

## DISCUSSION ON "DIFFERENT METHODS AND SYSTEMS OF USING ALTERNATING CURRENT IN ELECTRIC RAILWAY MOTORS."

MR. STEINMETZ: The problem which we have before us here for discussion—the problem of the direct application of alternating currents to electric railways—is not a new one, but it has become of primary importance and interest in the last few years. The early pioneers in electric railroading, 10 or 15 years ago, started the development of the alternating-current railway motor, and prominently among them may be mentioned Mr. R. Eickemeyer and Mr. Vandepoele, who designed alternating motors for railway purposes and investigated their characteristics. However, very little progress was made in this field for many years, for a number of reasons; one being that in those early days frequencies of 125 to 130 cycles were customary, far higher than we are using now, and the difficulties of the problem were thereby increased so formidably that advance was necessarily very slow. In addition, the very rapid development of the direct-current railway motor fully occupied the attention of all electrical engineers, and therefore the less urgent field of the alternating-current motor was necessarily somewhat sidetracked. Then the alternating-current polyphase induction motor came into the foreground, showed its superiority over other types of motors for stationary work, and impressed the engineers to such an extent that for a long time it overshadowed the work done by the early investigators on the variable-speed alternating-current motor; that is, on motors with series characteristic. Attempts then were made to introduce this very successful polyphase induction motor into electric railway work, attempts which have not been successful to any great extent. In the meantime, in the United States the synchronous converter was developed and became a standard piece of apparatus familiar to everybody—standard as much as the direct-current generator and the alternating-current generator; and experience with such synchronous converters shows that for electric railway work, for the violently fluctuating loads on the railway system, the synchronous converter is superior even to the direct-current generator: the absence of armature reaction, the phase control of pressure feasible in the converter, and corresponding close pressure regulation, make it specially able to withstand and take care of very violent fluctuations of load and to carry overloads which no direct-current generator can carry. This apparatus became standard, and with its introduction the field of the direct-current railway motor could—the distances which could be covered by the direct-current railway—was extended practically without limit, and a field opened which has been exploited in the last years, which was the field dreamed of by the early pioneers; the difficulties, however, being overcome, not by the development of the alternating-current motor, but by the development of methods of transmitting alternating currents and transforming

them into direct currents along the routes, in synchronous converter sub-stations.

Now, however, in the last year or two, with the still further development of the electric railroad, we have approached and in many instances reached the limits of applicability of this synchronous converter. The synchronous converter is a piece of machinery which requires sub-stations, requires some attendance, and as a necessary result has a high economical efficiency only where the traffic is sufficiently condensed to warrant the maintenance of sub-stations within relatively short distances from each other. Where the number of trains is less or the power per train greater than can be supplied at 500 volts from sub-stations, without excessive expenditure in line conductors, and too excessive fluctuations of load, pressures are required higher than can be utilized efficiently in direct-current motors, and there we strike the limit of the synchronous converter, and the alternating-current motor has to come in.

Personally the speaker does not believe that the alternating-current motor will make very serious inroads in the field now occupied by the direct-current railway motor. Nor does he believe that direct-current railway systems will be changed into alternating-current railway systems; but what he expects of the alternating-current railway motor is that it will find a field of its own, a new field: just as when the alternating-current method of distribution was developed in this country, it did not displace the direct-current method of distribution which occupied the centers of our large cities, but it found a field of its own, a field which has gradually developed so as to be equal in importance if not superior to the field occupied by the direct current. Hence, to conclude these remarks, what the speaker expects of the alternating-current railway motor is that it will find and develop a field of its own, that field which the direct-current railway motor cannot reach—suburban and interurban service, long-distance service, secondary railway service.

When considering the technical aspect of the subject before us for discussion to-day, the relative advantages and disadvantages of the direct- and alternating-current railway motors, we have to consider, first, the character of the problem we have to meet in electric propulsion; secondly, the character of the apparatus which we have available to solve these problems; thirdly, the additional features imposed upon the problem, or conditions more or less outside of the problem, as, for instance, the condition of the electrical industry at present, the existing investment in direct current and in steam railroads, which have to be taken into consideration when discussing any new system of railway propulsion.

Regarding the characteristics of the different types of motors—the direct-current series motor now in universal use for railroad work, the polyphase induction motor proposed, and, to a certain extent tried in the last years for railway work, a

motor eminently successful in stationary work—and the alternating-current single-phase railway motor with commutator, the speaker has, in a paper before the International Electrical Congress, given the results of a theoretical investigation and discussion of these different motors and shown the speed-torque curves, or characteristic curves of these motors in relation to each other. In Fig. 1 is given a comparison of the typical speed-torque curves of the different types of motors.

In general, the characteristic of the polyphase induction motor is essentially that of a constant-speed motor, with shunt-motor characteristics; that is, it can efficiently operate over a certain limited range of speed only, cannot exceed the synchronous speed, and when operating below its normal speed, it operates less efficiently; that is, when operating at a lower speed than normal, or approximately synchronous, as can be done by a rheostat in the secondary circuit, the polyphase induction motor merely wastes that part of the power corresponding to the difference between its actual speed and synchronous speed. Or in other words, at low speed the induction motor consumes the same power which it consumes with the same torque at full speed, though its power output is reduced in proportion to the speed, and its efficiency correspondingly.

In the direct-current series motor the torque developed by the motor decreases with increase of speed, and inversely with increasing load the speed of the motor decreases. The maximum torque of such a motor occurs in starting. All variable-speed commutator motors, alternating and direct, more or less differ from each other in the rate at which the torque varies with the speed, and that brings us to a consideration of the requirements of electric propulsion.

