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EFFECT OF ARMATURE REACTION IN SYNCHRONOUS MOTORS AND ROTARY CONVERTERS

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(Read before the Electrical Section, March 14, 1907.)

As a rule in treating the operation of synchronous motors and rotary converters, the diagrams are constructed without reference to the effect of armature reaction. The complete diagram of the rotary converter or synchronous motor depends upon the following laws:

1st—The vectorial sum of the generator or impressed E.M.F. E_g and the motor counter E.M.F. E_m is the reactance E.M.F. E_x.

2nd—The counter E.M.F. must be represented as lagging 90° behind the resultant field or magneto motive force.

3rd—The armature M.M.F. is in phase with the armature current.

4th—The E.M.F. component necessary to balance the reactance E.M.F. is equal and opposite to it in phase, and must, therefore, be represented as leading the current in quadrature.

5th—The resultant M.M.F., or that M.M.F. which when divided by the reluctance of the magnetic circuit gives the flux per pole, is equal to the vectorial sum of the M.M.F., due to the armature reaction, and the M.M.F. impressed upon the fields, as obtained from the ammeter readings in the field circuit.

6th—The total armature reaction may be expressed in ampere turns per pole as $.707\, an\frac{I}{2}$, where "a" equals conductors per phase per pole "n" equals number of phases and "I" is the current per conductor. This applies to the form of winding usually employed in alternators. For rotary converter windings better results are obtained by calculating the armature reaction in direct current terms.

General Synchronous Motor Diagram.

The quantities involved in the general synchronous motor diagram are so numerous and so interdependent that one is at a loss, when starting to construct the diagram, to decide what quantities to assume as fixed. We can always assume a constant source of E.M.F. E_g, and if we assume the load the motor is carrying and its losses, we immediately have the watt component of the current.

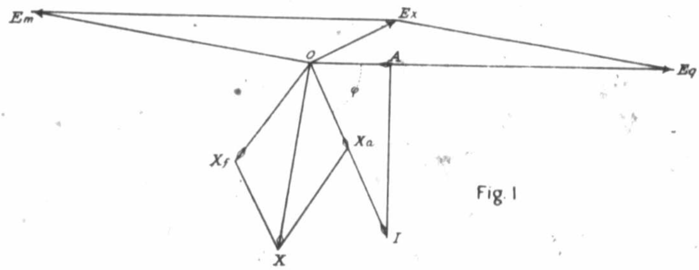

Fig. 1

It is a fact well known to all switchboard operators that with the given load on the synchronous motor, the power factor may be varied over a certain range by altering the field excitation of the motor. We have to start with, therefore, the impressed generator E.M.F. E_g the total current and power factor. Lay off E_g equal to the generator E.M.F. to any desired scale, also the watt component of current O.A. Lay off the total current O.I. making the angle between it and $E_g = \varphi$ whose cosine is equal to the power factor which we have assumed. (See Figure No. 1.) At right angles and leading the current 90°, lay off E_x, the reactance voltage which is the product of total current and total reactance in the circuit, the resistance being small in most cases is negligible. Combining E_g and E_x gives E_m, the counter E.M.F. of the motor. Lay off X_a in phase with the current, representing the armature reaction to any desired scale. Lay off X, leading the counter E.M.F. 90° representing the excitation required to produce the counter E.M.F. on open circuit, as read from the no load saturation curve of the synchronous motor. Since the resultant ampere turns X is the vectorial sum of the field and armature ampere turns, the field ampere turns are obtained by subtracting vectorially X_a from X, this gives X_f, the field excitation necessary for the motor to operate under the assumed conditions. The above diagram for any load on the motor gives us the value of field excitation required for the assumed value of power factor. The various values of power factor may be assumed and diagrams constructed, and the results plotted into a curve between field excitation and total current, or field excitation and power factor.

Figure No. 1 shows the diagram for a lagging current, and it will be noticed that the reactance voltage is in such a phase position as to subtract from the generator voltage, resulting in a

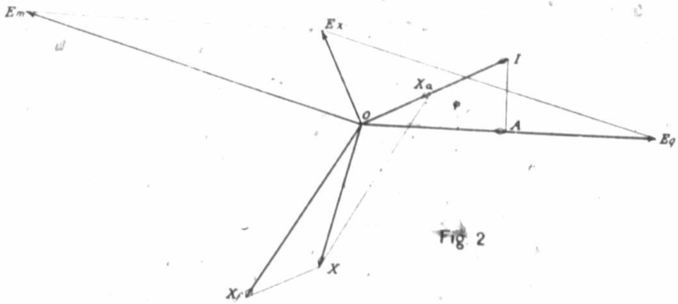

Fig. 2

smaller value of the necessary counter E.M.F. The armature reaction X_a is in such a position that, when subtracted from the resultant ampere turns X, the field ampere turns are smaller than the resultant ampere turns. It may, therefore, be stated as a general principle that with a lagging current on the synchronous motor the effect of the armature reaction is to strengthen the field, and in that way decrease the necessary field excitation.

