EFFICIENCY TEST

of a

General Electric Co. Variable Speed Form M

Induction Motor.

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At the present day the high cost of copper makes it imperative that the line construction for the transmission of power should be such as to require a minimum amount of copper. This condition is obtained by raising the voltage at which the power is transmitted. Since alternating current is the most adaptable for this work, it is being used more and more. For this reason alternating current motors have become one of the largest problems in the electrical industry.

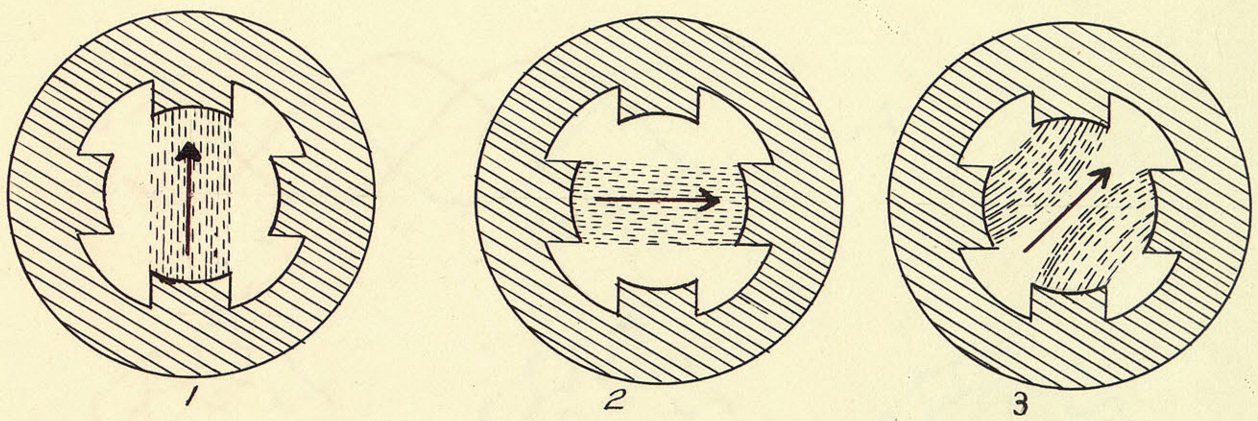
There are at the present time two general classes of alternating current motors, the synchronous motor and the induction motor. The synchronous motor does very well in sub-stations and power houses where it may be readily started. It gives a constant speed and by its use the power factor of a line may be improved, but the disadvantages due to requirements of an exciter and a means of starting, prohibit its installation in small units or in isolated places.

Theory of the Induction Motor.

The following theory of the induction motor is perfectly general for any motor of this type regardless of the number of phases.

Before entering into an analytical discussion of the induction motor it will be well to get a mental picture of what takes place when the motor is in operation.

