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EQUALIZING CONNECTIONS FOR COMPOUND- WOUND DYNAMOS COUPLED IN MULTIPLE.

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The successful operation of stations for electric lighting and power depends largely on the automatic regulation, not only of the speed of the prime movers, but also of the E.M.F. of the generators. In both of these essential features the last few years have brought forth marked development, in consequence of which we are now enabled to install plants for electric lighting and power, in which the speed of the engines will not vary more than $1\frac{1}{2}$ per cent. from the normal, when the full load is suddenly thrown on or off, while the builders of dynamo machinery can and do supply us with generators which are almost absolutely self-regulating as to E.M.F. A modern constant potential generator will not only compensate automatically for the variable losses due to armature reaction and internal resistance, but it can be made to give an E.M.F. at the brushes which, under varying conditions of load, will be such as to compensate not only for the variable losses in the machine itself, but also those due to the resistance of the external circuit.

The success which has thus been attained in the automatic regulation of constant potential generators is largely due to the careful study and application of compound winding; and while but a few years since, nearly all of the large stations were equipped with plain shunt-wound generators, we find that these have now been superseded by the compound-wound type, in almost every class of service.

This change from shunt to compound winding has necessitated a slight modification in the connections from dynamo to switchboard, where two or more generators are coupled in parallel. For such an arrangement of generators we must employ an additional conductor between the generators, commonly called the equalizer or tie line, whose function it is primarily to prevent a possible reversal of polarity of any of the machines, and further to equalize to some extent the output of each machine under varying conditions of the external load or speed of the prime movers.

That this connection is absolutely an essential for the successful operation of compound-wound generators in multiple is beyond dispute. On the other hand, there has been a great deal of dispute in regard to what strength of current it may be called upon to transmit. In fact, its mode of action does not seem to be entirely clear to many engineers who are perfectly familiar with the installation of dynamo machinery, and who would not think of omitting the equalizer where two or more compound machines are to be used in multiple. I desire to submit a mechanical analogy, which, though deficient in many of its details, will serve to show the action of compound machines together with the equalizer connection and the function which it has to perform.

Consider, for a moment, the arrangement shown in *Fig. 1*. We have two direct-acting steam pumps located at different points along a system of distributing mains. These pumps consist of a steam cylinder *S*, a water cylinder *W* and an auxiliary cylinder *A*, through which all the water passes before it enters the supply mains. There would be no particular utility for such an auxiliary cylinder in a pump; in fact, unless the details of such an arrangement are carefully worked out, it is more than likely that such a combination would not work at all. It will suffice, however, for the sake of the analogy, and we will assume that the details are so

FIG. 1.

arranged that the mechanism will operate in the manner desired. Suppose now we have a steam pressure of 100 pounds per square inch in the steam cylinder, a pressure of 70 pounds in the cylinder *W* and 60 pounds at the beginning of the supply mains, under normal conditions. The 10 pounds difference between the 70 pounds and 60 pounds, acting on either side of the auxiliary piston, which is intended to act in a manner similar to an hydraulic engine, will help the steam piston along, and so long as the two machines continue to act under normal conditions, everything will go smoothly, each machine taking its share of the load. But now suppose that the steam pressure in one of the engines should fall to, say, 95 pounds. We would immediately have a corresponding drop of pressure in *W* to, say, 65 pounds, while in the supply mains the pressure would still remain constant. We would now have an effective pressure of only 5 pounds in the auxiliary cylinder instead of 10 pounds, and consequently a still greater reduction of pressure in *W*. This, in turn, would still further diminish the effective pressure in *A*, and so on. Presently the back pressure from the main will be greater than the forward pressure in *A*, and if the difference becomes sufficiently great, the action of the auxiliary cylinder will overpower that of the steam cylinder, and the whole mechanism will be driven backwards by the water pressure in the mains. The machine will not only cease to contribute its share of water to the supply mains, but will actually consume enough to operate it as a motor, and thus make considerably more work for the other machine.

To avoid the possibility of this reversal taking place, we connect the water pipes where they enter the auxiliary cylinders, as shown by the dotted lines. If we make this tie line sufficiently large, there will always be supplied enough pressure to the front of the auxiliary piston to prevent the pressure in the mains from reversing the mechanism, and furthermore, to equalize in a measure, the work done by each unit, under varying conditions—the equalization being the more complete, the larger the tie line.

