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“Electrical Traction on Railways.”

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THE recent arbitration as to which of two systems should be adopted for the “Inner Circle” line of the Metropolitan and Metropolitan District Railways has raised many questions, one of the most important being whether electrical working of railways has yet reached such a stage of development that it is ripe for application to main lines and to the railway systems of the country generally.

A very interesting stage has been reached in the development of electric railways. For short and busy lines, electricity has now shown that it is able to supersede steam. The present seems a suitable time for a general review of the principal systems of electrical traction that are in use or that may be regarded as practicable, and for an examination of the advantages and disadvantages of each, keeping especially in view the qualities that seem essential, or at least desirable, for general railway work. If such an examination shows that, however suitable existing systems may be for short lines, or in special instances for long lines, none of them contains the essentials for success in main-line and general work, a useful purpose may be served, if only by indicating what difficulties still remain to be overcome.

The subject of this Paper is primarily the consideration of questions affecting railways as usually understood; but some of the matters dealt with apply equally, and all in some degree, to tramways. There is no natural distinction between electric railways and electric tramways; in practice they often merge into each other, a street tramway line becoming a railway when it traverses the open country.

Methods of electric-railway working may be divided into three classes :—

1. Continuous-current methods.
2. Composite continuous - current and alternating - current methods.
3. Alternating-current methods.

This classification of the methods is in the historical order of their development.

CONTINUOUS-CURRENT SYSTEMS.

The ordinary two-wire 500-volt continuous-current system, similar in all its essentials to the ordinary electric tramway system, has been used with success for many years on the Liverpool Overhead Railway,¹ on the underground City and South London Railway,² and more recently on the Waterloo and City Railway,³ as well as on lines in Chicago and other places. The pressure of 500 volts has become a standard in tramway and railway work, because, among other reasons, it presents no serious difficulties in the making or the working of the apparatus, or in the insulation of the conductor, and because it is not high enough to be dangerous under any ordinary conditions of working. With increase of distances or with heavier traffic has arisen the necessity for higher pressures than 500 volts, in order to keep down the cost of the transmission-lines.

For railway work, where the live conductor is a rail near the ground, the danger for any given pressure is clearly greater than with an overhead wire, as the conductor is more accessible. For this reason (and because of official restrictions based thereon) this standard pressure of 500 volts has been adhered to for railways, although in the large motors used in such work it would be possible and practicable to employ a somewhat higher pressure. Apart from the question of danger, the chief objection to a higher pressure with continuous currents is that the commutators of the motors, and in a less degree of the dynamos, would have a tendency to cause more trouble by sparking. With extreme variations of load and under traction conditions, it is not possible at present to get sparkless working of commutators; and the higher the pressure, the greater is this difficulty.

So long as 500 volts is adhered to as the working-pressure for the motors, and so long as continuous currents are used throughout, the practical alternatives to the simple 500-volt two-wire system are not numerous. They are:—

¹ Minutes of Proceedings Inst. C.E., vol. cxvii. p.471.

² *Ibid*, vol. cxii. p. 209.

³ *Ibid*, vol. cxxxix. p. 56.

- (a) Some form of the Hopkinson three-wire system.
- (b) Two-wire system with generation and transmission of high-tension continuous currents, and continuous-current converters for reducing the pressure; or some arrangement for raising and lowering the pressure to and from the transmission-lines.
- (c) Combination of (a) and (b).

(a) The three-wire system has some important advantages. It enables transmission to be effected economically to much greater distances than with the ordinary 500-volt system. It allows ordinary 500-volt apparatus to be used, in some cases without any change in the cars or trains. It is, therefore, a matter of surprise that it has not come into more extensive use. There is no example, in this country, at least, of a simple three-wire 1,000-volt tramway or railway system—there does not appear to be one anywhere. The system is used, however, on the City and South London Railway (to be referred to later), in combination with continuous-current high-tension transmission. The essentials of the three-wire 1,000-volt system as applied to traction are: the use of double the motor voltage, by arranging 500-volt motors or groups of motors in series; and the use of a middle conductor, at earth potential, to carry any current required to balance the two sides of the system, and to keep the maximum pressure between any live conductor and earth the same as in the two-wire 500-volt system.

It has sometimes been proposed to have both sides of the system on one train, having one or more motors on the positive side connected in series with the same number on the negative side; the middle point can then be connected with the rails, which would have to carry only the out-of-balance current; or, alternatively, an ordinary balancer-set might be carried on the train, so as to save the cost of bonding the rails. Probably in most instances the motors could be left to balance themselves, the same number of similar motors being always used on each side. In any case, the middle point of the system must be maintained at earth potential, if the voltage to earth is not to exceed that in the two-wire system; but this can always be effected equally well at the generating-station. It will be observed that in such a system, in order to obtain the advantages of series-parallel control, not less than four motors or at least two double-commutator motors must be used on each separate running unit.

The great objection to a system in which the train takes current at the full voltage from both of the outers of the three-wire system

is the necessity it involves of using two live conductors, either overhead or on the track, with the consequent complications of double collecting-arrangements and risks of short circuits.

Although it has been in use to a limited extent for some years at 500 volts, the double-trolley two-wire system has not spread in tramway work. Its extra overhead complications and increased liability to short circuits seem to outweigh the advantages it possesses in allowing a greater drop of pressure, in dispensing with the rails as a return conductor, and in avoiding earth leakage and electrolysis. The experimental line from Earl's Court to High Street, Kensington, on the District Railway, which was a two-wire system, showed that a 500-volt double-insulated system on the track level is at any rate feasible; but in a three-wire 1,000-volt system the pressure between either of the conductors and earth would be double that of a two-wire 500-volt system in which the middle point was effectively maintained at earth potential. Unless, however, this is effectively done, the negative of a two-wire system in practice would go to earth potential; so that the maximum voltage to earth (that of the positive conductor) would be the same in the two-wire 500-volt system, as in the three-wire 1,000-volt system. Hence, so far as regards the giving of shocks to workmen the three-wire 1,000-volt system is exactly the same as the 500-volt two-wire system. A 1,000-volt system with two insulated conductors, either overhead, or at the side of the line, or at the rail-level, would present serious if not insurmountable difficulties when applied to complicated junctions and yards. These difficulties could to some extent be reduced by having one of the live conductors at the rail-level and one overhead. But for any lines through the open country a live rail is not likely to be used even at 500 volts—the risk of accident and interruption would be too great.

The 1,000-volt three-wire system, however, does not necessarily involve the use of double-trolley wires or live rails, even on a single track. For double tracks the arrangement is very simple,

as shown in the diagram (*Fig. 1*). Two single-trolley lines (or their equivalent) are used, one for each track, with 500 volts pressure between each wire and earth, but with 1,000 volts between the two wires, the rails being used as the common or "middle" conductor.

The 1,000-volt three-wire system may be used on a single track with only one trolley-wire, if the line is divided into at least two portions; which should be arranged so that their loads approximately balance each other, otherwise large balancers may be necessary. With this arrangement the rails transmit the current between the cars on the two portions, as well as any difference of current to or from the balancing-point. Where there is an up and a down service on a single line, with crossing-places or turn-outs, then a possible way of working the three-wire 1,000-volt system, with reduced need for balancing and with reduced distances for the current to travel by the rails, would be to have two live conductors but only one trolley or collector on each car or train, the up cars or trains using one conductor, and the down cars the other. Reports of attempts to use the 1,000-volt three-wire system on tramways in America state that it failed mainly on account of the difficulties of balancing the two sides. It is satisfactory to find that on the City and South London Electric Railway no difficulties have been experienced from this cause.

(b) The second alternative to the simple 500-volt two-wire system is the addition thereto of the generation and transmission of high-tension continuous currents, with reduction by continuous-current converters to 500 volts for the trains. This system, which apparently has hardly been used, with primary and secondary circuits entirely separate, offers no advantage over a combined alternating- and continuous-current system with motor-generators.

(c) The third alternative is a combination of the three-wire 1,000-volt system—with increased pressure for transmission. This plan, which is in use on the City and South London Railway, is an interesting one for several reasons, and deserves careful study. It may be described as a three-wire 1,000-volt system for the two tracks, with a five-wire system of transmission to distant points at an effective pressure of 2,000 volts. The diagram (*Fig. 2*) shows the essential points of the arrangement, for particulars of which the Authors are indebted to Mr. P. V. McMahon, Assoc. M. Inst. C.E., the Company's chief engineer.

Two 500-volt dynamos in series at the power-house supply

Fig. 2.

CITY AND SOUTH LONDON ELECTRIC RAILWAY.

current to the conducting or live rail in each of the tunnels. These two live rails—which are shown on the diagram for clearness as trolley-wires—form the “outers” of the 1,000-volt three-wire system. The track or running rails of both tunnels form the earthed “middle” conductor. Balancers are connected across the system at intervals as shown in the diagram, and batteries are provided at the power-house and at two other points.

So far the arrangement is simply the Hopkinson three-wire system applied to a railway. For supplying the more distant parts of the line an interesting method of utilizing a higher voltage is used. Two additional 500-volt dynamos are connected in series with the main generators, one on either side. These additional dynamos may be steam-driven, or they may be motor-generators, electrically driven by the main dynamos. Thus there are four 500-volt dynamos in series supplying high-tension feeders at a pressure of 2,000 volts. Each pair of feeders is taken to a sub-station containing two dynamos, each dynamo having two 500-volt windings on its armature. Each of these double-wound machines forms a motor-generator. For the sake of clearness two separate machines, M and G, on one shaft are shown on the diagram, instead of one machine with two armature-windings. All the four windings are connected with their electromotive forces in series. The “middle wire” (the track or running rails) is connected to the middle point of the series, and the two live rails are respectively connected between the first and second and between the third and fourth armature-windings. The current in each high-tension feeder passes through one winding on its way to the live conducting rail, losing 500 volts or half its voltage to earth. This winding acts as a motor, and causes the second winding to act as a generator, which produces a current approximately equal to the motor current, also at 500 volts. The two currents in parallel enter the live rail at a pressure of 500 volts from earth. A similar action takes place at the other machine. Thus each machine halves the pressure and doubles the current. To distinguish these machines from balancers, they are termed “reducers.” As machines used in this way transmit half the energy without transformation and directly convert only the other half, they need be only half the size of ordinary continuous-current converters, and their losses are proportionately less. This method may also be applied to any two-wire 500-volt system, giving the advantages of 1,000-volt transmission for feeding distant points, which would be equivalent to one side of the City and South London system, but without balancers.

