A paper presented at the 18th Annual Convention of the American Institute of Electrical Engineers, Buffalo, August 22nd, 1901, President Steinmetz in the Chair.

PERFORMANCE OF AN ARTIFICIAL FORTY-MILE TRANSMISSION LINE.

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The artificial duplication and test of a 40-mile transmission line was carried out as far as facilities would permit in the Electrical Engineering Laboratory of the University of Illinois during the Spring semester of 1901. The combinations selected were such as would cover a wide range of conditions in practice. The results obtained represent closely those that might be expected under commercial conditions of a similar line. The characteristics of performance illustrate the evil effects of shifting phase displacement as the chief cause of poor regulation.

General Considerations and Requirements.—The kind of service and requirements at the receiver end of the line involve a consideration of the kind of load, such as synchronous motors or converters, induction motors, arc and incandescent lights, or any combination of these. In the design of the line the prime factors are load, distance, voltage, frequency and allowable drop and loss. There is usually allowed a maximum drop for the given conditions. Such an allowance depends upon the kind of service employed, the character of the load and the inherent properties of the line, such as ohmic resistance, self-inductance, capacity, frequency, line current and its phase displacement.

The character and variation of receiver loads also largely influence the line regulation, losses and efficiency. The voltage, cost of conductors, cost of construction and maintenance and insulation to prevent leakage deserve some share of consideration.

The energy or I^2R loss in the line, in per cent. of the full load power delivered to the line, usually varies between 5 and 10%, in the best modern transmission installations. The charging current and receiver wattless components of current, if any, will indirectly vary this I^2R loss according to whether they are neutralized or not.

Effect of Reactive Loads Upon Line Efficiency.—The effects of reactive loads upon the performance of the generator are well understood and have been set forth in numerous experiments. The effect of such loads upon the transmission is to increase the current for the same energy transmitted over that required when the current in the line is in phase with its impressed E. M. F., the line loss increasing, as the square of the current will be much increased with increase of phase displacement. From this consideration alone it would appear that the line current should be in phase with its E. M. F. for most efficient performance. Considering, however, the voltage and drop for a given amount of power delivered, it is to be noted that conditions may arise in practice in which an inductive line may transmit energy at a higher efficiency than a non-inductive one.

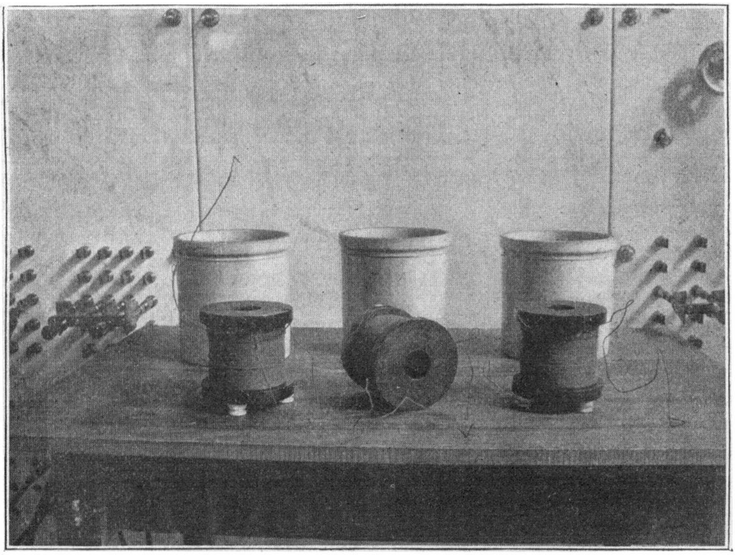

FIG. 1.—Coils for Artificial Reactances.

Conditions Assumed.—It is desired to transmit, by three-phase system, with step-up and step-down transformation, from 1 to 8 K. W., 40.75 miles, at 2,300 volts and 64 cycles, with a transmission efficiency, between generator terminals and receiver secondary terminals, of not less than 80%, at full and practically non-inductive load on the receiver secondary circuit. The size and frequency were necessarily determined by the polyphase generator available.

No. 4 (B. & S. gauge) copper wire was selected, giving a line loss per phase of 0.215 K. W., or about 8%, on a basis of 2.66 K. W. output per phase from receiver secondary terminals, under normal voltage and non-inductive load. The line constants chosen are suited to a distance apart of the wires of 18″ at the vertices of an equilateral triangle.

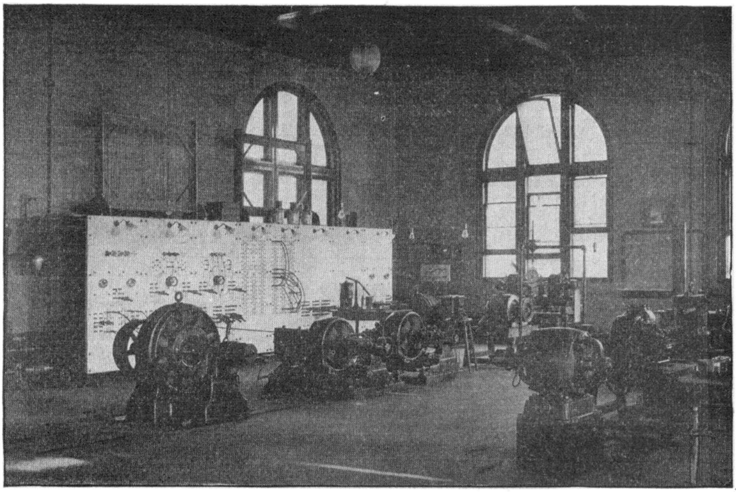

FIG. 2.—Arrangement of Artificial Line Above Switchboard.

Self-Inductance and Inductive Reactance.—The artificial inductive reactance provided for each wire of the three-phase line was an air-core coil, wound and adjusted to the proper self-inductance of this line wire under the conditions assumed. Maxwell's bridge method[1] was used in standardizing these three inductances. The accuracy of the standard inductance and resistances used and the sensitiveness of the galvanometer warranted an accuracy to within one-fifth of 1%. Air-core coils were selected to insure

