DISCUSSION ON "THE INTERCONNECTION OF ALTERNATING-CURRENT POWER STATIONS."*

Discussion before the North-Eastern Centre at Newcastle, 23 January, 1922.

Mr. E. Fawssett: In connection with the general subject of this paper it may be of interest briefly to describe some apparatus that has been developed for indicating, at a point remote from the measuring point, interchanged power. The load controller, or the head office, or the power station, often needs to know what is happening some miles away at a distant substation or point of interchange with another undertaking, and, while sometimes this information can be obtained by telephone, there are many obvious objections to this method. Simple alternating-current indicators are out of court where considerable distances are involved, owing to the necessarily high resistance of the pilot connection, probably 1 000 ohms and more per pair circuit. A quite robust direct-current indicator requires some 25 000 times less power to operate it than a very sensitive alternating-current instrument, so this property is taken advantage of through the intermediary of a thermopile. A small battery of thermo-junctions is warmed by a heater carrying a submultiple of the alternating current to be measured, these junctions giving an electromotive force up to 40 millivolts, proportional to the square of the alternating current. This is ample to operate a switchboard unipivot high-resistance indicator through a pilot of more than 1 000 ohms, allowing over 20 route-miles with a pilot having a resistance of 24 ohms per mile. This simple measurement may often suffice, but an accurate indication of alternating-current power is readily obtainable and has been in commission on the North-East Coast for some five years between two power stations 9 miles apart. If we take two heaters each with its own bank of couples, one heater being supplied with a current due to the voltage, and also one due to the current to be measured, so connected as to give the vector sum, the other heater being supplied similarly but so connected as to give the vector difference, then the electromotive force of the couples in the first case is proportional to the square of $(V + A \cos \theta)$ and in the second to the square of $(V - A \cos \theta)$. These electromotive forces are arranged to oppose each other, the net electromotive force being therefore proportional to $VA \cos \theta$, i.e. the power in the circuit being measured. This electromotive force can be transmitted and indicated in the same way, the instrument in this case having a straight-line law. Other quantities, such as reactive kVA or the synchronism (or lack of it) between two supplies, can be similarly indicated. This general method should be of great use in the near future.

Mr. C. Whillis: I am interested in the question of interconnecting networks from the point of view of their effects on contiguous telegraph and telephone plant, and I should be glad if the authors would give some information as to the practice with regard to multiple earthing on such systems in America. What type of transmission line is used for the extra-high voltages, and what is the effect on telegraph and telephone circuits in the area of an unbalanced earth fault on the power system ?

Mr. W. H. Palmer: We in the North usually think of the 20 000-volt underground cable going south, and in this respect I think a single interconnecting link—useful though it may be—gives rather a false sense of security. In the early days 60 to 70 amperes on this cable was thought to be a heavy load, but during the war it carried over 6 000 kW. It held out, however, and in no small measure contributed considerably to the successful supply of electricity on the North-East Coast. A bone of contention which usually led to heated arguments was " wattless " current; and we in the Tees area always maintained that we carried all the wattless current for the Tyne area, and they in turn stated that they carried our wattless current.

Messrs. L. Romero and J. B. Palmer (*in reply*): The device described by Mr. Fawssett for indicating alternating current, power, etc., at a distance by the use of direct currents through small pilot wires, should prove of very great value on interconnection schemes. We have in mind the particular case of an interconnecting feeder terminating at either end at a substation, where the attendant would have no control of the power interchanged except by the aid of the telephone to the power station. In an interconnection of this kind, Mr. Fawssett's device would make it possible to control closely from one power station the amount of power interchanged between the two systems, without the aid of the telephone.

In reply to Mr. Whillis, there are very many instances in the United States where power companies earth the neutrals of their high-voltage transformers as and when required, with the result that on any one system there may be numerous earths. In one case with which the authors are familiar, there are no less than 150 earths on the high-voltage system. Transmission lines constitute fairly extensive networks and are of the usual type as regards spacing and insulation, and the authors believe that the telephone companies have less trouble in the aggregate with transmission systems having multiple earths than they do with completely insulated systems.

The double interconnecting link mentioned by Mr. W. H. Palmer is certainly preferable to a single one from the point of view of security, but there must nevertheless be many cases where the extra security provided by a stand-by feeder would not justify the extra cost, particularly having regard to the very high degree of reliability obtained with modern extra-high-pressure underground cables.

* Paper by Messrs. L. Romero and J. B. Palmer (see page 287).

North-Western Centre, at Manchester, 7 February, 1922.

Mr. J. S. Peck: There are several problems which are of special interest and must occur in almost every case. Suppose it is wished to transmit a certain amount of energy, at a certain power factor, from one station to another. The question is: What voltage difference is required between the two stations, and also what would be the power factor of the load on the sending station, assuming that a certain power factor is required on the receiving station? Again, if the boost is fixed, or the difference in voltages which is allowed between the sending and receiving station has been settled, what is the maximum amount of power in kilowatts that can be delivered at a certain power factor? The third question is: Supposing that a voltage difference is not allowed between the two stations, what will be the power factor, assuming that it is desired to deliver a certain amount of energy at one station or the other? These are the most usual problems in connection with this subject, and the authors have given certain formulæ for determining, in some cases with considerable exactitude, in others approximately, the solutions of these problems. I think it would have added considerably to the value of the paper if they had worked out definite examples, and I suggest that they should do so in their reply. It seems to me that the problem can be looked at in this way. There are only four voltages which come into question, i.e. the voltage at the receiving end, the voltage at the sending end, the ohmic drop and the reactive drop in the line. If it be assumed that a certain current or a certain load has to be transmitted, and the power factor at which that must be received be fixed, then the voltage at the receiving end and the power factor can be determined at once. From the kilowatts and power factor the current can be found and, knowing the constants of the interconnector, the ohmic drop and the reactive drop can be calculated. By applying the Mershon chart it would be possible, in a very few moments, to solve almost any problem that might arise. Fig. A shows the Mershon chart. The numerals 10, 20, 30, etc., represent power factors and voltage. Suppose it is desired to deliver a certain amount of energy at 80 per cent power factor and assume that under this load the ohmic drop on the line (IR) is 6 per cent and the reactive drop (IX) is 10 per cent. From the intersection of the 80 per cent power-factor line with the 100 per cent voltage circle, draw the horizontal line $IR = 6$ per cent. From the end of IR erect the vertical line $IX = 10$ per cent. Then $IZ =$ the impedance-drop in per cent and $E_2 =$ the value and phase angle of the voltage at the sending station. It will be seen at once that the value of E_2 is 111 per cent and the power factor at the sending end 77·5 per cent, approximately. This means that the voltage at the sending end must be 11 per cent higher than that at the receiving end. This is the same construction as the authors show in Fig. 1, the advantage of the chart being that the results may be read off without drawing in any of the dotted lines shown in the diagram. Again, suppose the voltages at both stations are the same, and that the current in the interconnector is such as to give 7 per cent ohmic and 11 per cent reactive drop in the interconnector; by trial find a point on the 100 per cent voltage circle, such that when IR is drawn equal to 7 per cent and $IX = 11$ per cent, the end of IX will fall on the same circle; then $E_1 = E_2$, and the power factor at the sending end is approximately 89 per cent and at the receiving end 82 per cent, both leading. From these two examples the utility of the chart will be apparent. The paper takes account only of the ohmic and reactive drops in the line. If there is capacity in the line the conditions become rather more complicated. The authors have not attempted to deal with this, but it would be well if they could indicate in general how capacity in the interconnector would affect the operating conditions. I think it will improve them, providing it is not too great; i.e. it will reduce the boosting effect required. The paper offers a great many points for discussion. The question of

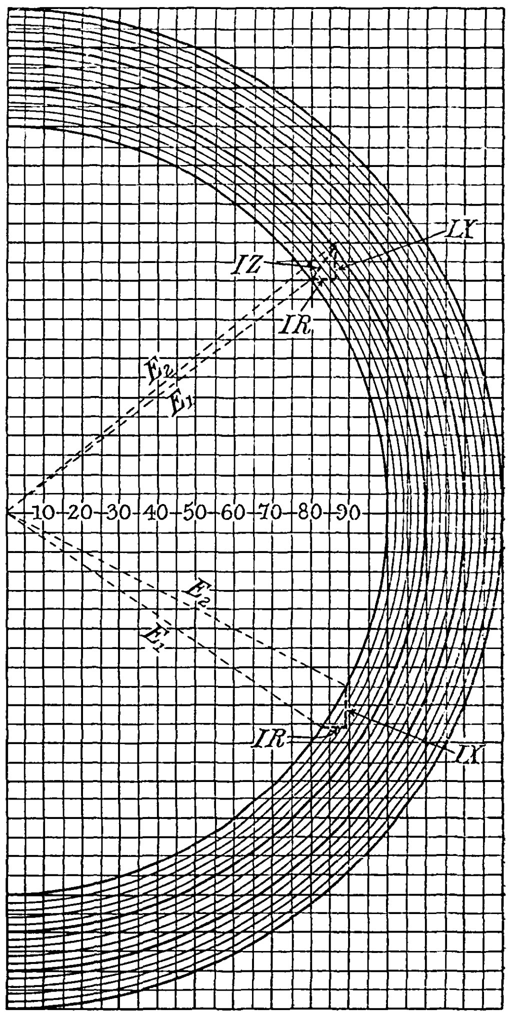


Fig. A.—Mershon chart.

regulators for securing the boost is, in itself, a large subject. The question of synchronizing power has been touched on by the authors in a very general way. Their formulæ might be applied to working out some specific examples of synchronizing power, from which conclusions could be drawn which would be an advantage to anyone considering the question of interlinking.

Mr. H. A. Ratcliff: When discussing the subject of the paper it is very necessary to get a correct perspective, because everything depends to such a large extent on local conditions. For that reason Appendix III is both interesting and valuable, because in a discussion of this nature reference to American conditions is inevitable. It should be recognized, however, that American conditions are not exactly comparable with those which are likely to obtain in this country. In the first place the line pressures are higher and most of the transmission is by means of overhead lines having a fairly high reactance, whereas in this country line pressures have been, and still are, comparatively low, and much of the transmission has been, and will be, by means of underground cables having a comparatively negligible reactance. Moreover, in America the distances covered are very much greater than in this country; and we are not likely to have 200-mile lines just yet. Offset against that, however, is the fact which the authors have mentioned, that close line-regulation and power-factor control have not usually been regarded as matters of much importance, although I understand that in the case of one or two of the more important American interlinked systems rather more attention has recently been given to power-factor control, for which purpose very large induction regulators have been installed. It appears very evident from the information given in Appendix III that the successful operation of the extensive interlinked systems depends to a very great extent on what may perhaps be referred to as the autocratic powers possessed by the "load despatcher," and there is no doubt that if we are to have really successful interlinking in this country the services of some such official will be necessary. "Load Controller" would, however, be a better title than "Load Despatcher." I think that the first important fact demonstrated by the paper is that the real cause of all the trouble is the line loss or, incidentally, the pressure-drop due to line resistance. A certain amount of reactance is beneficial, and in fact is usually essential in order to ensure that there shall be sufficient synchronizing power. If the busbar pressures at the two ends of a line are equal and there is no provision for boosting, it is impossible to transmit power (as distinct from idle kVA) unless there is a sufficient amount of reactance in the circuit. This will be evident from the conditions shown in Fig. 1 for equality of E_1 and E_2. That is perhaps an additional reason for having plenty of reactance in the transformers at either end of the line. A certain amount of reactance is essential in large transformers in order to limit the extent of the current in the event of a short-circuit, but it appears possible that in some cases transmission requirements may necessitate an increased amount of reactance in the transformers. It will be obvious from the information given in the paper that there is every advantage in having a high transmission pressure, and the tendency in the future will be to adopt higher pressures. As a rule it pays to change over from 6 600 to 33 000 volts, for example, when the resultant saving on the line loss will counterbalance the increase in the capital charges on the higher-voltage equipment; but in view of the important transmission requirements referred to in the paper it is evident that in many cases it may be advisable to adopt the higher pressure for a shorter transmission distance than would be justified by economic considerations. In this connection certain characteristics and advantages of 33 000-volt cables are of interest and importance. Naturally such cables are comparatively expensive, and further, owing mainly to the high cost of jointing, they are very expensive to lay. Moreover, in the light of present knowledge on the subjects of dielectric loss, and contraction and expansion of the conductors, it is not considered advisable to push the current density too high. For these reasons the tendency is to employ conductors having a fairly large sectional area. This, however, involves a still further reduction in the current density, owing to the proportionally smaller cooling surface on the larger conductors. For 6 600-volt distribution a 0·15 sq. in. 3-core cable is a size very frequently employed. For such a cable the permissible full-load current is about 210 amperes, giving a pressure-drop due to conductor resistance when hot of 1·87 per cent per mile. On a 0·3 sq. in. 33 000-volt cable with a full-load current of 315 amperes, the corresponding pressure-drop would be only 0·272 per cent per mile, representing a reduction in the ratio of 6·9 to 1, which naturally tends to simplify many of the problems incidental to interconnection referred to in the paper. The average distance involved in most of the proposed interlinking schemes is not more than 10 miles, and with a 0·3 sq. in. 33 000-volt cable the total resistance-drop would be 2·72 per cent and with, say, 0·5 per cent in the transformers at each end of the line the total overall drop would be about 4 per cent. Consequently a comparatively small amount of boost would be necessary in order to transmit at approximately unity power factor. With the amount of reactance usual in transformers of the type concerned no boost would be necessary if the load could be transmitted at an average leading power factor of about 0·93. With lagging power factors the amount of boost would naturally have to be correspondingly increased. The treatment of the technical features in the paper is very thorough indeed and the various diagrams and formulæ are most instructive and valuable. I should like to suggest, however, that Fig. 1 would be more instructive if the circle showing the locus of the sending voltages were added. The relative positions of the two circles as shown in Fig. B enable one to visualize much more clearly what happens as the voltage vectors swing round, and it will be obvious that below a certain value of the power factor (lagging) there is very little change in the amount of boost required. The maximum value occurs when angle θ = angle α. It is also obvious from Fig. 1 that when $E_1 = E_2$ it is not possible to transmit power without an appreciable amount of reactance in the line. The advantage of the "phase control" or leading-power-factor method of transmitting is that conditions are so adjusted that the reactive and ohmic drops in the line are exactly balanced, and being balanced for one load they are balanced for all loads, and consequently there is not the great change in power factor with load which occurs with a fixed amount of boost. The method of balancing the ohmic drop by a fixed boost is very useful when transmitting power in one direction only, but, as the authors point out, the great disadvantage is that the power factor varies with the load, and on light loads it may attain a very low lagging value. Moreover, the conditions are not reversible as it is possible to transmit in only one direction. A wide variation in the lagging value

