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A METHOD OF COMPOUNDING ALTERNATING CURRENT GENERATORS AND MOTORS, DIRECT CURRENT GENERATORS, SYNCHRONOUS MOTOR-GENERATORS AND SYNCHRONOUS CONVERTERS.

BY FRANK GEORGE BAUM.

The weakest element in the regulation of an alternating current system is usually the generator. Makers of engine and water wheel governors are able to keep the variations in speed in the machines which they send out much lower than builders of A. C. generators are able to keep the variations in voltage. The time is past when the man who is selling a generator points with pride to the fact that the machine may be short-circuited with little increase over nominal current. The argument that compounding of alternating current generators is not necessary because load changes are not rapid, does not hold, as the fluctuation of voltage of 10% or more in some stations testifies. Working an alternating current station without compounding is equivalent to operating a direct current station with shunt-wound separately excited generators. When induction motors are to be operated, as is usually the case, the conditions are worse. No electrical engineer would install shunt-wound direct current generators, even if the load changes were not rapid, and the only reason for not installing compounded alternators is that there is at present no method by which the compounding may be produced for large stations. There are methods of compounding single machines which are more or less successful, but no method, I believe, for large stations, which gives results that can be compared with those obtained by compounding D. C. generators.

The following method of compounding alternating current generators for any load and any power factor, so that we may get results equal to those obtained by compounding D. C. generators will, I believe, commend itself to electrical engineers. In some respects, the method is simpler than in the case of D. C. generators, as will be shown.

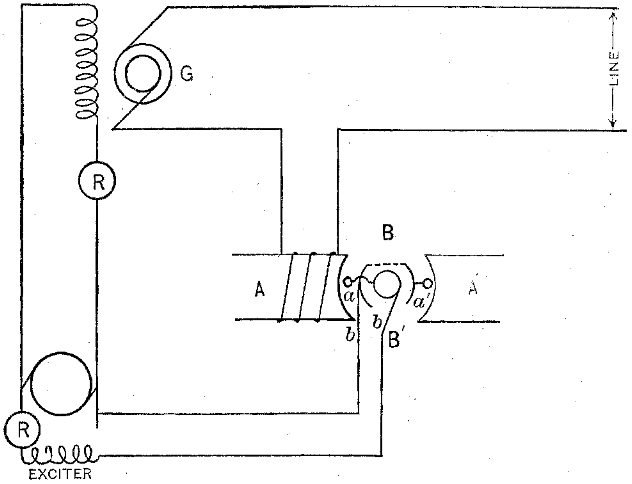

Fig. 1.—Showing Possible Connections of Compensator.

Fig. 1 shows the connections of the "compensator," as it may be called. G is the generator, which, for the purpose of explanation, may be considered a two-pole machine. From its shaft is driven the armature of the compensator *a a′*, having field poles A A′. The armature winding may be considered a single turn of wire, as shown. One end of the armature wire goes to a solid ring, and the other end to a ring broken as shown, but the two

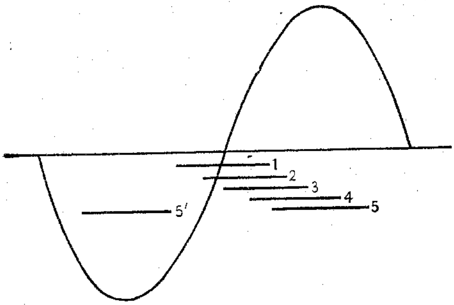

Fig. 2.—Showing Method of Obtaining a Rectified Potential.

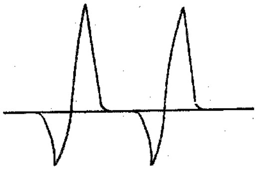

Fig. 3.—Trace of Oscillograph Record for Second Position in Fig. 2.

parts are metallically connected. It is to be noticed particularly that there is no commutation, the same armature wire being always connected to the same brush. Brushes are placed on these rings as shown, the brush on the broken ring being in the center of one pole. The metallic segments of the broken ring cover about 90 electrical degrees.