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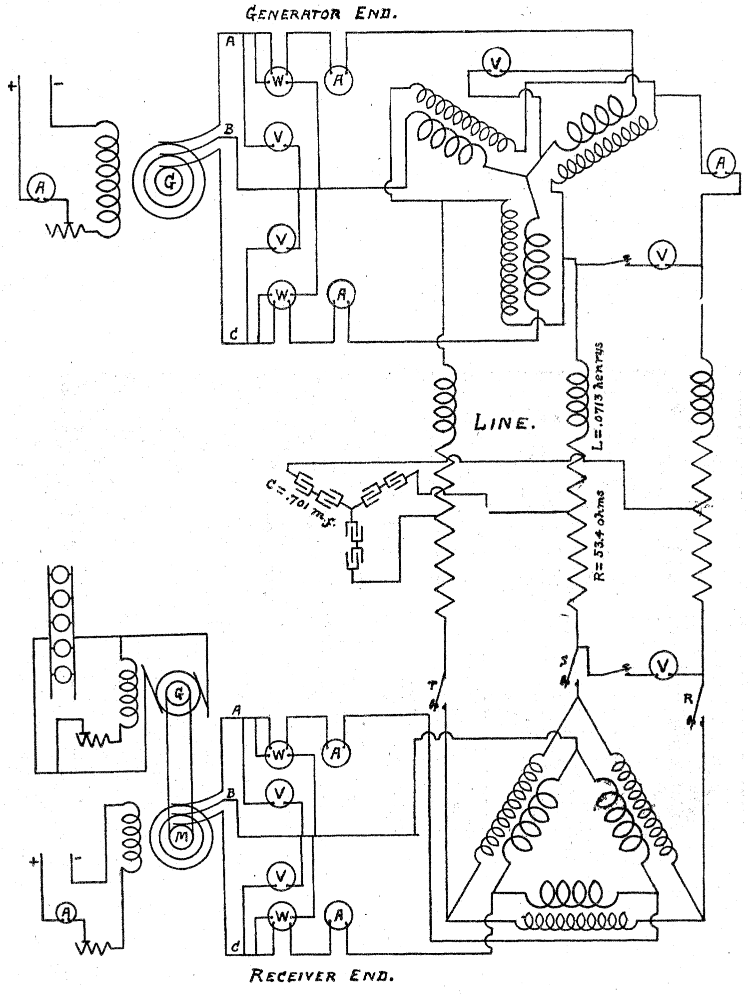
[1] Maxwell's "Electricity and Magnetism," vol. ii., p. 367.

that such equivalent inductance of the artificial line (and therefore its reactance at constant frequency) would remain constant throughout all variations of line current. These reactance coils, Fig. 1, were each immersed in earthenware jars filled with a high



Connections for Tests of 40-Mile Artificial Transmission Line.

Fig. 3.

grade of transformer oil and always used in this condition. While in use they attained a temperature of approximately 70° C., and remained practically at this temperature during the experiment. The resistance of each coil at this temperature was 9.0 ohms.

Ohmic Resistance.—The total ohmic resistance of each line wire for the given conditions should be 53.4 ohms. To supply the remaining 44.4 ohms for each line wire, three non-inductive resistances were constructed by winding No. 17 (B. & S. gauge) German silver wire non-inductively upon frames, as shown above the switchboard, Fig. 2. These resistances were each adjusted by an accurate Wheatstone bridge to the value of 44.4 ohms, at about 85° F., the temperature of the room.

Capacity and Capacity Reactance.—The artificial capacity of the three-phase line was composed of six commercial electrostatic condensers, two condensers each being connected in series and thence connected in star between the three line wires. These condensers were arranged so that the capacity between each of the line wires and the neutral was 0.701 micro-farads. The outer terminals of the star-connected condensers were respectively connected to the middle points of the non-inductive resistances of each line wire, Fig. 3. Such an arrangement was equivalent to concentrating all of the capacity of the 40.75–mile transmission line midway between the generator and receiver ends.

TABLE I.

DATA OF ARTIFICIAL TRANSMISSION LINE.

Length of transmission	40.75 miles
Diameter of conductors, No. 4 B. & S.	0.204 inches
Area of conductors	41,742 cir. mils.
Resistance per mile at 75° F.	1.31 ohms
Frequency, cycles per second	64

CONSTANTS OF THE LINE COMPUTED FROM THE ABOVE DATA.

Inductance per mile of wire or ½ mile of transmission	0.001750 henrys
Inductive reactance per mile of wire, 64 p. p. s.	0.703 ohms
Impedance per mile of wire, 64 p. p. s.	1.487 ohms
Impedance factor of line (impedance divided by resistance)	1.134
Resistance of 40.75–mile transmission line (or 81.50 miles of line wire)	106.8 ohms
Inductance of 40.75–mile transmission line (or 81.50 miles of line wire)	0.1426 henrys
Inductive reactance of 40.75–mile transmission line, 64 p. p. s.	57.3 ohms
Impedance of 40.75–mile transmission line, 64 p. p. s	121.2 ohms
Capacity of each wire to neutral per mile of transmission line	0.01722 m. f.
Capacity reactance between two wires per mile of transmission at 64 p. p. s.	1,449,300 ohms

Capacity of 40.75-mile transmission line considered as two parallel cylinders	0.701 m. f.
Capacity reactance between two wires of 40.75-mile transmission line	355,300 ohms
Charging current per phase of 40 75-mile transmission, 64 p. p. s. and 2,300 volts	0.374 amperes
Total apparent energy to charge line, 64 p. p. s. and 2,300 volts	1.49 K. W.
Total true energy to charge line, 64 p. p. s. and 2,300 volts, or total I^2R due to charging current	0.011 K. W.
Current per phase to transmit 8 K. W. at 2,300 volts and unity power factor	2.01 amperes

TABLE II.

DATA OF THE ARTIFICIAL SUBSTITUTES FOR LINE CONSTANTS.

Size of wire of reactance coil for each line wire	No. 18 B. & S. gauge
Inside diameter of each reactance coil	1.87 inches
Outside diameter of each reactance coil	4.0 inches
Length of each reactance coil	14.25 inches
Approximate number of turns on each reactance coil	1,420 turns
Inductance of each reactance coil	0.0713 henrys
Ohmic resistance of each reactance coil, 70° C.	9.0 ohms
Resistance of non-inductive portion of each line wire	44.4 ohms
Total ohmic resistance of each artificial line	53.4 ohms
Equivalent artificial capacity per phase of each line wire to neutral	0.701 m. f.

Connections Used in Operation.—The reactance coils were placed at the receiver end, all of the line reactance being assumed as concentrated at that point. In series with each of these reactance coils was placed one of the non-inductive resistances, with its respective condensers.

The connections of apparatus and instruments for the various experiments are shown in Fig. 3. In the experiments for charging current and resonant rise, the switches R, S and T were open.

Description of the Generator.—Three-phase current was generated from a machine made by the Westinghouse Electric and Manufacturing Company, constructed for single and polyphase work, as generator, synchronous motor or converter. The armature has a distributed winding, and was here tapped off as a three-phase delta combination.

DIMENSIONS AND MEASUREMENTS OF GENERATOR.

