SUMMERS & LINDSEY

A Study of a Five Horse-Power Single Phase Induction Motor

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A STUDY OF A FIVE HORSE-POWER SINGLE PHASE INDUCTION MOTOR

BY

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THESIS

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Abel Ross Summers George Heath Lindsey

ENTITLED A Study of a Five Horse-Power Single Phase

Induction Motor

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science
in
Electrical Engineering

Chas. R. Moore
Instructor in Charge

APPROVED: Ellery B. Paine

HEAD OF DEPARTMENT OF Electrical Engineering

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A STUDY OF A FIVE HORSE-POWER SINGLE PHASE INDUCTION MOTOR

I INTRODUCTION

The first method used for the distribution of alternating currents, which was for lighting purposes, was the single phase system. Later, the three phase system came into use for power work. Oftentimes the lighting customer wished to use a small motor but could not afford to have an extra circuit (three phase) brought to his house. As a result of the demand for small motors, the single phase motor was brought into use. Many types were put on the market, and among them was the "Century". The motor that was used in this thesis was a five horse power single phase motor made by the Century Electric Company of St. Louis, Missouri. This motor starts as a repulsion motor and when it has speeded up to approximately eighty percent of synchronous speed it automatically changes into an induction motor by mechanical changes in the rotor circuit.

In order to understand the starting and operating conditions of this motor, a knowledge, not only of its characteristics, but also the various relations existing between the current, flux, and voltage, is necessary. These may best be studied by means of oscillograms.

II DESCRIPTION OF THE MOTOR

The chief difficulty that confronted the engineers, who were interested in the single phase motor development, was the question of self-starting. Single phase motors have the peculiar property of giving zero torque when at rest. The flux produced in the stator when excited from alternating single phase current, is alternating in character but fixed in position. Hence the motor has no

tendency to rotate. However, after the motor has acquired approximately seventy-five to eighty percent of synchronous speed, it will pull up to nearly synchronism as an induction motor. Various schemes have been placed upon the market for giving this initial torque. A very good one makes use of the repulsion principle during starting. The characteristics of a motor making use of this principle resembles very closely the direct current series motor, and has exceptionally large starting torque.

The windings of the rotor are identical with that of a direct current armature. Four short circuited brushes spaced 180 electrical degrees apart, rest upon the commutator which is of the radial type. The angle these brushes make with a line passing through the center of the poles is approximately 15 electrical degrees. The direction of the flux through the rotor and set up by the rotor current is in line with the brushes which, as before stated, are short circuited by means of a heavy copper brush holder. The flux due to the stator current has a direction parallel to a radial line bisecting the poles. These two fluxes very nearly neutralize each other, because they are induced in opposite directions, except for the shift of the brush angle. The resultant of these fluxes gives a component magnetomotive force parallel to a tangent line to the rotor surface. The unneutralized component of the field flux is in such phase relation with rotor flux that a torque is produced; this torque producing rotation, the direction depending upon the side to which the stator flux is shifted with respect to the rotor flux by means of the brush position. When the rotor flux is in exact phase opposition to the stator flux a neutral position is established and is called the short circuited neutral. At this

point a very heavy current is induced in the rotor windings. Ninety electrical degrees from this position another neutral can be found, which is called the true neutral, however, as the fluxes have ninety degree phase relations a very small current is induced in the rotor windings.

The mechanism for changing over from a repulsion motor to an induction motor consists essentially of centrifugal weights, pivots, spring, short circuiting parts, and a device for lifting the brushes from the commutator. The weights used are made of 1/8 inch sheet iron, which are mounted on pivots on the end of the rotor opposite from the commutator. Attached to these weights are pins which extend through the rotor and rest upon a collar of the spring barrel. This barrel is machined out so that it slides freely over the shaft. It also supports a bracelet of small copper strips that resemble commutator segments, which are fastened together by means of a wire and rest upon a brass ring just back of the commutator segments. Fitting over this barrel is the brush holder, which allows the brushes to rest upon the commutator. The whole apparatus is rigidly held by a steel spring which is compressed by a threaded washer attached to the shaft. When the speed attains about seventy-five percent synchronous speed the weights attached to the shaft overcome the force of the spring by centrifugal action and fly out. This action forces the pins forward and these in turn push the barrel towards the commutator. The barrel carries the bracelet from the brass ring to the commutator segments, and thus short circuits them. The barrel also pushes against fingers attached to the brush holder and lifts the brushes off the commutator. When the speed is reduced the force of the compressed

spring reasserts itself and a reversible action takes place.

The stator is wound upon a laminated core and its windings are of the pancake coil type. It has four poles and can be connected for either 104/208 volts. Leads are brought out through porcelain bushings and by connecting in series or parallel the required voltage may be impressed.

Some of the constants of the motor are:

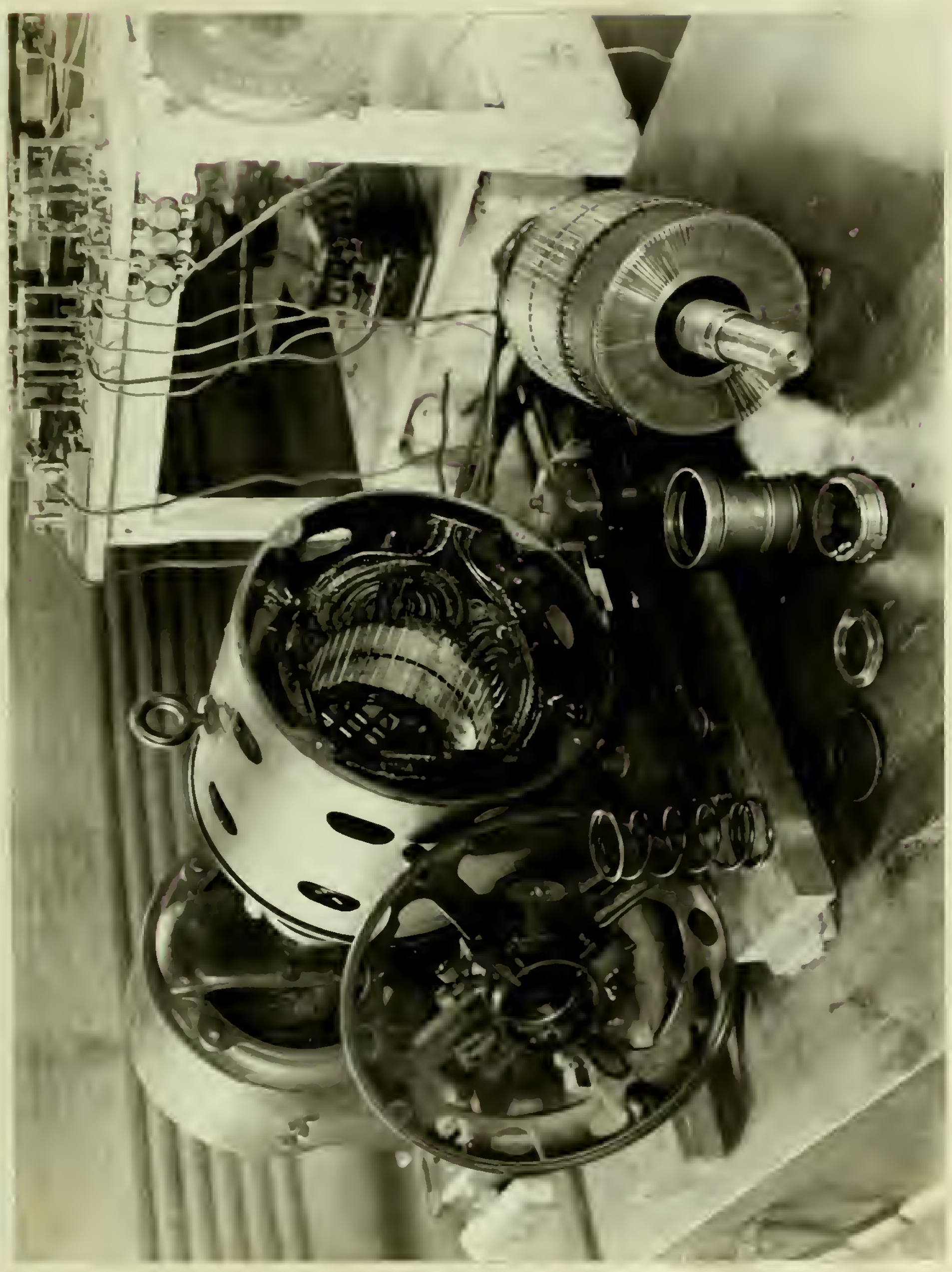
Capacity	5 H.P.
Normal terminal voltage	104/208 volts
Frequency	60 cycles
Full load speed	1750 R.P.M.
No. of stator slots	48
Number of stator poles	4
No. of coils per pole	4 1/2
No. of coils in series	4 1/2
Turns of wire	22 turns of No.11 B.S.
No. of rotor slots	61
No. of rotor coils	61
Turns of wire per coil	3 turns of 2 No. 12 B.S.

