The Synchronous Motor

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The synchronous motor

THE SYNCHRONOUS MOTOR

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- THE SYNCHRONOUS MOTOR -

INTRODUCTORY PARAGRAPH.

It is intended in this paper, to present a thorough treatment of the theory and operation of the synchronous motor. The data contained in the paper is the result of a series of tests made in the laboratories of Armour Institute of Technology, Chicago, the motor tested being of the 6-pole revolving field type, operating on 25 cycles and developing 10 horse power. The motor was made by the General Electric Company and was so designed as to permit of either two of three phase operation. The power was supplied by a two and three phase inverted rotary converter which was also made by the General Electric Company.

The subject is herein treated under two general heads; first, theoretical treatment and second, experimental investigations. The latter is further subdivided under four heads as follows:-

First; A series of complete performance tests,

Second; Hunting investigations,

Third; Variation of starting torque with field excitation,

and, Fourth; Determination of wave forms by means of the oscillograph.

In preparing the theoretical treatment of the subject we were guided to a certain extent by similar treatments in the various references found in the bibliography. In the performance of the experimental part we

received many valuable suggestions from Associate Professor John Edwin Snow, and Assistant Professor Ernest Harrison Freeman, both of the department of Electrical Engineering of the Institute.

FUNDAMENTAL CONCEPTION.

When a certain conductor on the armature of an alternating current generator is under a north pole of the field the current in the said conductor will be in a direction such that the force which the field exerts upon the conductor will tend to oppose the motion of the armature, and when the conductor has moved so that it is under a south pole of the field magnet the current will have reversed so that the force on the conductor will still oppose the motion of the armature. If now, the alternating current generator be driven by an engine or motor and alternating current be supplied to the revolving armature, then the motion of the armature will be assisted by the A.C. if the following conditions are satisfied:-

1. If the speed of the armature is such that said conductor moves from the middle of a north pole to the middle of the adjacent south pole during the time of one alternation of the supply.

2. If the direction of the supplied alternating current is opposite to that which would ordinarily flow in the armature when delivering current as a generator.

This is evident when we note that the current is reversed every time a conductor passes from one pole to the next, and that this reversed current will be acted upon by the different polarity of the next pole with a force always in the direction of rotation. Therefore,

if conditions 1 and 2 are fulfilled the engine or motor can be disconnected and the armature of the motor will continue to revolve at a speed depending upon the frequency of the supply and power may be delivered from its shaft.

When an alternator is used in this way it is known as a synchronous motor. Any alternator may be used as a synchronous motor without alteration of any kind for they are identical both electrically and mechanically.

PART I.

THEORETICAL TREATMENT.

Representation of the Power taken by a Synchronous Motor.

Suppose we have two machines, A and B (see diagram, Fig. 1.), one (A) running as a generator and the other (B) running as a motor. Draw a circle with a radius equal to the e.m.f. generated by the alternator A and draw OC equal to the c.e.m.f. of the motor and in its proper phase relation to the generator e.m.f.

Since the resultant e.m.f. is the vector sum of these two e.m.f.s, a line, such as OT, drawn from O to any point T on the circumference of the circle will represent the resultant e.m.f. both in magnitude and phase relation. The current flowing in this circuit will have a value

$$I = \frac{E}{\sqrt{R^2 + w^2L^2}}$$

in which E is the resultant e.m.f., R is the total resistance of the circuit, L is the total inductance of the circuit, including that of both armatures, and w is the frequency of the current in radians per second, this being equal to ?f where f is the frequency in cycles per second. This current, on account of the inductance in the circuit, will lag the impressed e.m.f. by the angle θ, the tan-

gent of which is $\frac{wL}{R}$, in which expression the letters have the same significance as in the equation above. The line is now drawn through O making the angle θ with B and a perpendicular to it is drawn from T, intersecting it in the point S.

Let P represent the input to the machine B.

Then,
$$P = -BI\cos(\alpha - 180)$$
$$= BI\cos\alpha$$

Also,
$$OS = OT\cos\alpha = E\cos\alpha$$
$$= I\sqrt{R^2 + (wL)^2}\cos\alpha$$

Or,
$$I\cos\alpha = \frac{OS}{\sqrt{R^2 + (wL)^2}}$$

Therefore,
$$P = \frac{B\,(OS)}{\sqrt{R^2 + (wL)^2}}$$

Now, in any particular case, the only variable is the quantity OS. This indicates that the power taken by the motor B is proportional to the line OS. Since we have measured the line OS to the left of O, calling this direction positive, if T should rotate around past x or z in either direction, the quantity (OS) and consequently the power P would become negative. This would mean that the machine would no longer be running as a motor and drawing power from the line but would be running as a generator and giving power back into the line.

Suppose we have the motor running on very light load so that the current and the c.e.m.f. of B are nearly

in quadrature. Then the point T will be very near to x, OS being very small but positive. Now as a load is put upon the motor it will fall behind the generator in phase, T passing around the arc of the circle and OS steadily increasing until the point M is reached, which gives the maximum value of OS and consequently the maximum power input. If now, the load is still further increased, the power input will decrease until the point z is reached, after which the machine will act as a generator. The load of the motor combined with its generator load causes it to fall farther and farther behind the generator, no power being supplied to it from the time T passes the point z till it reaches x. Under the combined influences of these forces the rotor of the motor will fall out of synchronism and stop.

In the diagrams so far discussed it has been assumed that the motor operates on a constant potential circuit with constant field excitation, a condition which fixes the value of the armature current, power factor, etc. for any particular value of the load. This condition will probably not be found in any practical case. There are always two independent variables in the operation of the synchronous motor, the field current and the load or output. This fact is of great importance in the practical operation of the machine as will be pointed out in another part of this paper, for on account of this fact the motor

may be made to serve the double purpose of carrying a certain load and at the same time furnishing a wattless current to the line. This wattless current will affect the phase relation of current to e.m.f. in the entire system and thus may be used to improve an otherwise poor power factor and regulate the voltage to a considerable extent. Moreover this current may be made either leading or lagging, the former by over excitation of the fields and the latter by under excitation. Hence this method of regulation will apply equally well to all conditions of load on the line.

Since these factors are variable it will be well to have a vector diagram for studying the relation of the various quantities of the synchronous motor. In the diagram (Fig. 3) we will assume that the impressed e.m.f., load, and field excitation, or the corresponding counter e.m.f. are given and that it is required to find the other quantities.

First we may draw OE_1 (Fig. 3), representing in magnitude the counter e.m.f. of the motor. Then the line OE, equal and opposite to it will represent the e.m.f. consumed by this counter e.m.f. (e). Now let P_o= the mechanical output of the motor. Then i_1 = the energy component of the current taken by the motor = P_o/e. This may be represented by the line OI_1, in phase with e. Since this is the projection of the current vector

upon the line OE, the current vector must terminate on a line such as i, perpendicular to OI_1. Now let r = the resistance and x = the reactance of the circuit between (e) counter e.m.f. and (e_o) impressed e.m.f. Then a line such as OE_r also in phase with e will represent $i_1 r$ = the e,m.f. consumed by the resistance, and OE_x in quadrature with this will represent $i_1 x$ = the e.m.f. consumed in the reactance of the energy current i_1. The resultant of these two components, which is OE_1' represents the e.m.f. consumed in the impedance of the energy component of the current i_1. Since this is a projection of the impedance voltage of the total current (e'), the vector representing e' must terminate in a line perpendicular to OE_1' through E_1', such as e". From the construction of the figure if we swing an arc from the point E_1 as center and radius equal to the impressed e.m.f. (e_o), the point of intersection of this arc with the line e" will locate the point E' such that when joined to the point O, OE' will represent the impedance voltage of the total current. Now we have the component of the impressed e.m.f. (e_o) absorbed by the counter e.m.f.(OE) and the component absorbed by the impedance (OE'), which gives the resultant OE_o, representing the total impressed e.m.f. (e_o).

From a study of the diagram we readily see that it is fully determined if the three quantities, impressed (e_o), counter e.m.f. (e), and load(P_o) are given, and that from it the other quantities such as current (OI),

the components of the e.m.f. consumed by the impedance (OE_r) (OE_x), the power factor ($\cos\angle IOE_o$), etc. may be determined.