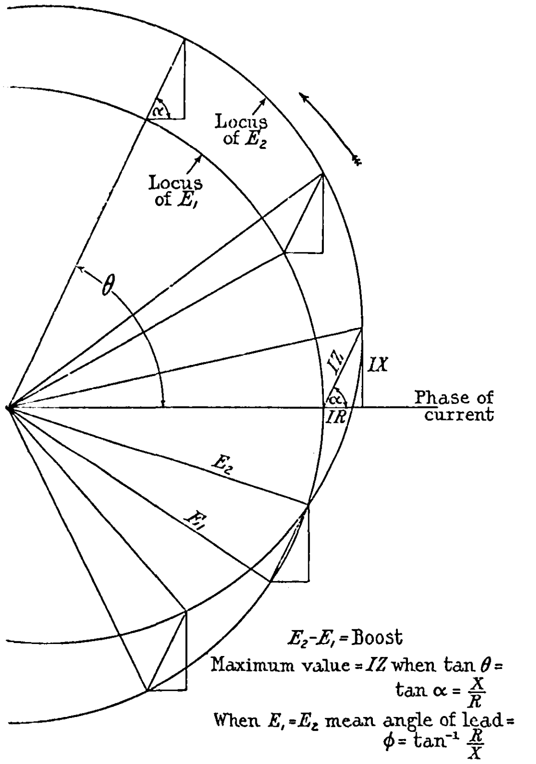


FIG. B.

of the power factor can be avoided, to some extent, by providing the boost for something less than full load, and that is perhaps a fair arrangement because the power factor varies with the load between a leading and a lagging value, and consequently the adverse conditions are not always experienced at one end of the line only. The ideal arrangement is method (3), for it permits of transmission in either direction, and the power factor can be adjusted to any desired value. The only objection to the method is the expense and complication involved, and it is therefore a matter for careful consideration, taking all the circumstances into account, as to whether the conditions are such as to justify the additional expense and complication for the particular case in question. With regard to the type of regulator, I am of the opinion that on the whole the advantages are with the induction type. They are robust, can be well insulated if immersed in oil like an ordinary transformer, are not complicated, and have no moving contacts carrying heavy currents. They give an infinite range of adjustment and are very suitable for hand, power, or automatic operation. I should like to ask the authors whether they can give any figures for the relative cost and efficiency of the two arrangements shown in Figs. 6 and 7. The first arrangement has the advantage that it avoids the additional link in the extra-high-tension line, but much will depend upon the relative cost of the two arrangements and the relative efficiencies. Apart from cost the only real disadvantage with the induction regulator is the phase displacement which it introduces into a line; and moreover, it is not a constant displacement but varies with the extent of the boost from a minimum to a maximum, and back again to a minimum. The effect is not serious, however, unless the regulators are installed on parallel circuits, in which case circulating currents may increase the I_2R losses, and the operation of isolating links, etc., may at times demand special care. The difficulty may be overcome, if necessary, by the use of double regulators having the phase rotation reversed in one as compared with the other, but naturally such an arrangement involves additional expense and complications. The paragraph at the foot of page 290 brings home very clearly the meaning of "line loss plant" and, further, there is also the necessary additional capacity in the generating plant. The authors have shown very clearly what an important bearing power factor has on transmission conditions. The power factor is really the crux of the whole matter, and in that connection I agree with the authors that in interlinking schemes there should be a certain amount of give and take between the various authorities on the subject of power factor; obviously they cannot all have it to their own advantage. Such co-operation must, of course, be subject to the condition that the operation of the plant and transmission lines involved is carried out in such a way as to conduce to the highest all-round economy. It will be possible to attain that result only by having centralized control by a thoroughly qualified controller, fully acquainted with the plant and the load conditions in the various stations, and the characteristics of the several transmission lines. I do not quite follow the argument at the bottom of page 292, because any supply undertaking would endeavour to induce, if possible, a consumer to improve a power factor as low as 0·7. A very important point arises here in connection with the measurement of power factor. It would obviously be unreasonable to say that the power factor must not fall below a certain value, then to install a recording power-factor meter, take a test reading, and say that the power factor had fallen below the guaranteed minimum. There is something to be said for the method which has been adopted on certain systems of installing two single-phase watt-hour meters and arriving at the mean power factor over a period of time from calculations based on the registrations of the two meters during the period in question. This method gives a perfectly equitable mean value, weighted in proportion to the extent of the load and the duration of the load. In connection with the question of power factor and the transmission of power over interlinking lines, it may be an advantage, in cases where there is old and somewhat inefficient plant at the receiving end of a line (provided the plant is capable of dealing with a lagging load), to allow it to handle as much as possible of the wattless component, and transmit over the line at the most favourable power factor for the more efficient plant in the larger and more modern station. That will perhaps provide an alternative to synchronous condensers which, under special conditions, may serve a very useful purpose, but which I hardly think should be installed unless there is a very strong case for them.

Mr. E. M. Johnson : The question of interlinking is one which will come into greater prominence in the next few years, and I think the main value of the authors' paper will ultimately be found in Appendix III. Reference is there made to the American interlinking systems, and to the high load factors obtained in that country. The same state of affairs exists in Switzerland, where about 1 million kW of generating plant are interlinked throughout the country over an area of about 16 000 square miles. Three hundred stations are interconnected, and load factors of 60 to 80 per cent are common. I gather from the appendix that the authors are of the opinion that these high load factors are mainly the result of the interlinking of distant stations on a single system and, in some measure, to the fact that these stations are hydraulic. I am not familiar with the conditions of supply in America, but I anticipate that the real explanation is to be found in a liberal system of graded tariffs, in the offer of low terms as an inducement to the use of current during off-peak periods (particularly for domestic purposes) and, finally, in the interlinking, practically without respect to distance, of stations and systems having different characteristics both as to load and as to motive power. In considering questions of interlinking it would be well to look beyond the limits of the neighbouring supply undertaking and endeavour to find, possibly at some considerable distance, an undertaking whose load curve is the inverse of one's own, instead of seeking simply to find a local company anxious to form what must otherwise be a temporary alliance.

Mr. W. A. Coates : The authors mention that the contactor-type and face-plate type step-by-step regulator cannot be constructed for pressures over 3 000 volts. I can understand that they have not been *commercially* constructed above that voltage, but I see no technical reason why they should not be constructed for any pressure for which transformers can be built. I should like to know whether it is a purely commercial limitation or whether there is some technical limitation of which I am not aware.

Mr. J. Collinge: The undertaking with which I am connected was linked up with the Lancashire Power Company in 1915. The Company supplied to a small substation about 1 mile away from the power station at a pressure of 10 000 volts, which was transformed down to 6 600. We ran most satisfactorily, connected up with them, and the question of power factor was certainly not troublesome. Later on we found occasion to obtain an additional supply from Manchester, and this resulted in a most interesting and perhaps unique experience in interconnecting systems. The power company, which has an overhead system for the major portion of the distance, Manchester and ourselves were all running together. We synchronized with Manchester at the Salford power station and the power company synchronized with us at their power station and still the question of power factor did not unduly trouble us. Then the question of load adjustment had to be dealt with. That was overcome by the power company agreeing to give us a definite load at their power station and keeping it, so far as possible, owing to the fluctuations of the systems, at that load, and we at Salford arranged the load we took from Manchester. I believe that when the three systems were running in parallel the power company were also supplying power to Wigan, to the South Lancashire Tramways and other townships. Another interesting fact is that the power company's system is earthed and ours at Salford is not, while that of Manchester is earthed on the 33 000-volt side. I do not mean to minimize the importance of power factor. It is undoubtedly most important in setting up interconnecting systems, and in arranging plant for supply it must be taken into consideration. If that is done, then the actual power factor can generally be regulated by other factors to a satisfactory figure, especially in this country where the interconnection systems are short as compared with those in America. It is very important to study the power factor in the case of interconnecting power stations, and to my mind it is equally important that the consumer should also study his power factor and give it very careful consideration. I know of cases where the installation of synchronous condensers at comparatively small cost, compared with the amount of current being taken, has reduced the latter by as much as 50 per cent.

Mr. A. G. Ellis : There is one point which this paper emphasizes and which has not been remarked upon, i.e. the development of extra-high-tension interconnection. Since the date of Mr. Peck's paper we have now in this country quite a number of 33 000-volt underground cable interconnecting systems, and it is not unlikely that in the near future we shall have underground cable systems at considerably higher voltages than this. I should like to call attention again to the author's statement on page 287, under "General Operating Conditions," on the question of transmitting load. This seems to me possibly the most important general statement in the paper. The only way in which the amount of load transmitted can be altered is not by adjustment of the voltage but wholly by the adjustment of the steam supply to the prime mover. This point should be borne in mind when considering the question of the voltage regulator which is primarily concerned with the adjustment of the power factor. Table 1 shows the rôle which the voltage regulator plays in this respect. The authors have dealt practically with a simple case of interlinking two stations, and the vector diagram given in the paper deals with that case very simply. I should have liked to see in the paper the case of three stations interlinked by a ring main. This can be worked out from the vector diagram given and is a very interesting case. One problem which often arises in this connection concerns the phase angle between the different stations. It may be found impossible to interlink three existing stations without changing some of the transformer connections, or possibly re-winding them for different connections to get the right phase angle around the whole of the system. There is another case on which I should like the authors' opinion, i.e. the case of interlinking two stations by parallel feeders. In the case of an existing plant with two points interlinked by a new 33 000-volt cable and by an 11 000-volt cable from which a local supply is tapped, the line characteristics of the two feeders may be such as to give a large difference in the power factors of the two feeders, and I should like to hear what the authors consider to be the best method of dealing with the wattless current. It would probably involve putting in an induction regulator in one or both feeders, or power-factor adjusters. As Mr. Peck remarked, the question of different types of voltage regulators is almost a subject in itself. In general I think I agree with Mr. Ratcliff that the induction regulator is the most satisfactory type of regulator, and the only reason that it is not always installed is the capital cost. The induction regulator is, generally speaking, a more costly piece of apparatus than the contact regulator referred to in the paper. The installation of induction regulators may be restricted by the limiting size of the induction regulator that it is possible to build. Figs. 6 and 7 represent the common system of transformer regulators. Mr. Ratcliff, referring to Fig. 7, mentioned that the regulating transformer C was placed on the low-tension side. This is quite a common practice because the regulating transformer is cheaper, is more efficient when wound for low voltage, and is also a more reliable piece of apparatus. I think that the method shown in Fig. 7 is the more reliable. Fig. 6 shows regulating tappings in the main transformer. Tappings are excellent and give a good degree of flexibility in the voltage, but the fewer tappings introduced in the main transformer the more reliable is the apparatus. All operating engineers will agree that, on this question of the type of voltage regulator, reliability is of paramount importance. Fig. 6 shows a type of regulating switch which I do not think is referred to in the text, viz. a regulating switch placed in the transformer. It is usually connected to the neutral end of the winding. This type of regulator has been developed recently in America and has already been applied, I understand, for feeders up to 66 000 volts, and for a fairly large output in kilovolt-amperes. I should like to ask the authors if they know of any of these switches in operation with the circuit alive. As far as I can gather, this type of switch has tappings on the neutral end of the transformer, operated by hand from outside, and can be operated only when the circuit is dead.

Mr. O. Howarth: The authors do not discuss the question of interconnected power stations with load tapped off the interconnector, or, what is practically the same, two stations interconnected at a point in the network of one of them. It does not seem to be a commercial proposition to transfer energy from one station to another and then back in the direction of the first station to the consumers, involving as it does extra copper, with consequent increased capital expenditure, and possibly extra copper losses when in operation. The station into which the interconnector is not carried will, of course, require to have some instrument which will indicate the load and power factor on the interconnector, and it would have been of interest if the authors had given particulars of any such instruments with which they are acquainted. If load is suddenly thrown on between two stations so connected, instead of the disturbance falling mainly on one station and so perhaps causing them to fall out of step, it will fall partly on each station, and less synchronizing power will therefore be required to maintain them in step. The conditions necessary for the satisfactory interconnection of power stations in the form of a ring have not been mentioned, and it seems to me that the difficulties of satisfactory operation in the case of a ring of stations such as shown in Fig. C will be very great. In the hypothetical case shown, the stations are connected as follows :—

Station A has an interconnector from the busbars to a point in the network of station B.
Station B has an interconnector from the busbars to a point in the network of station C.
Station C has an interconnector from the busbars to a point in the network of station D.
Station A has another interconnector from the busbars to a point in the network of station D.