A picture of the motor parts is shown on page 5, and the motor completely assembled on page 6.

III DESCRIPTION OF TESTS

In the tests which were made we confined our work to the oscillographic study of starting and operating characteristics of the motor at various loads. This phase of the work was studied in order to see the transient conditions occurring at various operating conditions.

The preliminary work consisted in determining the best



method of obtaining an unchanging load. A prony brake was first tried but it soon became evident that such a method was unsatisfactory for our purpose. The friction of the rope on the pulley varied due to the rise in temperature and caused a variation in the speed of the motor.

In order to overcome this difficulty a five horse power direct current generator was obtained. It was run as a motor with its field, which was kept constant, separately excited in order to avoid the calculation of the field I^2R losses. A resistance was put in series with the armature. By varying this resistance the voltage could be varied and the speed controlled. By this method the constant losses of the machine at the various speeds were found. The resistance of the armature was measured in the usual manner. The armature plus the brush contact resistance was also found for the various currents. From these resistances the variable losses of the armature at different loads were found.

After the direct current machine was calibrated, it was directly connected to the induction motor. The direct current machine then became a generator which was separately excited. The load was obtained by connecting two lamp banks in series with the armature. After the windings of the machine had heated up to normal operation, the load remained practically constant. Throughout the entire test the alternating current voltage was kept constant. Great care was taken to maintain the frequency at sixty cycles. The speed was checked accurately for each condition of loading.

The diagram of connections of the two machines is shown in Fig. 1.

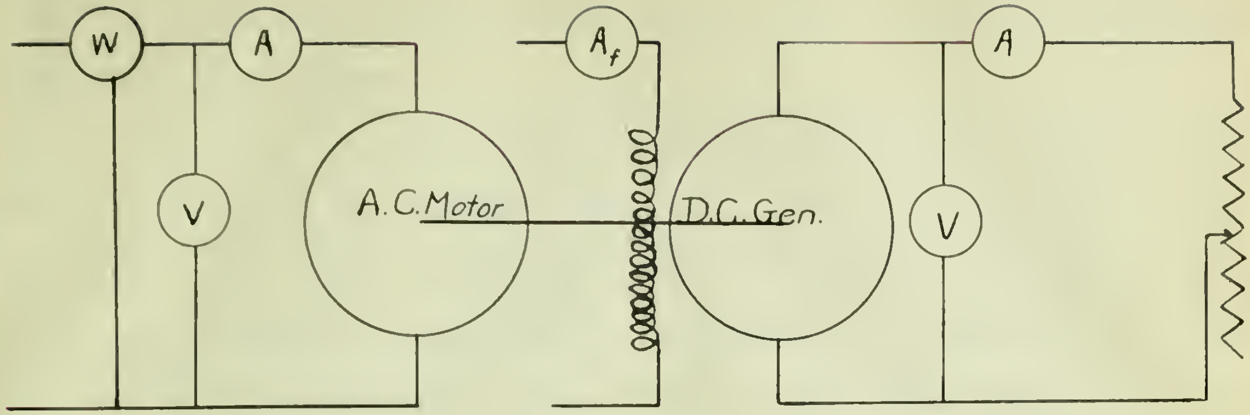


Fig. I.

After the characteristics of the motor were obtained the oscillograph was adjusted to suit conditions. The elements which contained the mirrors had to be shunted such that not over one-tenth of an ampere would be the maximum value of current, and that not over six-tenths of a volt would be impressed across the elements. In order to cause not over one-tenth ampere to flow, a german silver wire was calibrated such that the IR drop when fifty percent over load current passed through the motor, there was only six-tenths of a volt drop. The current element was then shunted across this wire. To produce the required voltage for the voltage element a high resistance was put in series with the element and then connected across the line.

Films showing the current and voltage waves of the stator were taken for the following loads: zero, one-half, three-fourths, full, one and one-fourth, and one and one-half loads. A series of

short films were taken showing conditions just before, at, and just after the transient conditions of change from repulsion to induction motor had taken place.

In order to study the flux relations in the rotor, a coil which consisted of two turns of No. 25 B. & S. wire was wound upon the rotor. This coil was spaced 15 slots apart or as nearly 180 electrical degrees as possible, and connected to insulated collector rings which were fastened to the rotor, Leads from these collector rings were connected to the oscillograph circuit. This coil acted as a search coil for the determination of the rotor flux. Films were taken under no load and full load conditions, which showed the voltage and current in the stator and the flux curve of the rotor in their respective phase positions.

IV CALCULATION OF RESULTS

The calculation of results first consisted in working up the data for the calibration of the direct current machine. By running the machine idle as a motor the iron losses, friction and windage, and the I^2R losses were found. Since the current at no load was only 1.12 amperes at 1800 R.P.M., and the resistance of the armature and brushes was .8 ohms, the I^2R losses were about one watt. The total loss was 245 watts, therefore the I^2R losses were not calculated separately, but included as iron losses for no load. Since the iron losses vary as some function of the speed, as is shown by the data, a curve may be plotted with watts as ordinates and speed as abscissa, and from this curve the losses may be obtained. This curve is shown on page 27. For a given speed this may be called the constant loss. As the armature current increases the brush contact resistance decreases. Multiplying the resistance of the armature and the brushes

by the square of the armature current, a curve may be plotted with watts as ordinates and armature current as abscissa. This curve, which shows the variable losses of the generator, is shown by the red line on page 27. For any desired load the speed is known, the variable losses are found from the red curve for the current at that load, and the constant losses are shown by the black curve for the speed at which test was made. The sum of these losses give the total losses of the machine for any load.

From the motor data as shown on pages 24 and 25 it is seen that the load varied from that corresponding with the generator constant losses to over fifty percent overload. By knowing the watts output and the generator losses, the output of the motor may be determined. The load efficiency curve (Curve No. 1 page 28), increased from zero at no load to eighty percent at half load, it remained almost constant up to 25 percent over load, and it then gradually decreased. This decrease was caused by the I^2R losses increasing faster than the output of the motor. Curve No. 2 of the same page shows the power factor which was calculated from test for the different loads. The power factor increased rapidly to about 50 percent load, then gradually increased to a maximum of .87 at 120 percent load, and then decreased to about .82 at 144 percent load. The increase of power factor is due to the increase of power component of the current, while the wattless component increases slowly (9.3 to 13.25 amperes at full load) up to full load.

The speed, see Curve No. 3, page 28, gradually fell off with the increase of load. Since in induction motors the speed depends upon its losses, the speed is proportional to the rotor I^2R losses, since the other losses are practically constant.

Curve No. 4 on the same page shows that the current increased faster than the load, the highest value being 49 amperes at 143 percent load. The torque curve No. 5 on the same page is directly proportional up to the limit of this test.

V DISCUSSION OF RESULTS

In the discussion of results of this thesis we will consider only the study of the various curves taken by the oscillograph. From the no load curves which are shown on page 17, the current and voltage waves are exhibited. The current, as would be expected, lags by a large angle behind the E.M.F. By careful measurement we found that the current crossed the zero axis about seventy-five degrees behind the corresponding point on the voltage curve. This angle of lag is characteristic of all induction motors at no load. The voltage wave is easily distinguished from the current curve because the voltage peaks shows small harmonics. Both waves, however, are very regular and resemble sine waves. The angle of displacement between the curves indicate the power factor. If the current wave was resolved into two curves, one in phase with the voltage, and the other lagging behind the voltage by ninety degrees, the latter would be the larger. For this reason the power factor is very small at no load. These relations may be shown by Fig. 2.

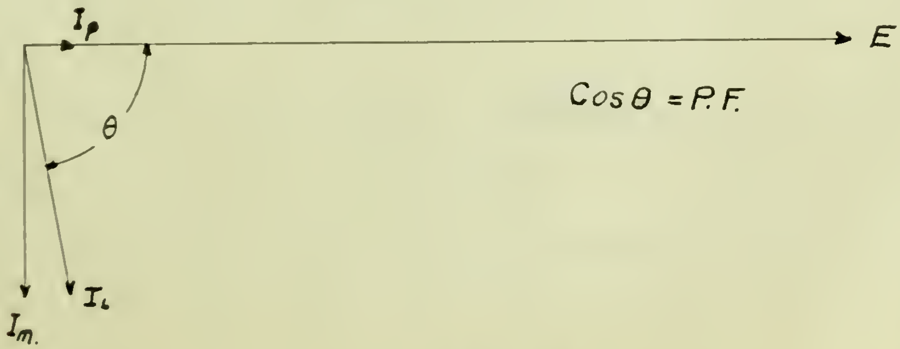


Fig. 2

In the set of curves for half load (See page 17) the current is much larger and is also nearer in phase with the voltage. Since the angle of displacement between the two curves is less, the power factor is greater. The reason for this difference is that the power component of the current increased from 2.44 to 12.1 amperes, while the wattless component of the current varied only from 9.3 to 10.3 amperes. The voltage curve is still easily distinguished by the small harmonics and is still the larger of the two curves. A diagram, Fig. 3, which is similar to the one for no load, may be used to show the increase of power factor.

