

## ELECTRIC RAILWAY APPARATUS.

BY ERNST J. BERG.

With the extended application of electricity to heavy railroad work within the last few years, a number of interesting features have been brought out, the most important being what system to adopt and what apparatus to use in each particular case.

The object of this paper is to discuss the characteristics of the various apparatus, and, to a certain extent, their limitations, which, indeed, have almost entirely the deciding influence on the choice of system. The discussion of storage batteries is purposely omitted since their characteristics are well known and have been written up very fully within the last few years.

*Continuous Current Generators.*—By far the greater number of these are of the direct connected type. Their frequency varies from 6 to 15 or 18 cycles, and in some cases as high as 25 cycles. This latter frequency is adopted when, in addition to commutator, the generator is supplied with collector rings intended to take off more or less of the power as alternating current, that is, when the machines are “double current generators.” With the exception of more extended use of direct connected units and double current generators, which are able to supply alternating as well as direct current power, very little if any radical modification in design or characteristics has been made during the last few years, but the progress has rather consisted in a steady and gradual improvement of design, especially in regard to sparkless commutator and overload capacity. Although the standard machines are over-compounded, in actual operation as a

rule the direct current potential is kept constant at all loads, the over-compounding being used only to compensate for drop in speed with the load. When used as double current generator, the compounding on the direct current side is taken care of in the same way as when used as direct current machine, that is, by series winding, and the compounding for the alternating current load made by phase control, that is, the load, which usually is rotary converters, is made to take leading or lagging currents which react on the machine and thereby raise or lower the voltage as the demand may be. In order to accomplish this satisfactorily, the double current generators should have fairly high armature reaction, which means not too close regulation. This high armature reaction, usually less than standard direct current practice, is not objectionable from the direct current generator point of view since the regulation of potential is taken care of by the series field. Nevertheless it has been customary to ask for a regulation as close as 6 per cent. on the alternating current side, the intention being not to attempt any phase control, but permit the voltage to drop slightly with the load. Under these conditions obviously the closer the regulation, the better. The limit is reached when, due to the necessarily low armature reaction and the many armature circuits in multiple, the cross current caused by slight inequality in pole shape or gap becomes excessive.

*Alternating Current Generators.*—These are in almost every case directly connected to the steam engine and operated at a frequency of 25 cycles per second. If, however, a considerable portion of the power must be used for lighting, a higher frequency may be used. It must, however, be borne in mind that satisfactory parallel operation depends largely upon the frequency, and that the tendency to hunt, and in general, the difficulties of operating any installation satisfactorily, increase as the frequency increases. Twenty-five-cycles has the disadvantage that it is too low for in-door and for efficient out-door incandescent lighting, and entirely too low for arc lighting, therefore it is hardly advisable to use it for any kind of lighting, but when such has to be done, it is accomplished by rotary converters or motor-generator sets or frequency converters. Twenty-five-cycles has, however, so many advantages for railway work that it must be recommended, at least in all cases where induction motor-direct current generator sets are not advisable. The generators are usually designed for a regulation of about six to ten per cent.

In view of the fact that usually a great many are operated in multiple in the same station, and therefore the load on individual feeders does not seriously affect one machine, it is preferable to go to rather high armature reaction since this limits the maximum flow of current and power in case of short-circuit, and suppresses large cross-current when operated in multiple from generators of not too close speed control. The European practice is to design these generators with polar windings for securing satisfactory parallel operation, but this has not been found necessary in America, where strict demands have been made upon the steam engine builders, who thereby not only proportion their machines with great care, but pay particular attention to the fly-wheel and governor construction. These generators are always of the revolving field type, and usually installed in connection with independent fly-wheel, whereas the practice in Europe is to make the armature of such a great fly-wheel capacity as to combine the fly-wheel and armature in one structure. One reason for the universal adoption of the fly-wheel type in Europe is that in most cases 50 cycles are used. With 50 or 60 cycles, and particularly with high-voltage machines, the diameter of the revolving field is, as a rule, enough to render it available as a fly-wheel, whereas with 25 cycles with relatively low peripheral speed, the cost of an unnecessarily heavy revolving field is often greater than that of an additional fly-wheel. Almost without exception they are designed for three-phase current and voltages ranging between 2000 and 13,000, depending upon the distance of transmission, etc. When used for voltages less than 6000, they have as a rule three slots per pole and phase, and for higher voltages two slots per pole and phase. The poles and the slots are shaped so as to give as nearly a sine wave as can be obtained by using machine-wound coils. (The use of machine-wound coils and entirely open slots is contrary to the European practice, at least until very recently, the practice being to use hand-wound coils in almost entirely closed slots).

Although smaller alternating current generators are made with automatic compounding, in no case is such compounding used with large direct-connected machines for railway work, but the control is done by hand, and the fields have only one winding.

*Inverted Converters.*—These are in their constants essentially direct current machines operating at 25 cycles, and are used to transform from direct current as obtained from the station

bus bars to alternating current, which after being transformed to higher potential, is transmitted to sub-stations a considerable distance from the main station. The use of inverted converters is decidedly more efficient than the use of boosters, and is being introduced considerably. Although an inverted converter and a straight converter, that is, a machine transforming from alternating to direct current, to all appearances are identical, it is not always advisable to use one or the other indiscriminately. An inverted converter should preferably have lower armature reaction than a straight converter, and consequently is, as a rule, a larger and more expensive machine. The object of the lower armature reaction is to obtain closer speed control and to prevent as much as possible the tendency of the inverted converter to run away, in case suddenly an alternating current load of considerable magnitude or of very low power factor is thrown on. But even with inverted converters of such design it is not advisable to omit speed limiting devices, which may consist of a circuit breaker in the direct current leads in connection with a centrifugal device, or the inverted converter is excited by a special exciter directly connected or belted thereto. Indeed such exciter or "a compensated exciter" is very essential for the frequency control. The plain exciter may be shunt or compound wound whereby it is easily seen that as the rotary begins to speed up, the exciter also speeds up and its voltage rises, causing more current to flow through the shunt fields, which has a tendency to prevent acceleration. The compensated exciter, which is also a direct driven exciter, changes its voltages not only with the speed, but with the phase relation of current, increasing the voltage with lagging current going from the converter and lowering it when leading current is taken, which obviously is just what is wanted for close speed control. The ratio between the alternating current voltage and the direct current voltage depends upon the system, characteristics of the machine, etc., and is discussed later in connection with converters proper. It suffices here to state that it is a fraction, or in other words, the alternating current voltage is always less than the direct current voltage. It is therefore obvious that the alternating current delivered from an inverted converter is always of too low a potential to be used directly, and step-up transformers have to be used. In its potential control an inverted converter has not the feature of a direct converter of compound-

ing for the load if required, but the voltage will drop with the load unless made up entirely of converters, which by taking leading or lagging current can react upon the inverted converter, but even with such load only a very low compounding can be obtained. Therefore, as a rule, the voltage of an inverted converter will drop with the load. In order to obtain constant potential at the receiving end of the system it is necessary that the converter proper should be compound wound and that reactances should be inserted in the leads so that the rise in voltage can be obtained across these reactances instead of at the inverted converter. Frequently inverted converters are operated in parallel with alternators on the alternating current side, and it is then as important to investigate the speed regulation of the prime mover driving the alternator as when contemplating running such alternators in multiple, since the inverted converter naturally runs at a uniform rate of rotation and therefore if the alternators to be run in parallel therewith are not run at a uniform rate of rotation, cross currents will be caused and serious difficulties might arise.