COMPOSITE CONTINUOUS-CURRENT AND ALTERNATING-CURRENT SYSTEMS.

With the great development of electric tramways in America on the simple 500-volt continuous-current system came a demand for transmitting the energy to the tramways by some better and cheaper way than by the enormous conductors necessary for working at this pressure. For this purpose, as with electric lighting, alternating currents offered advantages for the generation, transmission, and transformation of currents of very high voltage which were not possessed by continuous currents. By the use of rotary converters or motor-generators for turning the alternating into continuous current, the advantages of the two systems were combined, without any need for altering any part of the existing tramway equipments. This system is usually called a continuous-current system. It would perhaps prevent confusion if it were called a "composite system."

This composite system has been largely used in America for tramways, and to some extent for railways. The large overhead electric-railway system of Chicago, however, works by the simple 500-volt continuous-current system, as is the case with the much older Liverpool Overhead Railway.

The only working example of the composite system for railways in this country is the Central London Railway, the third of the "tube" railways and the fourth of the electric railways: *Fig. 3* is a diagram of this system. High-pressure three-phase currents are produced in the generating-station. On the Central London Railway the pressure is 5,000 volts; for the Inner Circle 11,000 volts is proposed. These currents are transmitted to transforming sub-stations placed at intervals along the line, where they are transformed first to low-pressure three-phase currents by static transformers, and then to 500-volt continuous current by rotary converters. The continuous current so produced passes to the railway at each sub-station. So far as the actual railway is concerned, it is worked exactly like an ordinary 500-volt two-wire tramway or railway—at least, this is the case in all applications of the method up to the present. The difference is in the generation, transmission and transformation.

All the parts of the composite system have been worked out to a high degree of perfection. Some considerable difficulties were experienced with the connecting link, namely, the rotary converter; but these have been mostly overcome, although it is still an open question whether it is not better to use motor-generators, that is, ordinary alternating-current three-phase motors driving continuous-current dynamos. Some comparative figures are given later.

The continuous-current part of the composite system is obviously

capable of a good deal of variation. It may be a 500-volt two-wire system with one insulated conductor at 500 volts above earth, the

other conductor being the rails, as on the Central London Railway ; or the second or return conductor may also be insulated to avoid

earth or electrolysis trouble, which is the system approved by the Board of Trade as the result of the recent arbitration. Or again, it may be a three-wire system with 1,000 volts across the two outer insulated conductors, and the middle conductor—the rails—earthed. Or it may be any other continuous-current arrangement, such as the three-wire system used on the City and South London Railway (Appendix I.).

ALTERNATING-CURRENT SYSTEMS.

Three-phase Working.—In this country and in America, although three-phase alternating currents are being used for generation and transmission, the actual working of the motors on the trains is being done in all cases by continuous currents.

On the Continent, development has been carried a stage further. Three-phase alternating currents are being used, not only for generating energy and transmitting it to the trains, but also for working them. It is interesting to note that, while in America there is no evidence of any movement in this direction, engineers in Switzerland, Italy, Hungary and Germany seem to have turned aside from continuous currents for railway working, and, as a matter of ordinary practice, are giving the preference to three-phase alternating currents for both long and short lines. Some of the most difficult problems in traction are being worked out in this way. In the countries mentioned, three-phase alternating current railways may be seen either regularly at work, under construction for regular work, or in use for experimental purposes. The following Table (p. 50) gives some particulars of these lines.

The first three examples are mountain railways of short length, but with gradients of 1 in 5 and 1 in 4.

The Burgdorf-Thun railway¹ has a special interest as a full-gauge three-phase railway, forming part of the general railway system of Switzerland. The trains get their energy by a 16,000-volt transmission-line from a water-power station where the Kander river enters the Lake of Thun. This generating-station is about $4\frac{1}{2}$ miles from the Thun end of the line and about 29 miles from the Burgdorf end. Part of the railway is traversed both by ordinary steam-driven trains and by trains drawn by three-phase locomotives.

The speed of the passenger trains is about twice that of the goods trains, the speeds mentioned being approximately synchronous speeds, fixed by the construction of the motors and the periodicity of the supply.

¹ Minutes of Proceedings Inst. C.E., vol. cxli. pp. 366 and 438.

THREE-PHASE ELECTRIC RAILWAYS.

Name.	Date Opened.	Length. Miles.	Gauge.	Maximum Gradient.	Speed, Miles per Hour.	Locomotives or Motor-Cars.	HP. per Train.	Periods per Second.	Trolley- Line Voltage.	Transmission Voltage.	Remarks.
Zermatt - Gor- ner Grati ¹ .	1898	5.7	Metre	Rack 1 in 5	4.35	Locomotive	180	40	540	5,400	Braking on down gradient by return- ing energy to line.
Jungfrau . .	"	2.2	"	" 1 in 4	"	"	200	38	500	7,000	Ditto.
Stansstad- Engelberg ² .	1899	14	"	{ Adhesion 1 in 20 Rack 1 in 4 }	{ 12.5 3 }	Motor-Car Locomotive	{ 105 150 }	40	750	5,300	About 1 mile of rack; braking on down gradient by returning energy to line.
Burgdorf- Thun . .	"	25	{ 4 feet 8½ inches }	{ 1 in 40 }	{ Passenger 22.5 Goods 11.2 }	Motor-Car Locomotive	{ 240 300 }	40	750	16,000	Generators 4,000 volts; step-up transformers. "Cascade" starting and braking. Re- turns energy to line when braking at speeds above half speed.
Valtellina . .	"	67	"	"	{ Passenger 42 Goods 20 }	Motor-Car Locomotive	{ .. 600 }	15	3,000	20,000	Step-down trans- formers on the train. Braking by separately excit- ing and short-cir- cuiting the motors and by reversing motors. Not yet open. Experiment- al military rail- way. (High speed.)
Zossen (Berlin)	"	14	"	1 in 185	102	Motor-Car	3,000	50	10,000	10,000	

¹ Minutes of Proceedings Inst. C.E., vol. cxxxv. p. 403.² *Ibid*, vol. cxxxviii. p. 558, and vol. cxxxix. p. 386.

The Table includes the military line at Zossen, on which experiments are being made at speeds of 100 miles per hour and more, with pressures of 10,000 volts supplied directly to the trains; and also the 67-mile Valtellina line¹ in Sondrio, Lombardy, of which so much has been heard in the recent arbitration. The Valtellina line is not yet working, and it is reported that the water-power is not yet available. It is the longest line, and differs from the others in having a much higher transmission-pressure; and also in the method of control, whereby the motors are arranged in "cascade" or "tandem" for accelerating and for braking. In this method, when starting, one motor of a pair has its stator or primary element connected to the line, whilst its rotor or secondary element, instead of wasting its induced current in resistances, sends it to the stator of the other motor. This arrangement can be used only up to half speed when accelerating, and down to half speed when braking. The second motor is altogether out of circuit at other times.

All these lines are three-phase; and all have two overhead trolley-lines and use the rails as the third conductor, except the Zossen line, which has three trolley-lines. The trolley-line pressure ranges from 500 volts, with transformers at intervals, to 10,000 volts without transformers. The transmission-pressure ranges from 5,300 volts to 20,000 volts. On most of the lines the motors are arranged to act as generators when going down hill or when braking, and are so enabled to return energy to the line.

COMPARISON OF SYSTEMS.

In reviewing the whole field of electric traction, it must be recognized that there is at present no system actually working which satisfies at once the requirements of short and busy town lines, of longer suburban lines, and of still longer main lines. The present continuous-current systems, whether with or without alternating current methods of generation and transmission, do not appear to contain the elements necessary for a comprehensive general system.

For short town lines there is no difficulty. If it is necessary to go beyond the simple 500-volt system used at Liverpool and Chicago, then the three-wire 1,000-volt system is available; and if this is not enough, there is the 2,000-volt method of feeding, as on the City and South London Railway. It is quite possible that the latter system will be found more economical, both in first cost and in working-expenses, than the Central London composite system (Appendix II.).

¹ Minutes of Proceedings Inst. C.E., vol. cxlviii. p. 439.

With any purely alternating-current system the transforming arrangements are cheaper, simpler and less wasteful than the rotary converter or motor-generator of the composite system, or than any continuous-current transforming system.

The curves of efficiency of transforming-stations given in *Fig. 4* show] that the transformation-losses with the alternating-current system at no load or at a small average load are about one-fifth or one-sixth of those of the composite system, while at larger loads they are about one-third or one-fourth. The efficiency of sub-stations on the City and South London Railway system may be taken as somewhere between those of the alternating-current system and the rotary-converter system.

It will be seen that in the composite system the aggregate losses on a large number of sub-stations may be very considerable. With the alternating-current system not only is the no-load loss small, but by automatic switching-gear it may be greatly reduced, which is not practicable with the rotating machinery necessary for the composite system.

The alternating-current system has the still greater advantage of dispensing with attendance at the sub-stations. It has a further advantage in the fact that the transformers for any given total power may be spread along the line, *i.e.*, there may be many small sub-stations instead of a few large ones. The distance the current has to travel along the line and along the rails may thus be reduced, and economies may be effected in the cost of the conductors and in the losses in them.

As to cost of sub-stations, the comparison is approximately as follows:—

COST OF TRANSFORMING-STATIONS.
(Pounds sterling per kilowatt.)