Type	Polyphase converter
Serial number	135,751
Capacity	10 kilowatts
Number of poles	4
R. P. M.	1,920

Frequency	64 cycles
Normal volts (three phase)	410
Full-load current per branch (three-phase)	14 amperes
Resistance of field (hot)	685 ohms
Resistance of armature per phase (hot)	0.92 ohms

External Characteristics of Generator.—External characteristics were taken of this machine under various reactive loads with lagging and leading phase displacement[1]. The results are shown in Fig. 4. In obtaining each of these curves the true power was measured by the two-wattmeter method. The power factor of the external circuit was kept constant throughout the whole range of load by maintaining constant the ratio of the two-wattmeter readings.[2]

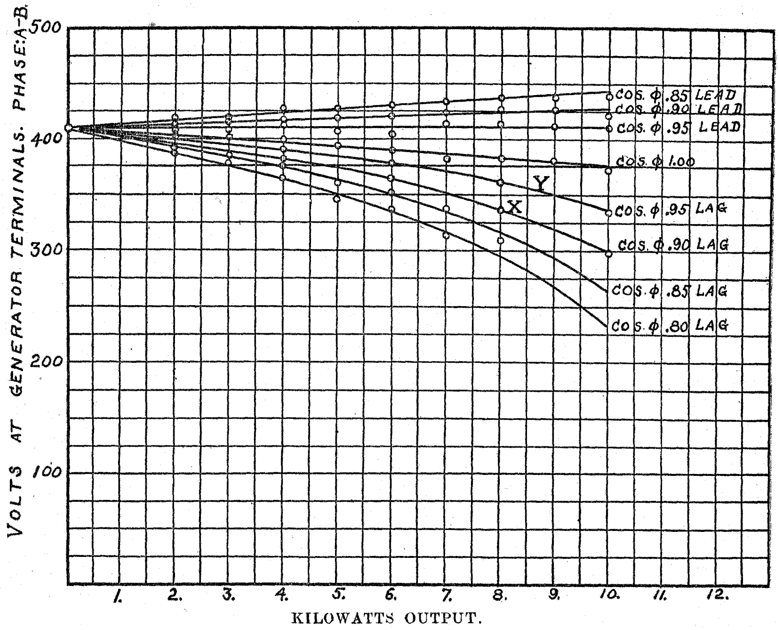


FIG. 4. External characteristics of Westinghouse 10 K.W. Alternator as three-phase Generator, showing the effect of Variable Reactive Loads on Regulation.

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[1] "The Regulation of Alternators under Variable Reactive Loads." Geo. W. Redfield, *Technograph*, University of Illinois. No. 15, p. 95, 1901.

[2] "Power Factor Measurements." B. Frankenfield. *Electrical World and Engineer*, vol. 35; p. 178. Feb. 3, 1900.

Charging Current of the Artificial Line.—The receiver end was open-circuited and the charging current measured as on a three-phase line. One of the line wires at the generator end was

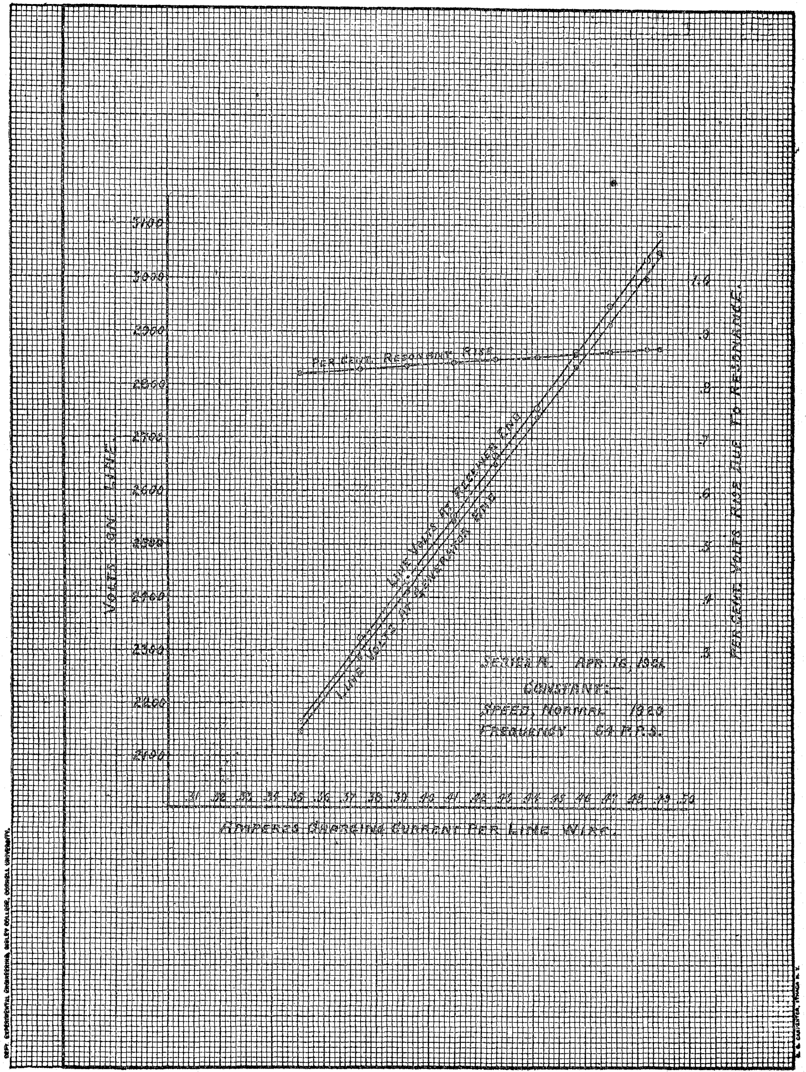

FIG. 5.—Relation Between Charging Current and Resonant Rise for Various Voltages at Generator End.

disconnected and the charging current measured with the same voltage and frequency applied to the line as before. In the case of the three-phase line the total charging current was $2/\sqrt{3}$ that of the charging current of the single-phase line.

Resonant Rise—An experiment was made to determine the rise of voltage at the receiver end primarily due to resonance. The line at the receiver end was opened and a Weston

