

## The Starting Conditions in Synchronous Machines.

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### INTRODUCTION.

In view of the growing popularity and importance of the synchronous motor as one of the standard types of motor available for power distribution purposes, and its increasing use as a means of improving the power factor of a load, no apology seems necessary for a paper containing a detailed study of the behaviour of such a motor during what has always been regarded as a somewhat critical period—*viz.*, the period when the motor is being accelerated from rest to synchronous speed. The subject is by no means a new one, and has already been dealt with by several writers ; not, however, in a manner sufficiently thorough and exhaustive to make farther contributions to it superfluous, and one of the main objects of the present paper is to explain a number of hitherto somewhat obscure points, and to draw attention to others which have not previously been noticed.

### REVIEW OF PREVIOUS WORK ON THE SUBJECT.

The earliest paper specially devoted to a study of the starting conditions in synchronous machines appears to be one read in 1912 before the American Institute of Electrical Engineers by C. J. Fehheimer.\* In this the author, after some general introductory remarks, gives an account of experiments made to determine (1) the relation connecting the starting torque with the impressed p. d. under various conditions and (2) the variation of torque, current and power factor with speed, while the rotor is accelerated from rest, a constant p. d. being maintained across the stator terminals. The experimental results are embodied in an interesting series of curves. Among the questions discussed by the author are the desirability or otherwise of keeping the field circuit open during the acceleration period, and the tendency of certain synchronous machines to run in the neighbourhood of half the speed of synchronism. Fehheimer's paper gave rise to a very interesting discussion.

\*C. J. Fehheimer : Proceedings of the American Institute of Electrical Engineers, Vol. 31, pp, 305 and 1942 (1912).

In 1913 E. Rosenberg\* read a paper on Self-Synchronising Machines before the Institution of Electrical Engineers, in which he considered, among other things, the occurrences during the starting period, and discussed in some detail the behaviour of the machine towards the end of the acceleration period, just before it is pulled into synchronism. It may be mentioned that in the discussion on Pechheimer's paper, it was stated by B. G. Lamme that it was "difficult to see just what is going on in the motor at the instant it pulls into synchronism". So far as the authors are aware, Rosenberg's was the first attempt to furnish a detailed explanation of the action in question.

The next contribution to the subject is one by F. D. Newbury, in the form of a paper read before the American Institute of Electrical Engineers in June 1913.† The main interest of this paper lies in the oscillographic records which are given of the starting period.

In December 1917 the authors of the present paper published, in the "Journal of the Indian Institute of Science," an account of some experimental investigations of the occurrences during the starting period of a synchronous machine, and a full theoretical discussion of the type of Induction Motor whose stator is supplied with polyphase currents, and whose rotor is provided with a single-magnetic-axis winding.

The most recent addition to the literature of the subject is an article by Theo. Schou in the "Electrical World" of April 6th, 1918 (Vol. 71, p. 71 b). In this article the author points out that a satisfactory self-starting synchronous motor should partake of certain characteristics of both an Induction Motor and an Alternator, and should present features of design intermediate between these two classes of machines. He accordingly advocates the use of a shorter air gap and longer polar arc than are customary in alternators of standard design. He further suggests the use of materials having a pronounced skin effect for the squirrel-cage windings of self-starting synchronous motors‡ and points out the advantages of part-slot windings in reducing the troubles from dead points.

\*E. Rosenberg: Self-Synchronising Machines. Journal of the Institution of Engineers, Vol. 51, p. 62 (1913).

†Transactions of the American Institute of Electrical Engineers, Vol. 32, p. 150.

‡The utilisation of the skin effect in the rotor conductors of Induction Motors was patented by H. M. Hobart in 1909.

TORQUES CONCERNED IN ACCELERATING THE MOTOR AND  
IN PULLING IT INTO SYNCHRONISM.

The self-starting synchronous motor is accelerated and finally pulled into synchronism by the action of a number of torques, differing widely from each other, and the resultant effect of which will largely depend on their relative importance. Cases may arise where, owing to the preponderance of a certain type of component torque, it may be impossible to get the machine to run up to synchronous speed. Again, the torques concerned in the initial acceleration of the rotor are quite distinct from the torque which finally pulls it into synchronism. The authors are of opinion that no really clear understanding of the occurrences during the starting period is attainable without a detailed study of the various torques which act on the rotor during that period. It will accordingly be necessary to consider the nature of the various torques concerned. These torques may be classified as follows :—

- (1) Torque due to varying magnetic reluctance (synchronous torque).
- (2) Torque due to hysteresis.
- (3) Torque due to starting squirrel-cage or damping coils if present.
- (4) Torque due to currents induced in the field winding, if this winding is closed.
- (5) Torque due to eddy currents.

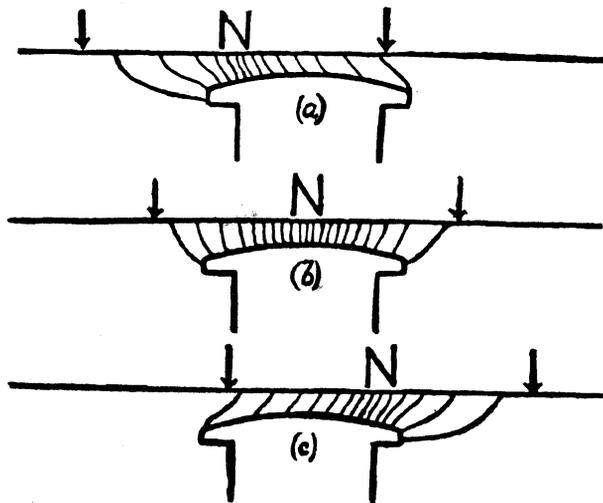
*1. Torque due to Varying Magnetic Reluctance.*

It is a well-known general principle of electro-magnetism that, any electro-magnetic system which includes a movable member tends to assume a configuration which corresponds to minimum reluctance and therefore maximum flux. Displacements of the movable member from the position of minimum reluctance call into play forces tending to restore it to that position. The application of this general principle to the special case of a salient pole rotor, which is acted on by the rotating field of the stator, will be easily understood by reference to Fig. 1. In this figure three different positions of one of the rotor poles are shown relatively to the stator polar surfaces. The centre of the stator polar surface is in each case marked with the letter N. In Fig. 1 (b), the relative positions of the rotor and stator polar surfaces correspond to minimum reluctance, and from the symmetry of flux distribution it is immediately obvious that there is no tangential pull on the rotor. In Fig. 1 (a) the rotor pole is

