# A STUDY OF SYNCHRONOUS MOTORS

by

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## INTRODUCTION

The object of this study is to point out the salient factors in the construction of synchronous motors, the theory explaining their operation, their advantages and disadvantages as compared with other machines, and their field of application with particular reference to single phase operation.

The results of an experiment performed in the laboratory with a single phase machine are stated and an attempt is made to explain their significance.

## CONSTRUCTION DETAILS OF SALIENT POLE THREE PHASE SYNCHRONOUS MOTORS

The construction employed in motors of this sort varies, but in practically all cases the machines have a wound stator with the poles built on the rotor.

Any synchronous motor will operate as a synchronous generator and vice versa. The general details of the two machines are the same; there being minor changes in design to make the machines best suited for their proposed use. The wound stator gives a more rugged machine at less original cost and less maintenance cost than is possible with a wound rotor.

In either case the three phase windings are distributed in such a way as to form an even number of poles corresponding to the number of poles which are to be excited by the direct current supplied to the pole windings. (Hereafter the wound part of the machine will be referred to as the stator, and the direct current excited part the rotor.) The exciter is usually a small direct current generator mounted on the shaft

of the motor unless a direct current supply is more conveniently available.

A synchronous motor is essentially a single speed machine, and if the frequency of the supply is known, the speed in R. P. M. depends on the number of poles according to the equation: R. P. M. = $\frac{(120)\ \text{frequency}}{\text{Number of poles}}$. Sometimes it is desirable to change the speed of a synchronous motor. This is possible through expensive wiring and construction features. It is not desirable to attempt to vary the speed of the machine except by multiples of two. The reason is simply one of balance and symmetry of winding.

To accomplish this expensive speed change, every other pole or every fourth or eighth pole is excited by a switch in wiring. Of course the wound part of the machine must be reconnected in such a way as to furnish a like number of poles which are a. c. excited. The number of stator poles for best operation must always equal the number of rotor poles which are excited. The inconveniences of such an arrangement consist of extra original cost, higher maintenance cost, and lower available capacity at the higher speeds. This loss in capacity might possibly be evaded if the changed wiring utilized all of the stator windings.

## THEORY OF THREE PHASE SYNCHRONOUS MOTORS

Assume the windings of the stator to be distributed in space in such a way that the field formed by any one phase winding takes a sine wave of shape in space. With the three phase windings so distributed, the flux of the different phases are represented by the following figure:

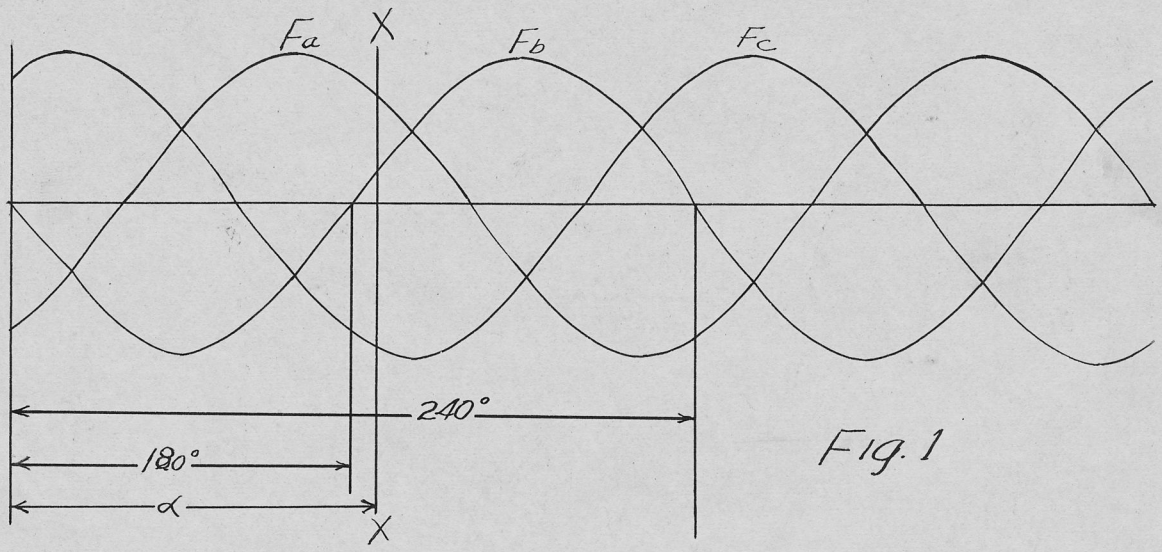



Fig. 1

The m.m.F's at the point "x" due to the three phases will be $F_x = F_{al} \sin\alpha + F_{bl} \sin(\alpha - 120) + F_{cl} \sin(\alpha + 120)$

