DISCUSSION ON "RELATIVE COSTS AND OPERATING EFFICIENCIES OF POLYPHASE AND SINGLE-PHASE GENERATING AND TRANSMITTING SYSTEMS." (HOBART) BOSTON, MASS., FEBRUARY 21, 1912.

W. C. Smith: Mr. Hobart has given us some very interesting figures on a phase of the railway problem which has been very little touched upon. I will add a few comments from the transformer standpoint. Let us take first the step-up transformers. We have, as Mr. Hobart has shown, 48,000 kw. to transform. The development of the transformer has kept pace with that of the generator and turbine, so that there would be no difficulty in providing three-phase units to transform the 48,000 kw. in 8000, 10,000 or 12,000-kw. sizes. These transformers would be water cooled, no doubt, and would cost, as Mr. Hobart has said, about \$2.50 per kv-a. We might take 8000 kv-a. for the capacity of each unit, one transformer corresponding to each turbine, so we would have six 8000-kv-a. three-phase units. Now in the single-phase station we should probably not employ over 4000 to 5000 kv-a. transformers. It is possible to secure bids today up to 6000 kv-a. but I think we can take 4000 for the units which would be chosen for this case. Since 75 per cent power factor has been set, we would have sixteen 4000-kv-a. units, which would probably also be water cooled. The high-tension side of the transformers would be 35,000-volt on the single-phase system and 30,000-volt on the three-phase, as Mr. Hobart has pointed out. He has also mentioned a few places where the single-phase situation has been aided by neglecting certain points. I might state here another point. If we have sixteen 4000-kv-a. units it is going to take a much greater space, and the piping arrangements, etc., will be much more in amount than for the three-phase, and altogether the station would have to be enlarged to some considerable extent over that for three phase. On the other end of the line on the three-phase side, the bulk of the transformers and converters are stated in one amount of \$20 per kv-a. Probably the transformers would cost in the neighborhood of \$3.25 or \$3.50 per kv-a., depending on the size. Would we not need more substations on the d-c. line than on the single-phase line? Not being a railway man, it would appear to me that the single-phase would not need as many substations as the d-c. line. However, assuming the same number of stations, we can state that the units would be three-phase and perhaps air blast, or water cooled, depending on the local conditions. The transformers would to-day probably be called for with inherent reactance to take care of compounding the converters. Up to a few years ago it was necessary to supply external reactances for compounding converters, so that perhaps the cost could be cut down somewhat now, due to the fact that we have our compounding reactance as an inherent part of the transformer.

Going to the single-phase substations, unquestionably these should be without attendants, which means self-cooled units. Self-cooled units within the last few years have been developed so that there would be no trouble in providing transformers of 1500 to 3000 kv-a., and I think we could take about 2000 kv-a. as the size that would be ordered under present conditions. With 64,000 kv-a. to be transformed, we would have 32 units. The cost of these was taken at \$4 per kv-a. I at first considered this too high. However, on second thought, considering that the transformers are self-cooled and that it has only been by very recent developments that we have gone up to such sizes, it is probable that \$4 as compared with the \$2.50 is an approximate figure.

Mr. Hobart pointed out the fact that three-phase units are cheaper than single phase. That may be taken wrongly, and I wish to say that a three-phase unit of the same capacity will cost some 15 per cent more than a single-phase, but three single-phase units having the same aggregate capacity as one three-phase unit will probably cost 10 to 15 per cent more than one three-phase unit. Then there is the question of voltage. On the three-phase and d-c. system, we have 30,000 for the high-tension line. The secondary would be in the neighborhood of 800 to 1000, depending on whether the direct current was 1200 or 1500 volts. On the other hand the single-phase would be 11,000 in all probability. At first thought the 11,000-volt secondaries would cost more than the 1000-volt, and I believe Mr. Hobart so stated, but I doubt if the cost would be more in the large units that we are considering, like 2000 kv-a., and I believe that the 11,000-volt secondary would be perhaps 3 to 5 per cent cheaper than the lower voltage, due to the very heavy current on such large capacities. I will close with one other comment. The last point brought out in Mr. Hobart's paper refers to the development of the static converter or rectifier. I wish to point out from a transformer standpoint the fact that the employment of static rectifiers would permit the use of 60 cycles, as he has stated, rather than 25 cycles. If this is accomplished, and the rectifier is developed to a stage where it can be used for such work, and 60 cycles is adopted, I wish to point out that the transformers would be some 15 to 20 per cent cheaper than those quoted in the paper, which are 25-cycle transformers. In other words, that change in frequency will allow of 15 to 20 per cent saving in the transformers. This is a considerable item.

C. M. Green: What is the comparative efficiency of the two?

W. C. Smith: Before answering that I would like to get an idea from Mr. Hobart as to my assumption that the three-phase synchronous converter stations would be about the same capacity as the single-phase.

H. M. Hobart: It is my opinion that the greater drop in the line with alternating current, owing largely to skin effect in the rails, and the desirability from the operating standpoint, of cutting the line up into sections would make it well to have

numerous substations. I do not see why you should forego that advantage in the number of single-phase substations, even though you have 11,000 volts. The system will comprise a great many route miles and I hardly think it would be expedient for a railway with the *very dense traffic* considered in this paper, not to be able to cut up its line into as small sections as, at most, ten miles, whatever system is used.

C. M. Green: Do I understand you to mean ten miles from the station or place the station in the middle?

H. M. Hobart: I mean along the line of the railway. I think you would want to divide that up into ten mile stations anyway for a line with such heavy traffic as that with which my paper deals.

W. C. Smith: I mentioned the fact that three-phase transformers would cost less than single-phase transformers of the same aggregate capacity. It is also true that at the present time they would, probably be more efficient; so that, choosing arbitrarily the three-phase at 8000 and single phase at 4000 kv-a., the probabilities are that the efficiencies would be about the same in the two systems. I think that would amount to a small consideration.

B. A. Behrend: I have consistently refrained in the past from expressing my personal opinion on the merits or demerits of the single-phase system as such, or of any particular part of the single-phase system, as the generating station, the transformer station, the substations, locomotives, etc. Perhaps few men have been so privileged as myself in obtaining an insight into the operation and also the construction and design, as well as cost and the waste of thought, labor and money expended in single-phase electrification, as I have, but I have resisted the great temptation for the last seven years in particular and for the last twenty years in general, to air my views in public. Mr. Hobart's judicial paper, treating this subject in a manner which takes it out of the range of polemics, allows me to express my opinion without compromising myself or the large manufacturing institutions with which I used to be connected for a great many years.

First allow me to express my entire agreement with Mr. Hobart's results. I believe he has stated these very fairly as to the cost of the generating stations. I believe his statement is not quite correct that units for three-phase current generation of 15,000 or 16,000 kw. at 1500 rev. per min. represent the limit at that particular speed. I myself worked out a year and a half ago a 25,000 kw. unit which, if it should ever be built, I have not the slightest hesitation in saying would be successful, and within the conservative guarantees as to temperature rise which it is now customary to make. I believe Mr. Hobart has given us an excellent summary, and after saying this, allow me to make a few critical remarks.