HUNTING.

Hunting is a term applied to the oscillatory motion often produced in synchronous machines, both motors and converters. This action may be produced in several different ways, the principal one of which is perhaps a variable load. Refer to Fig. 1 and suppose we have a certain load and field current such that the vector A assumes the position Ca, and the load is constant and the motor is running at a constant and uniform speed, that is it is not hunting. Now suppose that with the field current remaining constant the load is suddenly increased . A would need to rotate to the position Ca in order to give the necessary input to carry the increased load. Since the angle ϕ represents the angular displacement of the motor from the generator, the rotation of the vector A means an increase in the angular displacement or a slight momentary reduction in the speed of the motor. The rotor of the motor may be considered to be coupled to the generator through a magnetic coupling which is very elastic. Then, this being the case, the inertia of the rotor while being slowed down by the increasing load will tend to carry the vector A past the point d, thus increasing the power input above that necessary to carry the load. This increased input increases the torque and the motor falls back more nearly into phase with the generator, the inertia of the

rotor again carrying it past the point d so that the input is less than that necessary to carry the load. Then the speed of the motor is again decreased by the excessive load and the input again becomes too great. This action continues almost indefinitely in some cases and causes great trouble. All meters on the line are thrown into vibration by it and the load on the generator fluctuates in synchronism with the hunting, the effect on the line being known as surging. The current in the line especially fluctuates greatly and the counter e.m.f. varies widely.

Hunting may also be produced by the nonuniform speed of the driving engine. If it is a single expansion engine and the fly wheel is small the speed will increase when the steam is admitted to the cylinder and will decrease when cut off occurs, thus causing a sort of hunting action even in the engine which is transmitted through the intermediate apparatus to the motors.

Naturally this condition of operation is a very undesirable one and some method should be employed to prevent it as far as possible. One of the most common methods used on synchronous motors and converters is the use of "dampers" or " grids". These are heavy square frames of copper which are supported between the poles of the machine which act like short circuited coils, and the current induced in them by the variation in speed

reacts on the armature current in such a way as to tend to prevent this variation in speed.

If the machine is a motor and drives the load, the inertia introduced by the mass of the moving parts will tend to overcome this hunting. If the machine is a synchronous converter, the mass of the moving part is generally so small that a great deal of difficulty is experienced, but by the use of dampers and a heavy rotating part the trouble is minimized.

The tendency of a synchronous motor to hunt may be said to depend upon the three following conditions:-

First:- The amount of impedance in the circuit on the motor side of the line where the impressed pressure is maintained constant.

Second:- The ratio of reactance to resistance in the impedance referred to above.

Third:- The excitation of the motor field relatively to that of the generator.

PRACTICAL USES OF THE SYNCHRONOUS MOTOR.

In addition to the foregoing theoretical treatment it is desired to present, with more or less detail, the field of usefulness of the synchronous motor and to discuss the conditions which limit this field. It is evident that such a motor can not be used where variable speed is desired for the synchronous motor, as the title indicates, must run in synchronism with the generator supplying the power, that is the cyclic speed of the motor must be the same as that of the generator.

It is a well known fact that in a synchronous motor which is operating without load, the armature current can be varied by varying the field strength. A certain value of field excitation will give the minimum armature current, and any increase or decrease in the field excitation will cause an increase in the armature current, this increase being, to a great extent, wattless. The field excitation which produces this minimum armature current is known as normal field excitation.

In connection with variable field excitation, it is found that the armature current will lag the applied e.m.f. and lead the counter e.m.f. if the field excitation be below the normal value. Similarly, if the field excitation be above the normal value, the armature current will lead the applied e.m.f. and lag the counter e.m.f. A synchronous motor has therefore an inherent ten-

dency to correct for any conditions set up by improper adjustment of the field current. This tendency also has a correcting effect on the supply system, since the correcting currents are drawn from the line and tend to equalize the counter e.m.f. and the applied e.m.f. On account of this characteristic the synchronous motor may be used either to restore the power factor in a system or to secure good voltage regulation. The application of the motor for the former of these two purposes may be seen in the case where transformers are in circuit. The effect of the transformers would naturally be to produce a lagging current in the system, but by placing a synchronous motor in the circuit and over exciting its fields we may overcome the effect of the transformers to any desired extent and may even produce a leading current in the system. When a synchronous motor is thus used to restore the power factor in an inductive receiving circuit, it is often called a rotary condenser or a synchronous compensator, and it is found possible by this means to vary the power factor through a wide range, depending upon the location and current carrying capacity of the motor.

It is also evident, from what has been said above, that if the counter e.m.f. be held constant and the applied e.m.f. be varied, a leading or a lagging current may be made to flow in the armature. For example if the applied e.m.f. be dropped below the counter e.m.f.

the current will lag the counter e.m.f. and thus tend to demagnetize the motor field while at the same time it will lead the applied e.m.f. and thus tend to magnetize the generator fields. Similarly, if the applied e.m.f. be greater than the counter e.m.f. the tendency will be to magnetize the motor field and demagnetize the generator fields. The result is to equalize the applied e.m.f. or line e.m.f. and the counter e.m.f., and thus keep the pressure constant. The motor best adapted for use in voltage regulation is thus seen to be the one in which a small change in applied pressure will cause a large change in the value of the leading or lagging current.

The synchronous motor is especially useful in controlling the voltage at the end of a long transmission line which supplies induction motors and transformers. It is, of course, desirable to maintain a constant voltage independant of change of load or power factor. It is also desirable in all cases where practicable, to have the line current as small as possible, or in other words to have the highest possible power factor, thus reducing the line loss to a minimum. In such a case the increased output may more than compensate for the first cost of the synchronous motor. In general, the more current such a motor will give on short circuit, the better adapted it will be for use in regulating voltage and power factor. Any given synchronous motor, when used as a synchronous compensator, is most effective when operating at no load.

When a number of synchronous motors are installed in a power station, it is necessary to have very accurate field adjustment in order to avoid cross currents between the machines, and the saturation characteristics of the different machines should be as nearly as possible identical. It has been found that a synchronous motor can be used more economically when operating both as a regulator and as a motor, than when used as a regulator alone.

The vector diagrams in figures a and b show how it is possible for a synchronous motor to give a leading current to the system. Suppose we have a certain load and field current such that the vectors are in the phase relation shown in the diagram. If the field current is increased, the torque will be increased and the e.m.f.s A and B will be more nearly in opposition so that the point T will rotate toward the point x. When OT has rotated till it coincides with ef, the current and the counter e.m.f. are in opposition so that the current and the e.m.f. are in phase. If the field current is increased still more, the generator e.m.f. and the motor e.m.f. will fall more and more nearly into phase and the current vector will lead the e.m.f. vector.

SUMMARY OF PRECEDING STATEMENTS.

1. A synchronous motor can be used to establish leading or lagging currents in a system by changing the field excitation, and can thus be used to control the power factor or the phase relation of the e.m.f. and the current.

2. By keeping the field strength constant and varying the pressure of the supply system above or below the counter e.m.f. of the motor, leading or lagging currents may be produced in the supply system, thus regulating the voltage.

3. Such regulating action is most marked in those machines which have the closest true inherent regulation.

4. If the synchronous motor is used both for regulating the power factor and for voltage regulation, its normal regulating capacity will be diminished.

5. If the synchronous motor can be used both for regulation purposes and for power transmission, its apparent capacity will be increased.

PRACTICAL APPLICATIONS OF THE SYNCHRONOUS MOTOR IN CENTRAL STATION WORK.

There are several applications to which the synchronous motor may be put in central station work, for this appears to present the broadest field of usefulness for these motors.

In the Farady Street Station of the Worcester (Mass.) Electric Light Company's plant the dynamo equipment, which was installed a number of years ago, consisted of several belt driven generators which were all driven from an extensive line shaft placed in the basement of the building. Later, when changes were made, there was a 500 K.W., 2300 volt, General Electric, revolving field type alternator mounted upon this line shaft and used either as a synchronous motor or as a generator. Brush arc machines and a 250 K.W., 3-phase, 60 cycle, alternator for incandescent lighting, in addition to the direct current machinery for power purposes, are now driven from this shaft. 2000 K.W. in direct connected alternators were later installed. This arrangement is very flexible for if either of the alternators breaks down, or if either of their engines go wrong, the synchronous motor can be operated as a generator to help carry the load. If one of the three engines used to drive the line shafting becomes damaged, the motor can be used to help the operation of the power machines, power being supplied to the motor from the alternators.