*Rotary Converters.*—Although converters of a higher frequency than 25 cycles occasionally are used, in most cases, and particularly when the plant is intended for railway work, 25 cycles are chosen and the discussion will therefore apply to them. Were it not that rotary converters some times cause trouble by hunting, there is hardly any doubt they would be used universally, even with the limitations in voltage control imposed by their use, instead of synchronous motor or induction motor direct current generator sets. The question of hunting, however, is so serious that frequently it is good policy to introduce the complication of running two or three machines instead of one, even at the lower efficiency, to ensure satisfactory service. Hunting is caused by many circumstances, one being that the rate of rotation of the prime mover is not uniform, another that converters are operated in the same network, but interlinked by lines of relatively high resistance, another that the converter has sluggish magnetic circuit so that it cannot quickly respond to variations in impressed voltage, still another that the impressed voltage on the converter, for some outside reason, tends to fluctuate suddenly. The remedy for the first case of hunting is obviously to get the rate of rotation of the prime mover more uniform, which often is very difficult, particularly if the ma-

chines are already installed. (With the stipulations imposed upon the engine builders, this case of hunting is not now so serious and does not exist when the generators are driven by turbines.) Another remedy which occasionally gives satisfactory results is to use one or more induction motors of considerable size on the same circuit, or even a small induction motor with large fly-wheel, the tendency of the induction motor being essentially to steady the frequency by its momentum. The other cause, that of considerable resistance losses between converters or generators and converters, has a tendency to set up hunting also, since with a slight fluctuation in current, due to various causes, the voltages fluctuate also. This fluctuation in impressed voltage will react in the rotary converter, and if the magnetic circuit is not very sensitive, causes a state of unstable equilibrium which leads to hunting. It is obvious that if the E. M. F. supplied to the armature varies suddenly, the flux also must vary at the same rate to ensure the same relative position of the armature and the field. If the magnetism lags behind, the armature must take a different position from what it would have otherwise and thereby a pulsation in speed is set up and the rotary "hunts." It is therefore evident that the magnetic circuit should be as responsive as possible, in other words, all causes delaying change of magnetism should be eliminated. As a consequence it is not best to use magnetic material of low ohmic resistance, such as steel, but a considerable part of the magnetic circuit is made of cast iron which has high ohmic resistance, and damping devices are inserted not in the path of the main flux, that is in the poles, but midway between the poles. This damping device is only effective when the rotary hunts, that is, when there is an appreciable armature reaction which sets up currents to the circuit formed by the bridge. The last cases of hunting can be explained and remedied in much the same way as in the previous case, and sometimes preclude the use of converters in places where the rate of rotation might be uniform and where the ohmic losses between generators and converters might be small, the disturbing element being a fluctuating load placed near to the converter and therefore inducing periodic pulsations in voltage on the converter circuit.

Summarizing the hunting situation, we find that although there are a number of causes for this trouble, the phenomenon is fairly well understood and no great difficulties need be ex-

pected in well planned 25-cycle systems. The other limitation of rotaries is the difficulty of obtaining wide range of voltage as compared with direct current generators, and providing for automatic compounding over a wide range.

Although it is possible to compound rotary converters to some extent by merely using a series field similar to that on direct current generators, the amount of compounding is very slight indeed and is obtained by leading or lagging currents taken by the converter and passing over the very low reactance of the converter armature proper. In order to compound to any considerable extent, it is necessary to have some reactance in the circuit between converter and generator, and to permit the converter to take wattless currents at almost all loads. The proportion of wattless current and reactance can be varied considerably, and still the same results obtained, so for instance, roughly speaking, 10 per cent. compounding can be obtained by 50 per cent. leading current and 20 per cent. of reactance; or by 20 per cent. leading current and 50 per cent. reactance, etc. The more reactance over a certain limit, the more liability of an unstable operation and the more wattless current, the poorer the power factor at light loads, and the greater the armature heating; indeed, with quarter-phase or six-phase converters the saving in armature copper is not great over that in three-phase converters, if too large a percentage of wattless current is used in phase control. A fair average is to insert about 15 per cent. reactance. With such reactance in a circuit of 6 per cent. resistance, it is possible to obtain constant potential at all loads with a power factor of 60 per cent. at  $\frac{1}{4}$  load, 91.5 at  $\frac{3}{4}$  load, 100 per cent. at full load, 99.5 at 50 per cent. overload, and 96.5 at double load, or even higher if the series field is so adjusted that the converter runs non-inductive at  $\frac{3}{4}$  load, then a power factor of 73.5 at  $\frac{1}{4}$  load, 97.5 at  $\frac{1}{2}$  load, 100 per cent. at  $\frac{3}{4}$  load, 99.5 at full load, 98 per cent. at 50 per cent. overload, and 96 per cent. at double load. Under these conditions the voltage not only is approximately constant over the whole range of loads, but is still within a fraction of 1 per cent. up to 50 per cent. overload.

With several rotary converters operated in the same station, it is advisable to use independent transformers, or at least independent secondaries for each transformer, since, if this is not the case, considerable cross-currents are likely to flow if the direct current brushes on each individual converter are not placed identically the same.

The transformers themselves should preferably be designed with the greatest amount of self-induction, since, as stated above, in almost every converter installation some reactance is advisable. Thus the essential difference between a transformer used for lighting and a transformer used for converter is that transformers for rotary converters have more self-induction and higher efficiency than lighting transformers, or at least that in the design of these transformers this condition has been looked for.

The great advantage of rotary converters over motor-generator sets is the higher efficiency, due to the small copper and iron losses, and the facts that only one machine is used instead of two or more, that the power factor can be 100 per cent. at all loads, that they can act as condensers, and therefore compensate for lagging currents introduced by other apparatus on the system, that, in case of a very heavy load, they can give almost unlimited power, and that even as such shunt machines the voltage does not materially change with the load, but that it will at the most vary a few per cent. between no load and full load, whereas the direct current machine probably will vary perhaps 10 per cent. or more under the same conditions.

The ratio between alternating and direct current E.M.F. of a converter or inverted converter depends upon the system used, upon the ratio of maximum to square root of mean square value of impressed E.M.F. (that is, the E.M.F. given by the generating apparatus), upon the load of the machine, upon the ohmic losses in the machine, upon the position of the direct current brushes on the commutator, upon the excitation, upon the ratio of pole arc to pole pitch, and upon the operating conditions, that is, whether the machine is used to convert alternating to direct current power, or vice versa. Sixty cycle converters, which usually have shorter pole arc and higher commutator losses than 25-cycle converters, have, as a rule, higher ratios, and when used as inverted converters, lower ratios than 25-cycle machines.

At no load, with an average wave shape such as given by standard generating apparatus, the average ratios are :

Percentage pole arc .....	67%	74%	80%
Three-phase and six-phase double delta: ...	62	61	60.5
Six-phase, diam. and two-phase.....	72.5	71.5	71

With the average losses at brushes and armature winding, this will give the following ratios at full load of a 550-volt converter :



Percentage pole arc.....	67%	74%	80%
Three-phase and six-phase double delta. ....	63	62	61.5
Six-phase diam. and two-phase.....	73.5	72.5	72

## INVERTED CONVERTER.

Percentage pole arc....	67%	74%	80%
Three-phase and six-phase, double delta.....	61	0	59.5
Six-phase, diam. and two-phase.....	71.5	70.5	70

The values apply when the direct current brushes are placed on the exact neutral point. If the brushes for some reason or other are placed either leading or trailing, these ratios are increased, that is, the direct current voltage for a given impressed alternating current voltage is less. This variation may amount to several per cent., therefore moving the brushes makes it possible to lower the direct current voltage, and thereby change the ratio to some extent without changing the transformer connections. It is, however, impossible to increase the direct current voltage, no matter in what position the direct current brushes are placed.