The stations are assumed to be three-phase, receiving at 10 000 volts. Assuming that A is supplying 10 000 kW at 0·85 lagging power factor to B, and that the resistance between station busbars is 0·5 ohm per phase, the reactance voltage being equal to the resistance voltage, B will lag 0° 43′ behind A. Let the load which B supplies to C be 5 000 kW at 0·85 lagging power factor, and let the resistance between stations B and C be 1 ohm per phase, the reactance voltage again equalling the resistance voltage. Station C will lag another 0° 43′ behind B, i.e. a total of 1° 26′ behind A. Let A be supplying D with a load of 2 000 kW at 0·7 lagging power factor, and let the resistance between A and D be 1 ohm per phase, with the reactance voltage equal to the resistance voltage as before. D will then lead A by 0° 1′. The phase-difference between C and D is then 1° 27′ with D leading C, and, as this cannot be altered without disturbing the loading on the other stations, the power factor of the load between the two stations will be fixed for any given load. The relation of the power factor, load and voltage boosts are shown in Fig. F. It will be seen that it is impossible to close the interconnector switch without considerable disturbance. The minimum current is 103 amperes at 1 250 kW supplied to C by D, and closing the switch under these conditions, i.e. no voltage boost at either end, will disturb the loading of the other stations. If a boost of 250 volts is applied at C and the switch closed, 145 amperes will flow, but there will be no interchange of power, the line loss being supplied by one or both stations. Such an arrangement will obviously cause considerable inconvenience in operation. In order to have full control of power factor and load it will be necessary not only to install a voltage booster but to have a booster which will alter the phase angle by adding voltages differing by, say, 90° from the busbar phase voltages, and it will also be necessary to provide this at any point where the ring might be closed, as obviously, if the systems are run by separate authorities go. In such a system this will not, of course, matter any more than it does on an ordinary ring main. The objection to this system is the relatively high cost compared with the cost of that shown in Fig. C, and also the fact that it will not be so natural a growth as in Fig. C, which pictures a state of affairs which will grow naturally, due to undertakings making agreements to purchase in bulk from adjoining under-

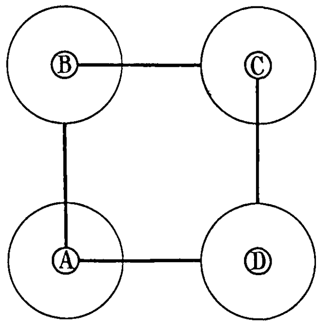


FIG. C.

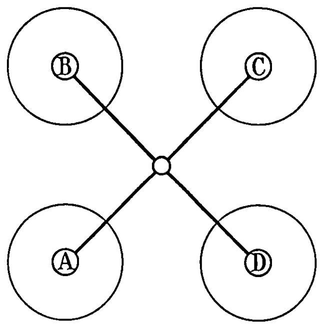


FIG. D.

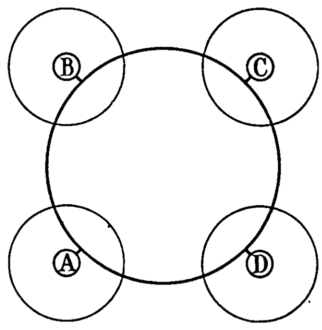


FIG. E.

who have agreements with each other as to the purchasing of electrical energy, they will not care to put extra copper into their systems and make the necessary alterations to their metering arrangements and agreements in order to cope with any disturbance which might be caused by the closing of the ring. The most satisfactory method of operating a number of stations in parallel will be to connect them "star," as shown

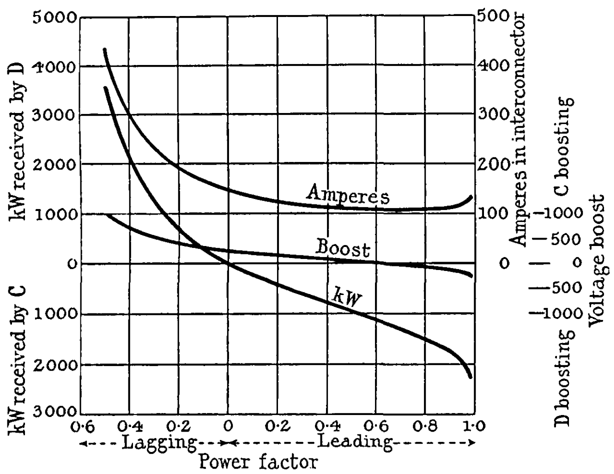


FIG. F.

in Fig. D, as each station can then control the load and power factor which it supplies into or receives from the common interconnector house without causing unexpected disturbance to the others. An alternative to this is shown in Fig. E, which is really the same as Fig. D with the busbars of the interconnector house pushed further out so that they form a ring main. Each station will then be able to control within limits the load and power factor which it supplies to or receives from the common ring, but it will not be able to determine which way round the ring the load will

takings. The question of varying the price of electricity as the "weighted mean power factor" varies has been mentioned, and as the method of installing two single-phase watt-hour meters from the ratio of the readings of which the power factor is to be determined has also been referred to, I should like the authors to express their views on this method. In the following table the "weighted mean power factor" has been calculated for certain loads, and the figure obtained from the ratio of readings is also shown :—

Load			Kelvins			Mean equivalent power factor	
kW	P.F.	Period in hours	W_1	W_2	Total	Actual	From W_1/W_2
150 50	0·866 lag 0·5 lag	8 16	400	1 600	2 000	0·72	0·693
150 15	0·866 lag 0·5 lag	8 16	400	1 040	1 440	0·805	0·792
150 150	unity 0·866 lag	8 16	1 400	2 200	3 600	0·911	0·933

It will be seen that the two are not necessarily the same, and taking the "weighted mean power factor" to be

$$\frac{\int \text{kW} \cos \theta dt}{\text{Kelvins}} \quad \text{(where } t \text{ is in hours)}$$

it is obvious that the power factor obtained from the ratio of the watt-hour meter readings will not necessarily give the same figure.

Mr. L. H. A. Carr: The authors use the phrase "synchronizing power of the line," but I am of opinion that there is only a de-synchronizing power. If 1 000 kW is thrown on suddenly at the receiving end of the line, and if the plant delivers 800 kW and the line feeds in 200 kW, I imagine that this 200 kW is what the authors have referred to as "synchronizing power of the line." I should be glad if they would confirm this view. The authors on page 294 refer to the oscillations produced in the line and discuss the magnitude of these oscillations, which they suggest are due to the strength of the original de-synchronizing power of the line. I do not see how that can be true. The oscillations must be due partly to the machines at each end of the line, and consequently those machines must exert an influence on the resulting oscillation. Does the line exert a damping influence on the oscillation, or not? One would imagine it is damped since the line has resistance. At the same time the machines themselves will of course provide a certain amount of damping. I would suggest that in their reply the authors should give some idea of how much the synchronizing power of the alternators is reduced by the line, because that is an important point.

Mr. D. S. Paxton: With regard to the question of the most economical power factor at which to transmit power from one system to another interlinked with it, it would appear, from a broad consideration of the question, that the best utilization factor for the whole plant will be obtained by an agreement that the transmitting station shall in general transmit at the power factor for which its generating plant is designed, with the reservation that if the power factor of its own system is at any time actually less than that for which the plant is designed, the operating engineer may have the option of informing the receiving station that power can be transmitted only at a rather higher power factor than usual but not exceeding unity. On the other hand, if the transmitting station habitually has a power factor higher than the figure for which it was designed (though I fear such cases will be few) an agreement may be made that the power transmitted through the interconnector shall be at a correspondingly lower power factor, which will bring the resultant power factor of the transmitting station to the value for which its plant is designed, thus fully utilizing the electrical portion of the machinery. In either event it may be accepted as an axiom that the transmitting station should be called upon to provide power only under conditions which do not unduly derange its own operation, and any additional wattless component required by the assisted system should be provided as far as possible at the receiving end of the line. Thus, if the receiving station is habitually loaded at a power factor below that of the transmitting station, it will probably be advisable to apply at the receiving station some artificial means of power-factor correction; whether by means of synchronous condensers, static condensers or, possibly, by over-excited synchronous induction motors on the station auxiliaries, etc., can be decided only in accordance with the special conditions in each case. Such artificial capacity or magnetization-current-producing plant should be dimensioned to provide the necessary wattless component to bring the resultant power factor, after receiving the supply through the interconnector on the agreed conditions, up to a value corresponding to the power factor for which the station is designed. In this way the generating plant in both stations will be utilized to the best advantage both in regard to kilowatt and kilovolt-ampere capacity; the interconnecting line can be designed for a power factor not widely deviating from unity, thus avoiding undue capital cost and/or copper losses; and artificial capacity only to cover the bare requirements of both stations need be installed. Where the direction of power transmission is reversible it may be advisable to install condensers or other such plant at both ends of the line, unless one of the stations works invariably at a higher power factor than the other, in which case it should be no hardship for the latter to transmit at the former's power factor. The foregoing remarks, as well as the paper itself, apply solely to station interconnecting links, but the future tendency will probably lie in interconnecting networks as opposed to central stations, as it certainly appears uneconomical to transmit power, say, 25 miles from one station to another and then to send it back perhaps $12\frac{1}{2}$ miles from the receiving station towards the transmitting station. The interconnection of networks would, however, entail financial amalgamation in a more or less complete degree, and this is not the subject at present under discussion. The question of a basis of payment for the transferred power does perhaps arise, however, and without any knowledge of what may have been arranged in any particular case I should like to suggest that both the kilowatt-hours and the kilovolt-ampere-hours should be metered, and the tariff based on a certain rate per unit with a surcharge of a fraction of this rate for the arithmetical difference between the two readings. This might equally be applied to power consumers, and would be more readily intelligible to them than cos ϕ calculations. It may be objected that no kilovolt-ampere-hour meter is available, but it is probably not beyond the wit of the meter manufacturer to evolve one. In view of the somewhat considerable trouble involved in synchronizing two independent stations, it is advisable that once established the link shall not be unnecessarily interrupted, and a reference to a method that has been devised to protect the alternators in such stations from the effects of short-circuits without disconnection from the line may be of interest. A short-circuit is dangerous to an alternator only as long as the machine is fully excited, and if the short-circuit is due to a flash-over, caused by a pressure surge or the like, a diminution of the voltage will probably extinguish the arc and clear the short-circuit. The system referred to consists in employing with each alternator, in addition to the usual automatic pressure regulator, a second similar regulator so connected that in the event of the maximum safe current for the alternator being exceeded, the excitation is reduced to a greater or less degree, until the fault clears itself or is cleared by switching out the feeders affected. Several traction stations, and others subjected to heavy short-circuits, have been protected in this manner, and have been in operation for considerable periods with satisfactory results.

Mr. C. M. Longbottom: In Fig. 1 it is pointed out that if $IX = IR$, which we must accept, from the statement on page 293, as being the most suitable condition for the line, the mean angle of lead will be 45° which will give a mean power factor of 0·7. This, of course, will be very unsuitable. There is another point in Figs. 4 and 5, in regard to the question of regulators at either end of the line and one end only. This is chiefly an economic question. To have one regulator is, of course, much more desirable than to have two, for the reason that the loss in transmitting one way—at least the loss in the distant one—will have to be carried across the line; also the average voltage in the line will be lower, and therefore the cost of the line will be increased. The objection might be raised that in a reversal of power the conditions will be very unsatisfactory, as borne out by Fig. 5, but the question of over-voltage is not, I think, serious, and in certain cases where the transmitting back to the first station would be only of short duration the extra loss on the line would not be large. The reason why the power factor is not considered so seriously in America is that certain companies try to arrange that their districts are supplied at different times, with the result that the stations will not be operating under peak conditions at the same time. The question of power factor and wattless components does not, then, seriously affect the case.

Mr. J. Williams (*communicated*): With regard to formula (7) on page 295, I should like to ask the authors what is the greatest difference in power factor between the sending and receiving stations which they have experienced. A very large difference in power factor can be obtained when the receiving station is taking only a light load (say 10 per cent) compared with the capacity of the transformers, such load having a high power factor. This is due to the fact that the sending station has to supply the iron losses of the transformers at a low power factor, such losses being a high percentage of the total load in the case mentioned above. I give below the following references for the benefit of those who may desire to study this question still further:—

(1) J. W. WELSH: "Operation of Two A.C. Stations through Parallel Circuits, and the Distribution of Load and Wattless Current between them." *Proceedings of the American Institute of Electrical Engineers*, April 18, 1912.

(2) H. W. SMITH: "Interconnection of Power Systems." *Electric Journal*, 1920, vol. 17, p. 515.

(3) R. BAILEY: "Voltage and Power Factor Control of 66 000-volt Transmission Lines connecting Two Generating Stations." *Journal of the American Institute of Electrical Engineers*, 1921, vol. 40, p. 462.

Messrs. L. Romero and **J. B. Palmer** (*in reply*): This paper was intended to be a sequel to Mr. Peck's 1916 paper, and it is therefore a source of satisfaction to us to find that Mr. Peck is generally in agreement with it. We agree that it would have added to the value of the paper if we had given definite examples of the working out of the formulæ, and we set out below the calculations for col. 1 of Table 1. It is of course quite simple, as Mr. Peck explains, to read the voltages and power factors directly from a Mershon chart fairly accurately, but we venture to think that the calculations from the formulæ are even simpler. If one had a number of these interconnector determinations to make, and great accuracy were not required, it would probably pay to have a large-scale Mershon chart as a permanent fixture in the office, but if a chart were not available a considerable number of accurate results could be obtained by calculation in the time taken to prepare the chart. Once available, however, we agree that all interconnector problems could be solved very quickly by it. It is true that we have attempted to deal only with short lines in which the capacity current is practically negligible. The calculation of long high-voltage lines is complicated by the capacity current and is quite a problem by itself. For accuracy it would be necessary to take into account also the watt and wattless components of the leakage represented by the exciting current of the transformers; the wattless component when expressed as an "admittance" being arithmetically subtractive from the capacity susceptance of the line. Dealing with the matter broadly, the effect of capacity in a line is to reduce the reactance and the resistance-drops, and this, for an example we have investigated, would (for a 0·9 power factor lagging load) have the effect of reducing the amount of boost required at full load, and of increasing slightly the phase-displacement between the sending and receiving voltages. The power factor at the sending end would, however, be improved.