shown displaced from the position of minimum reluctance in one direction, and in Fig. 1 (c) in the opposite direction. If we bear in mind that the dynamical stresses correspond to a tension along the lines of force and a pressure at right angles to them, it is easy to see that in Fig. 1 (a) there is a tangential force acting on the pole from right to left, while in Fig. 1 (c) it acts from left to right. If we now suppose that the stator polar surfaces travel past the pole in a direction from left to right, then the successive positions will be those shown in Fig. 1. For every displacement of the stator polar surface to one side of a rotor pole, there will be an equal displacement to the other side, and the forces corresponding to equal displacements in opposite directions will be equal and opposite. Thus the rotating field will exert an alternating torque on the rotor, and the positive and negative half-waves of this torque will be equal. The frequency of the torque will be equal to twice the supply frequency multiplied by the motor slip, and so long as the motor slips, the mean value of the alternating torque due to varying magnetic reluctance will be zero. The only effect of this torque is to throw the rotor into forced vibrations, having a frequency equal to that of the torque. Owing to the large moment of inertia of the rotor the vibrations will be imperceptible for large values of the slip, *i. e.*, during the greater part of the acceleration period. When, however, the slip has become sufficiently small and in consequence the frequency of the torque sufficiently low, the amplitude of the rotor oscillations will become marked, and will increase with decreasing slip.

Summing up, we see that the torque due to variable magnetic reluctance is for all speeds below synchronism an alternating torque consisting of equal positive and negative half-waves, and hence having a zero mean algebraic value. It is therefore quite inoperative so far as steady acceleration of the rotor is concerned, and only produces equal periodic accelerations and retardations *i. e.*, it causes oscillations of the rotor. The period of these oscillations is determined by the rotor slip, and steadily increases with decreasing slip: At the same time, the amplitude of the oscillations increases.

The graph of the varying magnetic reluctance torque expressed as a function of the speed is shown in Fig. 2 (a). For all speeds below synchronism its mean value is zero, while at synchronism it is capable of assuming any positive or negative value between definite limits. Since the speed of synchronism is the only speed at which this torque may have a value differing from zero, we may conveniently refer to it as the *synchronous torque*.



**Fig. 1. Flux distribution for three positions of field pole relative to stator.**

## 2. *Torque due to Hysteresis.*

In dealing with the torque due to varying magnetic reluctance, we have neglected the effect of hysteresis. It now becomes necessary to take this into account. Owing to hysteresis the rotor will tend to retain more or less strongly the effects of previous magnetisations. Thus referring to Figs. 1 (*a*) and 1 (*c*), if hysteresis were absent, the magnitudes of the torques in these two cases would be equal. Owing, however, to the fact that in the position of the rotating field corresponding to Fig. 1 (*a*) the magnetisation of the rotor is increasing from a lower to a higher value, while in position Fig. 1 (*c*) it is decreasing from a higher to a lower value, the actual flux in Fig. 1 (*c*) will be higher than that in Fig. 1 (*a*). The same applies to each pair of corresponding or equidistant positions on opposite sides of the position of maximum flux shown in Fig. 1 (*b*). For any such pair of positions, the driving torque is greater than the retarding torque. The effect of hysteresis is thus seen to be the production of a disparity between the positive and negative half-waves of the varying magnetic reluctance torque, the positive half-waves being uniformly larger than the negative ones. This effect is equivalent to raising the magnetic reluctance torque waves above the axis of time, *i. e.*, to the addition of a steady driving torque to the alternating magnetic reluctance torque. The torque due to hysteresis is thus seen to be a steady driving torque and is instrumental in producing acceleration of the rotor. It is to be noted that, assuming the flux per pole to remain constant during the acceleration period, the hysteresis torque has the same value for all speeds below synchronism. If the speed were made to pass through synchronism to higher values, the hysteresis torque would undergo reversal at synchronism.

The graph of the hysteresis torque as a function of the speed is shown in Fig. 2 (*b*).

## 3. *Torque due to Starting Squirrel-cage or Damping Coils if present.*

Little need be said about this torque, which may be called the induction motor torque, as everybody is familiar with the relation connecting the torque and speed of an induction motor. The squirrel-cage of a self-starting synchronous machine forms the rotor winding of an induction motor whose stator windings are represented by the armature; the relation connecting torque and speed will be of precisely the same nature as in an induction motor.

The graph of this torque as a function of the speed is of the well-known form shown in Fig. 2 (*e*).

The method of varying the torque-speed curve of an induction motor by the introduction of resistance into the rotor is also well known. The effect of introducing resistance is equivalent to a change in the slip scale, the maximum torque remaining unaffected in value, but occurring at a lower speed. If a very powerful torque is necessary at starting, it is advisable to use a high resistance squirrel-cage. On the other hand, with such a squirrel-cage the speed to which the motor finally settles down corresponds to a large slip, and this, as will be seen later on, makes it more difficult to pull the rotor into synchronism. The ideal arrangement would be one in which the squirrel-cage resistance at starting is such as to give maximum torque, the resistance then automatically decreasing with increase of speed in such a manner that at each speed maximum torque is maintained until finally the lowest possible resistance is reached, corresponding to a very small slip. The use of the skin effect in conductors for automatically decreasing the rotor resistance with increasing speed has recently been proposed by Theo. Schou.\*

#### 4. *Torque due to currents induced in field winding, if this winding is closed.*

If the field winding be closed, the currents induced in it will give rise to a torque, and a careful study of the nature of this torque is essential to a clear understanding of the occurrences during the starting period. The armature of the machine may again be regarded as forming the stator winding of an induction motor, of which the rotor winding is represented by the field coils. There is, however, this very important difference between the starting squirrel-cage and the field winding: the currents induced in the squirrel-cage are capable, according to their distribution in space, of giving rise to a field whose magnetic axes may occupy any positions whatsoever relatively to the centre lines of the field poles; but the currents induced in the field winding can only produce a field whose magnetic axes are coincident with the centre lines of the field poles. This is conveniently expressed by saying that the field winding is a "single-magnetic-axis" winding; because it can only produce a field having a single definite set of magnetic axes, namely, those corresponding to the centre lines of the salient poles. Now a Motor having a polyphase stator, but a

\*Loc. cit. In a more recent article (*Electrical World*, May 3, 1919) the same writer describes a compound squirrel-cage winding, consisting of an outer squirrel-cage of brass having a low reactance, and an inner squirrel-cage of copper at a greater depth and hence having a higher reactance.