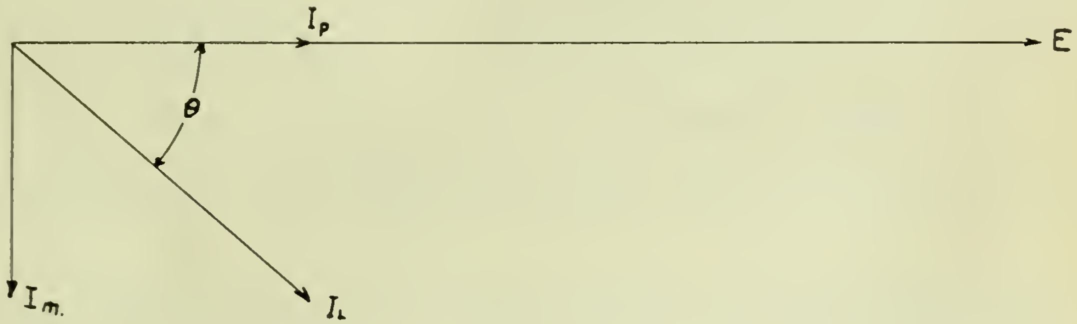


Fig. 3

The curves for three-fourth load as shown on page 18, indicates the current has increased in magnitude, and is more nearly in phase with the voltage. The power factor has also increased since the power current has increased faster than the magnetizing current. (See Table III).

For full load, page 18, the current is still increasing in magnitude, but the power factor remains practically the same. At this load the wattless and power components of the current vary in about the same ratio. In Fig. 4 the relation of the power factors

for three fourth and full load are shown.

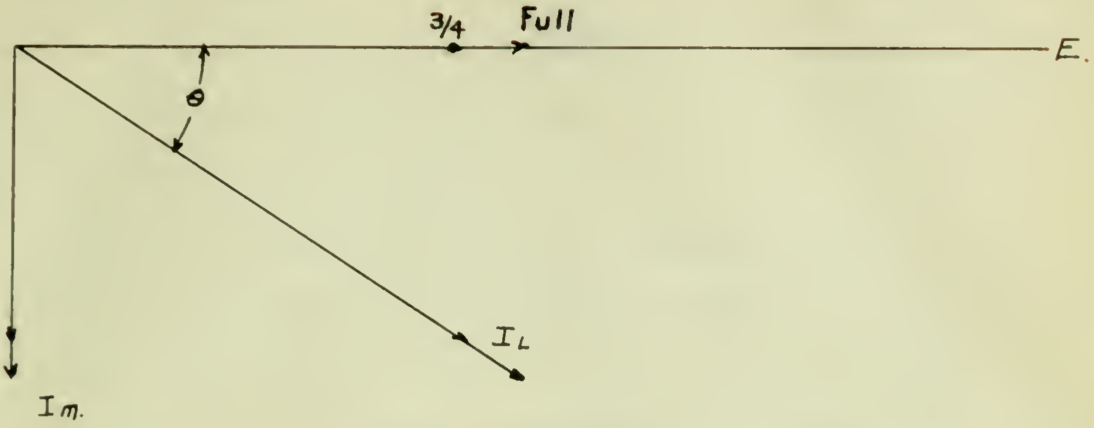


Fig. 4

At 1.25 load the power factor has passed its maximum value, since for this and larger loads the wattless current is increasing faster than the power current. A careful examination of the curves on page 19 will reveal this fact. For 1.5 load the power factor continues to decrease, a fact which is evident from the curve on page 19.

The curve showing the voltage and the current phenomena just before the motor changes from the repulsion to the induction type, is given on page 20. The voltage remains constant but the current steadily decreases until at the instant of change (knock out) it is very small. The cause of the decrease of the current is that the counter E.M.F. is building up and cuts down the current. It is evident that just at knock out there is an instant when no rotor current flows and the stator carries magnetizing current only, since the rotor circuit is open. After knock out the current quickly increases to a value much larger than normal. Oscillograms showing these phenomenae to a larger scale are given on pages 20 and 21. At knock out the slip is such that there is exerted on the rotor a

torque sufficient to carry the load and bring the rotor up to full speed. Just after knock out the motor is an induction motor with a large value of slip, which causes a large stator current to flow, As the motor comes up to speed the slip and the current decrease until normal conditions are reached.

As shown in Franklin and Esty, "Alternating Currents", pages 293, 294, 295, the following flux relations exist in a single phase induction motor. Assuming an ideal two pole motor of negligible resistance, reluctance and magnetic leakage, the stator bars at B B', Fig. 5, cause a flux θ to pulsate back and forth. This flux induces

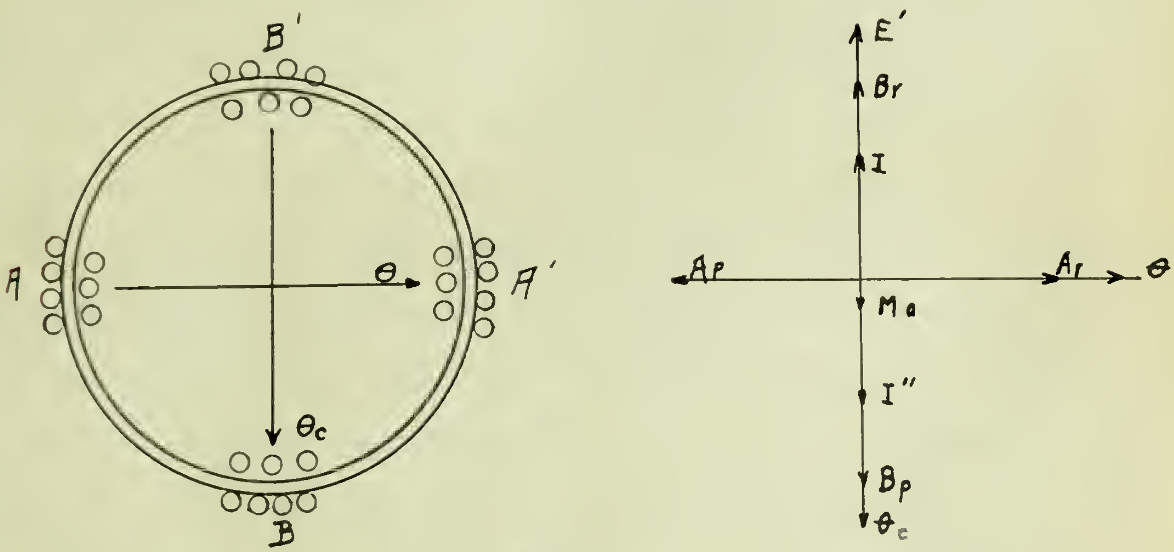


Fig. 5

a voltage B_p, 90 electrical degrees behind it. The rotor bars cutting this flux induces an E.M.F., A_r, in phase with it, and this E.M.F. in turn causes a cross flux θ_c to pulsate with the same frequency as the primary. Now this cross flux induces a voltage A_p, 90 electrical degrees behind it. By paying proper attention to signs and phase rotation, it is seen that the rotor bars cutting this cross flux induces a voltage B_r, 90 degrees behind A_p. When the motor is running at synchronous speed, B_p equals B_r, and no current flows in

the rotor; but when the speed is below synchronism, the difference between these two voltages produce a load current I" in the rotor. The magnetizing action of this current is balanced by a corresponding stator current I', and the rotor bars are pushed to one side by the cross flux. This torque furnishes mechanical power. The flux θ is called the transformer flux and is dependent only on the stator conditions. The cross flux, θ_c, is proportional to the speed, and at synchronous speed it is equal to the transformer flux. A search coil was used to study these relations, and was assumed to be practically non-inductive; therefore, when a voltage is induced in it, a current is caused to flow in phase with the voltage. Now as the voltage is proportional to the flux, and as the current flowing in the oscillograph circuit is in phase with that voltage, the vibrations in the oscillograph are proportional to the flux linkages.