Example showing the calculation of col. 1, *Table* 1. *Data.*

Station B is to receive 10 000 kW at 0·7 power factor lagging from station A.

Busbar voltage at stations A and B, 6 600, three-phase, 50 periods. Transformer capacity at each end, 15 000 kVA. Copper loss of each transformer at full load (90° C.), 161 kW. Reactance at full load, 4·85 per cent. Voltage ratio 6 600/33 000 at no load.

One cable 0·2 sq. inch, 16 miles long, 33 000 volts; resistance, 0·256 ohm per conductor at 60° C.; inductance, 0·52 millihenry per mile.

Resistance per phase (cable)

$$= 0{\cdot}256 \times 16 = 4{\cdot}1 \text{ ohms}$$

Equivalent resistance per phase (transformers)

$$= \frac{2 \times 161 \times 33\,000^2}{15\,000^2 \times 10^3} = 1{\cdot}56 \text{ ohms}$$

Total resistance per conductor, R, is therefore 5·66 ohms.

Reactance per phase (cable)

$$= \frac{2\pi 50 \times 16 \times 0{\cdot}52}{1\,000} = 2{\cdot}6 \text{ ohms}$$

Reactance per phase (transformers)

$$= \frac{2 \times 4{\cdot}85 \times 33\,000^2}{15\,000 \times 10^5} = 7{\cdot}0 \text{ ohms}$$

Total reactance per conductor, X, is therefore 9·6 ohms.

The current in the line, $I = \dfrac{kW_1 \times 1\,000}{3E_1 \times \cos\phi_1}$

$$= \frac{10\,000 \times 1\,000}{3 \times 19\,052 \times 0{\cdot}7}$$
$$= 250 \text{ amperes}$$

Whence $IR = 250 \times 5{\cdot}66 = 1\,415$ volts
and $IX = 250 \times 9{\cdot}6 = 2\,400$ volts.

The voltage to be added by the booster, in terms of the extra-high-pressure, is :—

$3(E_2 - E_1)$. (*Note that E_2 and E_1 are voltages to neutral.*)

$$E_2 = \sqrt{[(E_1 \cos\phi_1 + IR)^2 + (E_1 \sin\phi_1 + IX)^2]}$$
$$= \sqrt{[(19\,052 \times 0{\cdot}7 + 1\,415)^2 + (19\,052 \times 0{\cdot}714 + 2\,400)^2]}$$
$$= \sqrt{(14\,753^2 + 16\,005^2)}$$
$$= 21\,761$$

The voltage added by the booster is therefore

$$\sqrt{3}\,(21\,761 - 19\,052)$$
$$= 4\,680 \text{ volts (in terms of the E.H.P.)}$$

The booster capacity is $3I(E_2 - E_1)$ volt-amperes

$$= 3 \times 250\,(21\,761 - 19\,052)$$
$$= 2\,030 \text{ kVA}$$

Now let us consider the power factor at the sending end ($\cos\phi_2$).

$$\phi_2 = \text{arc tan}\,\frac{E_1 \sin\phi_1 + IX}{E_1 \cos\phi_1 + IR}$$
$$= \frac{16\,005}{14\,753}$$
$$= \tan 47^\circ\, 19'$$

Therefore $\cos\phi_2 = 0{\cdot}678$
The kVA at the sending end

$$= 3IE_2/1\,000$$
$$= 16\,300$$

The kW at the sending end $= 16\,300 \times 0{\cdot}678 = 11\,060$.
The kW at the receiving end $= 10\,000$.
Therefore the loss in transmission is 1 060 kW.

It will often be necessary to determine what the power factor of transmission would be with a given boost, for a given value of kVA transmitted.

Example : What would be the power factor of transmission in the line illustrated in the previous example if the load at the sending end of the interconnector were 16 300 kVA, and the voltage applied to the primary of the step-up transformer 7 536 ?

$$E_2 = \frac{7\,536 \times 33\,000}{6\,000 \times \sqrt{3}} = 21\,761 \text{ volts}$$
$$I = \frac{16\,300 \times 1\,000}{3 \times 21\,761} = 250 \text{ amperes}$$
$$IR = 250 \times 5{\cdot}66 = 1\,415 \text{ volts (as before)}$$
$$IX = 250 \times 9{\cdot}6 = 2\,400 \text{ volts (as before)}$$

As $E_2 - E_1 = 21\,761 - 19\,052 = 2\,709$ volts is greater than IR the power factor ($\cos\phi_2$) will be lagging, therefore

$$\phi_2 = \alpha - \epsilon_2$$
$$\tan\alpha = \frac{IX}{IR} = \frac{2\,400}{1\,415} = \tan 59^\circ\, 30'$$
$$IZ = \sqrt{(IR^2 + IX^2)} = \sqrt{(1\,415^2 + 2\,400^2)} = 2\,786$$
$$\cos\epsilon_2 = \frac{E_2^2 + IZ^2 - E_1^2}{2E_2 \times IZ}$$
$$= \frac{21\,761^2 + 2\,786^2 - 19\,052^2}{2 \times 21\,761 \times 2\,786}$$
$$= 0{\cdot}975$$
$$= \cos 12^\circ\, 36'$$
$$\phi_2 = \alpha - \epsilon_2$$
$$= 59^\circ\, 30' - 12^\circ\, 36'$$
$$= 46^\circ\, 54'$$

Therefore power factor $= \cos 46^\circ\, 54'$
$= 0{\cdot}68$ (approximately)

Following Mr. Peck's suggestion we give below the calculations for the synchronizing power for variations of phase angle of 1° and 10° based on the conditions in col. 1, Table 1, calculated from formula (13) in Appendix II.

$X = 9{\cdot}6$ ohms. $Z = 11{\cdot}14$ ohms.
E_1 and $E_2 = 33\,000/\sqrt{3}$. $\beta = 1^\circ\, 42'$.
When $\theta = 1^\circ$, synchronizing power $= 1\,464$ kW.
When $\theta = 10^\circ$, synchronizing power $= 14\,571$ kW.

We are of opinion that the synchronizing power of this line would be adequate for all ordinary conditions of working. The synchronizing power of interconnecting lines will obviously decrease as their carrying capacity in kVA decreases and as their length increases, and it is probable that the synchronizing power of a line of the same length but only 1/10th of the capacity of that worked out above would not be adequate except for very steady load conditions.

We are in substantial agreement with most of Mr. Ratcliff's remarks, but we cannot accept his suggested improvement for Fig. 1 in the paper. The practical problem to be considered is the effect on the power factors at the two ends of the line of varying the boost for a fixed load in kilowatts delivered to the receiving station. Under these conditions the line voltage triangle (showing resistance, reactance and impedance-drops) will grow in size as the boost varies from the value necessary for unity-power-factor transmission, owing to the increase in current as the power factor varies from unity in either direction, and the effect of this increase in current is to make the variations in power factor much less than those shown by Mr. Ratcliff. His assumption is correct only for a fixed current transmitted and, as this is a purely artificial condition, it is liable to obscure the problem, as is also his deduction from it as to the maximum value of the boost.

It would be difficult to compare the arrangements of step-by-step regulators shown in Figs. 6 and 7 on a cost and efficiency basis, as the methods have different fields of application. It is clear, however, that the arrangement shown in Fig. 6 requires less apparatus than that shown in Fig. 7, but the limitation imposed by the voltage of the circuit would often prevent the use of the former arrangement. Mr. Ratcliff questions our statement on page 292, and says that any supply undertaking would endeavour to induce a consumer to improve a power factor as low as 0·7, if possible. We feel that the only effective way of inducing consumers to improve their power factor is by giving them a financial interest in the improvement, and we are therefore of opinion that, whenever practicable, alternating-current supplies should be charged for on a power-factor basis. We agree that the two single-phase watt-hour-meter method of determining the power factor is probably the fairest and most satisfactory for ordinary consumers' supplies, but we are not so clear that it is the ideal method for use on power station interconnections.

Mr. Ellis raises an important point in mentioning the case where three or more stations are interconnected through a ring main. As he says, it is quite possible for two of the stations to find themselves unable to complete the interconnection owing to the phase angle introduced by transformer connections; for instance, the delta/star connection, which would require the stations to have a permanent minimum phase angle of 30 degrees at no load, if there were one delta/star bank in the interconnector. The phase angle introduced by transformers must not be confused with the difference in power factor which exists between the ends of an interconnector and which is caused wholly by the impedance of the line. The example Mr. Ellis gives, in which, in effect, two stations are interconnected by lines having widely different impedances, is an interesting one, and it is possible to get surprisingly large currents circulating. The remedy, as Mr. Ellis suggests, is to boost both interconnectors separately, and in some cases it would probably be necessary to equalize the impedances of the parallel circuits artificially. We agree with Mr. Ellis that it is generally undesirable to introduce a number of tappings into large high-voltage transformers. In America the tapping switch, capable of changing tappings under load, is used to some extent in distribution transformers, but, as far as we are aware, has not yet been applied to transformers feeding transmission lines. Some of the supply undertakings, however, appear to be calling for this development, and it is probable that the demand will be met in the near future.

In reply to Mr. Johnson, the position of the electricity supply industry in the United States is very different from that of the British industry. The interconnection of the supply undertakings' networks certainly has had a beneficial effect on the load factor, but the principal causes of the high load factors are the diversity of industry, the extent to which the railways are electrically operated, and (in California) the irrigation load. We have no information as to graded tariffs, but it is a fact that the use of electricity is very much more general than it is here, which goes to show that the supply is relatively cheap and abundant. The prospect of interconnecting undertakings whose load curves are the inverse of each other is very attractive, but the condition probably does not exist within the economical limits of transmission.

Mr. Coates and other speakers have questioned the statement in the paper that contactor-type and face-plate type regulators are limited to about 3 000 volts. As Mr. Coates mentions, there are no technical reasons why higher-voltage apparatus should not be constructed and, as a matter of fact, since the paper was written several have been installed.

Mr. Collinge's interesting account of his experience with interconnected systems does not call for reply.

Mr. Howarth raises the question of load tapped off the interconnector, and we would refer him to our reply to the discussion in London on this point. In reply to his question about instruments to be located at one power station to indicate the load and power factor of the supply fed into its network by another power station, we would refer him to a recent article in the *Electrical Review* by Mr. Fawssett of the Newcastle Electric Supply Company, describing an ingenious method which he has devised for making these measurements. We think that it would be difficult and inadvisable to run Mr. Howarth's four power stations as either a closed or an open ring, unless the loads delivered by each station, and the power factors, were under the control of one man. The open ring would be easier to operate, but it might be less economical in copper and losses. In a closed ring or in any other kind of parallel connection the loads on the power stations are governed entirely by the power supplied to the prime movers without regard to the electrical conditions, and in Mr. Howarth's example, as all the stations are already running in parallel, the closing of the ring between stations C and D would not appreciably alter the loads carried by the several stations, but it would certainly alter the power factors owing to the alteration in the distribution of the loads between the various interconnectors. We could not say what the distribution of the loads would be with the ring closed, without having full data of the loads on the networks, etc., but it is obvious that the power factors in the interconnectors would readjust themselves to the loads they would have to carry and to the electrical conditions in the whole ring, and the currents might be lagging in some of the interconnectors and leading in others. We agree with Mr. Howarth that in such a closed ring it would be impossible to adjust independently all the loads and power factors in the ring, as the conditions in the ring as a whole would obviously have to balance.

Mr. Howarth puts forward a star arrangement of interconnection as more satisfactory from the operating point of view than a ring, and states that under this arrangement each station could control the load and power factor which it supplies to or receives from the ring. We disagree with him here, as it seems clear that one station could increase or decrease its load only at the expense of the others, and confusion might result if the load distribution and power factor control were not under one man. The same criticism applies to the arrangement shown in Fig. 4.

Mr. Howarth proves clearly that the definition of the power factor given by the two watt-hour-meter method as " a mean value which is weighted in proportion to the extent and duration of the load " is not strictly correct.

In reply to Mr. Carr it may be as well to say at once that when we refer to the "synchronizing power of the line," the word "power" is used in its engineering sense and not in its general sense of "influence." The 200 kW to which Mr. Carr refers is load power and not synchronizing power, and we would refer him to the definition given in the paper and in our reply to the discussion in London. Mr. Carr starts off with the idea of two machines running in parallel and states that if a transmission line be inserted between them the effect of the line is a de-synchronizing one. This is correct, but is not the problem under consideration. We would remind Mr. Carr that the two machines are in reality running in two separate power stations; that the introduction of a transmission line between them is for the purpose of enabling them to be run in parallel; and that its effect is therefore to increase the synchronizing power which will flow between them from zero to something quite considerable. We believe that if Mr. Carr had not started with the idea of separating two generators in one power station by means of a transmission line he would not have found fault with the use of the expression "synchronizing power."

The statement on page 294 which Mr. Carr challenges was put forward tentatively, but further consideration has confirmed our opinion that it is substantially correct. We did not suggest that the magnitude of the oscillation through the line was independent of the type and design of generator plant running in the two power stations, but that, given machines of the same type and design, it was independent of the capacity of the plant running. We agree that the line will have a damping effect on the oscillations. The statement on page 293 with regard to synchronizing power which is challenged by Mr. Carr appears to us to be quite clear and correct, but in order to satisfy Mr. Carr it might be stated alternatively as follows: "For all values of E_1, E_2 and β, and for any given value of resistance the synchronizing power is a maximum when the reactance of the line is equal to the resistance of the line."

