TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JANUARY TO DECEMBER 1924.

VOL. XLIII

PUBLISHED BY THE
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS
33 WEST THIRTY-NINTH STREET
NEW YORK, N. Y., U. S. A.
1924

Preface

In issuing its forty-third annual volume of TRANSACTIONS, the American Institute of Electrical Engineers has published in chronological order the papers and discussions presented at the four conventions and two regional meetings held under its auspices during the year, 1924. The articles have all been printed in the JOURNAL either in full or in abridged form; they are published here in entirety with the discussions for each special group immediately following. Owing to lack of space several articles of importance but of somewhat transitory interest have been omitted. These will be found listed on page 1369. The reports of the Technical Committees at the Annual Convention are included; also the Board of Director's annual report for the fiscal year ending April 30, 1924, and lists of the several officers, committeemen, Section and Branch officers for the corresponding period, appear toward the end of the volume. The index contained herein is a greatly improved feature, the subjects being classified under general headings chosen with regard to the information contained in the papers. In many instances the subjects are also cross-referenced.

Superpower Transmission

Economies and Limitations of the Transmission System of Extraordinary Length

BY PERCY H. THOMAS
Fellow, A. I. E. E.
Consulting Engineer, New York, N. Y.

Review of the Subject.—*This paper is a study of the transmission of very large blocks of power for extraordinary distances and has for its purpose the bringing out of the major operating characteristics of such a system, the characteristics which it possesses which are different from those of shorter transmissions and the duties imposed upon generators, transformers, synchronous condensers, switches, etc., primarily as affecting their design. The paper defines a superpower transmission line as a line of great length in which the charging kilovolt-amperes per mile of length is of the same order of magnitude as the reactive kilovolt-amperes developed by the full-load line current passing through the reactance of the line and in which the resistance is small relative to the reactance.*

Such a line is adapted for economical transmission only for a fairly definite amount of load and any great increase or decrease below this po nt leads to poor economy or unstability. Since, however, the load appropriate to a given line depends upon the voltage, an appropriate line can be laid out for any reasonable amount of power to be transmitted.

In order to secure a definite set of conditions to serve as a specification for determining the performance of generators, transformers etc., all applying consistently to the same system, a typical hypothethical transmission has been assumed, namely, a delivery of 400,000 kw. over a distance of 500 miles over four circuits 220,000-volt at each end.

The characteristics of this line are worked out showing the efficiency, condenser capacity required, data on circuit breaker arrangements, protective relays connection to receiving network, provision for spare parts, switching of units and ratings of various apparatus.

It is shown that such a system is very sensitive to the receiving end voltage; when this voltage drops there will be a tendency for the generators to run away if the system is not properly laid out.

In addition a discussion is given of the effects of various prescribed values for the terminal voltage between 220,000 and 245,000 to show the effect of increasing the voltage 10 per cent, of maintaining the generating end 10 per cent higher than the receiving end and also of stabilizing the middle point wit h synchronous condensers.

The typical hypothetical case chosen shows one layout, it being recognized that other layouts may be chosen. This particular layout is operated without any high-tension switching of live lines. The layout is intended to relieve the duty on circuit breakers and as a matter of fact no breaker can be called upon to interrupt a short circuit of more than ¾ of a million kilovolt-amperes; this is a very favorable condition and is secured without materially limiting the equalization of the load. The layout connects with the assumed distribution net at a considerable number of points and no large portion of the total delivered power can be concentrated at any one point; this serves to secure a very intimate connection between the network and the transmission, and at the same time prevents any one breakdown, however, complete, from materially disturbing the major portion of the transmission system.

INTRODUCTORY

THE art of electric power transmission is just entering upon another stage of development, and this a most important one. The period characterized by the general adoption of the 100,000-volt line has been most fruitful. The coming period with lines of voltages in the neighborhood of 225,000 volts and of very great length will be marked by important changes from the old apparatus and the old practise. Considering electrical problems, the 100,000-volt line, to the usual designer, is a problem in drop, to keep the voltage at the substation within reasonable range of the generator voltage with varying load, to secure a good efficiency, and to watch the charging current to see that the light load conditions do not cause an unduly high potential or overload a generator. There is also the problem of insulation, but this is constituted largely of selecting a good make of insulator and watching the manufacturer, also the maintenance of the insulators in good condition during operation.

For the superline of the coming period, the problem of the designer is much more complex. The matter of power factor instead of being merely one of the underlying factors in drop calculations, becomes the all-important feature of the line, serving as the only feasible means of controlling voltage and efficiency. It must be completely under control of the operator. Instead of establishing the voltage at one end of the line as a means of controlling the voltage at the other end, the voltage in the superline must be controlled at both ends and care taken to keep track of the voltage at the center of the line to see that it does not rise too high. Instead of adding reactance to keep down the heavy current in short circuits, as in the 100,000-volt system, the designer will find that with the superline the short-circuit current may not greatly exceed full-load current and that the securing of enough current over the line to insure the holding of the machines on the two ends of the line in synchronism at times of disturbance becomes a serious problem. Other features bring forward novel conditions.

It is the purpose of this paper to discuss the nature of the super transmission system, bringing out some of the peculiarities characteristic of it and to offer some numerical data to give some measures of its economies and limitations. In order to give concreteness to the discussion, a typical but hypothetical example is chosen and the layout worked out in enough detail to develop the novel problems involved and suggest solutions. A sufficient number of calculations are made to determine

Presented at the Midwinter Convention of the A. I. E. E., Philadelphia, Pa., February 4-8, 1924.

the performance of the system under all conditions normal and abnormal.

CAPACITY

Unlike the ordinary 100,000-volt transmission line, chosen for efficiency or regulation, the superline has a substantially definite kilowatt capacity which cannot be practically exceeded. In this use of the term, a "Superline" is to be taken as a long line in which the kilovolt-ampere of charging current is numerically of the same order as the kilovolt-ampere developed by the load current in the reactance of the line, and in which the resistance is small in comparison with the reactance.

The dominating role of this relationship of charging kilovolt-ampere to line reactance kilovolt-ampere, set forth in a paper of my own in 1909, has been well expounded by Mr. Harold Goodwin, Jr.[1]

Very briefly its significance may be stated as follows: Since the resistance component of line drop is proportional only to the resistance, which can be made as small as desired, while the reactive component is proportional to the reactance of the line, which is substantially fixed beyond the control of the designer, the kilowatt capacity of a line cannot be made to exceed the fixed limitation imposed by the reactance unless some additional factor be introduced. The reactance considered alone would greatly reduce the capacity of superlines below that actually available. It would largely eliminate any advantage in the reduction of resistance beyond a certain point.

This situation may be avoided, however, by proper control of the line charging current; which fact may be explained as follows: For any definite section of line the charging current represents a certain kilovolt-ampere value, having a phase 90 deg. in advance of the voltage ($\frac{1}{2} C V^2$). Similarly in that section of line there is a kilovolt-ampere value due to the current passing through the line reactance ($\frac{1}{2} I^2 X$) which is 90 deg. behind the line current in phase. If now the power factor is unity and the current and voltage are in phase with each other, the phases of these two kilovolt-ampere values will be exactly opposite and if equal they will neutralize each other as far as the rest of the system is concerned. This will leave the resistance as the only quantity causing line drop. That is, by the proper correlating of power factor, line voltage, and load current, the voltage drop may be made to be that due to resistance only. To put it another way. In an excited open-circuited high-voltage line the charging current causes a rise of potential along the line toward the open end. On the other hand, in a loaded line without charging current, the line reactance causes a drop in voltage toward the loaded end. If these two tendencies be made numerically equal by properly choosing voltage and load and be made opposite by establishing unity power factor, the tendency to rise and the tendency to drop will neutralize, leaving the resistance to determine the actual line drop.

It goes without saying that in an actual line, some departure must be made from these ideal conditions, and it is the function of the designer of the superpower line to so control these departures as to secure the best compromise between efficiency, regulation, operating quality, etc. and cost.

For carrying large loads obviously a high voltage is necessary, but for any given load a particular voltage is most suitable. In this particular relation frequency plays little part, since the neutralization described above is not affected by change of frequency. Neither does the length enter as a factor theoretically, except to the extent that the consequences of a departure from ideal conditions will have a smaller effect with a short line and for the effect of ohmic resistance. Similarly frequency is of great importance when the ideal neutralization is not secured, as occurs with light load short circuits, etc.

Having chosen the load to be carried and the proper voltage, or having chosen the voltage and the proper load corresponding, the resistance can be chosen to determine the energy loss or efficiency. The designer does not, however, have a free hand to vary the resistance, as it is the resistance that is one of the potent factors tending to upset the balance of reactance and capacity, and is thus closely linked with power factor. The formula given by Goodwin, viz., kv-a. = $e^2/.04$ Where "*e*" is the line kilovolts gives a good idea of the equalizing capacity corresponding to various voltages.