	Alternating- Current System.	Composite System.	
	Transformer Sub-Station.	Rotary Converter Sub-Station.	Motor Generator Sub-Station.
Transformers	£1·8	£1·9	None
Rotary converters	None	4·8	None
Synchronous motors	None	None	£4·7
Continuous-current generator	None	None	5·7
Switch-gear, starting-gear, con- nections, etc.	1·3	4·0	3·3
Building	0·6	1·8	1·5
Total per kilowatt	£3·7	12·5	15·2

The above figures include a fair proportion of spare plant in each case.

Accumulators.—Both the composite and the continuous-current systems have the advantage over the alternating-current systems that they may easily use accumulators. There is an increasing tendency to use accumulators for traction. They reduce the “peaks” at times of momentary heavy loads, thus equalizing the load on the generating-station, and lessening the amount of running plant necessary. If distributed on the line or placed at a distance from the generating-station, they help to keep the pressure uniform and to reduce the need for feeders. They can deal with light traffic when the station is shut down. The arrangements of Mr. J. S. Highfield, whereby both charging and discharging are facilitated by special boosters, will probably increase greatly their usefulness, especially for meeting momentary heavy demands.

Batteries may, however, be used with alternating-current systems, although not as easily as with continuous-current or composite systems. The charging of accumulators on an alternating-current system involves precisely the same process as the ordinary transformation of alternating-current to continuous-current in the composite system; and the discharging involves simply an inversion of that process. An alternating-current motor, driven from the alternating-current system, may drive a continuous-current dynamo charging the battery. When discharging, the battery drives the continuous-current dynamo as a motor, and this drives the alternating-current motor as a generator, feeding back on the alternating-current line. The alternating-current motor may be either synchronous or non-synchronous, or may even be a rotary converter. With none of these is there any difficulty, if the object is merely to furnish a supply for a short time when the generators are shut down.

For helping momentary loads, however, whatever system is adopted must be automatic in its action, in order to meet the rapid and large fluctuations in the load. In this respect the method of using batteries for railway work must differ from methods suitable for lighting. Although the problem thus presented is more difficult with alternating than with continuous currents, it will not be found insoluble if it prove to be worth while to use accumulators for this purpose.

Compared with composite or continuous-current systems, multi-phase systems are at a disadvantage in requiring the use of at least two live conductors, instead of one. This difference increases the complication and cost of the overhead construction, and the risk of interruption by short circuits; and these matters become more

and more serious in proportion to the complexity of the junctions, shunting-yards, etc.

With multiphase systems the synchronous speed of the motors, corresponding with a definite speed of the train, cannot be exceeded; therefore lost time cannot be made up. This may be of importance to main-line railways. But, although it is true that the synchronous speed cannot be exceeded, it is not quite accurate to say that the full speed is fixed by the conditions of synchronism. As a matter of fact, between the full speed of a heavy train and that of a light one there is a difference represented by the "slip" of the motors. Thus a light train will gradually overtake a heavy one.

Continuous-current or composite systems are more flexible in respect of speed, although it is not advisable to run for more than a short time with the ordinary series-parallel arrangement, except at half or full speed; for at intermediate speeds wasteful resistances have to be inserted in the circuit. Nor is it advisable to run at more than the full normal speed in order to make up time, as this can be done only by weakening the field-excitation, with some risk of commutator-troubles. These remarks apply to series motors as usually arranged. It is reported from the Continent that the latter difficulty has been avoided in some large traction-motors by recourse to the old device of commutating poles.

Small variations of voltage do not seriously affect the maximum speed of alternating-current motors for any given load. With continuous-current motors the maximum speed for any given load is approximately proportional to the voltage of supply. With large variations of voltage, however, the effect with continuous current is different from that with alternating current. Continuous current has a decided advantage in this respect. However low the voltage may fall, continuous-current motors can develop a large torque, even if they cannot attain a high speed; with alternating-current induction motors, on the contrary, a considerable fall of voltage would prevent the motors from working at all. Fortunately for the future of alternating-current working, the pressure is more easily kept up than with continuous current.

The disadvantage of the composite system is the necessity for sub-stations at frequent intervals, equipped with running machinery which requires skilled attendants. Such machinery comprises static transformers and rotary converters; or motor-generators, high- and low-pressure switch-gear, and usually electric motors and fans for ventilating and cooling the apparatus, as well as motors for starting the converters. All this machinery, with its proper proportion of reserve, involves heavy capital expenditure, and large working-

expenses in power, attendance and maintenance. For short and busy lines, such as the Central London Railway, these burdens may not be too serious; but for longer lines with less frequent trains—main lines or even suburban lines 20 miles to 50 miles in length—it will probably be found that the working-expenses under this system will be too heavy to enable it to compete successfully with the steam-locomotive.

Before considering the requirements which seem desirable for a comprehensive system, attention may be directed to several matters of general importance.

STARTING-TORQUE OF ALTERNATING-CURRENT MOTORS.

Not many years ago alternating-current motors were inferior to continuous-current motors in their starting-torque. On the other hand, they possess some advantage in not having any commutators; and for transmission they have the further advantage that for high pressures they may be used much more conveniently than continuous-current motors. In large sizes they are easily made to work at very high pressures; and in small sizes they can be worked from high-pressure transmission lines by step-down transformers.

The development of multiphase motors has practically put continuous-current and alternating-current motors on an equal footing in regard to starting-torque. With single-phase motors, however, the starting difficulty has not yet been so successfully solved.

Of the two practical types of single-phase motors, viz., the synchronous motor and the non-synchronous induction motor, the former requires to be started from rest and run up to full speed by some auxiliary means. When got up to synchronous speed it is an excellent motor, running of course with absolute regularity, or at least following exactly the speed of the machine by which it is driven. The synchronous motor has a valuable quality not possessed by the induction motor. It usually has a high power-factor; that is to say, the idle current that it takes is very small, and by suitable variations of its field-excitation it may be made to compensate either for the capacity or for the self-induction of the circuit. By this means it is possible on long lines to keep the power-factor higher than with induction motors.

Single-phase induction motors have recently been considerably improved in their starting quality, but at some sacrifice of efficiency. Up to 2 or 3 years ago it was necessary to start them on a loose pulley, or at least without any load, as their starting-torque usually did not exceed one-fifth of their full-load torque; in fact, it was not always possible to get such motors to start from

rest without some slight assistance, although when started and run up to speed they were fairly satisfactory.

Recent improvements have been made in this respect, however, especially by Mr. A. Heyland, whose motors now, when required, are made to start with full-load torque, or even with slightly more.

A curve is given (*Fig. 5*) showing the various qualities of such a motor. It will be seen that the efficiency is not so high as with good continuous-current motors; but for many purposes such a single-phase induction motor will do all that is required of it.

Fig. 5.

It starts at full-load torque with about twice the normal full-load current. The "slip," or fall of speed from no load to full load, is about $8\frac{1}{2}$ per cent. It will do about two-thirds more than its full load with a drop in speed of about 20 per cent. Its efficiency at full load is about 76 per cent., at half-load about 70 per cent., and at quarter-load about 60 per cent. Its power-factor is about 0.83 at full load, 0.72 at half-load, and 0.57 at quarter-load. These results are for a 15-HP. motor. It is not as good as either a continuous-current motor or a multiphase motor of similar output.

It is given here in order to show the results now obtainable when a single-phase motor is designed for full starting-torque. Probably better results can be attained in larger sizes.

When large starting-torque is not required, single-phase motors are made with higher efficiency, larger power-factor and small slip. *Fig. 6* shows the characteristics of such a motor of 50 HP.,

made by Messrs. Brown, Boveri & Co. *Fig. 7* illustrates the starting-torque of a continuous-current series motor and of three-phase and single-phase alternating-current motors.

APPARENT RESISTANCE OF RAILS WITH ALTERNATING CURRENT.

A very important matter in connection with alternating-current railway working is the resistance offered by the rails when they are used for the purpose of carrying current. With continuous currents the problem is a simple one; the resistances of the rails are well known.

It is usually found in practice that a line of rails has about ten times the resistance of copper of equal cross-sectional area. The ratio, however, varies considerably with the composition of the rails, and with the degree to which they are insulated from the surrounding ground. This ratio of 10:1 is somewhat higher than the ratio of the specific resistances of the two metals, and it includes a certain amount of extra resistance due to the bonds or joints. With alternating currents, however, the "skin effect" has to be considered, which, in large conductors, causes the apparent resist-

ance to be greater than with continuous currents. The reason for this is that the alternating current is not conducted uniformly by the whole section of the metal, but is denser on the outside than inside. With copper conductors and ordinary periodicities the skin effect is not serious; in solid rods up to nearly 1 inch in diameter it is quite small. In flat or ribbed copper conductors $\frac{1}{2}$ inch or so in thickness, or in tubes of a similar thickness of copper, it is also unimportant; but in iron the condition is complicated by the varying magnetism set up by the alternating current, whereby the skin effect is intensified.

On the Burgdorf-Thun line, Mr. C. E. L. Brown has kindly

Fig. 7.

informed one of the Authors, some measurements have been made which show that the apparent resistance of the rails is equal to about eight times the ohmic resistance, and that the ohmic resistance is about nine times that of copper; on this basis the resistance is about seventy-two times that of an equal section of copper. But this increase of apparent resistance depends upon the amount of current and upon the periodicity. On the Burgdorf-Thun line the periodicity is about 40 cycles per second; the Authors do not know at what current-density Mr. Brown's tests were made.