Another important use of synchronous motors on a large scale is in the case where it is desirable to drive arc machines by motors instead of by line shafting, energy being furnished to the motors by engine driven alternators. Such a scheme as this is used in the L Street Station of the Boston Edison Company. The sets, of which there are twenty four, consist of one 150 K.W. motor direct connected to two Brush arc machines of 8500 volts and 6.6 amperes capacity, operating at a speed of 514 r.p.m. These synchronous motors take their current direct from the 2250 volt bus bars. By this arrangement the power factor of the system is readily controlled with a consequent increase in the capacity of the station.

In the Buffalo (New York) Substation of the Niagara Falls Power Company, it is said that, since the synchronous motor-generator sets have been installed, the power factor has been raised from a value of about .65 to a value nearly unity. These synchronous motors act both as regulators and as power machines.

PART II. SECTION I.

Performance Tests.

The complete performance of the motor was ascertained by a series of brake tests. The motor was operated on both two and three phase current, the power delivered being absorbed by a prony brake. The electrical connections for three phase operation were made as shown in wiring diagram (Fig. 4.) and those for two phase operation were made as shown in diagram (Fig. 5.). Both of these diagrams are very simple as they show only the main switch and switches for transferring the instrument connections from phase to phase. In the three phase system the power delivered to the motor was measured by the two wattmeter method; that is, the wattmeter had its pressure lead permanently connected to one line and the series coil was alternately placed in each of the others. The sum of the two wattmeter readings is the total power of the circuit. In the two phase system the power was measured by the two wattmeter system also, but here the instrument was transferred alternately into each of the two phases, each phase being treated as an entirely separate single phase circuit. Here also the total power of the system is the sum of the two wattmeter readings. The ammeter and voltmeter were so connected as to be transferred with the wattmeter. Besides the connections shown in these diagrams was the field circuit of the motor.

which contained the field ammeter and a series of rheostats for fine regulation of field current.

The brake tests were conducted as follows:- The field current was adjusted to some value and the amm meter, voltmeter, and wattmeter readings taken with the brake set loose. The brake was then set more tightly, the field current being the same, and the meter readings repeated. In this manner readings were taken until the motor was stopped by overload or the capacity of the supplying rotary was exceeded. Such series of readings were taken with various field currents within the limits allowed by the heating of the motor.

Since the motor was of small size the pressure of the supply was not reduced in starting, the motor armature being connected directly to the mains with open field circuit. When connected in this way it starts as an induction motor, currents being induced in the field poles which react on the armature current and produce the starting torque. In this way the motor may be brought up nearly to synchronous speed under no load, it coming up to synchronous spedd when the field is supplied with current.

Curves showing the relation between horse power output and efficiency, and horse power output and power factor are platted on the following pages. From the efficiency curves for three phase we note the highest efficiency at three amperes field current. Now turning to the power factor curves we also note that the power factor

is highest with three amperes field current, this field excitation giving almost unity power factor. Now, as the field excitation is increased, the efficiency and power factor drop off, showing that that which was a lagging current at first has on stronger field excitation become a leading current.

On observation of the power factor and efficiency curves for this motor operated on two phase supply we note again that three amperes field current gives the highest efficiency and power factor and, as before, lesser or greater field excitation will give lower power factor and efficiency, due to lagging or leading currents produced in the armature.

In the general comparison of the two sets of curves of the motor operated from two and three phase supply it is readily seen that under the same conditions of operation, the two phase supply gives the better efficiency but higher power factors are obtained on three phase.

--* 2-PHASE BRAKE TEST *--

Field current = 3 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	4.66	74.5	9.0	1340	610	6.98
2	9.66	73.5	10.4	1530	1100	14.50
3	14.66	73.5	12.1	1780	1580	21.95
4	19.66	72.9	15.7	2290	2110	29.50
5	24.66	73.0	19.2	2800	2710	36.95
6	29.66	72.5	22.4	3250	3020	44.40
7	34.66	71.9	26.5	3810	3500	51.90
8	39.66	70.7	31.4	4430	4120	59.55
9	44.66	71.5	37.6	5370	4920	67.00
10	49.66	70.0	44.2	6180	5500	74.40

#,	Watts. input.	HORSE Output.	POWER. Input.	Cos.θ.	E F F I C I E N C Y. True.	Apparent.
1	940	.66	1.26	.456	52.4	23.9
2	1430	1.38	1.92	.718	71.8	51.4
3	1910	2.09	2.56	.888	81.6	72.4
4	2440	2.80	3.27	.922	85.8	79.2
5	3040	3.52	4.08	.968	86.3	83.6
6	3350	4.23	4.49	.930	94.2	87.5
7	3830	4.94	5.13	.918	96.4	88.5
8	4450	5.65	5.97	.929	94.6	87.8
9	5250	6.37	7.04	.917	90.4	82.9
10	5830	7.08	7.82	.891	90.5	80.6

S-W&K

--* 2-PHASE BRAKE TEST *--

Field current = 4 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	19.66	74.4	19.0	2810	2200	29.50
2	24.66	74.0	22.2	3290	2780	36.95
3	29.66	73.4	25.2	3700	3270	44.40
4	34.66	73.0	28.2	4120	3770	51.90
5	39.66	72.0	31.9	4590	4320	59.55
6	44.66	72.0	36.1	5190	5060	67.00
7	49.66	71.5	41.7	5960	5720	74.40
8	54.66	71.0	45.6	6480	6340	82.00

#.	Watts input.	HORSE POWER. Output.	Input.	Cos. θ.	E F F I C I E N C Y. True.	Apparent.
1	2640	2.80	3.54	.783	79.1	61.9
2	3220	3.52	4.32	.845	81.5	68.8
3	3710	4.23	4.98	.884	84.9	75.1
4	4210	4.94	5.65	.917	87.5	80.2
5	4760	5.65	6.38	.921	88.5	81.5
6	5500	6.37	7.38	.975	86.3	84.1
7	6160	7.08	8.26	.961	85.8	82.5
8	6780	7.79	9.09	.977	85.7	83.6

S-W-K

--* 2-PHASE BRAKE TEST *--

Field current = 5 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	29.66	74.5	30.6	4560	3260	44.50
2	34.66	74.5	32.7	4870	3710	52.0
3	39.66	74.0	35.4	5230	4320	59.4
4	44.66	73.5	37.6	5530	4800	66.9
5	49.66	73.4	41.4	6080	5360	74.5
6	54.66	72.6	44.5	6460	5910	82.0
7	59.66	72.2	48.2	6940	6510	89.5
8	64.66	72.0	51.2	7370	7040	97.0

#.	Watts input.	HORSE POWER. Output.	Input.	Cos.θ.	E F F I C I E N C Y. True.	Apparent.
1	3810	4.23	5.12	.716	82.7	59.2
2	4260	4.94	5.70	.762	86.7	66.0
3	4870	5.66	6.52	.827	86.8	71.8
4	5350	6.36	7.18	.868	88.7	76.9
5	5910	7.08	7.92	.881	89.4	78.7
6	6460	7.79	8.66	.916	90.0	82.5
7	7060	8.50	9.47	.938	89.8	84.3
8	7590	9.22	10.18	.956	90.6	86.6

S-W-K

--* 3-PHASE BRAKE TEST *--

Field current = 2 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	4.66	62.7	25.3	2740	790	6.98
2	9.66	62.3	26.8	2880	1300	14.50
3	14.66	62.0	28.7	3080	1850	21.95
4	19.66	61.5	32.2	3430	2420	29.50
5	24.66	61.1	36.8	3890	3040	36.95
6	29.66	60.6	42.7	4480	3660	44.40
7	34.66	60.0	50.1	5200	4330	51.90
8	39.66	59.5	60.3	6210	5110	59.40

