POWER TRANSMISSION AND DISTRIBUTION FOR RAILWAY WORK.

BY ERNST J. BERG.

When electric power was first applied to railway work, the distances of transmission were comparatively short, so that one generating station usually located in the center of distribution was sufficient to furnish all power at a reasonable loss.

As the plants were extended it was soon evident that even disregarding the question of efficiency, the distances were very limited for commercial and practical reasons, and boosters connected in series with the line so as to raise the voltage proportional to the load were introduced. By their use it was possible to cover considerable distance and yet keep the potential up without too excessive an amount of copper. Since, however, any booster system must be very inefficient, such installations are not very common, and their field of usefulness limited to cases where considerable power is taken and at the end of a long line for a short time only. The next step towards extension was the introduction of power stations located in various places in the network, but the complication and inefficiency of such an arrangement was apparent, and the possibility of transmitting the power by alternating currents was brought out.

The first suggestion was to generate alternating current power in one station and transmit it at a reasonably high voltage to various sub-stations placed where the steam stations would have been located under former conditions, and there converting it to direct current by means of synchronous motors driving direct current generators. This method of transmitting and converting

electrical power was applied in a few cases but was soon superseded by the converters which not only gave a simpler means of converting alternating current to direct current, but which are more

FIG. 1.—Curve Showing how the Generator Voltage Depends upon the Power Factor of the Receiving Circuit. Constant Line Current. Voltage at Receiving End of Transmission Assumed as 1. $Z = .1 - .4j$.

efficient and permit of automatic potential control. Thus in 1894 large and representative converter systems were installed.

Since, with the introduction of long distance transmission the generators were placed far away from the converters and connected to them by lines of considerable resistance and self-induction, it was apparent that potential control could hardly be effected in the power station, at least a control of sufficient sensitiveness to follow the greatly fluctuating loads in a railway circuit, the more so as the voltage does not vary in the same proportion as the load.

To illustrate the variation in voltage at the receiving end of a line of considerable resistance and reactance as function of the phase relation in the current, in Fig. 1 is plotted a curve giving as abscissæ the power factor of the load, that is $\cos \omega$ and as ordinates the voltage at the receiving end. The line current is the same in all cases, the generator voltage is constant and assumed as unity, the resistance is 10 per cent. and reactance 40 per cent. The upper part of the curve gives the voltage with leading current, the lower with lagging current.

It is readily seen from this diagram how impossible it would be to control the potential at the generating station under these conditions, as, for instance, with a load of 90 per cent. power factor the voltage at the receiving end would be 69 per cent. of the generator voltage with lagging current, and the same as at the generator with leading current. Thus, if the generator should be controlled by the amount of current taken, it is evident that no indications whatever would be made by the current itself, since it is the same under these two conditions.

But even if a wattmeter were in the circuit at the power station, this would not help matters, since under the conditions referred to, the watts, that is the power, is the same, and yet the voltage so widely different.

In Fig. 2 this is demonstrated in a slightly different way. It is assumed that the voltage impressed upon the converter shall be constant at all loads, and shows how the generator voltage has to be varied in order to keep this constant at rated output with different power factors, and consequently at a variable line current. It is equally evident from this curve how unfeasible voltage control from the generating station would be.

It was therefore necessary to develop some means by which the potential could be controlled, not at the generator station, as is done in direct current railway circuits, but in the con-

FIG. 2.—Curve Showing how the Generator Voltage Depends upon Power Factor of Load. Constant Load of Receiving Circuit. Voltage at Receiving End of Transmission Assumed as 1., $Z = .1 - .4j$.

verter station. This means of regulating the potential was found in changing the phase relation of the current taken by the converter by means of a change of field excitation, raising or lowering the impressed alternating voltage, and consequently the direct current voltage by means of this current passing through lines of considerable self-induction, or through special reactive coils inserted in the circuit.

In the following I shall endeavor to explain this method of control, and discuss its effects on the operation in general.