My criticism first of all is this, that the paper deals with but

one-half of the problem, and unfortunately the least important half. The generating station, electric generators, transformers and the line, to my mind, are a mere bagatelle in comparison with the problem at the other end, the locomotive, etc. The problem of operating your locomotives successfully after you have built them is more important. Mr. Hobart's paper is distinctly analytic and analyzes the problem up to the critical point—the locomotive. The method of analysis is distinctly orthodox. The single-phase system has come into large use. I designed some single-phase generators in 1892, and my master designed some 22 years ago, which are still in operation. Mr. Hobart knows of one large successful single-phase power plant at Frankfort on the Main, built in 1892. We must take a heterodox view if we are to look at the single-phase system from the right angle. We must go back on the rules of standardization of the American Institute of Electrical Engineers. We must forget temperature rises as measured by thermometers. We must forget a great many things about electric generators and motors. Unless we do so, unless we turn heterodox, viewing this whole problem from a practical angle, we cannot understand the single-phase system, why it came and why it has done such wonderful good to the electrical engineering industry. I say we must become heterodox. Why? First take the generators—they are very large. Mr. Hobart is right in regard to his diagram only to some extent. Mr. Hobart shows two machines at 4000 kw. I would substitute one of 8000, which would reduce our cost a little. We should obtain a somewhat greater simplicity, which is quite essential. That is a minor matter, however, and does not enter into our argument, because the cost of the power station would be only 10 per cent greater. We must not figure in hundreds when our investment is in millions, and the money a railroad has to invest in a problem is not measured by the cost of the power house. Let your power house be twice as expensive and it will be still all right, if the operation of the locomotives and everything else were ideal; so I say we must be heterodox. We must size up the whole situation and view it not only as the power station—not important alone—or the locomotives—not important alone—but we must take the whole problem and view it as a unit. If the power house breaks down because the electric generators are not designed properly or because some important things are overlooked, very well, change it, and you may be able to obtain a successful generation of power. Let me assure you that after a great many trials and a great many mistakes one of the large corporations in this country engaged in the manufacturing of machinery, succeeded in making the New Haven road a success. I hold no brief for this company or for the New Haven road, but I do want to reiterate that the success of that single-phase power transmission from Woodlawn to Stamford has been a landmark in the engineering business.

Now the next step in the solution of the problem is how can you simplify it—how can you eliminate sources of trouble. Reliability is the whole thing. This must be capitalized—it should be expressed in figures. You cannot do it, but let me assure you that any experienced banker, in trying to form an opinion as to whether his client's funds should be placed in any enterprise, first of all looks not at the financial standing but at the personnel connected with the enterprise. It is the personnel that counts. In regard to this railroad problem, it is the reliability of your railroad, of your electrification problem, which counts in the end, and that cannot be expressed in figures.

The last pages of the paper touch a question of polemics again, the problem of single-phase railways. As I have said, I hold no brief for single-phase railways. I am expressing my opinion for what it is worth. My opinion is that the single-phase system has a field and that the d-c. system has a field; and I have held that opinion for 20 years. The essential point is that both these systems have a field, and let us acknowledge those fields. Let us have the decency to say that a system is all right under certain conditions, but is all wrong under other conditions. Let us remember that 1500 volts for railway purposes has not been tried out thoroughly. I built a number of those high voltage d-c. systems that operate today, with commutators worn fantastically—but still going and delivering current—and therefore I believe that the development of the two systems will be side by side to some extent. The single-phase system, if all the kinks are taken out, which I hope will happen in the end, will have its place. Whether it was properly applied in the case of the New Haven road I do not know. I would like to ask Mr. Hobart whether he would not be so good as to give us his own personal views of the single-phase system, taking the whole system together, for trunk line electrification? I personally do not believe I shall live to see many trunk lines operated by electricity, because it will take such an enormous amount of money that I fear it will be a long time before the railroads can make the purchasers willing to defray the expense of these electric problems.

H. M. Hobart: I do not see why we should use electricity where steam is better. I think the continuous-current system has its field, the single-phase has its field, and steam its field. Electrical transmission is appropriate where you can get a reasonable load factor. Where you cannot, there are other and more simple methods. These other methods may comprise the use of electric motors to drive the axles, and still not be electrical in the sense of transmitting electricity from a stationary generating plant to a moving train. I cannot recommend the continuous current system for all cases. It was in 1910 that I mentioned this in discussing a paper entitled "The Economics of Railway Electrification" read before the Institution of Mechanical Engineers, and which advocated the 1500-volt, continuous-electricity system for a road a hundred miles long,

with one train per hour in each direction, a stop every three miles and a scheduled speed of 33 miles per hour. In my contribution to the discussion I stated that for this road the single phase system would be cheaper than the continuous, and that *steam would be cheaper than either*. I gave quantitative calculations in support of my contention. These will be found on pages 1239 to 1245 of the *Proceedings* of the Institution of Mechanical Engineers (London), for 1910.

C. M. Green: It is my purpose to speak of one very small section of this important subject, which we have before us for discussion, and that is the replacement of the synchronous converter by the mercury arc rectifier. I have had the good fortune for the past six years to be associated with the development of the rectifier for series arc lighting up to 9000 volts, 4 amperes, and on multiple work up to 350 volts, 40 to 50 amperes. The growth of the rectifier has been phenomenal, and I consider the future brighter than the past. The reliability of service is of the first and utmost importance, and the life of rectifier tubes and their service varies all the way from absolutely nothing up to over 14,000 hours, and I should be very much disappointed if in five years from now there will not be some tubes which have run over 25,000 hours, and inside of ten years I predict that we shall have tubes in service over 30,000 hours. Seven years ago tomorrow I had the privilege of running 60 kw. (10,000 volts and 6 amperes load) of electrical energy on a single tube, 25,000 volts alternating current across the anodes of the tube. The load for the tube was very excessive, however it did not give out during the short run. Since that time I have seen very much larger currents rectified with lower voltages. I have seen tests run up as high as 1000 amperes and over 1000 volts, but not at that amperage. Frankly speaking, I expect to see the mercury arc rectifier replacing the synchronous converter for 600 and 1200-volt service for railway and other work. It of course means a considerable amount of development and patience on the part of some of the operating companies in order that this result may be accomplished. You can readily appreciate that experimentally the tests must necessarily be of comparatively short duration for the simple reason that the amount of energy required is large, and when consumed on water-barrel or resistance load it runs into dollars with great rapidity so that after comparatively short tests it will be necessary to put the apparatus out into commercial service where some use may be made of the rectified energy. This furthermore has the advantage that under these conditions the rectifier is performing useful work and the expense of operating it is almost forgotten.

A Member: About what power factor would you expect to get with a mercury arc rectifier of large capacity on the alternating-current supply?