#.	Watts input.	HORSE POWER. Output.	Input.	Cos.θ.	E F F I C I E N C Y. True.	Apparent.
1	1010	.66	1.35	.288	48.9	14.1
2	1520	1.38	2.04	.452	67.7	30.6
3	2070	2.09	2.78	.600	75.2	45.1
4	2650	2.80	3.55	.708	78.9	55.8
5	3260	3.51	4.37	.780	80.4	62.7
6	3880	4.23	5.20	.818	81.4	66.6
7	4550	4.94	6.10	.834	81.1	67.6
8	5330	5.65	7.15	.824	79.0	65.1

S-W-K

--* 3-PHASE BRAKE TEST *--

Field current = 3 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	14.66	61.0	16.3	1725	1625	21.95
2	19.66	60.4	21.3	2230	2155	29.48
3	24.66	59.8	27.2	2820	2760	37.00
4	29.66	59.8	32.3	3340	3310	44.50
5	34.66	59.0	38.6	3940	3900	52.00
6	39.66	58.2	45.8	4610	4520	59.55
7	44.66	58.0	53.5	5370	5190	67.00
8	49.66	57.5	63.7	6340	6080	74.40

#.	WATTS input.	HORSE POWER. Output.	Input.	Cos. θ.	E F F I C I E N C Y. True.	Apparent.
1	1955	2.09	2.62	.942	79.8	75.2
2	2485	2.80	3.32	.967	84.4	81.6
3	3090	3.51	4.14	.980	84.9	83.2
4	3640	4.23	4.88	.990	86.6	85.7
5	4230	4.94	5.68	.990	87.0	86.1
6	4850	5.65	6.50	.980	87.0	85.2
7	5520	6.37	7.41	.968	85.9	83.2
8	6410	7.08	8.59	.958	82.4	79.0

S-W-K

--* 3-PHASE BRAKE TEST *--

Field current = 4 amperes.

#.	Corrected scale.	Volts.	Amperes.	- W A T T S - Apparent.	True.	Torque.
1	19.66	62.0	27.4	2940	2210	29.50
2	24.66	61.5	29.7	3160	2750	37.00
3	29.66	61.0	34.1	3600	3310	44.50
4	34.66	60.5	39.1	4090	3830	52.00
5	39.66	60.2	44.3	4620	4500	59.50
6	44.66	59.2	50.2	5180	5100	67.00
7	49.66	59.0	56.4	5760	5690	74.50
8	54.66	58.4	61.2	6190	6150	82.00
9	59.66	57.6	69.6	6930	6870	89.50
10	64.66	57.2	77.9	7710	7630	97.00

#.	Watts input.	HORSE POWER. Output.	Input.	Cos.θ.	E F F I C I E N C Y. True.	Apparent.
1	2650	2.81	3.56	.752	79.0	59.4
2	3190	3.52	4.28	.871	82.2	71.6
3	3750	4.24	5.03	.920	84.4	77.6
4	4320	4.95	5.80	.948	85.3	80.9
5	4940	5.67	6.64	.975	85.4	83.3
6	5540	6.38	7.44	.935	85.8	84.5
7	6130	7.10	8.23	.990	86.2	85.3
8	6590	7.81	8.84	.993	88.3	87.6
9	7310	8.53	9.82	.992	86.9	86.2
10	8070	9.24	10.83	.990	85.2	84.3

S-W-K

--* 3-PHASE BRAKE TEST *--

Field current = 5 amperes.

#	Corrected scale.	Volts.	Amperes.	— WATTS — Apparent.	True.	Torque.
1	29.66	61.4	46.6	4950	3520	44.50
2	34.66	61.0	50.6	5350	4130	52.00
3	39.66	60.0	55.4	5750	4770	59.40
4	44.66	60.1	59.2	6150	5490	66.90
5	49.66	59.2	63.8	6530	6110	74.50
6	54.66	59.0	68.7	7020	6770	82.00
7	59.66	58.2	74.0	7450	7340	89.50
8	64.66	56.5	80.7	7880	7800	97.00
9	69.66	57.5	85.2	8480	8370	104.50

#	Watts input.	HORSE POWER. Output.	Input.	Cos. θ.	EFFICIENCY. True.	Apparent.
1	4070	4.23	5.46	.711	77.7	55.2
2	4680	4.94	6.28	.774	78.8	61.0
3	5320	5.66	7.14	.830	79.3	65.8
4	6040	6.36	8.11	.893	78.4	70.0
5	6660	7.08	8.94	.935	79.3	74.1
6	7320	7.79	9.83	.965	79.3	76.5
7	7890	8.50	10.59	.985	80.3	79.0
8	8350	9.22	11.20	.990	82.3	81.5
9	8920	9.92	11.96	.986	83.0	81.8

S-W-K

PART II. SECTION. II.

Hunting.

We found, in the course of our experimenting, that on light loads and heavy field currents, the synchronous motor was subject to hunting to a greater or less extent. We therefore conducted a series of experiments with various loads and field currents to ascertain quantitatively the extent of this hunting.

Our first difficulty lay in finding a method of proceedure and an apparatus which would give us fairly accurate results. After experimenting for some time with various pieces of apparatus, most of which were of our own design, we finally decided to use the apparatus shown in diagram on the following plate. One part of the apparatus consisted of a circular disc of thin soft wood, the face of which was covered with white pasteboard marked with black india ink in the manner shown on the diagram. This disc had a diameter of about fifteen inches and was fixed rigidly to the motor shaft by means of a tap bolt so that it would rotate with the motor shaft. The other part of the apparatus consisted of a piece of cardboard which was held in a fixed position as shown, by a wooden support. Its lower edge was cut along the circumference of a circle 14.5 inches in diameter, and the card card was then adjusted to set about half an inch inside of the edge of the rotating disc. This card was

divided into quarter inches, half inches, and inches, beginning with a central line which corresponded to a v vertical radius. This, of course, could have been divided into degrees so as to read directly and thus simplify the use of the apparatus somewhat. In connection with this apparatus we also used a tuning fork which had a frequency of 100 vibrations per second. This fork was especially designed with overlapping prongs, both of which were slotted so that a beam of light could pass through the slot when the fork was at rest, though it would be intercepted when the prongs were vibrating.

Since the rotating disc was marked with twelve black lines spaced at equal angles, and since the synchronous speed of the motor when operating on 25 cycle supply is 500 r.p.m., it is evident that these lines will pass any given point at the edge of the disc at the rate of six thousand per minute or one hundred per second, providing the motor is running at synchronous speed. If, then, one looks at the rotating disc through the slot in the tuning fork while the latter is vibrating, since the slot is opened and closed alternately one hundred times per second, the lines on the rotating disc will appear to stand still, for each line will have advanced to the position previously occupied by the one ahead of it during the time the slot remains closed. Again, if the motor is running above synchronous speed, any given line will advance, during the interval of interruption, to a position slightly in advance of that previously occupied by

the one ahead of it, and the lines on the disc will appear to rotate in the same direction as the motor. Similarly, if the motor runs below synchronous speed, the lines will appear to rotate in a direction opposite to that of the motor.

It is evident from the foregoing that if the motor is hunting, that is moving alternately above and below synchronous speed, these lines will appear to swing back and forth through some definite angle. Moreover, this angle will be a direct measure of the variation in speed. It will therefore be a measure of the phase displacement between the motor and the generator, and since the rotor swings both ways from the position of no angular displacement, the maximum angle of this swing will indicate twice the change in phase relation between the motor and generator.

The results of our tests are shown quite plainly by the following curve sheets. The hunting increased very rapidly with an increase of field excitation and was far greater when operating on three phase supply than when operating on two phase supply, the latter practically eliminating the trouble except on very light loads. When the motor was operating from three phase supply at no load the surging in the line became so bad at times as to release a circuit breaker in the direct current side of the supplying rotary while set at 130 amperes.

--* HUNTING INVESTIGATIONS *--

- TWO PHASE -

I_f.	Corrected scale.	# ' Torque.	Angle of variation.
4	4.66	6.98	.9
	9.66	14.50	Very small.
5	4.66	6.98	17.6
	9.66	14.50	14.4
	14.66	21.95	9.8
	19.66	29.50	5.9
	24.66	36.95	3.0
	29.66	44.40	Very small.