From the no load, (page 22), it is noted that every fourth wave is identical. The reason for this phenomena seems to be that the search coil assumes the same position with respect to like poles, as it was only wound on one quarter of the rotor surface. A great variation can be seen between successive cycles of the flux wave. This variation would seem to be caused by different characteristics of the transformer flux and the speed flux. These curves were very jagged, resembling saw teeth, due to the effect of the teeth and slots, since they cause a variation of the reluctance of the magnetic paths. The wave is more jagged on the negative than on the positive slope, which is probably due to the poles being considerably more saturated on one side than the other, such as is caused by armature action in direct current machines.

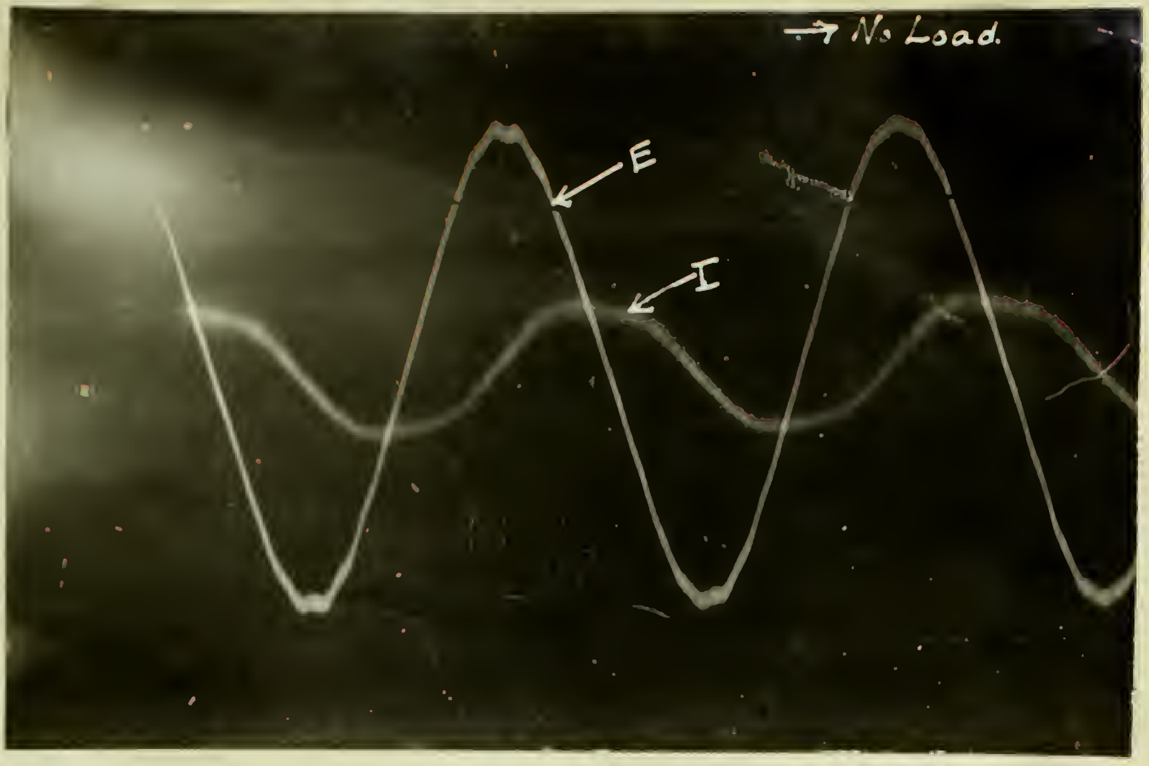
If the rotor were run at synchronous speed, the rotor current

would reduce to zero and the cross flux would disappear. The greater the rotor current, the larger will be the value of the magnetic flux as is shown by the full load curve, page 22. The differences of these flux waves are quite marked. The voltage and current of the stator is shown on both films, by tracing the flux wave with relation to the voltage or current wave, it is seen that the flux wave gradually shifts back. This shift is due to the slip of the rotor, and could easily be measured if a film of sufficient length could be obtained.

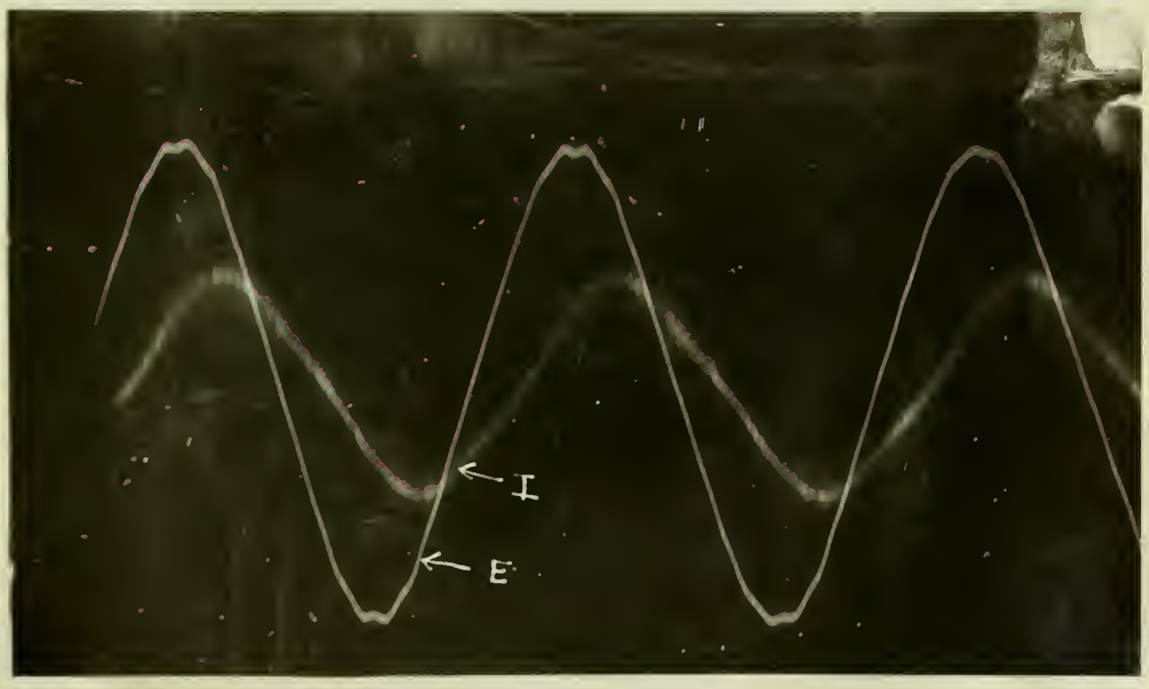
VI CONCLUSION

It is with regret that we close this thesis without a further study of the flux relations in the rotor. It would be of special interest to study flux relations at starting and knock out, and at various loads, but our time was not sufficient.

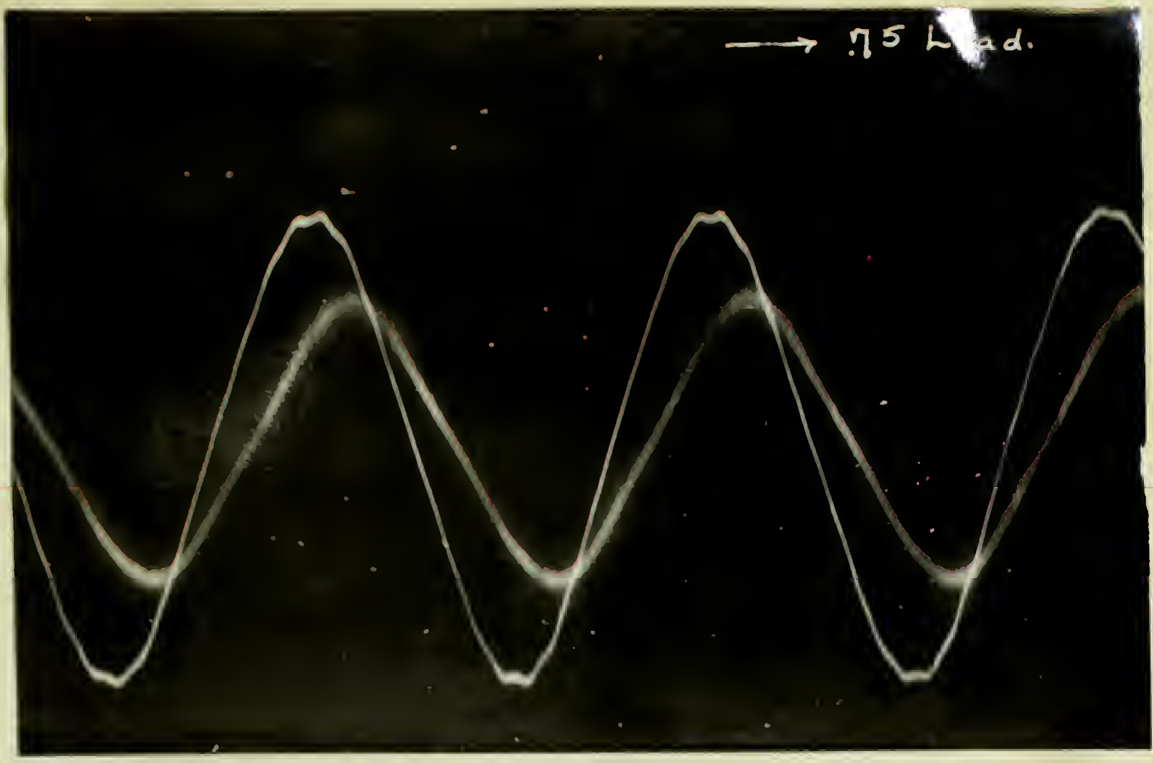
We wish to express our appreciation to Mr. C. R. Moore for the suggestions which he has offered, and the help he has given us in this work.