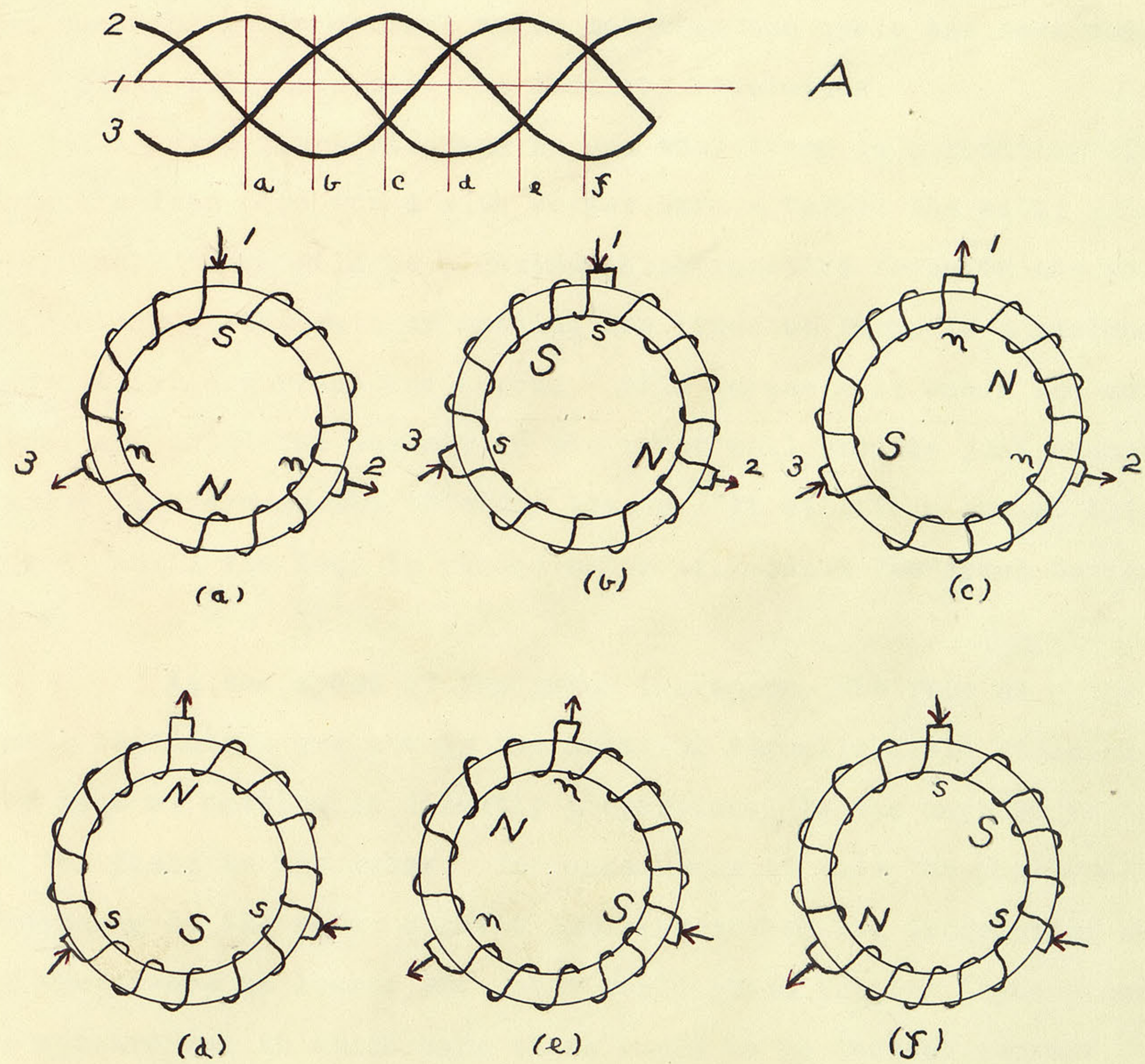
If a horse-shoe magnet is held over a compass, the needle will take a position parallel to the lines of force issuing from the magnet. If the magnet is rotated the needle will follow. Now if a four pole electromagnet is substituted for the horse-shoe magnet, and one set of poles is magnetized the needle will take a position parallel with the lines of force issuing from that pair as shown in Figures 1 and 2.



If both sets of poles are equally magnetized the needle will take a position diagonally half way between the two poles as shown in Fig. 3. If now one pair of poles is stronger, which necessitates, with equal windings, a stronger current, the needle will be attracted toward this pair and if the current about the other pair of poles is growing weaker the needle will be attracted to the stronger pole, when the current in it is a maximum and that in the weaker a minimum. Now if the two currents are alternating the minimum will reverse and grow stronger and the maximum will weaken. This action will cause the needle to be attracted by what was the weaker pole, thus causing it to rotate. When fed with alternating current this action is rapidly repeated the needle following the rotating field.

If the compass is replaced by an iron core wound with copper bars there will be induced currents in the bars which will react with the rotating flux and cause rotation in a manner exactly similar to that of the compass needle.

This explanation treats specifically of the two phase motor but the same principle applies to any motor.



The preceeding diagrams show the rotating field in a three phase motor. Let curve A show the current relations in a three phase system at any instant during a cycle. Let (a) represent the currents in the stator winding at the time "a" on the current curve. The current entering at 1 creates a south pole "S"; the current leaving at 2 and 3 creates two north poles whose resultant is "N". In "b" the current has changed; it is now entering at 1 and 3 thus forming a resultant southpole "S" and leaving at 2 forming a north pole "N".

In this manner it can be shown that the resultant poles move forward for each change in current value and when one cycle has been completed the field will have made one complete revolution.

From these diagrams we see that there is a rotating field. When the iron core wound with copper bars - termed the rotor - is stationary there will be a maximum electromotive force in the rotor conductors as the rate of cutting the lines of force is a maximum, hence a large current and torque. This torque will cause the motor to speed up, until the current in the rotor will produce just enough torque to overcome the friction losses. It will then run at this speed until the load is varied which will cause the speed to vary also.

As the speed of the rotor increases, the rate at which the rotor conductors are cut by the rotating magnetic field diminishes, as the rate of cutting is directly proportional to the angular velocity of the field to the rotor. In consequence of this the magnitude and frequency of the rotor current diminishes with the increase of speed. If there were no losses the motor would while running light speed up to synchronism in which case there would be no induced current. From this it is evident that the motor must run at some speed less than synchronism.