S-W-K

--* HUNTING INVESTIGATIONS *--

- THREE PHASE -

I_f.	Corrected scale.	# ' Torque.	Angle of variation.
3	4.66	6.98	.98
	7.16	10.74	1.95
	9.66	14.50	2.40
	12.16	18.24	.98
	14.66	22.00	0.00
4	4.66	6.98	15.7
	9.66	14.50	11.8
	14.66	22.00	6.8
	19.66	29.50	1.9
	24.66	37.00	Very small.
	29.66	44.45	0.0
5	4.66	6.98	29.4
	9.66	14.50	26.4
	14.66	22.00	23.5
	19.66	29.50	19.6
	24.66	37.00	13.7
	29.66	44.45	5.9
	34.66	52.00	1.9
	39.66	59.50	0.0

S-W-K

PART II. SECTION III.

Variation of Starting Torque With Field Excitation.

We conducted some experiments in order to determine whether or not it was possible to obtain a greater starting torque with a certain amount of field excitation than was obtained with the field on open circuit. In making these tests the rotor of the motor was clamped by means of the prony brake and the stator connected directly to the line, the frequency and voltage of which was kept constant. First the torque was measured with the field on open circuit, which is the customary condition of starting. In view of the fact that the fields are wound with a great many more turns of wire than are the armature coils, and that the armature is held stationary by the brake, there is a direct transformer action between the stator and the rotor which induces in the field coils a very high e.m.f. As long as the field circuit is broken the only effect of this e.m.f. is to strain the insulation of the coils, but in order to introduce a current into the fields it becomes necessary to close the field circuit, thus forming a path through which the current will be forced by this pressure. This current will have the same frequency as the supply and its value will be determined by the resistance and inductance in the circuit. We found that ten 110 volt incandescent lamps in series and in series with the field were lighted to

almost normal brightness.

The field circuit in this case, carries a direct current ranging from one hundredth to twenty five hundredths of an ampere and, superimposed on this, an alternating current of from one half to three amperes. The alternating current in the fields has no effect on the starting torque since it does not aid in magnetizing the poles and its reaction on the stator current is in a direction exactly through the center of the rotor shaft. This current, then, is to be neglected and only the direct current measured. This was done by means of a direct current ammeter of the Weston type, which reads the effective magnetizing value of the current.

We adjusted the direct current in the fields to the desired value by means of sets of ten incandescent lamps in series which could be placed in parallel with each other, thus reducing the resistance of the circuit. In this manner we determined the starting torque with the various field currents indicated on the accompanying data sheet.

Our results would seem to indicate that there is a certain small field current which gives the greatest starting torque. For three phase operation this field current is about .159 amperes, and for two phase it is about .124 amperes.

The small increase in starting torque together with the difficulty and danger which would be experienced in attempting this method of starting makes it highly

impractical. As stated before, the e.m.f. induced in the fields is so high at starting that the external apparatus necessary to the practical adoption of this method would be a constant source of danger. Also the amount of resistance necessary to keep the induced alternating field current within safe bounds and to secure the proper value of direct current would ordinarily be quite large, cumbersome, and expensive. It would probably never be found an economical investment.

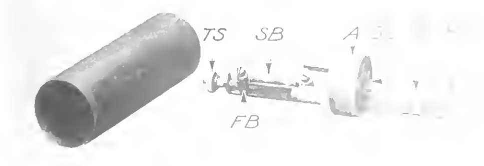
VARIATION OF STARTING TORQUE WITH FIELD CURRENT.

(a) Two Phase -

Field Amperes.	# Scale.	#' Torque.
.1925	32.0	32.4
.1600	32.0	32.4
.1250	32.9	33.8
.0750	32.8	33.6
.0400	32.7	33.5
.0000	32.0	32.4

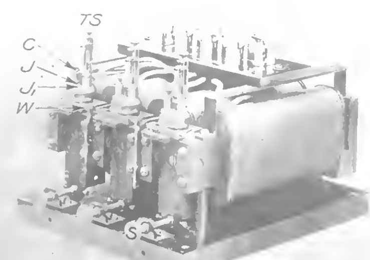
(b) Three Phase -

.2300	48.2	56.7
.1925	48.8	57.7
.1600	49.2	58.3
.1250	48.4	57.0
.0750	47.6	54.3
.0450	47.0	53.4
.0000	45.6	52.8



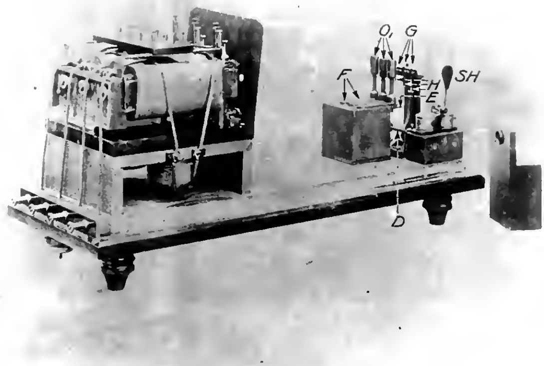
302103 TYPE EM, FORM B, [illegible]

Figure (a).



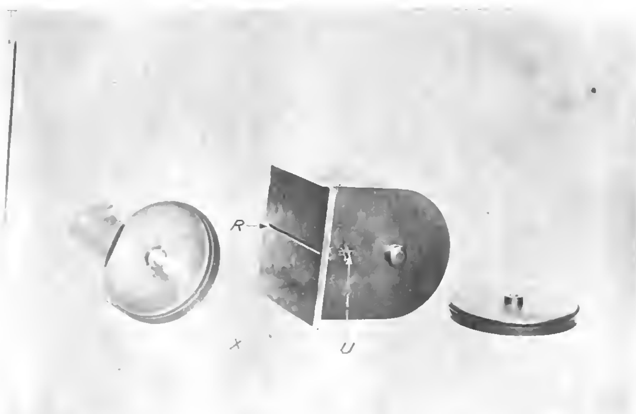
[illegible] TYPE EM, FORM B [illegible]

Figure (b).



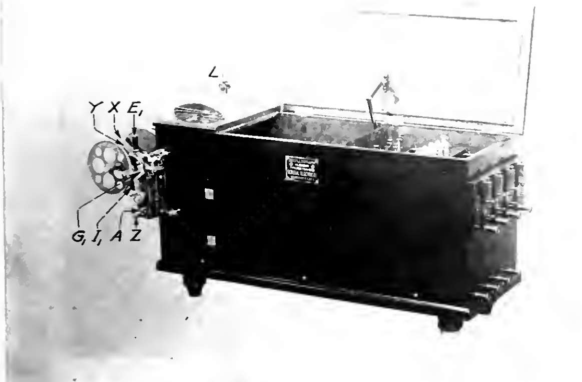
302104. TYPE EM, FORM B, OSCILLOGRAPH SHOWING INTERNAL ARRANGEMENT.

Figure (c).



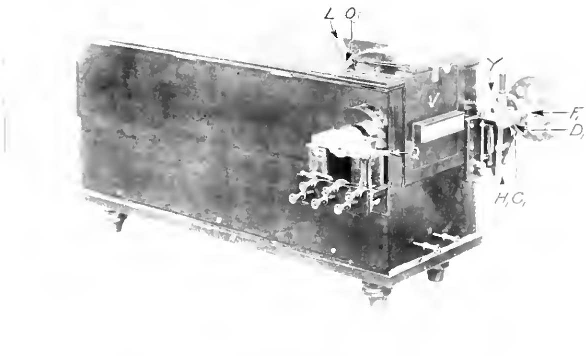
302102 TYPE EM, FORM B, OSCILLOGRAPH - FILM HOLDER FOR PHOTOGRAPHIC ATTACHMENT.

Figure (d).



302104 TYPE EM, FORM B, OSCILLOGRAPH SHOWING PHOTOGRAPHIC AND TRACING ATTACHMENTS.

Figure (e).



TYPE EM, FORM B, OSCILLOGRAPH - SHOWING PHOTOGRAPHIC AND TRACING ATTACHMENTS.

Figure (f).

PART II. SECTION IV.

Determination of Wave Forms by means of the Oscillograph.

In order to make a complete study of the forms and phase relations of the various current and e.m.f. waves we made use of the oscillograph. This piece of apparatus is made by the General Electric Company and operates on the reflecting galvanometer principle.