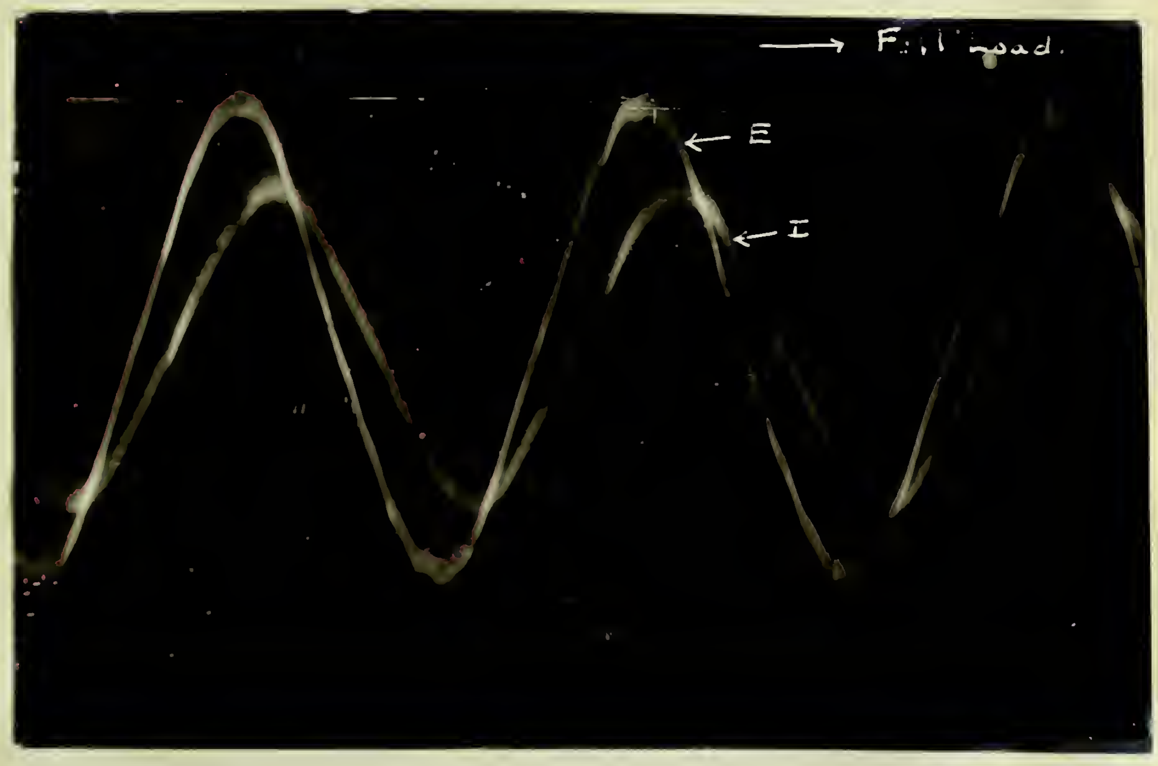
No Load.



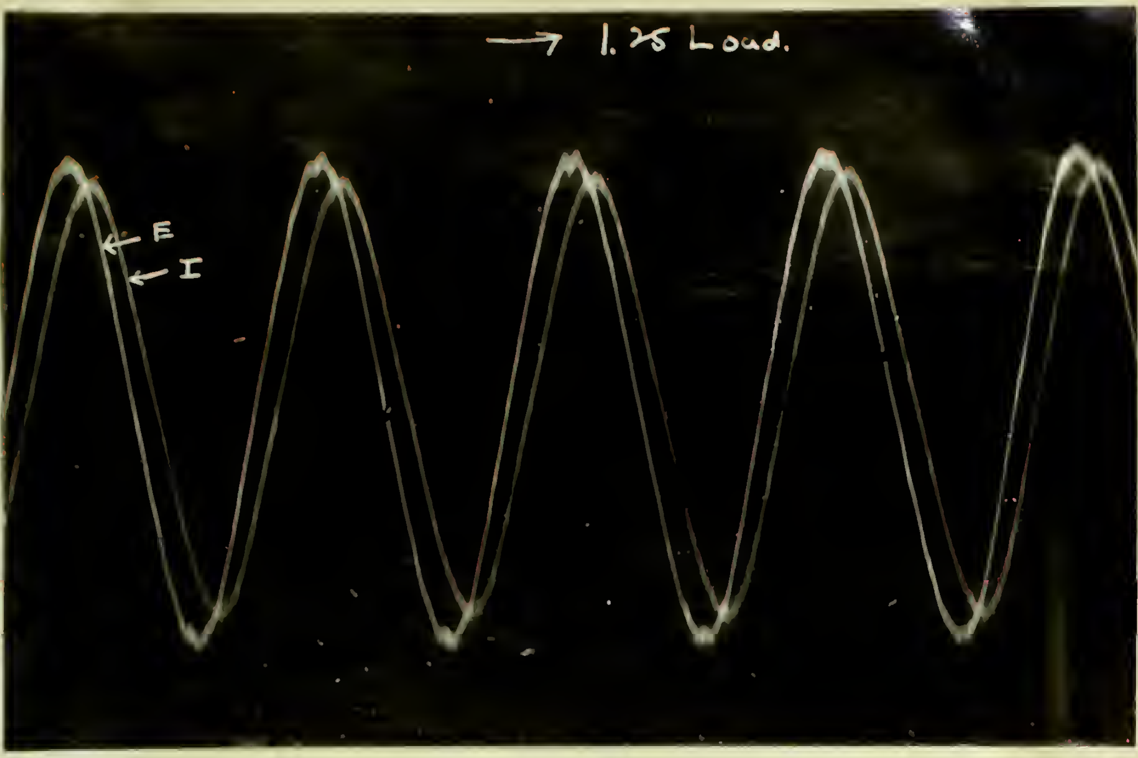
Half Load.



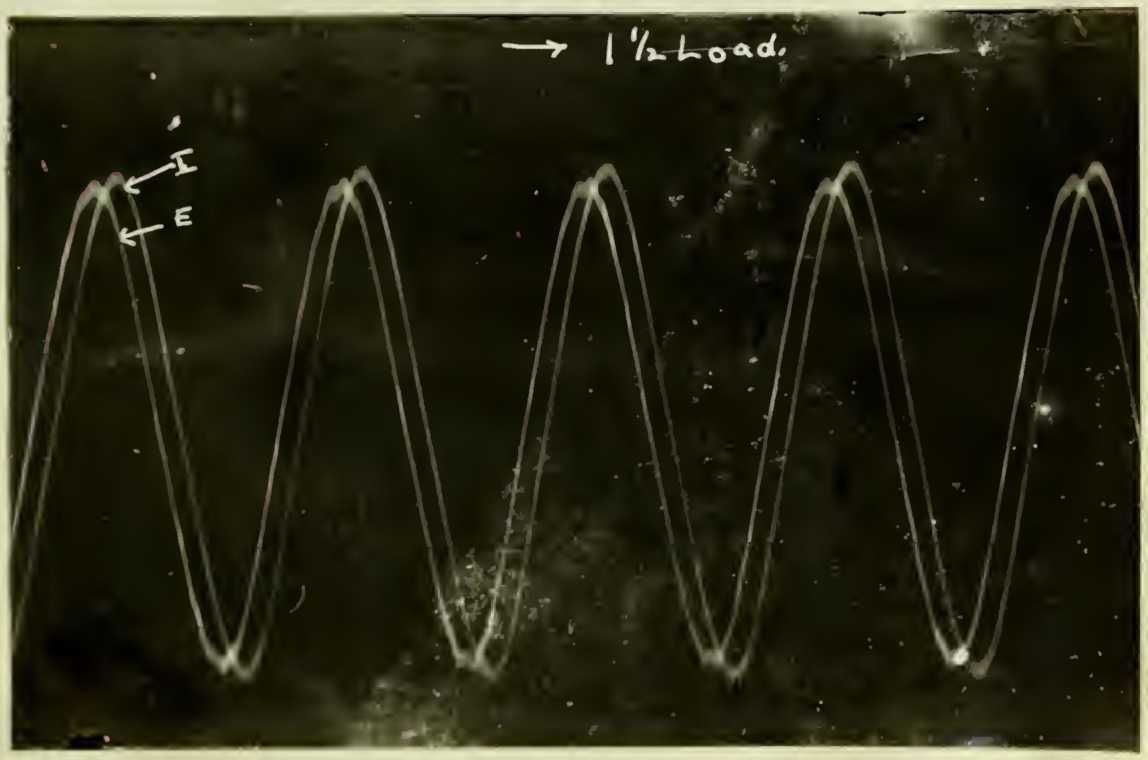
Three Fourth Load.