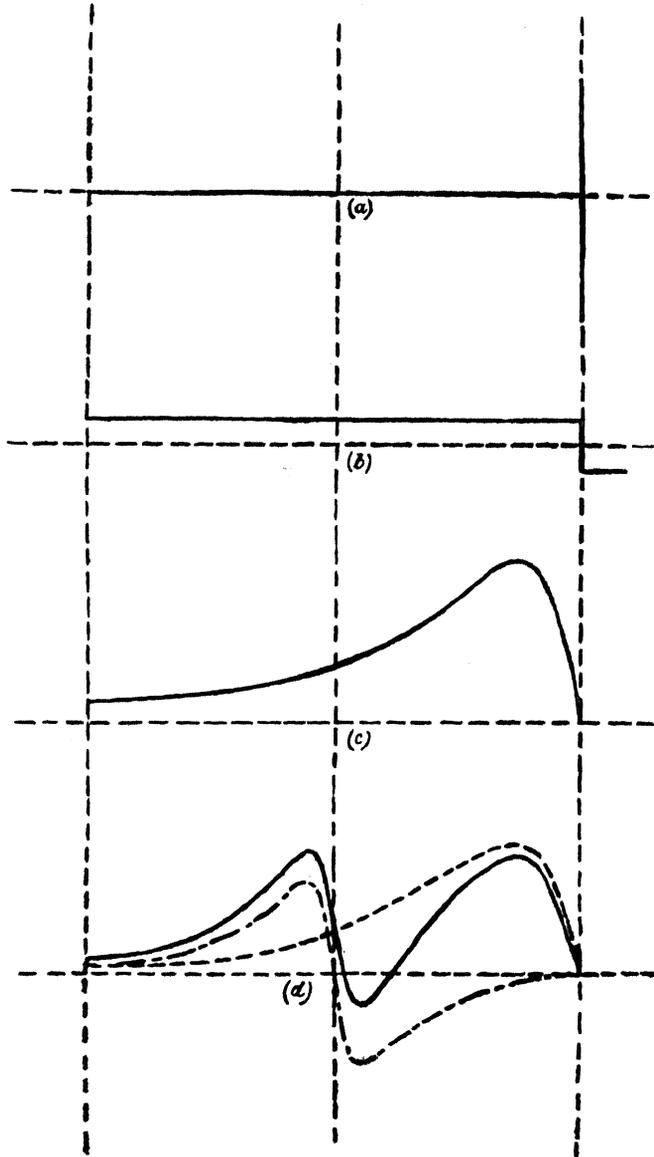


Fig. 2. Torque-speed curves.

single-phase or single-magnetic-axis rotor, exhibits certain striking peculiarities which differentiate it sharply from a motor in which both stator and rotor windings are polyphase. The earliest reference to this type of motor which the authors have been able to find occurs in a paper by H. Gorges.\* Since such motors are not ordinarily used in practice, their characteristics do not seem to be very generally known, and have only occasionally been referred to. A complete analytical theory of this type of motor has been given in a previous paper.<sup>t</sup> The torque-speed curve of such a motor is shown in Fig. 2 (*d*), and its most striking characteristic is the torque reversal which occurs over a certain range of speed in the neighbourhood of half-synchronism. The analytical theory of this type of motor is somewhat complicated, but the following general explanation based on a paper published in 1898 by P. Eichberg<sup>‡</sup> may be useful. The currents induced in the single-phase rotor winding by the rotating field of the stator give rise to a field which, relatively to the rotor core, is a simple alternating or oscillating field. By a well-known transformation this oscillating field may be replaced by two equal and (relatively to the rotor core) oppositely rotating fields, the crest value of each rotating field being half the maximum crest value of the oscillating field. Now if the slip of the motor be  $s$  and if its speed of synchronism be denoted by  $n$ , the frequency of the rotor currents will be  $sf$ , where  $f$  is the frequency of supply, and the speed of its component rotating fields relatively to the rotor core will be  $s n$ , the speed of the rotor in space being  $(1-s) n$ . Regarding the direction of rotation of the rotor as positive, the speed of one of the rotating fields relatively to the rotor core is  $+s n$ , while that of the other is  $-s n$ . Hence the speeds of the rotor rotating fields in space are  $s n + (1-s) n = n$ , and  $-s n + (1-s) n = (1-2s) n$ . The interaction between the stator field, and the first rotating component of the rotor field, whose speed  $n$  in space is the same as that of the stator field, gives rise to a torque in every respect similar to that of an ordinary induction motor with polyphase windings on both stator and rotor. The second rotating component of the rotor field, whose speed in space is  $(1-2s) n$ , is clearly incapable of reacting with the stator field in such a manner as to give rise to a resultant torque; for, owing to the difference of speed, the relative position of the fields is constantly changing, periodically passing through a succession of cycles

\*H. Gorges; Ueber Drehstrommotoren mit verminderter Tourenzahl. *Elektrotechnische Zeitschrift*, Vol. 17, p. 517 (1896).

†*Journal of the Indian Institute of Science*, Vol. T, p. 205; also *Transactions of the American Institute of Electrical Engineers*, Vol. 88, (1919).

‡F. Eichberg; *Zeitschrift für Elektrotechnik (Wien)*, Vol. 16, p. 573 (1898).

during each of which the average algebraic value of the torque is zero. Although incapable of torque production by interaction with the stator field, the second rotating component of the rotor field is capable of giving rise to a torque by a different kind of action. In sweeping across the stator conductors, it induces in them e. m. f. s. of frequency  $(1-2s)f$ , and these produce currents of the same frequency in the stator windings and the circuit external to them (represented by the mains and everything connected across them, generators, motors, lamps, etc.). Since the total impedance external to the stator windings is extremely small in comparison with that of the windings themselves, the result, so far as the currents of frequency  $(1-2s)f$  are concerned, is nearly the same as if the stator windings were short-circuited. The currents give rise to a rotating field whose speed  $(1-2s)n$  in space is the same as that of the inducing rotor field, and the interaction of these two fields, whose relative space position is invariable, results in the production of a torque. To fix ideas, we may think of the second component of the rotor field as produced by a polyphase winding on the rotor supplied with suitable polyphase currents having a frequency  $sf$ , and of the rotating field due to this as inducing currents of frequency  $(1-2s)f$  in the stator windings. The arrangements would then be equivalent to a polyphase motor whose primary is represented by the rotor and whose secondary is represented by the stator. The slip of this imaginary motor would be  $(1-2s)$ , and so long as  $s$  is less than  $\frac{1}{2}$ , the slip and torque would be positive. Zero slip would occur at  $s=\frac{1}{2}$ , *i.e.*, at half the speed of synchronism. Beyond this point the slip and torque would assume negative values.

The resultant torque of the motor would be obtained by taking the algebraic sum of the torques due to the two oppositely rotating components of the oscillating rotor field. This torque is represented by the full line curve in Fig. 2 (*d*), the dotted and chain-dotted curves corresponding to the component torques due to the two rotating components of the rotor field.

If we suppose that the torque arising from the current in the field winding is large in comparison with the other torques acting on the rotor, so that the dominant effect is that due to the field winding, then it is evident that the torque reversal which occurs at half-synchronous speed will tend to make the machine run in the neighbourhood of that speed, and it will then be impossible to run the machine up to full synchronism.