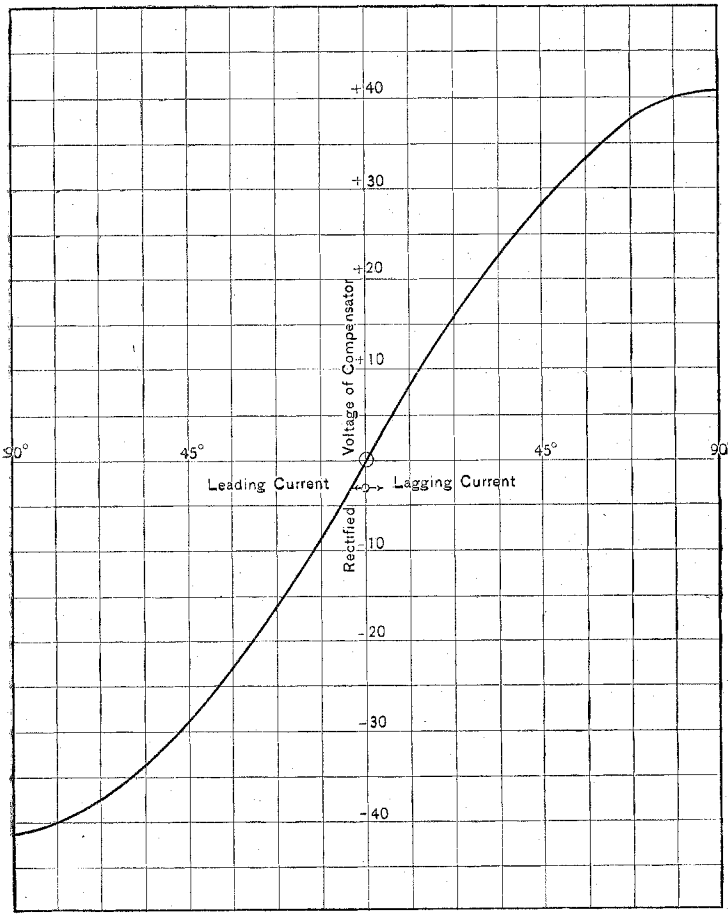

Fig. 4.—Curve of Rectified Voltage of Compensator, with Constant Field Current and Variable Angle.

If the field A A′ were excited by a direct current we would get at the brushes, parts of an alternating wave, a part of each wave being cut out owing to the fact that the ring is divided. If we excite A A′ by a sinusoidal alternating current in synchronism with the rotation of the armature *a a′*, we get waves of e.m.f. at the brushes of different forms, depending on the position of the armature coil when the current passes through its maximum value. For example, if the armature coil passes the position shown when the current in the field coil is a maximum, it will be evident that we get a rectified potential at the brushes *b b*. We really cut off the top of the wave and thus get a potential at *b b* which may be measured by an ordinary D. C. voltmeter. If the current in the field passes through zero when the armature coil passes the position shown, then we get no rectified potential.