Figure No. 2 shows the synchronous motor operating with the leading current, and it will be noted that the conditions are just the reverse of those shown in Figure No. 1. Here the reactance volts E_x adds to the generator volts E_g, producing a larger value of counter E.M.F. E_m, while the armature reaction, when subtracted from the resultant field, leaves an impressed field ampere turns greater than the required resultant field. It may, therefore, be stated as a general principle that when a synchronous motor is operated on leading current, the armature reaction tends to weaken the field, thus increasing the necessary excitation in order to produce the required resultant magneto motive force.

ROTARY CONVERTERS.

In a rotary converter the current in the windings may be considered as made up of two components, the alternating current flowing into the alternator from the line, and the direct current flowing out at the commutator. The alternating current is of two components, one a wattless component with respect to the counter E.M.F., and the other a component in phase with the counter E.M.F. of the rotary. It is only that component of alternating current which is in phase with the counter E.M.F. which is converted into direct current. It may, therefore, be said that the power component

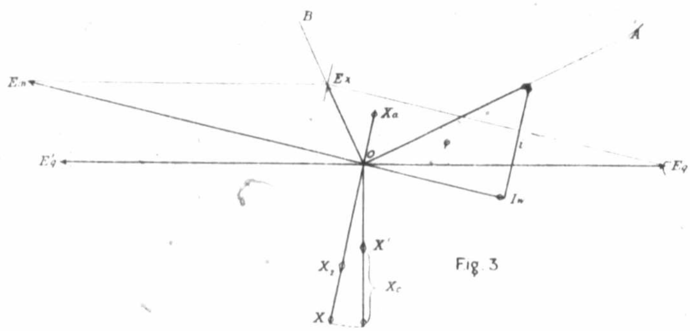

Fig. 3

of alternating current and the direct current, since they flow in opposite directions, neutralize each other, thus producing no armature reaction, and the armature reaction of the rotary can be, with a fair degree of accuracy, assumed to be produced only by the wattless component of alternating current.

The diagrams of the synchronous motor are applicable to the rotary converter with the above change of armature reaction. The construction of the rotary converter diagram will be made clear by the following example: (See Figure No. 3.) Given a rotary converter operating on no load, to find the reactance necessary for a given compounding at a given power factor of input. At no load the impressed E.M.F. E_m and counter E.M.F. E_g are very nearly equal. Lay off O.A., and extend indefinitely, making angle φ the angle corresponding to the required power factor. Lay off O.B. 90° ahead of O.A., and extend indefinitely. With E_g as a centre, and required counter E.M.F. E_m (voltage corresponding to D.C. voltage), as radius, strike an arc which locates point E. E_x then equals reactance volts. Complete the parallelogram E_m O E_g E_x. Lay off I_w in opposition phase to E_m and equal to the current corresponding to D.C. output. Erect a line at I_w perpendicular to OI_w. This gives i, the current which is wattless with respect to counter E.M.F., and the only current producing appreciable armature reaction. X_a equals this armature reaction and OX_2 equals field ampere turns necessary to give E_m on no load, as read from the no load saturation curve. Add X_a and X_2, which gives OX, the resultant excitation necessary. X′ equals excitation necessary to produce no load voltage, $-E_g'$. Subtracting X′ from X leaves X_c, the necessary compound ampere turns. This last subtraction must be performed algebraically, and not vectorially. As soon as I and E_x are known, the reactance which must be inserted in the line can be calculated. The above diagram may be constructed by using either alternating current or direct current quantities, but whichever quantities are chosen must be used throughout the diagram. The alternating voltages can be reduced to direct current voltages by dividing by .612, while alternating current amperes can be reduced to direct current amperes by multiplying by 1.06.