Important classes of work to which an electric motor may be put in locomotion are: first, city railway or tram-car work; secondly, rapid transit service as on elevated and underground roads; thirdly, suburban and interurban service; fourthly, trunk line passenger service; fifthly, long-distance freight service, and sixthly, elevator service.

Now, discussing these briefly in succession. The city tram-car service is characterized by frequent stops of irregular duration, at irregular intervals. To maintain good average speed it is therefore essential that the motor should get under way after the stop as rapidly as possible; that is, have a very high starting torque and accelerating torque, and carry this high torque up to a considerable speed. Beyond this speed, then, the torque of the motor should decrease fairly rapidly down to the torque required to run on a level track, which we may assume roughly to be at twice the speed to which the high torque of acceleration should be maintained. In addition thereto, it is necessary that the motor should accelerate efficiently and that it should be able to operate efficiently at low speeds in those city districts where the general traffic is dense

and where it is not possible to run at high speeds. The characteristics of this type of motor are preeminently given by the direct-current series motor. If we assume the torque required to run on a level track as 1, probably the starting or

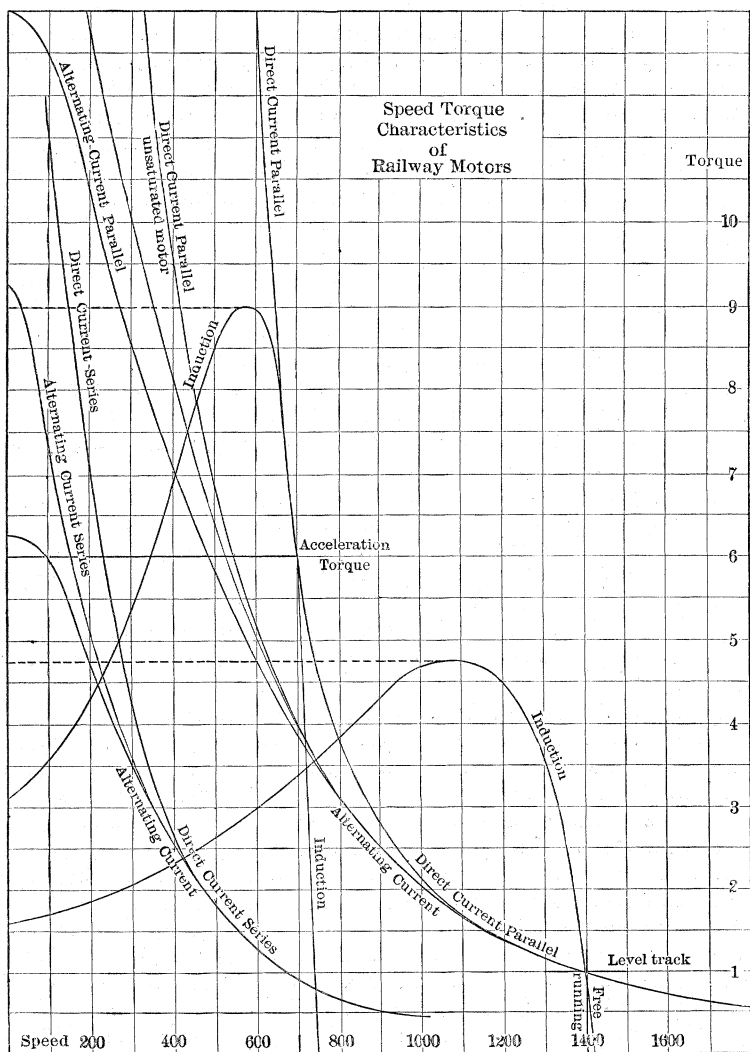


FIG. 1.

accelerating torque may be something like six times as high. At that torque we start and run up to considerable speed, and then strike what is called the *motor curve*, and after cutting out all regulating devices, accelerate with decreasing velocity

up to the free-running speed. Such a curve, that of a typical direct-current railway motor, is given in Fig. 1, marked "direct-current parallel" and "direct-current series." The induction motor, although it may accelerate with a high torque, at the end of acceleration, the speed is limited. It accelerates up to or near synchronous speed, and there the torque falls off to zero; and hence that part of the torque curve which is so essential to city tramway work, the curve of running with decreasing torque, from the limit of acceleration to the free running speed, does not exist in the induction motor. We can indeed reach the free-running speed of a direct-current motor with a polyphase induction motor by gearing it to twice the speed, making synchronism the free running speed, but this means that the available torque of acceleration, and therefore the rate of getting under way, is reduced by one-half or if we make it the same, the motor capacity is twice as great, requiring a motor twice as large. Considering that in this service a very considerable part of the running time is occupied running on approximately level track with torque very small compared with the accelerating torque, we see that the highest possible efficiency of the motor at light load is essential. Here, however, is the place where the induction motor falls down. A polyphase induction motor running at, say, one-tenth of its maximum output runs very uneconomically and with very poor power-factor. So in the polyphase induction motor, when used for railway service, you cannot combine very high acceleration with high efficiency in free running, and with the ability of running efficiently at low speeds, as you can in the direct-current series motor with series-parallel control. Therefore, the induction motor is not suitable to the class of work which we call city service or tram-car work.