The Authors have to thank Mr. Blathy for sending them a diagram (Fig. 8) giving results of tests at 15 and at 42 periods

per second on a round wrought-iron rod and on steel rails, the dimensions of which are given at the foot of the diagram. The curves show the voltage required to send various currents through the conductors. At the lower part of the diagram

the results are given with continuous current for comparison. The voltage with alternating current is much higher than with continuous current, and is nearly twice as great at 42 periods per second as at 15 periods. The alternating-current curves are not straight. With high current-densities they bend over in the manner of

magnetization curves, and probably for a similar reason. The observations do not carry the curves down to zero, but from their form it is probable that near the origin also they resemble magnetization curves. The extra drop with alternating current does not all indicate lost energy. Mr. Blathy's diagram gives the power-factor (P. F.) observed in his tests of the iron rod, showing that only 80 or 82 per cent. of the observed drop represents energy actually lost in the rod; and it may be assumed, though it is not stated, that a somewhat similar figure would hold for the steel rail.

It is evident from these results that the rail-return question with alternating currents requires careful study. It has always been a difficult question with continuous currents: in some ways it appears likely to be still more difficult with alternating currents.

It may be useful to consider what is involved by the effect of this rail-resistance, and to compare results with continuous current and alternating current, so far as it is possible to do so from the information available, and within the limits of a section of this Paper.

In continuous-current railways and tramways the drop of pressure in uninsulated rail-returns is now restricted by the Board-of-Trade rule to a maximum of 7 volts, or about 1·4 per cent. of the working-pressure; this limit being imposed mainly to prevent electrolytic action on gas- and water-pipes by continuous current. Were it not for this limit, a much larger drop might be used; for example, such a drop as is customary in the live line, viz., about 50 volts or 10 per cent. With alternating currents there is practically no electrolytic action, unless the current-density is very high; a much larger drop than 7 volts might therefore be allowed, if it were not for interference with telephone and telegraph lines.

The Table at p. 62 is deduced from Mr. Blathy's curves. It has been compiled for a single track using two 90-lb. rails as the return conductor. It gives the drop in voltage per mile, and the distance in yards at which the 7-volt Board-of-Trade limit is reached with various currents, both continuous and alternating—the latter at 15 and at 42 periods per second. This Table must be taken only as indicating approximately what will occur. In the first place it will be seen that the curves do not go down to very low current-densities, and it has been necessary to extend them towards zero; the form of this extension within the limits of the Table, however, is not open to much doubt. To bring the Table into accord with probable railway conditions, 90-lb. rails are taken, instead of the 60-lb. rails of the diagram, and the assumption is made that with alternating currents

LOSS OF VOLTAGE IN RAIL-RETURN.

Total Current in Two 90-lb. Rails. Amperes.	Amperes per Square Inch.	Volts per Mile.			Yards for 7 Volts.		
		Continuous Current.	Alternating Current.		Continuous Current.	Alternating Current.	
			15~	42~		15~	42~
1,000	56·5	21	120	210	585	103	59
900	50·8	19	101	176	650	122	70
800	45·2	16	85	147	730	145	84
700	39·5	14	66	112	835	185	110
600	33·9	12	53	87	972	233	141
500	28·2	11	39	67	1,160	318	185
400	22·6	8	28	50	1,460	446	244
300	16·9	6	21	34	1,950	597	358

for the same current-density the drop for a given distance will be the same in the large as in the small rail. This can only be considered as approximately true. Further, no allowance has been made for joints. There is some uncertainty as to what conductivity can be relied on with existing methods of bonding. Sometimes the bonded rail-joints may add as much as 20 per cent. to the total resistance. For some modes of bonding, however, it is claimed that the joint is so good that it adds nothing to the total resistance. The Table shows the conditions for the 7-volt limit, neglecting or eliminating resistance of joints.

With continuous currents the 7-volt limit is reached in 1 mile with 330 amperes, or 165 kilowatts at 500 volts. With alternating currents at 42 periods, 300 amperes give 34 volts per mile; at 15 periods the drop is 21 volts. The drop is not directly proportional to the current, otherwise 62 amperes would give 7 volts at 42 periods. At the lower currents, however, the probable form of the curve shows that a drop of 7 volts would be reached with about 100 amperes at 42 periods.

The increased resistance with alternating currents is a serious effect, and would be still more serious if it were not for the fact that with alternating-current distribution it is possible to put the transformer sub-stations nearer together without increasing the working-expenses, because constant attendance is not necessary. Hence the current need never have to travel any great distance along the

rails. Moreover, alternating-current methods of working enable much smaller currents to be used than are necessary for direct-current methods, because with alternating currents much higher pressures can be used for distributing the power to the trains.

It is probable that, as alternating-current methods become developed, this effect will lead to two changes from present continuous-current practice. In the first place an insulated return-conductor on the track is likely to be used, instead of the uninsulated rails. Such a return conductor will be earthed at one point: that is to say, it will be at earth potential, except for the voltage due to its own drop. It could hardly be regarded as a live conductor. There is much to be said for this course, even with continuous currents. It saves bonding of the rails, and allows as large a drop on the return as conditions of efficiency render advisable. As far as efficiency is concerned, the drop in an insulated return-rail might be several times the amount allowed by the Board of Trade.

The second probable change will be the use of copper instead of iron for the return conductor. Iron or steel is now used for insulated track-conductors for two reasons: it is cheaper, and it is stronger and more rigid. On all but very short lines, however, it is found necessary to supplement the rail conductor—whether it be the live iron rails or the uninsulated iron rails—by insulated copper feeders. With alternating currents it will only be necessary to carry out this plan more freely; either by using an insulated copper return-rail—possibly with a wearing surface of iron—or, if iron is necessary for rigidity, a copper conductor connected at frequent intervals to an iron rail.

In the relative cost of steel or iron and of copper there is now a less disproportion than might be supposed, even for continuous-current working. Taking the resistance of steel rails as ten times that of copper of equal section, and allowing for the specific gravity of copper being about 14 per cent. higher, the two metals become equal in cost, as electrical conductors for continuous current, when copper is 8·8 times the price of iron. The actual market prices at present are—steel rails about £5 10s. per ton, electrolytic copper about £66 per ton, or 11·5 times the price of iron. This comparison concerns continuous-current conductors alone; it must be taken as only approximately correct, because the ohmic resistance of the rails varies a good deal with the quality, and the prices of both metals vary from time to time; but it shows that, on the bases stated, copper is about 31 per cent. more costly than iron.

With alternating currents, however, the balance is greatly in

favour of copper; at least, within the range of the curves and Table. For example, the lowest figure in the Table shows that the apparent resistance of iron, at 15 periods per second and at the low density of about 17 amperes per square inch, is about three times the ohmic resistance. Under these conditions iron is about 2.3 times as dear as copper. At the highest value in the Table (viz., at 42 periods per second and 56.5 amperes per square inch) the apparent resistance is ten times the ohmic resistance. Under these conditions iron is 7.7 times as dear as copper. It is safe therefore to say that with alternating currents the balance will be in favour of copper under any conditions, except possibly at current-densities so low as to be hardly practicable.

There will be a drop due to self-induction, even when copper is used instead of iron; but as the phase of the back electromotive force of self-induction is at right-angles to the impressed electromotive force, it will generally cause but a small additional drop of voltage.

In continuous-current working, rail-drop is minimised by feeders, assisted in some cases by negative boosters on the plan originally proposed by Mr. Gisbert Kapp, M. Inst. C.E. A similar plan may be used with alternating current, by means of a static transformer, having its primary across the mains and its secondary arranged to add volts to one or more return feeders. This, however, would not be self-regulating. A static transformer may, however, be arranged as a self-regulating booster, for which purpose it should have two windings, one in series with the out-going feeder, the other in series with the return feeder. It would then add volts to the latter proportionately to the current, but would do so at the cost of a reduction of pressure in the out-going feeder. Or a self-regulating effect could be secured by a rotating booster, consisting of a small alternator synchronously driven and having its field compounded by re-dressed current from the out-going feeder. The return feeder would be passed through the armature, the voltage rising with the current.

PERIODICITY.

From the examples given in the Table of alternating-current railway systems (p. 50) it will be seen that, except on the Valtellina line, the periodicity is not very low, that is to say, it is between 38 and 50 cycles per second. This has no doubt been so arranged in order to enable lighting as well as the traction of the trains to be effected directly by the alternating current. On the Valtellina line the low periodicity of 15 cycles per second seems to have been

adopted to enable direct-coupled motors to be used having few poles. With the proposal to adopt geared motors, this necessity no longer existed, and it is understood that Messrs. Ganz and Co. proposed to use 25 periods on the Inner Circle, which is the periodicity now used on the Central London Railway, and is also proposed for the alternating-current working on the Inner Circle.

It may be that in some cases the considerations affecting the rail-return will prove the governing factor in the choice of periodicity with alternating-current working of trains: that the advantage of a low periodicity in this connection will more than counter-balance the disadvantage as regards lighting. For the composite system, a low rate is used because high-frequency rotary converters do not work satisfactorily.

Where the lighting is important, probably a lower periodicity than 40 cycles per second will not be used. It is significant that, in some of the more recent transmission projects, periodicities suitable for lighting as well as for power are being used.

In connection with electrostatic capacity, a high frequency is objectionable on account of increased loss from dielectric hysteresis; but it is favourable as regards the ability of the cables to counteract self-induction, and so to raise the power-factor. Condensers are coming into use largely for this latter purpose. Their effectiveness is directly proportional to the periodicity.

LIGHTING.

On all underground lines, the electric lighting of stations, lifts, and tunnels, should be on a circuit entirely separate from the circuit supplying energy to the trains. Interruption of the main supply should not interfere with the lighting.

On trains, separate provision may be made, either by a separate conducting line, or by a small dynamo or motor-generator on the train, arranged in conjunction with accumulators, so as to ensure a certain number of lamps being kept going. If this is not done, a number of oil or other lamps should always be kept alight.

On main lines there is now little difficulty in getting a cheap supply of electrical energy locally for station-lighting; or, failing this, motor-generators and accumulators are available, supplied from the traction-mains.

