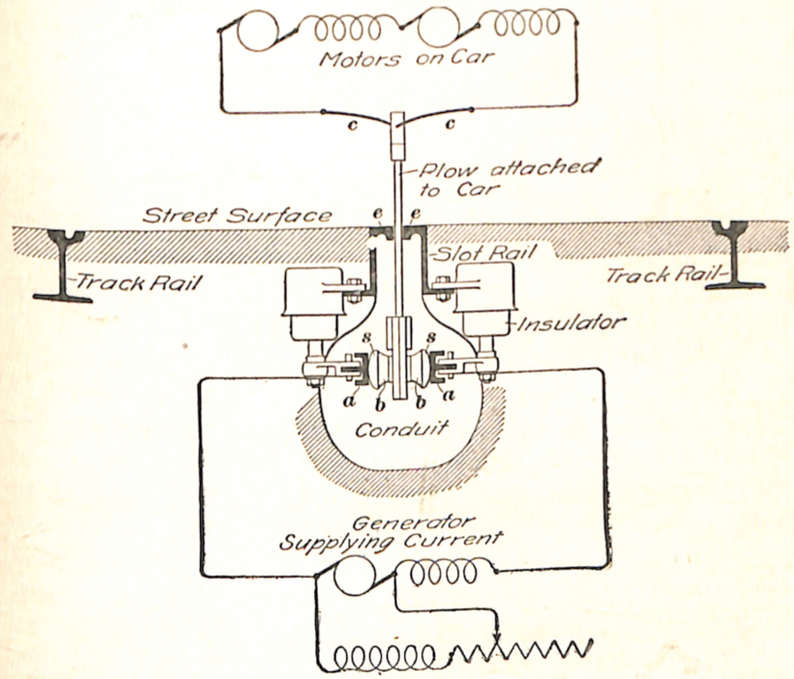


FIG. 3

car. The conductor rails a, a are connected to the power station by outgoing and return feeders run in ducts alongside the track. The part of the plow that passes between the slot rails e, e is made of steel plates riveted together, while tempered-steel wearing plates are fastened on the plow at the points where rubbing against the slot rails occurs.

While this system works satisfactorily if the conduit is kept properly cleaned, and avoids the use of overhead

conductors, it is not a generally applicable method. The cost of construction is from four to five times that of an overhead-trolley line, and it is only on roads having a dense traffic that it can be made to pay. The construction of the conduit in cities usually necessitates the removal or rearrangement of underground pipes, sewers, electric conduits, etc. that may lie in the path of the conduit, all of which increases the cost greatly.

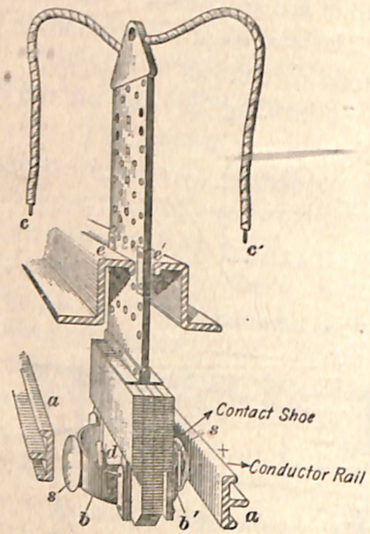


FIG. 4

ELECTROMAGNETIC, OR SURFACE-CONTACT, SYSTEMS

10. Surface-contact systems have not been used to any great extent though many such methods have been invented. In only a few special cases have they been used in the United States; but in England and also on the Continent of Europe a number of surface-contact roads have been in operation long enough to demonstrate their reliability and safety. These roads are more expensive to install than those using an overhead trolley, but they are less expensive than open-conduit roads, are cheaper to maintain, and are equally effective so far as avoiding overhead wires is concerned. It is reasonable, therefore, to expect that surface-contact systems will find wider application in the future than they have in the past. All electromagnetic systems are more or less complicated, and of all the switching devices that have been invented comparatively few have been commercially operated.

11. The general arrangement of such systems is shown in Fig. 5, where G is the generator with its negative terminal connected to the track rails, as in the overhead-trolley or third-rail systems. Insulated contact plates r, r are

mounted between the rails and project slightly above the pavement. In most systems, these contacts are in the form of small plates of hard steel designed to withstand the wear caused by traffic and by the current-collecting shoe on the car. Each contact is connected to the positive working conductor m through a switch s that is so arranged that the contact plate is connected to the live conductor only while the

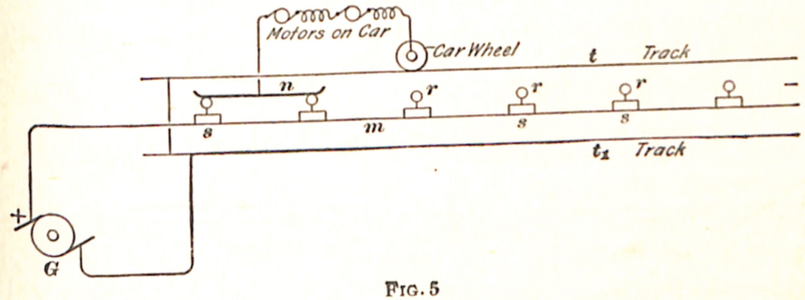


FIG. 5

car is over the plate. Thus, as the car moves along the switches operate, and the car is supplied with current by means of a shoe n that slides over the contact plates. In some systems, the switches are grouped in manholes, and operated electrically by means of solenoids or electromagnets; in others, the switches are placed under the contact plates and operated by means of powerful magnets carried underneath the car.

12. General Electric System.—Fig. 6 shows the essential features of the **General Electric surface-contact system,** which belongs to the class in which the switches are operated by means of solenoids. Two rows of contact studs N, N are placed between the rails; the negative terminal of the generator connects to the track rails and the positive conductor connects to one of the fixed contacts of each of the switches K, as shown. The operating coils of the switches are connected between the lower rail and the lower row of contact studs; the studs in the upper row are connected to the remaining fixed contacts on the switches as shown. Each car is equipped with a small storage battery B, which is kept charged by passing a portion of the motor current through it; this battery is used to operate the

surface-contact switches when the car is started and also for lighting the car. The car is equipped with two long shoes, and when it is in motion the current takes the path indicated by the arrows, flowing from the positive working conductor through the switch contacts to the upper contact stud, thence through the motor, or combination of motors, through the lower shoe and contact stud, and back to the rail by way of the magnet coil. The current passing through the coil holds up the switch, and as the car moves along, successive switches are