The alternating-current commutator motor of which two sets of curves are shown in Fig. 1, marked "alternating-current parallel" and "alternating-current series" has characteristics very closely similar to the direct-current railway motor, except that possibly the variation of torque with the speed is less. That means, with the same decrease of speed the torque does not increase at the same rate as with the direct-current motor; if we assume again the same free running torque as 1, and the torque of acceleration six times the free-running torque, the direct-current series motor will carry the acceleration torque up to half speed; the alternating-current motor not quite as high. This means with the same maximum acceleration you will strike the motor curve at a lower speed, accelerating on the motor curve, you get under way, then, slightly slower, or to get the same average acceleration you have to start with a higher maximum acceleration. Now, this is an advantage in some cases in so far as you run for a longer period of time and over a wider range of speed on the motor curve, that is without controlling devices, hence in the most efficient manner possible, and thereby make up

to a considerable extent for that power which the alternating-current motor inherently loses by its slightly lower efficiency due to the alternating character of the magnetic field, and the losses by magnetic hysteresis in the motor field of the alternating-current motor which do not exist in the direct-current motor. This difference in the speed-torque curve of the alternating-current series motor, compared with the direct-current series motor, is due to the lower magnetic density used in the alternating-motor field, and, at low speeds, also to the e.m.f. of self-induction. The first phenomenon, therefore, also occurs in an unsaturated direct-current series motor (Fig. 1), and such a direct current series motor therefore has at high and medium speeds the same characteristic as the alternating-current motor. It is undoubtedly true that alternating-current motors can be designed to give very closely the same characteristics as the standard direct-current series motor. However, the motor as it is before us at present reaches the motor curve at a lower speed, therefore with the same maximum acceleration, gives a lower average acceleration up to full speed, or with the same average acceleration requires slightly higher maximum acceleration.

Coming now to the second class of service, rapid transit service, here the problem and the conditions of operation are almost identically the same as in city service, except that the units are larger, the speeds are higher, the stops not as frequent, absolutely, but about just as frequent relatively in comparison to the maximum speed of the motor, so that we can directly apply our considerations to rapid transit service—regarding a comparison of polyphase induction motors of alternating-current commutator motors, and of direct-current motors.

In interurban and suburban work, that is, in railroads running out from the cities far across the country into the suburbs or into other cities, we have a much lesser frequency of stops. That means that rapidity of acceleration is of lesser importance, and we can well get along with a lesser average torque of acceleration, but we must have the same surplus torque as on city service work, or rather a greater surplus torque, because, while in city service and in rapid transit service where the distances are relatively short, we can count on maintaining fairly constant pressure in the supply system, we cannot to the same extent count in this on interurban and suburban service where we are far away across the country, except by investing much greater sums in line conductors and feeders than is commonly economically desirable or feasible. Hence, in this service the motor should have a greater surplus torque than in city service, so as to get a sufficient margin to start the train or the car under the most severe conditions on an up-grade or an overload, even if the pressure in the system is low. The motor which is most sensitive to pressure variation is the polyphase induction motor. The maximum torque which this motor can

give necessarily cannot very much exceed the acceleration torque without badly spoiling the characteristics of the motor either electrically or mechanically; but the maximum torque varies with the square of the pressure and hence rapidly decreases if the pressure of the system is low. In the motors with series characteristics, however, like the single-phase commutator motor, the direct-current series motor, the torque does not depend on the pressure; or rather, while the maximum torque so depends, the theoretical maximum torque which you get from the motor when standing still is so far in excess of the torque of self-destruction, or rather of slipping the car wheels, that it is not reached, and the effect of variation in the supply pressure is merely a variation in the motor speed. That is, if the pressure is low in the system, the direct-current motor and the alternating-current commutator motor runs at lower speeds, but still is able to give the same torque, while the polyphase induction motor runs at the same speed, but is not able to give the same margin of torque, and at a certain load falls down or does not start. That means that in designing a system of transmission and distribution for alternating-current commutator motors or direct-current motors we are permitted to design the system for the average drop of pressure in the system while in designing it for induction motor service, we have to take into consideration the maximum drop of pressure in the system which is very much greater than the average.

For interurban and suburban service we require an excess overload in torque, but do not require an acceleration up to high speed. The alternating-current commutator motor appears to be preeminently satisfactory in this work, and there is where the speaker believes it will be used extensively, and where the advantage of a high-pressure trolley and of the absence of substations is specially important.

In trunk line passenger service the rate of acceleration as given at present by the steam locomotive is very much less than every-day practice in electric railroad service. So here we do not need this excess acceleration torque sustained up to high speeds. Here, again, we find a field where we may apply the alternating-current commutator motors. The polyphase induction motors could be used if the question of pressure supply did not come in, as discussed above, and if furthermore the limit in speed of the induction motor was not so objectional in passenger trunk service, where, more than anywhere else, we desire to get the full benefit of the track by running at the highest safe speeds wherever the track is level. This the induction motor with its limited speed cannot do.

In trunk line freight service, the same considerations come in, except there the speeds are relatively low, the train weights great; and it is more than anywhere essential to have a very large surplus torque available to get under way or to hold the train on a grade. You must, therefore, in this class of service,

just as in suburban and interurban service, have a motor running efficiently at light load, but being able to give very high torque, although it does not need to carry this torque up to high speeds. On the contrary, it is not desirable in freight service that the motor should sustain a high torque up to high speeds, because that would mean the consumption of very large power. In freight service the highest possible economy is especially necessary, and the highest possible economy means the least fluctuations of power consumption; that means on up-grades you would desire to go slow and reduce the power consumption and get the high speeds on the level track.

In mountain railways and such classes of work, the running torque is of the same magnitude as the starting torque, and so the load on the motor is more nearly constant than in any other class of railway work, and on the down-grade the motor is preferably used for braking, by returning power into the line. Here then the polyphase induction motor appears well suited, and is indeed being used successfully. Such service, however, is in its character more nearly akin to elevator service than to railway service.