In a synchronous converter system we have to distinguish between three E. M. F.'s.; the impressed E. M. F., that is, the E. M. F. at the collector rings of the rotary converter; the counter E. M. F., which is the E. M. F. induced in the rotary converter by the armature revolving in the magnetic field, and consequently proportional to the field excitation; and the E. M. F. of impedance or the E. M. F. consumed by impedance, which is that caused by the current flowing through the reactance and resistance of the converter.

The first mentioned E. M. F., that is the impressed E. M. F., is entirely dependent upon the generator voltage; the counter E. M. F. is entirely dependent upon the field excitation of the converter, and is constant regardless of the load on a machine, and the E. M. F. consumed by the impedance changes with the load and is proportional to the current.

To explain the phase relations between these E. M. F.'s. let us for the sake of simplicity consider the converter running light or doing no work. Since the work done by a synchronous converter rotary is the product of the current taken by the rotary and the projection of the counter E. M. F. on this current at no load the current must be in quadrature, that is, at right angles to the counter E. M. F. Since, furthermore, the input of a rotary converter is expressed by the product of the impressed E. M. F. and the projection of the current on the impressed E. M. F. under the assumption that no energy is consumed, the current is also in quadrature or at right angles to the impressed E. M. F. Consequently the impressed E. M. F. and the counter E. M. F. must be in phase and in opposition to each other. Let, then, the field excitation of the converter be reduced, so that the counter E. M. F. is less than the impressed. Since only three E. M. F.'s. are acting in the system and their sum must always be zero, that is, the impressed E. M. F. must at any time be equal to the counter E.

M. F., plus the E. M. F. consumed by impedance or neglecting the resistance, the E. M. F. consumed by the reactance. The counter E. M. F. is assumed to be less than the impressed, therefore, the E. M. F. consumed by reactance must be in phase with the counter E. M. F. and add itself thereto. But since the current is always 90° ahead of the E. M. F. of self-induction it must be behind 90° the impressed E. M. F. and consequently be lagging.

If, on the contrary, the field excitation of the converter is increased so that its counter E. M. F. is higher than the impressed, it is evident that the E. M. F. consumed by reactance must be in phase with the impressed E. M. F. and add itself thereto. Consequently since the current is 90° ahead of the E. M. F. of self-induction it must be also ahead of the impressed E. M. F., in other words, the current is leading. By a similar discussion it is readily seen that the same argument is true, if the converter is loaded. That is, in this case the wattless lagging or leading current due to the difference between counter E. M. F. and impressed E. M. F., merely adds itself in its proper phase relation to the energy current representing the load.

It is thus seen how by means of converters, leading or lagging currents are caused to flow in the lines. It is readily shown how the voltage at the receiving end of the system can be changed by causing a leading or lagging current to flow over a line with some self-induction.

Graphically this is done in Fig. 3. Let $O I$ denote the current which is assumed to be in phase with the E. M. F. in diagram A. The E. M. F. consumed by resistance $O R$ is in phase with this current and the E. M. F. consumed by reactance $O X$ is 90° ahead of the current. Thus, the E. M. F. consumed by the impedance of the system is represented by $O Z$ and is the resultant of $O R$ and $O X$. The generator voltage is the resultant of this E. M. F. $O Z$ and the E. M. F. at the receiving end is thus represented by $O E_0$, which is larger than $O E$ and larger than $O E + O R$.

In diagram B, Fig 3, is assumed the same current flowing over the same line, but the current is made to lead by a certain angle. It is readily seen in this diagram that the E. M. F. which has to be generated is less than the E. M. F. desired at the receiving end, and of course much less than that in the first mentioned case, where the current was in phase with the voltage at the receiving end.

In diagram c Fig. 3, is shown the same condition with lagging current, and demonstrated plainly how the generator E. M. F. is still higher than the generator voltage for non-inductive load.

Since, however, there is considerable difficulty in getting definite numerical instances worked out with any degree of accuracy by means of graphic methods, the analytical treatment is given below :

FIG. 3.—Graphic Method of Obtaining the Generator Voltage, e_0 , in a Circuit of Resistance and Reactance.

Let e_0 = the generator voltage, the induced E. M. F., if the generator field excitation is kept constant or its terminal E. M. F. if the excitation is varied with the load so that the generator voltage is kept constant.

e = the E. M. F. at collector rings of rotary converters.