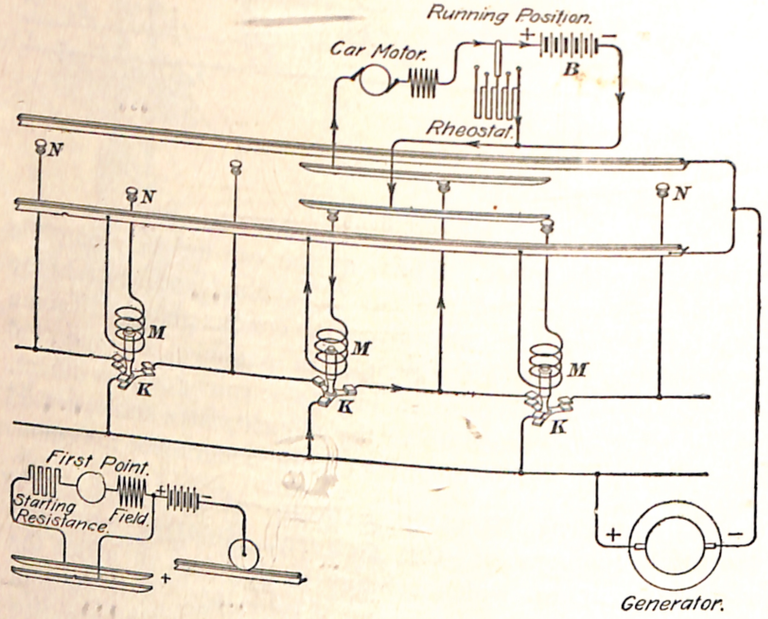


FIG. 6

brought into action, thus maintaining the path for the current through the car. The only live studs are those under the car, and as soon as the car moves off the studs become dead; there is thus no danger of shock unless some of the switches fail to operate. When the car is started, current must be supplied from the storage battery in order to operate the switch; this is done by making the connections at starting as shown in the small diagram, where the battery is connected between the lower shoe and rail, thus raising the switch and

allowing current to pass through the motors. As soon as the car has started, the main current operates the switches and the battery is no longer required for this purpose. By making the shoes long enough so that the forward stud is touched before connection with the one in the rear is broken, the forward switch will pick up before the rear one drops, thus maintaining the circuit and avoiding arcing at the switch contacts. In an actual installation, the switches are not distributed along the track, but those corresponding to about 200 yards of track are placed in a vault or manhole and connected to the studs by means of underground cables.

13. Lorain System.—As an example of a surface-contact system where the switches are operated by means of magnets carried under the car, the **Lorain system** may be taken. This method is in successful operation for regular city traffic, and continuous use has shown that the danger from shock on account of switches failing to work is negligible. A switch is placed directly beneath each contact plate. The upper switch contact connects to the plate and the lower contact to the working conductor through a flexible copper ribbon. The lower contact is mounted on a thin iron plate, and a series of magnets suspended under the car, with their poles near the surface of the ground, attract the plate with the lower contact and draw it up, thus bringing the lower contact against the upper one and establishing connection between the contact plate and the feeder. The contact plates and switches are placed 10 feet apart and the magnets under the car extend over a length of 16 feet. Thus, two switches are always closed at the same time; the forward switch is picked up before the rear one is dropped and there is no breaking of the circuit when a switch opens. The collecting shoe extends over two contacts, as in Fig. 5, and there is thus a continuous collection of current. As soon as the magnets pass from a switch, the iron plate, carrying the lower contact, drops, thus leaving the plate dead after the car has passed. The switch contacts are made of carbon so that there is very little danger of sticking.

A small storage battery is provided on the car to furnish current for energizing the magnets when the car is first started or to start the car after the current has been cut off from the line temporarily. Details as to the construction and method of mounting the switches will be given later in connection with track construction.

14. Sectional Third Rail.—Electromagnetic switching devices can be used for the operation of third-rail systems, where the contact rail is divided into a number of short sections that are energized only when the car is passing. In this case, the contact plates, Fig. 5, are replaced by short sections of third rail and the system is much safer than the ordinary one where the whole rail is energized from one end of the line to the other. Sectional third-rail systems are used, to some extent, for the operation of trains in tunnels and in other places where it is desired to reduce the danger from shock to a minimum.

STORAGE-BATTERY SYSTEMS

15. Many attempts have been made to operate electric street cars by means of storage batteries carried on the cars but none of them have proved really successful. The constant vibration and jarring soon cause the cells to deteriorate while the acid fumes given off by them have also proved a great drawback. It is not worth while devoting space to a consideration of cases where the storage battery has been tried and abandoned. For some special kinds of traction work, batteries have proved desirable; as, for example, the operation of small electric locomotives for use around manufacturing plants.

However, batteries may often be used to great advantage on railway systems when they are placed in power houses or substations to take up fluctuations in the load or to carry the whole load for short intervals. In work of this character, the battery is stationary and the deterioration is not nearly so great as when the cells are subjected to shocks and jars on a car. Moreover, a stationary battery can be made heavy enough to secure durability, whereas a street-car battery must be made as light as possible.

OPERATION BY DIRECT CURRENT

16. The simplest method of supplying current to cars is by direct current transmitted from the generators to the cars without the use of any intervening transforming devices. The ordinary 500-volt system with its connections has been explained, so that it is only necessary here to describe some special features connected with direct-current distribution that pertain particularly to electric railways.

The distance beyond which it becomes uneconomical or undesirable to operate cars by means of current transmitted at 500 volts depends so much on the character of the traffic and the frequency of the car service that it is difficult to assign any limits beyond which 500-volt distribution should not be used. Many roads are in successful operation where cars are operated 8 miles or more from the power station and, by installing storage batteries on the distant parts of the line, cars can be operated at greater distances without undue drop. On the other hand, roads with very dense traffic, as in large cities, cannot be operated for a radius of 8 miles from the power house without an excessive expenditure for copper. By careful laying out, however, there is no reason why most medium-sized roads cannot be operated over a radius of 6 to 8 miles by the 500-volt system and the use of alternating-current transmission is seldom necessary for such roads.

HIGH- AND LOW-POTENTIAL BUS-BARS

17. In many cases, the greater part of the traffic on a road is confined to a comparatively small area; lines run out to distant points, but the traffic on the outlying lines is light. By applying a higher pressure to the feeders running to these distant points, the pressure at the cars can be maintained without the installation of an alternating-current transmission plant. Thus, if two pressures, say 500 volts and 600 volts, are available at the station, the short feeders supplying near-by sections can be attached to the 500-volt bus and the long feeders running to outlying sections to the

600-volt bus, thus allowing a drop of 100 volts in the long feeders. By using this method, the district supplied may extend for a radius of 10 or 12 miles from the power house.