Changing the excitation will also change the ratio. With reduced excitation, that is, with lagging current, the ratio may increase a couple of per cent., and with over-excitation it may drop a couple of per cent. depending upon the electrical constants of the machine.

*Synchronous Motor Driven Direct Current Generators.*—These have the advantage over the rotary converters that they can be run on circuits of high voltage directly, without the use of step-down transformers, that the direct current voltage is independent of fluctuations in voltage on the alternating current side, and dependent only upon the speed control, and that by a mere change of field excitation the direct current voltage can be varied over a very wide range. Their limitation, however, is their tendency to hunt, which is quite as marked as with rotary converters. In other words, the limitations inherent to rotary converters exist also with synchronous motors and even to a greater extent, at least with synchronous motors wound for high voltages with relatively few slots, with which type it is decidedly more difficult to apply anti-hunting devices than with rotary converters, which, by their more distributed winding and large number of small slots, are less likely to have excessive eddy losses, in the anti-hunting devices. It is, therefore, questionable whether it is advisable to substitute such sets for converters under any con-

ditions, the more so as frequently the cost of a synchronous motor wound for very high voltage is not much less than the step-down transformers and a low voltage motor.

*Induction Motor Driven Direct Current Generators.*—This combination has decided advantages over the first mentioned types by its stability, and may therefore find considerable field of application in systems of unstable frequency and fluctuating voltage, or installations which already have a number of synchronous apparatus. As stated regarding rotary converters, it is some times possible to obtain good results with hunting converters by installing induction motors of considerable inertia on the same circuit, and such a set naturally lends itself very well for this purpose. At moderate voltages, up to say, 2000 to 3000, induction motors can be built with good constants at a reasonable cost, and do not, therefore, involve the use of step-down transformers. At higher voltages, however, and particularly up around 10,000 volts, it is found that the use of step-down transformers not only introduces much better constants but frequently makes a cheaper installation. Under these conditions it is decidedly questionable whether it does not pay to install more line copper, remedy the speed control of the generators, or, in general, remove the causes prohibiting the use of rotary converters, since the cost of such motor-generator sets is much higher, and the contents much lower, than when converters are used.

*Direct Current Railway Motors.*—The characteristics of this type of motor are so well known that it is not worth while to discuss them further than to say that in general the tendency seems to have been during the last few years to design the motors for a given train weight and maximum speed, disregarding the number of stops, provided the car is accelerated and retarded at a comfortable rate, which involves, of course, the schedule speed changing with the number of stops.

To accomplish this, the motors are so designed and particularly the ventilating conditions are such that the temperature of the fields will not rise more than a safe number of degrees if subjected to the accelerating current at the rate of say, ten times per mile, and the armature has such a low core loss that it can run for a considerable time at the maximum speed. Such condition is made possible with the modern mechanical design which readily conducts the heat from the inside to the outside, and thereby obviates great differences in temperature. The main

difference in electrical design is that much more precaution has to be taken to have low self-induction in commutation. This is necessary since, as stated above, the field winding has to stand the full current of acceleration for a much longer time than formerly was the practice, and therefore a less number of turns and a weaker field in general is used in modern motors, this condition causing sparking unless the armature reaction is reduced and the number of commutator segments increased. We therefore find now as a rule a higher flux and a greater number of commutator segments than in older types of motors.

*Alternating Current Railway Motors.*—A very superficial study will show that whenever this type of motor has been adopted the reason lies, not with the motors themselves, but in the fact that a lesser amount of feeder copper and possibly fewer attendants are required with an alternating current railway system than with a direct current system involving rotary converters. It is, however, only in cases of relatively long runs with few stops, or in mountainous roads where power can be returned by induction motors, that economy can be shown with this system as compared with the direct current system. It is very doubtful whether in many cases where alternating motors have been installed, direct current motors would not have been better engineering.

The alternating current railway motors are of the polyphase induction type and therefore their characteristics are essentially those of direct current shunt motors, that is, they run efficiently only at one speed, whereas the direct current series motor will operate at high efficiency over a considerable range of speed. It is therefore obvious than in railway service where the speed for many reasons has to vary during the run and where cars are stopped and started at rather short intervals, the actual power taken by the induction motor will be greater than that taken by the direct current motor. Since, furthermore, any induction motor must take a certain amount of wattless current, the apparent power input of the motor must be greater than with direct current. With the same mechanical clearance in the two types of motors, the amount of wattless current taken by the induction motor would be quite prohibitive, therefore these must be made with decidedly smaller air-gap than direct current motors, which necessitates more careful adjustment, and involves more repair work. The wattless current is also dependent upon the

voltage at which the motors are operated, and increases as the voltage increases. With the known methods of insulation and with the limited space available for railway motors, it seems that it is almost out of the question to consider a design at higher potential than 3,000 volts. Even with the smallest safe air-gap this will give a power factor of at the most 85 per cent. or 88 per cent. at full load under the best conditions, which with an efficiency of say 86 per cent. including gear loss, gives an apparent efficiency of at the most 77 per cent.; in other words, the K.V.A. input of the motor would be about 30 per cent. greater than that corresponding to the work done. Whereas with the direct current motor the power input would probably not be more than 12 per cent. or 15 per cent. greater than that corresponding to the work done. Therefore, and in view of the laws governing the design of such induction motors, it is to be expected that the copper losses in an alternating current motor will be decidedly greater than in a direct current motor. The core loss in the field of the induction motor is also greater than the core loss in the armature of the direct current motor at maximum speed, so that this gives another source of increased heating of the motor. This increased heating is decidedly objectionable, as it involves the use of a much larger machine than the direct current motor, which increases the cost and weight of the equipment. To illustrate this somewhat more concisely, consider the losses occurring in a couple of motors of direct and alternating current type while accelerating from standstill up to full speed. The core loss and eddy losses in the direct current motor are zero at standstill, and increase to a certain maximum at full speed. In the alternating current motor at standstill even under favorable conditions, the core loss in the field is the same as the maximum core loss in the armature of the direct current machine, and the core loss in the armature at standstill about the same as in the field. At full speed the core loss in the field still remains the same, but the core loss in the armature is zero and therefore, roughly speaking, the core loss of the direct current motor is in the neighborhood of half of the core loss at maximum speed, while accelerating, and is one and a half times as much in the alternating current motor. In other words, during acceleration the alternating current motors have three times as much core loss as the direct current. Adding to this loss the greater copper loss due to the larger power input of the motor, we find from

actual calculations that the alternating current motors of good design will have in the neighborhood of four times as much loss as the direct current motors when operating over relatively short lines, as would be the case in rapid transit systems. To dissipate four times as much energy means that the volume of the motor has to be very much greater, and its heating facilities decidedly better. This does not mean that the actual heating will be as much