In my paper of 1909 above referred to, I have suggested certain methods of increasing the load capacity of a super line without increasing the voltage, such as using divided conductors. While I see no reason why this method is not perfectly feasible, so far no occasion seems to have arisen in which there is not some other method less novel which would serve to secure the necessary capacity. This method is not a part of the subject matter of the present paper and will not be further touched on.

REGULATION

In the superpower line, voltage regulation is naturally a most important function and fortunately, thanks to the competent means available, may be very satisfactorily controlled.

In the first place it will be necessary to have control of the voltage at both ends of the line independently. Since synchronous type apparatus is used on both ends and since the voltage drop is extremely sensitive to power factor, no single setting of the field current on the synchronous machines on either end of the line would serve to secure satisfactory voltage at that point.

While not theoretically necessary, usually the most satisfactory regime for regulation will be to maintain voltage constant automatically at each end at whatever voltage may be most suitable at that end. The

1. Qualitative Analysis of Transmission Lines, A. I. E. E. JOURNAL, January 1923.

voltage, if necessary, may even be somewhat higher at the receiving end without serious additional expense. To arrive at the nature of voltage regulation in a superline, we may assume that the line is carrying full load with the capacity kilovolt-amperes and the reactance kilovolt-amperes equalized. If now a small leading current be made to flow from the generating to the receiving end, this leading current passing through the line reactance will cause a tendency for a rise in potential toward the receiving end. By choosing the amount of this leading current the amount of rise can be controlled. The effect of the resistance is of course, such as to cause a drop due to this leading current, but since in the superline the reactance is much greater than the resistance, and since the resistance component of the leading current voltage effect will be out of phase with the leading current, it will be substantially negligible; conversely with a lagging current.

To put this in another way. If we establish a voltage at each end of the line corresponding to the condition corresponding to the leading current just described, the line currents must flow as described to produce these voltages. Since any constant potential synchronous machine has a definite voltage and will supply, within its capacity, any current to its circuit required to maintain its voltage, such machines are entirely suitable for superpower line regulation especially in connection with field regulators.

Connected to the receiving end of such a line, a synchronous machine will tend to supply whatever current the transmission line takes at that voltage and at the same time to supply the load current required by the system connected to the line. The synchronous condenser actually takes, however, only the difference between these currents, which may be large or small and positive or negative as the case may be. In case the power factor of the load is low and the power factor required by the line close to unity, there will be a large out-of-phase kilovolt-amperes to be supplied by the synchronous machine at the receiving end and this is the most salient fact about the use of the synchronous machines, usually synchronous condensers.

Thus it is clear that any fixed voltage at either end may be easily maintained and for any load up to full load if proper synchronous condensers are available. This voltage will be held fixed by automatic regulators.

Equation of Typical Line

To illustrate numerically where these fundamental principals lead, I have assumed a superline of rather an ambitious capacity, but still an entirely feasible one for our present day knowledge, and have made the necessary calculations.

This line is 500 miles long, this being taken as an exceptionally long line and is insulated for 250,000 volts, 60 cycles. Its conductor has an outside diameter of $1\,^3/_{32}$ in. and its resistance is 0.015 ohms per thousand feet of cable, or the equivalent of 700,000 cm. The mean conductor spacing is 15.8 feet[2].

Performance of Line

Fig. 1 shows the efficiencies of this line for loads from about 10,000 kw. delivered up to 150,000 kw. on the following four assumptions as to terminal voltage conditions:

(A) that a voltage of 220,000 is maintained at each end.

(B) that a voltage of 220,000 is maintained at each end and that 220,000 volts is also maintained at the middle.

(C) that voltage of 220,000, is maintained steady at the receiving end and of 245,000 volts at the generator end.

(D) that the voltage is maintained constant at both ends at 245,000 volts.

Fig. 1 also shows the power factor at both ends for each of the four assumptions and the voltage at the middle of the line for (A) and (C).

These four cases are chosen to illustrate the relative effect on efficiencies and power factors of these variations of voltage.

As a matter of interest the efficiency of one half the length of this line, giving a transmission of 250 miles is added in Fig. 1 with 220,000 volts maintained on both ends.

Method (*A*) shows the same voltage at both ends, viz. 220,000 with no limitations on the voltage at the middle of the line, which will rise above the ends on light loads. Method (*B*) the same voltage at both ends and in addition the voltage at the middle stabilized at the same value. This can be accomplished by placing a step-down station at the center of the line with synchronous machines of some sort provided with automatic means of fixing the voltage.

The effect of this middle station as far as voltage conditions go is to divide the line into two lines, each of half the total length. Since the voltage at the middle of the line is maintained constant either half of the line may be considered as a line independent of the other half, except that the energy delivered by the receiving end of the first line must equal the energy delivered to the second line (plus the energy loss in the synchronous

2. As a matter of information it may be noted that the "Equations" of this line are

$$V \sin \varphi = .532\, S \sin (\theta + 5^\circ\, 4') + 606.5\, Q \operatorname{Sin} 84^\circ\, 58'$$

$$I \operatorname{Sin} \psi = .532\, Q \operatorname{Sin} 5^\circ\, 4' - 0.00119\, S \operatorname{Sin} (\theta - 88^\circ\, 56')$$

Where
V = Generator voltage
S = Load voltage
I = Generator current
Q = Load current
θ = Angle of advance of S over Q
$\operatorname{Cos} \theta$ = Power factor of load
φ = Phase of V
ψ = Phase of I
$\operatorname{Cos} (\varphi - \psi)$ = Power factor of generator current

From these equations any desired set of terminal conditions may be calculated.