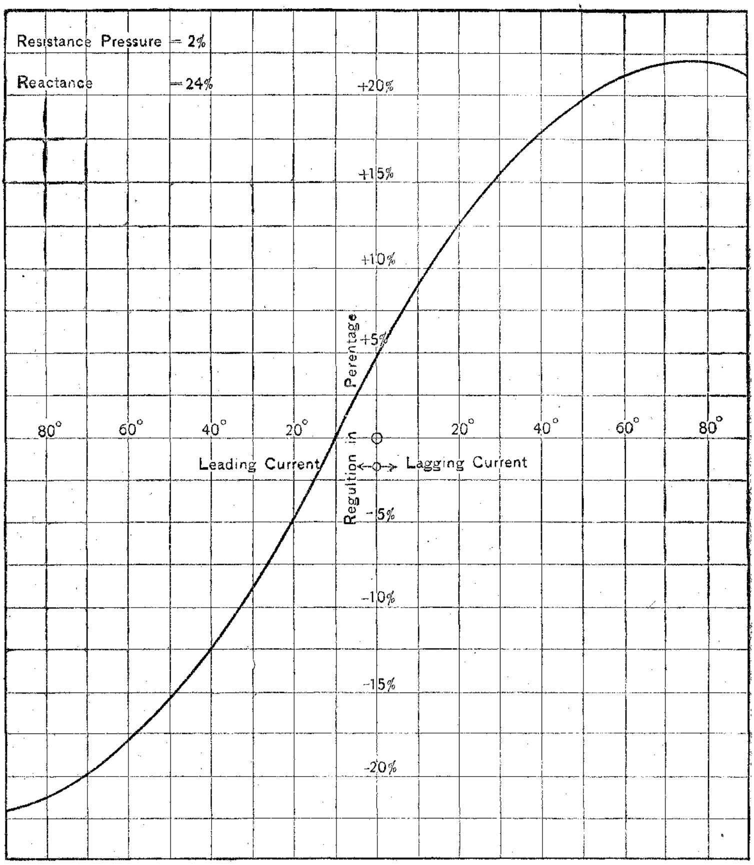

FIG. 5.—Regulation of Generator on Constant Armature Current and Variable Power Factor.

What really occurs for the different positions may be explained with reference to Fig. 2. The sine wave is the wave of current from the alternator, and may also represent the wave of magnetism in the compensator poles A A′. The lines 1, 2, etc., represent the metallic segment for different positions of the armature coil with respect to the wave of magnetism. If the current is passing through zero when the coil is in the position shown in Fig. 1, then we cut off the part of the wave under the line 1, and hence get an alternating potential. There will also be an alternating e.m.f. due to the transformer action, but no account need be taken of this. Now, suppose the current lags behind this position. This is equivalent to a motion ahead of the metallic segment with respect to the wave of current. For the position 2 of the metallic segment, we would cut off that part of the wave under the line 2. Fig. 3 shows a trace of the e.m.f. wave for the second position in Fig. 2. This record was taken with a Blondel band oscillograph. As the current lags more and more, we pass through the positions 1, 2, 3, 4, to 5, for a lag of 90°, which gives us maximum rectified potential. If the current leads, there is a relative motion between the wave of magnetism and the metallic segment in the opposite direction. For 90° lead we get the position 5′, giving us a reading equal and opposite to that obtained for the position 5.

Fig. 4 shows a curve between the voltage read by a D. C voltmeter across *b b* and the angle of lag of current (the zero angle does not correspond to a non-inductive current from the generator, but corresponds to the position 1 of the metallic segment in Fig. 2), the current in the field of the compensator being constant. The form of the rectified voltage curve may be changed very easily by varying the arc of the metallic segment. It will be seen that the curve in Fig. 4 is very similar to that shown in Fig. 5, which shows the regulation of a generator delivering constant current, but at different power factors. (By the regulation is meant the percentage by which the generated pressure must exceed the terminal pressure.) We get this same kind of a curve for the regulation of a transmission line. If it were possible, now, to add to the excitation of the generator, amounts proportional to the ordinates in Fig. 5, we would obtain a generator which would regulate on any load and any power factor from 90° lead to 90° lag. The field poles A A′ may be rotated with respect to the armature so that when the alternator is working on a constant load, the different voltages across *b b*, shown by the curve in Fig. 4, may be obtained. Now, we set the poles A A′ with respect to the poles of the alternator, when the alternator is working on a non-inductive load, to correspond about to position 2 for the metallic segment in Fig. 2. That is, we work approximately, as many degrees to the right of the zero point in Fig. 4 as the current lags through the generator. This point may be easily found with a D. C. voltmeter across *b b*, as we merely rotate the field until a certain fraction of the maximum voltage is obtained. This setting takes but a moment and may be made while the alternator and compensator are running

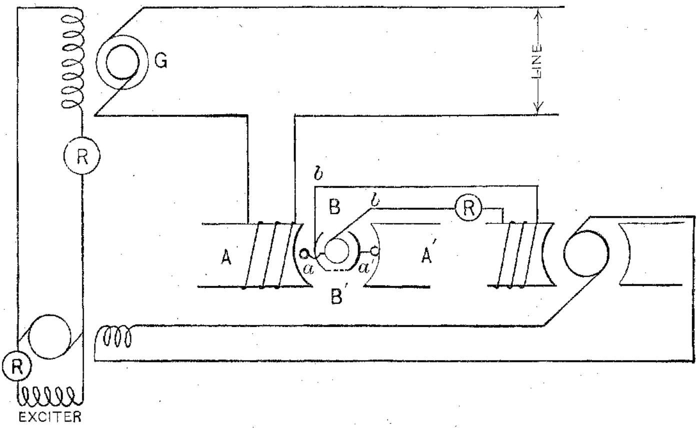

Fig. 6.—Showing Connections of Compensator Used in Practice.