In the discussion so far we have considered the requirements of the different classes of railway service, irrespective of extraneous conditions. When considering the alternating-current motor and the direct-current motor, we have to take in view what exists at the present time in this country and abroad. There exists the enormous network of steam railroad and of direct-current electric railways. The steam locomotive is a unit of very high efficiency, but a very large unit. It therefore for efficient operation requires the massing of traffic in heavy trains, and results in less frequent but large trains. This has practically rearranged and reorganized the whole system of locomotion by collecting it into a small number of very large units. That is not the most efficient manner of operating electrically-propelled vehicles, but rather the contrary. Furthermore, you have to consider that every city and almost every village has a direct-current railway system. Now, the main and most important features by which the electric railway motor and electric propulsion has gained and is gaining rapidly in competition with the steam locomotive, appears to the speaker to be the frequency of headway and the absence of passenger stations, not the speed, which frequently in electric lines is lower than that on steam railways paralleled by them. The electric railway picks up its passengers anywhere in the city and deposits them anywhere and it does not require them to consult time tables, but runs its cars so frequently that the passenger can always find a car within a few minutes at any point; on the other hand, the steam locomotive requires you to consult a time table and go to a depot. As soon as the electric railroad gives up this advantage which has just been mentioned, one of the main advantages of the electric

railroad over the steam railroad will be lost, and this, therefore, is the feature which has to be kept in view. It means that whatever type of motor may be adopted in interurban or suburban service, etc., it must be able to carry the passengers through the cities over existing railways.

The existing railways are direct-current railways, and probably will remain so. That means that the long-distance motor, at least the suburban and interurban motor, must be able to run over the direct-current system. Hence, it must be a type of motor equally applicable and capable of operation on a high-pressure alternating-current or on the 500 volt direct-current system.

Taking this for granted the methods of control must also be as simple as possible, that is, the same control for alternating as for direct current. Even if the motor could be used on direct current and alternating current, if we would have to carry a double system of control, one for city service and direct current, the other for long-distance service and alternating current, this would be a very serious handicap. It means that really to solve the problem before us, or extending the electric railroad into interurban and suburban service, and into the field now occupied by the steam railroad systems, and into new fields not yet developed, to a large extent not even dreamed of, that we must have a motor which with the same controlling appliances and the same characteristics, can run either on the high-pressure alternating circuits or on the existing direct-current circuits.

Furthermore, the enormous investment in electric railway systems existing at present has all been made, in the large systems, on 25-cycle, three-phase apparatus. That means that we shall have to continue to operate at 25 cycles. It may be preferable, possibly, to run at lower frequencies, or it may be preferable to run at higher frequency in this instance or that instance, but regardless of whether it is preferable or not, if it can be done on 25 cycles, it will have to be done on 25 cycles, and if another frequency had to be used, it would be a very severe handicap to the new system. The speaker is glad to say that there is no doubt that 25 cycles is the frequency best suited to the alternating-current single-phase railway motor.

PRESIDENT GRAY: Dr. Steinmetz's remarks have been so clearly stated and so closely reasoned out that they do not give us much chance for discussion, but the speaker is glad to refer to an English colleague, Professor John Perry, upon whom he calls to take part in this discussion.

PROFESSOR PERRY: The speaker has to confess that he is not prepared to take part in the discussion. We have had the address of President Arnold and this excellent address of Professor Steinmetz, and two such addresses in one morning we have never had before. Clearly, they are men who have thoroughly studied the subject of traction, and it seems to the

speaker that they have both come to the conclusion that the electrification of steam railroads in the next ten years depends on the success of the single-phase alternating-current motor. Of the progress that has been made by the General Electric Company and the Westinghouse Company, in getting such motors to work well, the speaker had heard a great deal before leaving the other side, and it is one of the things that he promised himself to learn something about during his visit here. He has not yet been able to do much in the way of getting accurate knowledge on the subject. He has been on a tram-car at Schenectady, the motor of which was driven by direct current and the car ran well; and then he would get on another car, and was told that the motor was driven by alternating current, and it seemed to run just as well. He had no means of experimenting or ascertaining what the efficiencies of the various arrangements were. Some 10 or 12 years ago he was greatly interested in the single-phase alternating-current motor, perhaps for a selfish interest, as he had invented a system of traction which required the use of that system. That interest is increasing. The speaker wanted to go to the section in which Mr. Steinmetz was giving an account of the work yesterday, but was told it was his duty to attend a discussion upon the subject of electromagnetic units in another section, and as a man cannot be in two places at once, the doing of his duty robbed him of a great pleasure. In these circumstances, he can only say that he should like to hear the discussion of this subject proceed further before he shall feel able to take any part in it.

B. G. LAMME: Away back in the dark ages of electric traction, about 15 years ago, there was great confusion in the types of apparatus used. There were all kinds of motors and all kinds of apparatus on the car. They only had one property in common—they were all direct current. After putting a number of these systems into commercial use it was discovered that certain types of apparatus were superior to others, and those particularly interested in the manufacture of such apparatus followed up this matter to ascertain what properties were of the greatest value. It was gradually discovered that one type of motor was taking precedence of all others, namely, the series motor. Practically all development for a certain time was in the direction of the direct-current series motor.

The reasons which led to this were partly based on theory and partly on practice. The series motor gave the effect of a cushion on a car. The motor is inherently a variable-speed machine and automatically varies its speed with the condition of the load. That was discovered to be a matter of first importance in the smooth operation of electric cars. Also the motor automatically increases its torque in a greater proportion than the current, which is of great importance in regard to

starting and acceleration. These points were possibly not as well understood at that time as at present, but experience showed that certain equipments were superior to others and development was along that line.