Mr. Paxton has summed up the effects of power-factor variation very ably indeed, and the conclusions he arrives at in regard to the equitable division of the wattless component are quite sound in the conditions we have considered, namely, the case of the interconnection of two or more independent self-contained undertakings. It is possible, however, that a joint electricity authority, having autocratic powers over a number of stations, might find it more economical and convenient to run the most efficient stations at the highest possible power factors, as some of the hydro-electric companies do in America, but every case would have to be considered on its merits. Mr. Paxton's remarks, and the paper itself, deal mainly with the interconnection of stations, which is often the only feasible method of interconnecting systems, but we agree that the interconnection of networks is often possible and in many cases would be more effective and less costly than the interconnection of station busbars. The reduction of generator excitation either automatically or by hand on the occurrence of a fault, is common practice in America, and in the case of overhead transmission lines there can be little or no objection to it, since the majority of faults are insulator flash-overs which, when the arc has broken, generally leave the line unimpaired and fit for service. This method would probably not be effective on an underground cable system, on which a fault usually puts a cable out of commission until it can be repaired.

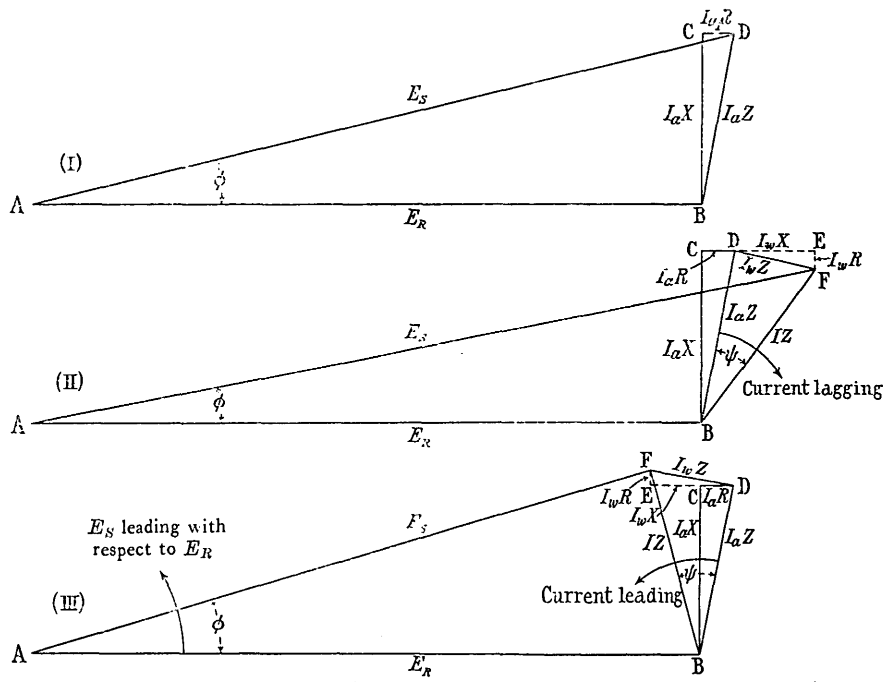
In reply to Mr. Longbottom, we said on page 293 that for a given resistance of line the synchronizing power is a maximum when the reactance of the line is equal to the resistance, but we do not suggest that this relationship is the most suitable for the transmission of power with station voltages constant and equal. On the contrary, we indicate that the mean power factor of transmission might be fairly near unity if the value of X were made as large as would be safe from the point of view of synchronizing power. We agree that if satisfactory operation can be obtained with a regulator at one end of the line only, there is very little to be gained by installing regulators at both ends, but the case illustrated in Fig. 5 shows that in many cases two regulators would be necessary. It is not entirely a question of extra loss in the line, as Mr. Longbottom suggests, as shown in Fig. 5; when the flow of power is towards the station having the regulator there would either be some loss of power-factor control or the busbar voltage at the receiver station would have to be lowered.

Mr. Williams raises the point of the large difference in power factor which may obtain between the two ends of the interconnecting line when it is transmitting only a small percentage of its full load. This point, although interesting, is not of much practical importance, as a low power factor at light loads is not troublesome and does not add appreciably to the cost of transmission. Where transformers are employed in the line this would arise, as Mr. Williams points out, from the effect of the wattless component of the magnetizing currents of the transformers which, being a fixed quantity, becomes relatively important when the load through the line is small, and makes the power factor at the sending end lag behind the power factor at the receiving end by an amount greater than would be given by formula (7) on page 295. We would point out, however, that this effect is produced by the difference in value and phase angle of the currents at the two ends of the line and not to any increase in the phase angle between the station voltages, which on the contrary is slightly reduced. A similar effect would be produced by consumers with low, lagging power factors being tapped off the line. Capacity in the line would have the opposite effect of reducing the difference in power factor between the two ends of the line. We have dealt with the general effect of line capacity in replying to Mr. Peck.

NORTH MIDLAND CENTRE, AT LEEDS, 14 MARCH, 1922.

Mr. G. A. Juhlin: The questions dealt with by the authors are extremely interesting and of considerable value. The authors state on page 288 that without the provision of a regulator the sudden making or breaking of the large wattless current which would flow at no load would have serious effects on the busbar pressures at one or both stations. It seems to me that even with the voltage regulator in use there will be a considerable variation in voltage if the load should suddenly be reduced at the receiving station, due to the fact that the drop in the interconnector will change materially and, while this drop will to a certain extent be reduced by the changes in the wattless current, it may in some cases be quite considerable. I should like to have the opinion of the authors on this point. The figures given in the paper for obtaining the relation of the voltage vectors with varying power factors of the load to be transmitted over the interconnector will solve most of the problems but will not give a solution when a booster is not in use. I believe that under these conditions the problem is indeterminate unless the current is split up into its components of useful current and wattless current. If this method is adopted, an accurate and easy solution of the problems under any conditions is possible. Fig. G shows the diagrams of electromotive forces for different conditions as regards wattless current. The following symbols are used: I_a = load current; I_w = wattless current; X = total reactance of interconnector (including transformers); R = total resistance of interconnector; and Z = total impedance of interconnector.

Fig. G (I) shows the relation between the E.M.F.'s when power is transmitted at unity power factor. AB is the E.M.F. at the delivery end of the interconnector; BC denotes the E.M.F. due to the load current I_aX and displaced 90° from E_R; CD is equal to I_aR or the ohmic drop due to the load current, and is of course in phase with E_R. AD then represents the E.M.F. E_S required at the sending end of the interconnector. If the power factor of the load to be transmitted varies from unity, the relation between E_S and E_R is somewhat more complex, on account of the wattless current. Fig. G (II) represents the E.M.F.'s when load having a lagging power factor is transmitted. AB is, as before, the voltage at the receiving end;



(I) Unity power factor (II) Lagging power factor (III) Leading power factor

FIG. G.

BC = I_aX, the E.M.F. due to the load current through the reactance, and CD = I_aR, the E.M.F. due to the ohmic drop of the load current. BD is then the impedance drop due to the load current and is equal to I_aZ. Referring to the E.M.F.'s due to the wattless current I_w, the value of this current is readily obtainable as it is fixed by the power factor of the load to be transmitted. It is clear that the impedance E.M.F. due to this current must be at right angles to I_aZ. It consists of two components, I_wX and I_wR. I_wX is in (time) phase with ER, while I_wR is displaced 90° from I_wX. The E.M.F. I_wZ due to the wattless current flowing through the impedance is then represented by DF, and the E.M.F. due to the total current flowing through the impedance by the line BF,* and from this value the

* The E.M.F. required at the sending end of the interconnector is then equal to AF.

amount of boost required may be obtained. Fig. G (III) shows the diagram when the power transmitted has a leading power factor. Considering the problem of transmitting a certain amount of power over the interconnector,* the solution may be obtained by drawing the diagram exactly as in Fig. G (II), except that the line DF representing the E.M.F. of the wattless current I_w through the impedance Z will be on the left-hand side of the line I_aZ, instead of on the right-hand side as in the previous diagram. Now as there is no boost the voltage at the sending end must be equal to that of the receiving end. Consequently E_S is known. I_wZ may then be obtained by taking A as a centre of a circle with radius E_S and striking an arc intersecting a line at right angles to BD. The wattless current required is, of course, obtained by dividing the E.M.F. by the impedance. The power factor of transmission may now readily be obtained from the diagram by the angles ψ and ϕ. It should be remembered that the current is lagging when I_wZ lies on the right-hand side of BD, and leading when on the left-hand side, and that the E.M.F. E_S leads E_R when it lies above the latter, and lags when below. Taking the plus sign as indicating leading, and minus for lagging power factor, the power factor of transmission is denoted by the expression cos $(\psi + \phi)$. Having obtained the power factor of transmission, it is a simple matter to calculate the power factor of either sending or receiving station from the load conditions of the respective stations. I have checked the figures given in the table shown by the authors, and obtained the power factors within $\frac{1}{2}$ per cent, which is sufficiently close for practical purposes.

Mr. P. Furness : The American practice appears to be to charge for current on two different scales—regulated and unregulated. Can the authors tell us what the difference is in price for the regulated supply as compared with the unregulated supply ? Is it the custom in America to tap the interconnector for individual consumers ? Voltage regulation would not have to be a very important consideration to a consumer connected to an interconnector. Referring again to the unregulated supply, what regulation is commercially necessary in practice ?

Mr. R. M. Longman : Fig. 1 is very interesting, and will be of great assistance to engineers considering this question. It shows at once that in the case of stations with equal voltages we can transmit power at only one power factor, but the power factor of the load transmitted depends on the ratio of resistance to reactance of the interconnecting line or cables. It is at once evident that if we wish to improve the power factor of the transmitted load the resistance must be diminished. I should like to know whether the formula for synchronizing power on page 293 includes the reactance of the generators. Also, can the authors give us some particulars as regards the reactance, resistance and capacity of some of the American transmission lines—although the actual conditions of America are not likely to be repeated here ? On the interconnection of two stations in this district about 15 miles apart in which the smaller station has more load on its network than it can usually deal with, a bank of transformers has been used as auto-transformers—the incoming interconnectors have been connected to the lowest tapping and the busbars to the highest tapping of the same winding, thus obtaining a boost of about 10 per cent. This has been of considerable value while larger sets were being installed, and has saved the expense of a regulator. The question of synchronizing power becomes of importance when the smaller sets are being replaced by larger ones. I once witnessed a good example of phase-swinging between two stations, many miles apart, which were normally connected through two lines—one having more copper and load capacity than the other. The systems were paralleled only through the smaller line, and as conditions were unstable the synchroscope was plugged in preparatory to closing up on the other line. The synchroscope pointer started swinging through a repeatedly increasing arc and finally had swung completely round, indicating that the other interconnecting switch had opened. One of the chief causes of hunting or phase-swinging is in the prime mover, and may be due to the governor of a turbine set. Cases have been known of stations operating in parallel and considerable hunting taking place ; this has been traced to the governor of a particular machine, and on this being taken off the trouble ceased. The switching-out of part of the interconnecting feeders between two systems has also been seen to cause phase-swinging, and on closing the switch more stable conditions have immediately resulted ; this is generally due to an increase in the amount of copper in the interconnection. The authors have mentioned the case of two regulators —one at each end of the line—as theoretically giving the best results, but that should not be allowed unless it is clearly understood that the operation of these regulators is under the control of one authority. Referring to the use of induction regulators for voltages of 11 000, I feel rather dubious about the advisability of using on this voltage movable flexible connections such as would be required for the rotor portion. One method of overcoming this difficulty would be to put the series windings of the regulator on the stator, and to use a transformer to step down the voltage for the rotor. A standard transformer could be used for this purpose, and the shunt winding could be for a voltage of 2 000 or even less. I do not know whether this method has been tried, but in any case I should like to know the authors' opinion regarding the advisability of using induction regulators at 11 000 volts, and whether the experience of their use in the States has been satisfactory. With further reference to the interconnection of two stations in which load has always to be transmitted in one direction, Fig. H has been made out for two particular stations showing, for a given load on the network of the smaller station, the amount of load in kilovolt-amperes and its power factor which the generators have to supply for varying amounts of power transmitted by the interconnectors at different power factors, the power factor of the network load being assumed to be 0·8. The method of using the diagram is as follows : For a given load supplied by the interconnector, say 20 per cent at a power factor of 0·9

* Without the use of a booster.

(lead), look along the 20 per cent line and where this cuts the 0·9 (lead) full line read off the value on the left-hand ordinate—in this case 92·3 per cent. Also see where the 20 per cent line cuts the 0·9 (lead) dotted curve and read off the value on the right-hand ordinate —in this case 0·67 (lag). This means that with 20 per cent of the network load transmitted by the interconnectors at 0·9 (lead) power factor the station in question has to generate 92·3 per cent load at a power factor of 0·67 (lag). A curve like this should, of course, be used in conjunction with another curve showing the voltage-drop on the interconnecting lines at the different power factors, and the two together should be of considerable assistance to a load despatcher.

ments is delivered into the Power Company's mains. It is not possible, however, during the dinner hour to keep the load to 1 000 kW, as the local load has fallen off and the amount of power delivered into the Company's mains is limited by the large wattless current which would trip the circuit breaker between the two systems. This is partly obviated by generating current at about 0·9 power factor, which reduces the wattless current supplied into the Company's mains ; at the same time, however, the pressure rises, but this is not very disturbing at that period of the day. With the exception of some surges and two or three cases of severe oscillations apparently caused by heavy fluctuations of load on the Company's system, the running has been very satisfactory, and it is pleasing to know that on one or two occasions the small station has been able to render slight assistance to the large one.