$i_1 + j i_2$ in symbolic expression the current taken by the rotary, i_1 the energy current, and i_2 the wattless current, and

$z = r - jx$ the total impedance between e_0 and e , that is the total impedance of transmission system and generator in the case of a generator with constant excitation, and the impedance of the transmission line¹ if the generator voltage is constant.

We have the following equations :

$$e_0 = e + (i_1 + j i_2) (r - jx) \text{ or} \quad (\text{A})$$

$$e_0^2 = (e + i_1 r + i_2 x)^2 + (i_1 x - i_2 r)^2 \quad (\text{B})$$

At non-inductive load $i_2 = 0$

$$\text{therefore } e_0^2 = (e + i_1 r)^2 + i_1^2 x^2 \quad (\text{C})$$

At no load $i_1 = 0$

$$\text{therefore } e_0^2 = (e + i_2 x)^2 + i_2^2 r^2 \quad (\text{D})$$

Usually it is required that the converter voltage shall remain constant or increase with the load, when the generator voltage or excitation is kept constant. If each converter is operated from its own generator, it is preferable to leave the generator field excitation constant and thereby use the generator reactance for phase control and avoid any necessity of regulation in the generating station. If, however, many converters are operated from one generator, or if all generators in the power station are operated in multiple, it is preferable to keep the generator terminal voltage constant, and control the converter voltage by outside reactances in a low reactance transmission, or by the line reactance in a highly inductive transmission.

In either case equation B applies, if it is borne in mind that the impedance $Z = r - jx$ includes the generator in the first case and only refers to the transmission system between generator and converter in the latter. Furthermore, if it is desired to have overcompounding, that is, converters which increase their voltage with the load, the converter voltage e should be expressed by $e = e + p i_1$ where e is the no load E. M. F. and $p i_1$ gives the increase in E. M. F. at a load of i_1 amperes.

Thus the general equation of phase control becomes

$$e_0^2 = (e + p i_1 + i_1 r + i_2 x)^2 + (i_1 x - i_2 r)^2 \quad (\text{E})$$

where $p i_1$ is 0 in a rotary with constant voltage at all loads. As seen, the overcompounding enters the equation in essentially the same way as a resistance and can therefore in most problems be assumed as such.

1. Including transformers and other intermediary apparatus.

Looking over equation A, we find that it is the relation of E. M. F.'s and currents in an alternating current transmission line, indeed, the usual equation for determining line drop, etc., and corresponds to equation $e_0 = e + i r$ in a direct current line.

Since a converter can be made to take leading or lagging current by changing its field excitation and thus its counter E. M. F., such an installation gives the most favorable opportunity to study the fundamental principles of alternating current.

It may perhaps seem as if it would be rather a delicate operation to accomplish this potential control in commercial circuits where available instruments, etc., would prohibit the determination of leading or lagging currents necessary for the control with any degree of accuracy, yet the problem is perfectly simple and resolves itself to adjusting the shunt excitation for a given running light current which is predetermined by calculation, and afterwards to adjust the series field so that the converter takes minimum current, that is, runs non-inductively at the desired load.

It will then follow that the potential control for all intermediate loads is perfect, at least within very close limits, as I shall show later.

The running light current is readily determined from equations (B) and (C).

Let $i_1 = i_n$ at non-inductive load where $i_2 = 0$

$i_2 = i_0$ running light where $i_1 = 0$

then $e_0 = (e + e_n r)^2 + i_n^2 x^2$ which substituted in equation (C) gives $(e + i_n r)^2 + i_n^2 x^2 = (e + i_0 x)^2 + i_0^2 r^2$ which solved in reference to i_0 the running light current gives

$$i_0 = \frac{e x}{z^2} + \sqrt{\frac{e^2 x^2}{z^4} + i_n^2 + \frac{2 e i_n r}{z^2}} \quad (F)$$

denoting the converter voltage $e = 1$

The converter full load current $i_1 = 1$

and assuming the converter non-inductive at full load we get the equation of running light current.

$$i_0 = -\frac{x}{z^2} + \sqrt{\frac{x^2}{z^4} + 1 + \frac{2 r}{z^2}}$$

The magnitude of this current is calculated and plotted in Fig. 4 for different conditions of resistance and reactance.