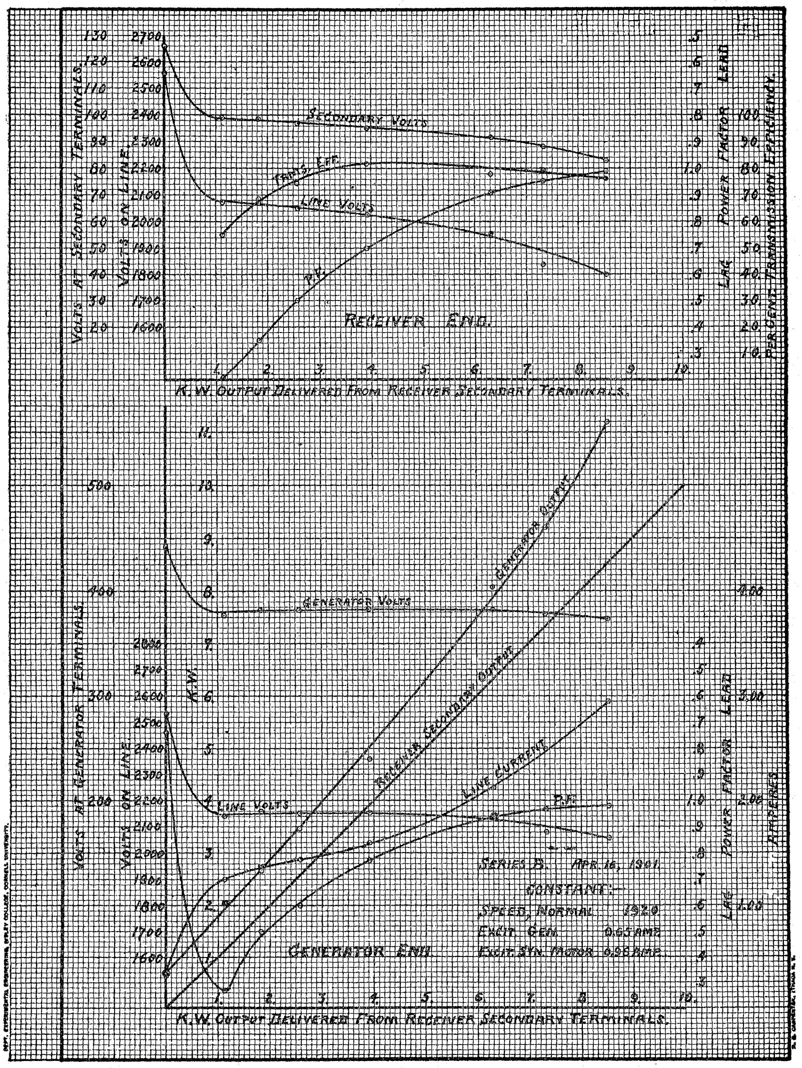

FIG. 6.—Performance of Transmission at Variable Load with Under-Excited Synchronous Motor.

voltmeter, with suitable multiplier, was then placed across the terminal of one of the phases. Fig. 5 shows the results of this experiment, giving the relation between charging current and resonant rise for various voltages at generator end. During the interval when the charging current was measured the voltmeter was not in circuit, and hence there was no current taken off the line at the receiver end.

Let e = percentage rise of potential due to resonance.[1]
C = total capacity of line, in farads.
L = inductance in henrys, of total length of one circuit.
$\omega = 2\pi n$, where n is the frequency or p.p.s.

$$\text{Then, } e = \frac{C\,\omega\,L\,\omega\,100}{2}$$

The quantities C and L are proportional to the length of line and therefore the percentage rise in potential varies practically as the square of the length of the line and the square of the frequency.

Substituting in this formula the values for the 40.75-mile line, we have,

$$e = \frac{10^{-6}\times 0.701\times 401.5\times(0.0713\times 2)\times 401.5\times 100}{2} = 0.816$$

this being the calculated per cent. rise due to resonance for this line. By a glance at Fig. 5, it will be noticed that the observed values for the per cent. resonant rise agree very closely with the above computed value. It also shows that this per cent. resonant rise is practically independent of the voltage applied to the line.

All power factor values of the three-phase circuit were determined from two-wattmeter measurements by use of the well-known curve of ratios of wattmeter readings in connection with the cosine curves for balanced three-phase system.[3]

Power Factor at Generator End on Open Receiver Secondary.—When the receiver secondary circuit is open it will be noticed in all of the curves of performance that the power factor at the generator end is leading. The reason for this will be evident upon considering a series of readings by the two-wattmeter method, one or the other wattmeter always having the larger

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[1] "The Use of Aluminium Line Wire, and Some Constants for Transmission Lines," by F. A. C. Perrine and F. G. Baum, TRANSACTIONS, vol. xvii., p. 345.

[2] Ibid. Frankenfield.

reading according to whether the resultant power factor of the three-phase line is leading or lagging. The current in the line under these given conditions is known to be leading because the charging current is in excess of the no-load current required by the transformers. Further evidence that the power factor at the generator end is leading is shown by the line voltage at the receiver end being higher than the line voltage at the generator end, and such a condition could not be possible, owing to the inductance of the line unless there was a leading current in the line. For no-load on the secondary, at the receiver end, similar conditions are obtained in all subsequent tests; hence, the resulting leading power factor of the three-phase transmission is the same in all cases of open receiver secondary.

Description of the Synchronous Motor.—The transmitted power was absorbed at the receiver end by a machine made by the General Electric Company, constructed for single and polyphase work, as a generator, synchronous motor or converter. The armature has a distributed winding and and was used as a three-phase machine.

DESCRIPTION OF SYNCHRONOUS MOTOR.

Type	Synchronous Machine.
Capacity	7½ K.W.
No. of poles	4.
R. P. M.	1920.
Frequency	64 cycles
Normal voltage (three phase)	110
Full load current per branch (three-phase)	40 amp.

Performance of Transmission at Variable Load with Under-Excited Synchronous Motor.—The curves of performance, Fig. 6, show that as soon as the synchronous motor is thrown on, as a lightly loaded receiver, at constant excitation of 0.96 amperes, taking about 1.1 K.W., the phase displacement at the generator end immediately changes from lead to lag. The line current rises quite rapidly and the high-tension and low-tension pressures at each end drop considerably, due to the presence of lagging currents in the line and generator circuit. Under such conditions the regulation of the generator is greatly impaired, as shown in Fig. 4. The under-excited synchronous motor is similar in its effects upon the transmission system to an induction motor, producing lagging phase displacement materially affecting the regulation of the system. As the load increases, the line drop at receiver end falls off gradually, while the current comes rapidly into phase with the impressed E.M.F., reaching unity power factor at a trifle over full load. This effect partially compensates for the increased drop due to heavier loads and therefore has a tendency to keep the voltages up. The phase displacement at the receiver end controls the phase relations of