With alternating current there is a great advantage in using periodicities of between 40 and 50, inasmuch as these enable all lighting to be done by the alternating current transformed by static transformers to any desired pressure, without any necessity for rotary transformers. It is probably for this reason that the

Continental lines have in most cases adopted 40 to 50 periods per second. Messrs. Ganz and Co. state that, by using three-phase lamps at very low periodicities, they are able to get a fairly satisfactory light. The lamps have three filaments, one in each phase, and the flicker, which would be objectionable with a single filament, becomes equalized when the three flickers overlap one another: but the arrangement is not a good one.

RETURN OF ENERGY TO THE LINE.

More than twenty years have elapsed since Sir William Siemens pointed out¹ that, if two trains were driven electrically by a common source of energy, a train descending a hill would help an ascending train almost as if they were connected by a rope or chain. Till recent years little practical use has been made of the principle underlying this observation, namely, that a motor when driven by a train can be made to act as a generator and send current back to the line. Attempts have been made to utilize this property on continuous-current systems, but not with any marked success.

Some years ago Mr. Frank Sprague, M. Inst. C.E., attempted to introduce a system in which shunt motors were used, and energy was returned to the line during braking or coasting; but nothing came of it. With ordinary shunt motors the range of speed through which such an action is possible is small. When attempts are made to increase the range by using compound motors, complication becomes excessive. With series motors, such as are now always used for tramways or railways, the difficulty is greater still.

Although various arrangements have been proposed for returning energy to the line, they do not seem to have come to anything, so far as continuous currents are concerned. On long level lines where the braking periods are short relatively to the whole length of the run, it is obvious that little advantage can be gained by returning power. With lines on which the stoppages are frequent, it may be worth while to make use of the energy of the train in this way. One simple way of using the energy of the moving train—involving nothing electrical—is that adopted on the Central London Railway, where most of the stations are at the top of an incline. The energy is stored in the train when driving itself up the incline to the station; and is returned again, assisting the acceleration of the train, when descending the incline from each station.

¹ Journal of the Society of Telegraph Engineers, vol. ix. p. 301.

With the introduction of three-phase alternating-current, attempts to return energy to the line have been revived, as it is easier to return it by alternating-current motors than by continuous-current motors. The Table of the existing three-phase lines (p. 50) shows where this method is used. On those lines it is done not so much for the sake of economy as because it provides a convenient controllable brake for descending steep gradients. On some lines for which water-power is used, economy is quite a secondary consideration. In fact, where there are few trains running, there may be no ascending train to take the power returned to the line by the descending train. In using this as a braking method, therefore, it is necessary to make sure that there is some means of disposing of the returned energy. It may be dissipated by a resistance carried on the train or in connection with the line. On the Engelberg line a water-resistance is connected across the line at the power-house for the purpose. On the Gorner-Grat line a similar arrangement is used. In the event of there being no ascending train, the descending train drives the generating-station. When the turbines have reached a certain increased speed, a resistance is put across the line, which absorbs the incoming energy. It is a pretty sight to see these trains coming down 1-in-5 gradients braked in this way.

The action may be explained thus:—The three-phase induction motors at light load run practically synchronously. As the load increases, they fall below synchronism by a small amount; this is called the “slip,” and is a small percentage of the synchronous speed. If such motors are driven above synchronous speed, they become generators, giving power approximately equal to that which, as motors, they would take at the same percentage below synchronous speed. In this way the motor can be made to exert its full torque as a brake when it is being driven by the train at a speed only 4 or 5 per cent. above its normal speed when working as a motor fully loaded. Trains driven by continuous-current shunt motors and those driven by alternating-current induction-motors have a power of self-control somewhat similar, except that the control is more marked in alternating-current motors, because the variation of speed necessary to change from the condition of fully-loaded motor to that of generator is smaller.

VARIABLE-RATIO CONTROL.

Constant-voltage is the only practical mode of supply, whatever system is used. For large starting-torque, large current is necessary, but not high voltage or large power. The saving of

power at starting is important, not only because of the cost of the energy, but also because the saving reduces the plant necessary to meet momentary heavy demands. Some variable-ratio process is wanted, by which at starting a small current may be taken at full voltage and converted into a large current at low voltage, if possible, without involving the use of wasteful resistances. Such a process would reduce the "peaks" in the output curve, lessen the amount of generating-plant required, prevent large fluctuations in the pressure of the supply, and save energy. Efficient starting is relatively of less moment on long than on short lines; but on all it is important.

At present there is no good variable-ratio process in use. The continuous-current series-parallel with two motors is at best a 2 to 1 ratio process, and does not avoid the use of wasteful resistances absorbing about two-thirds of the energy at starting. The multiphase "cascade" arrangement is also a 2 to 1 process, with the disadvantage that half the motors are idle after half-speed has been attained. In the ordinary multiphase system the motors are simply in parallel, and do not form a variable-ratio arrangement at all.

A variable-ratio process would not only effect economies at starting; it would have advantages in regulating speed, and possibly would enable energy to be returned to the line through a considerable range of speed. The need for such a process may be judged from the fact that in present methods the maximum loss occurs with minimum useful power. The greatest output of the station, the greatest losses in the line, in the motors, and in the resistances, all occur when the least horse-power is being exerted by the train-motors—namely, at the moment of starting.

REQUIREMENTS FOR A GENERAL SYSTEM.

Having considered the systems available, the requirements for railway working may now be examined under different heads.

First as to the generation of the power and its distribution to trains on a railway, for the equipment of the line the more important requirements are as follows:—

- (1) For main lines current must be supplied at extra high voltage for feeding the sub-stations placed along the line.
- (2) These sub-stations must not contain any moving machinery, so that there need be no constant attendance or supervision.
- (3) For main lines, or for lines more than about 50 miles in length, which run into the country, some form of high-pressure

or extra high-pressure supply must be adopted for distributing the power from the sub-stations to the trains.

(4) With a high-pressure distributing-system, overhead conductors must be used in order to make them inaccessible.

(5) The overhead distributing-system should admit of unlimited extension, and be such as could be adopted as a standard by all railways; for it is nearly as important that the overhead equipment should be the same on all railways as it is that they should all have the same rail-gauge.

(6) The overhead distributing-system should be able to supply energy to trains with different kinds of motors and different systems of controlling them.

Considering next the equipment of the trains, the more important requirements are:—

(7) A high acceleration must be possible when starting the train.

(8) On a falling gradient, or when stopping, the energy of the moving train should, if possible, be returned to the line.

(9) It should be possible to vary the speed economically within wide ranges in order to admit of running with the same train-equipment on suburban lines and on main lines: and so as to enable lost time to be made up.

(10) The motors should form, or should be combined with, a variable-ratio arrangement for starting, for speed-regulation, and for returning energy.

(11) It should be possible either to have all the motors on a locomotive, or to distribute them throughout the train.

(12) The train-equipment and control should admit of unlimited extension, and should be capable of modification so as to work with other distributing-systems than its own.

What limitations do the foregoing conditions impose?

Examining them in order, the first five lead to the following conclusions:—

(1) In order to transmit the current at extra high voltage, the generators in the power-station must be alternators, generating single-phase or multiphase alternating currents.

(2) To do without moving machinery at the sub-stations, static transformers only can be used there; and the power must therefore be distributed from the sub-stations as single-phase or multiphase alternating currents.

(3) Distribution of power to the trains at high or extra-high pressure can be effected only by alternating currents, either single-phase or multiphase.

(4) With overhead conductors, two at least must be used for three-phase currents, but one only is required for single-phase. A distributing-system which uses a single overhead conductor has such immense advantages over a system requiring two or more overhead conductors that it should certainly be adopted if possible. The advantages are the simplicity of construction and working, with the absence of insulated crossings and with freedom from the dangers of short circuits.

(5) A single-phase overhead conductor, on account of its safety and simplicity, would best admit of unlimited extension and of adoption as a standard by all railways.

The selection is thus brought down by a process of elimination to a single-phase alternating-current system for the generation, transmission and distribution of the power, with one overhead conductor, and a return conductor on the ground, which can be either the rails or an insulated conductor, at practically the earth's potential.

SINGLE-PHASE ALTERNATING-CURRENT WORKING.

Before dealing with the remainder of the requirements consideration must be given to the means by which a single-phase system can be used for driving the trains.

At present there is no example of a single-phase railway or tramway, but such a system is possible, and should be included in any account of practicable methods in view of the great advantages which it would possess were it fully carried out. From what has been said as to the starting-torque of single-phase motors, it will be evident that, at present at least, railways can be worked by such motors only if they are started without any heavy load on them. They must therefore be started independently of the train, and some means must be found for starting and driving the train by coupling the running motors to it. For this purpose it is clear a variable-ratio coupling must be used. Any arrangement of mechanical clutches for such a purpose would present great, if not insuperable, mechanical difficulties. Magnetic clutches offer a better prospect of success, if efficiency is not of primary importance. For example, a laminated multipolar magnet carried by the alternating-current motor, and another attached or geared to the axle of a driving-wheel, might be used: or two such clutches, with poles arranged to break joint. There would be a small air-gap between the polar surfaces. By varying the excitation of such a clutch, a difference of speed between the two

parts would be possible. At starting, and when the two portions were going at different speeds, the loss would be proportional to the difference of speed; it would be due to magnetic hysteresis and to eddy-currents. When full or synchronous speed of the poles was reached the loss would almost entirely cease. An exciter driven by the single-phase motor would be necessary. The whole control could be effected by adjustment of the exciting circuit of the clutch.

An electrical method of solving this problem has been proposed by Mr. Ward Leonard.¹ It presents many features of great interest, and in the Authors' opinion it is well worth careful consideration. Although it has some serious disadvantages, it appears to possess more of the essentials of a comprehensive system than any other method known. No perfect general system is ever likely to be devised; it remains to be seen whether the one under consideration affords a reasonable and practicable solution of the problem. It has been used for lifts and other purposes, but, so far as the Authors know, it has not been used for railways. It has many incidental advantages which do not seem to have been recognised.