After a few years, when the motors had reached standard proportions and practically but one type was used, a second limitation was discovered; namely, in the transmission conditions. It was found that in the extension of the railway system, the ordinary 550- or 600-volt direct-current system was becoming cumbersome, and it was evident that some method of transmitting power at higher pressure and transforming to lower pressure for utilization would be necessary. The most evident method was naturally to transmit by alternating current and convert to direct current, in order to use existing car equipment. This led to the use of motor-generators, and later to synchronous converters.

The motor-generator was found to fit the existing alternating system fairly well, but in the development of the synchronous converter the manufacturers discovered a great difficulty in existing systems. The frequencies of 125 and 133, which were the standards for many plants, were entirely unsuited for synchronous converters and also not well adapted for synchronous motors. Another frequency, coming into general use, namely, 60 cycles, was found to be possible for use with synchronous converters, but the difficulties of design were very great in that case, and the synchronous converters were rather heavy and cumbersome.

At that time there was fortunately a new frequency adopted which was of prime importance in the development of the synchronous converter, namely, 25 cycles. So far as the speaker knows, the origin of that on a large scale, was as follows: in the Niagara Falls power plant, when it was first laid out, the engineers for the power company had arranged for a frequency of 2000 alternations per minute, or  $16\frac{2}{3}$  cycles per second. They wished to use 8-pole machines, running at 250 revolutions. The company which the speaker represents, which was one of the prominent bidders on the contract, objected seriously to the proposed frequency, as it was considered entirely uncommercial and also not suited for the best design of machine. The engineers of this company recommended 4000 alternations per minute or  $33\frac{1}{3}$  cycles per second. That was considered extremely low compared with anything then in use. As we could not come to any agreement to use that frequency, we finally compromised on 3000 alternations per minute, or 25 cycles per second, and the first Niagara machines were built in that way. There were various reasons for the adoption of a low frequency, one of which was that commutator type of motors might possibly come into use. Another reason was that it was better adapted to synchronous converters, but it was admitted that  $33\frac{1}{3}$  cycles would also be satisfactory.

After the Niagara Falls plant was installed, there was then a precedent for the adoption of this frequency for large units, and the manufacturers began to build apparatus of this frequency for the Niagara Falls plant and also adopted it for other plants. This opened quite a field for the synchronous converter and it soon began to be extensively used for railway work, as it was recognized that this was the link needed for extending the direct-current system. Even at the early date of 1893 and 1894 it was believed by many engineers that the synchronous converter was simply a machine to meet an emergency condition, that it would not last, that the time would come when synchronous converters would be dropped from the railway service, but as the most convenient and apparently the best solution of the problem, it was adopted extensively. About that time electric railway service began to be greatly extended and synchronous converters have thus come into very general use. By the use of synchronous converters, the advantages of the alternating-current system in transmission are obtained and the advantages of the direct-current system with the series motor were retained. Distances could be extended indefinitely by increasing the number of synchronous converter stations and raising the pressure of the alternating-current lines.

Shortly after this system came into general use it was recognized that a purely alternating-current system, in which purely alternating current was supplied to the motors, would be advantageous and considerable work was done along that line. The polyphase motor apparently had the field, and naturally the manufacturing companies took up the question of the application of the polyphase motor to traction work. The company which I represent, the Westinghouse Electric and Manufacturing Company, took up this question in an active way about 1895, and built two motors of 75 h.p. each for traction work. These motors were equipped with collector rings and rheostatic control and tests were made in regard to performance, both with straight rheostatic control and with the now well known "tandem" control, in which the secondary of one motor is connected to the primary of the other to obtain half-speed conditions. Even with this latter arrangement it was found that the motors would not compare at all favorably with the direct-current motor or the system with the direct-current system using synchronous converters, and this work was abandoned. It was recognized that the polyphase motor did not possess the proper series characteristics which long experience had shown to be so necessary for railway work. Other experiments along this line were made, using polyphase motors wound for two or more speeds, and two 100 h.p. motors were built which were wound for several speeds. While this was better than the other arrangements, it still appeared that this was not a solution of the problem. Previous to this time the company had done some work in the direction of using single phase, but not as a solution of the problem which presented itself in 1895 and later.

In 1892 the question of the use of the commutator type alternating-current motor for railway work was taken up. Two motors of nominally 10 h.p. each were designed and built. These were built for a frequency of 2000 alternations per minute, or  $16\frac{2}{3}$  cycles per second. They were mounted on a car and were operated for a while, but the system was not a success. In the first place the pressure used—400 volts as compared with 550 in the direct-current motor—was rather low. It was considered that as 550 volts was the limit in the direct-current motor, 400 volts would be the limit with alternating current. The motors were tested on a track of iron rails with practically no bonding. The track drops were excessive and the pressure fluctuations were great. The generator used—of about 20 kw. capacity—was entirely too small for this work and it was not adapted to handle the inductive loads which were found with alternating-current motors. A series of tests was run and it was finally decided that for city work, for which the system was then laid out, the motor could not compete with the direct-current motor. It was decided, however, that such a type of motor would probably furnish the solution of the heavy railroad problem, but as there was no such heavy railroad problem at that time, the work was dropped for a while. But in 1897 the question of the use of the commutator type of alternating-current motor was again taken up—this time on a somewhat larger scale. Motors of 50 h.p. were built for variable-speed work, and given a long series of tests. Then after sufficient experience had been obtained, the work was gradually carried to the larger sizes.

In 1900 and 1901, when the question of the polyphase traction in Europe was so extensively advertised, it became evident that there was actually a demand for an alternating-current railway system. It was therefore decided to continue the previous work with large motors of the commutator type, and two motors of 100 h.p. were designed and built. For these also, the frequency adopted was 2000 alternations per minute, or  $16\frac{2}{3}$  cycles per second. This fractional figure was primarily adopted on account of certain steam-engine conditions. It was recognized that an even frequency of 16 or 18 would have been practically as good.