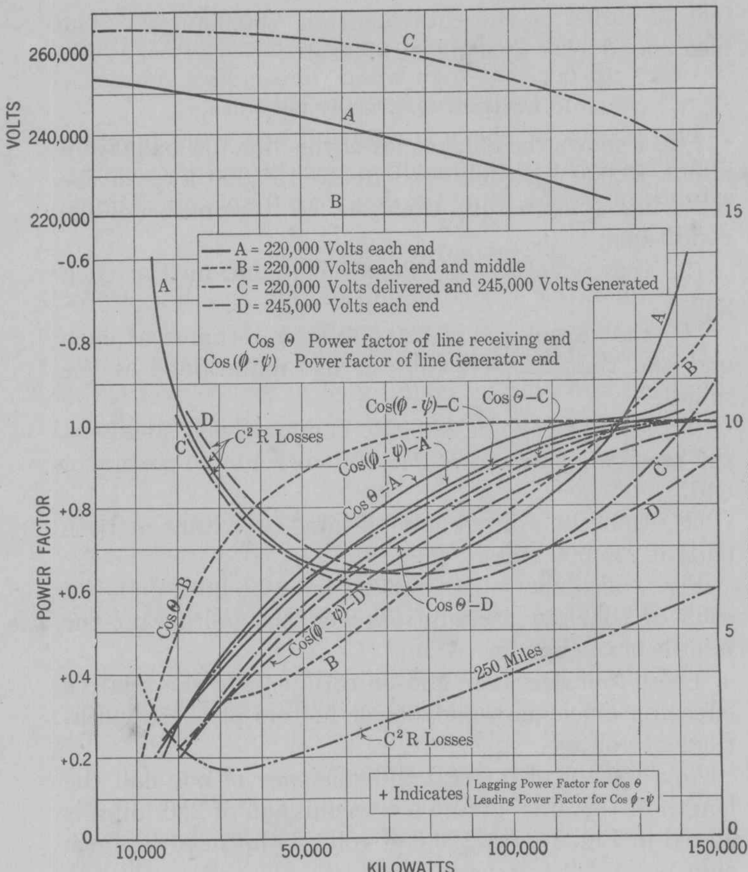


Fig. 1—Power Factor and Line Loss

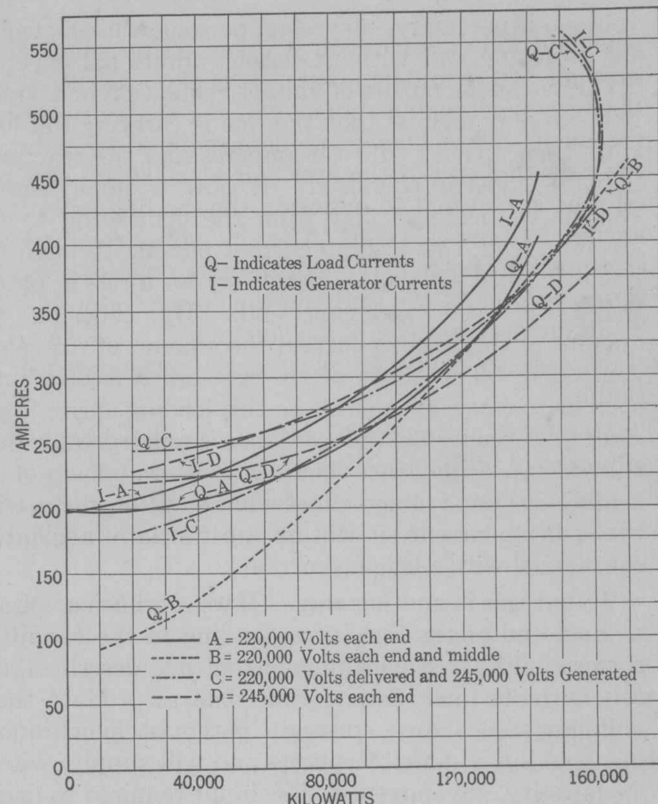


Fig. 2—Generator Currents

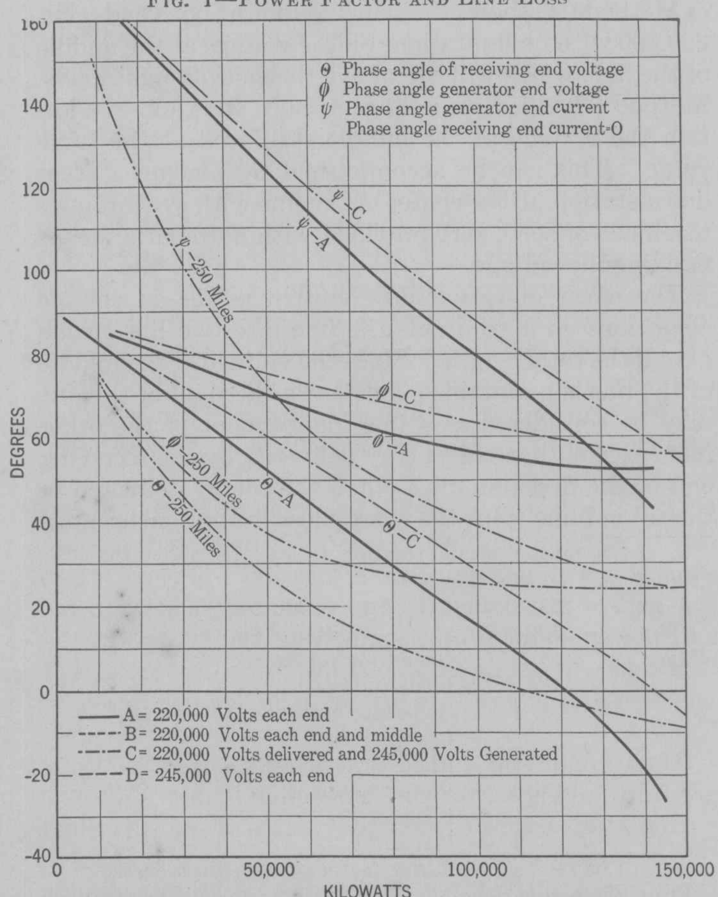


Fig. 3—Phase Position of Voltages and Currents Phase of Load Current Assumed as O

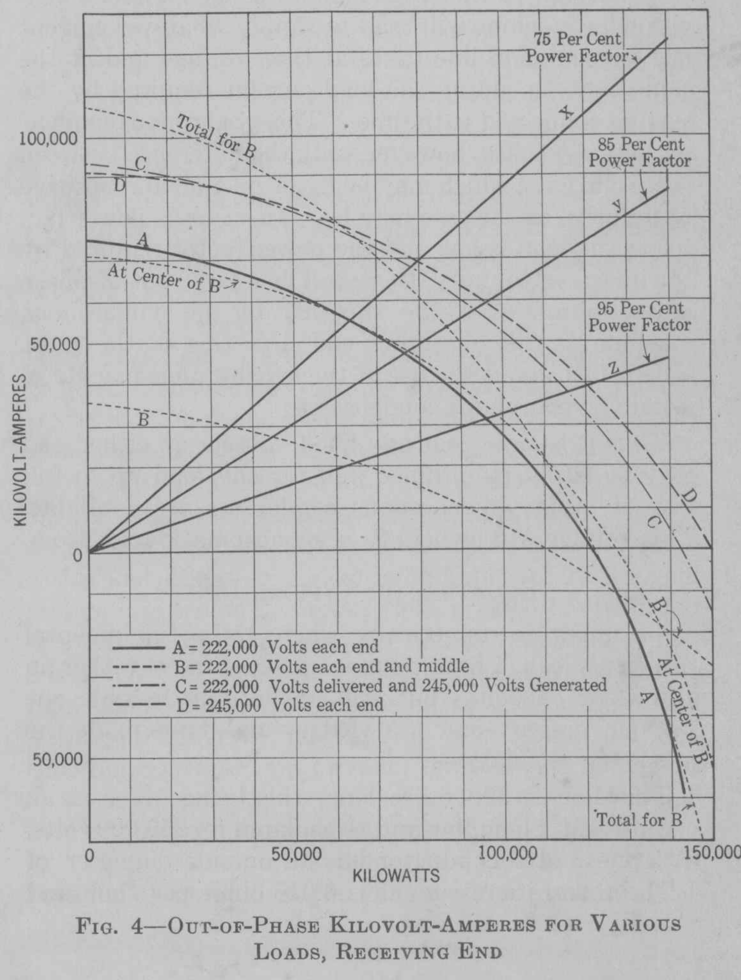


Fig. 4—Out-of-Phase Kilovolt-Amperes for Various Loads, Receiving End

machine) unless some load is taken off or some power supplied at the middle point. It is of course necessary that the synchronous machine at the center supply all the out-of-phase kilovolt-ampere required to maintain the receiving end of the first half at 220,000 volts and all that is required to maintain the sending end of the second half at 220,000. The kilovolts required for these two purposes may be of the same sign or opposite sign according to the load and the power factor and the resultant may be leading or lagging. This is the constant voltage transmission recently recommended by Baum.

Method (*C*) is to show the effect of a 10 per cent slope of potential in the direction of the load.

Method (*D*) is to show the effect of a 10 per cent increase in voltage over Method (*A*), the voltage being 245,000 volts at both ends.

With regard to the power factor curves of Fig. 1 it should be remembered that for any particular value of energy delivered the voltage assumed can be attained only with the load power factors shown.

To further illustrate the relations of these quantities Fig. 2 is added showing the currents at the two ends of the line with varying loads and Fig. 3 to show the relative phase positions of the voltages and currents at the ends of the line, the load current phase being taken as 0.

Since the delivery of any desired load at a definite voltage requires that the power must be delivered at a definite power factor, the synchronous condensers at the end of the line must be prepared automatically to deliver as much leading or lagging kilovolt-amperes as may be required and if they cannot supply this amount of energy the voltage will change appropriately.

As a practical matter of cost, the kilovolt-amperes required to maintain this prescribed power factor is a most important matter. These kilovolt-ampere quantities for controlling the line are shown in the set of curves in Fig. 4.

Three curves are added, marked *X*, *Y* and *Z*, showing the out-of-phase kilovolt-ampere component of the *load* the curve *X* being for a load power factor of 75 per cent, *Y* for 85 per cent and *Z* for 95 per cent. The condenser must supply both of these out of phase quantities.

Some comments may profitably be made on the curves of Figs. 1, 2 and 3. The efficiency curves no longer have the old familiar form. Good efficiencies are obtained only over a short range. The use of a middle point condenser station changes the form of the efficiency curve as seen in Fig. 1 in curve *B*. While the line losses are less with the middle point station at high and low loads, they are greater over the operating range and this without including transformer and condenser losses.

As would be supposed the maximum output occurs with power factors pretty near to unity.

The voltage at the middle of the line runs 15 per cent high at no-load with both ends at the same voltage, but only 10 per cent high when the sending voltage is 10 per cent higher than the receiving voltage.

The phases of the voltages and the corresponding phase positions of the machine armatures vary over an astonishing range, some 135 deg. for different conditions.

Special Conditions

The following special conditions on this line are of interest.

If the receiving end of this line be open-circuited and the generated voltage maintained at 220,000 volts, the open end will rise to 413,000 volts and the charging current will be 302 amperes, case 4, Table "A".

If the receiving end be short-circuited and 220,000 volts maintained at the generator, the generator current will be 223 amperes and the current at the receiving end will be 420 amperes. The power at the generator will be 7470 kw. at a power factor of 0.176 lag, case 8, Table "A".

Should the synchronous condenser pass out of step with the voltage at each end 220,000 volts, the maximum possible current that would be developed would be about 640 amperes approximately, the same on both ends. At the moment of maximum current the power factor would be 0.182 lag at the generator, giving a drag of 44,000 kw. with a negative load of 12,700 kw. at the receiving end with a power factor of 0.053 lead.

This condition is transitory but existing momentarily as the synchronous machines pass the condition of maximum current, case 7, Table "A".

The minimum line current with the voltage of 220,000 at both ends will be 196 amperes as shown in Fig. 2, with a load delivered of 10,000 kw.

The maximum power that can be delivered by the generator theoretically with its voltage kept at 220,000 as distinguished from the maximum current, is 166,000 kw. and will occur with the generator current about 441 amperes with a power factor of 0.986 lagging and the load delivered would be about 143,000 kw., the load current about 405 amperes at a power factor of 0.925 lead, if the load voltage is kept at 220,000 volts, case 3, Table A.