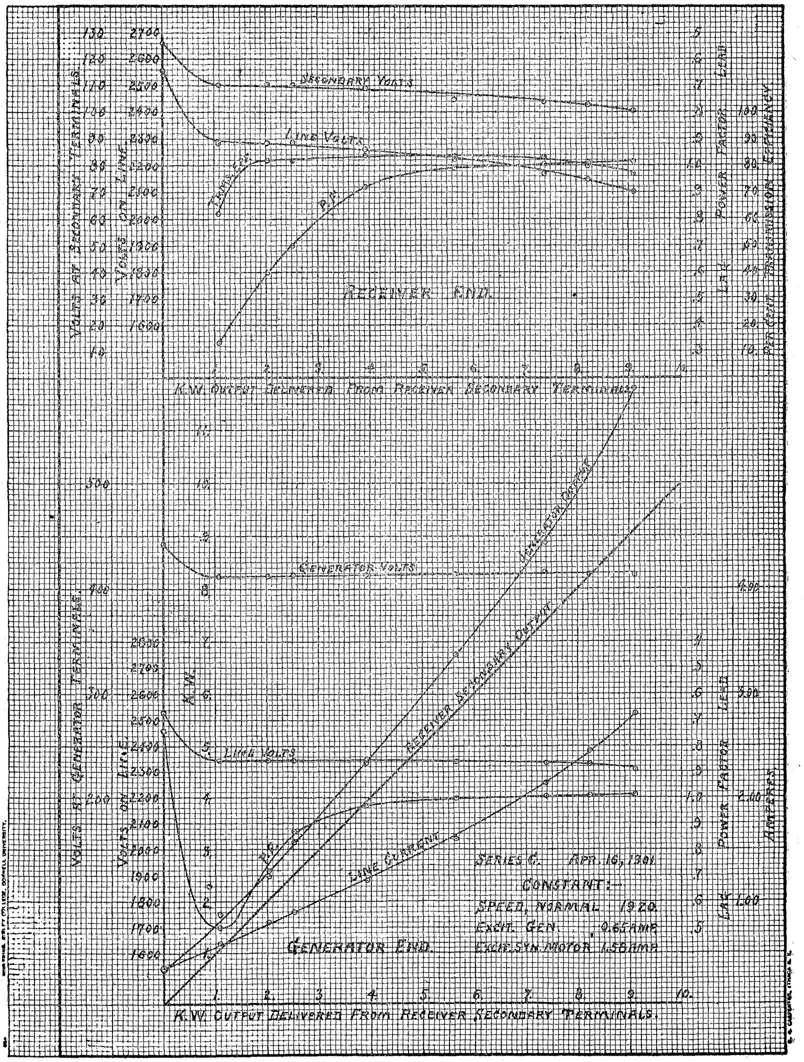

FIG. 7.—Performance with Normally-Excited Synchronous Motor.

these E.M.F.'s. The line current is exceptionally high under light loads, because under such conditions the receiver power factor is very low.

$$\text{Transmission efficiency} = \frac{\text{Output of receiver secondary}}{\text{Input from generator terminals}}$$

The efficiency in this case reaches a maximum value of 82%, at about half load, and has a maintained value of 80% and over from one-third to two-third load.

Performance with Normally Excited Synchronous Motor.—The characteristics under this condition, are shown in Fig. 7. The constant excitation of the synchronous motor was 1.58 amperes, the excitation for its operating at practically unity power factor above half load. The resulting power factors are much improved at the generator and receiver ends under light loads. As the load increases, each of these power factors increase more rapidly than in the preceding case, and at full load they reach unity while beyond this point they are a trifle leading. The line drop is not so marked, resulting in better inherent regulation of the system.

The pressure at the generator end remains practically constant after the synchronous motor is thrown on the line. The line current rises gradually, improving the line efficiency by reducing the phase displacement, also improving the transformer efficiencies. Owing to this the transmission efficiency rises quickly and maintains a high value of 82% and over from one-fifth to full load. This bears out the earlier statements of this paper that best results are to be obtained in such a transmission system when the resulting phase displacement is a minimum.

PERFORMANCE WITH OVER-EXCITED SYNCHRONOUS MOTOR LOAD.

The curves of performance under this condition are shown in Fig. 8. The constant excitation of the synchronous motor was 2.58 amperes. The pressure at the generator end does not drop at all when the over-excited synchronous motor is thrown on, having a tendency to rise, due to the phase displacement of its external circuit remaining leading at all loads. This is equivalent, in its effects upon the generator, to over-compounding, producing the so-called "boosting" effect, as shown in Fig. 4, for an equivalent power factor of about 0.90 leading. The secondary pressure regulation at the receiver end is better than in any previous case, being exceptionally good due to a leading phase displacement which increases with the heavier loads. This has a

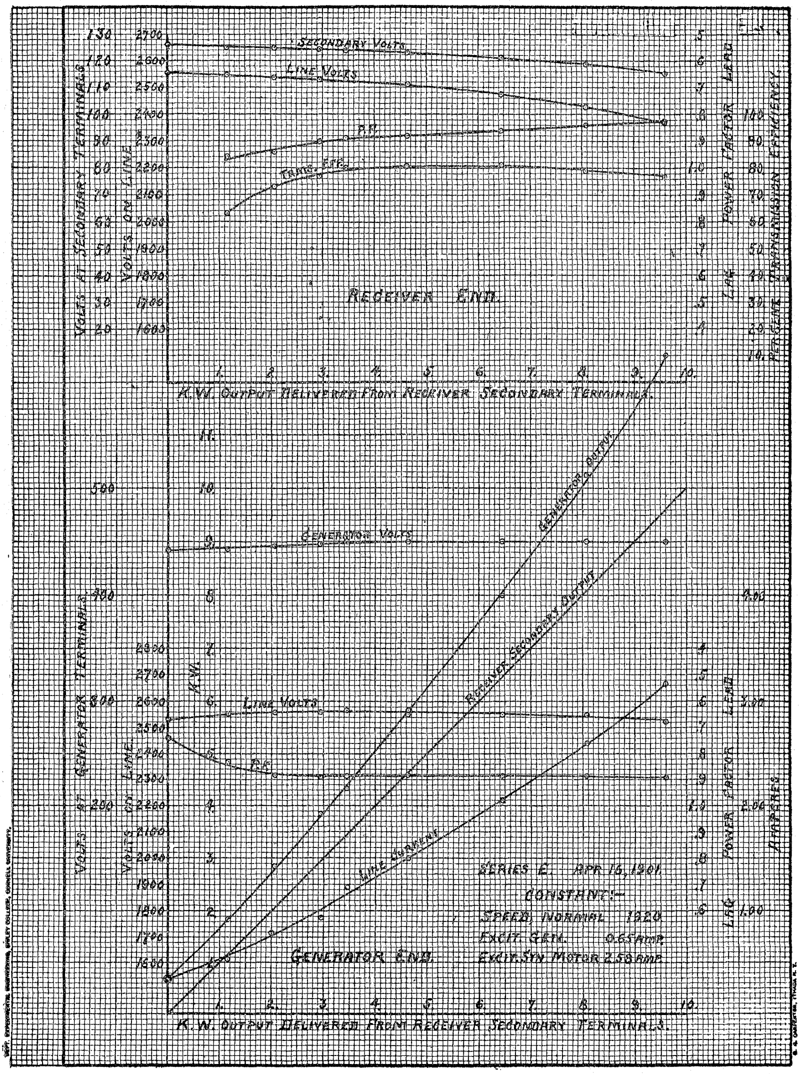

FIG. 8.—Performance with Over-Excited Synchronous Motor Load.

compensating effect upon the secondary receiver voltage which will be noted later.

The transmission efficiency is 80% and over from half to full load. In this case the efficiencies of the transformers are evidently re duced at their respective loads by the increased core losses under the higher impressed voltages. Their I^2R losses are also increased for the same respective loads owing to the increasing phase displacement.