C. M. Green: I should be very much disappointed if we could not readily obtain on a three-phase supply a power factor of at

least 95 per cent. However, the question of power factor depends very largely upon the transformer design and other constants of the rectifier, wave distortion, etc. On single-phase rectifiers for series arc lighting which requires a certain amount of reactance and resistance or impedance in the circuit for successful operation, 65 per cent is about the highest power factor which is obtainable, or an apparent efficiency of approximately 60 per cent, or an actual efficiency of from 90 to 92 per cent on 50-light sets, and above. The power factor for this apparatus is determined almost entirely by the load which it is required to operate. In other words, the situation is more or less similar to operating an arc lamp from a direct-current multiple circuit, 110 volts at terminals of lamp, about 80 volts at the arc and about 72.6 per cent efficiency. Some designs of series rectifiers give a very bad wave distortion of the primary.

Multiple rectifiers for the charging of storage batteries are also limited in a certain respect with reference to the power factor. In other words, if the apparatus is designed for too high a power factor, as the battery is charged the voltage across the terminals of the battery rises and the current falls off very rapidly; the set drops out and the service is unsatisfactory.

Rectifiers to replace synchronous converters would not, to the best of my knowledge, have any of the above limitations, and I believe apparatus could be designed to give a power factor on the alternating-current side somewhat above 95 per cent.

Dugald C. Jackson: I wish to express the interest and satisfaction which Mr. Hobart's presentation of his subject has given to me. With respect to the conclusions, I imagine that with equally reliable data equally well founded on practice, one could come to conclusions which would vary considerably from his, and yet the final result perhaps would be very little different as between the cost of delivering power at a certain point by three-phase generator with converter stations on the one hand and single-phase generator and transformers on the other hand. But when we look at the problem of electric lighting, or electric transmission of power and its distribution, or the special problem of the electrical utilization of power which comes into the railway problem, we must recognize that the question of delivering the power is not the final criterion. The question of making the power available for its purpose in the most satisfactory manner for the least reasonable expense is the final criterion, and the consequence is that while the old war of the alternating current versus the direct current which was waged with great vigor and some acrimony many years ago in the electric lighting field has recently seemed to break forth again in the electric railway field, that phase of the argument does not fairly represent the question before electrical engineers. The question is what will give us motive power for the railway, industrial power for the factory, or service for the electric light that is needed respectively, in the most satisfactory manner for the most

reasonable expense. It has long since been settled for industrial and electric lighting affairs that the direct current has many advantages and the alternating current also has many advantages—sometimes single-phase and sometimes three-phase; neither can occupy the whole field; and I am thoroughly convinced that the same thing will be worked out for the railways. I have already expressed my opinion on that matter before the Institute, especially at the 1911 convention in the discussion of similar papers.

Mr. Behrend is a pessimist in regard to his age in years; I will admit that he is an old man measured in accomplishments, but I believe he will live to see many trunk roads electrified and I therefore must take a certain amount of opposition to his standpoint. In respect to the accomplishments that have been heretofore brought about by the alternating current in the field of electrical transmission of power I can fully agree with him.

A. E. Kennelly: It is a comfort to find a paper on such a complicated subject as this without having to indulge in speculation as to what may have been in the author's mind. The old controversy of the direct versus the alternating current is still with us, and it will be a sad day when it disappears. I look forward to the continuance of that discussion with ever new delight. This particular paper is only on one aspect of it, but it is a very important and practical aspect; and I think the conclusions which are brought out here are a surprise to a great many. We shall hope that an equally strong paper may be written on the other side and we shall enjoy hearing the contest continued over that; but whatever may be said in regard to the exact figures of three-phase versus single-phase power delivered, whatever may be the exact numerical ratio in a particular case, this at least is evident; that Mr. Hobart's paper is a plea for eliminating the stray power, I mean reactive power. Here are cases where the station applies a certain amount of effective power to a track and to a railroad, but in the one case a very large amount of reactive power is supplied which is not utilized, that is in the single-phase case, whereas in the three-phase case very little stray power is generated; and this paper is really a plea for eliminating the extravagance and the incidental cost of that stray power. The discrepancies between the size of the units two to one, the size of the conductors and the size of the various elements of the conducting system are partly due to the fact that there is spare power, unutilized power, in the single-phase system. It carries around one-third for luck and for reserve, being out of use. Of course that is a certain advantage, but it is expensive in size, first cost, etc., but in addition to that there is a very large amount of power that is not being utilized. If we remember, we are all familiar with the fact that on 80 per cent power factor for every kilowatt you deliver usefully you are also generating three-fourths of a kilowatt that is not being utilized at all, and is simply filling

up the machine and utilizing the plant without being dissipated. Three quarters of a kilowatt goes into the magnetic field of the system, into the motor and other parts of the system, and is stored there for a quarter of a cycle, and then comes back in the generator. It is as though in a large steam engine there were auxiliary elements in the plant that required to be fed with a great deal of steam and its heat was dissipated and it came back again into the engine. Of course the boilers would have to supply the engine and also supply the steam necessary for this circuitous auxiliary power. The single-phasers are supplying not only the effective energy that is being utilized for driving the thrust, but they are also creating a lot of energy that is oscillating to and fro in the circuit; and this paper is an indication of the misfortune and the extravagance of that procedure. At the present time that misfortune lies with us, because we cannot bring our power factors on this kind of motor above 75 per cent, whereas with the aid of the converter and the three-phase apparatus it is possible to run nearly 100 per cent; but if this single-phase motor system should eliminate this extravagant oscillation of power which is not being utilized but acts as storage power for a hundredth part of a second, the greater part of this difference between the apparent cost and the final cost would disappear; and if we do not owe Mr. Hobart a vote of thanks for the masterly way in which he presented this subject, we certainly do owe him a vote of thanks for his dissertation upon low power factor and reactive power.

C. T. Mosman: In reading over Mr. Hobart's paper the principal thing that impressed me was the fact that he appeared to be trying to make the strongest possible case for the single-phase, whereas I had always supposed that his sympathies were the other way. There seemed to be many little items where he might have squeezed the single-phase system a little harder, but he lets it get by. The other point I want to mention is that I have heard several people comment that it would be so much better if he had continued and given us the whole story. There is one point in his paper that seemed to me rather extravagant and that was the figure of \$20,000 a mile for line construction, which I understood covered the steel tower transmission line. I cannot say that I have had experience on these things at all, but I should think that \$20,000 a mile would come pretty near covering all the construction along the right of way for the delivery of power to the cars. It would seem large enough for that. To me it seems very high for a transmission line. Another point is that 30,000 volts would seem very low in figuring out the amount of copper necessary to transmit the amount of power he is considering. I would like to have him speak a few words as to why 60,000 volts would not be a lot better and there would be saved a good deal of investment. I made just a rough estimate that it was three times too high and that you could build the line for nearer \$7,000 a mile; and I was surprised that instead

of getting 18 per cent in favor of the single-phase I got 18.5 per cent, so it did not seem to make very much difference and I was considerably disappointed. Coal at \$2 a ton struck me as being very low. I had an idea that coal in this neighborhood would cost between \$3 and \$3.50 at the fire door and my previous impression was that even near the mouth of the mine you probably could not get coal for much less than \$1.50 and perhaps a little more at the furnace door. So I would be very much interested in having Mr. Hobart say where \$2 a ton applies for first class coal. Outside of these minor points it seems to me the paper is very well taken and although this part of the discussion as applied to railways generally may be a mere bagatelle, it is the particular bagatelle that Mr. Hobart was after and he seems to have found it.