If in this last case the load voltage drops to 110,000 the maximum power that can be delivered by the generator will be about 94,000 kw. and will occur when the generator current is approximately 332 amperes and power factor 0.745 lagging and the energy at the load end will be about 75,000 kw. with current of 433 amperes and a power factor of 0.90 leading; case 6, Table A.

These conditions and several other special conditions are fully tabulated for convenience in Table "A".

Important as are the above features of the superline, the operating characteristics are more so and involve some most interesting discussions. Various aspects will be considered in turn.

TABLE A—500-MILE, 60-CYCLE TRANSMISSION

Case Number	Kw. on Generator High-Tension Side Transformers	Generator Power Factor "—" = leading	Generator Current, amperes I	Relative Phase Positions LoadCurrent = 0: Generator Voltage φ	Generator Current ψ	Load Voltage θ	Voltage, kv. Generator End	Voltage, kv-Load End	Kw. in Load-High Tension side	Load Power Factor, taken in Line "—" = leading	Current of Load, amperes	Line Energy Loss, %.	
				500 Miles—Voltage Constant at Both Ends. 220,000 Volts									
1	108,400	−.922	308	56° 30′	79°	15° 30′	220	220	100,000	+.962	272.5	7.64%	Normal full load
2	132,200	−.984	354	53° 20′	63° 30′	0 50′	220	220	120,000	+.999	316	9.27%	Maximum load, to be taken as required in emergency
3	166,000	+.986	441	52° 30′	43°	22° 27′	220	220	143,000	−.925	405	..	Maximum possible deliverable power, approximate
4	8,060	−.070	302	5° 4′	91° 4′	0	220	413	0	..	0	..	Line open at load end
5	1,660	−.0233	195.3	90° 30′	179° 10′	90°	220	220	0	..	198	..	No load at receiving end
6	94,080	+.745	332	69° 45′	41° 51′	−25° 4′	220	110	75,000	−.903	433	..	Maximum power possible with half voltage load end, approximate
7	44,400	+.182	640	80° 50′	1° 0′	−93°	220	220	−12,700	−.053	640	..	Maximum possible current, approximate
8	7,470	+.176	223	84° 58′	5° 4′	..	220	0	..	..	420	..	Short circuit on receiving end
9	70,800	−.722	253.3	64° 30′	107° 30′	39°	220	220	66,667	+.784	225	6.4 %	Two thirds of normal full load
				500 Miles—Voltage Constant at Both Ends and at the Middle. 220,000 Volts									
10	300,000	+.82	960	..	..	..	220		220,000	..		27%	Maximum possible delivered power, voltage fixed at 220 kv. at middle of line
11	108,640	−.973	..	..	..	..	220	220	100,000	+.998	..	7.96%	Full load with voltage fixed at middle point by condensers at 220 kv.
12	63,400	−.878	..	..	..	..	220	220	60,000	+.931	..	4.83%	6/10 Full load with voltage fixed at middle point by condensers at 220 kv.
13	132,640	−.992	..	..	..	..	220	220	120,000	−.999	..	9.55%	Maximum load taken as required in emergency, witn voltage fixed at middle point by condensers at 220 kv.
				500 Miles—Voltage Constant at Both Ends. 245,000 Volts at Generator End, 220,000 Volts at Load End									
14	10,700	−.907	279	63° 0′	87° 0′	27° 40′	245	220	100,000	+.885	296	6.5 %	Normal full load
15	205,000	..	480	58°	37°	−22°	245	220	166,000	..	463	..	Maximum possible delivered power, approximate
16	104,000	+.812	302	70° 45′	35°	− 5° 4′	245	110	83,660	−.996	443	..	Maximum power possible with half voltage, load end, approximate
17	62,480	+.554	266	77° 24′	21°	− 5° 4′	245	55	43,400	−.996	458	..	Maximum power possible with quarter voltage, load end, approximate
18	48,800	−.625	184	102° 40′	231° 20′	120°	245	220	−52,000	+.50	274	6.16%	Example — half load delivered backward over line
				250 Miles—Voltage Maintained Constant at Both Ends. 220,000 Volts									
19	104,000	−.97	282	24° 45′	38° 50′	3°	220	220	100,000	+.998	262	4.0	Normal full load
20	126,000	−.99	336	23° 15′	31°	− 2° 40′	220	220	120,000	−.999	316	4.77	Maximum load taken as requred in emergency
21	130,800	+.688	523	..	..	..	210	110	111,760	1.0	588	..	Maximum possible power delivered—half voltage at load, approximate
22	70,000	+.352	681	..	..	..	210	55	62,060	−.866	755	..	Maximum possible power delivered—one quarter voltage at load, approximate

Starting

When one end of a super transmission line is open and the other end excited, the voltage at the open end rises very high; in our case to 413,000 volts from 220,000 volts. This is an impracticable operating condition and the open-circuiting of either end of the line cannot be permitted. Fortunately the maximum current that can be gotten steadily by any combination of conditions is not greatly in excess of full-load current at the receiving end so that for the duration of a starting period or an emergency, such as a short circuit or falling out of step, no damage would be done to apparatus permanently connected to the line, even if its capacity be considerably less than the full current of the line, while an excessive rise of potential would be prevented.

If it be then assumed that the synchronous apparatus at the receiving end of the line be permanently connected to the line the problem of starting may be cared for in several ways.

(a) The generator may be excited and started up from rest and the synchronous condenser will fall into step as the generator comes up to speed.

(b) The generator may be brought up to speed with the field open and then the exciting of the field will start the synchronous motor, if properly designed, which will then pull quickly into step.

(c) If means for revolving the synchronous condenser be provided, both this machine and the generator while still connected may be brought up to speed and they lock into step when their speeds become equal.

It is not the purpose of this paper, however, to discuss the details of starting, but merely to point out how the starting may be practically accomplished.

Synchronizing

Synchronizing may be accomplished in the low tension at either end. As a matter of fact, as a first approximation this superline is in some ways the equivalent of a very high reactance connected between the synchronous machines at the two ends of the line, so great in value that to get full power over the line it is necessary for the two synchronous machines to swing out of step by a very wide angle, thus developing enough voltage to support full-load current.

Considering "*A*" in Fig. 3, the difference in phase of the voltage of the two synchronous machines at the two ends of the line changes from about 5 deg. at a load of 8500 kw. to about 70 deg. with a load of 140,000 kw. That is, if a line with synchronous condensers carrying no load is connected at one end to a similar line loaded, there will be a very wide phase difference between the voltages at the unconnected ends of two lines. When these are connected, however, their phases will come together and the load will divide between them. However, while under the assumed conditions the line conditions can adjust themselves without disturbance on synchronizing at the second point, the condenser must adjust its position more slowly and may cause some heavy current interchange with other condensers but it will very likely be possible to accomplish synchronizing in a manner to avoid such a violent change in the phase position of the condenser. This is a matter of interest rather than a serious difficulty of operation. However, syncroscopes used in the ordinary way would not indicate at all correctly, as to the proper moment for closing the synchronizing switches. Of course, if one end of the two lines is already connected, the other may be also connected without use of a synchroscope, provided it be proper to make this connection at all.

Synchronizing a lone line with an operating substation works differently. If the line be idling the phase of the voltage at the receiving end will be nearly in phase with that at the generator end, as there is little load passing over the line. If it then be synchronized with the load system already operating there will be no immediate change, for the phase of the generator must advance relatively by many degrees before it can take much load. This will occur in a few cycles if the governor of the generator prime mover be set to take such load. It must also drop behind many degrees to take power from the main system. This adjustment of position will occur very quickly in actual practise.

Presumably this connecting of an idle line to the substation is the proper condition for synchronizing. The governor of the generator prime mover can be set for higher speed to cause it to take load when the synchronizing has been accomplished. If one line thus synchronized to a substation is then to be paralleled on the generator end with other already synchronized lines, it should be so loaded (the voltage being maintained constant automatically) that the generators are all in phase before closing the synchronizing switch at the generator end.

While synchronizing is not likely to cause much difficulty, the matter of pull-out torque and holding in synchronism through electrical trouble is much more difficult. If a generator feeds a superpower line synchronized at the receiving end with a load system and a sudden increase of load comes the load system will tend to slow down momentarily. To escape losing synchronism the generator must slow down also, but to accomplish this slowing down, more load must be passed over the transmission line. If now the generator be already loaded as far as the line will permit *by efficiency and voltage* considerations, as for example to 140,000 kw. it will be found by examining the curves of Figs. 1 and 2 and case 3 Table "A" that very little more load can be got over the line. If, however, a certain margin exists so that the normal full load over the line may be increased by perhaps 50 per cent when called upon by a load increase, then a sudden increase of load and slowing down of the load system will cause an increase of power delivered over the line and the generator will slow down, if properly designed, especially if it be a waterwheel with the usual small overload capacity and if its governor have a wide range of speed variation with load.