$= \frac{NIa}{3} \sin\alpha + \frac{NIb}{3} \sin(\alpha - 120) + \frac{NIc}{3} \sin(\alpha + 120)$ where

N = turns per pole

$I_a = I \max \sin wt$

$I_b = I \max \sin (wt - 120)$

$I_c = I \max \sin (wt + 120)$

$F_x = \frac{N}{3} \left[ I_m \sin\alpha \sin wt + I_m \sin(\alpha - 120) \sin(wt - 120) + I_m \sin(\alpha + 120) \sin(wt + 120) \right]$

$\sin a \pm b = \sin a \cos b \pm \cos a \sin b$

$\sin(\alpha - 120) = \sin\alpha \cos 120 - \cos\alpha \sin 120 = -\frac{1}{2} \sin\alpha - \sqrt{\frac{3}{2}} \cos\alpha$

$\sin(wt - 120) = \sin\alpha \cos 120 - \cos\alpha \sin 120 = -\frac{1}{2} \sin wt - \sqrt{\frac{3}{2}} \times \cos wt$

$\sin(\alpha + 120) = -\frac{1}{2} \sin\alpha + \sqrt{\frac{3}{2}} \cos\alpha$

$\sin(wt + 120) = -\frac{1}{2} \sin wt + \sqrt{\frac{3}{2}} \cos wt$

and $\sin(\alpha - 120) \sin(wt - 120) =$

$\frac{1}{4} \sin\alpha \sin wt + \frac{3}{4} \cos\alpha \cos wt + \sqrt{\frac{3}{4}} \sin wt \cos\alpha + \sqrt{\frac{3}{4}} \sin\alpha \times \cos wt$

$\sin(\alpha + 120) \sin(wt + 120) =$

$$\frac{1}{4}\sin\alpha \sin wt + \frac{3}{4}\cos\alpha \cos wt - \frac{\sqrt{3}}{4}\sin wt \cos\alpha - \frac{\sqrt{3}}{4}\sin\alpha \cos wt$$

$$F_x = \frac{N}{3} I_m \left(\sin\alpha \sin wt + \frac{1}{2}\sin\alpha \sin wt + \frac{3}{2}\cos\alpha \cos wt\right)$$

$$= \frac{3}{2} \times \frac{N}{3} I \max \left(\sin\alpha \sin wt + \cos\alpha \cos wt\right)$$

$$= \frac{N}{2} I \max \cos (wt - \alpha)$$

substituting $I_m = \sqrt{2} \times I$

$$F_x = 0.707\, NI_m \cos (wt - \alpha)$$

From this equation it is seen that at any instant the flux is distributed along the stator in a sine wave shape. It is also seen that at any point the flux varies with time according to a sine wave. For this equation to hold it follows that there is a flux rotating around the stator at synchronous speed. It indicates that this rotating flux is distributed in space in the shape of a sine wave.

The assumptions made in this proof of the revolving flux are as follows: A sine wave of flux results when any single phase is excited. Regular three phase power is supplied to the stator. The leakage flux and the air gap resistance to magnetic flux is disregarded. (For a more vigorous proof of the revolving flux see Alternating Current Circuits and Machinery, Chapter 4 part 2 by J. G. Tarboux).

After the machine has been brought up nearly to synchronous speed and the poles excited, the rotor immediately attains synchronous speed and is locked into step with the revolving flux by means of the attraction between the magnetic fields of the rotor and stator.

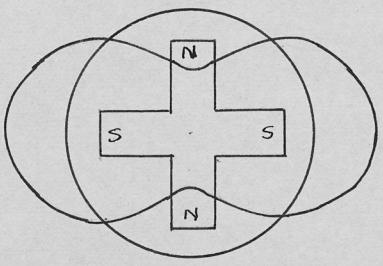



Fig.2.