Figure No. 4 shows the application of the foregoing methods to the determination of the "V" curve of the synchronous motor. The motor has six poles, with 2,500 field turns per pole, and 324 armature coils of one turn each. The "V" curve was taken with a reactance of .0416 ohms in each leg, and the A.C. voltage was kept constant at 360 volts. As the curve was taken at no load, the power factor is so low in all cases that it is not necessary to lay out the diagram, as all vectors with which we have to deal will lie so nearly in phase with those with which they add or subtract that the operations can be performed algebraically instead of vectorially. All the values will be considered in A.C. terms. We will first take the 200 ampere point for leading current—the reactance voltage $E_x = 200 \times .0416 \sqrt{3}$ — the factor $\sqrt{3}$ being used to change reactance volts from volts per leg to volts across lines. With the leading current reactance volts will add directly to the generator E.M.F. This gives $E_g = 360 + 14.35 = 374.35$, which corresponds on the no load saturation curve to 5.9 field amperes. Since the rotary converter when considered from the standpoint of a D.C. machine is a six circuit winding, the current per conductor in D.C. terms would be 200×1.06 divided by 6. This, when multiplied by the total number of turns, 324, and divided by the number of poles, will give the ampere turns armature reaction per pole.

$$X_a = \frac{200 \times 1.06 \times 324}{6 \times 6 \times 2500} = .76 \text{ amps.}$$

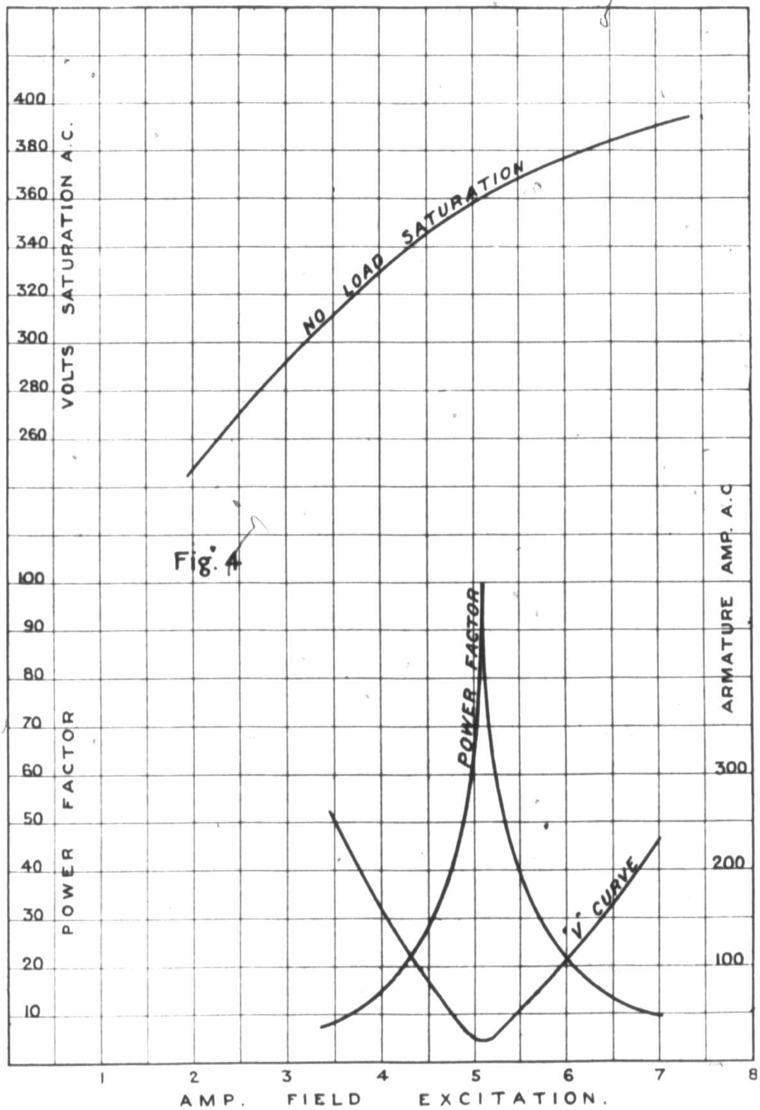
400
380
360
340
320
300
280
260
VOLTS SATURATION A.C.
NO LOAD SATURATION
Fig. 4
100
90
80
70
60
50
40
30
20
10
POWER FACTOR
ARMATURE AMP. A.C.
300
200
100
POWER FACTOR
'V' CURVE
1
2
3
4
5
6
7
8
AMP. FIELD EXCITATION.

Fig. 4.

in which the 2,500 appears in the denominator to reduce to field amperes. This armature reaction will weaken the field, and require an excitation of 55.9 plus .76 = 666 amperes.

Checking the above for lagging current E_m = 360 minus 14.35 = 34565. This corresponds to no load excitation of 4.5 amps. X_1 as before equals .76 and X, 374 amperes. As it will be seen, the two above points coincide very closely with the curve which represents values actually observed on test.