Again, if a local short circuit occur in the load system near the receiving end of the line, the local voltage will drop, which greatly limits the power that can pass over the line as shown in cases 6, 15 and 16, Table "A" and the generator will immediately tend to pull out of step if the rest of the system *tends to slow down.* Obviously this is a more serious matter and at first sight a most difficult one to handle.

Cases 21 and 22 of Table "A" show that a line of half the length is considerably better and that the maximum power that can theoretically be delivered is greater than for the full length of line with the same terminal voltages. A further treatment of this subject will be found below:

Typical System Diagram

The determination of the best arrangement for the use of breakers on the superpower line and its connected load network, when taken in connection with automatic relay protection for short circuits, will be found to be a very complex matter. The purposes of this paper, which is largely illustrative, will be best served by assuming a layout which is well suited to the usual conditions and discussing its action under various normal and abnormal conditions. Such an arrangement is shown in the one line diagram in Fig. 5.

It will be assumed that the line voltage is normally maintained automatically at 220,000 volts 60 cycles, at each end by regulators working on the fields of the generators and condensers. The amount of synchronous capacity required for various cases is shown in Fig. 4.

The four circuits, which may well be carried by two two-circuit tower lines, make a well rounded super transmission installation. One circuit may be taken out for repairs and the other three lines be made to carry the total or nearly the whole power.

This overloading of the three remaining lines calls for a very large capacity of synchronous condensers. By reference to Figs. 1, 2 and 4, it will be seen that the demands on the synchronous condensers will be less excessive if at the same time the voltage at the generating end be raised even by such a small amount as 5 per cent and this should be permissible for temporary operation. In this case account is being taken of the requirements of the load as well as the line. This resultant will be the difference between the *X*, *Y* and *Z*, and the *A*, *B*, *C* and *D*, curves.

Synchronous Condensers

We may take as an illustration 400,000 kw. as the total normal load on the transmission with 220,000 volts at each end. This means 100,000 kw. delivered per circuit. From the curves, case 1, Table "A" it will be seen the normal generator power factor is 0.92 leading. An approximate capacity of 115,000 kv-a. is required, but to cover somewhat less favorable contingencies and some overload, 130,000 kv-a. may be taken at a power factor of 90 per cent. If the prime movers are waterwheels they will presumably be given a *maximum* continuous rating corresponding to about 140,000 kw. per circuit.

As to the condensers, we must always satisfy the condition when the line is disconnected from the load circuit, which calls for out-of-phase kilovolt-amperes of about 75,000 kv-a. lag (see Fig. 4) on the line. This means 78,000 kv-a. lag on the condenser terminals. Condenser capacity to meet this no-load condition must be furnished, whatever loading may be assumed for full load. The effect of raising the voltage of the sending end of the line is seen from case *C*, Fig. 4, viz., to increase the no-load kilovolt-amperes required. The *full load* kilovolt-ampere requirements, however, will be less with the higher generator voltage.

Strangely the major part of the charging current is fed from the lower voltage end. This is because the voltage naturally rises along an unloaded line away from the generator. By referring to case 4, Table "A", it is seen that if the receiving voltage were raised to 413,000 volts, this end would supply no charging current at all.

In order, however, to take account of the effect of transformers and condensers we may assume that if the load at the receiving low-tension bus bars is 100,000 kw. at 85 per cent power factor the load will be 105,000 kw. in the high tension, allowing for transformer and condenser losses. The high-tension out-of-phase component of the *load* will be 71,500 kv-a. lagging, assuming the transformer has 8 per cent reactance e. m. f. The line delivering 105,000 kv-a. requires 22,500 of lagging kv-a., giving 49,000 kv-a. lead to be supplied by the condenser in the high tension. Therefore, the kv-a. required from the condenser in its low-tension circuit is 51,500 kv-a. lead, assuming a 5 per cent reactance in the transformer tertiary winding. This is well within the capacity required for the light line running, *viz.*, 75,000 kv-a., the difference being available as overload capacity.

If one line be down and each of the remaining lines deliver 133,000 kw. low tension, the high-tension, out-of-phase kv-a. of the *load* (85 per cent power factor) on the 220,000-volt busbars is 94,000 lag. The out-of-phase high tension required by the line is 47,000 leading, giving a total condenser requirement of 141,000 kv-a. lead on the high-tension side and 5 per cent in excess on the low-tension side or 148,000 kv-a. lead. The amount is far in excess of that required for light line and this is not a desirable operating condition.

Various expedients may be used to reduce this requirement of 148,000 kv-a. For example:

(1) If one line is taken out, the total load required of the system may usually be somewhat reduced, say to 120,000 kw. per circuit, which will naturally reduce the requirements from the condensers.

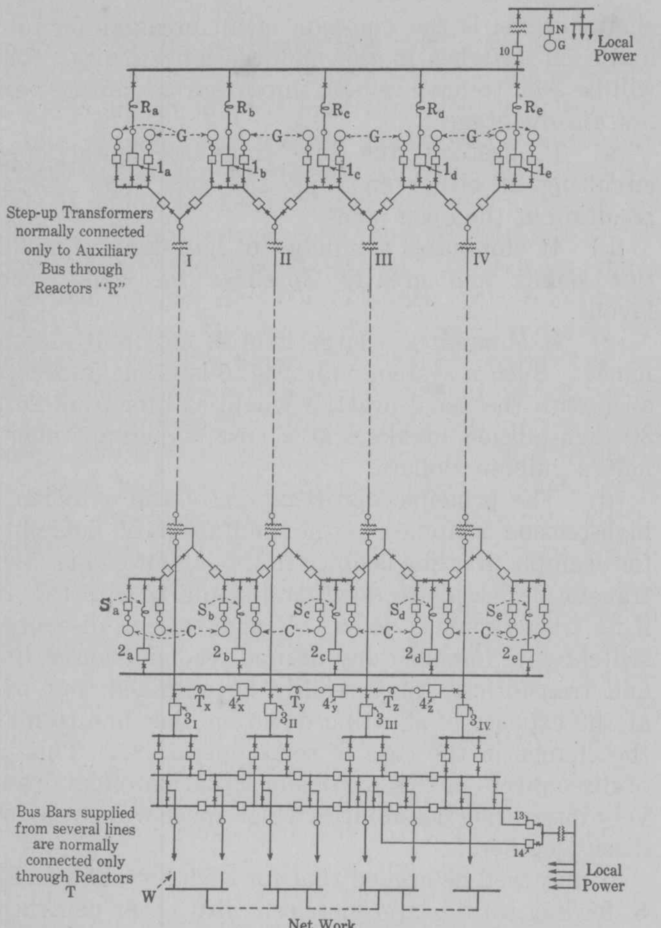
(2) If the generator voltage be raised 10 per cent to 245,000 volts, the requirements of the condensers will be reduced to 95,000 kv-a. lead which is somewhat more than the no-load requirement.

(3) If the power factor of the load at the step-down bus bars be raised to 95 per cent, the kv-a. out of phase of the load is 55,000 high tension, giving with the 47,000 required by the line, $102,000 \times 105 = 107,200$ lead.

(4) Since when one line is down its condensers are not in use, these may be added to give additional capacity to the three good lines. This will bring the available condenser capacity for each of the three operating lines to 133 per cent of normal, or 100,000 kv-a. if normal be taken as 75,000 kv-a.

(5) Normally spare capacity will be provided for condensers, and if it be assumed that this may be used when one line is out and the spare be 20 per cent of the total as in the system of Fig. 5, there will be capacity of two extra condensers for the three circuits which will provide the requisite capacity for 133,000 kw. delivered, counting somewhat on overloading.

However, it would no doubt be more practicable



Ⓖ —Main generator and prime mover, 65,000 kw-95 % P. F. units.

Ⓒ —Synchronous condensers, 75,000 kv-a.

[1] —Automatic oil circuit breaker.

□ —Oil switch, non automatic.

× —Disconnect switches, air break.

○ —Relays for breakers—actions as described below.

—Reactors—at generator station—to pass 400,000 kv-a. on full voltage at condenser end—to pass 300,000 kv-a.

—Step up transformers—130,000 kv-a. Internal reactance as low as practicable, say 8 per cent.

—Step down transformers, 110,000 kv-a. on secondary, and 75,000 kv-a. on tertiary, reactance between primary and secondary say 8 per cent. Between primary and tertiary—very low—say 5 per cent and between tertiary and secondary very high say 12 to 15 per cent.

↓ —Feeders to network.

FIG. 5—ONE LINE DIAGRAM OF TYPICAL SYSTEM SUPERPOWER TRANSMISSION

In generator leads, relay kills the field of its own generator but only while short lasts; inverse time limit 0.2 seconds on 750,000 kv-a.,—0.5 seconds on 400,000 kv-a.

In lead to breaker [1], relay overload instantaneous, minimum setting 160,000 kv-a.