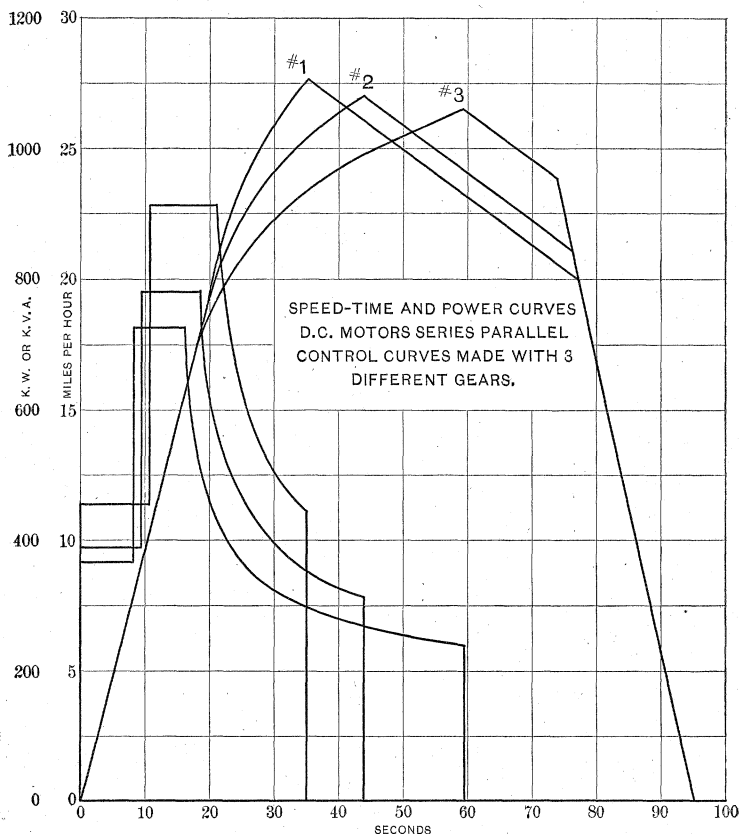


FIG. 1.

more, since at least in long distance runs, the time of accelerating is short compared with the total time of the run, nevertheless the loss will be decidedly more and consequently it would seem as if the actual cost of the induction motor equipment per car would be from 50 per cent. to double that of direct equipments, depending upon the service. Since the cost of the motor equipment is a very large factor in the installation of a plant, and

since the direct current equipment is so standardized and brought down to the least possible cost here in the United States, this is

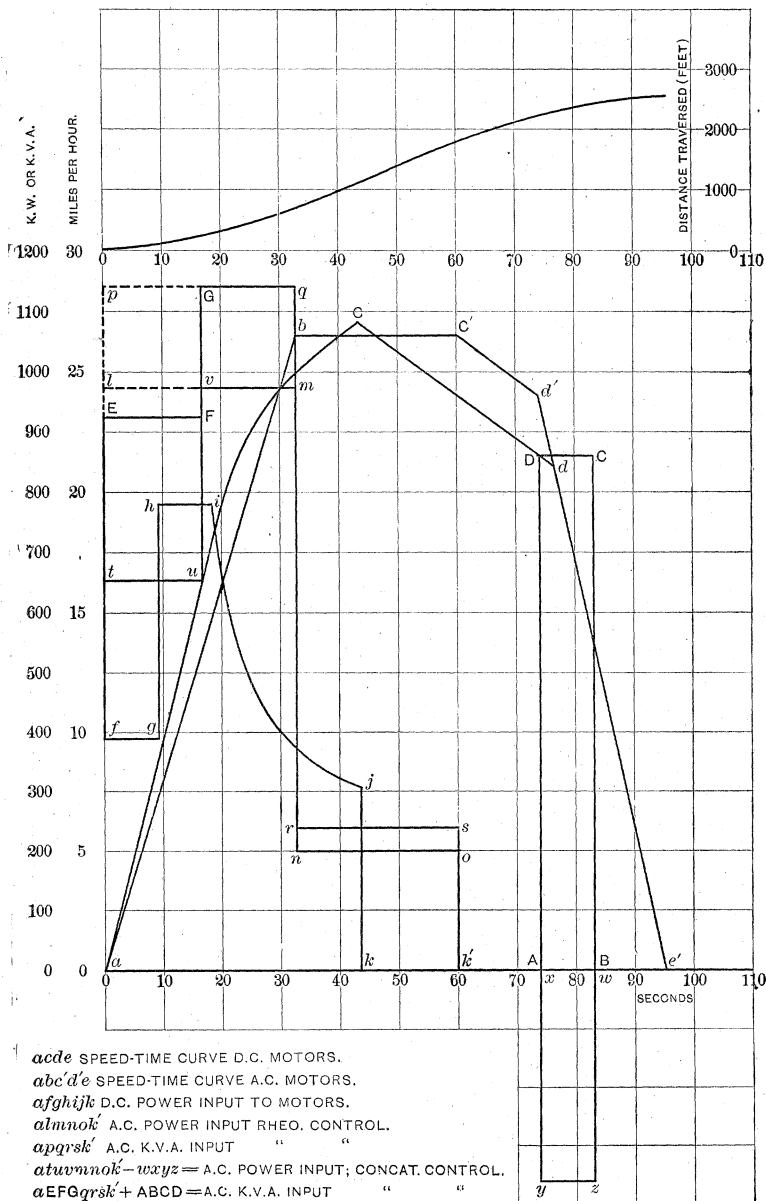
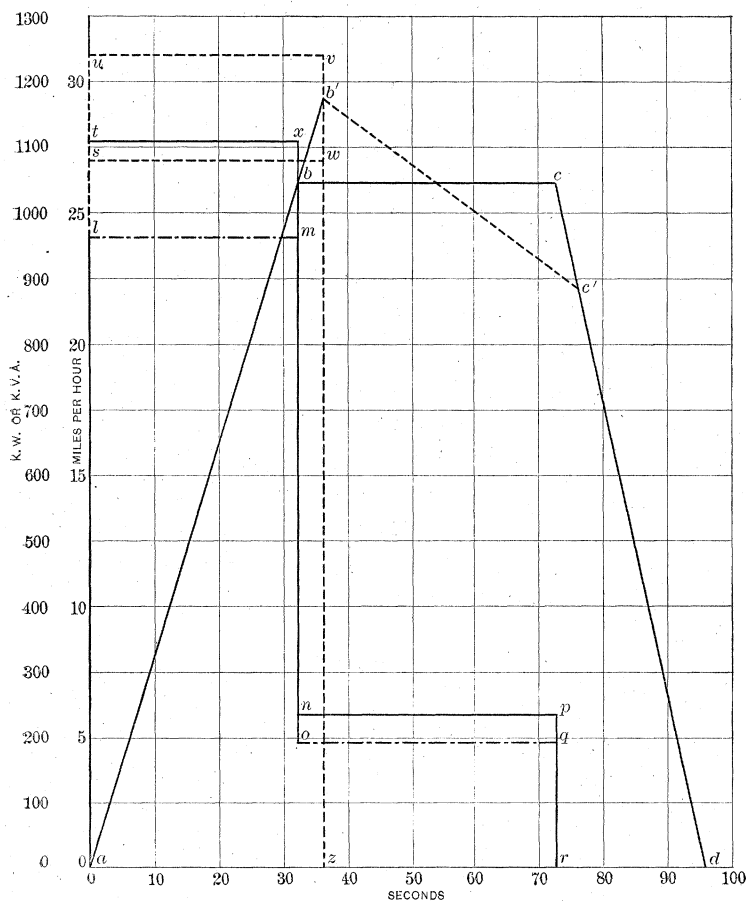


FIG. 2.

probably one of the main reasons why upon careful examination it has been found not only a saving of power, but great economy

in the first cost to install direct current rotary converters instead of alternating current systems. In places, however, where the direct current railway system is not so fully developed, the difference in cost between the two systems might



*abcd* AND *ab'c'd'*: SPEED TIME CURVE.

*aswz*: A.C. POWER INPUT; RHEO. CONTROL; NO RUN AT UNIFORM SPEED.

*auvz*: A.C. K.V.A. INPUT; RHEO. CONTROL; NO RUN AT UNIFORM SPEED.

*almogr*: A.C. POWER INPUT; RHEO. CONTROL; NO COAST.