One of the very small reflecting galvanometers is shown in figure (a) of the following plates. A strand of very fine silver ribbon is seen issuing from the orifice in the center of the cylinder A, passing over the insulating bridges B and B_1 to the pulley P, thence passing back parallel to and very near the first strand. This strand forms the one-loop coil constituting the moving part of the galvanometer and supporting the small mirror seen between the insulating bridges B and B_1, whose object it is to reflect the beam of light. This moving system is so light as to be able to vibrate at a natural period of six thousand oscillations per second. In order to steady its motion the system is immersed in a damping liquid of castor oil.

A set of these galvanometers are built together as shown in figure (b). Here also are shown the large field coils which are excited from a 110 volt circuit and furnish the strong magnetic field in which the galvanometer coils operate. Figure (c) shows the complete

internal arrangement of the apparatus. SH is an electrically operated shutter which intercepts the beam of light when making photographs, but for visual work this is drawn aside and the beam allowed to pass to the three prisms located at G. From these the light is refracted through the slits O_1 to the galvanometers located at the left of the view. After reflection the beam passes back and may be photographed on a revolving sensitized film or it may be reflected upward by means of a synchronous mirror, which is a mirror supported at either end and given a vibratory motion in synchronism with the current through the galvanometer by means of a small synchronous motor. The spot of light reflected from this mirror is caught on a celluloid screen above where it traces the wave form, the vibration of the reflecting galvanometer determining the ordinate at any point and the corresponding abscissa being determined by the position of the synchronous mirror. The sensitized film is wound on the drum shown in figure (d) which is made to rotate by means of a small motor. In this case the synchronous mirror is turned out of the path of the beam of light and the abscissa for any ordinate is determined by the position of the revolving cylinder.

Figures (e) and (f) show the complete instrument as it appears. The small visual and tracing attachment is shown on top at the end and the synchronous motor and apparatus for driving the photographic attachment are seen on one end, while the binding posts and fuses for

the various galvanometer circuits are on the other end of the case.

A current transformer was used for reducing the armature current so that it might be lead into the oscillograph galvanometers. Because of this the current in the armature and that in the galvanometer circuits were 180° out of phase, or in exact opposition (neglecting the mechanical imperfections of the transformer). Then all stator current curves as shown on the oscillograms must be turned upside down so that the negative values become positive and vice versa, in order to make comparisons with the other curves. This fact will not be mentioned in the following discussion but must be constantly borne in mind while studying the curves.

Oscillograms A, B, C, and D show the relation of field current, armature current, and impressed e.m.f. for two, three, four, and five amperes in the field respectively, the motor running on no load and operating from the three phase supply. Figure A shows the e.m.f. and armature current nearly in quadrature, the current lagging the e.m.f., and no hunting can be noticed. The field current is pulsating in all the oscillograms, due to the effect of the teeth on the stator. Figure B, taken on three amperes, shows a certain amount of hunting. The field current is not constant but fluctuates in value as shown by the rising and falling curve. Also the armature current is seen increasing and decreasing in value but the e.m.f. is more uniform. With the higher field

currents became so bad that it is impossible to determine the phase relation of the current and e.m.f. from the oscillograms.

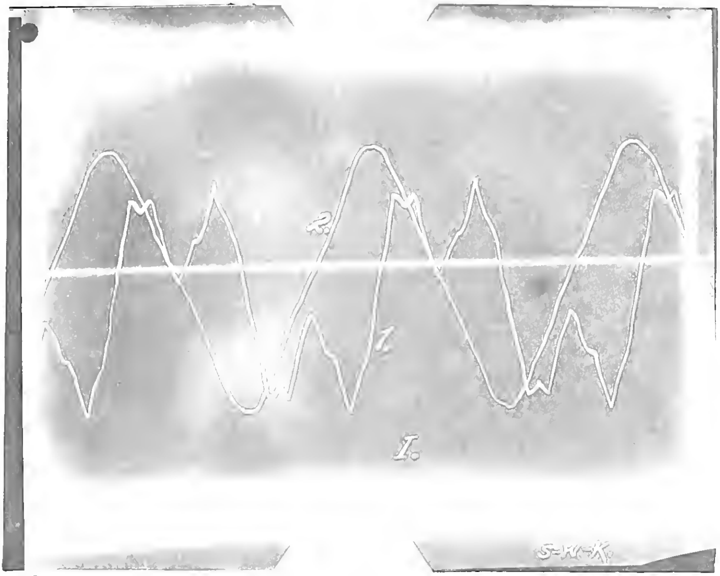
The next four oscillograms, E, F, G, and H form a set taken with a load represented by a torque of sixty pounds feet and field current of 2, 3, 4, and 5 amperes respectively. From these curves we can see the change in phase between the current and e.m.f. as the field excitation is increased, since hunting is almost entirely eliminated by the load. The first of these shows the current lagging greatly while, as we proceed through the series, it lags less and less till in the last we have a slightly leading current.

The next is a series of three sheets, I, J, and K, taken with no load on the motor while operating from the two phase supply. These oscillograms show only the applied and counter e.m.f.s for three field currents, .7, 2, and 4 amperes respectively. The two e.m.f.s remain constantly in quadrature but the counter e.m.f. changes from a depressed wave with the lowest excitation to a peaked wave with the highest excitation. The number of kinks in the counter e.m.f. wave correspond to the number of stator teeth covered by a rotor pole piece.

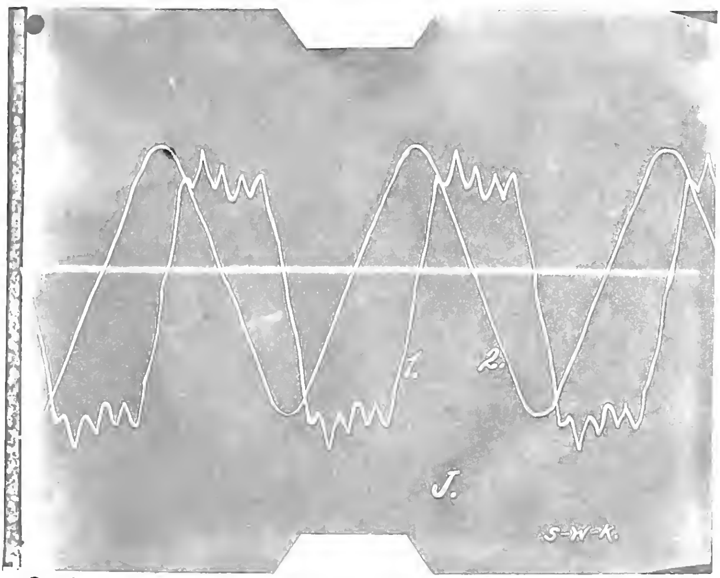
In order to more clearly show the effect of hunting, oscillogram M was taken. This, in combination with D, shows clearly how the current fluctuates in value and changes its phase relation with respect to the impressed

e.m.f., even shifting from a lagging to a leading current in oscillogram D. The fluctuations of the field current are also plainly shown by these figures.

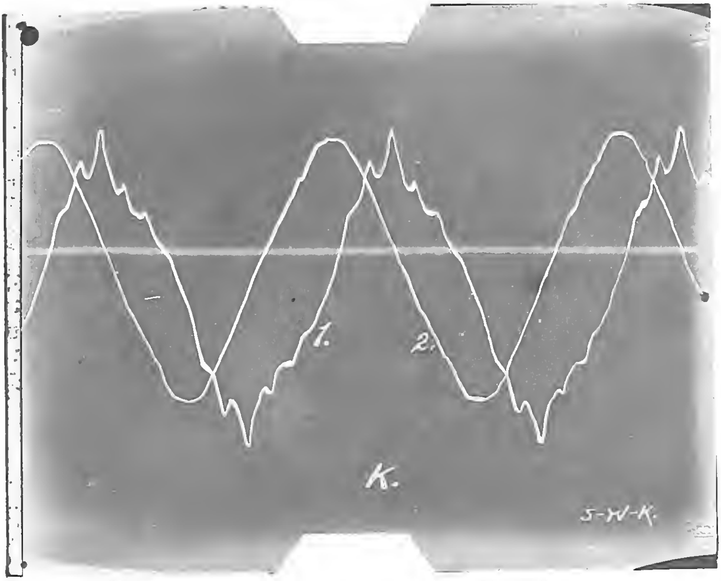
Having noticed a peculiar effect produced on the stator and rotor current wave forms by opening one line of the three phase supply we took oscillogram N to illustrate this. Where the stator current is a maximum the rotor current is a minimum, showing the depressing effect of the stator magnetism.