The revolving field shown by the curve above rotates at synchronous speed and drags the rotor poles along with it. The rotor poles are excited and they create quite a strong magnetic field which acts on the stator windings according to the fundamental generator equation:

$$E_g = \frac{\phi P N n}{p 10^8} = K \phi n$$

It is seen that the generated voltage varies directly with the pole flux . It follows that the generated voltage varies with the field current of the rotor depending on the saturation curve of the rotor pole material and the air gap resistance to the passage of the flux.

The voltage applied to the stator windings added to the voltage induced in the stator windings by the pole flux is the resultant voltage in those windings. This voltage leads the current in the windings by 90 degrees. By varying the exciting current, this resultant voltage is varied in magnitude and its phase relation with the applied voltage as shown in figure 4

For a given power output the stator current varies with the power factor. The stator current for such a load is a minimum at unity power factor. The field current required to give unity power factor varies somewhat for different loads. Typical synchronous motor v-curves are shown on sheets

## THEORY OF SINGLE PHASE SYNCHRONOUS MOTORS

In any single phase motor the field formed by the stator is a pulsating field. Obviously there would be no torque if the stator were energized.

If the single phase machine is brought nearly to synchronous speed and the poles are excited, it will operate as

a single phase synchronous motor. Various means are employed to give the machine its initial speed.

If two windings are connected in parallel across a single phase and if one of the windings has more inductance or capacity than the other, the fields formed by the two windings will be displaced slightly with respect to time.

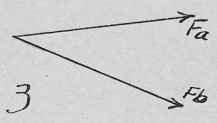



Fig. 3

If now these two fields are allowed to influence a squirrel cage rotor a slight torque results as in the repulsion motor. The amount of torque depends on the time angle between the two fields, the strength of the two fields and the position of the two windings with respect to each other on the stator.

This torque is usually not very great but is sufficient to cause the machine to approach synchronous speed. When the machine is rotating fairly fast the poles may be excited and the motor attains synchronism quickly. After the poles have been excited the starting winding is disconnected and the machine operates as a single phase synchronous motor.

The manufacture of single phase synchronous motors was discontinued several years ago on the continent, and this type of machine is practically unknown in the United States.

## ADVANTAGES AND DISADVANTAGES

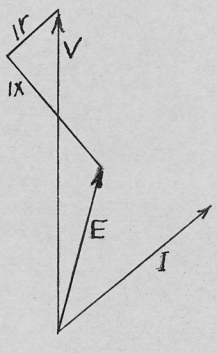
The chief advantage of the synchronous motor is in its ability to operate at different power factors and the ease with which the power factor may be adjusted. Its comparative simplicity and the possibility of winding it economically for

high voltages, thus doing away with the necessity of transformers, are advantages, but these are also possessed by the induction motor. Its invariable speed under varying load is also an advantage under certain conditions.

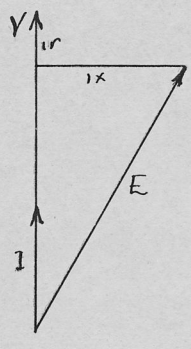
Its main disadvantages are its tendency to hunt and its lack of any inherent starting torque. In the case of polyphase motors, neither of these objections are serious and they are of little consequence when a motor is provided with a properly designed damper and operates under reasonably good conditions. The lack of starting torque limits the use of synchronous motors to places where frequent starting is unnecessary. Synchronous motors are seldom built in small sizes.

The power factor of a synchronous machine at a given load may be varied over wide limits by alternating the field excitation. A motor is said to be over-excited or under-excited according as its excitation is greater or less than normal. Normal excitation is that which produces unity power factor. Over excitation produces condensive action and causes a motor to take a leading current. An under-excited motor will take a lagging current. This action is explained by the following vector diagrams:

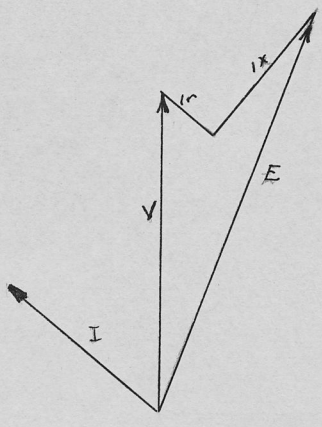
Fig. 4




Under Excited
Lagging P.F.