The rectified voltage may now be added to the alternator in several ways. If, then, the current delivered lags behind the terminal pressure of the generator, the potential added ill increase according to the curve in Fig. 4. If the current leads, the voltage added will decrease, pass through zero, and then increase in the negative direction.

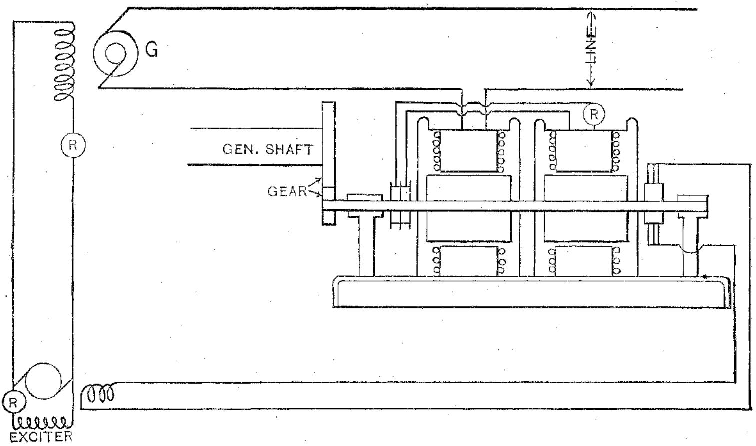

Fig. 7.—Compounding Generator or Synchronous Motor, Showing General Arrangement of Compensator.

The rectified potential may be added in series with the exciter field, as shown in Fig. 1. This method gives very good results. It is found that loads of any character may be added to the machine without disturbing the voltage. The generator may also be over-compounded to maintain constant potential at some point on the line.

There are some objections, however, to this arrangement, because it is not "fool proof." The arrangement shown diagrammatically in Fig. 6 has therefore been adopted. As shown, the rectified potential is used to excite a small D. C. generator of 100 to 500 watts capacity, and the armature of the D. C. machine connected in series with the series winding on the exciter. The D. C. current is large, so that only a few turns are needed on the exciter. These may be easily threaded on by hand, if there is not already a series winding on the exciter, so that no new exciter is needed. The percentage compounding may be changed simply by turning the rheostat handle in the armature circuit of the compensator. The compensator has four poles and is driven in synchronism by a gearing on the generator shaft. Fig. 7 shows the general arrangement of the compensator. The compensator set being small, it is a simple matter to add the compensator to any generator.

This method may be applied to compounding alternators operating in parallel, whether the generators have separate exciters or are all excited from the same exciter. When there is a separate exciter for each machine, the compensator may be applied to each generator, or a single compensator may be put on one generator and the current from the D. C. side carried around each exciter field. The station will then, of course, be compounded only when the compensator is running. The entire station may be compounded by a single compensator set where all generators are excited from the same exciter. In this case, the current for the field of the compensator would be taken from the bus-bars.

Since we must supply only a fraction of the exciting energy of the exciter, the compensator set of 500 watts capacity is large enough to compound a 10,000 k.w. station.

Another method of obtaining a rectified potential is that used by Mr. Fitzhugh Townsend[1] in determining the curve of an al-

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[1] —"A New Method of Tracing Alternating Current Curves" by Fitzhugh Towsend, *Transactions*, January, 1900.

ternator. His contact maker consisted of a disk, the perimeter of which in a bipolar alternator, is divided into two sections. One section only is conducting and current flows only for half a period.

This method differs only in detail from that used in commutating the current in the compensator types of alternators now on the market. For numerous reasons this method of compounding is not entirely successful and cannot be used to compound machines running in parallel. The alternating current cannot be successfully rectified, applied directly to the field of the alternator to produce the compounding. If however, we apply the rectified voltage to the field of an auxiliary exciter, the troubles due to commutating the current disappear.

It will be seen that this method of compounding is in some respects simpler than the present method of compounding D. C. machines. The following are some of its advantages:

(1) Generators have a single winding.

(2) No equalizer bus-bars, switches, etc. are necessary.

(3) No adjustment of low resistance shunts is necessary to make machines take their proper share of load.

(4) When the generators are over-compounded, there is no drop in voltage when a fresh machine is added.