18. Fig. 7 illustrates a plan of connections where high- and low-potential bus-bars are provided. Generators *1*, *2*, *3* are compound wound, as is always the case in street-railway

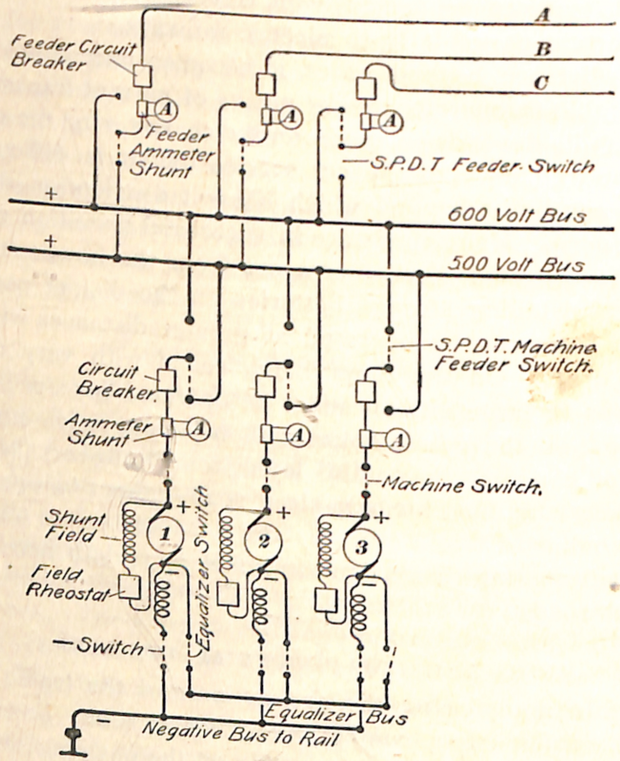


FIG. 7

power stations, and their — terminals are connected to the rail bus-bar. Each + terminal is connected through a main switch, ammeter, and circuit-breaker to the middle point of a single-pole double-throw switch, by means of which the + side of the generator can be connected to either the upper or lower bus-bar.

In Fig. 7, machines *1* and *2* are connected to the lower bar and are operating in parallel, their equalizing switches being closed. Machine *3* is connected to the upper bus, as indicated by the dotted position of the machine feeder switch. Most standard railway generators will generate 600 volts without difficulty, and machine *3* is supposed to generate 600 volts while *1* and *2* generate 500 volts. With the connections shown, any machine can be connected to either bus-bar. The feeders are also provided with single-pole double-throw switches to enable any feeder to be connected to either bus. Thus, if feeders *A* and *B* were supplying near-by sections, or if the load on them were light, they could be run from the 500-volt bus; while if feeder *C* supplied a distant or heavily loaded section it could be connected to the 600-volt bus by throwing its switch to the upper position, as indicated. By this method, a fairly uniform voltage can be maintained at the cars under widely varying conditions of load and distance of transmission. It should be noted, Fig. 7, that the generators are equalized on the — side, a practice that is now very common in railway plants. The — main switch and the equalizer switch are mounted side by side near the machine, and the negative leads are carried directly to the rail bus, thus simplifying the conditions.

BOOSTERS

19. When a road operates several sections a long distance from the power house, the generators, even when run at 600 volts, may not furnish sufficient pressure to make up for the large drop in the feeders. In such cases the road may be operated, without using high-pressure alternating-current transmission, by using *boosters* in connection with the main generators. A **booster** is a generator connected in series with the feeder or feeders on which the voltage is to be raised, in such manner that the voltage that it generates is added to that of the main generators, thus increasing the voltage applied to the feeders by the amount of the pressure generated by the booster.

In Fig. 8, *a* represents the armature of the main generator and *b* the booster armature. Short feeders supplying near-by sections are connected to the + bus-bar of the generator in the usual manner. Long feeders are connected to the + bus-bar through the booster, which in this case is supposed to generate 200 volts. For railway work, boosters are nearly always of the series type; i. e., the field winding is in series with the armature so that the voltage generated increases in proportion to the current that passes through the booster. Thus, when the load on the long-distance feeders

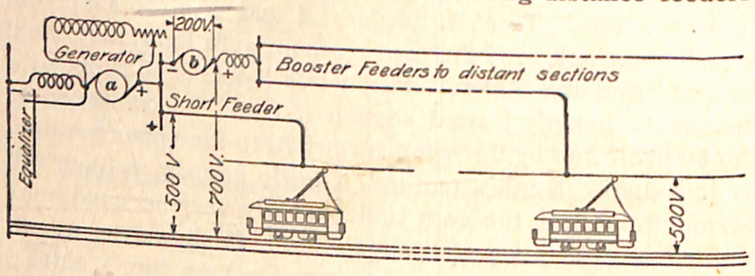


FIG. 8

is light, the booster voltage is low because the field is weak. When a heavy load comes on, the booster voltage increases and automatically compensates for the drop in the long feeders supplied through the booster. If the booster were shunt or compound wound and thus generated a practically constant voltage regardless of the current supplied over the feeders, an excessive voltage would be applied to the cars at light loads because there would then be little loss in the line to take up the booster voltage.

20. Method of Driving Boosters.—Boosters are nearly always driven by means of shunt-wound motors. Fig. 9 shows a typical General Electric booster set, consisting of a shunt-wound motor *M* coupled to a series-wound booster *B*. Boosters do not differ in their general construction from other dynamos, except that their commutators are often larger than on standard generators, because of the large current that they carry in proportion to their size. Boosters could be driven by steam engines or any other convenient