Normal
Unity P.F.




Over-Excited
Leading P.F.

By operating all synchronous motors at leading power factor, the power factor of the total plant load may be raised. This flexibility of power factor results in the advantage of cheaper power rates.

This advantage, however, is slightly diminished by the lower efficiency of the motor at leading power factor, due to the increased exciting current for such operation.

Higher voltages may be used on a synchronous motor due to the fact that connections are made directly to the stator and the stator windings may be highly insulated.

## HUNTING

The tendency of a synchronous motor to hunt may be diminished in two ways. One of these methods is by increasing the moment of inertia of the rotor by adding a fly-wheel. This is impracticable for small applications, however, so we will leave it and pass on to the method of diminishing hunting by the use of damper windings.

Damper windings are short-circuited low resistance windings placed in the pole faces. When this amortisseur or damper winding is used on a single phase motor, double-frequency currents are induced in it by the double-frequency flux variation produced by armature reaction in the poles. This double frequency current increases the copper loss in the damper and tends to damp out the flux variation which causes it.

These windings usually take the form of copper grids placed in the pole faces and copper bridges between the poles. The grids are usually made by placing copper bars in

the pole faces near their surfaces and then short-circuiting these bars by bolting or welding them to end straps of brass or copper.

For most effective damping, the damper should have as low resistance as possible, but if this winding is to also be used for starting the motor, the resistance which gives the best damping action may be too low to give the best starting torque.

The armature reaction of a polyphase synchronous motor, which operates under steady conditions is fixed in space phase with respect to the poles. Under this condition, the resultant flux is also fixed with respect to the poles, and the damper is inactive and produces no effect whatsoever upon the operation of the motor. When, however, hunting starts, the armature reaction is no longer constant or fixed in space phase with respect to the poles, but sweeps back and forth across them with a period equal to the period of ascillation of the rotor. This causes the resultant flux to cut the damper and to induce currents in it. Eddy-current and hysteresis losses will be produced in the pole faces which will assist, to a slight extent, in damping out hunting. The main damping action is due to the currents induced in the damper which are in such direction as to oppose the change in the angular velocity of the rotor which produces them.

If a damping winding is used on a single-phase synchronous motor, there will be currents induced in it even when the motor is entirely free from hunting. These currents are caused by the armature reaction which in a single-phase synchronous motor is neither constant in space phase nor in

magnitude. The main effect of a short-circuited winding on a single-phase synchronous machine is to damp out any harmonies there may be in its wave form. The copper loss of such a winding will considerably lower the efficiency.

## APPLICATIONS

The machines to which synchronous motors are usually applied can be divided into three general classifications:

First: Machines such as compressors, jordans, pulp grinders etc., that permit at least partial unloading during starting. Motors for these applications, therefore, usually have relatively low starting and pull-in torques ranging from 30 to 50 per cent for the former and from 30 to 40 per cent for the latter, and since the load for these applications is generally uniform, 140 to 150 per cent pull-out torque is, in most cases, ample.

Second: Applications requiring relatively low starting torques but high pull-in torques. These machines are usually of the centrifugal type, such as fans or pumps, and on this type of equipment the starting load is only that resulting from friction and inertia, and consequently low starting torque can be used. Modern practice is to equip most fans and pumps with automatically operated discharge valves so that the pump or fan is connected to the system at about the time it reaches full speed conditions. This, of course, necessitates that the motor must develop full-load torque at pull-in. Pull-out torque can be relatively low, however, since here again the load is usually uniform.

Third: Those applications requiring high starting and pull-in torque, as tube mills, ball mills, metal rolling mills, lines shafts and many others. No general torque specifications for this class can be made, since each application presents its own problem.

The first problem to be considered when applying a synchronous motor is that of selecting the proper torques for the drive. Three different values of torques must be given consideration. First, the starting torque, representing the ability of the motor to start the load; second, the pull-in torque, representing the ability of the motor to maintain operation during the change over from induction to synchronous operation, and, third, the pull-out torque, representing the ability of the motor to maintain operation under peak-load conditions.