In high-tension of step up transformers relay instantaneous to ring a bell as long as power factor is below 50 per cent, lagging.

In primary of step down transformer, (or a combination of currents representing tertiary and secondary windings to give the same result) relay to open breakers [2], [3] and [4], instantaneous, minimum setting 175,000 kv-a. Also opening [2], [3] and [4] when power factor drops below 50 per cent leading (as motor), in 3 seconds.

In leads to step-down transformer secondary, relay opening [3] in 0.4 seconds.

In leads to synchronous condensers or to transformer, relay opening [2] inverse time limit 0.2 seconds on 400,000 kv-a., and minimum operating value 100,000 kv-a.

In leads to switch [4]—relay definite time limit 0.75 seconds—minimum operating kv-a., 125,000.

In feeders, relay inverse time limit but clearing any short as high as 100,000 kw. in less than 0.25 seconds.

Standard protection for short circuits for generators and local station power.

to count on operating only 120,000 kw. on each of the three remaining circuits when one goes out, thus requiring 95,000 kv-a. lead from each synchronous condenser, this being based on a network load power factor of 85 per cent. Even with this arrangement some of the idle condenser capacity should be used for continuous running at 120,000 kw. generator.

Apparently a very effective arrangement could be secured by providing to have the generator voltage automatically run lower on light load and higher on heavy load. A change of 5 per cent would be an important help and one of 10 per cent would greatly reduce the required condenser capacity.

Thus it is seen that for economic conditions involving the transmission of very heavy loads, capacity in synchronous apparatus may be required numerically in the neighborhood of the amount of the load transmitted. On the other hand a number of simple expedients may be used to materially curtail these requirements. It should be clearly understood that the values so far given are not intended to indicate that these are practicable for an actual installation. They are offered as a basis for discussion. No doubt more consideration will be given to these subjects before such an installation will be made.

It should be noted that to maintain constant voltage on the high tension at full load or with the overload condition, that voltages on the condenser circuits must be regulated to be a little above or a little below the line voltage according to whether the passing of power causes a rise or a fall of voltage in the transformers. For this line and normal full load there will be a drop through the step down transformer and the condenser voltage should be at a lower value than the ratio of turns of the transformer and the line voltage would indicate. This refers to the ratio of turns of primary and tertiary windings. If the load be increased for example, to the point where three lines will carry the load of four or under the conditions when a sudden disturbance calls for a still larger flow of current the condenser will be forced to supply a leading current and the drop in the step-down transformers will become a rise, so that the condenser terminal voltage must be higher than the ratio of turns would call for. The synchronous condenser must be adapted to sustain this condition. Since the primary and tertiary windings are closely related magnetically, these voltage variations will be small.

Similarly at the generating end the voltage regulator must be laid out to correct for the voltage drop or rise of the step-up transformer. Space will not permit a fuller discussion of this point at this time.

As a matter of good design, it is likely that it will be more favorable to provide most of the power factor correction as far as it is required to raise the power factor of the load by synchronous apparatus in the neighborhood of the load itself as this will improve the regulation and efficiency performance of the network as well as adapting the load to the requirements of the line. It will also reduce the kv-a. load on the step down transformers. For this purpose any available existing synchronous apparatus would serve. The part of the corrective kv-a. that must be varied during changes in operation should be under immediate control and should be supplied by condensers at the step-down station.

For spares add a fifth unit to generators and condensers.

The original assumption of the loading of the line may now be modified to give a favorable layout as follows:

Normal full-load 400,000 kw., 100,000 per circuit on the distribution bus bars (requiring 420,000 kw., 105,000 per circuit on the high-tension side at power factor of 98 per cent lagging). Condenser kv-a. required per circuit 24,000 kv-a. lagging including requirement of step-down transformer, assuming *load* corrected in the network to *unity power factor* at the high-tension side.

Kilovolt-ampere required for no-load condition 79,000 lag per circuit on condenser terminals (only occasionally and for brief periods).

Maximum steady load provided for on three lines 360,000 total, 120,000 per circuit on distribution bus bar (380,000 kw., 127,000 per circuit on high-tension side at power factor 0.995 per cent leading) calling for 11,400 kv-a. per circuit leading on condenser terminals assuming the load corrected in the network to unity power factor at the high-tension side.

Capacity of condensers provided 75,000 kv-a. per circuit. Note that when the 79,000 kv-a. above is required on no-load that the spare condenser can be called upon should this condition continue indefinitely. The extra condenser capacity on the over load condition is highly desirable as a margin for operating reasons. Sufficient corrective capacity must be provided in the network (or at the condensers) to bring the load power factor to unity. The amount of this is shown for various power load factors in Fig. 4.

Efficiency of line, normal 92 per cent, loss 8 per cent; add transformer loss 2×1.5 per cent and condenser losses 4 per cent of 75,000 kw. total 14 per cent loss.

Step-up transformer capacity 130,000 kv-a. per circuit, step-down transformers capacity for load winding 110,000 kv-a., for tertiary winding 75,000 kv-a. This apparatus will carry the overload corresponding to one line out as above, until additional capacity can be added, but will be sensitive to voltage drop.

Generator capacity 130,000 kw. per circuit at 95 per cent power factor.

It should again be noted that this layout is proposed for discussion as a maximum and optimum system and no doubt a more conservative design would be adopted in any particular installation.

Switching

Considering the layout of Fig. 5 more particularly from the point of switching, the most conspicuous characteristic is the omission of all breakers or automatic oil switches in the high-tension circuits. This will be seen to have several important advantages and few disadvantages.

(a) It protects the line from accidental open-circuiting at either end and the very high voltage resulting at the open point.

(b) It eliminates a number of high-tension insulation points and greatly simplifies the high-tension layout.

(c) It eliminates a large item of cost and maintenance. Such a system as in Fig. 5 laid out in accordance with the usual practise would call for from 25 to 30 high-tension breakers at a cost of perhaps over a half a million dollars.

(d) The principle disadvantage of the omission of high-tension switches is the limitation of flexibility; for example, if a line is down in the layout of Fig. 5, its transformers are also down and similarly with the line if its transformer is down. If high-tension disconnect switches are installed any desired reconnection of lines and transformers may readily be obtained, but only at the expense of shutting down another line to make the change in the case of some operations. This use of disconnects in this particular situation offers several very interesting possibilities which space will not permit discussing here.

It may well be argued that for such a system as Fig. 5, feeding into a large network with other generating stations of large aggregate capacity, the simplicity of this layout is of great advantage. Here there is the one function of carrying a large block of power, 24 hours a day with no occasion for changing of connections except in case of some accident and for the regular inspection of generators and condensers. This inspection is provided for by the spare units shown which can be switched in and out one at a time without disturbing load. In case of emergency or to make the infrequent inspections of transformers and lines (that is—such line inspection and testing as cannot be done alive), three lines can be made to carry nearly the load of four. Ordinarily, however, when one line is to be shut down it will be feasible to arrange for a reduction of the load by 10 or 15 per cent on the transmission system. With careful line inspection and maintenance it may be confidently expected that trouble in the major elements of the system will be very rare. This favorable result assumes a very careful design, with the most painstaking scrutiny of details, but not an elaborate or excessively conservative design. The important thing is not to have an extreme factor of safety, but to insure an adequate factor of safety at *all* points. In making this statement as to the rarity of major trouble, reservation must be made to cover the possibility of some unusual and unexpected local disturbance. Such a condition might be malicious interference or one of the rare locally occurring fog belts which coat insulators or (possibly but very improbably) extreme lightning severity, etc.

At this point I would like to state that the practise of working on live lines at 100,000 volts and higher is worthy of most serious consideration on these super lines. While at first thought this practise seems dangerous, a more careful analysis does not bear out this appearance; neither does the experience with such work. I think there is little question that live line testing of high-tension insulators is feasible and reasonably safe. It has already been carried out very extensively. The question then arises whether very simple line operations are not also feasible. The best example of such a simple operation is the changing of an insulator string and this is the most useful operation in practise. A little consideration will show what a wonderful advantage the possibility of changing defective insulators without taking load off the line would be, especially in a line of the length of the one under discussion. In my judgment this advantage is so great as to warrant very considerable exertions. Some superintendents who do not care to do this work with their own crews may obtain more or less the same result by contracting to have their defective insulators changed periodically by outside expert crews as has already been done in many cases. While there will naturally be a great inertia of conservatism holding back the adoption of live line work, such as insulator changing, it is difficult to see how it can be logically ruled out in the end, when the live line testing is already pretty well accepted.

Automatic Relay Protection

Most of the features of the relay protection of Fig. 5 involve the standard use of standard apparatus but there are a number of novel features. The most satisfactory way of bringing out the intended operation will be the analyzing of the effect of various possible accidents. Single-phase grounds and short circuits will have the same effect on these lines since the high-tension neutral is assumed substantially dead grounded at a sufficient number of points. Assume all the generators except the right hand pair are operating, each pair on its own line and all breakers [1] closed, also all condensers except the left hand pair operating, each pair connected to its own transformer and all switches [2] closed; also all breakers [4] closed but distribution bus bars all operated in four groups.