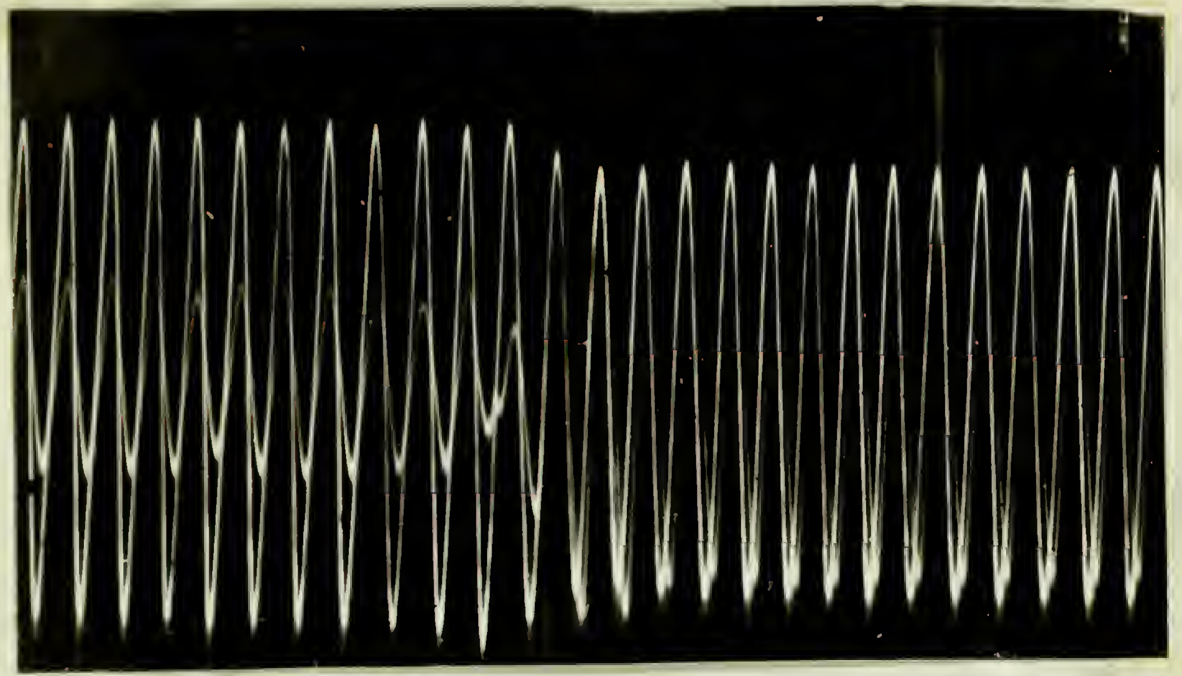
Full Load.



One and One Fourth Load.

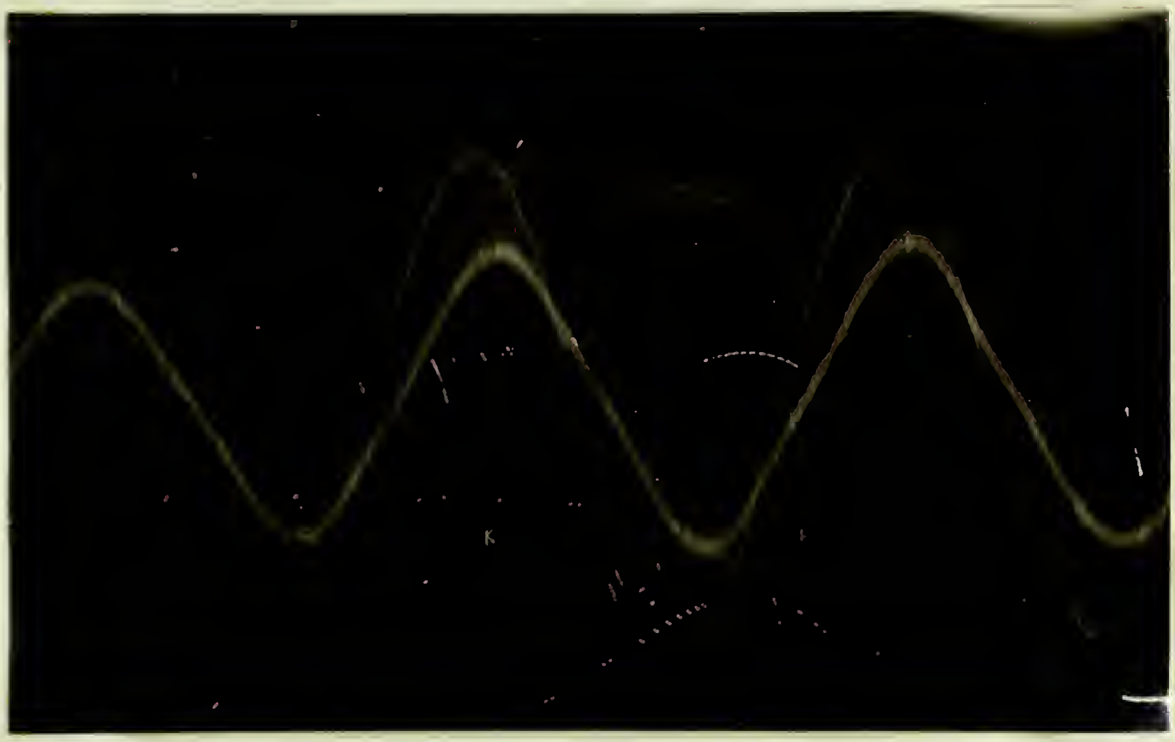


One and One Half Load.



(Full load conditions)

Knock Out

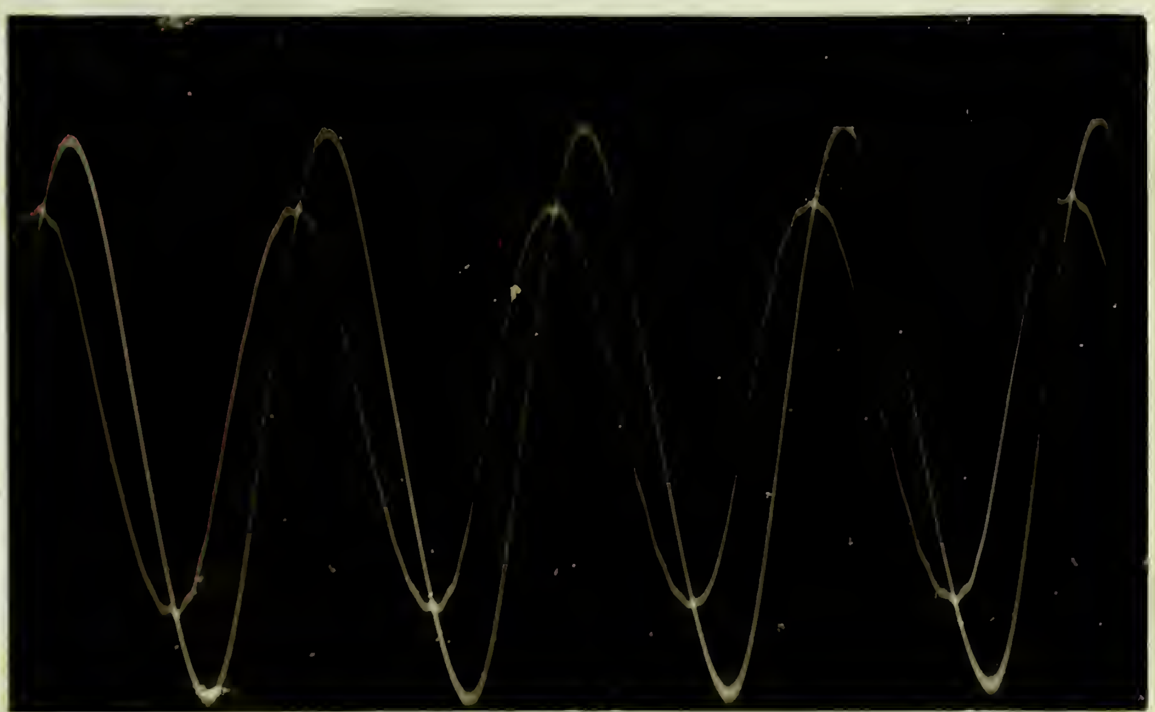


(Full load conditions)