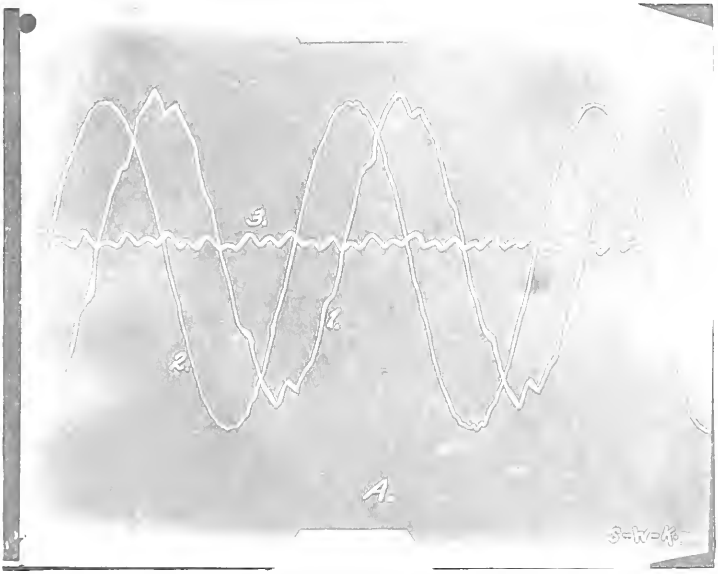
2-phase. I_f = .7 amperes. Load = 0.
1 = counter e.m.f.
2 = impressed e.m.f.



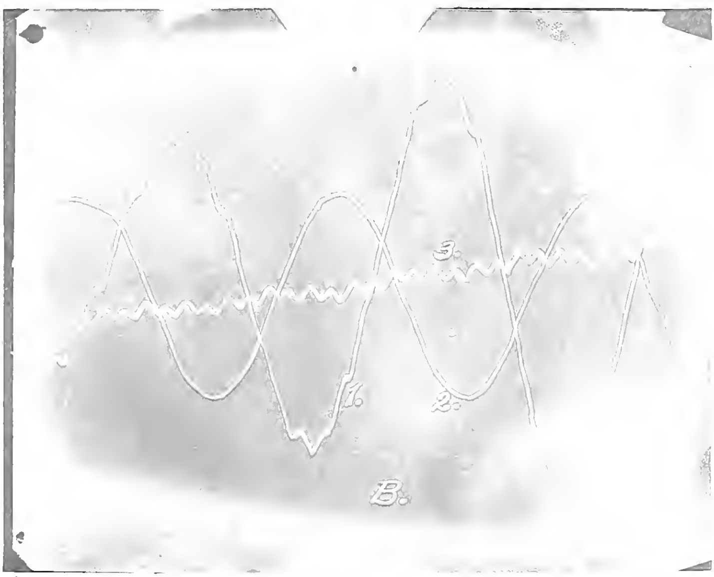
2-phase. I_f = 2 amperes. Load = 0.
1 = counter e.m.f.
2 = impressed e.m.f.



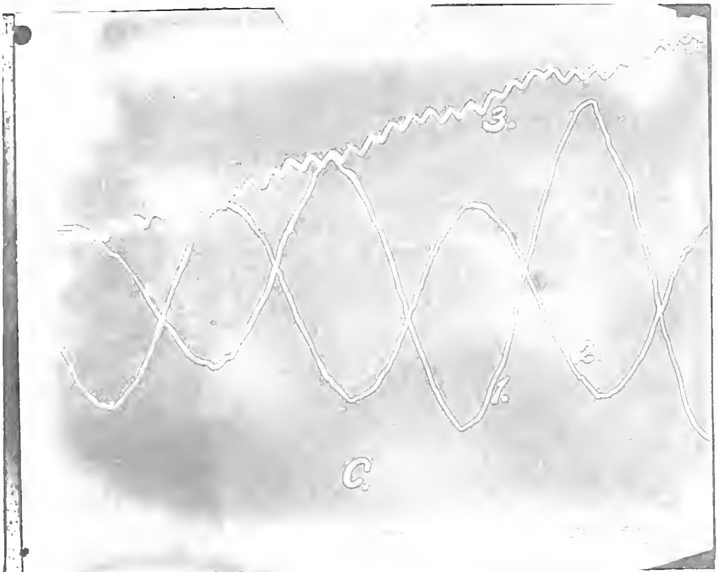
2-phase. I = 4 amperes. Load = 0.
f1 = counter e.m.f.
2 = impressed e.m.f.



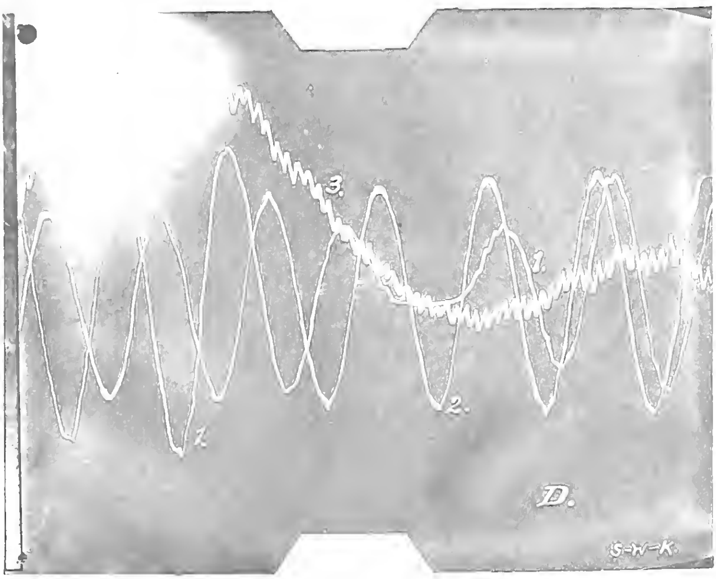
3-phase. I_f = 2 amperes. Load = 0.
1 = stator current.
2 = impressed e.m.f.
3 = rotor current.



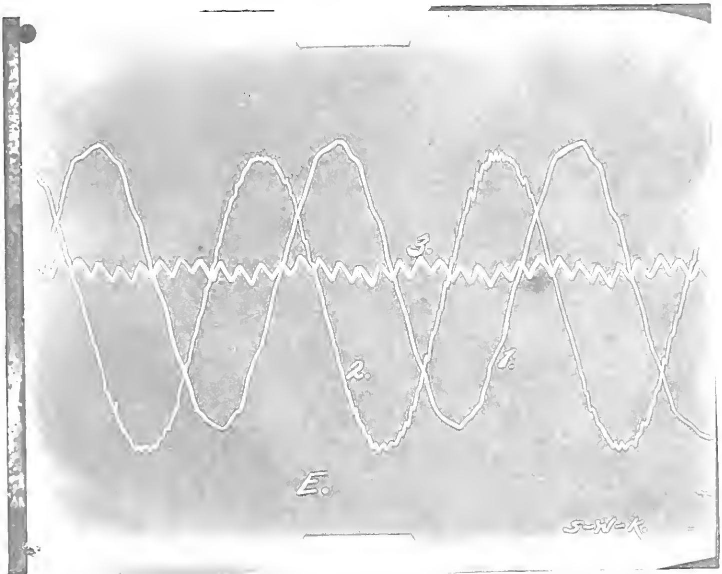
3-phase. I_f = 3 amperes. Load = 0.
1 = stator current.
2 = impressed e.m.f.
3 = rotor current.