(5) Percentage compounding may be changed instantly by turning a rheostat handle.

(6) The cost of compounding a large station will be less than compounding the same number and capacity of D. C. generators.

(7) Owing to the absence of equalizer switches, the operation of the station is simpler.

COMPOUNDING SYNCHRONOUS MOTORS.

At the present time, there is no method of compounding the excitation of synchronous motors other than those driving D. C. generators. The method given for compounding alternating current generators may be used to compound the excitation of alternating current motors. This removes one serious objection to the use of synchronous motors on transmission lines for other purposes than for operating D. C. machines.

COMPOUNDING DIRECT CURRENT GENERATORS.

The method given for compounding alternating current generators is comparable with the method of compounding D. C. generators shown in Fig. 8. Here we excite all the D. C. generators by one exciter and compound this exciter with the load current from the generators. This does away with the series winding on each machine, as well as all equalizer connections and switches. We are not bothered with the troublesome problem of adjusting a number of low resistance shunts in such a way that all machines will take their proper share of load. There will be no reversal of magnetism and less " slopping over " due to the reversal of the series current. Except for the addition of the exciter, the operation of the station is very much simplified. To provide against the possibility of an injury to the exciter and the consequent disabling of the entire station, the generator fields should be provided with double-throw switches, so that in case of injury to the exciter the generators could be temporarily operated as shunt-wound machines. Shunts 1, 2, 3, etc., with switches, may be put on the exciter series field, so that the compounding may be made to suit the number of generators running, or to vary the compounding when desired. When the generators are over-compounded, there will not be a drop of line potential when a fresh machine is added, as is the case in the method of compounding each generator. Where there are a number of large generators in a station, this method of compounding seems to be cheaper and simpler in nearly every way, than that commonly used.

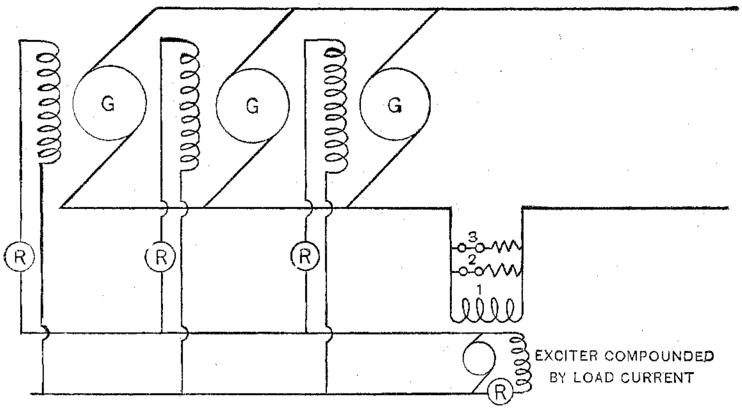

FIG. 8.—Compounding D. C. Generators.

Compounding Synchronous Motor-Generators and Synchronous Converters.

The above method of compounding the exciter has been very successfully used to compound the excitation of three motor-generator sets operating on a street railway load at the end of a 150-mile transmission line. The arrangement is shown in Fig. 9

for a single set. All the synchronous motors were, of course, excited from the same exciter. No new exciter was needed, as the motors were already excited by a compound wound exciter. All that was necessary to apply the method was to shunt part of the current from the D. C. side around the exciter series coil. This varied the excitation of the motor so that changes of load had little effect on the line potential at the motor terminals. Before the synchronous motors were compounded, lights could not be operated on account of the excessive variations of potential.

Since a separate exciter is generally used for this kind of work, this method is very much cheaper and simpler than carrying a series winding around the field poles of each motor. This method may also be applied to compounding synchronous converters.

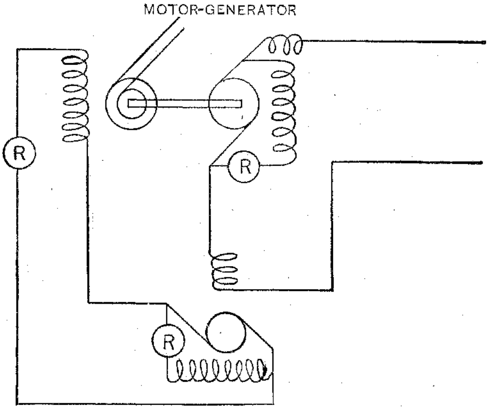

FIG. 9.—Compounding Motor-Generator.—Exciter Compounded by Load Current.