A—Short Circuit on Generator End of Line I

The relays in the leads of the generators feeding the short circuit kill the generator fields, operating in 0.6 seconds. The breaker [1-*a*] will open instantaneously opening about 300,000 arc kv-a.; the other breakers [1] do not open as the current will be too small. The short circuit is then killed as far as the generating end is concerned. Meanwhile the only effect at the receiving end is to develop a current of 223 amperes and to change the power factor of the line to say 18 per cent leading (Table A, Case 8) (current would be lagging if condenser is considered a generator) and to drop the delivery of power that had been passing over this line. Through the action of a relay designed for this purpose, this low leading power factor in the step down transformer primary will open the breaker [3-I] in 3 seconds and at the same time [2 *b*] and [4 *x*]. This disconnects the line entirely from the system but leaves both generator and condensers connected and running. If this renews the short circuit the generator fields will be restored and the condensers fall into step again or, if so designed, once opened, the generator field circuit may remain open in which case the condenser will come to rest and restarting will be necessary. The delay of three seconds is to give the short circuit a chance to clear. No harm is done, since the short circuit will not pull more than about 7500 kw. to 15,000 kw., (Table "A", case 8) and less than full-load current. When the operators see that one line is out they should immediately connect in the spare generators and condensers. If the bad line can then be put in again this may be done at once, but otherwise the full load or a suitable portion can be taken over the three good lines. In case of the dropping out of line *I*, the three water-wheels still on the line will open up their governors and may take load up to the extent of their capacity—say 20 per cent excess making, 60 per cent excess in all of the loss from the bad line and the rest of the load will be taken by the generators in the network. If the latter have more sensitive governors they may take still more of the load. The steady distribution of the load between line circuits can be controlled at will by hand adjustment of the speed of the generator governors.

When the opening of [3-I] cuts off certain feeders to the network, the corresponding load will presumably be supplied around through the network by other routes over the good circuits.

B—Short circuit on primary leads of step up transformers

Substantially the same actions as in Case "*A*", but currents will be 50 per cent heavier.

C—Short circuit on auxiliary bus, generator station

All breakers [1] go out instantaneously and before the relay in the generator leads can open the fields, since these are inverse time limit and the short circuit is limited by the reactances. No other effect will be produced as the line units can all run perfectly well without the auxiliary connection. A short circuit on the auxiliary bus should be very rare.

D—Short circuit at condenser end of line I

Breaker [3-I] opens instantaneously from relay on primary of step-down transformer and [2 *b*] and [4 *x*] are open by the same relay. Nothing happens at the generator end until the attendant cuts off this line at his leisure. The generator end current will be only 223 amperes (Table "A", case 8) and the current at the load end only 420 amperes. It might be well to have the low generator power factor 0.176 lag, ring a bell to call attention to the condition.

E—Short circuit at the middle of the line 1

This will pull 640 amperes at the generator end and cut off the generator fields, which will open [1-*a*] in 0.5 seconds clearing this end. It will act the same as *A* at the receiving end, [3-1], [2-*b*] and [4-*x*] going out by the same relay.

F—Short circuit on left hand operating condenser leads

Corresponding breaker [2] opens in 0.2 seconds leaving line to go down as in *A* – [3-*I*] opens in 0.4 seconds and [4-*x*] in 0.75 seconds.

G—Short circuit on condenser auxiliary bus

Breakers [2] go out in 0.2 seconds clearing the trouble without disturbing the operation, provided synchronism can be held. If reactances are used with switches [2], conditions will be much easier.

H—Short circuit on distribution feeders

[3 *x*] opens in 0.4 seconds on overload leaving the power from line 1 to pass through [4 *x*] to the other feeders and into the network where it would find its way to the original destination. The time limit of 0.4 seconds is to permit a feeder breaker to clear the individual feeder before [3 *x*] opens. If [3-I] fails to clear the circuit [4-*x*] opens in 0.75 seconds and line I will be disconnected.

The protection of the local station power circuits involves no particularly difficult problems and need not be discussed here.

Synchronizing Power in Typical System

As already pointed out, the characteristics of the superline for efficient full-load transmission of power are so extremely favorable on account of the neutralizing of the reactance effect by the capacity effect, that for other conditions when this neutralization does not occur to the same favorable extent, as for example with overloads, very light load or low voltage, transmission becomes very unfavorable. The very light load condition has been considered above. The overload condition, as an overload problem, is the least serious and easiest to meet, but the low voltage or short-circuit condition is serious and difficult from the point of view of holding synchronism.

Before discussing this matter with regard to the system of Fig. 5, I will consider a single superline circuit such as one of the four here shown. It will transmit considerably more power than full-load power if the voltage at both ends be kept at normal even as high as 145,000 kw. (See Table "A", case 3). If, however, this voltage drop below normal, even if at the receiving end only, the amount of power that can be delivered is greatly reduced as seen in Table "A", case 6. For example, in this case the actual power delivered with half voltage at the receiving end is less than the full load, viz., only 75,000 and this condition gives nearly the maximum deliverable power for this voltage. Since, however, there is little likelihood that the failure to deliver *power* under conditions of abnormal voltages (due presumably to short circuits) will be *per se* of importance, since such conditions can exist for a period of perhaps only one or two seconds, we have only to consider the danger of loss of synchronism or the opening of breakers.

Several cases occur which have to be considered independently.

First, when a short circuit occurs at the receiving end of the system on the step-down side. In this case there is a tendency for the receiving end voltage to drop, which will tend to limit the amount of power delivered by a line. But the full input to the generator continues to be delivered by the prime mover, and the only thing that prevents its speeding up to the light load speed of the governor (considering now one circuit by itself) is such power as may be taken by the line. This is the most serious condition to be met in maintaining synchronism and will be critical when the short circuit is such as to tend to cause the network machines to *slow down;* for example, when the short circuit is through a feeder line with very little armature reaction drop in the generator voltage. Of course, the overspeed governor on the generator prime mover will prevent any dangerous increase of speed, but it will be useless for preserving synchronism.

It follows from the above that for this case the critical factor will be the load developed by the generator, not the load delivered by the line and this generated power may be considerably greater than the delivered power. For example, the drag on the generator in Table "A", case 6, is 94,000 kw. compared with 75,000 kw.

But short circuits are of many varieties. If of such a sort that the actual kw. developed in the short is less than at full load, on account of low power factor in the short circuit, the generators in the network and the main generators, at opposite ends of the line will tend to *speed up* and the load that can be delivered over the line in one direction or the other may be sufficient to hold them in step, even if less in amount than full load power. In this case the governors of the prime movers will have to ultimately control the speeds and the more nearly their speed curves are alike the better the chance of staying in step. The range through which synchronism would be retained would be, on the one hand that condition in which the receiving end prime movers speed up more rapidly than the main generators and are only restrained from exceeding the speed of the latter by the load sent backward over the line helping the prime mover to speed up the main generators and on the other hand the condition in which the main prime movers are just able to pull up the speed of the receiving end machines until equilibrium is reached. This is presumably a very wide range and successful operation through this range is not limited to line voltage conditions in which full load may be passed over the line.

In the case of a single line and a condition such that the prime movers in the net work at the receiving end tend to slow down, synchronism cannot be maintained if the receiving voltage on the line drops to the point where full load cannot be delivered over the line. In this case it must be noted, however, that the critical voltage is the high-tension line voltage and not the step-down voltage. This is a very important distinction for the drop in the step-down transformer will be considerable on a short circuit especially if the design of the step-down transformer is such that the magnetic inter-linking of the tertiary with the primary is much closer than that of the tertiary with the secondary, for the short-circuit kv-a. supplied by the condensers must go through this step-down transformer before reaching the short circuit and this tends to sustain the line voltage. As a matter of fact, if the condensers were connected to taps in the grounded end of the primary windings some gain would result in close interlinkage. A heavy fly-wheel capacity in the condensers is presumably very helpful in maintaining stable conditions.

is, the restoring torque will develop at least *partially* with the *progressive* separation of the phase positions of the several prime movers generators. The form of curve connecting power transmitted with phase displacement (Fig. 6) shows a condition very favorable for suppressing the pendulum action without the machine getting out of step. Of course, proper *damping* devices will also be of *great* assistance.

Enough has been said to make it clear that for any given case the resultant action is very complex, involving the relative flywheel effects of the different units, their different short-circuit characteristics, their governor speed curves and the damping factor. It may very likely be that in an actual installation the most favorable adjustment of conditions may be secured by providing adjustment in such factors as flywheel effect, short circuit kv-a., etc., and making a final determination in the field. These are matters for the study of specialists and cannot be profitably carried further at this point.