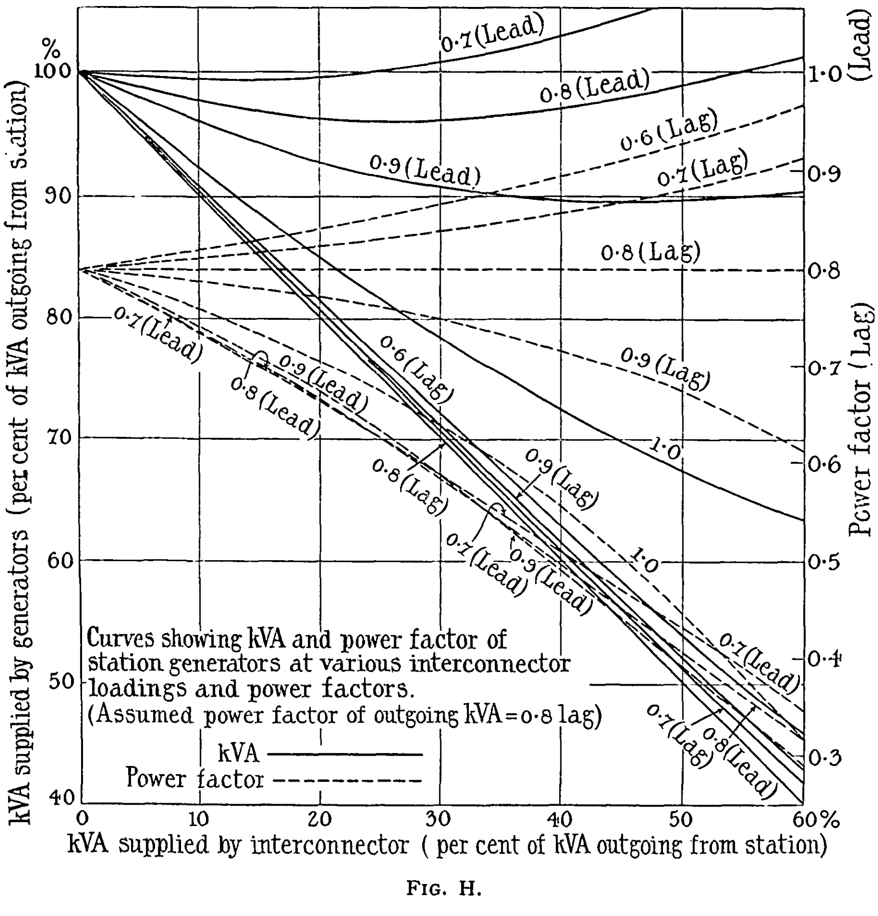


FIG. H.

Mr. S. D. Jones : This paper deals chiefly with large stations delivering power to one another. My case is that of a comparatively small station running in parallel with the Yorkshire Power Co.'s system. The bulk of our supply is direct current, and is a tramway, lighting and power load. We have also a growing alternating-current load. We have now been running in parallel with the Power Company's system for over a year and, on the whole, we have had little difficulty. The load is a steady one of 1 000 kW during the day, the steam plant being shut down during the night and at week-ends, the supply then being taken from the Company. Any excess load above local require-

Mr. C. A. Gillin : I think that I am not going beyond the scope of the paper in considering the case of several stations electrically interconnected but individually under the managerial control of the present undertakers. That is the position likely to result in some of the districts already delimited by the Electricity Commissioners. Unity of operation-control is shown in this paper to be absolutely necessary ; and the allocation of wattless current and its cost is a matter which may or may not be satisfactorily settled between the parties concerned.

The question as to how this control should be effected is another matter, and the authors appear to have had in view only the interchange of power on a comparatively small scale between two stations. Cases will arise in the near future when the interchange of power will range from small amounts up to 50 000 kVA or more. This means that several comparatively large cables, with their corresponding transformers, will be in parallel at high voltages, and, as the ratio of the reactance to the resistance will be high, no difficulties should arise in regard to the synchronizing capacity of the interconnecting lines. I agree with the authors that condition 3(*b*) referred to on page 289 will be essential for satisfactory control under these conditions, but I should like to have their views as to the number, size, and type of regulators to handle loads up to 50 000 kVA divided between 3, 4 or 5 large cables. Would they suggest stub busbars and one regulator; or one regulator per feeder with the transformer as part of the feeder unit; and, if the latter, should not the regulators be electrically interconnected? I should imagine that with these arrangements the electrical interconnection of the regulators would be extremely expensive, if not prohibitive. It appears to me that as there is at present absolutely no experience to guide one in these matters, it will be advisable to do the job first and tackle the troubles as they arise.

Messrs. L. Romero and **J. B. Palmer** (*in reply*): We agree with Mr. Juhlin that there would quite possibly be a considerable variation in voltage if the load were suddenly reduced at the receiver station, but it would be possible to adjust the voltage quickly if a regulator were installed. Our point is, however, that when condition (2) prevails, i.e. when a permanent "boost" is given to the interconnector, it is necessary to provide some means of adjusting the voltage difference to approximately zero before switching in and, while, of course, sudden variations in load will generally cause variations in voltage, we think that voltage conditions are more likely to be improved by the provision of regulating apparatus. The effect mentioned by Mr. Juhlin is an abnormal condition, whereas our statement refers to normal working.

Mr. Juhlin's diagram for determining the relationship of the voltage vectors in the interconnecter system is most interesting. We have compared the working out of a number of problems by the formulæ given in the appendix, with results obtained by Mr. Juhlin's graphical method, and find the latter to be reasonably accurate. For cases where the receiver power factor is known we find the use of our formulæ to be the simpler method, but in those cases where the receiver power factor is unknown, these including practically all the leading-power-factor conditions, Mr. Juhlin's method is undoubtedly more simple and satisfactory than the rather cumbersome trial-and-error calculations from the formulæ, and we consider Mr. Juhlin's contribution to the discussion to be very useful.

In reply to Mr. Furness, we are unable to say if it is general practice in the United States for the power companies to charge on two different scales for regulated and unregulated supply. The authors know of one case where this is done, but they have no information as to the difference in price. The amount of regulation required is not very large in the majority of cases, considering all the factors attending long-distance transmission which tend towards poor regulation, and in general does not exceed 10 per cent.

In reply to Mr. Longman, the formulæ for synchronizing power do not include the reactance of the generators; by definition the symbols E_1 and E_2 are the voltages at the end of the interconnecting cable. The point has already been dealt with in our replies to previous discussions. The reactance, resistance and capacity of transmission lines depend on a number of variables, e.g. length, size of wire and spacing, which in turn vary according to the voltage and total power to be carried. It would therefore be very difficult for us to give Mr. Longman any figures for the reactance, etc., of American transmission lines, except for a specific case.

We agree that the installation of regulators at both ends of a line would be likely to lead to difficulties if there was not a definite understanding at all times as to which station was responsible for the voltage control. With regard to induction regulators we agree that there will undoubtedly be cases where the size of the regulator or other circumstances might make it desirable to supply the rotor at a moderate voltage from a step-down transformer, but we think that there is no ground for apprehension in connecting induction regulator rotors direct on to the lines at 11 000 volts, and experience in the United States and elsewhere corroborates this view. The curves shown in Mr. Longman's diagram should be useful to the station staff, and could probably be constructed for any particular system for values of kVA or amperes instead of percentages of the total kVA load on the station.

Mr. Jones's experience of interconnection with the Yorkshire Electric Power Company is interesting. It goes to show that a small undertaking can be successfully run in parallel with a large one. We gather that the voltage and power-factor variations inseparable from interconnection without regulating apparatus are within the limits with which Mr. Jones is able to deal.

Mr. Gillin's questions, in so far as they apply to a general case, are difficult to answer. If an interconnection of 50 000 kVA or more were contemplated it would be necessary to take a number of factors into consideration. It is possible that a station of this capacity would be a new station delivering the whole of its output at one point, in which case there might be no objection to the busbar voltage being maintained at such a value as to give the maximum economy in transmission losses. A station of this capacity would possibly also be run as a high-load-factor station, in which case a permanent boost given by transformer ratio would probably be adequate to deal with the normal voltage requirements. If, however, the circumstances were such that only a portion of the outgoing feeders from a station had to be regulated, it would be quite possible to operate two or more regulators simultaneously from one controller. The "stub" busbar system suggested by Mr. Gillin would be worth consideration, but for interconnections of the size he is considering it would rarely be possible to effect all the adjustment by one regulator. We do not think it is possible to make a definite recommendation as to the best way of regulating very large interconnections, since there are so many variables, but we should be inclined to give full consideration to the synchronous condenser in these special circumstances, and we can imagine cases where it should be possible to transfer large blocks of power without employing any regulating apparatus at all.

LIVERPOOL SUB-CENTRE, AT LIVERPOOL, 20 MARCH, 1922.

Mr. J. A. Morton : The literature of this subject, in this country at any rate, is rather scarce, although a certain amount has been published in the United States. The problems in America are, however, rather different from those we have to consider here, as the distances are greater and the interconnections are made by overhead lines and not by cables, as is more often the case in England. The parallel operation of two power stations is similar to the running in parallel of two generators on the same busbars, the only difference being the impedance of the cable connecting the two stations, and one looks upon the cable as merely a reactance like that between two sections of busbar in the same station. At first sight it seems as though all one had to do to get the power to flow through it would be to raise the voltage at one end ; but in practice it is not so simple. The authors point out that the division of the load depends entirely upon the supply of energy to the prime movers and not upon the voltage adjustment. A difference in pressure between the two ends of the interconnector will not cause a transference of power through the cable, unless there is power available I wish to refer chiefly to the figures given in Tables 1 and 2. In col. 1 the size of the booster is given as 2 320 kVA ; this seems to be too large. With regard to Table 2, the comparisons are based on a 0·2 sq. in. cable, which will just carry the load, but it does not necessarily follow that this is the most economical size. In fact, it will be found that a 0·25 sq. in. cable would be more economical than a 0·2 sq. in. cable, because a considerable portion of the cable capital charges are for laying and jointing, and street work, and are constant for any size of cable. A 0·25 sq. in. cable would increase the capital charge by only about 10 per cent, but the energy loss in the cable would be reduced by 20 per cent. I merely mention this, not because it makes any difference to the authors' comparisons, but to show that the problem of the best size of interconnector is a separate problem inside the main problem. If a 0·25 sq. in. cable had been taken, the total costs of transmission would have been slightly reduced. In the authors' formulæ the capacity current is ignored, but I thought it would be interesting in this particular case to see what difference the capacity current would make. The capacity current in the 16 miles of cable is about 35 amperes (total), and when this is taken into account we get a smaller resultant current in the interconnector, a reduced loss, and a higher power factor of the current in the cable. It seems to me that a booster 10 or 12 per cent smaller can be used if the capacity current is taken into account in this particular instance. This is a point that might be worth looking into, particularly with a longer line. If the load were 5 000 kW instead of 10 000 kW the capacity current would make a much greater difference, because it would remain practically constant, while the load current would be halved and would thus have a proportionately bigger effect. On page 293 the ratio of reactance to resistance is given as 1 : 1. In a paper read by Mr. Wedmore some time ago the relationship was given as 2 : 1 as being reasonable between the machines, i.e. in the interconnector. I think that in the discussion which followed it was suggested that this ratio included the machine reactance as well as the reactance in the connecting link. The question arises as to whether the machine reactance should be taken into account in considering the 1 : 1 ratio proposed by the authors. We might take the case of a 6 600-volt interconnector, where there are no transformers in the circuit. If an underground cable were used, it would have very little reactance in itself, but if we assume the usual 10 per cent generator reactance and include this at one end of the cable we can go up to about 10 miles without inserting any extraneous reactance in the cable. If, however, the generator reactance is left out of account we should have to insert an extraneous reactance of about 10 per cent in such an interconnector, as a working necessity for the purposes indicated in the paper. Probably we should insert such a reactance in any case for safety. If the tie line between these two stations were not a cable but an overhead line, its inherent reactance, which is about 4 times as much as in a cable, would be sufficient so far as reactance is considered as a working necessity. As an alternative to varying the voltage, the impedance of the line could be varied by altering an extraneous reactance, and I should like to know whether this has been done in practice. It seems to me that the condenser method is the most ideal for purposes of regulation, because condensers will deal with power-factor variation and pressure variation, and the transmission losses will be kept low : the kVA load on the alternators is also reduced. If static condensers could be built for 6 600 volts, and I see no reason why they should not be, the loss in them would be much smaller than with moving synchronous condensers and they would require less attention. One point that is not touched upon in the paper is the question of the earthing of the neutral point where power has to be transmitted between two interconnected stations in both directions.