*atxnpr*: A.C. K.V.A. INPUT; RHEO. CONTROL; NO COAST.

FIG. 3.

not be so much, and that accounts for some European concerns installing alternating current motors.

To illustrate more fully the characteristics of the two types of motors, the following instance is considered, although it neces-

sarily introduces some questions slightly outside of the scope of the paper.

A double track road with 27 stations is supplied power from a station located a distance from the tracks. Eight trains are running in each direction, which cover the entire distance in 52 minutes.

Weight of loaded train, including locomotive = 180 tons (2000 lbs.)

Weight on driving wheels, = 50 tons.

Thus maximum drawbar pull at 25% of weight = 25000 lbs.

Which corresponds to a maximum acceleration of two feet per second, per second.

Distance of run is 2560 feet.

Schedule speed, 15 miles per hour.

Maximum speed, 27 miles per hour.

Total distance is covered in 95.5 seconds, 20 seconds allowed for stops at each station.

No appreciable grades exist and effect of curves is negligible.

The three systems considered are:

A. The standard direct current railway system with series parallel control of the motors.

B. Three-phase induction motor system with rheostatic control.

C. Three-phase induction motor system with concatenated control in accelerating as well as braking.

Obviously when running at uniform and maximum speed one system offers no advantage over any other in energy consumption, assuming same efficiency of the motors (which is very nearly the case) while the volt-amperes taken by the motors are about 20 per cent. greater with the alternating current system (running at relatively light load).

While braking, the use of either of the first mentioned systems is immaterial, since no return of power can take place, but the third, that with concatenated control, offers some advantage in returning power which, however, is practically offset by the large current taken, and the complication of control and design of motor.

While accelerating, however, marked differences exist in the three systems, therefore the choice of one or the other is largely dependent upon the relative time of accelerating, running at uniform speed, and braking. Since, furthermore, the power required with any particular system depends upon the method of accomplishing the run, a number of schedules have been worked out, having about 1.2 ft. per sec. per sec. as an average rate of acceleration in all cases except Fig. 1.

So, for instance, in Fig. 1 are given three runs with direct current motors. Of these, Nos. 1 and 3 require more power than No. 2, therefore No. 2 run is referred to as the direct current motor run in the discussion following.



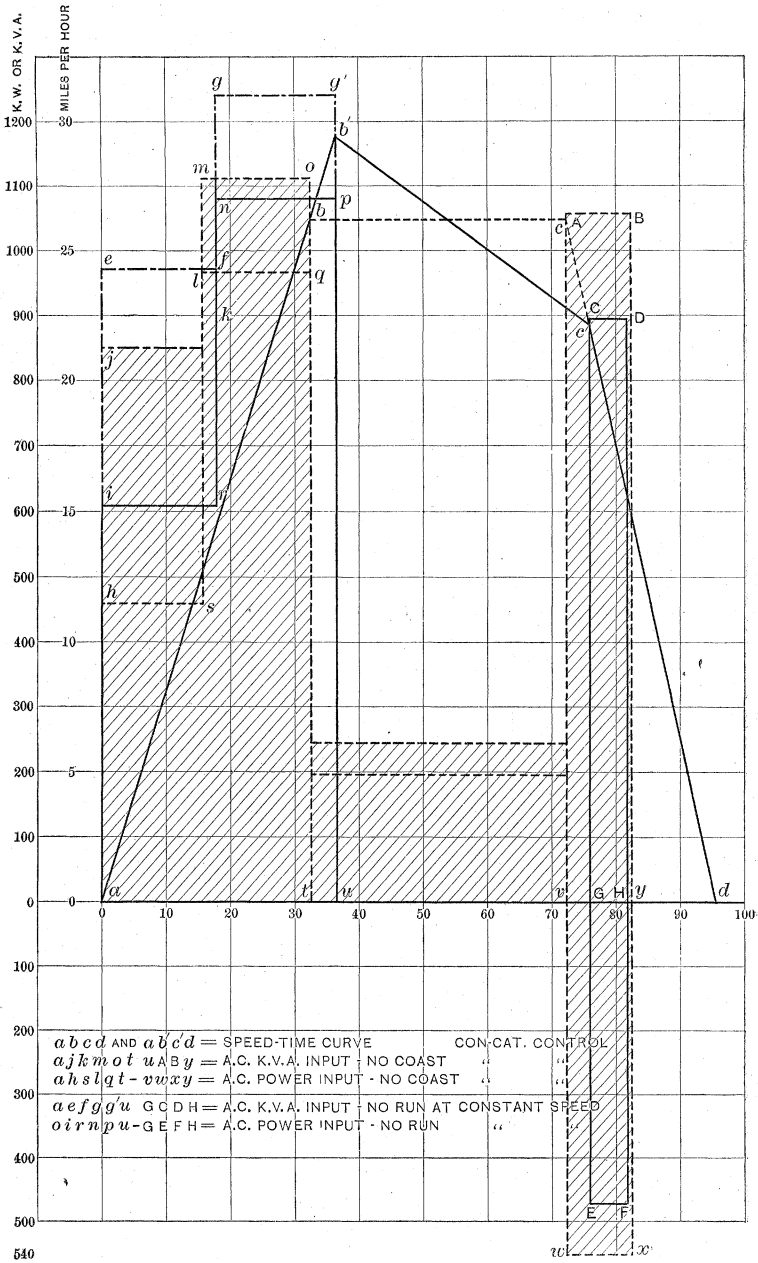


FIG. 4.

In Fig. 2 are given what is considered the best alternating current runs. One curve shows the conditions with rheostatic control, and the other with concatenated control in accelerating as well as braking. These two curves will be referred to as the alternating current runs in the discussion following.

In Fig. 3 are given two runs with rheostatic control, both of which take more power than the corresponding run in Fig. 2, and are given merely to show that with widely different methods of running, the power does not vary more than 5 per cent.

In Fig. 4 are given two different runs in which concatenated control is used. These seem not so favorable as those in Fig. 2, therefore they are not referred to later except in the general table given below. The chief object of including them is to show the merits of coasting with concatenated motors. As should be expected, if the motors are connected in concatenation, when accelerating only, it is advisable to go up to as high speed as possible, and then coast without running at constant speed, whereas if power is returned by concatenation it is advisable to maintain the maximum speed until time of braking.

So, for instance, the least average power taken per run is found if the cars are not permitted to coast, but accelerated and retarded in concatenation, which power is only 15 per cent. more than the least direct current power. The apparent power is, however, 2.4 times as great. In view of this very large apparent power this method is not the most favorable, but that given in Fig. 2 is preferable.

The important results of the various runs are shown in the table given below, which undoubtedly is more comprehensive than the diagrams for a superficial investigation.

Columns A, B and C are most important, and show the conditions of the best runs. Upon the constants given there and the corresponding curves the rest of the investigation is based.

Columns D and E show two direct current runs at different gear ratios.

Columns F and G show two runs with rheostatic control only.

Columns H, I and J show three runs with concatenated control in accelerating only.

Columns K and L show two runs with concatenated control in braking as well as in accelerating.

In going over the matter in more detail are considered the direct current run as shown in heavy lines in Fig. 1, and in Column A, and the alternating current runs with rheostatic and concatenated control as shown in Fig. 2, and Columns B and C.