In the discussions which have taken place regarding the tendency of the machine to settle down to a speed in the neighbourhood of half-synchronism, erroneous views have frequently been

expressed. Some Engineers appear to hold the opinion that the machine *locks* into exact half-synchronism. As we have seen, the speed to which it settles down, although near half-synchronism, is not definite, and may, according to the special circumstances of each case, be anywhere in the neighbourhood of that speed. It is no more correct to say that the machine locks into half-synchronism, than it would be to say that an ordinary induction motor locks into full synchronism.

##### 5. *Torque, due to eddy currents.*

If the field structure is laminated throughout, the torque due to eddy currents will be insignificant. The case is otherwise, however, with solid field poles in which large eddy-currents may arise. If we were to imagine the rotor replaced by a solid cylinder of conducting material, then the rotating field of the stator would give rise to rotating eddy-current sheets in the conducting cylinder, and the axes of such current sheets\* would follow the axes of the rotating stator field. There would in this case be perfect freedom of motion of the axes of the current sheets relatively to the rotor, and this condition is closely approximated to in an ordinary squirrel-cage winding. If we next suppose that the conducting cylinder is cut up into a number of sectors by radial barriers of insulating material, then the freedom of motion of the axes of the current sheets relatively to the rotor would be largely destroyed, and these axes could only swing through an angular distance not exceeding the angular width, of a sector. Now this is approximately the case corresponding to a salient pole rotor with solid poles. In such a rotor, owing to the restriction imposed on the free development of eddy currents by the relatively large spaces between the field poles, the axes of the eddy currents can only travel through a relatively short distance. If the axes could not travel at all, the arrangement would be identical with that of a rotor having a single magnetic axis winding; while if the axes could travel with perfect freedom, it would be identical with that of a squirrel-cage rotor. Hence we see that the torque due to eddy currents in the solid field cores will partake partly of the nature of the torque due to a single magnetic axis rotor winding, and partly of that due to an ordinary polyphase rotor. The single magnetic axis effect is, however, in many cases found to predominate, and considerable difficulty may then be experienced in getting the rotor to pass well beyond half-synchronous speed.

\*By the axes of the current sheets are meant the lines along which the current density is zero or the lines with which all the individual current filaments

## PULLING INTO SYNCHRONISM.

Of the various torques concerned in accelerating the rotor from rest to synchronism, three, namely, the induction motor, the single-magnetic axis, and the eddy current torque, are functions of the speed, and may hence conveniently be referred to as the speed torques. Let us suppose that by the action of the speed and hysteresis torques the rotor has been brought to a speed not far removed from synchronism. Since in the neighbourhood of synchronism, the speed torques rapidly decrease with decreasing slip—as shown in Fig. 2—and assume zero values at synchronism, it is evident that these torques would never be able to bring the rotor up to full synchronism; and the hysteresis torque is generally much too weak to effect this. The rotor is finally pulled into synchronism by the varying magnetic reluctance torque, and is maintained at synchronous speed by the same torque, all the other torques vanishing at that speed. As already explained, the varying magnetic reluctance torque may for this reason be conveniently termed the synchronous torque, and we shall in what follows refer to it as such.

We have already seen that the synchronous torque is an alternating torque having a zero mean value for all speeds other than that of synchronism, and is thus incapable of exerting any steady driving or accelerating effect so long as the speed of the rotor is below synchronism. The frequency of the synchronous torque is given by  $2sf$ , and the forced oscillations of the rotor to which the synchronous torque gives rise have the same frequency as the torque itself. Now the rotor speed oscillations call into play a further alternating or oscillating torque, owing to the fact that the speed torques change with the speed of the rotor. The speed torques may for small values of the slip be taken to be proportional to the slip, and hence their changes to be proportional to the changes in the speed. The effect is the same as if we were to substitute for the fluctuating speed torques a constant torque equal to the sum of the mean values of the speed torques, together with an oscillating torque whose amplitude is proportional to that of the speed fluctuations.

For the sake of simplicity we shall assume the speed fluctuations to obey the simple harmonic law. They then be graphically represented in a vector diagram by the projections on the vertical axis of the vector  $OV$  in Fig. 3, this vector rotating at  $2sf$  revolutions per second. The instantaneous projection of  $OV$  gives the difference between the instantaneous speed and the mean speed. Since the oscillating component of the speed

torques may, as we have seen, in the neighbourhood of synchronism be taken to be proportional at every instant to the difference between the instantaneous and the mean speed, and since increase of speed produces decrease of speed torques, it is evident that the oscillating or fluctuating component of the speed torques may be represented by a vector  $OF$  in direct phase opposition to  $OV$ . Next, if we assume that the alternating synchronous torque is also a simple harmonic function of the time, then the resultant of the synchronous torque and the oscillating component of the speed torques will give us the alternating torque which gives rise to the periodic accelerations and retardations of the rotor. The phase of this resultant torque is easily determined; for since its zero value must occur at the instant of maximum speed, it is evident that the vector  $OR$ , which represents the resultant torque, must be  $90^\circ$  ahead of  $OV$ , as shown in Fig. 3. Lastly, the synchronous torque vector  $OS$  is obtained by subtracting from the resultant accelerating torque  $OR$  the oscillating component  $OF$  of the speed torques. The angular velocity of all the vectors in the diagram of Fig. 3 is directly proportional to the slip, being, in fact, equal to  $4\pi sf$ .

Let  $\omega$  denote the excess of the instantaneous rotor speed over the mean speed (corresponding to the vertical projection of  $OV$  in Fig. 3), and let  $y$  stand for the instantaneous resultant accelerating torque (vertical projection of  $OR$ ). Then, if  $K$  is the moment of inertia of the rotor

$$y = K \frac{d\omega}{dt},$$

or

$$d\omega = \frac{1}{K} y dt,$$

and hence, taking as the origin of time the instant at which  $\omega$  is zero,

$$\omega = \frac{1}{K} \int y dt,$$

from which it is seen that the amplitude of the speed fluctuation  $OV$  is proportional to the time-integral over a quarter-period of the resultant accelerating torque; or, since the period of this

torque varies inversely as the slip,  $OV$  is proportional to  $\frac{OR}{s}$

By means of the vector diagram of Fig. 3 we can easily show that the amplitude of the speed fluctuations must increase

with decreasing rotor slip. For, assuming the diagram to represent the conditions prevailing at a given mean speed, if the mean speed increases, OR must decrease; for if it were to remain constant, then owing to the increase of its period, due to the decrease of slip, its time-integral over a quarter-period would be increased, and OV, which is proportional to this time-integral, would increase. This again would cause OF (SR), which is proportional to OV, to increase; but since the length OS is constant, an increase of SR could only be brought about by a decrease of OB (as shown by the dotted lines OS' and R'S' in the figure). It follows *a fortiori* that OR could not increase with increase of mean speed.