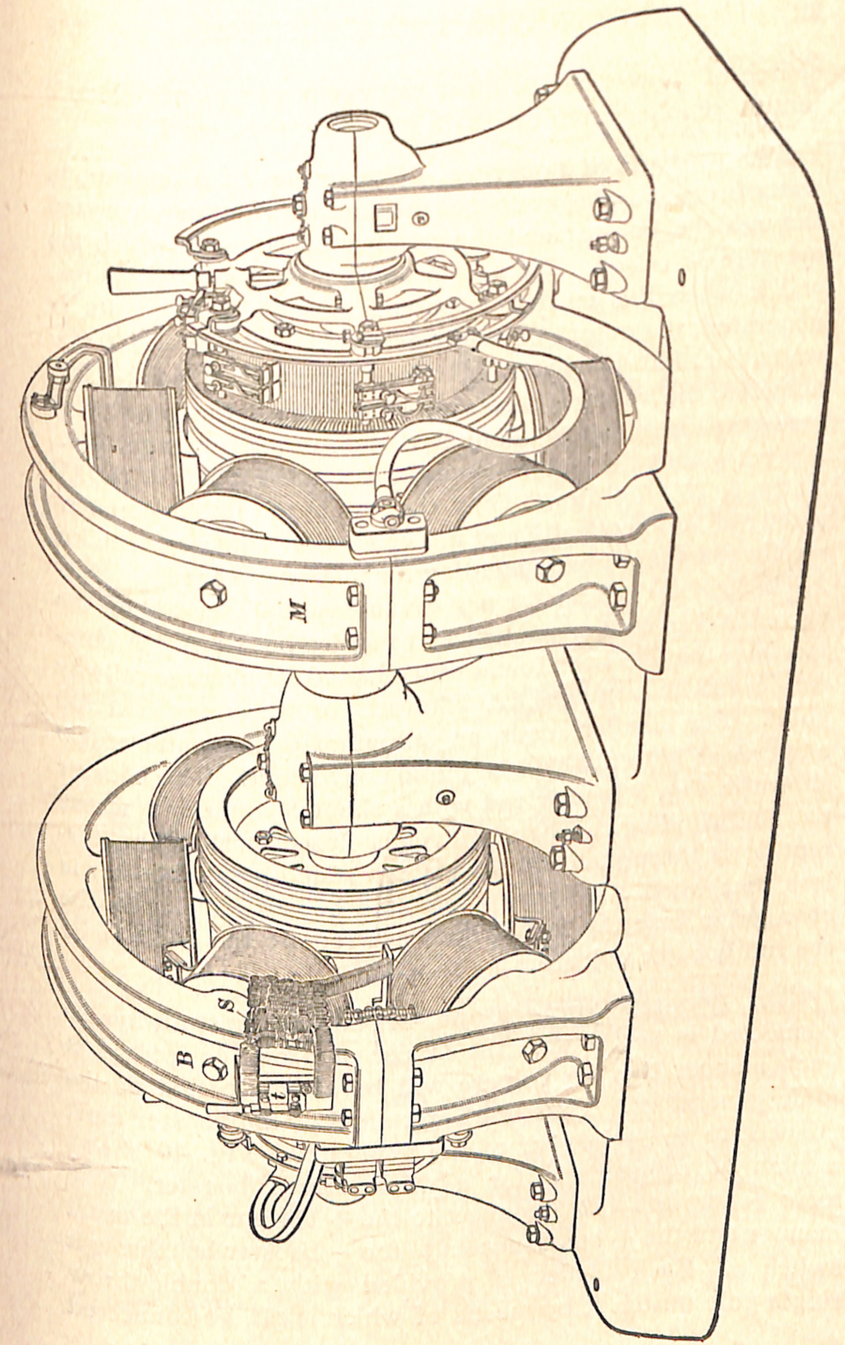


FIG. 9

source of power, but in most railway power plants electric motors supplied from the main generators are used.

21. Output of Boosters.—The output of a booster, in watts, is equal to the product of the number of amperes passed through the booster and the number of volts by which the pressure is raised. Thus, if a booster carries 600 amperes, and if when this current is passed through it 200 volts is generated, the output of the booster is $600 \times 200 = 120{,}000$ watts, or 120 kilowatts. If the current dropped to 300 amperes, the voltage generated would, since the booster is series-wound, drop to about half the full-load voltage, i. e., 100 volts, and the output would then be $300 \times 100 = 30{,}000$ watts, or 30 kilowatts. Thus, the loss in the line is compensated for automatically and the voltage at the cars remains nearly constant notwithstanding fluctuations in load.

The booster output for any given case will depend on the current taken by the feeders that require boosting. A common size that has been found well adapted for average railway service has an output of 120 kilowatts, or 600 amperes at 200 volts. For smaller roads, an output of 60 kilowatts or 600 amperes at 100 volts will be found convenient. The booster shown in Fig. 9 is provided with a shunt S connected across the field winding. When switch t is closed, part of the current flows through S and the voltage added by the booster is less than when t is open. Thus, the boosting effect can be changed in case the feeder does not require the addition of the full booster voltage.

22. Booster Connections.—A booster must always be connected in series with the feeder or group of feeders in such manner that its voltage will be added to that of the main generators. Thus, the − terminal of the booster must connect to the + bus-bar of the generator. Fig. 10 shows a plan of connections for a motor-driven booster. The main generators *1, 2, 3* connect to the + bus-bar in the usual manner and the + bus connects to the − booster bus through switch *a*. Each feeder is provided with a double-throw single-pole switch *b*, by means of which it can be connected

either to the main + bus or to the + bus of the booster. As indicated by the dotted lines, the long feeders A, B are connected to the booster, while short feeder C is supplied with current directly from the main generator. The booster is driven by a shunt motor supplied with current from the main generators, and equipped with a circuit-breaker and

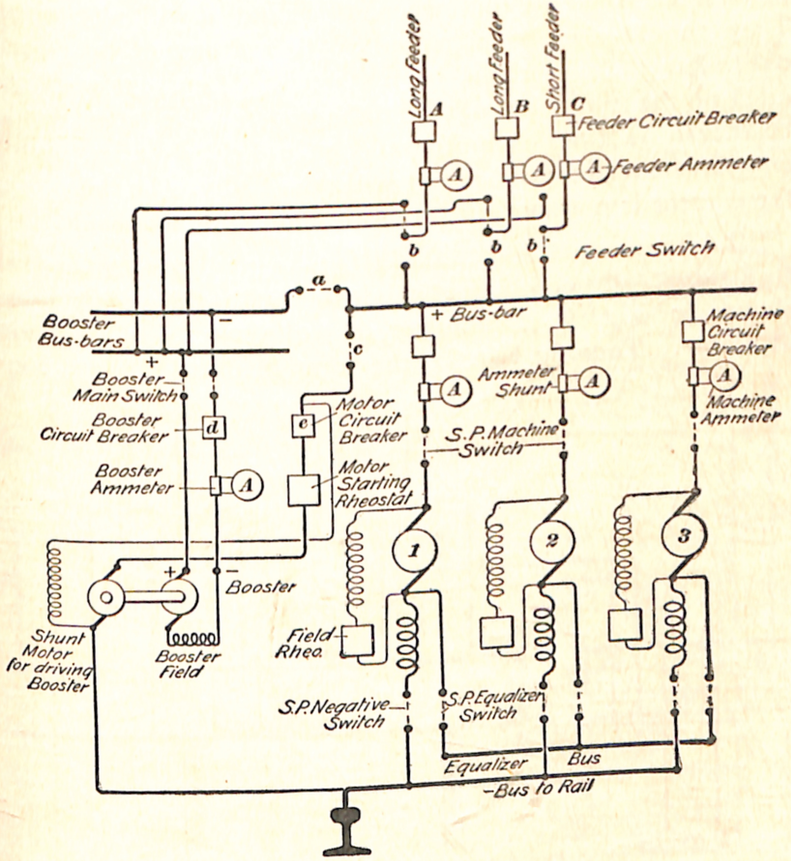


FIG. 10

starting rheostat. The booster is connected to the booster bus-bars through an ammeter, circuit-breaker, and double-pole main switch. By following out the connections in Fig. 10, they will be found equivalent to the elementary connections in Fig. 8; all current supplied to feeders A and B

passes through the booster and the voltage applied to them is increased by an amount proportional to the current.

The motor circuit-breaker should be arranged so that in case it opens the motor circuit, the current will also be cut off from the booster. The simplest way of doing this is to mount the two circuit-breakers d, e side by side and have them interlocked so that when e flies out, d will also open. They should also be arranged so that d cannot be closed until after the motor has been started. If current were cut off from the motor but not from the booster, the latter would be driven as a series motor and an unloaded series motor on a constant-potential circuit will race badly. If, therefore, the current is not shut off promptly damage may result.