The arrangement is illustrated diagrammatically by *Fig. 9*, which differs from Mr. Leonard's only in showing a single-phase self-starting induction-motor, instead of a synchronous non-starting motor; in principle it is the same. Its main feature is a motor-generator on the train, transforming from alternating to continuous current. A single overhead conductor is supplied with single-phase alternating current at any suitable pressure. If the distance is great or the power large, the primary mains might be at extra high-pressure, static transformers being placed at intervals for transforming down to a lower voltage.² One such transformer is shown in the diagram. The alternating current passes through the induction motor, and returns to the generating-station or to the transformer either by the rails or by another conductor, insulated or not. The motor is coupled to and drives a continuous-current dynamo, which in its turn supplies current to the continuous-current motor or motors driving the train. A small exciter is also driven by the induction motor, and is used to excite the dynamo

¹ British patent 14,509 of 1891.

² These transforming-stations will be simpler, cheaper and more compact than those in the three-phase system, inasmuch as the transformer will not require to be made up of three smaller transformers; the switch-gear and connections will similarly be simplified.

and the train-motor: it may also be used for lighting and heating the train, although the alternating current would be equally

available for these purposes by the use of step-down transformers. An air-compressor for the brakes might also be driven by the

motor, either direct or otherwise. The motor-generator can be started with no load on it, just before the train has to be started. For short stops it can be kept running; and for longer stops it can be shut down and started again when wanted.

This apparently complicated system is in reality a fairly simple one. But some complication is allowable, since the system forms a variable-ratio transforming and driving gear of elastic qualities and long range. One interesting feature is that the complete control of the train is possible without any appreciable loss in external resistance. This result is attained by varying the excitation of the dynamo by means of the small resistance in its field-circuit. At starting, the train-motor requires a large current at low pressure, which is obtained by adjusting the field of the dynamo so that the voltage is just enough. There is no need for any starting- or other resistance in the motor-circuit. Then, as the speed rises, the excitation of the dynamo is gradually raised, until at full speed it is giving its full voltage and sending its full current through the train-motor against the full back electromotive force of the latter. When slowing down, or when varying the speed, the voltage of the dynamo is adjusted to supply the proper current to the train-motor without the insertion of resistances. Energy can be returned to the line when running down an incline or when braking, and at practically any speed of the train. This is done by reducing the excitation of the dynamo until its electromotive force is less than that of the train-motor. The same thing can be done by increasing the excitation of the train-motor (if it is separately excited, as shown in *Fig. 9*); or the fields of both dynamo and train-motor can be adjusted until the train-motor becomes the generator and drives back to the dynamo, which mechanically drives the alternating-current motor at slightly above synchronous speed, and so returns energy to the line. To reverse the direction of driving, the field of either the dynamo or the train-motor can be reversed. All the operations of starting, stopping, reversing, braking, and returning energy to the line, are done by adjustment of the field-excitation alone.

This variable-ratio gear is completely reversible, acting in either direction. Thus it gives large torque at low speed for starting, taking a small current at high voltage from the line, and transforming it into a large current at low voltage for the motor. It gives large reversed torque at low speed when braking, returning to the line a small current at high voltage, transformed from the large current and low voltage of the motor (now a generator). It gives either large or small torque at any speed from the lowest

to the highest, being always reversible; and it gives, what no other system gives, a relatively high efficiency at low speeds.

In this system there need be no irregularities of control or of speed, such as are caused by the "notches" in the ordinary series-parallel controller. A perfectly smooth transition can be obtained through the whole range, from large torque at starting and at low speeds, through all the variations of speed, to large power returned at stopping or braking.

A possible objection in detail to this system is in connection with the commutator of the continuous-current dynamo. The collection of the large current may be difficult in the weak field necessary to give the low voltage at starting. The reaction and sparking tendency will then be greater; but it is now known that dynamos may be made to collect quite well with practically no field at all.

The no-load losses, or the losses when the train is standing, are confined to the power necessary for driving the single-phase motor and the exciter unloaded, including their friction and that of the main dynamo. At low speeds of the trains the dynamo will work with very low pressure, very low excitation, and comparatively small losses. The motor-generator runs at or near its maximum speed, and is therefore always capable of a considerable fly-wheel effort. It should probably be considerably over-loaded during the last part of the acceleration of the train, as the over-load lasts only a short time. The motor-generator can in this way be made to work at normal full load and highest efficiency when running the train at full speed and under normal conditions, but not accelerating.

The voltage of the line and of the motor may be selected according to the conditions, as the single-phase motor may be made for almost any practical pressure—at least for sizes such as would be wanted for railways.

The alternating-current motors automatically take from the line enough energy to enable them to do the work that is at any moment imposed on them; no control is necessary so far as the alternating-current part of the system is concerned.

With this single-phase induction-motor arrangement, using motors that are now available, there is no difficulty in starting the motors, nor is there anything to fear from their not keeping up to speed. Momentary interruptions of the circuit would not cause them to slow down to rest, as would be the case with synchronous motors. The latter, however, have the advantage of a higher power-factor and a higher efficiency, and it might on that

account be found desirable to adopt them, using a small induction motor for running them up to synchronous speed.

The drawback to this system is that there is so much machinery to be carried. Besides its motors, the train must carry continuous-current plant sufficient to drive these motors, and alternating-current plant sufficient to drive the whole. It is a question whether the advantages the system offers in some very important respects will be sufficient to make it advisable to carry on the train three times the amount of machinery necessary for actually driving the train. The answer to this question depends partly on whether there is any better way, and partly on the size and character of the plant so carried. From the proceedings in the recent arbitration it was clear that in the Ganz system, as installed and tested on the Valtellina line, although half the motors are cut out after half-speed is reached, being used only for accelerating and for braking, the working qualities and efficiency were nevertheless of a high order. Again, at Zossen the step-down transformers are on the motor-cars, instead of in sub-stations.

The addition of weight in this system is serious; but its importance must not be exaggerated, for in passenger-trains weight-efficiency, *i.e.*, the ratio of paying load to dead load, is never high. Thus on the Burgdorf-Thun multiphase trains and on the Chicago continuous-current trains the dead weight is between 1,000 lbs. and 1,100 lbs. per passenger. It is stated that in saloon carriages on ordinary railways several tons of cast iron have been added per coach in order to increase stability. It may truly be objected that each train must carry a little central station of its own; but it may be better that each train should do this, and have it at all times under control, than that there should be along the whole line of railway rotary-converter or motor-generator sub-stations at frequent intervals, with the attendant expenses, and with the necessity of keeping most or all of them running, however light the traffic.

The number of transformations required with this system is not more than with the composite system. As compared with the latter, each train motor-generator is working only when the train is in service, and then under fairly efficient conditions; whereas (at least with an infrequent service) composite sub-stations are working only a small part of their time under economical conditions. Again, the maximum load which has to be met by the motor-generator is that for one train only, and is under the control of the driver; whereas a sub-station may have exceptional loads, resulting from the starting of a number of trains near it at the same time—a condition difficult to deal with.

One very important point in the single-phase alternating-current system is that it involves a much lower "maximum demand" than either the continuous-current or the composite system. As already pointed out, in the latter systems—and the same is true of the three-phase system—the maximum demand occurs at the moment of starting, when the least power is being developed in the train. The output of the generating-station, and the losses in transmission, in transformation, and in wasteful resistance, are then all greatest. Two-thirds of the power produced is lost in resistances. The single-phase system, with its variable-ratio gear, saves all this loss, or a large part of it. The travelling sub-station need not be as large for the same train as a fixed sub-station on the composite system. Whatever transforming-losses may be involved they are much less than in the latter plan, and are not greatest at the moment of least power, but are then relatively small.

If the single-phase system is capable of being applied successfully, there is no advantage in the three-phase system that is worth the extra complication. The good starting-torque of the three-phase motors disappears as an advantage, when compared with the single-phase motor-generator method. There is no substantial advantage with the three-phase system as regards the current to be carried or the amount of copper necessary. For any given power, and with the same voltage between the conductors, the three-phase requires per conductor 0.58 of the single-phase current; but as that current is in three conductors instead of in two, the ratio is 1.74 for the three-phase against 2 for single-phase. This slight reduction in the current to be carried involves at least one extra live wire. If the single-phase system were worked with a second live wire—to make the comparison complete—there would be no need for a rail- or earth-return, and any desired drop might be used. The three-phase system, however, has an undoubted advantage over the single-phase in the smaller first cost of the generators; against which has to be set the greater complication of the switch-gear, etc., required.

Large starting-torque of the single-phase motors is not necessary. Even if they should be so improved as to have a starting-torque equal to that of continuous-current motors, it is likely that a variable-ratio process would still be worth using, especially on lines with frequent stoppages.

REQUIREMENTS FOR A GENERAL SYSTEM (*continued*).

The requirements for a general system may now be further examined. Twelve conditions were stated (pp. 68 and 69) which it is essential, or at least desirable, to combine in one system. It was found that the first five of these, which relate to generating the energy and transmitting it to the train, are best complied with by the single-phase system. An examination of the remaining seven conditions leads to a similar conclusion. Taking these in order, they are as follows:—

(6) The overhead distributing-system should be able to serve trains having different kinds of motors and different methods of controlling or working them. The single-phase motor-generator system enables any method of driving to be used on the train. Ordinary 500-volt motors may be arranged as desired, with the advantage, however, that energy need not be wasted in resistances. Or a three-phase generator may be used, supplying three-phase motors on the ordinary or on the “cascade” plan. Interchangeability of traffic between different systems may be secured by suitably varying the kind of motor and of generator which form the connecting link between the distributing-system and the train-equipment.

(7) The condition that a high acceleration must be possible when starting the train is fully met in the single-phase system. The maximum torque that can be exerted by any continuous-current (or other) motors is obtainable under this system with a minimum call on the generating-station and on the transmission-plant.

(8) On a falling gradient, or when stopping, the kinetic energy of the train can be returned to the line as already described, at any speed and very simply.