In the earlier work, with the 10 h.p. motors at the low frequency, it was recognized that it would be absurd to put such a system on the market, as at that time even 25 cycles had not been adopted. The frequencies in common use were 50 or 60 and a drop to 16 cycles was considered prohibitive. In the latter work, as 25 cycles had come into general use, and 15 or 20 cycles had been talked of and proposed by certain companies, it was considered that in view of their advantages for railway work such frequencies should be adopted. The motors were hence built for the above frequency. The results obtained with these large motors were so satisfactory that a contract was taken for

a rather large road and the apparatus prepared. Knowing that news of this would soon be abroad, it was decided that the matter should be brought before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and a paper was presented on the 26th of September—two years ago—which the speaker believes was the first announcement of the application of the single-phase alternating current to railway motors. There was considerable discussion—mostly criticism—and it was generally considered by the engineering public that the weak point of the system was the commutation. At the present time, however, the speaker believes this is no longer considered as a serious point.

Previous to building the 100 h.p. motors considerable experience was had with the commutation of such motors. Besides a long series of tests, we had run 40 h.p. motors at practically full load on a 60-cycle system for nine months, day and night. At the end of the nine months the commutators were in practically as good condition as in the beginning, showing that the commutator on such machines could be made to have a long life. The conditions of the 60-cycle machines were much worse than on the lower frequency, and the nine months of operation under the condition of steady service probably equalled two or three years of traction service; but the commutator stood up so well that we decided definitely that there was no difficulty on that point.

The principal reasons which led to the adoption of the single-phase motor were stated in the paper above referred to, and were that but one trolley wire would be required and that the motors had the series characteristics. It was considered that no motor, except one of the commutator type, would give suitable characteristics for the service, and it was stated that there were several types of motors, with commutators, which had the proper characteristics. All of these may be classed as series motors, although some of them are combined with transformers and may be considered as transformer series motors, or, under another name, as repulsion motors, and others are pure series motors. The pure series motor is one which can operate on direct current as well as alternating current. The repulsion motor can be modified so as to operate on direct current, but as ordinarily arranged it is not as well adapted for this as the other type. It was recognized in the first undertakings with this system that the motor would probably be required to operate on direct current at times, and the fact that the pure series motor was primarily a direct-current motor of a first-class design was one of the reasons which led us toward the adoption of that type. As both theory and experience indicated that such motors would probably be wound for 200 or 250 volts, it was recognized that the motors would probably have to be operated in series for direct current, and either in series or in parallel for alternating current, as might be desired. The arrangement required for permitting operation on direct current as well as on

alternating are rather complicated, due to the fact that it is necessary to switch from one system to the other in passing from the alternating to the direct current. We did not suppose that the electrical public would consent to such a combination, but since that time we have found that in some instances they do not object seriously to the increased complication.

At the time that the alternating-current system was brought out it was considered that the principal field would be in heavy railroad work, because this motor furnished what was considered a general solution of the railway problem; as the railroads would have their own terminals and their own rights of way, the system would be an alternating-current system throughout. At the present time, however, roads are being installed which operate primarily on alternating current, but at the terminals and where they pass through intervening towns they operate on direct current.

The direct-current motor has never been considered as entirely suitable for the heavy railroad problem, as usually but two speeds, and at most but three speeds can be obtained with four motors, the third speed increasing the complication considerably. With the alternating-current motor of the commutator type any speed can be obtained for locomotive work, because any pressure can be applied to the terminals of the motor. As soon as alternating current is used for motors, we at once have a ready means of pressure transformation. As on locomotives for large capacity the difficulty of handling the current is considered a very prominent one, it was considered that some form of pressure control which varied the pressure without opening the circuit would probably be the best one. One form of pressure control permissible is what is called the induction regulator. This regulator varies the pressure without opening the circuit. The relation of the primary and secondary windings with respect to each other is varied. This gives a means of varying the pressure to the motors and varying the speed of very large motors with no tendency to sparking at the controller. The only time the circuit is opened is at the end of the operation when cutting it off. Therefore it was considered as an important feature in the solution of the general railway problem.

The single-phase system is the one means presented at the present time as the solution of the heavy railway problem. It has all the advantages of the direct-current motor in the variable-speed characteristic, and has also the advantage possessed by alternating current in the ability to use any line pressure desired, and to vary the pressure applied to the motor and thus vary the speed over any range desired. It also has the advantage of permitting a system of control that can be obtained without sparking.

In the adaptation of the alternating-current motor to direct-current service, two 250-volt motors can be connected in series

for 500 volts; also in operating on alternating current the motors can be connected in series, if desired, or in parallel. There is a possibility of danger in operating two motors in series in this way on alternating current, or even on ordinary direct current. In ordinary direct-current practice the use of two motors in series for part of the service is common practice, but there is this difference between the direct-current equipment and the alternating-current equipment. In the direct current we have motors wound normally for 500 or 600 volts. When operating in series the motors are connected, two in series, each one receiving 250 volts. Therefore, if one motor should slip its wheels and take the full pressure of the pair, it would still be operating at its normal pressure. But with two 250-volt motors connected across a 500-volt circuit, we have a different condition. In case one motor should take the entire pressure, we should have 500 volts across a 250-volt motor. That condition was considered early, and in the Washington, Baltimore, Annapolis project, a description of which was given in the AMERICAN INSTITUTE paper read two years ago, we showed an arrangement by which this could be avoided. Balancing transformers were connected across the two motors in series. The balancing transformer was across the outside terminals, and a tap from the middle of the transformer was connected between the two motors. In this way equal pressure was supplied to the two motors in series, and the danger of a runaway was thus avoided. It is not yet determined how important this is, but the speaker believes that something like this will be found advisable for the operation of motors in series, especially where high-power motors are used on medium weight cars for high-speed service. Possibly with comparatively low speed, and with very heavy cars, there may not be the same tendency to slip. On the direct-current part of the road, of course, the balancing transformer could not have any effect; but as the direct current is usually a very small part of the service, this danger would be lessened, due to the proportionate time in service.