Curve *a* shows the conditions at 15% energy loss.

“ *b* “ “ “ “ 10% “ “

“ *c* “ “ “ “ 5% “ “

FIG. 4.—Dependence of Running Light Current on the Reactance and Resistance of the Circuit. Converter Adjusted to Run Non-Inductively at Full Load.

It shows plainly that the lesser the loss the lesser is the running light current and the lesser reactance is necessary. In a system of 5% loss 30% reactance, that is such a reactance should be inserted as gives 30% of rated voltage at full load current. In a

system of 15% loss, however, 50% reactance would be about as low as we would go, and yet the running light current is 50% of full load current.

It is evident also that the more energy loss, the higher should the generator voltage be relative to the converter voltage as shown by the equations.

In the above case we assumed that the converter should run non-inductively at full load; usually, however, it is preferable to run it non-inductively at a somewhat lighter load, say $\frac{3}{4}$ load. Under these conditions substituting in equation F' for $i_n = .75$ the equation of the running light current and non-inductive load at $\frac{3}{4}$ load becomes,

$$i_0 = -\frac{x}{z^2} + \sqrt{\frac{x^2}{z^4} + .56 + \frac{1.5}{z^2}}$$

In this case with 40% reactance, the running light current is only 20% of full load current at 10% energy loss, and with 50% reactance only 34% at 15% energy loss. Therefore it would indeed seem as if it always were more favorable to run with non-inductive load at $\frac{3}{4}$ load. This is still more evident, when investigating the power factor curves with these adjustments, yet there are some reasons why sometimes converters are adjusted for non inductive load at full load as will be seen.

The maximum output of a converter is practically unlimited provided the generator voltage can be increased, and there is sufficient capacity behind the generator.

With the best arrangement of reactance, resistance and generator voltage, this is limited only by the resistance in the transmission and is expressed by equation $i_1 = \frac{e_0^2}{4 e r}$ as will be shown later. Usually, however, the maximum output is less than this, so that only the maximum value can be obtained by this equation, so that the above equation should be written $i_1 = \frac{e_0^2}{4 e r}$ where i_1 is the limit of energy current, that is output, e_0 and e the generator and converter E. M. F.'s respectively and r the resistance in the system.

To obtain the maximum possible output with a given line impedance, the converter should run non-inductively at higher outputs as the generator voltage increases, so that for instance, if the system has 10% energy loss and 40% reactance and the

generator voltage is kept 12½% above the converter voltage, the maximum output is 2.12 times rated output and the converter should run non-inductively at $\frac{5}{8}$ of rated load. If the generator voltage were 18% higher than the converter voltage, the output would have been 2¼ times the rated, and the converter would run non-inductive at full load and finally, if the generator voltage were 30% higher than the converter voltage the maximum output would be 2.55 times the normal output but the non-inductive load would have been 1½ times full load. In other words the converter should run with lagging current up to 50% overload.

In commercial installations, however, where there is always a limit to the generator voltage, which limit is caused by saturation of the machine, or outside conditions which do not permit of excessive voltage in the power station, the output of a converter is by no means unlimited, and thus some care has to be taken, to get the proper reactance, since with a given difference in generator and converter potential, the output changes as we change the reactance and resistance.

Referring again to equation (B).

By solving the equation in reference to i_2 , it is

$$i_2^2 = -\frac{e x}{z^2} + \sqrt{\frac{e^2 x^2}{z^4} - i_1^2 - \frac{2 e i_1 r}{z^2} + \frac{e_0^2 - e^2}{z^2}}$$

i_2 becomes maximum for

$$\frac{e^2 x^2}{z^4} - i_1^2 - \frac{2 e i_1 r}{z^2} + e_0^2 - \frac{e^2}{z^2} = 0$$

or

$$i_1 = -\frac{e r}{z^2} + \sqrt{\frac{e^2 r^2}{z^4} + \frac{e^2 x^2}{z^4} + \frac{e_0^2 - e^2}{z^2}}$$

where c_1 is the limiting current which directly represents the limit in output.