	A	B	C	D	E	F	G	H	I	I	K	L
k. w. Secs Accelerating.....	21800	31700	25100	22700	23000	30100	31100	30900	25100	22700	30900	22700
k. w. Secs Uniform Speed.....		5400	5400				7800		5400	7800		7800
k. w. Secs Braking.....		37100	27270	22700	23000	30100	38900	30900	30500	30500	28100	28100
Total k. w. Secs.....	21800	37100	27270	22700	23000	30100	38900	30900	30500	30500	28100	28100
Average k. w. per Run.....	190	322	237	107	200	340	338	268	265	265	244	218
k. v. A. Secs Accelerating.....	21800	37000	33600	22700	23000	44900	35800	40000	31600	32100	40000	32100
k. v. A. Secs Uniform Speed.....		6600	6600				9500		6600	9500		9500
k. v. A. Secs Braking.....		7730	7730				45300	40000	40200	41600	5400	10000
Total k. v. A. Secs.....	21800	43000	47930	22700	23000	44900	45300	40000	40200	41600	45400	52200
Average k. v. A. per Run.....	190	379	416	107	200	390	394	348	350	362	394	454
Maximum k. w. per Run.....	780	977	977	912	725	1080	965	1080	977	965	1080	965
Maximum k. v. A. per Run.....	780	1140	1140	912	725	1240	1110	1240	1140	1110	1240	1110
Watt Hours per Ton-mile.....	70	120	88	73	74	126	125	99	98	98	91	81
v. A. Hours per Ton-mile.....	70	138	154	73	74	145	146	129	129.5	134	146	168
Ratio Average a-c k. w. ....		1.72	1.26			1.80	1.79	1.41	1.40	1.40	1.30	1.16
Average d-c k. w. ....												
Ratio Average a-c k. v. A. ....		1.97	2.20			2.07	2.09	1.85	1.85	1.92	2.09	2.40
Average d-c k. v. A. ....												
Average P. F. ....	1	87	57	1	1	87	86	77	75.5	73	62	48

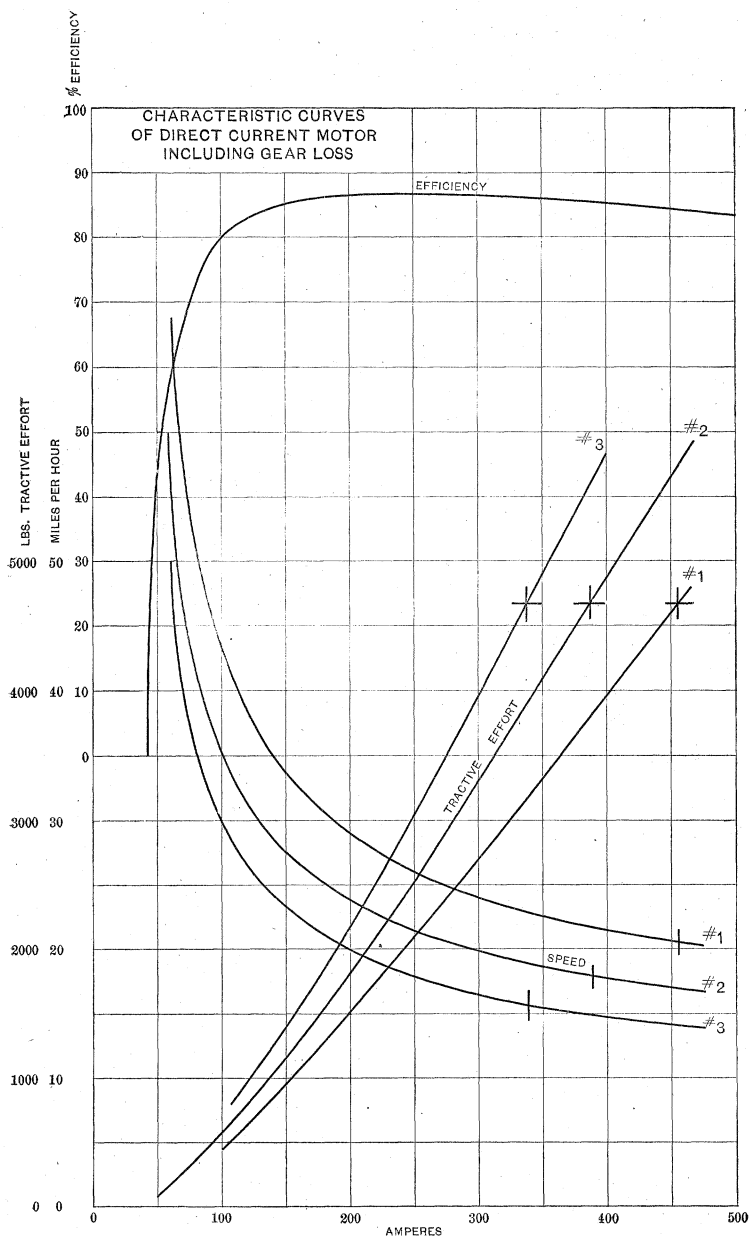


FIG. 5.

The characteristic curves of the motors are shown in Figs. 5, 6 and 7. Fig. 5 gives the direct current motor curves, Fig. 6 the alternating current motor curves, and Fig. 7 curves of the same motors in concatenation. No special curves are given for this latter motor when used as generator to return power, since it is essentially the same as when used as motor.

To sum up the results, it is found from the various methods of running trains, first, that under apparently the most favorable as well as average conditions, the most economical alternating current system will take 26 per cent. more power and 2.2 times as

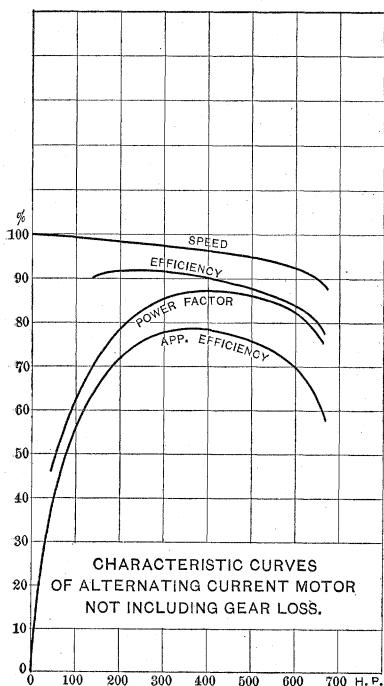


FIG. 6.

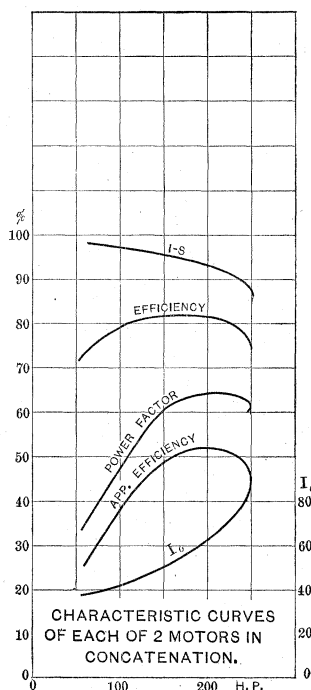


FIG. 7.

many volt-amperes as the direct current system. Second, that the concatenated control takes 26 per cent. less power but only 10 per cent. more apparent power than the alternating current system with rheostatic control. It must, however, be borne in mind that these values refer to power input at the motors, not the relations at the sub-stations and power-house, as will be seen later.

Power is supplied to four sub-stations located respectively 16,600 feet, 17,400 feet, 22,800 feet, and 35,000 feet from the generating station. The transmission potential is 11,500 volts.

*Capacity of Power House, Electrical Machinery, Lines, etc.*  
—Since the supply of power is located at some distance from the receiving circuit, high potential three-phase generators are proposed in all three cases.