Professor E. W. Marchant : I should like to say a word on the purely economical side of interconnection, because it is very important. It is necessary first of all to consider the question of interconnection purely from the point of view of economy. I have worked out from figures given in the paper—I understand they are on the high side—the actual cost of transmitting energy over the 6 600-volt cable, data for which are given in Table 2 ; the figures work out at almost exactly 0·01d. per kilowatt-hour per mile, for transmission. If two power stations are separated by any distance it is easy to find out from that figure whether it is going to be really economical to interconnect the stations, that is, to put additional plant in one station or to increase the plant in both of them. If it will be cheaper to take coal to one station rather than to the other, by the amount corresponding to 0·01d., then the interconnection is sound from the purely economical standpoint. That is only one side of interconnection. The other side of the question is what we might call the insurance side. If there is an interconnecting cable between two such stations as those given in the paper it will cost about £100 000 to install, but 10 000 kW of spare plant will be saved in one or other of the stations, because instead of putting spare plant in both stations it has to be put in only one, and it therefore seems to me from the insurance point of view that the cost of an interconnection cable can be balanced against the cost of spare plant. From that point of view it is cheaper to install cables than additional plant, which is certainly going to cost more than £100 000. I have not calculated the probabilities of breakdown occurring simultaneously in these stations, but obviously it will be very small. If the probability of a breakdown in one station is taken to be 1/100, then the probability of a breakdown occurring in the two simultaneously will be 1/10 000. The risk of breakdown in the cables is smaller still, and I think the assumption I have made, that the interconnection is equivalent to spare plant, is justified from the insurance side of the question. The cost of the cable can be set against that of the plant. It is clear from the paper that there is an economic limit to the distance over which interconnection can be successfully carried out. Now I come to the operating side, which is the main subject of discussion in the paper. The problem of running two stations in parallel seems to be fairly simple, but it is not actually so simple as it seems. To ensure successful parallel running between generators, a large synchronizing power is usually necessary, and the current flowing in the interconnector for this purpose must lag nearly 90 degrees behind the difference in the pressures at the generating stations. The transmission of power between the two stations will alter the phase of the synchronizing current, and I should like to ask the authors whether they have heard of any difficulties in parallel running with interconnected stations. It should be possible to compensate for the additional resistance and reactance inserted in the path between the two parallel-running generators, by the use of boosters. Where long cables only are used for interconnection, I should imagine that there might be considerable difficulty. The synchronizing power between the two stations must be less than when the two generators are side by side. To emphasize that point take a modern machine, in which the resistance of the stator absorbs from $\frac{1}{4}$ to $\frac{1}{2}$ per cent of the full potential difference when full-load current is passing. In the interconnector about 10 per cent of full-load pressure is absorbed when full-load current is passing, i.e. there is 20 times as much resistance as there would be if the two machines were side by side, and it follows that the synchronizing power must be very much reduced.

Mr. L. Breach: One of the authors suggested that I should say a few words in reference to the last slide which they showed. The slide refers to that part of the system of the Hydro-Electric Commission of Ontario which is supplied from plant at Niagara Falls. There were 4 stations when I was there, and a fifth has been put into operation quite recently. On the American side there is one station of 400 000 kVA capacity, and on the Canadian side two of 100 000 kVA each and one of 200 000 kVA. This latter is the only one at present under the control of the Commission, though the 800 000 kVA are coupled and feed into this system and other systems. These four stations generate about 12 000 000 kWh per day, while other steam-driven plant of about 200 000 kVA feeds into the systems, making a total of about 1 000 000 kVA interconnected. While I was visiting one of the steam stations the question of power factor was brought home to me very forcibly; there were three 20 000-kVA and one 35 000-kVA sets installed, about 50 000 kVA being taken from the Falls 25 miles away by overhead transmission. The 35 000-kVA set was running with only 7 000 kW of load but about 22 000 kVA apparent load, and the power factor was 0·35. This 15 000-kVA wattless component was due to the Falls insisting on unity power factor; and when one considers what it means in increased capital to the sending end in additional generating and transforming plant and also in transmission, one is not surprised at this insistence. At another Canadian station there were two 6 000-kVA rotary condensers at the end of two 75 000-volt transmission lines. These had their own transformers, automatic field and regulating gear, and high-pressure pumps to enable the condensers to start up as induction sets. This seemed to me to be very complicated and showed me most forcibly the necessity of always taking care of the power factor of the supply. It might be thought that the present paper deals with conditions which do not exist in this country, but this is not so, as in the case to which I have referred the supply and receiving ends were only 25 miles apart. I agree with the authors' statement that constant voltage should be kept at both sending and receiving ends, but surely if the transformers form part of a transmission line the busbar voltages could be kept constant by varying tappings on the winding of the transformers and allowing the power factor to swing with the load. It must be admitted, however, that Fig. 5 seems to point to the desirability of the induction regulator. I should like to know if the regulator in the sending end of one feeder and that in the receiving end of the same feeder can be adjusted electrically and coupled by pilot wires controlled by hand or automatically so that the adjustment is done from the sending end only, and whether this is advisable. I should also like to know the temperature-rise that might be expected in the regulator under normal conditions, and also the cost per kilovolt-ampere of the regulator.

Mr. H. Dickinson: I should like to know if the authors can say why the load factor is so much higher in the United States than in this country, as shown in the table. Is it due to the system of selling at a contract rate of so much per lamp or so much per horsepower per annum, or to the fact that the factories work longer hours than is the custom in this country? At the bottom of page 289 a new type of boosting apparatus is referred to. I should be glad if the authors could give any information as to the principle upon which this apparatus is being developed.

Mr. A. E. Malpas: When we come to consider again the question of coupling up stations, the figures given in the paper might be of assistance. I was rather struck at the outset with the various difficulties that we are encountering; in fact, the first pages would lead a novice to expect that the problem had no solution, but towards the end of the paper I was rather comforted to know that in America they have carried out these long-distance interconnections and, as the authors point out, the problem there is slightly different from that in England, but it is a case that one meets with in different parts of the world. I have had it in my own experience in Spain, where we interconnected a 100-km line. In Madrid we had a gas power-driven station that was not very economical and reliable, and we had to go further afield and then install a 20 000-kW long-distance transmission. Coming to more recent times we have also a problem in this immediate neighbourhood where many outlying stations will have to link up. Bootle and Liverpool have already done so, but that is a short line and I should like to know what troubles were experienced.

Mr. C. Rettie: The serious breakdown which occurred in 1919 on the Chicago power supply system, which consists of three stations, divided into 4 sections and having a total capacity approaching 500 000 kW, was due to a short-circuit, and 18 minutes elapsed before synchronism was finally obtained. I should like the authors to say if, to their knowledge, the system of interconnectors referred to in the paper was in service in Chicago at the time of the breakdown, and, if not, whether the use of such a system would have saved the situation.

Mr. L. B. Wilson: There does not appear to be any mention in the paper as to how a receiving station would connect the transferred current to its supply. Taking the 10 000 kVA mentioned in the paper, would it be treated by the receiving station as a separate unit to replace a generator which for some reason has shut down, or as a general addition to the supply? If the former, then where the busbars were sectionalized and connected through reactances it would be necessary to have facilities for connecting up to any section of the busbar, or if the latter, where a permanent connection was made on to one section, it would probably necessitate the provision of busbar reactances of almost equivalent value to those already in use in other sections of the busbars. There would certainly be the inherent reactance of the inductor regulators and transformers, where used, but these, being the probable places where breakdowns would occur, could not be relied upon to limit the fault current, as under certain conditions the fault would be fed from at least two stations. If the authors think that additional reactances are necessary, how will the working of the inductor regulators be affected? In the case of stations which will be connected together, more or less permanently, it will not be possible to use the present method of earthing the neutral points of the generators at the different stations, owing to the heavy circulating currents which might arise, causing trouble to the telephone and telegraph services. If only one station were earthed, what would be the effect of this condition on the other? I think that a combination of reactances and a resistance has been used in one station for earthing the generators, and probably this method would be satisfactory for earthing interconnected stations; the neutral points of all the generators would be connected together through separate reactances to a common point at each station. These two points would be connected by means of an insulated cable which would be earthed through a single resistance. The circulating currents at triple frequency, between generators, would be taken care of by the reactances, which at this frequency have 3 times their nominal ohmic value, and any possibility of trouble due to resonance is prevented by the resistance in series with the reactances The amount of reactance mentioned as being inserted in the interconnector seems to be rather low. In many cases at the present time the insertion of 15 per cent, 20 per cent and 25 per cent reactance in these cables is being considered. How will the added reactance affect the regulators? When two stations are coupled together it is quite possible that with any fault between them they will be fed from two generators; where, therefore, is it proposed to put whatever protecting gear is required for the regulators, because when coupling up is proceeding the regulating gear will be one of the weakest points and will be fairly near the stations? In this case it would appear to be necessary to put in protecting gear such as reactances between the regulators and stations. If so, will they upset the operation of the stations?

Mr. H. Midgley: I should be glad if the authors in their reply would give a diagram of connections of an induction regulator, showing three phases. In the case of a consumer taking power at a low power factor, is it possible to save copper and reduce heating losses by installing an induction regulator and so loading the supply cable at unity power factor? If so, how would the regulator be connected up? I understand that where induction regulators have been installed in conjunction with interconnectors carrying varying loads, it is the usual practice for the operators to adjust them to suit the load at regular intervals, say every 10 minutes. I should like to know whether there would be any difficulties in the way of automatic operation. Professor Marchant touched on the synchronization of interconnected power stations, and I should like to amplify his remarks. If two stations are linked upon the high-tension side, and adjacent points which have a phase difference are found on their low-tension networks, what would be the effect of connecting these two points? Can the authors give any comparison of calculations and actual working figures obtained from such an interconnected system as the Newcastle Electric Supply Company? I should like them to incorporate in their reply the calculated figures for the loads on the interconnectors of a system of three or more stations working in parallel.

Messrs. L. Romero and **J. B. Palmer** (*in reply*): Mr. Morton points out an error in the capacity of the booster given in col. 1 of Table 1. This has since been corrected for the *Journal*.

The determination of the most economical size of conductor to use for transmission lines did not form part of the scheme of the paper. For any given set of conditions it is of course a fairly simple problem, but in practice the principal condition, viz. the extent and duration of the load, is always unknown and has to be estimated. These estimates are often falsified by the event, and we think that for underground cables it is a safe rule when in doubt to select the larger size.

Mr. Morton's remarks on the effect of capacity current are interesting, and we agree that for long lines it would be of importance and would have to be fully considered.

The greater capacity of cables as compared with that of overhead lines will be quite an important advantage where long transmission lines are concerned, as the improvement of power factor on the whole system due to the capacity current of the cables will be very beneficial.

We have already dealt with the effect of capacity and the contra effect of the magnetizing current of transformers at greater length in our reply to the Manchester discussion (see page 811).

We would also refer Mr. Morton to our reply to the Manchester discussion on the question of the ratio of reactance to resistance.

We are not aware of any cases where the control of power factor in tie lines is obtained by varying the reactance in the line, although we see no reason why this method should not have a limited field of application in conjunction with fixed boost and transmission of power in one direction only.

When double-wound transformers are used in the tie line there is no difficulty about the earthing of the neutral points at both stations. If transformers are not employed the present Board of Trade rule allows the neutral point to be earthed at only one station, although in the light of American experience we are of opinion that this rule might very well be modified.

Professor Marchant's remarks on the economy and insurance sides of interconnection are most valuable, and he states that side of the question very clearly indeed. He also touches briefly on the chief technical points and we are in general agreement with what he says.

Mr. Breach gives some very interesting information about the system of the Hydro-Electric Commission of Ontario, emphasizing, as he says, the importance of taking care of the power factor of the system.

The method of controlling the power factor in the tie line by variable regulating tappings on the main transformers was mentioned in the paper, and is certainly the most economical if the practical difficulty of designing thoroughly reliable step-by-step switchgear for such high voltages and large currents can be overcome.

We have no doubt that the operation of two regulators, one at either end of the tie line, could be controlled together from one station only with the aid of pilot wires, but we do not think that the cost and complication of such an arrangement would ever be justified, as with boosters installed at both ends a pre-arranged system of control aided by the telephone should ensure satisfactory working.

Induction regulators are designed for the same maximum temperature as ordinary oil-insulated transformers, viz. 90° C.

In reply to Mr. Dickinson, the high load factors of the American power companies are due to numerous causes. The very large financial outlay involved in hydro-electric generation and long-distance transmission tends to limit the number of undertakings engaged in the industry; the area of supply of any one undertaking therefore is generally very large. This allows the greatest possible advantage to be taken of the diversity of industry and non-coincidence of peak loads. In California irrigation gives inherently a high load factor, and in addition the electrification of railways has been carried much further than in this country. There does not appear to be any tendency in the United States for the railway companies to erect power stations for their exclusive use, and the railway load is therefore an important factor in raising the load factor of the power companies' systems.

The boosting apparatus referred to on page 289 consists of a contactor-type step-by-step regulator in conjunction with static transformers, and is proving satisfactory.

We are sorry that we have not the necessary information about the Chicago power supply system to enable us to reply to Mr. Rettie's question.

Mr. Wilson asks how we would propose to connect the tie line to the busbars. Where busbar reactances are not employed the connection would be the same as for the other circuits, and even where busbar reactances are employed it would probably be quite safe to treat the tie line as a feeder circuit, owing to the fairly high inherent reactance of a line with step-up and step-down transformers at the ends.

We have already dealt with the subject of earthing the neutral point in replying to Mr. Morton and also in our reply to the London discussion (see page 301). We can only add here that the method of earthing the neutral points of two interconnected power stations by means of a special earthing cable between the two stations which Mr. Wilson mentions seems to us to be costly and unnecessary.

Mr. Midgley appears to have confused the functions of an induction regulator with those of a synchronous condenser. The induction regulator is simply a booster and does not improve the power factor of the system as a whole in the slightest, its only function in a tie line being to control the power factor of the load in the tie line or, in other words, to control the division of wattless current between the two stations without reducing the total wattless current to be supplied by the generators as a whole. The answer to his first question is, therefore, in the negative.

The automatic operation of induction regulators in the tie lines to keep the power factor constant would present no special difficulties. We would refer Mr.

Midgley to our reply to Mr. Howarth in the Manchester discussion in regard to the effect of interconnected networks in parallel with tie lines.

We can assure Mr. Midgley that our calculations agree with actual working results on interconnected systems. The method of calculation given in the paper can be applied as well to three or more interconnected stations as to two, and we therefore think that no useful purpose would be served by working out such examples here.