Solving this equation in reference to z the impedance, the following expression gives the impedance corresponding to a given maximum output :

$$Z = + \frac{1}{e_1 \sqrt{2}} \sqrt{e_0^2 - 2 e r i_1 \sqrt{e_0^4 - 4 i_1 r e e_0}}$$

for maximum output

$$e_0^4 = 4 i_1 r e e_0^2 \text{ or } i_1 = \frac{e_0^2}{4 e r}$$

as given above.

Inserting this value we get,

$$Z = \frac{e_0}{2 i_1}$$

Or if

$$\frac{e_0}{e} = k, z = \frac{2}{k} r$$

FIG. 5.—Curve Giving Maximum Possible Output and Corresponding Ratio of Reactance and Resistance for Given Ratios of Generator and Converter Voltages.

and

$$x = \frac{r}{k} \sqrt{4 - k^2}$$

or to get maximum output for a given ratio of generator and

converter voltage the ratio of reactance and resistance is fixed by equation

$$\frac{x}{r} = \sqrt{\frac{4 - k^2}{k}}$$

thus

$\frac{e_0}{e} =$	1	1.1	1.15	1.2
$m = \frac{x}{r} =$	1.73	1.52	1.42	1.33
max. output =	$.25 \frac{e_0}{r}$	$.275 \frac{e_0}{r}$	$.2875 \frac{e_0}{r}$	$.302 \frac{e_0}{r}$

FIG. 6.—*a* and *a'* are Curves Showing How the Maximum Output of a Converter Depends Upon the Reactance in the System. Full Load Assumed to be 1. Energy Loss 10%. Generator Voltage 19% Higher than Converter Voltage. *b* and *b'* show how Output Depends upon the Resistance at 40% Reactance.

$$E_o^2 = 1.4 \quad E = 1.$$

$r = .1$ and Variable x = curve *a*.

$x = 4$ and Variable r = curve *b*.

Curve *a'* = Position of Non-Inductive Load Variable x .

Curve *b'* = Position of Non-Inductive Load Variable r .

It must, however, be borne in mind that this limiting value by no means represents the best "all around" condition. Indeed by choosing the reactances from results obtained from this equation

and Fig. 5, the power factor of the system would in general be very poor, therefore it would be better either to sacrifice some in output and increase the reactance, or raise the generator voltage some and thus keep the output with the greater reactance.

In Fig. 6 a couple of curves a and a_1 are given showing the relation between reactance in the transmission line and the maximum output of a converter for given energy loss, and also at which load the converter should run non-inductively under those conditions. These particular curves are figured out for a generator voltage 19% higher than the converter voltage and 10% energy loss in transmission.

As seen, the maximum output would be 3.45 times rated output with a reactance of only 15% and with the converter so adjusted as to run non-inductively at about 1.6 times full load current. This condition is of course rather absurd, since it means a very large running light current with consequent very low power factors at all loads up to full load or thereabouts. The curve also shows that if it was desired to run the converter non-inductively at full load, a reactance of 42% should be chosen and the maximum output would be 2.2 times full load output.

Fig. 7 shows similar curves with a lesser difference between generator and rotary voltage. The generator voltage is kept ten per cent. higher than the rotary voltage and the energy loss is the same as in previous case, that is, ten per cent. It is shown that the maximum output is three times rated output, and that this is obtained by a reactance of about 15 per cent. Also that the converter then should run non-inductively at 95 per cent. of rated load. With this small reactance the running light current will be quite large and the power factors comparably low at lighter loads, so that although the power factor is high at full load, it is really not as good a feasible arrangement. If, under these conditions, that is with ten per cent. higher generator voltage than converter voltage, it was desired to get a maximum output of double rated output of the converter, a reactance of 42 per cent. would be suitable, and the converter should run non-inductively at 65 per cent. of full load, which gives very good general characteristics as far as power factors are concerned.