H. M. Hobart: Mr. Smith was quite right in correcting me and pointing out that there probably would not be much choice between the cost of large transformers whether supplied with 11,000-volt secondaries or with 1000-volt secondaries. High pressure does not always mean greater cost in transformer construction. An exceedingly low pressure transformer in big sizes is one of the most difficult things you can undertake. I probably did not make myself quite clear on pp. 136 and 137 in discussing the static rectifier and the advantage of 60 cycles. The case is not quite as good as it seems at first sight. As has been pointed out, there is a certain power factor loss there and you have to have your windings proportioned more liberally in consequence. Certain subsidiary windings must also be provided. Probably the transformers for static rectifiers at 60 cycles would cost nearly as much as transformers for synchronous converters at 25 cycles. If you could employ 60-cycle synchronous converters you would make a gain, because 60-cycle transformers would be lighter and cheaper, but if you substitute static rectifiers, you would introduce difficulties in power factor which offset part of the gain. But the net advantage in lower first cost and greater efficiency of the substation will nevertheless be very great.

C. M. Green: I doubt if you would go up over 5 per cent. There would still be a little advantage in the 60 cycles.

H. M. Hobart: Coming to Mr. Behrend's remarks, I did not mean to imply that 16,000 kv-a. was an utterly impracticable size for a 1500 rev. per min., 25-cycle, three-phase generator, but I intended rather to state my opinion that in the present state of the art, it would not be the best engineering to employ such generators, as they are in the developmental stage. Consequently I took 8000 kv-a. and 1500 rev. per min. as a conservative upper limit. I wanted to employ six generating sets in the station. I then pointed out that the single-phase machine if it was in one generator, would be equivalent in size to a 16,000 kv-a. three-phase machine. I should not consider it approved engineering, at the present stage

of development to employ 16,000 kv-a. generators for 1500 rev. per min.

B. A. Behrend: There are a number of 15,000-kw. 1500- rev. per min. generators in operation now, and I do not know that it would be impossible to build within reasonable temperature limits 25,000 kw. at this speed.

H. M. Hobart: Nevertheless it is not sound engineering to base comparisons on the very uppermost limits that have ever been employed. I was pleased to have Mr. Behrend refer to the great skill, ingenuity and hard work that has been put into the development of the single-phase system. I fully believe that there is a field for single-phase, but that most of the work that has been done has been misapplied effort; well meant but on the wrong track. There is a sort of fatality about the single-phase system. In several of the systems for which it has been put forward, there does not appear to be much of a case for electric transmission to the train. I fully agree with Prof. Jackson that all systems are useful, and it is just exactly that standpoint which I felt ought to be upheld as distinguished from staking everything on one system, whether single-phase, three-phase, or continuous electricity. Dr. Kennelly emphasizes the point that the bad features are not so much due to its being single-phase as due to its being 75 per cent power factor. That is where the greatest disadvantage comes in. If the power factor of the three-phase generating and transmitting plant were 75 per cent instead of unity, the showing would be nearly as unfavorable as for single-phase. Mr. Mosman spoke of the \$20,000 per mile as being too high. The transmission system would cost at least \$700,000 for a scheme of this order of magnitude. The precise cost has to be settled according to just how many substations there are and just what distance away the generating station is. This, in turn would depend on the facilities for getting coal, etc. You would so locate your generating station as to minimize these costs so long as you did not sacrifice too much advantage in some other direction. I was conservative in putting the cost of fuel low, and the over-all efficiency of the generating station high, since I therein favored the single-phase system.

W. S. Murray (by letter): I have the following commentary and inquiries to make with reference to Mr. Hobart's paper:

1. The title of this paper, "The Relative Costs and Efficiencies of Polyphase and Single-Phase Generating and Transmitting Systems," does not properly indicate either the scope or the object of the paper. The statements in the first and last paragraphs with reference to the "single-phase railway system" and the continuous current system more clearly bring out the motive of the author.

The attempt of the author to disqualify the single-phase system for railway electrification is so evident throughout the paper that all who read it must take this object for the

subject rather than the title given by the author. I consider an explanation is due from Mr. Hobart for this inconsistency.

2. Since the object of the paper is to discuss electric operation of railroads, why does Mr. Hobart stop at the substation? Note the table of efficiencies he has presented for the two systems. On the three-phase side the chain stops at the substation. Is there no line loss on the d-c. distribution system? Wireless transmissions have made great progress of late, but I doubt their practical application in such a case as this. Again, why throw in the step-up and step-down transformers on the single-phase side? Just because they are on the three-phase? Or because it balances the table, thus making four items for each table? As a practical example, they are not used in the case of the single-phase electrification of the New Haven road. Why charge up 8 per cent on line losses for the single-phase side, when, for example, our commercial experience allows a loss less than half that amount as the total average loss between generators and locomotives.

3. In the history of engineering, can any one point to the method Mr. Hobart has used to show the relation between the efficiencies of two systems—starting at the power house and working toward the railroad? I am glad he stopped at the substation, for had he arrived at the driving wheels of the train, which by the way would have something to do with the schedule, his explanations would indeed have been impossible.

Mr. Hobart starts with 160,000,000 kw-hr. per annum as the outputs of the two stations. Now it is manifestly clear that unless the efficiencies of the two systems are identical from the generators to the driving wheels of the train, if one system provides the tractive effort necessary, the other will generate either too much or not enough power, depending on whether the efficiency of the second system is respectively greater or less than the first system. A graphical example of this is as follows:

In the above figure, *A* in both systems 1 and 2 represents the output of the station. *B* represents the amount of power that must be delivered to the drivers of the trains, and thus system 1 provides the exact amount needed. System 2, having higher efficiency than system 1, not only provides enough power $C = B$ for the railroad, but has left over an amount *D* (not needed). I believe this simple diagram will make clear the error Mr. Hobart has made in starting toward the driving wheels from the power house, rather than vice-versa.

Let us reverse the direction now and work from the tractive

effort requirements to the generating station, still adhering to our simple diagram:

$B = C$ again represents the power requirements of the rail-road. Both systems supply the exact amount required, but now note the difference in output between the two stations; the A of system 2 no longer equals the A of system 1.

If, to produce an equal tractive effort, a system employing a chain of higher transmission efficiencies requires less output than another, is it fair to compare transmission efficiencies starting with equal outputs from each station? I think it is only necessary for me to point out this erroneous assumption to make clear the fact that the deductions must be equally erroneous.

Before leaving the question of transmission efficiencies, let us look at a table that has associated with it the facts of actual practise, and this time, following the plan as outlined in Fig. 2, we will trace the power requirements in the two systems from the driving wheels to the steam turbines, starting with—say 100,000,000 kw-hr. as the necessary driving-wheel power.