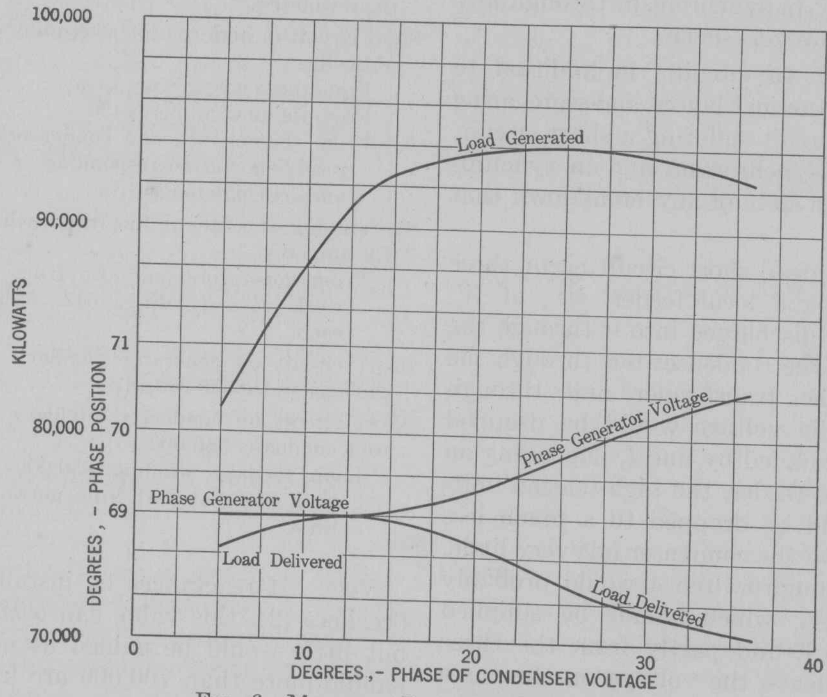


Fig. 6—Maximum Power Transmission

As has been pointed out by others, the tendency for the various parts of the system to fall apart is theoretically markedly increased by the pendulum effect between two machines starting in equilibrium under normal conditions and subject to a sudden changing in conditions due to a short or even load change due to switching. A new equilibrium position must be assumed and in swinging to this new position there will be a tendency to over run the position of equilibrium and if this position of equilibrium be the maximum torque position also, the temporary over run may cause a falling out of synchronism. The seriousness of this can be determined only after further data are available, for the percentage increase of torque required for maintaining synchronism may not be great and the change will probably not be very sudden, that

This discussion so far applies to a single circuit or a group of circuits connected directly in parallel. The action of the system of Fig. 5, however, is in effect quite otherwise. There are several critical points of difference.

First: The four lines while dividing the load freely between one another, are yet sufficiently separate electrically so that a short circuit on one or on the step-down end of one will not greatly disturb the voltage on the others. The high-tension circuits are not directly connected, but the step-down transformers secondaries are connected together through choke coils having a suitable reactance to permit equalization of the loads.

A similar interconnection exists at the generator end.

Second: The synchronous condensers are in parallel and are thus able to hold strongly together at times of disturbance in the network. This serves to hold all four high-tension circuits together. If found desirable to prevent too much disturbance of a condenser by trouble on another line, reactances can be connected between each condenser and the auxiliary bus.

Third: The main generators are connected in parallel through reactances. This serves to tie these generators all in parallel so that no one generator is likely to drop out of synchronism.

Fourth: The feeders on the step down side of the four transmission circuits are so connected through the reactances that a dead short circuit on one will not greatly disturb the voltage of the others, which will, therefore, continue firmly in synchronism through any kind of disturbance, however severe.

Thus this combination of circuits, in addition to providing a simple and practical layout for segregating and disconnecting any circuit suffering a short circuit, will hold itself firmly in synchronism and in synchronism with the network in spite of any breakdown that may occur.

For example should a dead short circuit occur three miles out on the left hand local feeder, *viz.*, at *W*, Fig. 5, current would be discharged into it through the feeder from line *I*, from the condenser bus through the tertiary winding of the transformer and through breaker [4 *x*]. While the voltage would be dropped materially on the local bus fed by line *I*, depending on the reactance of the bad feeder, the high-tension voltage on the line *I* would be dropped to a much less extent and the voltage on the condenser bus very little. The current passed through switch 4 would probably not exceed 200,000 kv-a. which would be supplied partly from the network and partly from the three other lines and would leave the voltage on the three good lines practically undisturbed. Meanwhile the relays would cut off the fault.

This system, to use an analogy, compared to the usual system, is like a locomotive which has an equalized, spring supported frame, compared to the farmer's hay wagon without springs. Every stone in the road causes a shock to the whole wagon while it would be passed over by the locomotive almost unnoticed.

SUMMARY

To give a more concrete idea, numerically, of the effect of abnormal conditions in producing heavy short circuits and to indicate the duty of the oil breakers, the following approximate values are given, assuming a load of 90 per cent power factor at low-tension busses.

	Kw.	Kv-a.
Normal full load per circuit, low-tension bus	100,000	111,000
Maximum synchronous converter load per circuit	3,000	75,000
Normal current in reactors (4) representing interchange of load, estimated	10,000	12,000
Short circuit in high tension at receiving end of high-tension circuit, arc kv-a. from generator, at point of short circuit, 420 amperes		160,000
Kv-a. corresponding at generator, 223 amperes		85,000
Kv-a. through receiving transformer from condensers and network about		1,250,000
of this say 200,000 comes through reactors (*T*) and 350,000 from network. Of the 200,000, part comes from network and part from three good lines, the balance of 750,000 from the condensers and tertiary windings		
Short circuit in high tension at sending end of the line—		
From the generators arc kv-a.		600,000
From the line, amperes 420		160,000
From the network and condensers at receiving end corresponding to 223 amperes high tension		85,000
Short circuit at center of line, from each end 735 amperes		280,000
From generators and also from network corresponding, 642 amperes each		244,000
Short circuit on generator auxiliary bus, each generator 350,000 all		1,400,000
Short circuit on condenser auxiliary bus, each condenser 350,000		
Each tertiary winding 350,000 part from line and part from network—total		2,800,000

Note: If reactances be installed in series with the breakers (2), this value can easily cut in half or less, but little would be gained as no one breaker has to handle more than 700,000 arc kv-a.

The essential features of the system of Fig. 5 have now all been touched upon and the performance of the whole system seems to be very favorable. Of course, many variations can be made and changes introduced to meet special cases, but as long as the essential characteristics are maintained, the good performance should still be retained. The more fundamental features are the maintaining substantially separate of the main units as far as short circuits are concerned, the interconnection for purposes of load equalization, the means of maintaining a high voltage at both ends of the line on the high-tension side even when short-circuits occur, the automatic control of voltage and power factor for purposes of regulation and the proper choice of governor characteristics and flywheel effects for the various units.

Intermediate Condenser Station

An intermediate station at the middle of the line with synchronous condensers materially improves certain features of the line performance as for example, synchronizing power at time of disturbance and variation of voltage along the line. Furthermore, a much smaller synchronous condenser capacity is required at the receiving end. This advantage is more than balanced, however, by the large condenser capacity required at the center of the line.

Considering the layout of Fig. 5 as distinguished from a single transmission circuit, apparently, on the whole, little or nothing would be gained in efficiency or operating performance by the intermediate condenser station. The no-load voltage at the center would be reduced 15 per cent which is a material point, the line efficiency over the working range would be no better and at least 30,000 kv-a. of condensers additional total would be required, representing a loss and expense. The synchronizing power would be materially greater, perhaps 50 per cent greater. On the other hand the extra cost, especially when spare apparatus and interconnections are considered, and the very serious operating handicap of a third station with a third set of operators to be coordinated and the problem of relay protection, make it clear that very considerable sacrifices would be justified in avoiding the intermediate station and retain the simpler layout of Fig. 5.

It is interesting to note from case 18, Table "A", that power can be transmitted backward over the line with 220,000 volts at the condenser end and 245,000 volts at the generator end and at a better efficiency than in the normal direction.

Conclusion

The net upshot of this layout of Fig. 5 is a system delivering regularly 400,000 kw. (perhaps reduced to 360,000 for brief intervals, for work on a transmission circuit) over a distance of 500 miles, with losses including line, transformers and condensers of about 15 per cent, with flexibility such that any unit may be shut down at will without disturbing operation. This is a system in which disturbance caused by short circuits will apparently be less than with the usual transmission system and a system well adapted for automatic relay protection.

On the basis of power generated at $20.00 per kw. year on the switchboard and saleable at the receiving step-down bus bars in quantity at $50.00 per kw. year, an expenditure of something between $75,000,000 and $90,000,000 would seem to be justified, assuming 12 per cent to be sufficient to cover all fixed charges, or $75,000 to $90,000 a mile for a double circuit tower line including cost of condensers and auxiliaries.

It appears from the above discussion that the superline, while it has great possibilities of astonishing efficiency and an extraordinary range of transmission, has also some very distinct limitations and some real problems of its own that will warrant much study and discussion.

Discussion

For discussion of this paper see page 71.