We thus see that as the mean speed of the rotor gradually increases, the vector OV undergoes steady elongation, the vector OF=SR a similar steady elongation (OF is proportional to OV) and the vector OR a steady contraction. The vector OS remains fixed in magnitude, but gradually approaches OV. At the same time the angular velocity of all the vectors in the diagram steadily decreases. If we were to consider the actual paths traced out by the extremities of the vectors during the last few cycles preceding synchronism, we should find that V traces out a spiral path opening outwards, P a similar path, R a spiral path contracting inwards, while S continues to move in its original circular path. Just before synchronism is reached, OV is moving with extreme slowness and OS is only very slightly in advance of it. As OV, having passed through the horizontal position, moves into the first quadrant, its projection gradually increases until the value of this projection, when added to the mean rotor speed, gives the speed of synchronism. At this instant all the torques have disappeared with the exception of the synchronous torque.

It is clear that at the instant when synchronism is first reached the synchronous torque cannot be less than the total torque resisting the motion. For, if such were the case, then balance of the total driving and resisting torques must have taken place at some instant preceding synchronism, and such balance would have prevented any further increase of speed, *i. e.*, it would have prevented the rotor from reaching synchronism. Hence at the instant when synchronism is reached, the synchronous torque must either equal or exceed the total resisting torque. In the first case, the rotor will steadily maintain synchronous speed. In the second, further acceleration will take place, and the rotor will settle down to the steady speed of synchronism

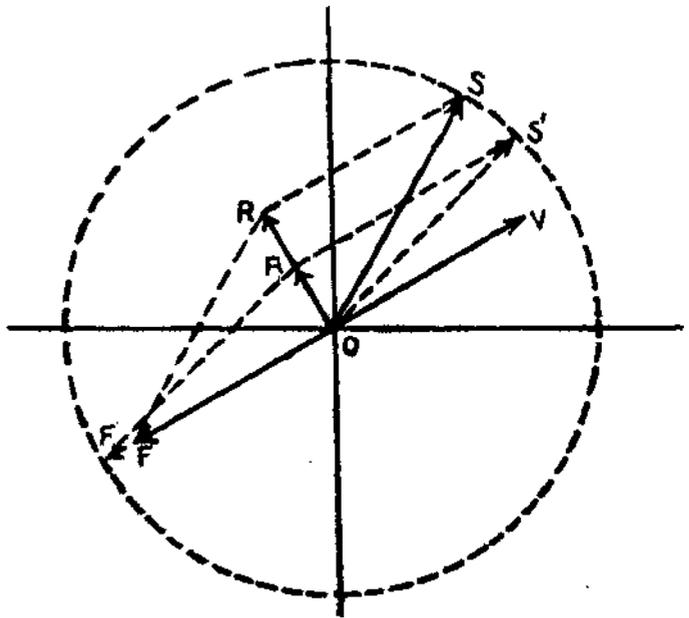


Fig. 3. Vector diagram

only after a number of oscillations, the final position which it takes up relative to the stator poles being such that the synchronous torque arising from the displacement of the magnetic axes of the stator and rotor is exactly equal to the total resisting torque. Whether the rotor comes up to synchronous speed quietly without oscillations, or whether such oscillations take place before it finally settles down to the steady speed of synchronism, the running will correspond to stable conditions. For in either case a momentary increase of speed results in decrease of driving torque, and a momentary decrease of speed in increase of driving torque. The momentary changes in the driving torque which arise during speed fluctuations are due partly to changes in the synchronous torque, which tend to check such fluctuations, and partly to the reappearance of the speed and hysteresis torques, which have a similar effect.

#### OPEN *versus* CLOSED FIELD WINDINGS AT STARTING.

The advisability or otherwise of closing the field windings at starting has been repeatedly discussed. The danger of breaking down the insulation by the high voltage induced in the field windings when the stator circuits are first connected to the mains must be taken into account. Although this danger is entirely avoided by short-circuiting the windings before the stator is connected to the mains, there is no doubt that, from the point of view of initial torque and rapidity of starting, it is inadvisable to have the field circuit closed. The effect of closing the field windings is similar to that of reducing the resistance of the squirrel-cage or eddy-current paths—a procedure which is well-known to lower the initial torque. Again, as the neighbourhood of half-synchronism is approached, the powerful single-axis rotor effect may seriously affect the acceleration of the rotor, and may frequently entirely prevent the machine from attaining any speed greatly exceeding that of half-synchronism. In order therefore to increase the acceleration of the rotor during the early stages of the starting process, the field should be kept open; any risk of breaking down the insulation may be guarded against by the use of a suitable field break-up switch.

Now although it is advisable to keep the field circuit open during the initial stages of the starting operation, it by no means follows that it would be equally advantageous to keep it open until the machine has been pulled into synchronism. The slip with which the rotor ultimately tends to run under the action of the speed torques will depend on the resistance of the circuits in which the currents giving rise to the speed torques

circulate. By lowering this resistance the torque will be momentarily raised and the speed increased. Now closing the field circuit would be equivalent to such reduction of resistance, so that the short-circuiting of the field during the final stages of the starting operation will cause the mean rotor speed to approach more closely to the speed of synchronism than would otherwise be the case. There is thus a distinct advantage in closing the field circuit during the final stages of the starting operation, after the rotor speed has reached a value not differing greatly from synchronism. Cases may in fact arise where a machine with its field open might refuse to pull into synchronism, but could be made to do so by closing the field circuit. This conclusion has been verified experimentally. A certain rotary converter was started with its field open, the slip-ring p. d. being HO low that the rotor settled down to a speed below synchronism, and refused to pull into synchronism. The moment, however, that the field circuit was closed, the rotor locked into synchronism.

#### OSCILLATIONS IN STATOR CURRENT DURING THE PERIOD IMMEDIATELY PRECEDING SYNCHRONISM.

It is well known that as the speed of synchronism is approached violent fluctuations in the current gradually become noticeable. Those are indicated in Fig. 5 of Rosen paper, and are easily accounted for. So long as the speed is below synchronism, the field poles are slipping past the stator poles, and periodic fluctuations are taking place in the reluctance, accompanied by corresponding fluctuations of reactance which throw the stator current into oscillations. The frequency of these oscillations being  $2sf$  (since the reluctance returns to the same instantaneous value after the pole has moved through a distance equal to the pole-pitch, they are not noticeable at low speeds and only become apparent when the slip has become sufficiently small.