The starting and pull-in torques are characteristics of the motor operating as an induction motor, and as such are closely related one to the other. The pull-out torque is a characteristic of the motor when it is operating as a synchronous motor; while it is not closely allied to the two preceeding values of torque, it does have some influence on the starting characteristics of the motor, particularly regarding in-rush.

Torque characteristics of synchronous motors which, though they can be varied, are fairly standard for different types and applications.

## CHARACTERISTICS OF AVAILABLE MOTORS

Modern synchronous motors are available, which produce starting torques ranging from about 50 per cent to well above 200 per cent of full-load torque; pull-in torques ranging

from 35 per cent to 110 to 125 per cent of full-load torque; and pull-out torques running as high as 350 per cent and even 400 per cent of full-load torque. It is desirable, from an economic standpoint, when specifying these three quantities, to keep them as low as is consistent with the application, with a reasonable factor of safety for varying voltage, etc., since an increase in any of the three factors involved results generally in a larger machine with increased first cost. Manifestly, in determining the starting torques of the motor, sufficient torques must be developed to insure starting and accelerating the load. The pull-in torque should be very nearly equal to the torque required to drive the machine under starting conditions, but at synchronous speed. Pull-in torque should be kept as low as possible, since high pull-in torque is accompanied by high starting current. Compared with a motor with 50 per cent starting torque, 40 per cent pull-in torque and 150 per cent pull-out torque, a motor with the same starting and pull-out torque but with 100 per cent pull-in torque would be about 15 per cent higher in price. The efficiency would be about three-tenths of one per cent lower at full load, while the starting current would be nearly twice that of the motor with the lower value of pull-in torque. For this reason it is advisable, if it can be done, to arrange to relieve the load as much as possible at the start, thereby obtaining a less expensive motor and preventing possible voltage fluctuation.

## PULL-OUT TORQUE REQUIREMENTS

The pull-out torque of the motor must be selected for the maximum peak load conditions of the application. In

determining the pull-out torque, it should be kept in mind that the maximum pull-out torque of the synchronous motor required to keep it in operation under low voltage conditions need not be as great as that of an induction motor, since the pull-out torque of the synchronous motor varies directly as the voltage, whereas that of the induction motor varies as the square of the voltage.

The pull-out torque of a synchronous motor is in direct relation to the field strength of the motor. Therefore, to obtain high pull-out torque it is necessary to build a larger machine, because of the increased heating resulting from the greater current that must be put through the field circuit. The pull-out torque also has an effect on the starting current required by the motor, the starting current increasing as the pull-out torque increases, assuming of course, that the constant values of starting and pull-in torque are maintained. Since the resistance and reactance of the rotor circuit are factors in determining all three values of torque, as well as the starting inrush, a change in design to change any one of the three torque values will be reflected by some change in the values of the other two torques and the inrush.

As a part of the experiment performed in the laboratory, the three phases were connected in parallel across one line, as shown in figure 5. By adjusting the amount of capacity and inductance, a fairly well balanced rotating field was formed and maintained.

Due to the fact that the angles formed could not be maintained during varying power factors, this plan was discontinued.