In the application of the motor to use on both alternating and direct current, we have found some special conditions which affect the arrangement of control. Take, for instance, a large road being installed between Cincinnati and Indianapolis, where it is intended to run on direct current at the terminals and alternating current on the rest of the line. The normal speed on the alternating current part of the line is so great that it would be prohibited in the towns, and it is found that to get the speed down to the desired rate in the city service on the direct-current portion of the road, it is necessary to connect the four motors all in series, and thus no series-parallel arrangement can be used. Pure rheostatic control is therefore necessary in the city. On the suburban part, a switch is used to throw the current from direct to alternating, simply throwing the four motors in parallel, and taps are used on the lowering

transformers to get a number of pressures. In that way we get the effect of series-parallel control and even better, by having more than two steps. On a long line it is possibly of no great advantage to have many steps, but as a rule the more steps there are, the easier is the service on the controlling apparatus, and the more running speeds are available.

With regard to the application of the system to locomotives, on the steam roads where the systems are not tied up with existing electric plants, it is probable that in time the railroads will adopt their own pressures, and possibly their own frequency. This may not be 25 cycles but may be somewhat lower. The speaker believes that the electrification of the steam road may be a controlling factor in the change from direct to alternating current in city service. If the large railroads with their own large power plants adopt alternating current throughout, then the towns lying along the roads will in time probably adopt the same power system, and even the large cities will sooner or later adopt the same system. At the present time the railroads, as far as they have gone, have adopted direct current because the cities through which they pass or enter are using direct current. When the railroads make the big end of the project, however, then the cities will adopt what the railroads are using. When this comes about the direct-current railway systems in the cities will be superseded by the alternating.

C. V. DRYSDALE: At this late hour in the discussion, the speaker does not propose to take up your time very much, especially as he is afraid that very few of us over in England have had much experience concerning this important subject. The speaker should like, in the first place, to take this opportunity of congratulating you on this side of the water on having carried this important problem to such an extremely successful issue as has been recently shown in Ballston and in other places. This subject has been worked on in several countries, but to America belongs the honor of having constructed the first line of any considerable length working on the single-phase system. The way in which it has been done is admirable, when we remember that the result has been achieved by getting over the great difficulties that were first encountered with the series motor, and that in so doing it has been found practicable to use the same motive plants on direct- and alternating-current lines. That, in itself, is an enormous advantage over and above that of being able to use the single-phase alternating current.

It would be impossible to criticize any of the statements that have been made this morning, because they come from gentlemen who have had such exceedingly minute experience in the special branch of the subject, that their remarks must be taken as gospel, at any rate for the present.

The speaker's object in taking part in the discussion is rather to bring the matter back to first principles. This subject has been

worked upon in many different ways and although the laminated series motor seems to have been the first to give us results and will probably survive as a practical solution of the problem, yet there are some interesting questions as to whether there are any other ways of fulfilling the requirements which may have other advantages. There is one thing that does not seem always to be sufficiently kept in view in traction matters, in relation to the starting of the cars, and that is the very simple matter that in the starting of the car you do not require power, you require force. If you wish to get anything into motion, what you require in the first instance is purely force, and until the body moves it does not require power at all. One of the great advantages which the steam-engine has over any electrical system up to the present time, is the fact that when steam is first admitted into the cylinder you get the pressure on the back of the piston and get the starting force without taking any power from the steam. If it were not for the other disadvantages of the locomotive, there is no question that this one feature would give it a superiority over anything we have of an electrical nature, because if we turn to the ordinary direct-current motor, we find that we have to use half, or with one motor, the whole, of the full-load power merely to secure full-load torque. This has several objections. Not only is this uneconomical and wasteful of power, but it throws a sudden strain on the generating plant, and furthermore the unnecessary power has to be wasted in resistances, and these resistances sometimes attain a considerable magnitude. With alternating-current motors these evils are worse although less power is taken, as we then have low power-factors and consequently difficulties in regulation.

The time is too short to refer to many other systems, but the speaker will mention one, that known as the Ward Leonard system, which at first sight appears to be an unpromising one. In the Ward Leonard system, as the speaker understands it, the system is to use a single-phase motor coupled to a direct-current generator which supplies direct current to the car motor. Of course, the indirectness of the method seems to put it at fault, but on the continent that method has been developed with considerable hope of success, in fact with considerable practical success; and it has this great advantage that by the use of this arrangement you can get your starting effort with very small power taken from your station. In this system—it is too well known to be described here—you have your single-phase motor continuously running, and you can do the whole of the regulation of your speed, etc., by merely regulating the excitation of the generator. The result is that it is possible to get the full starting effort with only something like one-third or one-quarter of the full-load current on the motors. That is so important a matter, especially in view of the huge trains liable to be thrown on the plant in the

large schemes which we are hoping to see realized in the future, that we should give that method the consideration which it deserves, although it at first sight appears to be roundabout. In addition to that, we have the magnificent system devised by your President, Mr. Arnold, and the speaker hopes we shall hear more of that in the future. The speaker's chief object in rising was to ask that we should hear as much about these systems as possible.

PRESIDENT ARNOLD:—The speaker is pleased to be put down as one of the speakers on this subject, but Messrs. Steinmetz and Lamme have so thoroughly covered the subject, and Dr. Drysdale has so kindly referred to the other systems known to most of you, that it is not necessary to say much more, particularly as the time is growing short.