Three-phase d.c.		Items	Single-Phase.	
Kw-hr. per annum	Per cent efficiency		Per cent. efficiency	Kw-hr. per annum
100,000,000		Drivers.		100,000,000
116,150,000	86	Loco. motors.	84	119,050,000
		Loco. transformers.	96.7	123,150,000
120,400,000	96.7	Loco. resistances.		
132,100,000	91	D-c. line.		
141,400,000	93.5	Synchronous converters.		
145,000,000	97.5	Step-down transformers.		
149,800,000	97	High-tension a-c. line.	97	127,000,000
153,750,000	97.4	Generators.	95.8	132,700,000
		Turbines.		
		132,700,000		
		———— = 86.6 per cent.		
		153,750,000		
		153,750,000		
		———— = 1.16 per cent.		
		132,700,000		

or 16 per cent more power for the three-phase d-c. system.

Thus it is apparent that *for the same tractive effort developed in the driving wheels of the trains* the number of kilowatt-hours to be generated in the single-phase power station is 86.6 per cent of the three-phase station, or, stated in another way, the

three-phase station will have to generate 16 per cent more power than the single-phase station to accomplish the same result at the *driving wheels* of the train equipment.

Having now drawn attention to the attempt to disqualify the single-phase system by this fallacious treatment of the transmission question, I wish to point out a few isolated errors in assumption and design that Mr. Hobart has made.

Let us take a look first at Mr. Hobart's 8000-kw. machine. Now just why did he select this size? It is a rather odd one. I do not recall ever having seen this size of generator in print before, and certainly not on the floor of a power station.

By a selection of this size Mr. Hobart has admittedly and erroneously assumed it will carry him out of the environment of 1500 rev. per min. for the single-phase generator, as after he has allowed for the larger capacity made necessary by the star winding *using only two legs* and increased the copper for his 75 per cent power factor conditions, he has built the unit up until it represents in three-phase capacity a generator of 16,000 kw. Of course, had Mr. Hobart allowed his generators to retain the modest capacity of 5000 kw., then his double generator single-phase unit would not have been safe.

Notwithstanding, however, Mr. Hobart has calculated without his host, for there are other manufacturers who have built 1500-rev. per min. generators, whose three-phase capacity has been 14,000 kw., and have offered tenders on machines of 20,000 kw. capacity. Thus Mr. Hobart's double generator proposition fails. Two hundred and forty tons is indeed a weighty generator to charge up for a 16,000-kw. machine, when one of 14,000 kw. has already actually been built which weighs but 95 tons.

Before leaving the generator end of things, I am forced to draw Mr. Hobart's attention to the fact that his statements concerning steam economy at high speeds is at variance with the statements his company has advanced with reference to economies at low speeds. We will grant that two generators, each of half the capacity of one, weigh more than the one generator (and we reserve the privilege of using one), but his statements as to steam economy for the type of turbine used are contradicted by other advocates of the same type of turbine. However, it is all summed up when it can be stated as a fact that the manufacturers who have been in the business of real single-phase machinery can build *one* generator in the form of a single unit, large enough and with the same speed, to match up with Mr. Hobart's single unit three-phase machine. Let us not forget, however, that Mr. Hobart will owe us either a refutation or explanation of the low economy he applies to high economy, four-pole, 750-rev. per min. Curtis turbines. Throughout his paper in text and foot-notes we are reminded constantly that he is being liberal with the single-phase. A too great liberality might do a great injustice to the three-phase. Why not be just? Say what it is, not less or more than it is. I might say Mr. Hobart

showed, for instance, great liberality in choosing that 8000-kw. generator, as 240 tons of single-phase generator was a far too liberal supply.

Now having shown the error in proposing the double generators, let us have a look at some of Mr. Hobart's thoughts on generator design. It is evident that Mr. Hobart has had little to do with dampers—that is, field dampers. He tells us the loss in the dampers is just equal to the armature loss, and backs it up by quoting 13 kw. for the field damper of the single-phase generator and 13 kw. for the armature loss. Evidently Mr. Hobart has assumed that the damper has to neutralize the complete magnetic flux due to the armature turns. If it did, even then its loss would not be what he has stated. He evidently does not appreciate that the armature field is made up of two components, each revolving in opposite directions and of equal value. One of them is in synchronism with the rotor and is therefore not acted upon by the damper. The other component revolving in the opposite direction to the rotor flux is compensated for by the damper. Here, therefore, Mr. Hobart's figures are reduced to one half. Now let us go a step further: On account of the long armature connectors necessary to a two-pole winding, and the short connectors inherent to the squirrel cage wound damper, the proportion again is cut in half due to the resistance of the damper being in that proportion to the armature, and so Mr. Hobart's figures sink to 25 per cent of their value.

Still in the domain of machine design, let us discuss for a moment Mr. Hobart's views on regulation. He says "Incidentally the three-phase unity power factor installations will have some 6 to 8 per cent inherent regulation, whereas the inherent regulation of the single-phase 75 per cent power factor installation will be of the order of 15 per cent or worse, and will be thus so inferior as to require that some type of automatic regulators be provided."

Can it be possible at this late stage of generator design Mr. Hobart is not awake to the fact that an inherently poor regulation in a machine, which compared kilowatt for kilowatt with another of equal weight and better regulation, gives the best account of itself when measured on the scales of efficiency. The 6 per cent machine has no regulator, less kilowatt capacity and poor regulation. The 15 per cent machine has a regulator, more kilowatt capacity and perfect regulation. Thus the regulator pays for itself many times over. Besides this its inherent regulation is in marked economical contrast to the revolving mass of substation apparatus which the author recommends to buffet the short circuits of the line.

In conclusion, let us compare Mr. Hobart's hypothetical single-phase system with the actual single-phase system in operation on the New Haven road. He gives the single phase aggregate annual efficiency as 81 per cent thus involving a loss of 19 per cent. The aggregate loss between the steam turbines and the electric locomotives on the largest single-phase road in operation

is 7 per cent; thus giving an efficiency of 93 per cent. Mr. Hobart's assumed losses are, therefore, $2\frac{1}{2}$ times as great as the actual losses. Hence, there is nothing left but a choice between the theory propounded by the author in his paper and practise as we find it; which?

Edgar Knowlton (by letter): In the first part of Mr. Hobart's paper is a comparison of the weights of the three-phase 8000-kw. generator at 1500 rev. per min. and a single-phase 8000-kw. generator at 750 rev. per min. I believe that the weights of these two generators will be more nearly represented by 100 and 200 tons since this is the ratio of the three-phase ratings of the two machines and the reduction in speed will not greatly increase the weight of the single-phase machine.

A single-phase 8000-kw. 1500-rev. per min. generator is a practicable machine but, as explained above, its weight, cost, and efficiency, would vary but little from that of the same capacity machine at 750 rev. per min.

For the losses and efficiencies given a little further on I would be inclined to substitute the following:

THREE-PHASE 8000-KW., 100 PER CENT POWER FACTOR., 1500
REV. PER MIN.

Armature I^2R loss.....	25 kw.
Field " "	25 kw.
Core loss.....	115 kw.
Windage loss.....	100 kw.
Total loss.....	280 kw. (3.25 per cent)
Eff. (Excluding bearing friction).....	96.75 per cent.