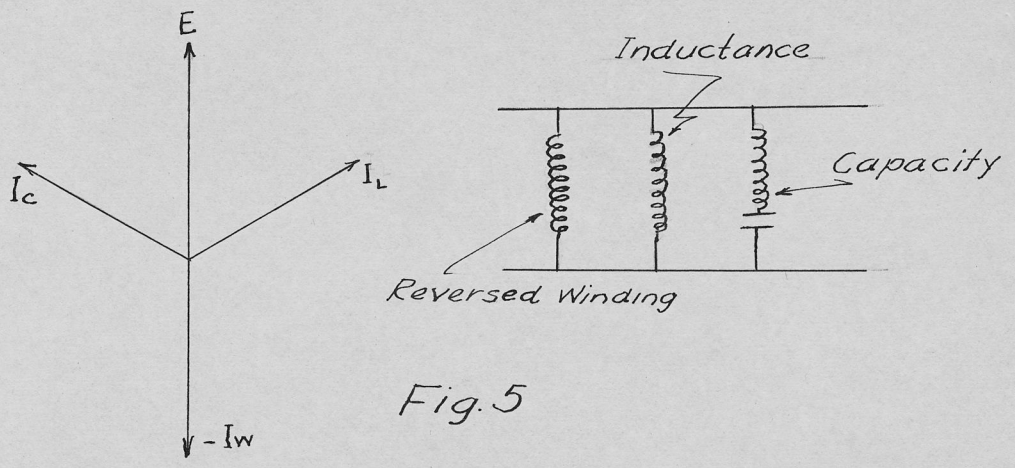



Fig. 5

With the three windings in parallel, it is possible to displace the currents in the three windings by 120 degrees for a given load and a given field current. If, however, the field current or the load or the inductance or the capacity is changed, the angles between the current varies. It is impossible to displace the currents 120 degrees from each other without reversing one of the windings, as shown in the above diagram. If $I_L$ lags 60 degrees and $I_C$ leads 60 degrees and $I_W$ is reversed for 0 degree lag, the currents are displaced by 120 degrees from each other. This gives a revolving flux which easily brings the machine, as an induction motor, nearly up to synchronous speed. After the poles are excited, the machine acts as a synchronous motor.

Due to the instability of such operation this plan was discontinued. Two phase windings were next connected in series and the third winding was connected in parallel with them with some inductance in its circuit.

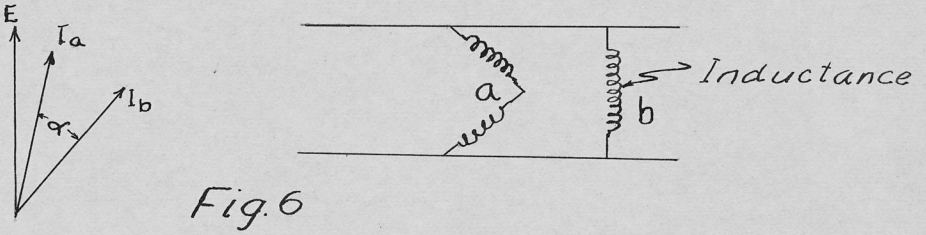



Fig. 6

By varying the amount of external inductance, the angle could be varied. With these two currents so displaced, a revolving flux was formed which, however imperfect, cut the induction motor bars and gave the machine its initial rotation. After the induction motor is rotating quite rapidly, the poles are excited and the machine acts as a synchronous motor.

We found that the machine would come up to the speed with two such windings connected, as shown in the previous figure, and the operation was quite satisfactory. The starting winding, which contained the external inductance, was then disconnected, and the machine continued to operate as a synchronous motor.

A regular three phase motor was used with the windings distributed for three phase operation. This distribution probably shows up the single phase machine to a greater disadvantage than is due.

The power in a three phase circuit is 3 $E_L$ $I_L$ cos . The power in a single phase circuit is $E_L$ $I_L$ cos . With the same line current the power in a three phase circuit is 1.73 times that of a single phase circuit. This ratio is apparent in a comparison of the pull-in torque. The single phase machine will pull in a load only about 0.58 of that which a three phase machine will pull in. The pull-out torque of the single phase machine at unity power factor is about 65 per cent of the pull-out torque of the three phase machine at the same power factor.