The output of the converter depends also necessarily upon the resistance in the line. To illustrate this another set of curves is plotted in Fig. 6 denoted by b and b_1 , b showing the

maximum output for different values of energy loss with a reactance in the system of 40 per cent., and b_1 at which load the converter should run non-inductively under those conditions.

FIG. 7.—Curve Showing How the Maximum Output of a Converter Depends Upon the Reactance in the System. 10% Energy Loss, Generator Voltage 10% Higher than Converter Voltage, and Full Load Output of Converter Assumed as 1.

As seen, the output increases very rapidly as the energy loss decreases at least within commercial conditions, that is between five and 20 per cent. loss. The maximum output with 40 per cent. reactance and zero resistance would be three times rated output.

With five per cent. energy loss the maximum output would be 2.6 times rated output, and the converter should be adjusted for non-inductive load at $1\frac{1}{4}$ full load.

The condition which is to be met with in a commercial installation is, that the generator is limited to a certain value,

FIG. 8.— $E_o = 1.15$ $E = 1$. $r = .1$ x variable.
 Power Factors for various Reactances. Maximum Output for
 $x = .142$ is 330% of full load.
 Power Factor Curves of Converters Operated from Generator
 with 15% Higher Voltage than the Converter Voltage. Energy
 Loss 10%.

that the converter voltage shall be maintained constant at all loads or increase with the load, and that there shall be a certain margin in maximum output and the highest power factors at all loads.

As an illustration, in Fig. 8 is plotted a number of curves giving the power factors at the converter under the assumption that the generator voltage is constant and 15 per cent. higher than the converter voltage, that the full load E. M. F. and current is unity, and the resistance or rather the energy loss is ten per cent. for different values of reactance.

FIG. 9.—

$$x = .4, \quad r = \begin{cases} .05 & \text{Curve I.} \\ .10 & \text{“ II.} \\ .15 & \text{“ III.} \end{cases}$$

$$e = 1 \quad \text{Non-ind. at } \frac{1}{2} \text{ load.}$$

$$\text{Wattless Current given } \begin{cases} \text{Curve 1.} \\ \text{“ 2.} \\ \text{“ 3.} \end{cases}$$

Curves Showing Power Factors of Converters adjusted to run non-inductively at $\frac{1}{2}$ load on a Circuit of 40% Reactance, and 5, 10 and 15% Energy Loss, and Constant Voltage at Converter at all loads.

As can be ascertained by equations given above, the maximum output that could be obtained under such circumstances is 3.3 times rated output with a reactance of 14.2 per cent. The power factor under these conditions is as seen, exceedingly unsatisfactory. The converter would have to run non-inductive at 140 per cent. load, and the power factor at $\frac{1}{4}$ load is 20 per cent., $\frac{1}{2}$ load 60 per cent., at $\frac{3}{4}$ load 82 per cent. Apparently, judging from the power factor curve the most satisfactory reactance would be about 46 per cent. The converter is practically non-inductive at full load, has 95 per cent. power factor at $\frac{1}{2}$ load and 71 per cent. at $\frac{1}{4}$ load with an output of over 2.5 times rated load.

In general it may be quite satisfactory to decide upon a certain reactance and load at which the converter shall run non-inductively, and let the generator E. M. F. correspond thereto. In Fig. 9 are plotted some curves under a similar assumption with a reactance of 40 per cent., resistance of five per cent., 10 per cent. and 15 per cent. respectively, and assumption that the non-inductive load should be $\frac{3}{4}$ of full load. As seen, the power factor is better the lower the resistance is, yet even over this range of energy loss there is very little difference around loads between half and full load. The running light current, however, depends greatly on the line loss, and is, as seen, 20 per cent. with five per cent. energy loss, 30 with 10 per cent., 38 with 15 per cent. energy loss. The current is necessarily lagging up to $\frac{3}{4}$ load and then becomes leading.

If the converter were to be over-compounded the power factors would have been somewhat poorer, since as stated above, over-compounding acts in essentially the same way as increased energy loss.

This is illustrated in Fig. 10 where corresponding curves are plotted for a converter of ten per cent. over-compounding, that is, for a converter where the terminal voltage is expressed by $i = e + p i_1$.