This is precisely what takes place in compound- or series-

wound generators; and if we consider the cylinders *W* as replaced by armatures, the auxiliary cylinder by series or compound windings, the steam cylinders by the shunt windings, and the steam pressure acting on the piston by the speed of rotation of the armatures, we have two compound-wound generators coupled in parallel.

Fig. 2 shows this arrangement as commonly used. The equalizer connection, as here shown by the dotted lines, was first suggested by Gramme for series machines, and by Mordey for compound. If made sufficiently heavy, it will not only effectually prevent the reversal of polarity of any of the machines so connected, but will, in a great measure, equalize the work done by the generators under varying conditions of speed. Any number of dynamos may be connected up in this manner, and, even if they are of different

FIG. 2.

FIG. 3.

capacities, each machine will give current in proportion to its rated output, provided the combined resistances of the leads to the bus bars, the armatures and the series fields, are inversely proportional to the ampère capacities of the machines. Without the equalizer connections, or if these are not sufficiently heavy, a change of speed or of load is liable to produce a reversal of polarity in the deficient machine, in which case it will run as a motor, supplying none of its share of the current, but, on the contrary, making an additional load for the other machines, and perhaps causing a costly interruption in the operation of the plant.

The question now arises—how shall we proportion the equalizer connection?

In *Fig. 3* we have a diagrammatic representation of two compound-wound generators, of equal capacities, in paral-

lel, supplying current to a common line of resistance, r , and having an equalizer connection of resistance, x . So long as the E.M.F.'s generated by the two machines are the same, equal currents will flow through the series fields and there will be no current in the tie line. If, however, the E.M.F. (E) of one machine becomes greater than that (e) of the other, there will immediately be a greater current in the series fields of the machine generating the higher E.M.F., and a flow of current in the tie line tending to equalize the currents in the series fields, which current we will call X . But this flow of current in the equalizer will cause a fall of potential $= Xx$, and so long as there is a fall of potential in this line, the currents in the series windings, which we will call A and B , respectively, can never be equal. Hence, it

FIG. 4.

FIG. 5

follows that we can only have A equal to B when $x = 0$, which is evidently impossible.

A little consideration will further show that even if we could make $x = 0$, we would not have succeeded in equalizing the currents in the armatures, but merely those in the series windings, because, if there is any inequality in the E.M.F.'s, that armature which is generating the higher will carry not only the current in its own series windings, but, in addition, that supplied to the other machine to make the two equal. That is, it will carry a current $C = A + X$, while the other armature carries only $D = B - X$. In other words, if the resistance of the equalizer could be made equal to zero, so that $A = B$, one armature would carry more current than the other by an amount equal to twice that in the equalizer.

It is evident, therefore, that in this method we effectually

prevent the reversal of polarity of any of the machines so connected, while we only tend to equalize the currents in the series windings, the tendency being the more nearly realized, the less the resistance of the tie line.

There is another method of attaining this end, and one which, if it could be successfully applied, would attain it much more perfectly. This method, which is an old one, is illustrated in *Figs. 4 and 5*.

It consists in passing the current of one armature around the series coils of the other machine, and *vice versa*. The method is perfectly feasible, and the mutual action of the output and strength of field of the two machines insures an equal division of the load.

Fig. 4 shows how this might be arranged at the switch-board, and it will be seen that by closing the single pole switch either machine could be operated alone. Unfortunately, however, this system can be used only for two machines, and moreover, these two must be exactly alike both in capacity and design. As this state of affairs rarely occurs in practice, the method has but little value.

Returning now to the consideration of the first-mentioned method, let us see what will be the distribution of the currents for given resistances, and for varying values of the E.M.F.