One statement by Mr. Lamme, rather puts the speaker on the defensive. The speaker understood him to state that his announcement of the single-phase motor made in September 1902 was the first announcement of a single-phase system. In the month of June preceding, the speaker read a paper on a single-phase railway, known as the Lansing, St. Johns & St. Louis Railway, which was built at that time and which has since been put in operation. The speaker does not think it is just for the statement to be placed on record just in the manner in which it was made. Perhaps Mr. Lamme meant to say that his paper was the first formal paper on the subject, but the speaker's road was built and almost ready to operate at the time that he made his announcement.

F. J. SPRAGUE: The subject on the card is how best to use the alternating current in railway motors. It is largely a technical question. The alternating current motor is like a somewhat brilliant boy, who being exposed to various diseases has contracted a number of them; he has had a moderate experience in mumps and measles, and a touch of typhoid fever, and the various doctors, many able ones here and elsewhere, have administered, sometimes in homeopathic but oftentimes in allopathic doses, large measures of quinin and other drugs. Whether, as the child grows—and we are all hopeful of that child—and he is subjected to the various climatic conditions of commercial introduction and use, those undercurrents of disease common to all fevers will recur, or whether the child will outlive them and become strong and robust is a matter which must be left to future developments.

There is a larger problem. It is perhaps a more popular one, but of vital interest to us as engineers who are called upon to advise managers and others as to their financial expenditures, and that is: will electricity be used on trunk lines? Our worthy President, with whom the speaker has the honor to be associated on some important work in that line, is very hopeful, and so is the speaker. But what are the reasons which may dictate the adoption of electricity on trunk lines?

Will it be because an economical service cannot be gotten by steam? No. Will it be because there cannot be obtained to-day an efficient service? Again, no. Will it be because of aesthetic reasons? Distinctly not. If electricity be adopted on any trunk line service it will be because of the hard and fast rule of financial necessity, not because we engineers urge it. It will be because the men who raise the money, run the road and have to provide dividends find that it is the best way to do it, and the reasons which will apply to one road are not necessarily those which will apply to another. It is the speaker's belief that some of the largest expenditures, and those most fruitful of return to those who own the steam railroads of the country to-day will be for the purchase and control of competing electric railways which, having in the past acquired franchises of undoubted value which cannot be duplicated, have built up a profitable business which they can hold and which will increase. Many a steam railway will be better off financially and get bigger returns if it gathers in these franchises and systems, and operates its whole property with proper regard to the needs and capacities of each division than by electrification of its main lines, at least for a long time to come.

ELIHU THOMSON: It is certainly a pleasure to listen to a discussion of this kind in a joint meeting of the Institution of Electrical Engineers of Great Britain and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and the members of the Congress taking part. It is gratifying to find that there is so little dissent from the statements which have been made as to the future of alternating-current traction. Many of you will recall, no doubt, that at one time the electrical profession might have been said to have been divided into two camps, the alternating-current camp and the direct-current camp. The gentleman who preceded me was probably at that time more to be found in the direct-current camp than any other. The other gentlemen who have preceded me were to be found in the alternating-current camp. It is a fact, however, and those who have visited the power stations on the circular tour have noticed that the direct-current men have called in the alternating current to help them out, and combine, therefore, the virtues of the alternating current with the virtues of the direct current.

In the early days the speaker was connected and is still connected, with an organization which had not many prejudices of one kind or another. We had direct current, we had constant current series arc lights, constant-potential direct-current systems, and when the alternating current came we were ready to take that up without prejudice, and find out what there was in it.

In 1886 we put out our original alternating-current apparatus, and finding that the necessity might perhaps arise for motors

on the system, it was at that time the speaker undertook to get a motor for that system, a self-starting alternating-current motor, and the first motor of the repulsion type was made in 1886 and finished in the fall of that year. It was a little affair and was found not to operate very well on the higher frequencies, but by connecting it to a machine, which the speaker was using for electric welding, giving 30 cycles, the speaker found it operated very well and satisfied him as to the general features of the machine. That machine, unfortunately, was sent to an exposition and lost. The Paris Exposition of 1889 had a couple of examples of machines on a little different basis. One of them, the speaker believes, is in England, at the Royal Institution, and another we have at Lynn. It was a machine which was started as a series alternating-current motor, and as soon as it reached a certain speed the commutator was short-circuited and it became an induction motor. It combined, therefore, the elements of both, but the design of such machines in those days was poor. We did not have even the distributed winding; we did not have the arrangements and the proportioning which we have to-day; nevertheless those little motors would give a half horse power for a moderate sized motor on 125 cycles, which was the highest frequency used. The speaker merely mentions these items as matters of history touching on the discussion. They have nothing to do with the discussion as to the different methods and systems of using alternating current in electric railway motors, but the speaker is a strong believer in the field being open for such work. He believes that not only will the direct-current motor maintain its place, but that certain lines of service which the direct-current motor cannot easily take will undoubtedly be taken by the alternating-current motor for railway service, and the exhibition of a system, which you have been able to see in use, and which adapts itself to the use of both currents, is certainly a very instructive one.

PRESIDENT ARNOLD: It occurs to the speaker that he may not have put his explanation in regard to Mr. Lamme's statement in just the way it should be put. The speaker thinks what he meant was that his announcement was the first of a purely single-phase commutator motor system. The speaker thinks with this correction Mr. Lamme will accept his statement. He has not sent the speaker any word, but this additional statement is due him. The speaker thinks his work was first, but Mr. Lamme got in with his announcement in September regarding the single-phase commutator motor.