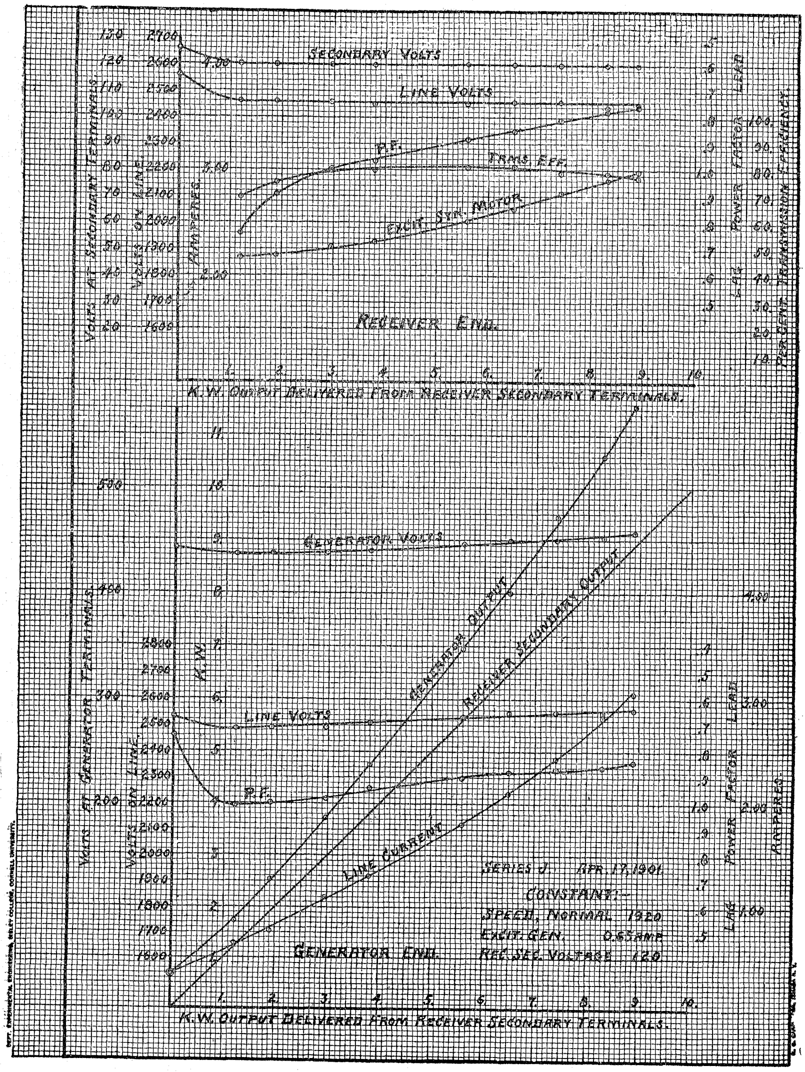

FIG. 9.—Performance with Constant Receiver Secondary Voltage, 120 Volts, and Variable Excitation of Synchronous Motor.

Constant Receiver Secondary Voltage and Variable Excitation of Synchronous Motor.—Fig. 9 illustrates the performance where a constant pressure of 120 volts was maintained at the receiver secondary terminals while the excitation was correspondingly increased with the load. There is increasing leading phase displacement after the small loads are passed. The transmission efficiency is at and above 80% from one-third to full load. Under similar conditions the receiver secondary voltage was maintained at 125, the no-load pressure, and the results are plotted in Fig. 10. The phase displacement at each end is de-

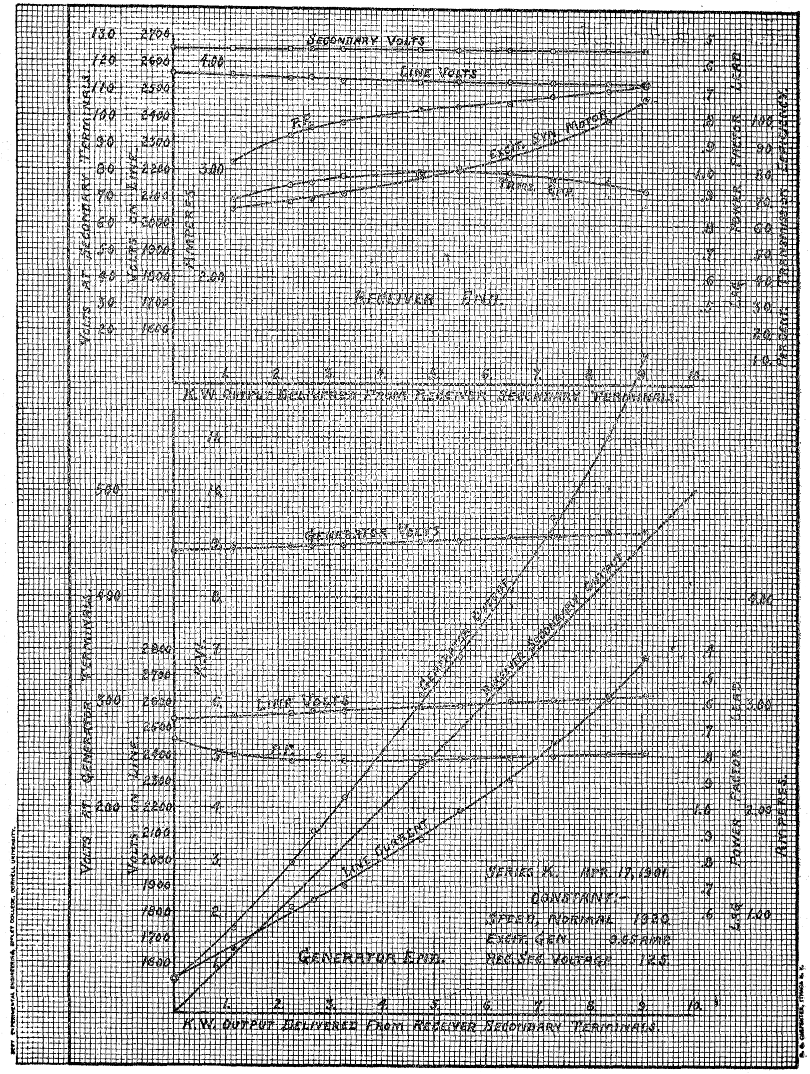

FIG. 10.—Performance with Constant Receiver Secondary Voltage, 125 Volts, and Variable Excitation of Synchronous Motor.

cidedly leading. Therefore the line current is materially raised, increasing the I^2R losses. Under this condition the transformers were operated at still higher pressures, correspondingly decreasing the efficiency of transmission.