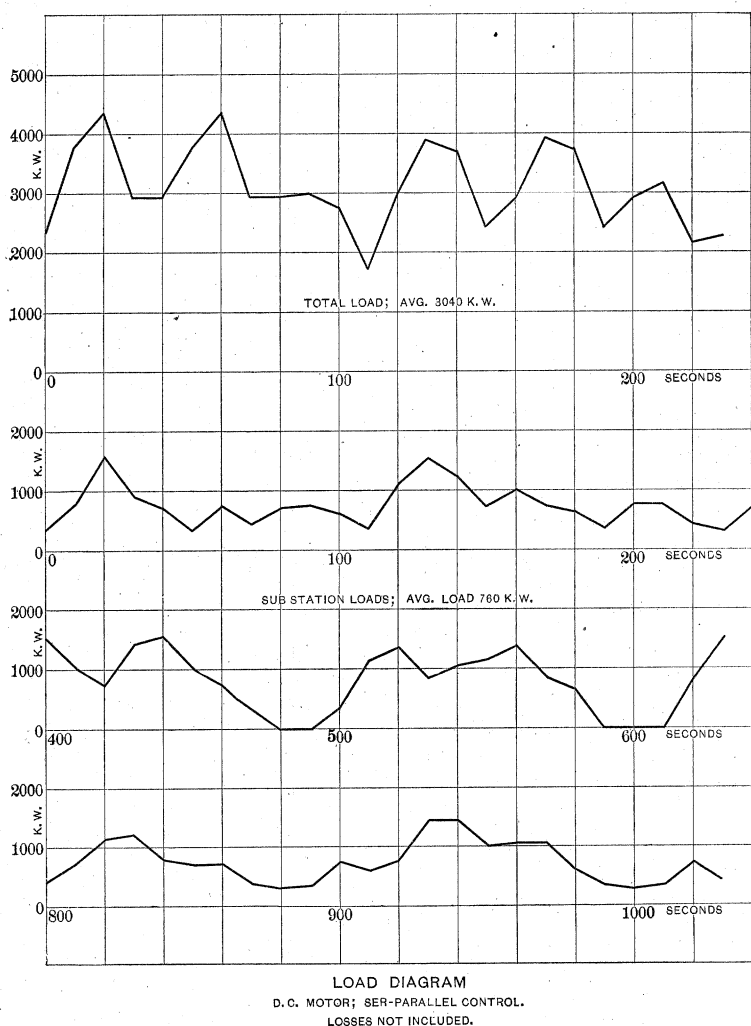


FIG. 8.

#### A. Direct current motors with series parallel control.

*Installation.*—The road bed has double tracks of 85-lb. rails and the combined cross-sections of feeders and trolleys for two tracks is 1 sq. in. of copper. In the calculations all tracks and

feeders are assumed interconnected, and the feeder copper strung all around the track.

The resistance of steel rails is assumed as 12 times that of the corresponding copper, and that of bonds as 50 per cent. of rails. This gives the ohmic resistance of four rails in multiple between two sub-stations (average 17,100 ft.) as .09 ohms and the corresponding resistance of copper as .159 ohms, or a total resistance of .25 ohms.

Each sub-station has three 650 k. w. converters (one as spare) and ten 240 k. w. transformers. The high potential lines consist of two cables No. 0 B. & S. (one of which is spare) for each of the two distant stations and two cables No. 3 B. & S. for the two nearer stations.

Distance between sub-stations = 17,100 feet.

The transformers have two per cent. *I. R.* loss and one per cent. core loss. The converter has 94 per cent. efficiency over considerable range of loads. The generating station has four 1,600 k. w. generators (one as spare) and engines.

Referring to Fig. 8 we find that neglecting losses,

	Killowatts.
Average load in k. w. on one sub-station is .....	760
Maximum load on one sub-station is .....	1600
Average load on the generating station is .....	3040
Maximum load on the generating station is .....	4400

This brings the average actual load on a rotary converter to 832 k. w.

Maximum load on rotary converter .....	1910
Average load on generating station .....	3650
Maximum load on generating station .....	5650

The converters run at 64% load at average load,  
 " " 146% load at maximum load.  
 The generators run at 76% load at average load,  
 " " 118% load at maximum load.

#### B. *Alternating Current Motors with Rheostatic Control.*—

The motors are supplied power from four sub-stations at an average potential of 3,000 volts over two sets of three-trolley wires, No. 00 B. & S. (interconnected). Each sub-station has four 700 k. w. transformers (one to spare). The high potential lines are two sets of No. 00 B. & S. and No. 2 B. & S. respectively for the longer and shorter distances.

The generating station has five 1,800 k. w. three-phase 11,500 volt generators and five 1,600 k. w. steam engines.

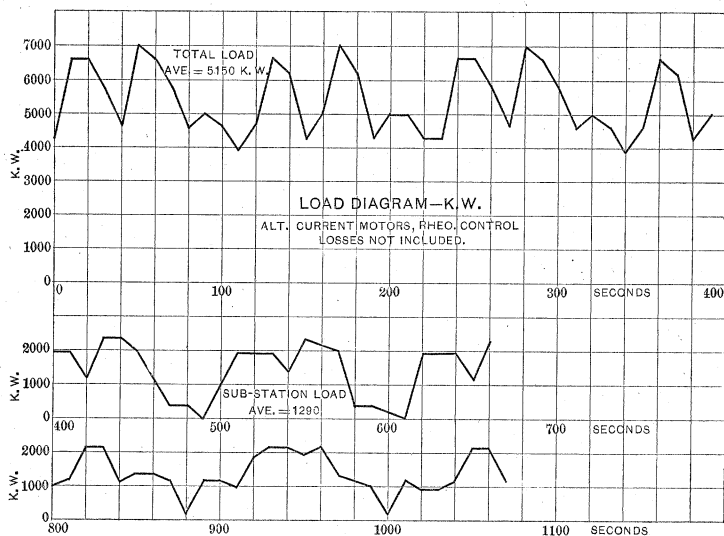


FIG. 9.

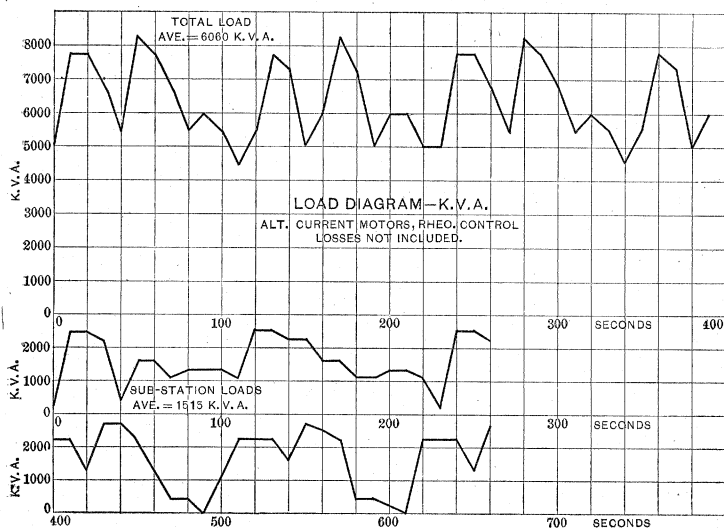


FIG. 10.



From the load diagrams, Figs. 9 and 10, is found that neglecting losses,

	Kilowatts.
Average power on sub-station is .....	1290
Average K. V. A. " .....	1515
Maximum power " .....	2300
Maximum K. V. A. " .....	2800
Average power generating station is .....	5150
Average K. V. A. " " .....	6060
Maximum power " " .....	7100
Maximum K. V. A. " " .....	8300
This gives an average K. W. output of power station .....	5600
" " K. V. A. " " " .....	6500
" maximum K. W. " " " .....	7780
" " K. V. A. " " " .....	8880

The generators will run at 90% load at average load,  
 " " 123% load at maximum load.  
 The engines will run at 92% load at average load,  
 " " 126% load at maximum load.