COMPOUNDING TRANSMISSION SYSTEMS.

In applying these methods of compounding to the most general case of a transmission system with a long trunk line with several branch lines, the generators would be compounded for the center of distribution, and the synchronous motors on each branch line compounded also with respect to the center of distribution.

It is well known that poor regulation is usually the besetting sin of many long-distance transmission systems, and very often the only solution of the problem of getting rid of a large percentage of the power generated is to restrict the motion of the recording voltmeter needles so as to impress possible customers more favorably. Systems are in operation where there is a variation in voltage of 10 %, and very often when synchronous motors operating on the line get to surging, owing to the bad regulation, there will be a drop or rise of perhaps 20%. This sometimes makes the cost of lamp renewals as great as the cost of power. Such a system for a mixed load of lights and power must in the end be displaced by something better. On long-distance transmission systems, where the generator capacity is large compared with the load changes which are likely to occur, the pressure at the powerhouse may remain fairly constant and yet vary 10% at the receiver.

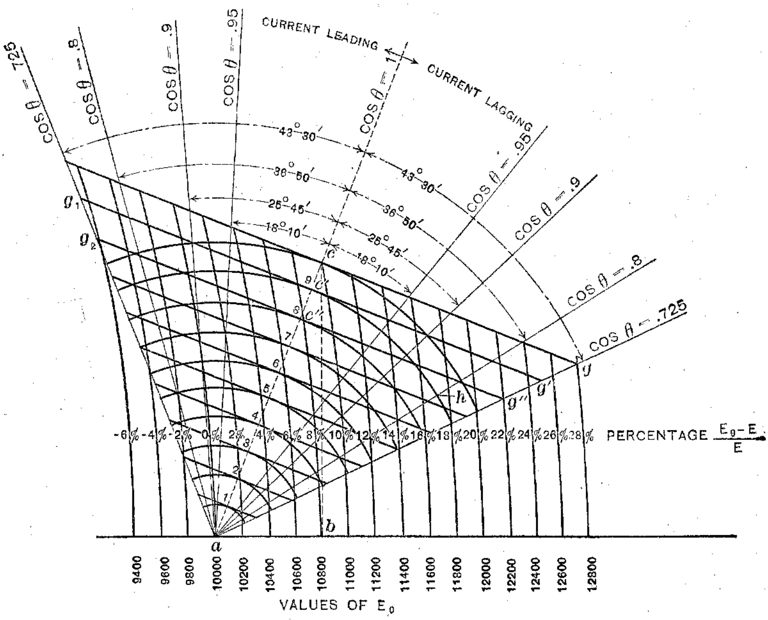

FIG. 10.—Regulation of Transmission System.

Fig. 10 and Fig. 11 bring out in a striking way the effect of changes of load and especially of changes of power factor on the regulation of the line.[1] Fig. 10 represents a 15-mile, 60 p.p.s., three-phase transmission system, with 10,000 volts between neutral and line wire The power transmitted is 3,000 k.w. at full load, with a copper loss of 8%, including step-up and step-down transformers: *o a* is the receiver pressure, the point o not being shown. The pressure consumed over the line by the

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1—A Simple Diagram Showing the Regulation of a Transmission System for Any Load and Any Power Factor. By F. G. Baum, *Elec. World and Eng.* May 18, 1901 power component of current is measured along *a c*, and the pressure consumed by the wattless current is measured at right