THREE-PHASE 6000-KW., 80 PER CENT POWER FACTOR

Armature I^2R loss.....	25 kw.
Field " "	40 kw.
Core loss and windage (excluding bearing friction).....	215 kw.
Total loss.....	280 kw. (4.5 per cent)
Eff. (excluding bearing friction).....	95.5 per cent.

SINGLE-PHASE 4000-KW., 75 PER CENT POWER FACTOR, 1500 REV.
PER MIN.

Armature I^2R loss.....	17 kw.
Pole face winding I^2R loss.....	17 kw.
Field I^2R loss.....	33 kw.
Core and windage loss (excluding bearing friction).....	215 kw.
Total loss.....	282 kw. (6.6 per cent)
Efficiency (excluding bearing friction).....	93.4 per cent.

A comparison of the estimated losses is given in the following table:

	Estimate in the paper	Loss Estimate as above
Three-phase, 800 kw., 100 per cent power factor, 1500 rev. per min.....	2.6 per cent	3.25 per cent
Three-phase, 6000 kw., 75 per cent power factor, 1500 rev. per min.....	3.5 per cent	4.5 per cent
Single-phase, 4000 kw., 75 per cent power factor, 1500 rev. per min.....	5.2 per cent	6.6 per cent

The differences in the weights and losses, however, do not affect Mr. Hobart's conclusions as to the relative cost of the two systems.

John B. Sparks (by letter): Mr. Hobart's comparison between the cost of single-phase and three-phase current at the distant end of the transmission line is of considerable interest in view of the fact that both systems of generation and transmission are being adopted on the Continent for single-phase railways. While Mr. Hobart calculates single-phase current to be 9 per cent more costly at this point, the additional cost in the three-phase case of the rotary machinery required to transform to single-phase and the attendant losses practically balance this, so that there is little to choose between the two systems. In most cases indeed the all-single-phase proposition will be found strictly the most economical, but where the current may be used for power as well as for traction, generating and transmitting three-phase may be found most satisfactory.

Mr. Hobart's arguments as to the comparative size and cost of single-phase and three-phase generators are not very clear. A simple calculation shows that the three-phase rating of any machine is 1.73 times the single-phase rating (using two phases in series) on the basis of equal current density, or about 1.4 times on the basis of equal armature copper losses. The actual figures, however, obtained from a well-known Continental firm for four generators ranging from 2500 to 10,000 kw. single-phase output show an average three-phase rating of 30 per cent greater than the single-phase rating (the full-load efficiencies are only about 0.5 per cent greater and the regulation full-load to no-load 3 per cent less in the case of three-phase working). Assuming unity power factor for the three-phase machine and 0.75 power factor for the single-phase machine, the latter will weigh and cost, therefore, about 1.75 times as much as the three-phase machine of the same kilowatt output. It is not clear why Mr. Hobart has not taken the same transmission line pressures in the two cases; presumably the increased cost due to the higher single-phase pressure is covered by there being two instead of three insulators per pole. It would have been more economical to have taken a larger total copper section in the single-phase case.

It would be interesting if Mr. Hobart would complete his synthesis of the cost of current per unit by including the distribution costs and losses and stating the cost per unit at the trains. Continuous current at 600 to 1200 volts costs, he concludes, only 18 per cent more than single-phase current at from 6000 to 12,000 volts. The cost of the distribution and contact wire system in the latter case is very much greater than the cost of the distribution and third rail system for direct current working, and the cost per unit at the trains might consequently be even greater for single-phase current. In view, however, of the admitted higher cost of single-phase as compared with direct-current

equipments and the higher maintenance costs in the former case, any slight superiority of the single-phase system in the cost of current supplied to the trains is of little importance.

Roger T. Smith (by letter): Incidentally the figures in Mr. Hobart's paper serve to show the advantage of the purchase of electricity for railway traction purposes wherever the railway load factor is low, and indeed other things being equal (which is seldom the case) it is a great advantage to a railway company to buy its electrical energy from a supply for general purposes, where that energy is only one item tending to increase the diversity factor of the whole supply, and to pay for it, as it is used, out of revenue, rather than to be obliged to pay interest on capital invested in a generating station which may for many years be a burden on traffic returns out of all proportions to the receipts.

Before dealing with the argument it may be of interest to refer to one or two points which in themselves do not affect the argument.

Dealing with the table of substation machine load factor and "all-year" efficiency, the figures may be compared with those of a substation supplying continuous current for the Hammer-smith & City Railway forming a small item in London suburban electric railway service. The substation is equipped with La Cour motor converters and not with synchronous converters and the average power factor is never as much as 1 per cent below unity. The machines work in parallel with a battery whose input and output is controlled by automatic boosters. For 1911 the machine load factor was 63.9 per cent and the all-year efficiency 84.1 per cent including the battery and 86.6 per cent excluding the battery. Turning to the next table, the two substations supplying this railway (with only 10 miles of single track) for an annual output of 8,000,000 kw-hr. had a combined load factor of 60 per cent and cost 0.12 cents per kw-hr. for wages, oil and stores. Surely the machine load factor as defined for substation performance, is the correct load factor to use for generating station as well as substation performance. The rated output is the continuous capacity of the station and the percentage of this obtained during the hours the machines actually run alone tells the station engineer if his plant is used in the most economical way. Skilful management can increase the machine load factor while the maximum-power load factor may remain nearly stationary.

A small generating station belonging to the Great Western Railway, equipped with reciprocating engines, supplies the two substations, of which one has already been referred to, with three-phase current. It has an output of 10,000,000 kw-hr. for traction only, yet it may be interesting to give the figures corresponding to note (9) of Mr. Hobart's paper. During 1911 the average B.t.u. of the coal used was 11,900, *i.e.*, the calorific value is 3.46 kw-hr. per lb. This for 100 per cent efficiency

between furnace and feeders corresponds to 0.288 lb. per kw-hr. but the actual thermal efficiency was 7.9 per cent. Comparing this generating station with that referred to in the note for the West Jersey & Seashore Railway the results for 1911 for coal of 11,900 B.t.u. are as follows:

Year	Output, traction and lighting, in million kw-hr.	Lb. of coal per kw-hr. output	Overall efficiency per cent
1911	11.8	3.65	7.9

Coming to the argument itself regarding the efficiency, from the steam turbine to the distribution system, of three-phase continuous current supply as compared with single-phase supply, the actual advantage of one over the other depends wholly on the single-phase power factor assumed. Mr. Hobart has taken this average power factor at 0.75, and while any figure given must be accepted with caution (since in the United Kingdom charges are always based on kilowatt-hours so that kilowatt-ampere hours are not metered) I think for British railways 0.75 may be unnecessarily low. There are only two single-phase railways in the United Kingdom, the Heysham-Morecambe line of the Midland Railway and the South London Suburban lines of the London, Brighton & South Coast Railway.