(9) As regards varying the speed within wide ranges, it is possible to have the full range of speed that is obtained in ordinary continuous-current working, and in addition it is possible to raise the voltage of the dynamo, and consequently the speed of the motors. With separately-excited motors it is possible to vary the excitation, and so to regulate the speed even more easily than can be done with the ordinary series motor. The system does not impose the limits of a synchronous speed, which are imposed with three-phase train-motors. By having a higher periodicity for express lines, a still greater range of speed may be obtained.

(10) A variable-ratio arrangement for starting, for speed-regulation, and for returning energy is provided in a very complete way.

(11) As an ordinary continuous-current supply is given by the motor-generator, any continuous-current system of using motors on the locomotive or distributed throughout the train can be used. Series-parallel coupling of the motors could be used or not, as found best. In any case the controller would be simple, as no resistances would be required.

(12) The trying condition that the train-equipment should admit not only of unlimited extension for different speeds, but also of modification for different distributing-systems, is impossible of fulfilment with any existing plan; but it will be recognized that with the single-phase system the use of motor-generators on the train opens up many possibilities and removes many difficulties which now stand in the way of interchange of traffic between lines with different systems. The motor-generator forms a connecting link between the distributing-system along the line and the electrical equipment of the train; and this link can be varied to suit any conditions. It enables the best method of transmission and distribution to be combined with the best system of train-equipment. Should one main line adopt continuous-current motors on its cars, with a single-phase distribution, the motor-generator as described above could be adopted. Should it be wished to run such a train over another line having a three-phase overhead distribution, it would be possible to use the same equipment, taking energy from one phase only: or a tender might be attached to the train with a motor-generator, consisting of a three-phase motor and a continuous-current generator. This tender would be fitted with proper collecting-trolleys for the two or three overhead conductors. Again, should a railway company decide to adopt three-phase motors on its cars with a three-phase distributing-system, it would be possible to run these cars over a single-phase line by attaching a motor-generator consisting of a single-phase motor driving a three-phase generator. Lastly, in a multiple-unit system designed to run with single-phase distribution and with continuous-current motors on the cars, it might be convenient to attach a tender transforming from the three-phase, or other mode of distribution, to single-phase; so that the motor-generators, if placed on the different cars, would still be in use. This, no doubt, would not be so economical as if the transformation from the three-phase distribution to the continuous current taken by the motors were made in one machine. It shows, however, that

it is possible to interconnect any distributing-system with any system which may be adopted on the trains.¹

Returning to the single-phase distribution with continuous-current motors on the cars, a multiple-unit system with a motor-generator on each car can obviously be worked out, either with the ordinary series-parallel control, but with the resistances left out, or with automatic or handworked regulation of the generator-fields. A method of control could also be designed whereby car-motors would be worked in parallel from start to full speed; in which case the only regulation necessary would be by alteration of the dynamo fields, and by a switch for reversing the motors. With a motor-generator placed on each car it would probably be found quite unnecessary to control the alternating motors from the front end of the train, as these motors once started and run up to speed would take care of themselves, unless there was a failure of supply. If, however, the control at the front end of the train appeared desirable, it would be a simple matter to arrange.

Combinations of ordinary tramway and railway working may quite possibly come in the near future. With such a system as that now described, the possibility is foreseen that the cars used on the tram lines and light railways which feed the main lines may be run as separate cars at 500 volts, collecting passengers from all directions. They could then be coupled up into a train, and be run at high speed on the main line to town, the necessary motor-generator going with them only on the main line, which would be worked with a high-pressure distribution. On the train arriving at the town, the cars could again be uncoupled and be run through the town as separate cars on the ordinary tramway lines.

The single-phase system lends itself to modifications in a way that compares favourably with either the three-phase system or the continuous-current system. It may for example be applied as a three-wire system on one or two tracks, as with continuous currents. Balancers will not usually be needed, because the transformers for reducing the pressure from the high-tension mains may

¹ The single-phase method described presents little difficulty for goods yards. But if it is desired to get rid of the overhead conductors in such places continuous-current motors could be used, collecting from a track rail fed at low pressure by a motor-generator at the yard. As 500 volts is too high a pressure for live rails under such conditions, a much lower pressure, such as 100 volts, could be used with advantage. At this voltage the motors would be able to develop power enough for the slow speeds required. Such an arrangement is obviously applicable to any ordinary continuous-current working.

themselves be arranged to act as such. If, however, it is desired to balance at points between transformer-stations, static balancers—highly efficient and requiring no attention—can be used instead of less efficient rotary machines. Similar balancers may be used on the trains when necessary. Feeders of different lengths, or carrying different loads, may have their pressure suitably varied by static instead of rotary boosters. Difficulties will not be experienced such as might arise on a three-phase system having unequally loaded branches. Measurement will be simple and more accurate than with the three-phase system, and the control of circuits will be easier.

It is needless to multiply examples of possible modifications. Sufficient has been said to show that the system here advocated possesses great flexibility, and offers at least a practicable solution of the problem of a comprehensive general system of electric traction for railways.

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In Appendix III. are given brief descriptions of some of the systems of electrical traction now in use or proposed, which are illustrated by the diagrams of Plate 3.

The Paper is accompanied by twenty-one drawings, from which Plate 3 and the Figures in the text have been prepared.

APPENDIXES.

APPENDIX I.

CENTRAL LONDON RAILWAY.

Mr. G. C. Cuninghame, M. Inst. C.E., General Manager of the Central London Railway, has kindly given the Authors the following information as to some of the results of the working of that line for the three months September to November 1901.

Train-miles	303,449
Car-miles	1,980,051
Ton-miles	40,442,133
Main-station output, ¹ Board of Trade Units . .	4,113,815
Sub-station output, ¹ Board of Trade Units . .	3,833,207

From these figures are obtained the following :—

	Main Station.	Sub-Station.
Board of Trade Units per train-mile	13·55	12·63
“ “ “ “ car- “	2·077	1·936
“ “ “ “ ton- “	0·102	0·095

According to these figures a surprisingly high efficiency is attained, viz., 93 per cent. of the main-station output is turned out by the sub-stations.

As will be seen by reference to *Fig. 4*, such a result is possible only if the sub-stations work at full load or more than full load during all the working-time. This result shows a total loss in transmission and transformation of about 7 per cent., which does not include any loss after the energy leaves the sub-station.

APPENDIX II.

CENTRAL LONDON RAILWAY AND CITY AND SOUTH LONDON RAILWAY.

The accounts for the half-year ending 31 December, 1901, show :—

	Central London Railway.	City and South London Railway.
Number of passengers carried .	20,802,650	7,008,842 ²
Gross revenue	£168,359 0s. 4d.	£62,601 4s. 8d.
Expenses	£90,544 6s. 10d.	£29,257 16s. 2d.
Ratio per cent.	53·78	46·74
Passenger receipts	£162,816 19s. 7d.	£57,547 12s. 2d. ²
Average fare	1·8785d.	1·971d. ²

¹ Since the Paper was written the Authors have been informed that the output figures include power used for lifts and for the lighting of trains, stations and tunnels; in fact, all the power used. Therefore the units per train-mile, etc., include all the energy used, outside of the power-house, for the working of the railway.—*July, 1902.*

² Season tickets excluded.

If the Central London Railway had received the same average fare as the City and South London Railway, its receipts would have been £8,017 more, and the ratio would have been 51·33 per cent. instead of 53·78 per cent. As the average fare per passenger is nearly equal on the two lines, a comparison has been made on the basis of cost per passenger. To enable this to be done, the season-ticket receipts of the City and South London Railway have been taken at the rate of 1·971d., equivalent to 266,300 passengers, and making the total 7,275,142.

Cost per Passenger.

	Central London Railway.	City and South London Railway.
	Pence.	Pence.
Maintenance of way, works and stations	0·048	0·037
Locomotive and generating power	0·377	0·313
Repairs of carriages, etc.	0·056	0·036
Traffic expenses	0·401	0·428
General charges	0·075	0·079
Law charges and compensation	0·013	0·002
Rates and taxes	0·070	0·064
Government duty	0·005	0·006
	1·045	0·965

The train-miles and passengers per train-mile are as follows:—

	Train-miles.	Passengers per Train-mile.
Central London Railway	614,517	33·87
City and South London Railway	495,106	14·7

The mileage of the Central London Railway is 6·43; the City and South London Railway at the beginning of the half-year had 4·75 miles open; but since the 17th November 6·01, or a mean of about 5 miles.

APPENDIX III.

Plate 3 shows diagrammatically the connections of some of the systems that are at present in use, or proposed, and which are referred to in the Paper.

For simplicity the trolley by which the current is collected by the train or car from the distributing conductors is shown as a circle, or trolley-wheel, such as is used on tramways. In practice it might be such a trolley-wheel or a bow or slipper. The conductor by which the current is distributed to the train is indicated as if it were an overhead conductor. In practice the conductors might in some of the systems be placed near the ground-level, either between or beside the running rails. Where the return is by a conductor at or near the potential of the earth throughout its whole length, it is indicated on the diagrams as if the rails themselves were used.

The mechanical connection between the motors and the wheels of the cars is indicated diagrammatically by a belt or chain connection. In practice the connection might be carried out either in this way or by gearing, or the motor might be placed on the axle so as to drive the wheels direct.

Diagram A.—The system shown on this diagram is a continuous-current 500-volt system, in which one conductor is used to distribute power to the train or cars, each of which is fitted with a single trolley or collector. The return is by the rails or by a conductor at earth potential. Where the conductor is placed overhead and a single line of rails with passing-places is used, the conductor has to be doubled at the passing-place so as to allow the trolleys or collectors on the cars to pass each other.