If, in *Fig. 3*, we let

a = resistance of positive lead and series field ;	}	for the machine whose E.M.F. = E ;
c = resistance of negative lead and parallel resistance of armature and shunt field ;		

b = resistance of positive lead and series field ;	}	for the machine whose E.M.F. = e ;
d = resistance of negative lead and parallel resistance of armature and shunt field ;		

r = resistance of external circuit ;

x = resistance of equalizer circuit, and

A, C, B, D, R and X = respectively, the currents in the different branches of the circuit, we have, from Kirchhoff's laws :

$$C = A + X \quad (1)$$

$$R = A + B \quad (2)$$

$$D = B - X \quad (3)$$

$$Cc + Xx - Dd = E - e \quad (4)$$

$$Cc + Aa + Rr = E \quad (5)$$

$$Dd + Bb + Rr = e \quad (6)$$

Solving these equations for A, B and X , we obtain, by making the necessary transformations and reductions :

$$(A + X)c + Xx - (B - X)d = E - e$$

$$(A + X)c + Aa + (A + B)r = E$$

$$(B - X)d + Bb + (A + B)r = e$$

$$Ac - Bd + X(c + d + x) = E - e$$

$$A(a + c + r) + Br + Xc = E$$

$$Ar + B(b + d + r) - Xd = e$$

$$A(a + c + r)(c + d + x) + Br(c + d + x) + (E - e)c - Ac^2 + Bcd = E(c + d + x)$$

$$Ar(c + d + x) + B(b + d + r)(c + d + x) - (E - e)d + Acd - Bd^2 = e(c + d + x)$$

$$A[(a + c + r)(c + d + x) - c^2] + B[r(c + d + x) + cd] = E(d + x) + ec$$

$$A[r(c + d + x) + cd] + B[(b + d + r)(c + d + x) - d^2] = e(c + x) + Ed$$

$$A = \frac{[(b + d + r)(c + d + x) - d^2][(d + x)E + ec] - [(a + c + r)(c + d + x) - c^2][(b + d + r)(c + d + x) - d^2][r(c + d + x) + cd][e(c + x) + Ed]}{d^2 - [r(c + d + x) + cd]^2} \quad (7)$$

$$B = \frac{[e(c + x) + Ed][(a + c + r)(c + d + x) - c^2] - [(a + c + r)(c + d + x) - c^2][(b + d + r)(c + d + x) - d^2][r(c + d + x) + cd][E(d + x) + ec]}{d^2 - [r(c + d + x) + cd]^2} \quad (8)$$

$$X = \frac{E - e - Ac + Bd}{c + d + x} \quad (9)$$

from which the currents in all the branches of the circuit may be calculated, if the resistances are known and the E.M.F.'s assumed.

It may be of interest to show, from an example, what is liable to occur in actual practice.

At one of the hotels in this city the electric lighting plant consists of two direct connected compound-wound multipolar generators, intended to give 400 ampères each at 115 volts. The internal resistances of the machines are as follows:

	<i>Armature.</i>	<i>Series Coils.</i>	<i>Shunt Coils</i>
First machine	'011	'0041	15'5
Second machine	'015	'0036	11'5

The leads of the machines and the equalizers, which are arranged as in *Fig. 2*, are all about 20 feet long (to the switch-board), and they are made of a cable of 350,000 circular mills cross-section, so that

$$\begin{aligned} a &= '0047 \text{ ohms,} \\ b &= '0042 \text{ ohms,} \\ c &= '0116 \text{ ohms,} \\ d &= '0156 \text{ ohms,} \\ x &= '0012 \text{ ohms,} \\ r &= '1437 \text{ ohms (at full load).} \end{aligned}$$

Since the machines are direct connected, there is a possibility of a variation in speed in the two dynamos, and, furthermore, there is quite a little difference in the characteristic curves of the two machines, although the field frames and armatures were intended to be exact copies of one another. Hence, a change of load may produce a material difference in the generated E.M.F.'s. Let us assume that, at full load, both machines were generating exactly 115 volts, at which voltage the current in each armature was 400 ampères, but that a change of load and speed has caused the pressure of one of the machines to fall to say 110 volts. If then we substitute the values given above for the inter-

nal resistances and for E and e , the values 115 and 110, respectively, we have from (7) and (8)

$$\begin{aligned} A &= 390 \text{ ampères,} \\ B &= 374 \text{ ampères,} \end{aligned}$$

for the values of the currents in the series coils. That is, for a difference of 5 volts in the two machines, we have a difference of only 16 ampères, or about $3\frac{1}{2}$ per cent. in the series field currents.