#### EXPERIMENTAL RESULTS.

- (a) *Relations connecting stator p. d. with full-load current, stator input and power-factor, rotor speed and field e. m. f. when field is open-circuited*

The experiments embodied in the series of curves given below were carried out on a 4-pole, 5 kv., 3-phase converter designed for a continuous current voltage of 100—130 volts at a speed of 750 r. p. m. This machine had laminated main poles, and was fitted with commutating poles, but had no special starting devices. While the experiments about to be described were

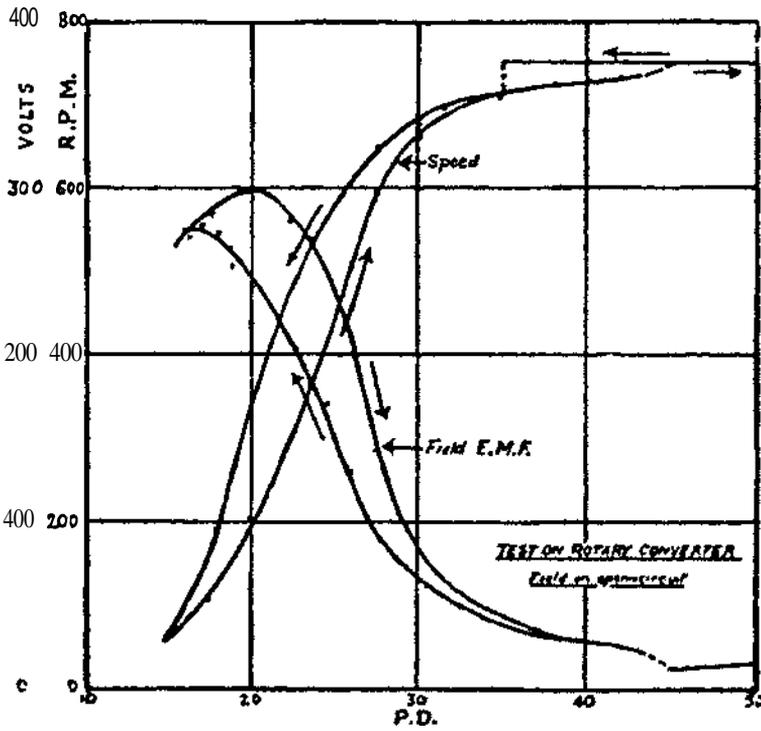


Fig. 4. Curves connecting speed and field e. TO. f. with p. d.  
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carried out, the brushes were entirely removed from the commutator. Before each set of readings the machine was allowed to run light for a sufficiently long time to get the bearings into a steady state.

In the first set of experiments, the results of which are exhibited graphically in Figs. 1. and 5, a number of gradually increasing p. d. s. were applied to the rotor slip rings, and after the speed corresponding to any given p. d. had settled down to a constant value readings of the speed, current, power, etc., were taken. When the p. d. had been raised sufficiently to enable the machine to lock into synchronism, it was still further increased, and then a second series of readings corresponding to decreasing values of the p. d. was obtained. In the figures both the ascending and descending branches of the various curves are

Fig. 4 shows the relations connecting speed and field e. m. f. with stator p. d. Below a p. d. of about 15 volts across the slip rings the machine would not run at all. The speed then gradually increased with the p. d., the increase becoming much slower beyond a certain point, and at a slip ring p. d. of about 45 volts the machine was able to lock into synchronism. During the descending set of readings, synchronism was maintained down to a voltage of about 35 volts. Below this point the speeds obtained with given voltages were found to be uniformly higher than those corresponding to the ascending branch of the curve. Since, as shown by Fig. 5, the power supplied to the machine was found to be lower for decreasing values of the p. d., in spite of the higher value of the speed, it is to be inferred that for decreasing values of the p. d. the resisting torque was uniformly less. This would indicate a decrease in the frictional resistances, probably due to the temperature of the bearings being higher during the descending set of readings than during the ascending set,

The changes in the field e. m. f. are related to those in the speed. The field e. m. f. may be regarded as proportional to the product of two factors namely, the maximum flux per pole and the slip. At first the field e. m. f. rises with increase of p. d., indicating that the increase of flux is more important than the decrease of slip. Beyond a certain point the decrease of slip is more important than the increase of flux, and the field e. m. f. begins to decrease. It does not vanish at synchronism, indicating that there is either swaying or pulsation of the flux which enters the main poles. Since for descending values of the p. d. the speed is uniformly higher and hence the slip lower than for

ascending values, we should expect the field e. m. f. to be uniformly lower in the former case, and the curve of field e. m. f. shows that such is the case.

Fig. 5 shows the relations connecting stator current, stator power and power-factor with p. d. The difference between the ascending and descending branches of the power or input curve has already been referred to. It must be remembered that when the machine is not running synchronously, its behaviour is similar to that of an induction motor. Hence, owing to the lower resisting torque during the descending set of readings we should expect a smaller current and also a lower power-factor (as is at once evident from consideration of the circle diagram) than during the ascending set; and the curves of Fig. 5 fully confirm this.

(b) *Relations connecting stator p. d. with speed and field current, when the field circuit is closed.*

Figs. 6 and 7 give the connection between p. d. and speed when the field circuit is closed through various resistances, and in Fig. 6 the curve corresponding to the field on open circuit, previously shown in Fig. 4, is repeated for the sake of comparison.

When the field was on dead short-circuit, the machine refused to run up to anything like synchronous speed, and seemed to approach asymptotically a speed somewhat above half-synchronism.\* The explanation of this fact has already been given (reference may be made in this connection to Fig. 2 (d)).

The curves of Fig. 7 show that by the introduction of a suitable amount of resistance into the field circuit the tendency of the machine to settle down to a speed in the neighbourhood of half-synchronism may be overcome, and that the machine may be made to lock into synchronism. This result may be explained as follows. Considering the complete torque-speed curve of an induction machine over the entire range of slip, positive and negative, we may regard the point of zero slip as dividing this curve into two branches, one of which corresponds to positive values of the slip, and the other to negative values. If we now suppose resistance to be introduced into the rotor circuit, then, as it well known, the result is to produce a horizontal displacement of the points on the two branches of the torque-speed curve in opposite directions from the point of zero slip. Referring now to the torque-speed curves of Fig. 2 (d), it must be noticed that

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\* Incidentally the fact that the machine reached a speed in excess of half-synchronism definitely disposes of the erroneous view previously referred to that the machine tends to lock into exact half-synchronism.