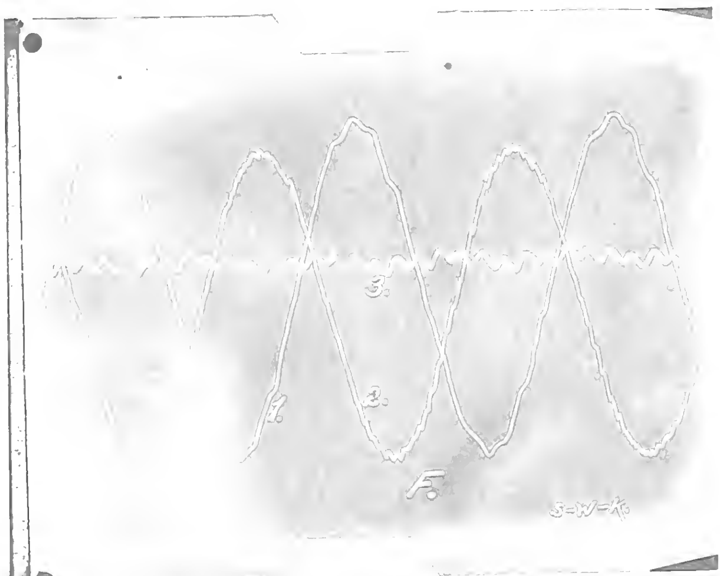
3-phase. I_f = 4 amperes. Load = 0.
1 = stator current.
2 = impressed e.m.f.
3 = rotor current.



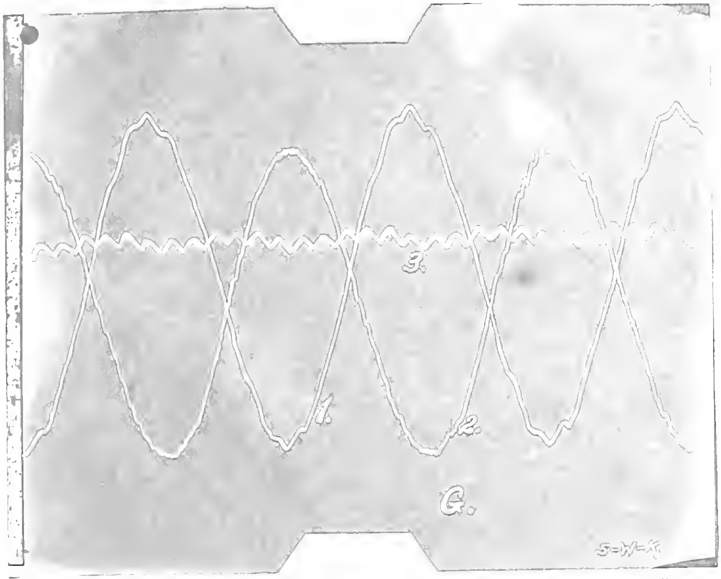
3-phase. I_f= 5 amperes. Load = 0.
1 = stator current.
2 = impressed e.m.g.
3 = rotor current.



3-phase. I_f = 2 amperes. Load = 50#'
1 = stator current.
2 = impressed e.m.f.
3 = rotor current.

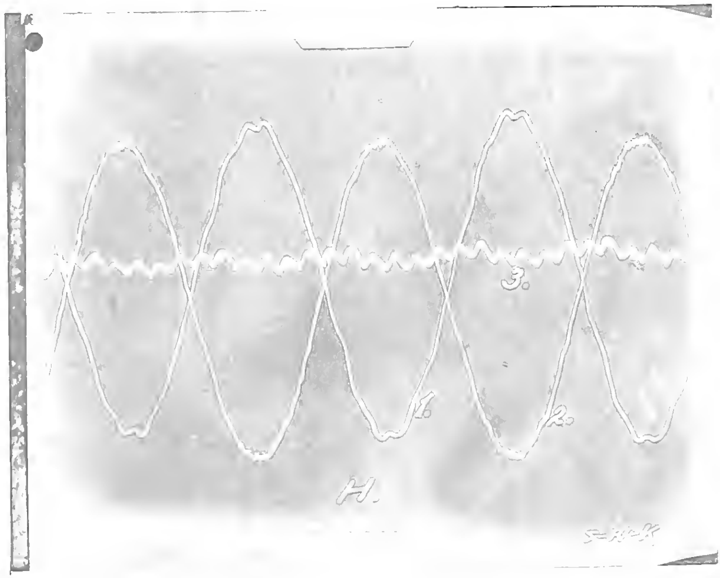


3-phase. I_f = 3 amperes. Load = 50#'
1 = stator current.
2 = impressed e.m.f.
3 = rotor current.



3-phase. I_f = 4 amperes. Load = 50#'

1 = stator current.
2 = impressed e.m.f.
3 = rotor current.



3-phase. I_f = 5 amperes. Load = 50#'

1 = stator current.
2 = impressed e.m.f.
3 = rotor current.

--* BIBLIOGRAPHY *--

The Synchronous Motor.

1. American Practice in Electric Motor Construction.
   H. S. Knowlton.
   AMER. ELECT. 15:20

2. Synchronous Motors in Central Stations.
   AMER. ELECT. 17:15

3. Principles of the Synchronous Motor.
   AMER. ELECT. 17:208

4. The Synchronous Motor - Phase Relations.
   AMER. ELECT. 17:265

5. A.C. Synchronous and Induction Motors. E. J. Berg.
   AMER. ELECT. 11:17

6. Method of Compounding A.C. Generators and Motors, D.C. Generators, and Synchronous Motor-Generators, and Converters. F. G. Baum.
   A. I. E. E. 19:745

7. Notes on the Theory of the Synchronous Motor.
   C. P. Steinmetz.
   A. I. E. E. 19:781

8. Synchronous Motors for Regulation of Power Factor and Line Pressure. B. G. Lamme.
   A. I. E. E. 23:481

9. Synchronous Converters and Motor-Generators.
   W. L. Waters.
   A. I. E. E. 24:717

10, The Induction Motor and the Rotary Converter and their Relation to the Transmission System.

ELECT. JOURNAL 2:86

11. Synchronous Motors.

ELECT. JOURNAL 2:115

12. Synchronous Motor Stability and Overload Capacity Curves.

ELECT. WORLD 39:XXX548 F. G. Baum.

13. Synchronous Motor Calculations. F. G. Baum.

ELECT. WORLD 39:861

14. Influence of the Line on Parallel Operation of Synchronous Motors.

ELECT. WORLD 43:1155

15. A Working Diagram of the A.C. Synchronous Motor. A. E. Kennelly.

ELECT. WORLD 45:195

16. The Synchronous Motor as Compensator in A.C. Distributions. E. J. Berg.

ELECT. WORLD 28:622

17. Troubles with Synchronous Motors.

ENGINEER (U.S.A.) 43:752

18. Tests on Synchronous Motors.

JOURNAL OF ELECTRICITY 15:380

19. Running of Synchronous Motors.

JOURNAL OF I. of E.E. 33:1144

20. Influence of Synchronous Motor Load upon Wave Form.

JOURNAL OF I. of E.E. 35:152

21. Electric Motors and their Applications. W. E. Reed.

ENGINEERS' SOCIETY OF WEST. PENN. 21:343

22. Electric Motors.

STEVENS INDICATOR 18:138

23. Division of Load Between Synchronous Motor-Generator Sets Obtained by Reactance.

WEST. ELECT. 35:60

24. Synchronous Motor Adapted for Railway Work.

WEST. ELECT. 35:132

25. Tesla Synchronous Motor, Patents Upheld.

WEST. ELECT. 36:172

26. Difference between Synchronous and Asynchronous Motors.

WEST. ELECT. 38:321

27. Device for Synchronizing Motors.

ELECT. REVIEW (N.Y.) 40:357

28. Synchronous A.C. Motor.

ELECT. REVIEW (N.Y.) 41:310

29. Churchward's Anti-hunting Device for Synchronous Motors and Rotary Converters.

ELECT. REVIEW (N.Y.) 43:905

30. Synchronous Motors for Regulation of Power Factor and Line Pressure.

ELECT. REVIEW (N.Y.) 45:54

31. Use of Synchronous Motors for Phase Compensation.

ELECT. REVIEW (N.Y.) 46:316

32. Synchronous Motors.

ELECT. REVIEW (N.Y.) 46:589

33. Some Features Affecting the Parallel Operation of Synchronous Motor-Generator Sets.

ELECT. REVIEW (N.Y.) 48:497