The current in the equalizer from (9) is

$$X = 222 \text{ ampères,}$$

and in the armatures from (1) and (3)

$$\begin{aligned} C &= 612 \text{ ampères,} \\ D &= 152 \text{ ampères.} \end{aligned}$$

In other words, a difference of 5 volts in the E.M.F.'s of the two machines has caused a flow of current in one armature which is over four times as great as that in the other, while the equalizer has made the currents in the series windings nearly equal, there being a difference of only $3\frac{1}{2}$ per cent.

Of course, these results are not accurate, because we have entirely neglected the resistances of the switches, fuses and contacts in the calculation. At the same time the results show to what extent the generators might be unbalanced under adverse conditions; and, moreover, it is evident that the equalizer may be called upon to carry currents of very considerable strength.

There are three factors which exert an unbalancing influence on a system of generators coupled in multiple :

- (1) A variation of speed in one or more of the generators.
- (2) A variation in the external load.
- (3) A variation in the strength of the magnetizing current.

The first of these, speed variation, is, perhaps, the most serious, and we cannot attach too much importance to the matter of inherent regulation of the prime movers, the belt transmission and other factors which affect the speed of the generators.

The second, variation of the external load, affects the distribution of the load the more, the greater the divergence between the characteristic curves of the machines. As already stated, the development in this respect during the past few years has been very decided, and there is, as a rule, but little trouble from this source.

The third unbalancing factor, viz.: a change in the strength of the magnetizing current, is of a secondary nature, and would, evidently, not exist were the speed of the prime movers and the E.M.F. of the generators absolutely self-regulating. This is not the case, however, and, consequently, any variation in the distribution of the load due to the first two causes is aggravated by the third. As already stated, it is the function of the equalizer to remedy this, and it was shown that this cannot be done absolutely except by making the resistance of the equalizer = 0.

FIG. 6.

FIG. 7.

In the arrangement of Gramme and Mordey the equalizer must always have an appreciable resistance, and consequently there will always be a loss of potential in it. Moreover, this loss of potential is always at the expense of the weaker machines.

I desire, in conclusion, to suggest an equalizing arrangement in which the drop of potential in the equalizer is divided equally among the machines, in consequence of which the currents in the series windings of all the machines are equal under all conditions. The arrangement is shown in *Figs. 6 and 7*.

It will be seen that this is accomplished by connecting the beginnings of all of the series coils to an extra bus bar, to which is connected also one brush of each machine, in-

stead of connecting the series windings direct to the brushes and the junctions of these to the equalizing bus bar, as in Gramme's method.

By arranging the connections in this manner it is evident that the currents in the series coils of the machines will, at all times, be proportional to the capacities of the machines, provided the resistances are proportioned in such a way that the drop of potential from the brushes of all the machines to the bus bars will be the same at full load.

Fig. 6 shows how this method would be arranged at the switchboard. The mode of operation would be as follows: Whenever it is desired to throw in an additional machine the single pole switch is first closed. This completes the series field circuit, and we immediately have a current in the series coils of the new machine, which will be proportional to its capacity. The rheostat in the shunt circuit is then adjusted until the new machine generates the desired E.M.F. After this is done the main switch may be closed without producing any further disturbance in the E.M.F. of the system.

While this system does not equalize the currents in the armatures, it does equalize those in the series coils, an effect which is only partially accomplished in the first-mentioned system. Moreover, it is applicable to any number of generators of equal or of different capacities, and in no way interferes with the continuity of operation, while the throwing in or out of additional units is greatly facilitated.

It has these disadvantages, however: It necessitates an additional conductor from the dynamo to the switchboard, and, moreover, the full current passes through the conductors which here replace the equalizer. Hence, the first cost is somewhat increased, and, further, a certain amount of energy is lost in heating the conductors. In very large installations, where the distance between dynamos and switchboard is considerable and where the currents are of great magnitude, the loss of energy which this method involves may be sufficient to preclude its application. In smaller installations, however, the increase in first cost and the loss of energy in the additional conductors will be inappreciable.