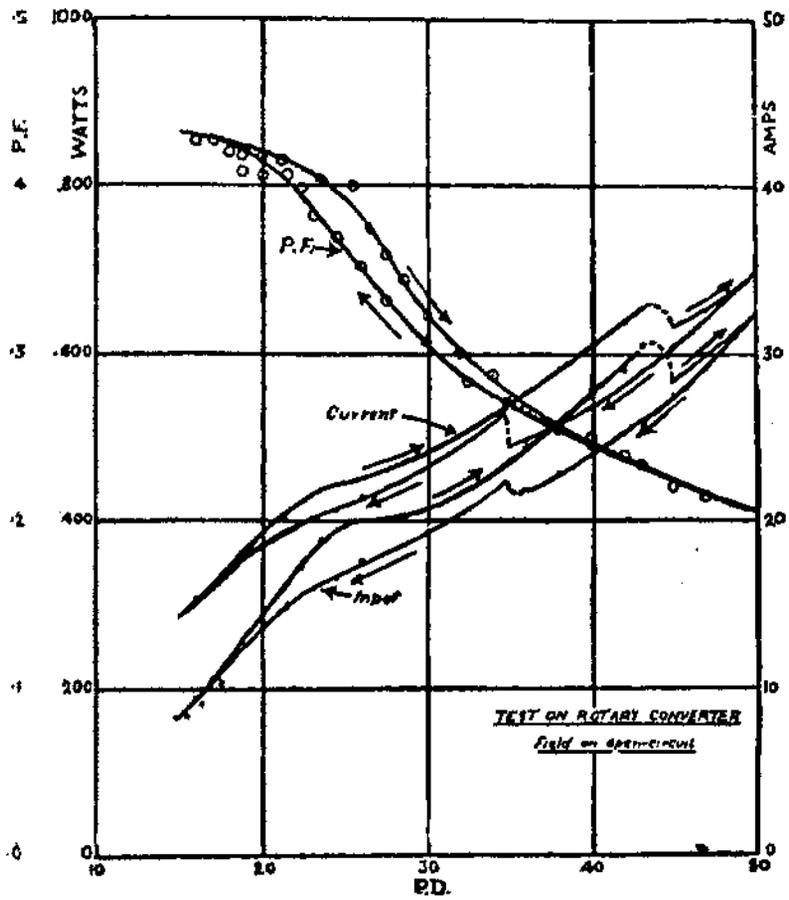


Fig. 5. Curves connecting stator input, current and power factor with stator p. d. when field is open-circuited.

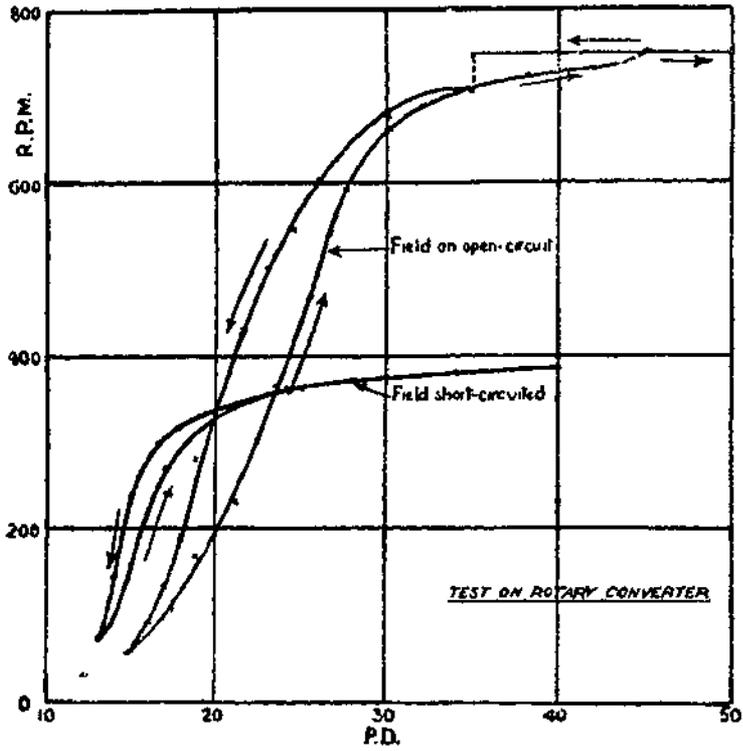


Fig. 6. Curves connecting speed with p. d. when field is (a) open-circuited and (b) short-circuited.

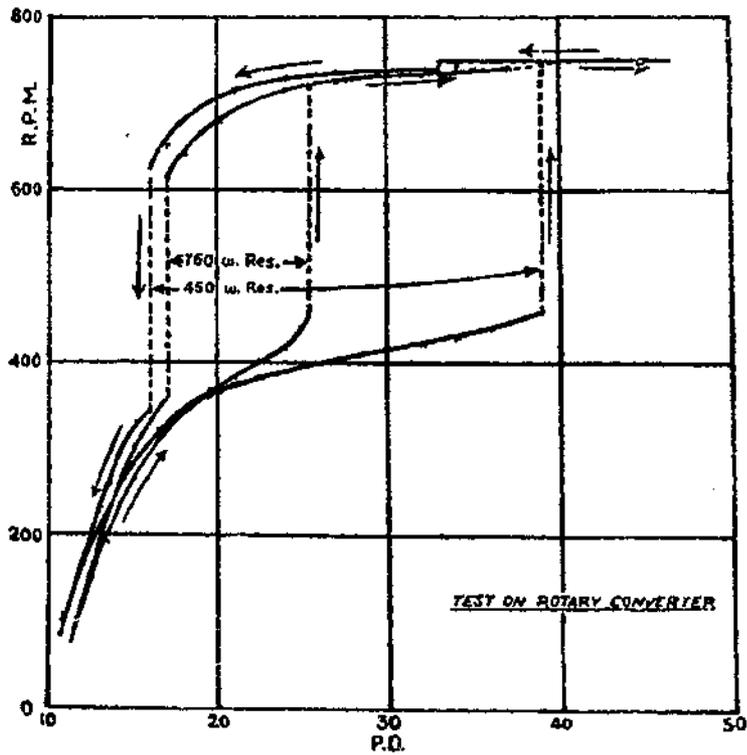


Fig. 7. Curves connecting speed with p. d. when field is closed through external resistance

the point of zero slip for the chain-dotted curve correspond to half-synchronism, while for the dotted curve the point of zero slip is at full synchronism. From this it follows that the introduction of resistance will, in the region between half and full synchronism, cause a displacement of the dotted and chain-dotted curves in opposite directions, the dotted curve being displaced from left to right, while the chain-dotted one is displaced from right to left. It is easy to see that this will cause a rise of the minimum in the resultant curve (the full line curve of Fig. 2 (d)), and if the resistance remains sufficiently large the minimum resultant torque will assume a positive value, so that the driving torque will be positive over the entire range of speed from zero to synchronism. The displacement of the dotted and chain-dotted curves in opposite directions in the region between half and full synchronism is, however, only one of the causes concerned in suppressing the negative portion of the resultant torque-speed curve, and besides this there is another cause. The dotted curve is the torque-speed curve of an induction motor whose stator is supplied at constant p. d. and frequency; whereas the chain-dotted curve is the curve of an imaginary induction motor whose stator is supplied at variable p. d. and variable frequency, the p. d. being proportional to the frequency. Now the introduction of resistance into the field windings is equivalent to the introduction of resistance into the primary winding of the imaginary motor (since the primary winding of this imaginary motor is represented by the field winding) and is thus equivalent to a reduction of the p. d. across its terminals. This will result in a reduction of all the ordinates of the chain-dotted curve. While, therefore, the introduction of resistance into the field circuit results in a simple elongation of the abscissæ of the dotted curve from right to left unaccompanied by any change in the values of the ordinates, the effect on the chain-dotted curve is a twofold one, namely, an elongation of the abscissæ accompanied by a shrinkage of the ordinates. This shrinkage of the ordinates will further help to suppress the negative portion of the resultant curve.