Before Knock Cut

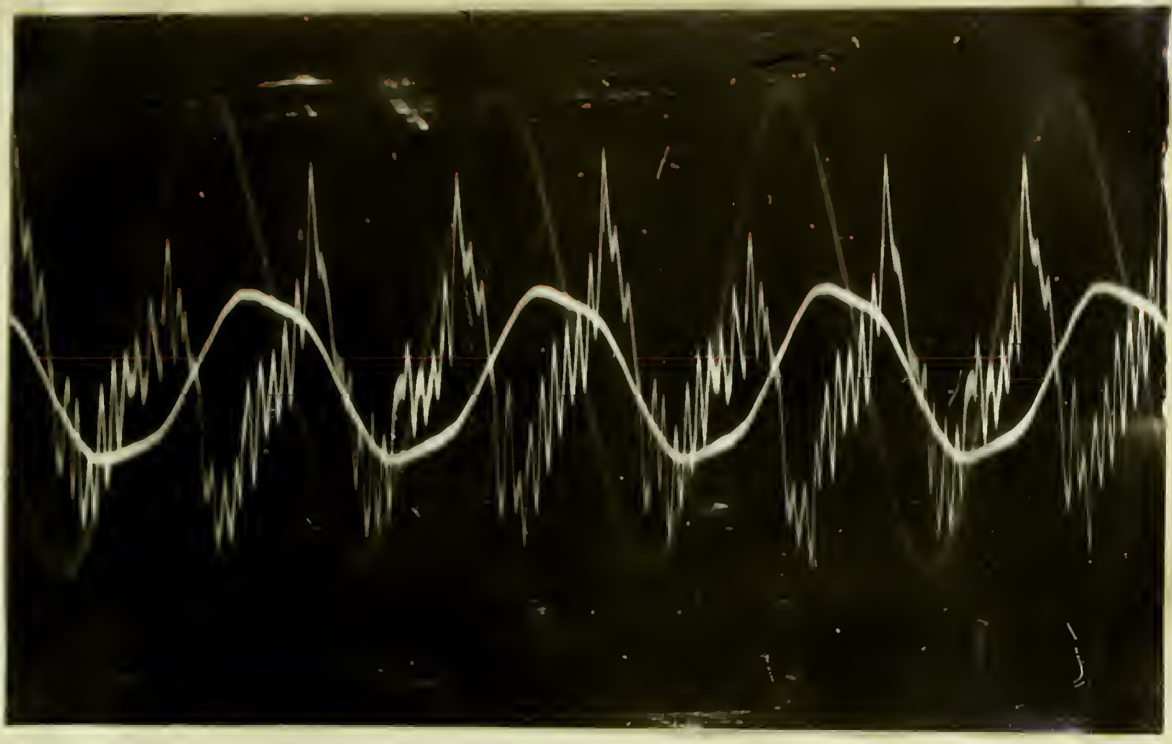
(Full load conditions)

At Knock Out

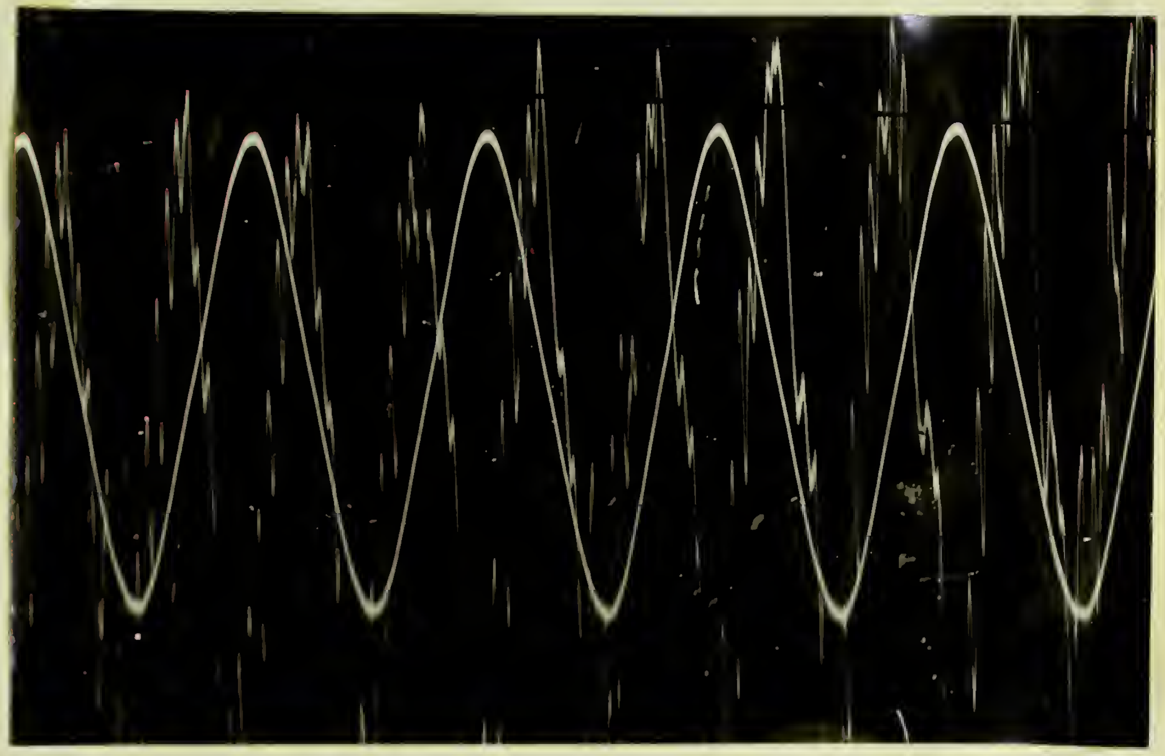


(Full load conditions)

After Knock Out



No Load Flux Wave.



Full Load Flux Wave.

TABLE I

Losses in Direct Current Generator

Constant Losses

V	I_A	W	Speed	I_f Sep.Ex.
180	1.06	191	1472	.25
188	1.07	201	1530	.25
194	1.08	210	1600	.25
200	1.08	216	1650	.25
204	1.10	224	1700	.25
210	1.11	231	1725	.25
218.5	1.12	245	1800	.25

Resistance Arm

V	I	R
5.7	8.8	.64
8.8	13.3	.66
14.2	21.6	.655

Resistance Arm + Brushes

V	I	R_{A+B}
15.9	21.6	.737
15.	20.2	.742
12.5	16.6	.753
8.2	10.4	.788
3.5	4.4	.795

TABLE II

Data on the Characteristics on the Motor

Direct Current

V	I_a	I_f	W	W Losses	W Total
9	0.0	.25	0	244	244
207	5.7	.25	1180	264	1444
203	8.0	.25	1625	290	1915
195	11.2	.25	2180	344	2524
188	14.4	.25	2700	416	3116
181	17.0	.25	3080	469	3549
176	18.9	.25	3320	522	3842
168	21.1	.25	3545	585	4130
157	24.6	.25	3860	707	4567
149	27.0	.25	4020	807	4827
129	32.5	.25	4195	1017	5212
122	34.3	.25	4180	1073	5253
109	37.4	.25	4085	1250	5335