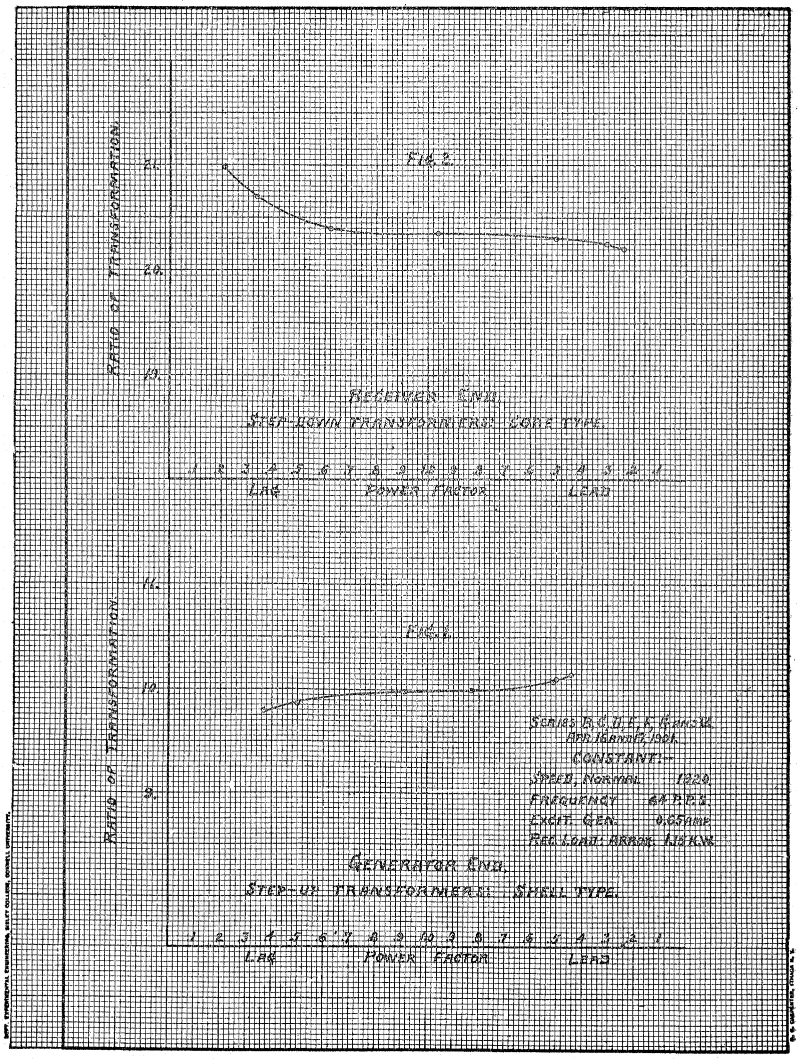

FIG. 11.—Variation of the Transformer Ratios as Function of the Phase Displacement.

Effect on Generator Voltage by Increasing Synchronous Motor Excitation.—Under the leading phase displacement of the last two experiments the pressures at the generator show the characteristic increase earlier noted in Fig. 4.

The leading wattless components of current are comparatively large, and therefore have an appreciable influence upon the performance and regulation of the generator.

Regulation of Transformers Under Variable Phase Displacement.—An examination of the transformer ratios as determined by the voltage curves at the generator and receiver ends of the preceding curves of performance, will show that for the small loads especially, the ratio of transformation at each end of the line varies greatly with the phase displacement. This variation of transformer ratios is a function of the phase displacement depending upon whether it is lagging or leading.

Fig. 11 shows the plotted values of these variable transformer ratios, as a function of the power factor for the step-up and step-down transformers respectively. The load was practically constant, at 1.15 K.W., for all of these determinations. The variation in the ratio of the step-down transformers is opposite to that of the step-up transformers.

The following is the general principle for either step-up or step-down transformers, respecting the variation in transformer ratios with variable phase displacement:

The output voltage increases as the lagging phase displacement decreases, which voltage continues to increase as the displacement passes through unity and becomes more and more leading.

This variation of transformation ratio will become apparent upon a consideration of the effect of variable phase displacement upon the resultant flux. In any given case this flux is smaller with a lagging phase displacement than with no displacement, and, therefore increases as the displacement becomes more and more leading.

Therefore, with a given primary impressed E.M.F. the secondary E.M.F. will be smaller with a lagging and larger with a leading load, than with a simple non-inductive load. Furthermore, it is to be seen that a difference of phase existing in the secondary circuit of a transformer reappears in the primary circuit somewhat decreased if leading, and slightly increased if lagging.

PRECAUTIONS TO BE TAKEN WITH UNLOADED TRANSMISSION LINES.

Judging from the results of the earlier sets of these experiments it should not be permitted to throw the generator onto an unloaded transmission line where the per cent. resonant rise may be comparatively large. If this should occur it may produce a marked resonant rise in pressure at the receiver end, and moreover increase the ratio of the step-up transformers. It is therefore advisable always to have induction motors or similar inductive reactance connected in the circuit. Furthermore, in designing a transmission line care should be taken to keep very low the ratio of the charging current to the full load power current, so as not to necessitate increasing the size of generating units to supply this charging current.

Transmission Efficiency.—The tendency to higher efficiency by increase of the impressed E.M.F., due to any so-called "boosting" throws the current out of phase with its E.M.F. It is evident that when high transmission efficiency is desired it is necessary to keep down the wattless components of current to whatever cause they may be due, quite as much on account of the impairment of transformer efficiency as in the general operation of the system. The three transformers used at each end of the line were of 3 K.W. capacity, of well-known modern types; Fort Wayne for the step-up, and Packard, for the step-down transformers. In almost all instances in these experiments they were operated at somewhat higher voltages than intended. Their I^2R losses were necessarily increased by the extreme range of reactive loads.

Voltage Regulation.—The results throughout are given for one phase (A–B) of the three-phase system, which was always balanced. There was comparatively little "hunting" of the synchronous motor under any of the conditions of operation. The transformers had a drop of 3% between no-load and full non-inductive load when operated at their normal voltage. There was also a drop of about 2% in the speed of the alternator between no-load and full-load, due to the increased slip of the induction motor used as a prime mover. After taking these factors into consideration regarding the regulation of the several parts of the system, it is evident that the performance of the transmission system was satisfactory.

Wave Forms from the Experimental Transmission System.[1] The instrument used in taking these wave forms was a modification of the Blondel oscillograph. To a small reflecting mirror was attached a very soft Norway iron needle, with a natural period of about one thousandth of a second. This was suspended vertically by a very fine silk fiber in line of prolongation of horizontal axis of an air-core solenoid of sixty turns of No. 20 (B. & S.) soft single cotton-covered magnet wire. The directive force of the needle was supplied by a pair of permanent steel magnets of horse-shoe form, producing practically a constant field. When an alternating current was passed through the solenoid it produced simultaneous deflection of the needle in frequency, direction and amount proportional to that of the current flowing.

By suitably arranged lenses a beam of light from an arc lamp will be reflected by the mirror upon highly sensitized paper mounted on a rapidly-revolving drum.