It will be noticed that in the curves of Fig. 6, which refer to the open-circuit and short-circuit conditions of the field, there are no discontinuities in the speed curves (except that which occurs at the instant of breaking from synchronism in the case of the open-circuit curve); whereas the curves of Fig. 7 show two well-marked discontinuities (one on each of the curves), in addition to the discontinuities at break from synchronism. These discontinuities are readily accounted for by considering the shape of the resultant or full-line torque-speed curve of Fig. 2 (d). In the cases to which Fig. 7 refers the resultant torque-speed curve

lies, as already explained, wholly above the axis of speed, all its ordinates being positive; but the curve has two maxima separated by a minimum. It is the existence of this minimum which causes the discontinuities in the speed curves. Stability of running can only be secured by working on a portion of the torque-speed curve which has a downward slope from left to right. With increasing p. d. and speed the point on the (varying) torque-speed curve corresponding to the stable running condition for the given p. d. gets displaced further and further to the right, until finally it reaches the minimum point on the curve. An increase of p. d. beyond the value corresponding to minimum point results in a passage into the unstable region which lies between the minimum and the second minimum, and no stable running is possible in this region. It is only after the speed has passed beyond the second maximum of the torque-speed curve that stability can again be reached. The point where the discontinuity occurs along the ascending branch gives approximately the speed corresponding to minimum torque; while the discontinuity on the descending branch marks approximately the second maximum of torque. The first maximum of torque would correspond roughly to the lowest speed at which the machine will run,

In Fig. 8 are shown the relations connecting speed and p. d., and field current and p. d., with the field on dead short-circuit. Each curve is shown as having three branches. Two of these correspond to the values obtained by first increasing the speed to a certain value and then decreasing it. The third branch, marked "return from synchronism," was obtained by first open-circuiting the field and raising the p. d. to a value sufficient to enable the machine to lock into synchronism, then circuiting the field and taking a set of readings while the p. d. was being decreased. The first two branches of the speed curve are identical with those shown in Fig. 6. The relations connecting current and power factor with p. d. are given by Fig. 9.

Returning to Fig. 6, it will be seen that the machine starts with a lower p. d. when the field is short-circuited than when it is on open circuit; and this might at first sight appear to contradict the statement previously made regarding the advantage of starting with the field circuit open. Such, however, is not the case; for the real basis of comparison is not the p. d. applied to the rotor, but the *current* taken by it. The relation connecting speed with current for the various arrangements tried is shown in Fig. 10, and it will be seen at once that the machine starts up with a considerably lower current when the field is open-circuited. If the field is closed through a resistance, there

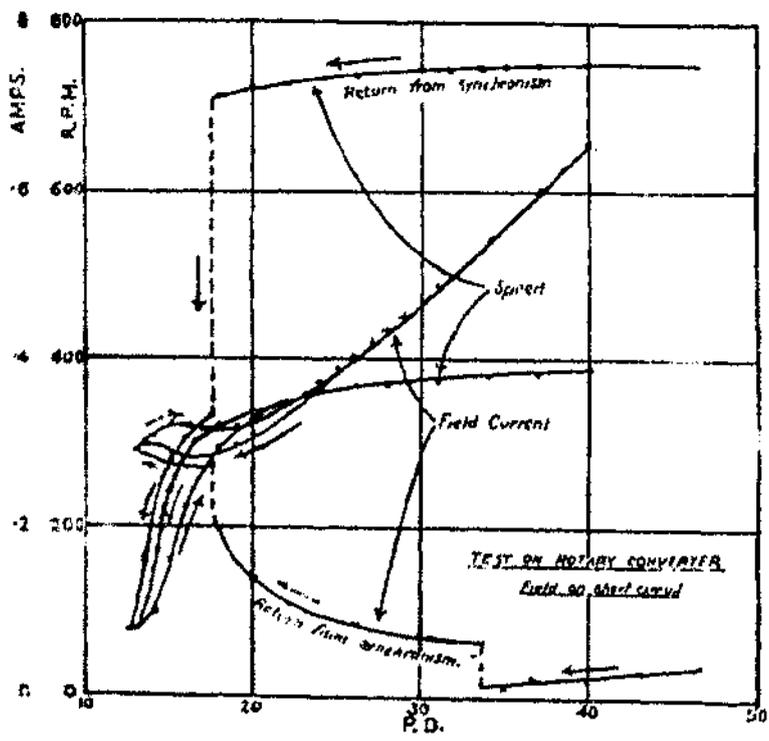


Fig. 8. Curves connecting speed and field current with p. d. when field is short-circuited.

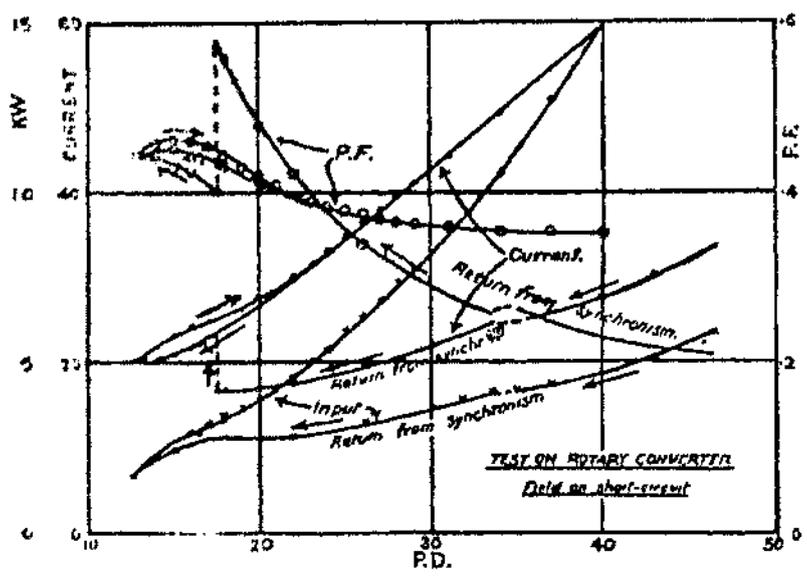


Fig. 9. Curves connecting stator input, current and power factor with p. d. when field is short-circuited.