23. Booster Used With High- and Low-Potential Bus-Bars.—By combining a booster with the connections shown in Fig. 7, a number of voltages may be made available. Thus, in Fig. 11, the long feeders A, B are connected to double-throw switches b, b, by means of which they can be connected either to the booster or to the 600-volt bus. The shorter feeders C, D can be connected through double-throw switches c, c to either the 500-volt bus or 600-volt bus. A double-throw switch a permits the

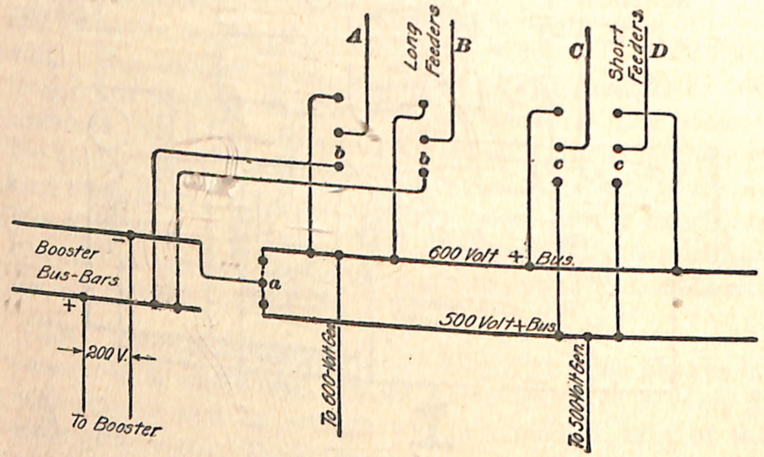


FIG. 11

booster to be connected to either machine bus. Thus, assuming that the maximum booster voltage is 200, the maximum voltage applied to feeders A, B may be either 600 or 800. Short feeders can be supplied with either 500 or 600 volts, thus giving a flexible arrangement that allows the voltage to be suited to the demands of any particular section of the road.

24. Convertible Booster.—It is possible to arrange one of the regular station generators so that it can be used as a booster if necessary; this is often convenient on small roads or for temporary work where it would not pay to

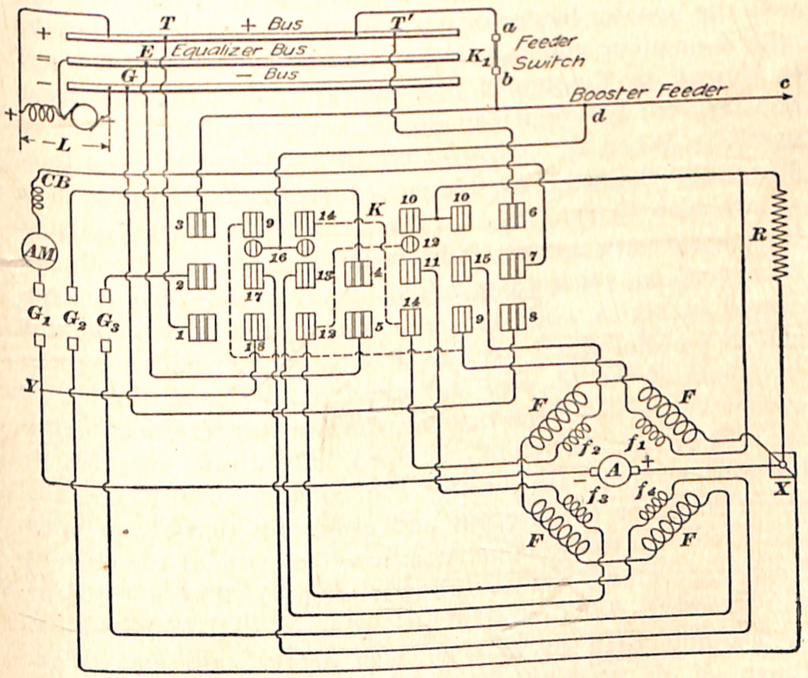


FIG. 12

install a regular booster. A machine so used should be arranged so that it can normally be run as a regular generator and by means of suitable switches changed over to act as a booster, as shown in Fig. 12, where L is one of the regular generators connected to the bus-bars.

In this case the +, −, and equalizer bars are shown together, but the negative and equalizer bars may be located near the generators; also, the machines are shown equalized on the + side; but this is immaterial so far as the general plan of connections is concerned. The convertible booster is shown in the lower right-hand corner, F, F, F, F being the series field coils and f_1, f_2, f_3, f_4 the shunt coils. With a machine of this kind, the series coils alone will not give sufficient excitation, so that it is necessary to use the shunt coils also. G_1, G_2, G_3 are the main generator switches and K is a special double-throw switch for changing over the connections so that the machine acts either as a booster in series with the booster feeder or as a regular generator in parallel with L or other generators that may be in service. When K is thrown to the upper position, the machine acts as a booster; but before it can do so, feeder switch K_1 must be opened. When K is thrown up, block *2* is connected to *3*; *7* to *6*; blocks *9*, *14*, *16*, *17*, and *13* are connected together, as are also blocks *10*, *11*, *12*, and *15*. The series coils of the machine are connected in series, but the shunt coils are connected to separate terminals so that they can be connected in series when the machine is used as a generator and in parallel when used as a booster. T' and b are the terminals of the booster and when K_1 is closed, the feeder connects directly to the bus-bar, the booster terminals being short-circuited. When K_1 is open, all current supplied to the feeder must pass through the booster. Neglecting the shunt field for the present and assuming that K_1 is open and K thrown to the upper position, the path of the current from generator L is as follows: $L+$ –T–T'–*6*–*7*–CB (circuit-breaker)–AM (ammeter)–G_1–$A-$ –$A+$ –X–F–F–F–F–G_3 –*2*–*3*–c and back to $L-$ by way of the cars and track. When K_1 is closed, the path is $L+$ –T–a–K_1–b–c, and the booster is cut out. The shunt field is excited by connecting the four coils in parallel so that a low voltage will provide sufficient excitation. The voltage for exciting the shunt coils is obtained by connecting them in parallel with a certain length of the feeder, thereby subjecting them to a

pressure equal to the drop in that part. Thus, the shunt coils are subjected to a voltage that varies with the current supplied over the feeder and their excitation will be proportional to the current; their effect will, therefore, be the same as if an equal number of ampere-turns were supplied by coils connected in series. One end of coil f_1 connects to block *9* and the other end to *10*; the ends of f_2 connect to blocks *14* and *15*; f_3 to *11* and *13*; and f_4 to *12* and *17*. When the booster switch is thrown up, similar ends of the shunt coils are connected together, positive ends being connected to blocks *10*, *11*, *12*, and *15* and negative ends to *9*, *13*, *14*, and *17*. Block *16* connects to the feeder at some point d determined by the amount of feeder required to give the drop necessary for the excitation of the shunt field. When switch K is thrown down, the path of the current is $A+$ –X–F–F–F–F–G_3–*2*–*1*–T; out on the line by way of switch K_1 and feeder c to the cars and thence back to the rail bus-bar G through *8*–*7*–CB–AM–G_1–$A-$. The shunt coils are now in series, as shown by the path $A+$ –X–R–f_1 –*9*–*15*–f_2–*14*–*11*–f_3–*13*–*12*–f_4–*17*–*18*–Y and current flows through them in the same direction as through the series coils.