Diagram B.—This shows a continuous-current 500-volt system with two conductors and a return by the rails. The cars are arranged exactly in the same way as in diagram A, each with one trolley or collector. The cars travelling in one direction are supplied from one conductor, and those going in the opposite direction from the other conductor. If the conductor is overhead, and a single line of rails with passing-places is used, this arrangement has the great advantage of avoiding points in the conductor at passing-places, should trolley-wheels be used for collecting the current. The same arrangement of conductors and trolleys can be used with a double set of rails, one conductor being placed over each line. Both conductors are at the same potential, about 500 volts above earth, and can therefore, where necessary, be electrically connected. This system is the one most commonly used for tramways.

Diagram C.—This shows a continuous-current 500-volt system with two overhead conductors. The conductors are connected to opposite poles of the generator, and have, therefore, the full pressure of 500 volts between them. Each car is fitted with two trolleys or collectors, the current passing to the car by one, through the motor, and returning through the second trolley to the second conductor. In this way the whole electrical system can be insulated throughout, and the rails are not used to carry any current, nor are they connected electrically to any point in the system. This system requires insulated crossings in the conductors if only one pair of conductors is used on a single line of rails with passing-places. If trolley-wheels are used, points have to be provided in the conductors, as well as insulated crossings. If slippers or bows are used for collecting the current the points are not required, but the insulated crossings must still be retained to prevent a short circuit at passing-places. With a double line of rails two conductors must be placed over each line, instead of only one as in diagram B.

Diagram D.—This shows a continuous-current 1,000-volt three-wire system with one conductor and a balancing return by the rails. Each car is fitted with a single trolley or collector as in diagrams A and B. The conductor is divided into sections. These sections are connected alternately to one or other side of the three-wire system, and have therefore the full 1,000 volts difference of potential between them. The current passes by the positive feeder to one section of conductor through the trolley, motor and car-wheel to the rails. It then passes along the rails to a car on another section of the conductor, through the wheels and motor and trolley on that car, and so to a section of the conductor which is connected to the negative feeder by which it returns to the generating-station. Should there not be the same number of cars on the two sides of the system the out-of-balance current returns by the rails to the generating-station. With a single line of rails and passing-places the conductor must be doubled as in diagram A.

Diagram E.—This shows a continuous-current 1,000-volt three-wire system with two conductors and a balancing return by the rails. The cars are exactly the same as in diagrams A, B and D, and the system of working is exactly the same as in diagram D, with the exception that as the conductor is doubled throughout no special work is required at passing-places. There is, however, a difference of potential of 1,000 volts between the two conductors. At crossings, and where

lines branch, long insulated or dead sections of conductor have to be used. This system can be used with a double line of rails, and corresponds for the three-wire system to diagram B for the two-wire system. It is perhaps the simplest arrangement possible of the three-wire system, as there is only one collector on each car and no complication at single-line passing-places. All the cars travelling in one direction are on one side of the system, and those travelling in the opposite direction on the other side, which would probably make the difficulty of balancing the two sides of the system much less than in the system shown in diagram D.

Diagram F.—This shows a continuous-current 1,000-volt three-wire system with two conductors and a balancing return by the rails. The cars are fitted with two trolleys, or collectors, as in diagram C. In general the system F corresponds for a three-wire system to diagram C for a two-wire system, but has the middle point of the system earthed. The two conductors have a pressure of 1,000 volts between them, and as each car has two collectors the full pressure has to be used for driving the motors in each car. If ordinary 500-volt motors are used, this would be done by placing two motors in series, as shown on the diagram. As long as the motors are arranged in this way it will be seen that each car has one motor connected on one side of the three-wire system, and the other motor on the opposite side. As the two motors take approximately the same current under all conditions of running, each car forms a balanced load on the three-wire system, and the only current which would pass along the rails from car to car, or back to the generating-station, would be the slight amount due to small differences in the motors or to the out-of-balance current from some car in which one of the motors had failed, and had consequently been cut out of circuit. The arrangement of conductors at passing-places is exactly the same as described in diagram C, but requires better insulation on account of the higher pressure between conductors.

Diagram G.—This shows a composite system such as is in use on the Central London Railway, and which is shown in greater detail in *Fig. 3*. The generator supplies three-phase high-tension current, which is carried by feeders to sub-stations, where it is changed to continuous current at 500 volts. Two sub-stations are shown on the diagram, that marked (a) has a step-down transformer and rotary converter, and that marked (b) has a three-phase motor driving a continuous-current generator. The system of distribution to the cars and the arrangement of the cars is exactly the same as shown in diagram A. A step-down transformer must be used at sub-station (a), as the three-phase pressure supplied to the rotary converter has to be adjusted to give the correct 500-volt continuous-current pressure at the commutator of the rotary converter. At sub-station (b) no such step-down transformer is shown, as it is possible to make the three-phase motor work at such pressures as would be used in generating and transmitting three-phase currents.

Diagram H.—This shows a complete three-phase system. The three-phase current is generated and fed at high tension to the sub-stations, where it is transformed down by static transformers to some suitable pressure for distribution to the cars by the three conductors. In this way all running machinery at the sub-station is avoided, but the system necessitates the use of alternating currents on the cars. This is the first diagram in which anything but continuous current is shown as being used on the cars. As three-phase current is supplied from the step-down transformers, three distributing conductors must be carried along the line. Two of these are shown as overhead and the third as connected to the rails. Each car has two trolleys or collectors. Car (a) is shown as fitted with a three-phase motor, as in the case of the Burgdorf-Thun

and other lines referred to in the Paper; car (b) shows two three-phase motors connected together in cascade. This is meant to represent the Ganz system as proposed for the Metropolitan and District Railways.

Diagram J.—This shows exactly the same system as in diagram H, so far as the generation and transmission to the sub-stations and transformation at the sub-stations is concerned. Three overhead conductors are shown, so that the system is entirely insulated. The car must therefore be fitted with three trolleys or collectors. The car is shown with a single three-phase motor similar to car (a) on diagram H.

Diagram K.—This shows a three-phase system in which high pressure is used in the conductors. It represents the system in use on the high-speed experimental line in Berlin, in which the power is transmitted at 10,000 volts and fed to the conductors at this pressure. Each car is fitted with three trolleys or collectors, and the current is taken into the cars at 10,000 volts. Such a car fitted with a step-down transformer and a three-phase motor is shown at (a). Both types of car that have been experimented with in Berlin have this step-down transformer, although the arrangement of it and of the motors differs in the two cars. It is possible that in the future a car such as that shown at (b) might be used, in which the full transmission- and distributing-pressure is used in the motor so as to avoid the use of a step-down transformer. In such a system the current would be generated, transmitted and distributed from the generator to the motor without any intervening transformation whatever.

Diagram L.—This shows a single-phase system with static step-down transformers at the sub-station. It corresponds for single phase with diagram H for three phase. As the rails, or a conductor at or near the earth potential, is used for the return, one overhead conductor is all that is required. Each car need, therefore, be fitted with only one trolley or collector. Car (a) is fitted with a single-phase motor driving a motor-generator such as is indicated in *Fig. 9* and described in the Paper. Car (b) is fitted with a single-phase motor, which is coupled to the driving-wheels direct. It is possible that in the future, by the improvement of single-phase motors, such a system could be used for driving the car exactly as the three-phase motors are being used at present, as shown on diagrams H and J.

Diagram M.—This shows a single-phase system, generating, transmitting and distributing at high tension without any transformation at sub-stations. It shows for single-phase current the system corresponding to diagram K for three-phase. Each car would be fitted with a single trolley or collector. Car (a) is fitted with a step-down transformer and a motor-generator. It corresponds to car (a) in diagram L, with the addition of the step-down transformer. Car (b) is driven by a single-phase motor, but the step-down transformer is retained to reduce the pressure to one suitable for the motor. This car corresponds for single phase to the experimental three-phase cars on the high-speed railway shown at (a) in diagram K. The car (c) shows a single-phase motor taking high-tension current direct from the conductor without any transformation between the single-phase generator and the single-phase motor. It corresponds for single phase to car (b) on diagram K for three-phase.

If a single-phase motor can be developed in the future suitable for driving a car direct, the final stage reached would be the simplest system possible and would correspond exactly with the system at present nearly universally used on 500-volt tramway systems; that is to say, the current would be generated and transmitted to the motor without any intervening transformation and by the use of only one overhead conductor. The car would be fitted with a single trolley or collector and the current would pass directly from it to the motor and back by

the rails or an insulated conductor at or near earth potential. It will be seen at once that car (c) in diagram M corresponds exactly with the car in diagram A. The difference is, however, that instead of having to work with continuous current at low pressure in the overhead conductor the current is generated as a single-phase high-tension current, and could therefore be economically and easily transmitted and distributed over long lines. The motor would be worked at high tension instead of at low tension, which is possible with a single-phase motor as the whole circuit through which the high-tension current passes is stationary and completely enclosed and insulated, and there is no commutator or other exposed live connections or parts. The fact that high tension can be used enables such a system to be adopted for the working of long lines and with a car essentially the same as is at present in use on tramways. Such a system depends on the development of the single-phase motor, but if it can be shown that there is a real use for such a motor there is no doubt that it will be developed very rapidly, and probably before long be quite as good a motor as is the present high-tension three-phase motor.

CONTINUOUS CURRENT AT 500 VOLTS. ONE TROLLEY; ONE CONDUCTOR; RAIL RETURN.

CONTINUOUS CURRENT, 1000-VOLT, THREE-WIRE SYSTEM. ONE TROLLEY; ONE CONDUCTOR, RAIL RETURN.

CONTINUOUS CURRENT AT 500 VOLTS. ONE TROLLEY; TWO CONDUCTORS; RAIL RETURN.

CONTINUOUS CURRENT, 1000-VOLT, THREE-WIRE SYSTEM. ONE TROLLEY; TWO CONDUCTORS; RAIL RETURN.

CONTINUOUS CURRENT AT 500 VOLTS. TWO TROLLEYS; TWO CONDUCTORS.

CONTINUOUS CURRENT, 1000-VOLT, THREE-WIRE SYSTEM. TWO TROLLEYS; TWO CONDUCTORS; RAIL RETURN.