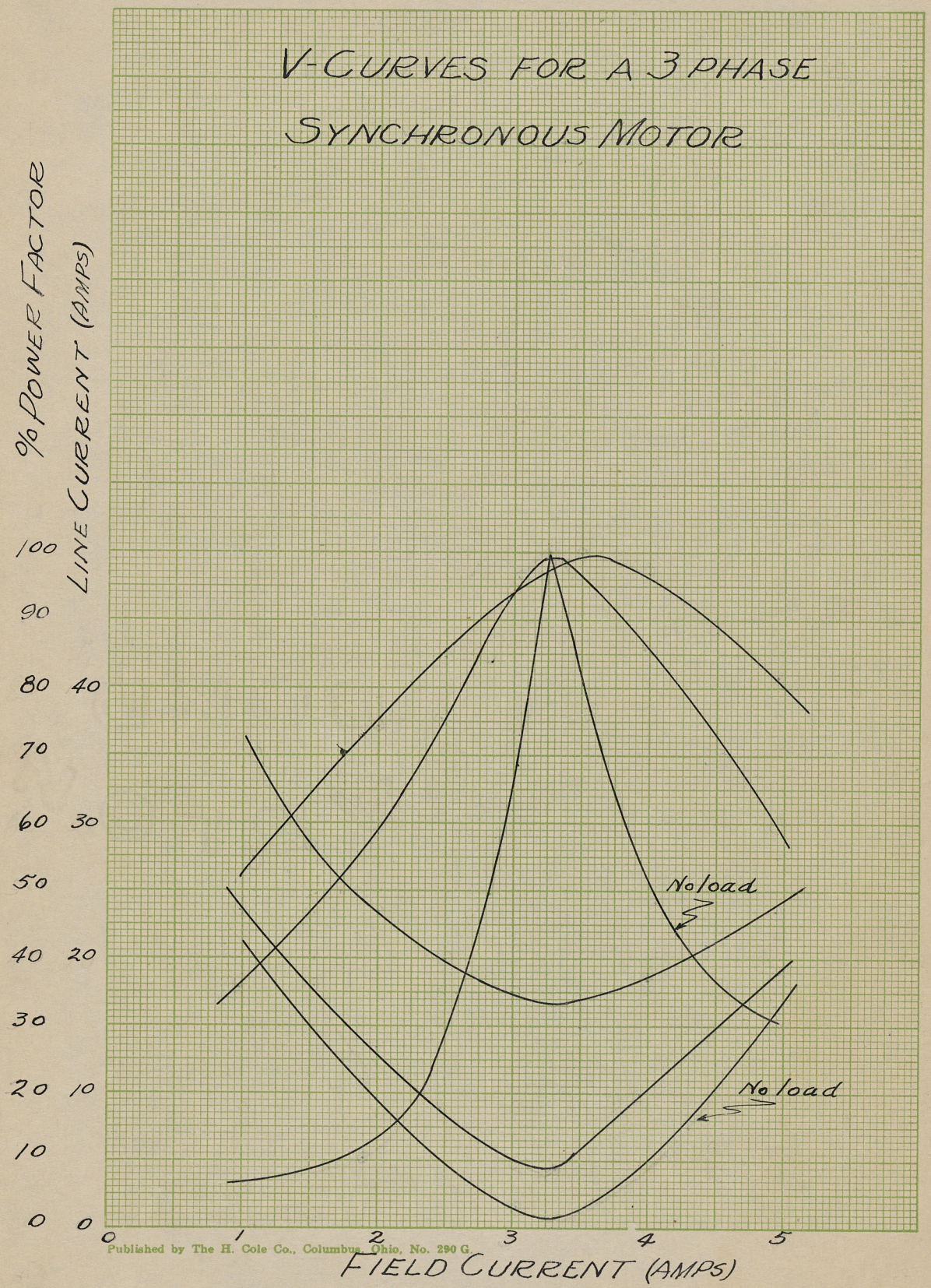
The pull out tests were made as follows: Holding the power factor at unity, the machine was loaded by the use of a dynamometer until it pulled out of step and stopped.

The machine was started as a three phase induction

motor and one phase was disconnected. The maximum load under which the single phase machine will pull into step is the pull-in torque. The pull-in torque of the three phase machine was found in the same way, except that all the phases were in use.

As the load was increased, it was found that the single phase motor power factor would lag less and less without pulling out. Under light loads and a leading power factor the single phase machine hunted slightly. As the load was increased, however, the constant torque of the dynamometer damped out this hunting.

V-curves illustrating the operation of the same machine three phase and single phase are shown on the curve sheets figures 7 and 8. It is seen that the disadvantages of the single phase machine are lower capacity, lower efficiency, a tendency to hunt when overexcited, and a higher line current at a given power output.