25. Location of Booster.—Boosters are nearly always located in the power house. If located at any point out on the line they will, as a rule, entail an additional charge for attendance; and if motor-driven the power for their operation will have to be transmitted from the station, thus increasing the line loss. If the boosters were driven from some other source of power, this latter objection would not count, but there would still be the cost of attendance, which amounts to practically nothing when the boosters are placed in the power station, as they require such a small amount of attention that no additional help is required.

26. Economy of Booster.—At first glance, the use of boosters for supplying distant parts of a railway system appears to be a very uneconomical method and that it would be much better to use high-tension alternating-current transmission with substations situated near the outlying districts.

It takes power to drive a booster, but it is only expended while it is needed, and the load on a given booster may be quite light for the greater part of the time. That is, a booster wastes a considerable amount of power only when the load is heavy. Again, with alternating-current transmission there is considerable loss in the transforming devices that is the same no matter what the useful load on a substation may be, and the annual cost of attendance alone for a substation may more than counterbalance the cost of power wasted by a booster, as compared with the cost of power wasted with alternating-current transmission. The use of boosters allows a given system to be extended without making any change in the generating equipment already installed, and distant sections can be fed without an excessive outlay for copper. These advantages are still more fully realized if storage batteries are installed out on the line and charged from the booster feeders. The batteries will charge during periods of light load and discharge when the load is heavy, thus keeping a fairly uniform load on the feeder and working it to best advantage.

It is thus seen that the annual cost of operation with boosters may be actually less than with alternating-current transmission, and the question as to which is the best method for a given road is one that can only be decided by a very careful comparison of the cost of operation under the two systems. Roads are in regular operation where cars are run over a radius that in some cases exceeds 20 miles, by the use of boosters and storage batteries. These roads give satisfactory service, they are fully as economical in their operation as similar roads for which alternating-current transmission is used, and are less liable to interruptions from breakdowns in the various transforming appliances necessary with alternating-current transmission and direct-current distribution from substations.

ALTERNATING-CURRENT SUPPLY

POLYPHASE TRANSMISSION

27. Where roads are such that it is necessary to transmit the power for their operation by means of high-tension alternating current, the general practice has been to use two-phase or three-phase transmission and change to direct current by means of rotary converters located in substations. In some cases, as, for example, at Niagara Falls, current is generated by two-phase machines and transmitted as three-phase by connecting the step-up transformers on the Scott plan. On some of the largest systems, the alternators are wound for pressures as high as 11,000 volts and feed directly into the distributing system without the use of step-up transformers. Revolving field alternators are now almost universally installed in preference to those of the revolving armature type.

28. Fig. 13 shows the general scheme of distributing current for the Manhattan Elevated Railway, of New York. Current is generated in one large central station by revolving-field three-phase alternators direct-connected to 8,000-horse-power engines. The use of the revolving-field type of machine enables the current to be generated at 11,000 volts in the machine. It is distributed by means of heavily insulated lead-covered cables, run in underground conduits, to a number of substations, and there passed through stationary transformers that step-down the voltage. The rotary converters change the alternating current to direct current at about 625 volts, and from the substations it is supplied to the cars by means of a third rail and the ordinary track. The systems of distribution used by the Metropolitan Railway Company, of New York, and the London Underground are almost exactly the same as this one, except that the distributing pressures are somewhat lower. In the case of the Metropolitan road the distributing pressure is 6,600 volts.

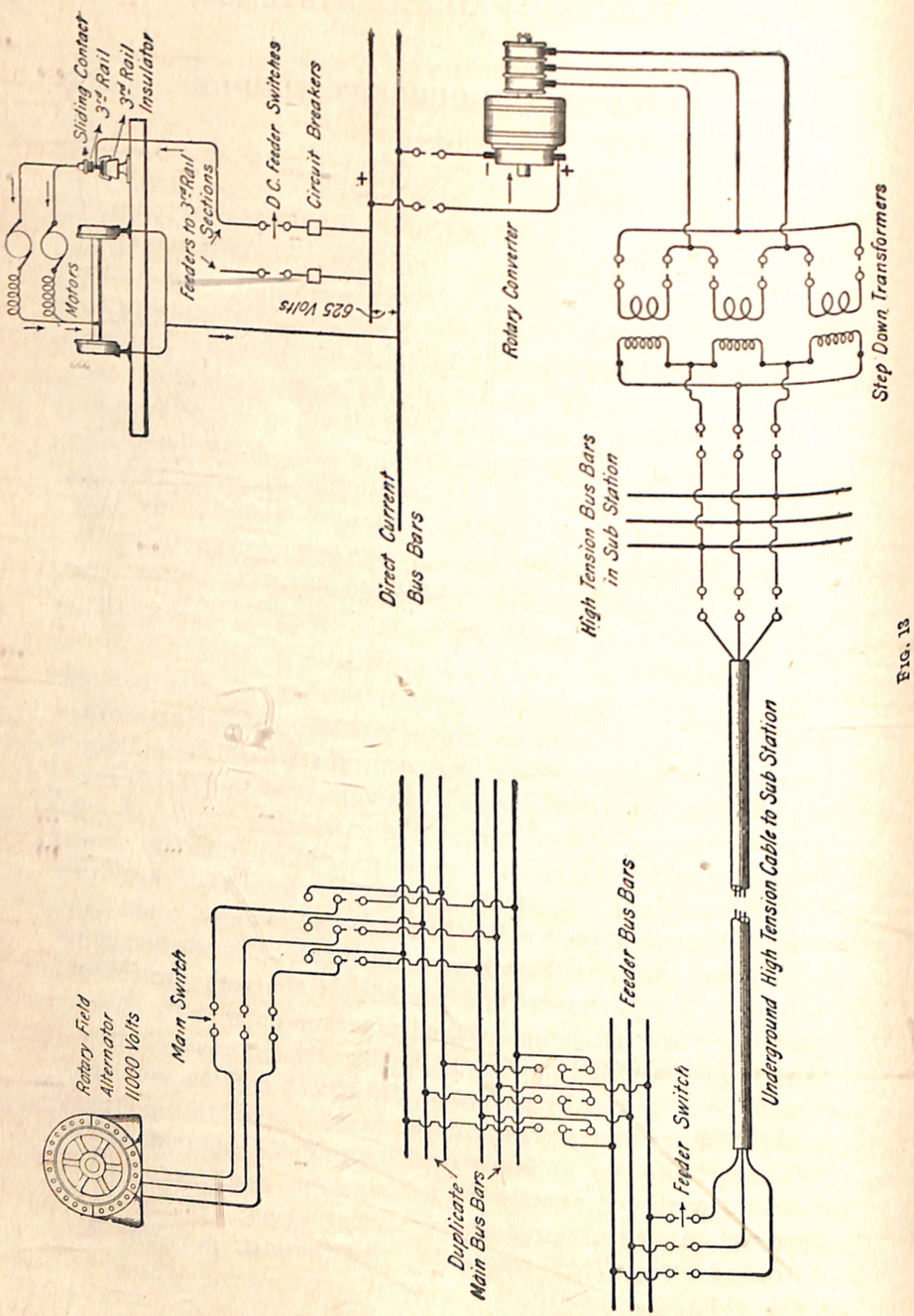


FIG. 13

On some roads, where a considerable part of the power is required near the station in the form of direct current, it may be advisable to use double-current generators and step-up the alternating current for transmission to the distant parts of the system. In most cases, however, where both alternating and direct currents are required it is better to install alternators, which are simpler than double-current machines, and obtain what direct current is required by means of rotary converters.