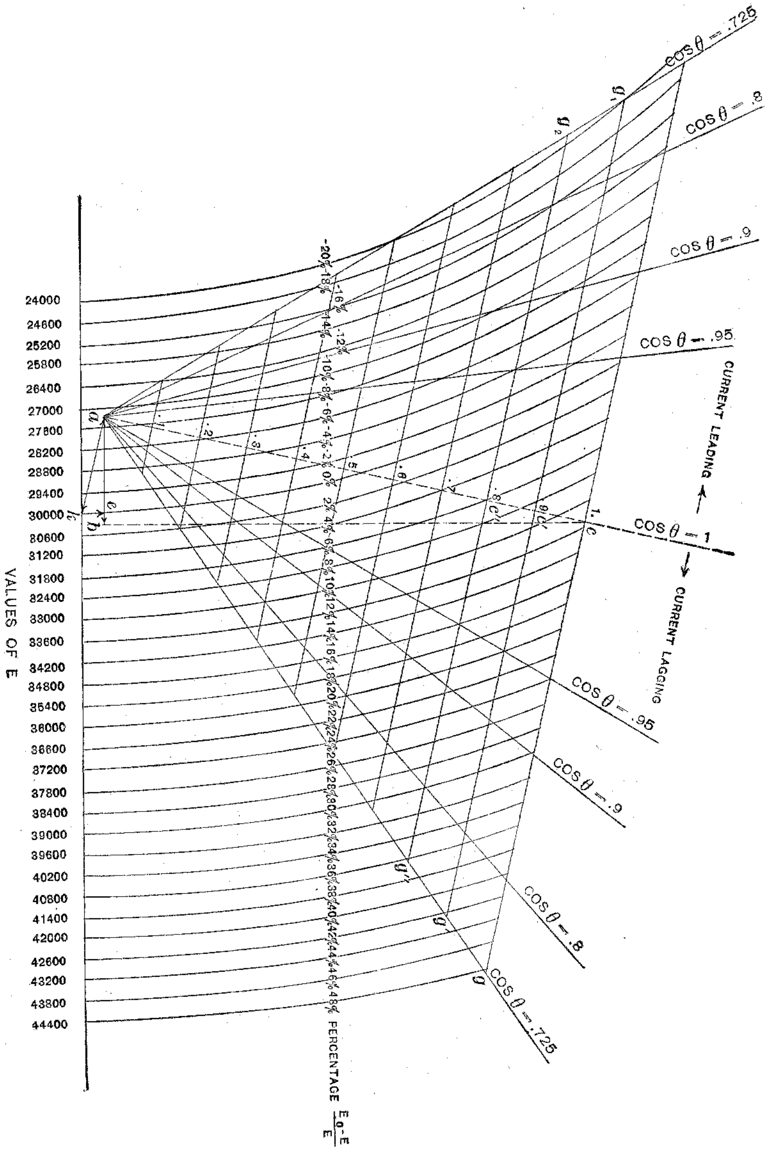

Fig. 11.—Regulation of 150-Mile Transmission Line.

angles to *a c*, to the right of *a c* for lagging currents, to the left for leading. *a c*, which represents full load, has been divided into ten equal parts, corresponding to .1, .2, etc., of full load. Through points marked .1, .2, etc., lines have been drawn at right angles to *a c*. Radial lines making angles corresponding to cos $\theta = .95$, cos $\theta = .9$, etc., for lagging and leading currents, have been drawn from *a*. Circular arcs, with the point *a* as center, have also been drawn through points along *a c* marked .1, .2, etc. The regulation for any load and any power factor may be determined from the figure. For example, find the regulation at .9 full load at .8 power factor: Go along *a c* to $c' = .9$, then along $c'\,g'$ to the intersection with the line cos $\theta = .8$. The regulation is seen to be about 21½%. For .9 full load current, and the same power factor, the regulation is 17%, as shown by the point *h*.

Fig. 11 shows the regulation of a 150-mile, 60 p.p.s., three-phase transmission system, with 30,000 volts between neutral and outside. The power transmitted is 9,000 k.w., with a line loss of 10%, including step-up and step-down transformers. The triangle *k l a* shows the rise in pressure over the line due to the charging current. The regulation of the line for any load and any power factor is shown.

As an example find *E o* for 0.8 load at 0.725 power factor. Follow *a c* to point c'' (marked .8), then follow $c''\,g''$ to point of intersection of $c''\,g''$ with line marked *cos* $\theta = 0.725$. The point is on the circle 40,800. This is the value of *E o* (36% above *E*). (Lagging current assumed in example, for leading current *E o* is given by *p t.* g_2).

An intelligent application of the methods here given will, it is believed, even in the worst case, give us a system with very satisfactory regulation.

I wish to thank Mr. Frank Adams, Superintendent of the Stockton Gas and Electric Company, for allowing me the privilege of making the preliminary tests on the compensator in the company's station.

STANFORD UNIVERSITY, CAL.
April, 1902.