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Fig. 7

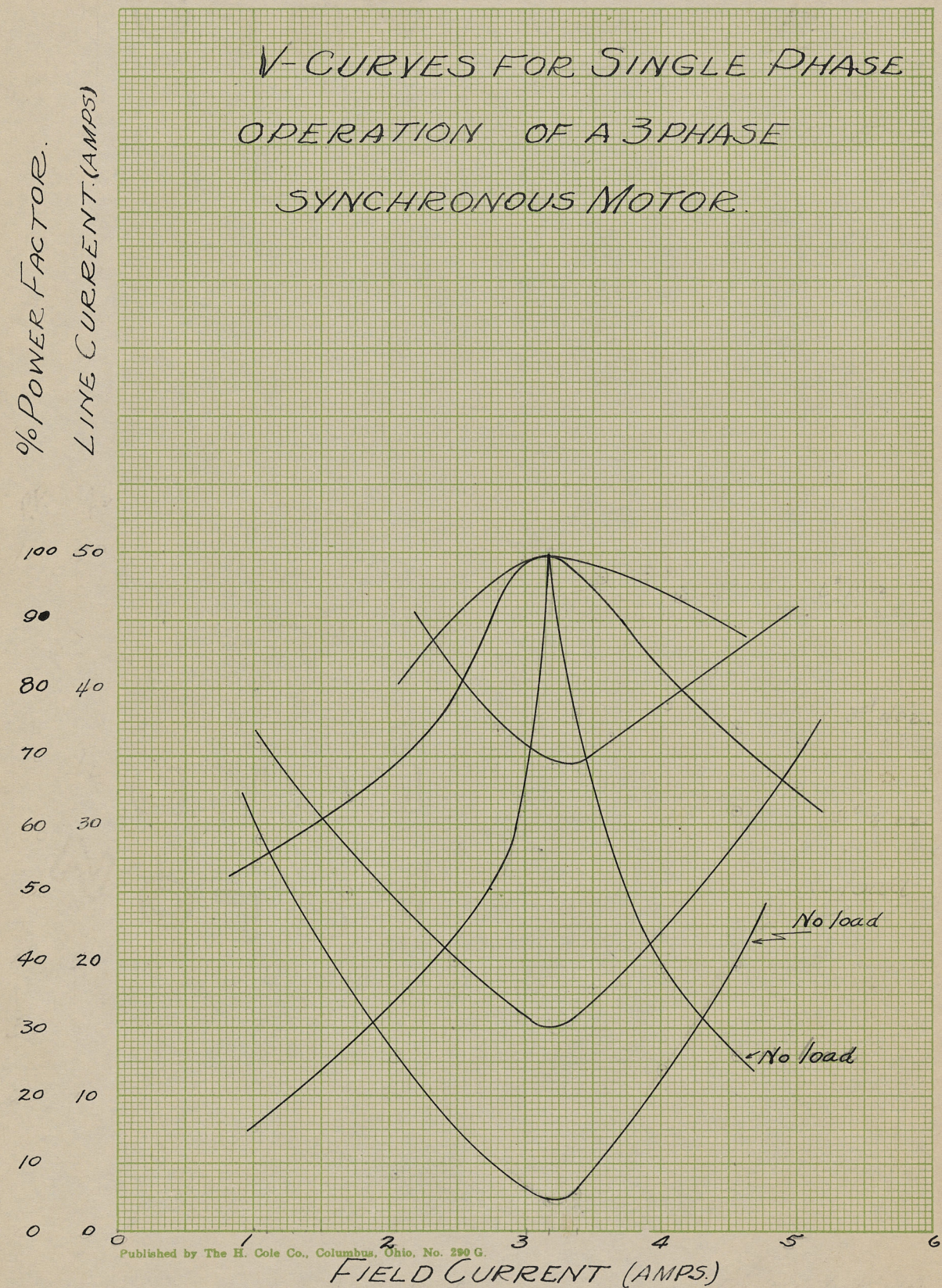

V-CURVES FOR SINGLE PHASE
OPERATION OF A 3 PHASE
SYNCHRONOUS MOTOR.
% POWER FACTOR.
LINE CURRENT. (AMPS)
100
90
80
70
60
50
40
30
20
10
0
50
40
30
20
10
0
No load
No load
0
1
2
3
4
5
6
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FIELD CURRENT (AMPS.)

Fig. 8.

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APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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