SINGLE-PHASE TRANSMISSION

29. The use of **single-phase motors** on electric cars is such a recent development that practice has not become settled regarding the best methods of distribution to be used. A number of plans are available and the one adopted in any given case will depend largely on whether the road is to be supplied from an existing transmission system or

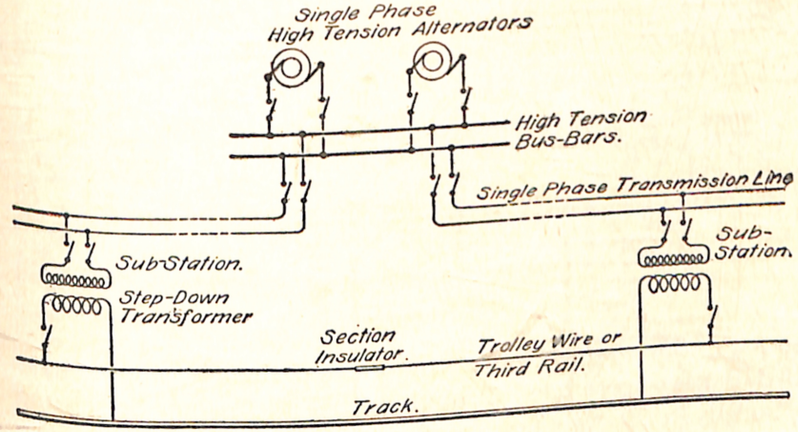


FIG. 14

whether new apparatus is to be installed throughout. Fig. 14 shows a plan where single-phase generators are used, the line voltage being stepped-down by transformers. This is the simplest plan and the one that would quite likely be adopted in case a new outfit were to be installed throughout. The trolley might be worked at a pressure of 2,000 to 3,000 volts

and the transmission carried out with a line pressure of 20,000 or 30,000 volts. It should be noted in Fig. 14 that adjacent sections of the trolley wire are at the same potential and that, under ordinary working conditions, there is no electric strain on the insulator used to divide the trolley wire into sections.

There are so many large transmission plants already in operation on the two-phase and three-phase systems that cases will frequently arise when single-phase railroads must be operated from them. This can be done by splitting the road into a number of sections and distributing them on the different phases so as to keep the load approximately balanced, thus

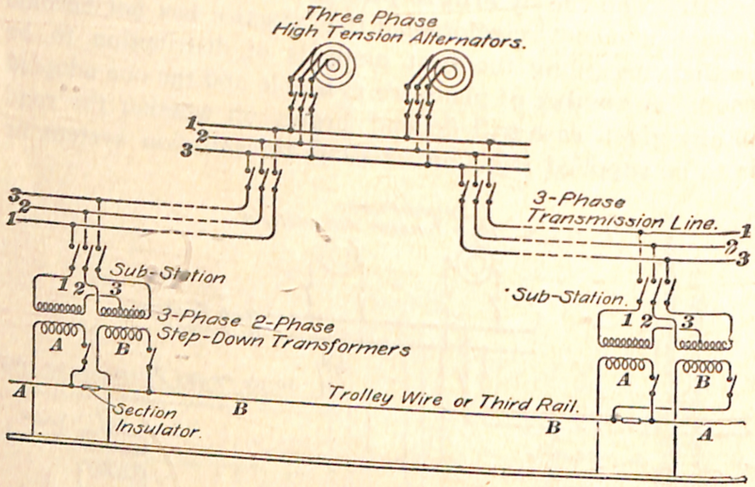


FIG. 15

making the system more complicated than if single-phase distribution were used throughout. Fig. 15 shows a scheme whereby a single-phase road is supplied from three-phase alternators. In the substations, the current is transformed from three-phase to two-phase by the Scott arrangement of transformers and alternate trolley sections are fed from different phases, thus balancing the load. By transforming from three-phase to two-phase, the secondary connections are considerably simplified. With this plan the trolley-section insulators are always subjected to a high pressure.