The power factor at the generator will be slightly poorer at light load and slightly better at heavy load than at the converter, assuming that the transmission line has considerable self-induction.

In Fig. 11 is plotted in a different way the wattless current in the line corresponding to condition given in Fig. 9. Here it is plainly seen how the amount of lagging or leading current is not

proportional to the load, consequently the magnetizing or demagnetizing effect of the armature current is not proportional thereto.

In practice the shunt field is so adjusted that the converter takes the required lagging current running light, and the series

FIG. 10.--

$$x = .4, \quad r = \begin{cases} .05 & \text{Curve I.} \\ .10 & \text{II.} \\ .15 & \text{III.} \end{cases}$$

$$e = 1 + .1 i_1 \text{ non-ind. at } \frac{1}{4} \text{ load.}$$

Curves giving Power Factors of Converter. Reactance is Assumed as 40%, Energy Loss, 5, 10 and 15% respectively. Converter Runs Non-inductively at $\frac{1}{4}$ Load, and Over-compounded 10%.

field is made to increase the excitation so as to give the required field strength at non-inductive load. Since, however, the series excitation is proportional to the load, it is evident that without

hand adjustment, it would be theoretically impossible to accomplish perfect phase control; or rather, it would be impossible to have constant voltage at the rotary converter with constant voltage at the generator. The difference, however, is exceedingly small, the series field being slightly too strong at light load and too weak at overload, in other words the voltage will be slightly

FIG. 11.—

$$x = .4, \quad r = \begin{cases} .05 & \text{Curve I.} \\ .10 & \text{“ II.} \\ .15 & \text{“ III.} \end{cases}$$

Curve Showing amount of Leading and Lagging Current in Line in order to get perfect Phase Control. 40% Reactance. 5, 10 and 15% Energy Loss.

increased at the converter up to non-inductive load and will drop slightly at overload.

In the preceding we have not considered this point and have assumed that the theoretical leading or lagging current can be obtained at any load. Consequently the values which we have given of maximum output of the converter are not quite true in

practice but the output is always less. The amount of this decrease in output depends upon the magnetic characteristic of the machine and can readily be determined in practice.

Before closing the paper it might be well to discuss the conditions which govern the amount of reactance, etc., in the machines. As stated in the beginning of the paper, in plants where one converter is operated from one generator it is convenient to use the generator reactance for phase-control. Since, however, as seen, it requires considerable self-induction to do this at high power factors, it means a generator of high armature reaction and self-induction, in other words a generator with rather limited output with constant field excitation. This is not objectionable, since by leading or lagging currents the output can really be made as high as desired, even if the armature reaction is high. Yet when considering that it is often desirable to start the rotaries from the generator and therefore its voltage may be reduced greatly at the starting moment when the converter necessarily takes a large lagging current, it may not always be the best policy to use the generator reactance alone for phase control.

Often, however, converters are started from the direct current side and sometimes by auxiliary motors. Under these conditions the generator might conveniently be made with very high armature reaction.

In plants where several converters are operated from one generator, or from a number of generators in parallel, control by generator reactance is not to be recommended, since it involves the change of series field adjustments with the change of generator capacity. The generators may be made of any armature reaction since several of them are used in parallel in starting, yet it must of course be borne in mind even then, that if the armature reaction is too high, the large current taken in starting a converter from the alternating current side, may cause the voltage to drop so far as to seriously disturb the system in general.

Regarding converters themselves, it is obvious from the preceding discussion that they must be of composite type, that is, they must have shunt and series excitation.

Shunt wound converters do not permit of automatic phase control, but at constant adjustment of the field will always run at the same wattless current at all loads, so that, for instance, if the field is adjusted for non-inductive load at one load, the

converter will run non-inductively at all loads, and therefore the drop in voltage at full load will correspond to the energy loss in the system, and the converter voltage will be higher at lighter loads than at heavier loads, therefore will vary as the load varies, and phase control is thus feasible only by hand regulation, that is, in systems where the load varies only slowly as in lighting circuits.

Reaction converters take lagging currents at all loads and thus are in general objectionable, the more so as they do not allow any automatic potential control.