For the Heysham line, with an intermittent service of about twelve trains each way per day, average results are of no use since when no trains are running and the line is only charged there is a leading current. The tendency of this charging current is to raise the power factor, but the inductance of the line outweighing its capacity, the general effect of the line when trains are running is to lower the power factor. On the official trial runs the power factor of the low tension energy during a set of tests giving maximum acceleration (closely corresponding to suburban running) was 87 per cent and during a set of non-stop runs between Morecambe and Heysham (with a large percentage of coasting) the power factor was 86 per cent. Both figures will be reduced at the generating station by the inductance of step-down transformers on the train and by the line, but these were not measured. On the Brighton Railway the power factor during trial runs works out as 80 per cent but the average power factor of the generating station has not been measured. From these two results, one during the test of a service on the Midland electrified system imitating suburban traffic and the other during the test of a typical London suburban service, it would seem that Mr. Hobart's estimate of average power factor may be too low. The figure of 0.75 is to be accepted with caution and there is every probability that in some actual railways it is exceeded, while means for improving the power-factor of the whole supply are not beyond the power of the electrical engineer.

Perhaps the most interesting part of the paper is the general

conclusion, where the combined use of both three-phase-continuous current and single-phase current are advocated to deal with different classes of traffic—a view first publicly advanced as far as Mr. Hobart is concerned in his Royal Engineers' lecture at Chatham in 1909.

Mr. Aspinall's statement made before the Institution of Civil Engineers and quoted by Mr. Hobart puts the matter very clearly, and it may be said that there are very few railways in Great Britain and Ireland possessing a suburban service of sufficient importance to warrant electrification, in which the stopping trains do not run over roads kept entirely separate from those used by the long distance traffic. If this is not the case for the whole of the suburban traffic it certainly is so in the majority of cases. For instance the London & North Western Railway has under consideration the electrification of some 80 miles (single track) of suburban road. This is entirely distinct from its main line although the Euston and Watford electric line will run for many miles beside its main line. The system on which the company must electrify its suburban railways is settled for it by the fact that the rolling stock must run over sections already electrified on the third and fourth rail continuous current system, but it is difficult to see what possible difference this could make to the use of any other system of electrification it may choose to use on its main line should the time ever come for it to be electrified.

On the other hand there are English railways where the suburban system forms such a large portion of the whole system and is so intimately interwoven with the main line that two systems would be bad engineering. The Brighton Railway is such a case and it has chosen one system to suit all conditions.

H. M. Hobart: The plan adopted by Mr. Murray, of carrying out the tabular comparison in his discussion, is of interest and I am of the opinion that, by suitably modifying and extending the conception, instructive results may be obtained. I propose to illustrate by an example the method by which we may, in any given case, establish a comparison of the power required at the generating stations for each of the two systems under discussion.

A hypothetical railway's rolling stock comprises the equivalent of 70 trains, each train consisting of five 60-seat passenger cars, or a total of 300 seats per train.

Let the *average* service provide a schedule speed of 25 miles per hour, and let the average distance between stops be one mile. If the average duration of each stop is 20 seconds, then, since there will be 25 stops per hour, the average speed from start to stop will be

$$\frac{3600}{3600 - 25 \times 20} \times 25.0 = 29.0 \text{ miles per hour.}$$

For good rolling stock operated over a well-constructed straight and level track, the energy required at the axles may be estimated from the formula

$$\text{Watt-hours per ton-mile} = 0.074 \times \frac{S^2}{D}$$

where S = average speed from start to stop, in miles per hour ($= 29.0$)

D = average distance between stops in miles ($= 1.00$)

Thus we have:

Energy required *at axles* $= 0.074 \times \frac{29^2}{1.00} = 62$ watt-hr. per ton mile.

For such a service the overall efficiency of the electrical equipment on the train will be about 70 per cent, irrespective of whether continuous-electricity apparatus or single-phase apparatus is employed. Consequently the input *to the train* will be

$$\frac{62}{0.70} = 89 \text{ watt-hr. per ton mile.}$$

This value corresponds to the condition of test runs made with well-designed and well-constructed rolling stock over well-built straight and level track in calm weather. The conditions of actual practice may be assumed, in this hypothetical case, to increase the consumption of the train up to the gross average of 115 watt-hr. per ton mile and this value may be considered as being sufficiently liberal to allow for non-productive train movements. By methods¹ known to be correct, it can be estimated that the weight of such a 300-seat train will be:

210 American tons when the motive power is supplied by continuous-current train equipment.

270 American tons when the motive power is supplied by single-phase train equipment.

Consequently for the consumption per train we have

$210 \times 0.115 = 24.2$ kw-hr. per train mile for the trains equipped with continuous-current apparatus and

$270 \times 0.115 = 31.0$ kw-hr. per train mile for the trains equipped with single-phase apparatus.

Let the requirements of the service be such as to call for 50,000 miles per train per annum for each of the 70 trains. Then the total annual consumption at the trains amounts to

$70 \times 50,000 \times 24.2 = 85,000,000$ kw-hr. for the continuous current trains and

$70 \times 50,000 \times 31.0 = 108,000,000$ kw-hr. for the single-phase trains.

We may throw these results into a tabulated form similar to that preferred by Mr. Murray and may complete the calculations in the way he has outlined. This is done herewith.

¹These methods are explained in the author's treatise entitled "Electric Trains" and were employed and discussed at the July 1910 meeting of the Institution of Mechanical Engineers in London. Considerations of space render it inexpedient to set forth here the steps in the estimation of these train weights.

Three-phase, synchronous substation system. (Generator pressure = 11,000 volts)			Single-phase system without transformers except on train (Gen. pressure = 11,000, volts)	
Kw-hr. per annum	Per cent efficiency	Items	Per cent efficiency	Kw-hr. per annum
59,500,000	—	Drivers	—	75,500,000
85,000,000	70.0	Train equipments	70.0	108,000,000
88,500,000	96.0	Circuits from substations	—	—
97,200,000	91.0	Substations	—	—
102,000,000	95.5	High-pressure line	89.4	121,000,000
105,000,000	97.4	Generators	94.8	127,500,000

Since $\frac{127,500,000}{105,000,000} = 1.21$ we see that for the single-phase system

21 per cent more energy is required to be provided annually by the steam turbines in the generating station.

Thus for supplying the needs of the stipulated passenger service, 21 per cent more energy must be delivered annually from the power house turbines when the single-phase system is employed than when the three-phase system with synchronous substations is employed.

I am aware that the percentage at which I have arrived applies exclusively to the particular assumptions and service relating to the hypothetical case which I have studied. For a more sparse passenger service with greater average distance between stops, and for freight service the results will be less unfavorable to the single-phase system, but there is a big margin to be overcome before the 21-per cent. greater amount of energy required by the single-phase system is wiped out. I have not dealt with the far greater *capital outlay* required for single-phase rolling stock, as Mr. Murray does not mention the question of the relative capital costs of rolling stock for the two systems. Mr. Murray is wrong in employing efficiency as a criterion of merit. It is necessary to also consider the capital outlay by which that efficiency has been attained. Mr. Murray gives the efficiency of the high pressure line on the New Haven road as being 97 per cent. Obviously by trebling the outlay for line copper he could increase this efficiency to 99 per cent. But it would not be true economy to do so. The highest economy might correspond to half as much line copper, even though the efficiency is thereby decreased to 94 per cent. Presumably 97 per cent was the right value to adopt for the case he had in hand but it has no bearing whatsoever on the appropriateness or otherwise, of the line efficiencies adopted in my estimates.