The photographic records of the wave forms are necessarily small, from one-half to one inch in amplitude. They were enlarged by throwing onto a screen by a projection lantern and then retraced by hand. Similar recording arrangements have been used with curve tracers. These are necessarily slow and tedious, requiring about half an hour for a complete record of the wave form. The record, therefore, is really a kind of composite photograph, as the wave form meanwhile may have undergone almost an infinite variety of changes. In the modification of the oscillograph as here used the deflections of the needle follow very closely and faithfully any variation in the alternating current, and a record of the wave form is obtained in about one-sixtieth of a second.

Figs. 12 and 13 illustrate the generator and receiver wave forms under typical conditions. Series X is an E. M. F. wave form of the three-phase generator on open circuit. Series Y of Fig. 12 and Series Y^1 of Fig. 13 are E. M. F. wave forms taken off the generator and receiver secondary terminals, respectively, under the same conditions of load and simultaneous conditions of operation, with leading phase displacement. These wave forms are very similar,

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[1] These wave forms were taken by Mr. E. F. Bracken, B.S., in Electrical Engineering, University of Illinois, by the method described in his thesis on "Investigation of the Wave Forms of Alternators and Synchronous Converters," June, 1901.

but the receiver end is distorted more than the one from that of the generator end, as the receiver end power factor was somewhat lower. They show the flattening due to the capacity effect of the leading currents present.

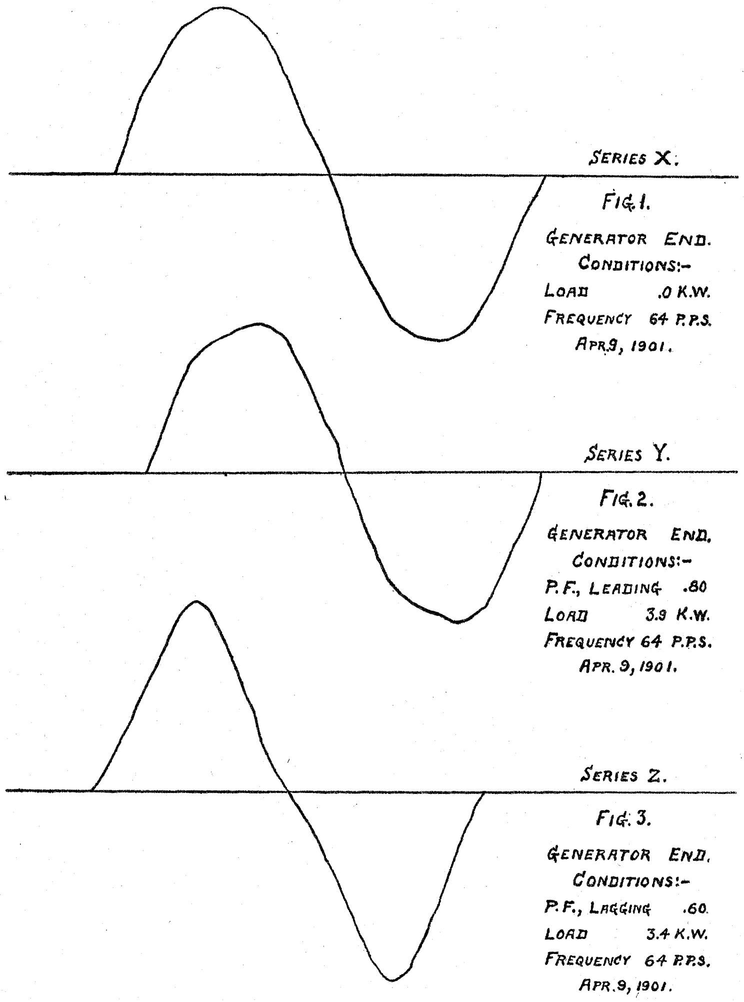

FIG. 12.—Wave Forms from the Generator.

Series z of Fig. 12 and Series z^1 of Fig. 13 are E. M. F. wave forms taken off the generator and receiver secondary terminals under the same conditions of load and simultaneous conditions of operation, but with decided lagging phase displacement. These waves are also similar, but that of the receiver end is more distorted than that of the generator, due to a lower power factor at the generator end. These waves illustrate the effect of lagging currents and show the characteristic peak due to the presence of inductance. From examination of them it is evident that to wave-form peculiarities are to be attributed many cases of bad regulation and other difficulties appearing in the earlier transmission systems with mixed apparatus and uncertain line conditions. They illustrate also the great influence upon the E. M. F. waves of the line and generator of the phase relation between the E. M. F. and the current.

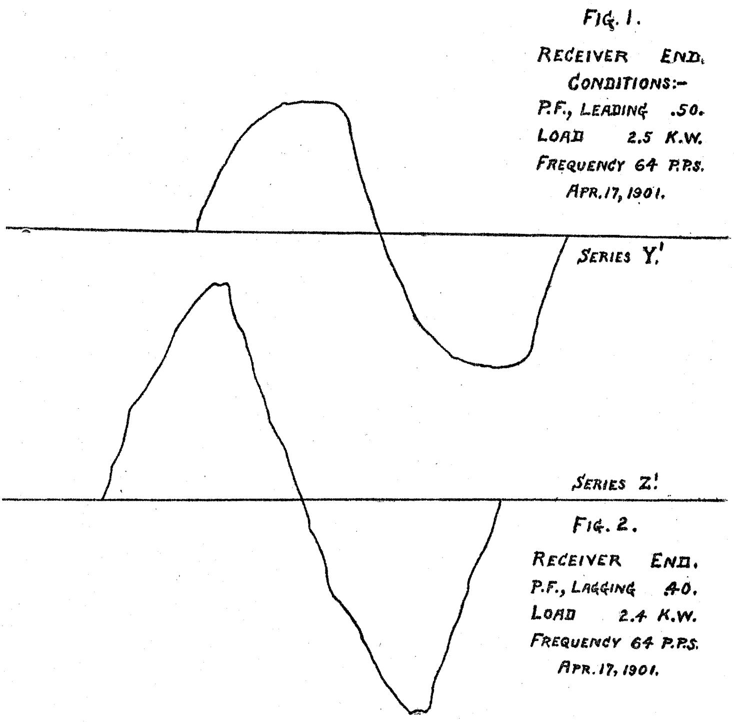

FIG. 13.—Wave Forms from the Receiver Secondary Terminals.

If synchronous motors or converters are used, giving wave forms quite different from those of their impressed E. M. F., they will become very unstable in regard to remaining in synchronism. This dissimilarity of wave forms also necessitates excessive currents, without any regard to the accompanying disadvantages inherent in phase displacement of synchronous machines, and such dissimilarities are purely relative and do not materially concern the question of the intrinsic value of synchronous machines in effecting neutralization of phase displacement.