TABLE IIa

Data on the Characteristics on the Motor

Alternating Current

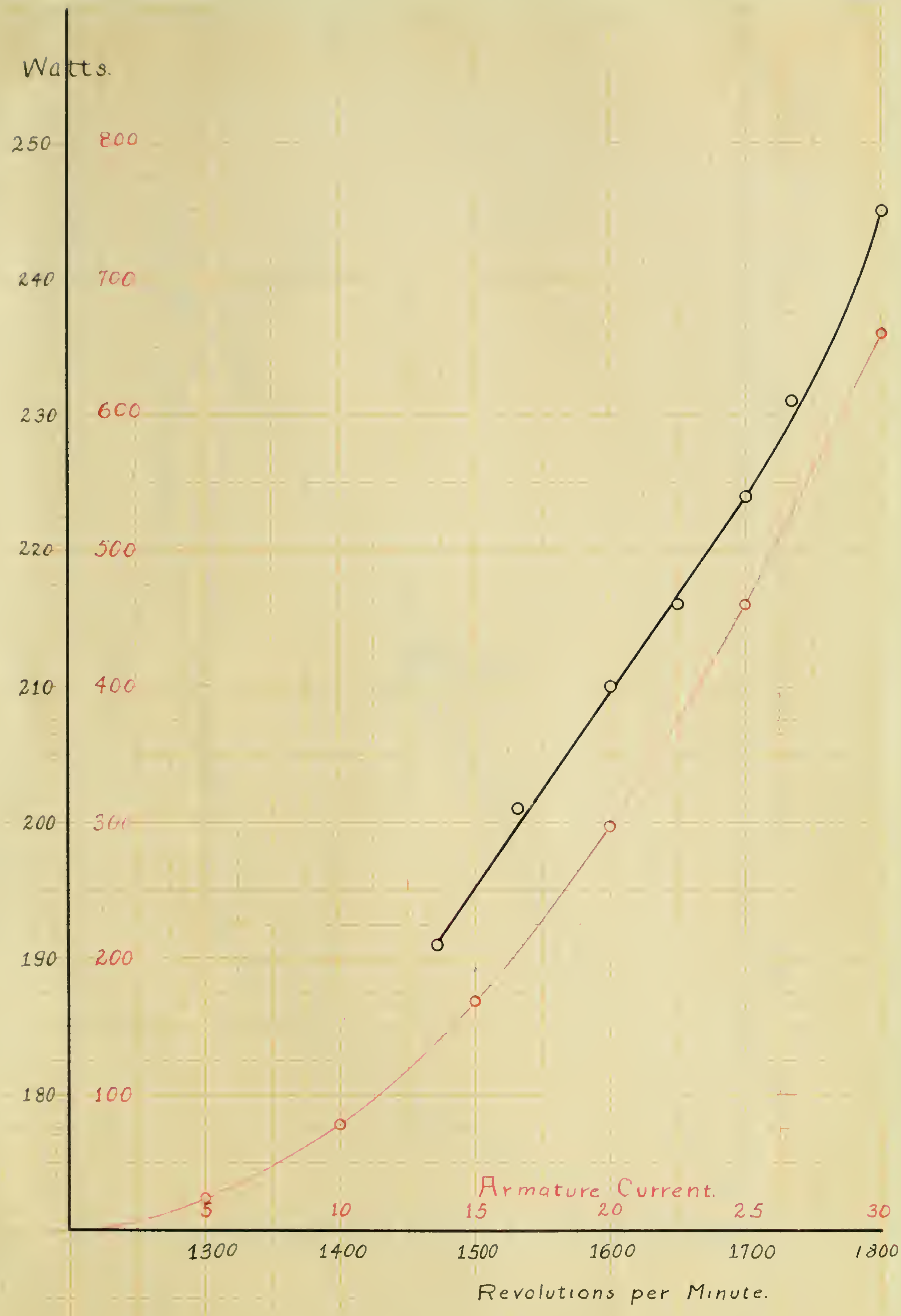
V	A	W	Speed	% Load	Input	P.F.	Eff.	Torque
208	9.6	328.0	1793	.065	328	.164	.745*	.96
208	13.5	1900.	1790	.382	1900	.675	.75	5.6
208	15.8	2416.	1785	.514	2416	.735	.797	7.56
208	19.0	3140	1773	.675	3140	.795	.805	9.94
208	22.3	3872	1760	.830	3872	.834	.805	12.25
208	24.6	4480	1750	.948	4480	.875	.791	13.95
208	27.5	4800	1740	1.027	4800	.840	.802	15.10
208	29.5	5320	1730	1.100	5320	.866	.776	16.25
208	33.5	6080	1725	1.210	6080	.872	.75	17.95
208	36.0	6400	1707	1.278	6400	.855	.753	19.00
208	41.8	7460	1683	1.375	7460	.857	.705	20.75
208	44.2	7760	1656	1.390	7760	.845	.688	21.00
208	49.2	8480	1630	1.430	8480	.830	.639	20.90

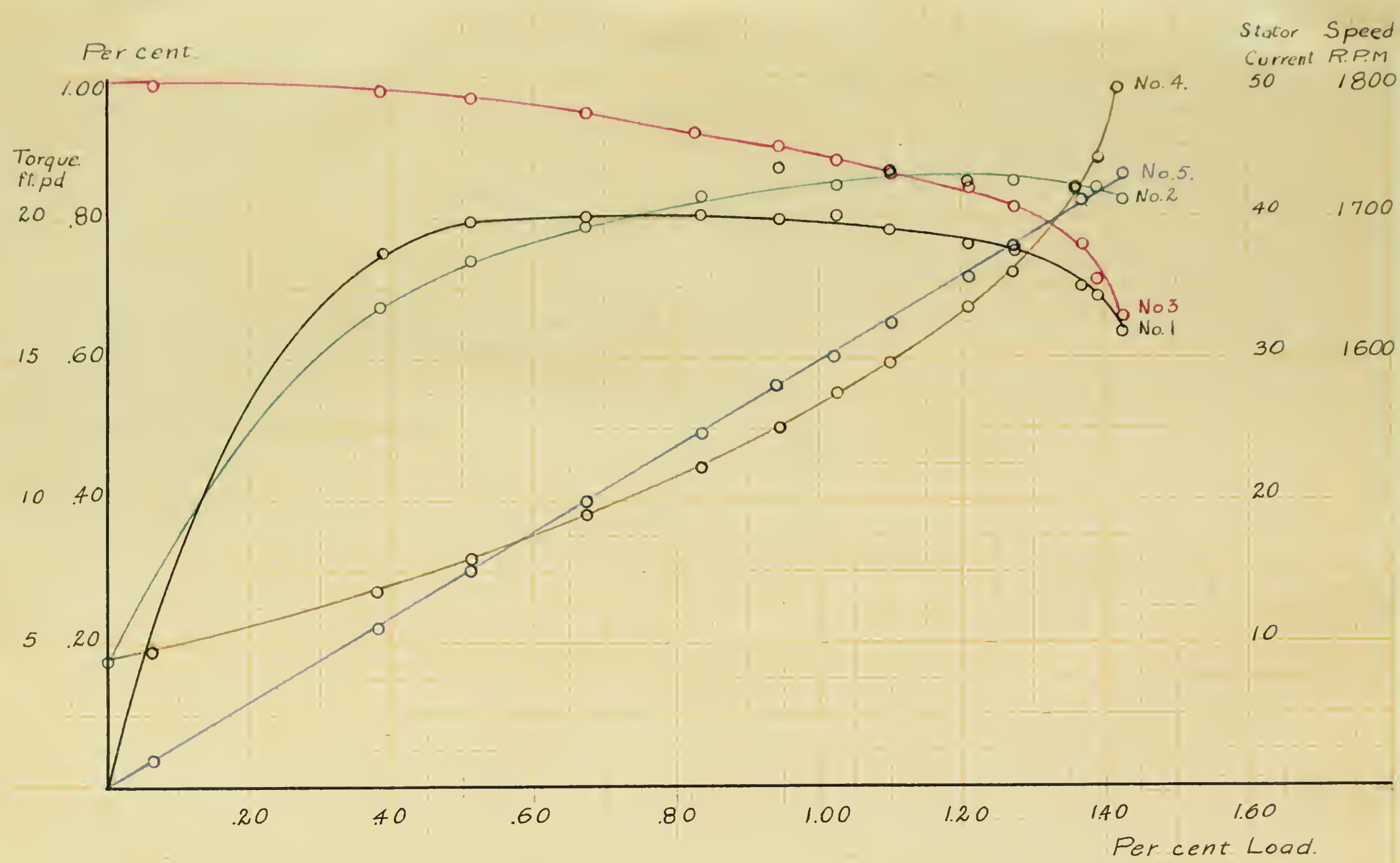
*Error

TABLE III

Data for Oscillograms

	Alternating Current					Direct Current		
	V	I	W	I_m	I_p	V	I_a	I_f
No Load	208	9.8	520	9.3	2.44	217	0.0	.25
1/2 Load	208	15.9	2520	10.3	12.1	198	9.0	.25
3/4 Load	208	21.2	3680	11.75	17.7	184	14.6	.25
1 Load	208	24.8	4350	13.25	21.0	174	18.1	.25
1 1/4 Load	208	28.	5000	14.4	24.0	164	21.	.25
1 1/2 Load	208	32.	5620	17.0	28.2	150	25.5	.25


Watts.
250
240
230
220
210
200
190
180
800
700
600
500
400
300
200
100
Armature Current.
5
10
15
20
25
30
1300
1400
1500
1600
1700
1800
Revolutions per Minute.


Per cent
Torque ft. pd
1.00
20 .80
15 .60
10 .40
5 .20
Stator Current
Speed R.P.M
50 1800
40 1700
30 1600
20
10
No. 4.
No. 5.
No. 2
No 3
No. 1
.20
.40
.60
.80
1.00
1.20
1.40
1.60
Per cent Load.