*C. Alternating Current Motors, Concatenated Control.*—The secondary net work is laid out as in previous case, but the high potential lines are duplicate sets of No. 000 B. & S. and two No. 000 B. & S. cables in multiple for the shorter and longer distances respectively.

Each of the four sub-stations has four 800 K. W. transformers. The power station has five 2,000 K. W. generators and five 1,400 K. W. engines.

From the load diagram, Figs. 11 and 12, is found that neglecting all losses,

	Kilowatts.
Average power on sub-station is .....	948
" K. V. A. " .....	1660
Maximum power " .....	2000
" K. V. A. " .....	3500
Average power on generating station is .....	3800
" K. V. A. " " .....	6650
Maximum power " " .....	6000
" K. V. A. " " .....	10000
This gives an average K. W. output of power station .....	4170
" " K. V. A. " " " .....	6850
" a maximum K. W. " " " .....	6000
" " K. V. A. " " " .....	10000

The generators will run at 85% load at average load,  
 " " 125% load at maximum load.  
 The engines will run at 75% load at average load,  
 " " 107% load at maximum load.

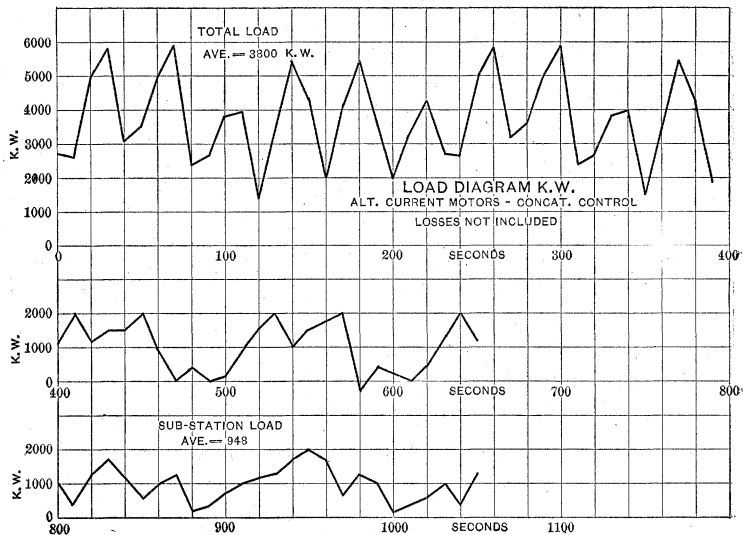


FIG. 11.

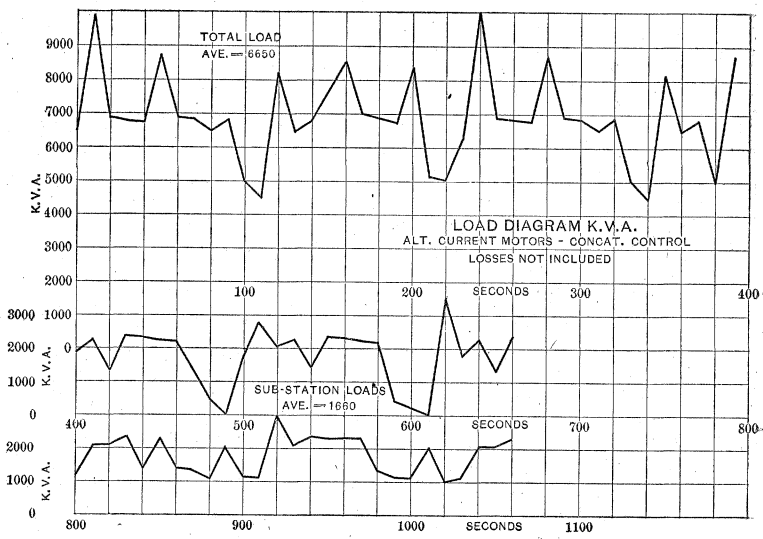


FIG. 12.

The selling prices of the various items referred to are assumed as follows:

Complete steam equipment, including installation.	\$75.00	k. w.
High potential generators, switchboards and instruments.....	26.00	"
Rotary converter sub-stations and apparatus.....	40.00	"
Transformers (700 k. w.).....	4.50	"
Direct current electric locomotive complete.....	\$15,000.00	
Alternating current electric locomotive complete.	19,000.00	
Passenger coaches (70 seats).....	4,500.00	
High potential cables (10,000-v.) No. 000 B & S. ..	1,060.00	per M. ft.
" " " " " 00 " ..	930.00	"
" " " " " 0 " ..	840.00	"
" " " " " 1 " ..	710.00	"
" " " " " 2 " ..	650.00	"
" " " " " 3 " ..	600.00	"
Copper.....	.186	per lb.
Direct current trolley construction ...	900.00	per mile.
Alternating current trolley construction.....	1,200.00	"
85-lb. rails, per ton.....	26.00	
Track construction .....	500.00	per mile.

#### EXPENSES OF INSTALLATION AND AMOUNT POWER REQUIRED.

- A. Continuous current motors with series parallel control.  
 B. Alternating " " " rheostatic current.  
 C. " " " " concatenated control,

	A	B	C
Power house steam equipment.....	\$480,000	\$600,000	\$525,000
" electrical " .....	166,000	234,000	260,000
	646,000	834,000	785,000
Rotary converter station.....	312,000	.....	.....
Transformers.....	.....	50,500	57,500
	312,000	50,500	57,500
17 locomotives, complete.....	225,000	322,000	322,000
68 passengers coaches.....	306,000	306,000	306,000
	531,000	628,000	628,000
Cables, duplicate.....	157,000	172,000	366,000
Trolley and feeder copper.....	49,000	31,000	31,000
	206,000	203,000	397,000
Track, material and construction....	109,000	109,000	109,000
Trolley construction.....	23,400	31,200	31,200
	132,400	140,200	140,200
Total cost.....	\$1,857,000	\$1,856,000	\$2,008,000

Average k. w. power required.....	3650	5600	4170
k. w. average loss.....	600	440	380
% loss.....	16.4	7.8	9.1
Percentage of d. c. power.....	100	153	114
Percentage cost of d. c. installation.	100	100	107

It is thus apparent in this particular instance, which is fairly representative for heavy urban work, that the direct current system offers decided advantages in economy if installed at the same price as the alternating current system, and that the same economy cannot be obtained with alternating current, no matter at what cost, furthermore, that the alternating current system with concatenated control is preferable to that with rheostatic control. It must, however, be borne in mind that for an actual installation, practical conditions might warrant different amount of machinery and different units, and that allowances must be made for sharp turns, grades, etc., and that the prices given are somewhat arbitrary. The three systems are, however, placed on as nearly as possible the same footing, so that the comparison should be fair, even if the actual cost of the installation is considerably different.

To conclude, it might be stated that due to the favorable characteristics of the direct current railway motor and the rotary converters, compared with the alternative current motor for this class of work, very few propositions warrant the use of the alternating current throughout. Indeed there is no question that the stand taken by the American engineers in this matter in recommending rotary converter systems almost exclusively, is correct and warranted by considerations of economy and first cost, no matter what the adverse criticisms have been of late. There is undoubtedly a field for alternating current motors, but it is strictly limited to long distance schemes with very few stops, or to mountain roads.