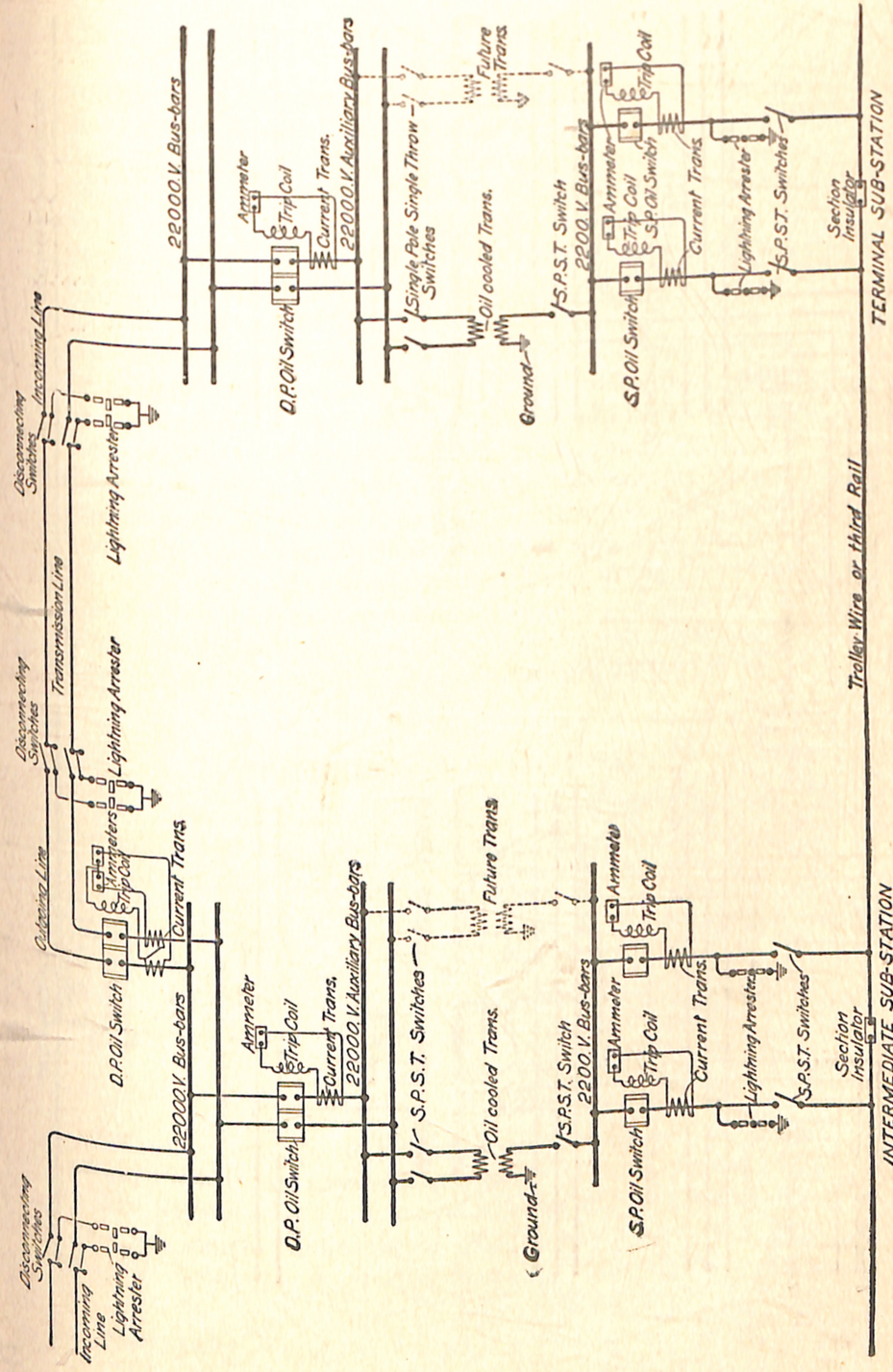


FIG. 16

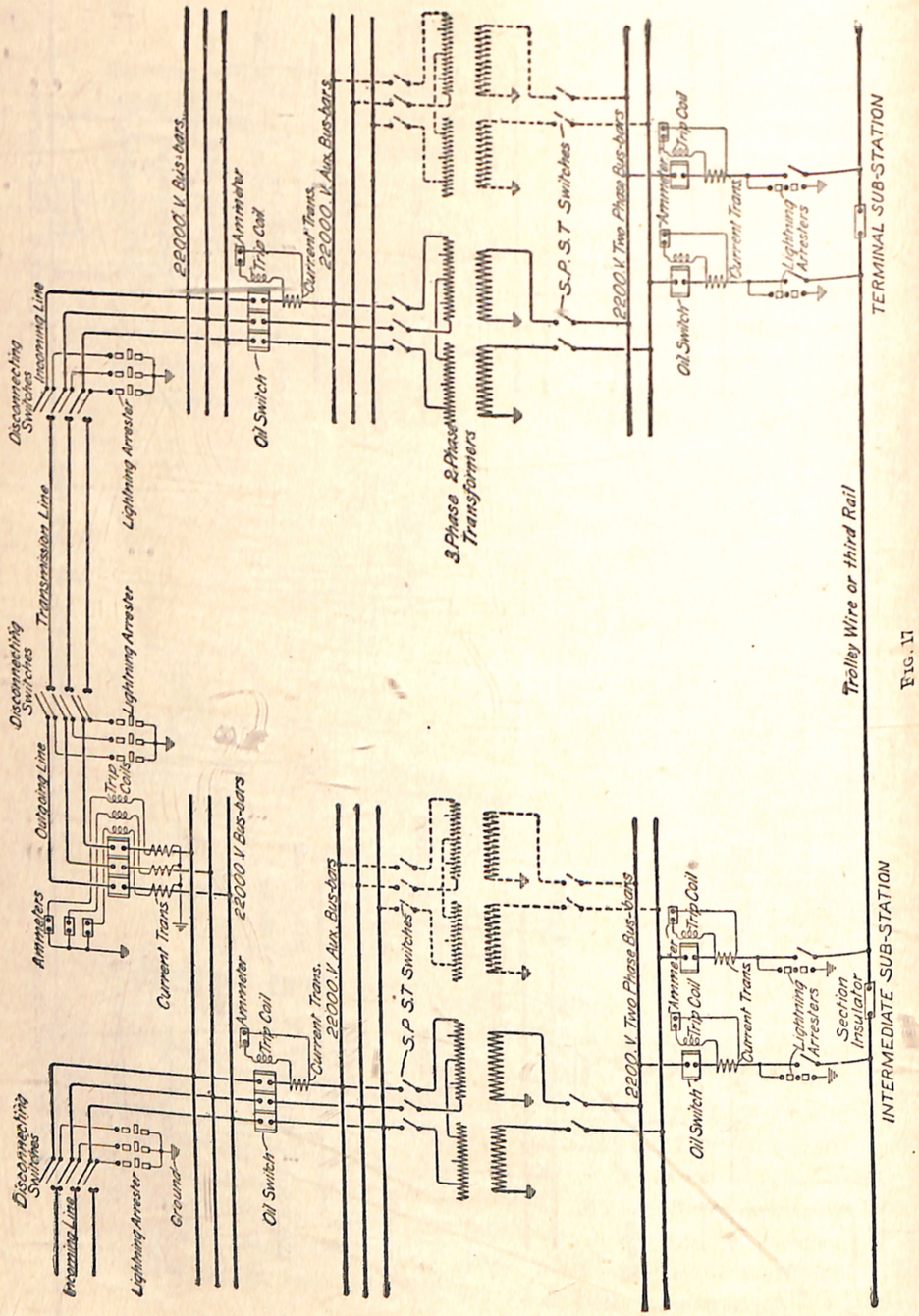


Fig. 17

30. Figs. 16 and 17 show substation connections for single-phase railways as proposed by the General Electric Company, Fig. 16 showing substations supplied from a single-phase transmission line and Fig. 17 from a three-phase line. The plans are the same as indicated in the elementary diagrams, Figs. 14 and 15, the three-phase current being transformed to two-phase in Fig. 17. Two substations feed into the same trolley section, thus dividing the load between the stations. The substation connections are very simple when compared with those for a station using rotary converters. All that is required in addition to the step-down transformers are the switches and protective devices. There is no moving machinery in the substations, constant attendance is unnecessary, and the use of single-phase motors makes the system as a whole nearly as simple as one using direct current. All switches used for interrupting the current are of the oil-break type; knife switches are provided for disconnecting various parts of the system, but these are not intended for opening the circuits when the current is on.

THE POWER HOUSE

31. Having explained the general methods of supplying current to electric cars from the working conductor, and the different systems available for transmitting the current from the central station to the cars, it will be necessary to take up the different parts of the road and describe them in detail. For this purpose the subject may be considered under the following heads: (*a*) The *power house*; (*b*) the *line and track*; (*c*) the *car equipment*.

LOCATION OF POWER HOUSE

32. The general design of power houses and the class of apparatus to be used in them has been fully covered elsewhere, so that only a few considerations affecting their location will be mentioned here. The power house, or power station, should be situated as near the center of the system