South Midland Centre, at Birmingham, 26 April, 1922.

Mr. R. A. Chattock: The paper deals with a very important subject from the power station engineer's point of view, and a question that is likely to assume greater importance in the future in view of the lines upon which supply is now being developed in this country. The authors deal more especially with the theoretical requirements for interconnecting a.c. power stations, and have apparently overlooked the practical requirements, which are quite as important. I wish to call attention to the practical difficulty of synchronizing and interconnecting two loaded stations after these have become disconnected due to any disturbance on the system. In the Birmingham Electric Supply Department there are two large-capacity stations and two stations of smaller capacity all running in parallel on one system, and, due to a disturbance on the system, two large sections of the supply were disconnected. In order to re-interconnect them, very great care had to be taken to get the two sides running in perfect synchronism before the connection was made, as otherwise a very heavy strain would probably have been thrown on to the system at the moment of closing the interconnector, due to the inertia of all the plant running on circuit—both generators and motors—which had to be pulled into synchronism if the two sides were not exactly in step. Such a strain, if it occurred, would probably set up a very heavy surge on the system, and would most likely have the effect of again opening the interconnector. It is generally found necessary to have men standing by to throw in additional interconnecting cables directly the first one is connected, so as to give ample capacity in the link for dealing with a surge of reasonable dimensions. What arrangements are made in the large American undertakings referred to in the paper, for metering the current that is interchanged ? This current might be passing in one direction one day and in an opposite direction the next, and it would be interesting to know how the practical difficulties are obviated.

Mr. W. Lawson: The authors do not state whether the values given in Table 1 for transmission losses as a percentage of kilowatts delivered include booster and transformer losses. I should be glad to know the extent of these losses. Although the booster and transformer losses are probably small relatively, they should obviously be included in the losses involved in the scheme of interconnection. It is clear that the transmission losses in the interconnector can under certain circumstances be considerable, and it is desirable that in the parallel working of power stations they should be ascertainable. The consideration of these losses raises the question as to whether they should be put down to generation or distribution. In the simple case of two stations linked up by an interconnector which is not connected to the network at any point between the stations, the interconnector may be regarded purely as a busbar, and the two stations as portions of one larger station. In this case it would appear that in calculating the efficiency of the stations the losses in the interconnector should be taken into account. A method of ascertaining the transmission losses is to install at each station two watt-hour meters, one to measure the input and the other the output, each meter having a ratchet and pawl attachment to prevent reverse registration. With this arrangement the total kWh lost in the interconnector would be represented by the difference between the kWh registered by the output meters and those registered by the input meters. Changes in the direction of the load transmitted would not affect the accuracy of the result. It should be borne in mind, however, that this method would not entirely hold good if the interconnector were used to supply feeders along its route. In such a case the kWh delivered to the feeders would have to be metered and taken into account in computing the losses in the interconnector. The authors' statement as to the effects of power-factor variation shows the importance of ensuring that the power factor is accurately measured, as a false indication of the instrument might lead to the undesirable effects described being created unknowingly. I suggest that the use of graphic recording instruments at both ends of the interconnector would be advantageous as affording a convenient means to the engineer for ascertaining whether the prescribed conditions of operation are being maintained.

Mr. W. Wilson: The authors have not devoted a section to the advantages of interconnection, and I think that a few words from them would be of interest, if for no other reason than to bring home the importance of their subject. There is, however, one advantage which is made evident in the last appendix. This advantage is an indirect one, which might be overlooked until actual working had brought it to light. The undertakings in this country are largely of municipal origin, instituted by a borough or city authority to supply the needs of a limited area. The result has been that in addition to their being on the whole comparatively small and inefficient, the tendency has been not to see much further than the supply of street lamps, the lighting of the more accessible shops and dwellings, and such favourable motor loads as have come within the reticulation. Thus the cost of current, even where it is easily available, is on the average much too high, the load factors are far too low, and the use of electricity is enjoyed by but a favoured few town dwellers. A policy of interconnection, by joining up the separate plants into a combined system, would, in addition to its other advantages, bring the supply within the reach of many other less favourably situated customers, with consequent improvement in these various respects. It is by the provision of power for the host of miscellaneous consumers situated away from the dense part of the town, such as brick works, flour mills, tanneries, dairy factories and farms, that the good load factors experienced abroad, and evident in the list given on page 297, are secured. It may be interesting to mention that the two islands of New Zealand, each of which has a length approximating to that of the power area in the Western States illustrated by one of the lantern slides shown, namely about 550 miles, are being equipped with generating plant in a series of large hydro-electric stations, which are designed to be interconnected much in the manner described in the last appendix. The schemes are being laid out with that end in view, and already the advantages of a high load factor have been experienced. There is no doubt, on the other hand, that harm has been done in the past by considering interconnection as a substitute for centralization, in the case of districts like Greater London which are supplied by a large collection of miscellaneous, small stations. The improvement of the London supply by the institution of a few large plants, in place of the extraordinary number of small ones that did the work in the past, appears to have been considerably delayed by the recurring proposal to interlink the existing stations, an expedient which, according to the supporters of the proposal, would effect the same end. As a matter of fact, until the war the two schemes mutually conflicted and neither was carried out; but there is little doubt that the result of joining together these heterogeneous plants would have been chiefly to increase the overhead charges without securing anything like a corresponding advantage. In the main, however, interconnection is a most important principle.

Mr. G. Rogers: The interconnection of generating stations belonging to the same authority and situated at no great distance apart offers no special difficulty. In such cases it is largely a matter of careful design of the interconnector and feeder system, with particular attention to the sectionalizing of the busbars into groups with graded reactances to minimize trouble under fault conditions. The transfer of load to meet changing conditions can be readily effected by voltage variation and adjustment of the steam supply to the generators, without the necessity for booster plant. In Birmingham the interconnection of the generating stations is effected by a combination of tie lines and feeders which feed into substations situated between the generating stations. The arrangement is very satisfactory and efficient. The problem as it affects power stations belonging to different authorities and situated at considerable distances apart becomes a different proposition.

The authors have shown very clearly the difficulties involved. A study of Table 1 emphasizes the fact that the power factor of the transferred load is one of the vital points to be determined. In the hypothetical case taken it would appear that to transmit the load at unity power factor—the most economical condition as far as the interconnector feeder is concerned—would make the position of the receiving station rather unfortunate in so far as it has to deal with a very large wattless component. It is obvious that in such a case amicable co-operation by the authorities concerned would be necessary to arrive at a definite design of interconnection, power factor of the load to be transmitted, choice of booster plant, and the best means of dealing with the wattless component. If possible, the combination of tie lines and interconnector feeders feeding into common substations would be advantageous in most cases. In regard to the types of booster plant, I consider that the induction regulator, though expensive, is the best to adopt. It is a most reliable apparatus and does not seem to offer the difficulties involved in a step-by-step regulator.

Messrs. L. Romero and **J. B. Palmer** (*in reply*): We are inclined to think that the difficulties experienced by Mr. Chattock in synchronizing and interconnecting two large loaded stations must be due to some special conditions obtaining on his system, as we have not encountered in our experience difficulties of this nature which were not overcome after a little practice in synchronizing. If the synchronizing is done at one of the power stations the usual plan is to close the switch when the station which is required to draw load is running at a very slightly lower speed than the other, after which the load is at once regulated by the governor control switches. We have had no experience of attempting to parallel two systems at a substation where the control of the steam supply could be carried out only over the telephone, but we can imagine that this might be a lengthy process and perhaps hardly feasible.

The metering problem which Mr. Chattock mentions is probably best dealt with in the manner explained by Mr. Lawson, with one meter to register input and the other output, but a.c. meters are made to register in both directions with sufficient accuracy, and if only the difference between input and output is required a standard meter could be used.

In reply to Mr. Lawson, the values given in Table 1 of the paper do not include the transformer iron losses and booster losses, as these losses do not affect the voltage condition. They do, however, include the transformer copper losses.

The transformer losses will prove the major portion of the total losses in a short interconnector employing step-up and step-down transformers, and in all interconnections employing transformers likely to be carried out in this country the transformer losses will be an important part of the total losses. The booster losses will generally be only a very small percentage of the total losses. We agree with Mr. Lawson that the losses in the interconnector should be taken into account in calculating the efficiencies of the stations, and we think that his suggestion for the use of graphic recording instruments is a good one.

Various speakers who have taken part in the discussion on our paper at other Centres have brought out the advantages of interconnection, and we will only add here that these advantages should be very considerable in an interconnected system designed and controlled under one supreme authority to obtain the maximum efficiency and reliability over the whole system, as the most economical plant available would be run at all times, and at week-ends and possibly at night only one station need be run. In addition, there would be a large saving on capital expenditure for spare plant.

We quite agree that the interconnection of a number of small, inefficient stations is not the best cure for their high costs.

The arrangement of interconnection mentioned by Mr. Rogers with tie lines and interconnecting feeders feeding common substations is a good one, but the power-factor effects on parallel feeders having different reactances and resistances should receive careful considerations before they are installed, particularly where transformers are employed in one line and not in the other, as undesirable and unexpected results might otherwise ensue.

DISCUSSION ON "THE EFFECT OF HEAT ON THE ELECTRIC STRENGTH OF SOME COMMERCIAL INSULATING MATERIALS." *

Mr. A. Collins (*communicated*): The term "micarta" appears to have been used by the author to describe all materials composed of layers of paper stuck together with a varnish. This term however, is, generally understood to be a trade name describing only one variety of the product, and as a generic term "varnish-paper boards and tubes" is gradually being adopted. In the study of data dealing with such material as a class it must be remembered that, apart from being manufactured by various firms, individual firms may supply different grades depending upon the class of service. High dielectric properties may on occasion be of less importance than other features, and in any case the dielectric strength is not the only property to be considered when comparing the merits of different materials. Again, boards and moulded troughs may be made up of quite different materials from those used for transformer cylinders, bushings and terminals. This distinction is of importance when the results of tests are being compared. The section of the paper dealing with this material is of exceptional interest because of the rapid developments which are taking place in high-voltage oil-immersed apparatus for which, in the case of transformers, oil temperatures as high as 90° C. are permitted by the British Engineering Standards Association.

A study of Figs. 6, 7 and 8, particularly Figs. 6 and 8, gives rise to speculation as to the factor of safety of apparatus insulated with such materials, when the temperature of the oil approaches 90° C., and users of such apparatus may feel some cause for alarm when the author suggests that more satisfactory results are still to some extent in the experimental stage. Large quantities of "varnish-paper tubing" are employed in the construction of oil-immersed switchgear and transformers as bushes, terminals and cylinders, and this question of the effect of temperature has for a long time been fully appreciated by a number of engineers. Obviously, apparatus should be pressure-tested at the maximum permissible temperature, otherwise with characteristics similar to those illustrated in the paper the factor of safety may easily fall below unity at the higher temperatures. The testing of finished apparatus hot, or even the application of an equivalent test, may be inconvenient, but it is nearly always possible to test individual insulators or pieces of insulating material at the maximum permissible temperature of the apparatus. This has for some time been the practice of at least one firm in this country specializing in high-tension insulating materials. The paper will no doubt tend to make this condition more general. Some information as to the behaviour of the actual materials used in the manufacture of switchgear and transformer bushings and terminals should be of interest as a record of up-to-date practice, and as an illustration of the improvements that have resulted from systematic research.

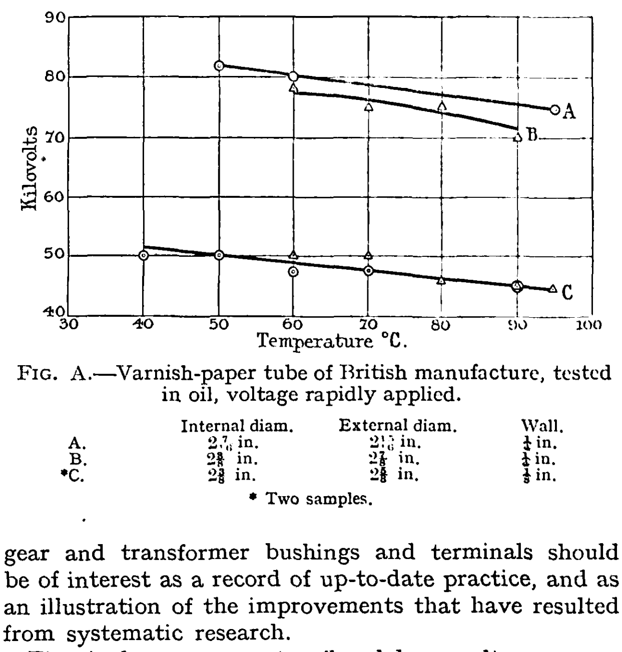


Fig. A.—Varnish-paper tube of British manufacture, tested in oil, voltage rapidly applied.

	Internal diam.	External diam.	Wall.
A.	$2\frac{7}{16}$ in.	$2\frac{15}{16}$ in.	$\frac{1}{4}$ in.
B.	$2\frac{3}{8}$ in.	$2\frac{7}{8}$ in.	$\frac{1}{4}$ in.
*C.	$2\frac{3}{8}$ in.	$2\frac{5}{8}$ in.	$\frac{1}{8}$ in.

* Two samples.

Fig. A shows temperature/breakdown-voltage curves taken on four samples of tube. These samples were tested in the normal condition, without any special heat treatment, and the figures represent instantaneous breakdown, i.e. breakdowns obtained by raising the voltage rapidly, so that failure occurs in about 5 seconds. It has in the past so often been the practice among engineers to discuss insulation in terms of instantaneous breakdown that the curves have been produced in

* Paper by Mr. W. S. Flight (see page 218).