In the above tabulated comparison I have left out the step-up transformers, to bring the comparison into conformity with Mr.

Murray's preferences, but it is obvious that this policy will, on extensive systems, mean resorting to several smaller generating stations instead of a very few large ones, thus involving lower load factors and also requiring the location of the generating stations at other than the most favorable sites and thus decreasing their commercial economy. I have taken the three-phase transmission line's efficiency at 95.5 per cent, the value taken in my paper, but instead of taking the single-phase line at the efficiency of 92.0 per cent which corresponds to a 15 per cent higher transmission pressure as explained in foot-note 10 of my paper, I have reduced it to 89.4 per cent the value which, as I explain in that foot-note, corresponds to the same outlay for copper as for the three-phase line and the same generator pressure of 11,000 volts. This change is also necessitated by Mr. Murray's preferences for eliminating step-up transformers.

Mr. Murray may take exception to my plan of basing my calculations upon the requirements of a single class of passenger service, but I would ask him to observe that corresponding calculations can be made for any other class of train service and that the case I have taken represents an exceedingly important one. I frankly admit that for a sparse long distance passenger service with infrequent stops, and for freight service, the case will not be so desperate a one for the single-phase system. For such a system as the New Haven, where several classes of rolling stock will be operated electrically, each class can be analyzed in accordance with the plan I have illustrated, and the aggregate taken for the road's entire equipment. For cases where the single-phase system shows up to be the most economical when both capital and operating costs are taken into consideration, that system should obviously be the one put forward. My own personal opinion is, however, that such cases will be rare. I have stated in the paper that I am of the opinion that engineers have greatly magnified any difficulties associated with the use of both systems, each dealing with its appropriate class of rolling stock. This is also, as stated in my paper, the view of Mr. J. A. F. Aspinall, general manager of the Lancashire and Yorkshire Railway, and, also as we find in this discussion, a close approximation to the view of Mr. Roger T. Smith, chief electrical engineer of the Great Western Railway. Both of these gentlemen have been responsible for many years for extensive electrified sections of main-line railway and each dissents strongly from the view that there is usually any need for using other than the most appropriate system for each class of traffic.

As regards the rest of Mr. Murray's criticisms of my paper—they are chiefly directed to suggesting that I have painted too lurid a picture of the conditions in three-phase generators when employed for providing a supply of single-phase electricity direct to railways without the interposition of substation machinery. My answer is to quote from the 1911 A.I.E.E. TRANSACTIONS, Vol. XXX, p. 1511, Mr. B. G.

Lamme's description of the single-phase generators as finally modified to withstand the conditions of operation on Mr. Murray's road.

Mr. Lamme states:

" There is one feature in connection with the generating plant which has not had its full significance brought out before. I refer to the use of 11,000-volt machines with one terminal grounded. These generators have three-phase armature windings of the star type with one of the three terminals permanently grounded. Two of the legs of the star are used for the single-phase circuit, while the third leg is used in connection with certain three-phase work. Across the railway phase the potential is regulated for 11,000 volts normal, by means of an automatic regulator in connection with the fields of the generator. The third leg gives a little higher voltage normally, due to the small load which it carries at present. In consequence, its voltage is usually somewhere between 11,000 and 12,000 volts. Assuming this at 11,000 volts, then in these machines we have an equivalent, as far as insulation stresses go, of a three-phase generator with grounded neutral *with 11,000 volts between the neutral and the terminals*. This therefore is practically the equivalent of a *19,000-volt three-phase generator with the neutral grounded*. It is more than this, as it is the equivalent of a 19,000-volt machine with the neutral grounded and *with the terminals tied directly to 100 miles of 11,000-volt overhead system without the interposition of transformers*. This is a very abnormal condition compared with anything that is being done in this country at present. 16,500 volts is the highest generator now used on a large scale, as far as I know. But here we are actually running under conditions corresponding to 19,000 volts with the hardest kind of service and with an overhead line without transformers which is going to be extended to about 500 miles. Under these conditions the generating plant has made an extremely good record, as indicated by Mr. Murray in his table of delays due to power house. I may say that for about two years, or possibly more, there has been practically no trouble as far as the generators are concerned; that is, any trouble which would shut down the system. There has been one breakdown in one machine, but a careful examination of this one case developed no cause for the breakdown other than a damage to the insulation in originally putting the coil on the machine. There were no signs of deterioration of the insulation, and the insulating materials on the damaged coil appeared to be as sound and flexible as when first put on. So here we are running machines *at the equivalent of 19,000 volts on a three-phase system*, and during two years there has been continuous service. This is a most excellent record. If we compare this with a late practice, now being advocated here and there, of winding large turbo generators for low voltage, such as 2200 volts, and then stepping up to voltages, even as low as 6600 volts, we can see what a *wonderful thing* this New Haven operation is. In some cases at the present time, 11,000 volts, or even 6600 volts on the generator is being condemned as bad practice because of dangers from line voltage, surges, lightning and such things, but in this New Haven plant there are 100 miles of overhead system under conditions where it is exposed to surges of the worst sort."

In the above extract Mr. Lamme portrays far more vividly

than I have done in my paper, various features in which single-phase generators supplying electricity direct to the trains are more elaborate, heavy and expensive than three-phase generators supplying substations. I stand by my figure of 240 tons for the weight of the 8000 kw., 75 per cent power factor, 25-cycle, single-phase generators. I am aware of instances in England and America where much lighter single-phase generators have been installed for railway work. I am also aware that they have been utter failures.

Mr. Roger T. Smith gives us the advantage of some carefully prepared results from his own experience. His data for the overall efficiencies of substations and for the outlay for wages, oil and stores per kw-hr. are not quite so favorable as those in my paper, but it must be noted that I have dealt with large units. It had been my hope that my paper would serve to bring forth in the discussion a large amount of specific data from the experience of other engineers, such data, for instance, as this which Mr. Roger Smith has contributed, as also the data contributed by Mr. Knowlton and Mr. W. C. Smith. It is a most laborious task to derive such data for concrete cases, and engineers are tempted to base their conclusions on abstract reasoning. Sooner or later, however, recourse must always be had to rigorous quantitative comparisons of the commercial economies attainable by the alternative methods by which the desired results may be reached. Often this is not done till after large sums have been expended on the wrong system but it might just as well be done in the first instance. Great economies would thereby be effected and electrification propositions would command more respect from the railways.

Mr. Sparks and several other contributors to the discussion have expressed the opinion that the comparisons should have extended from the generating station to the train and should not have stopped short at the substations. I have briefly met this criticism in the section of my reply which dealt with Mr. Murray's remarks. I have dealt very thoroughly with the rolling stock end of the comparison in various contributions to British engineering societies and on these occasions, the chief criticism has been that I appeared not to realize that the grave disadvantages of single-phase rolling stock were far more than offset by the advantages of single-phase methods in all *other* parts of a railway electrification system. The results arrived at in the present paper show that the disabilities of single-phase methods extend right through the system, from and including the generators in the station, to and including the motors on the train.