Due to this transfer of energy from the stator to the rotor windings, we can treat the induction motor as a transformer with a short circuited secondary.

Let N_1 = Number of turns in each circuit of the stator,

N_2 = Number of turns in each circuit of the rotor,

r_1 = Resistance per circuit in stator,

r_2 = resistance per circuit in rotor,

S_1 = reactance per circuit in stator at rest, Let S_2 = reactance per circuit in rotor at rest,

ω_1 = velocity of the rotating field,

ω_2 = velocity of the rotor,

e = Electro-Motive Force induced per turn in the stator coils,

f = frequency of impressed current,

K = the slip,

Then,
$$K = \frac{\omega_1 - \omega_2}{\omega_1}$$

The E. M. F., E_2 induced per turn in the rotor coils is Ke since the E. M. F. induced in the rotor is proportional to the angular velocity of the field with respect to the rotor. The total induced E. M. F. of the rotor circuit is then:-

$$E_2 = KN_2e.$$

This voltage is used up in the resistance and reactance of the circuit or:-

$$E_2 = V_2I_2 + jKS_2I_2 = KN_2e.$$

The reactance while in motion being KS_2 since the frequency of the rotor currents equals Kf,

Then,
$$I_2 = \frac{KN_2e}{r_2 + jKS_2} = \frac{(r_2 - jKS_2)KN_2e}{r_2^2 + K^2S_2^2}.$$

Then the power wasted in heating the armature is the product of E_2 and i_2:-

$$\text{Power wasted} = \frac{K^2N_2^2\ e^2r_2}{r_2^2 + K^2S_2^2}.$$

The E. M. F. induced in the stator coils $E_1 = N_1e$.

The current in the stator coils consists of two parts; the magnetization current "I_1'" and the energy current i_1'',

$$\text{But } i_1'' = -\frac{N_2}{N_1}i_2.$$

Substituting the value for I_2 we get

$$i_1'' = \frac{(r_2 - jKS_2)KN_2^2 e}{N_1(r^2 + K^2S_2^2)}$$

The energy transmitted per circuit is the scalar product of the vector E_1 and i_1'' or

$$\text{Power transmitted} = \frac{KN_2^2 e^2 r_2}{r_2^2 + K^2 S_2^2}.$$

The output of the motor is equal to the input minus the losses.

$$\therefore \text{Output} = \frac{KN_2^2 e^2 r_2}{r_2^2 + K^2 S_2^2} - \frac{K^2 N_2^2 e^2 r_2}{r_2^2 + K^2 S_2^2} = \frac{N_2^2 e^2 r_2 K(1-K)}{r_2^2 + K^2 S_2^2}$$

Then the torque for any load is equal to the output divided by the angular velocity of the rotor "ω_2".

$$\text{But } K = \frac{\omega_1 - \omega_2}{\omega_1} \text{ or } \omega_1 K = \omega_1 - \omega_2.$$

$$\therefore \omega_2 = \omega_1 (1-K)$$

Then the torque equals -

$$T = \frac{N_2^2 e^2 r_2 K(1-K)}{\omega_2 (r_2^2 + K^2 S_2^2)}$$

Substituting for ω_2

$$T = \frac{N_2^2 e^2 r_2 K}{\omega_1 (r_2^2 + K^2 S_2^2)}$$

From this equation we see that the starting torque will be

$$T_o = \frac{N_2^2 e^2 r_2}{\omega_1 (r_2^2 + S_2^2)}$$ for when the rotor is at rest K = 1.

This equation shows that the starting torque is greater the smaller the reactance of the rotor circuit. Also the starting torque is a maximum when $r_2 = S_2$ then

$$T_o = \frac{N_2^2 e^2}{2\omega_1 r_2}$$ which varies inversely as the resistance.

Thus to produce a great starting torque the resistance and reactance should be equal to each other and as small as possible. The equation for torque also shows that for a constant torque a variation of the rotor resistance will cause a variation in the slip; an increase of resistance causing an increase of slip and hence a lower rate of speed and in the same way an increase in speed with a decrease of rotor resistance.

Also since "e" is proportional to the rotating flux linked with the rotor, it follows that a great torque can only be obtained when the air gap is small and magnetic leakage is very nearly eliminated.

We now see that the induction motor acts similarly to a shunt motor, an increase in load causing just enough drop in speed to allow current enough to flow to overcome the increase in torque. Sometimes a variable speed motor is very desirable and for this class of machines special appliances must be made use of.

In a generator the frequency $f = \frac{PV}{60}$ so in a motor $V = \frac{60f}{P}$

where V = R. P. M.

f = frequency

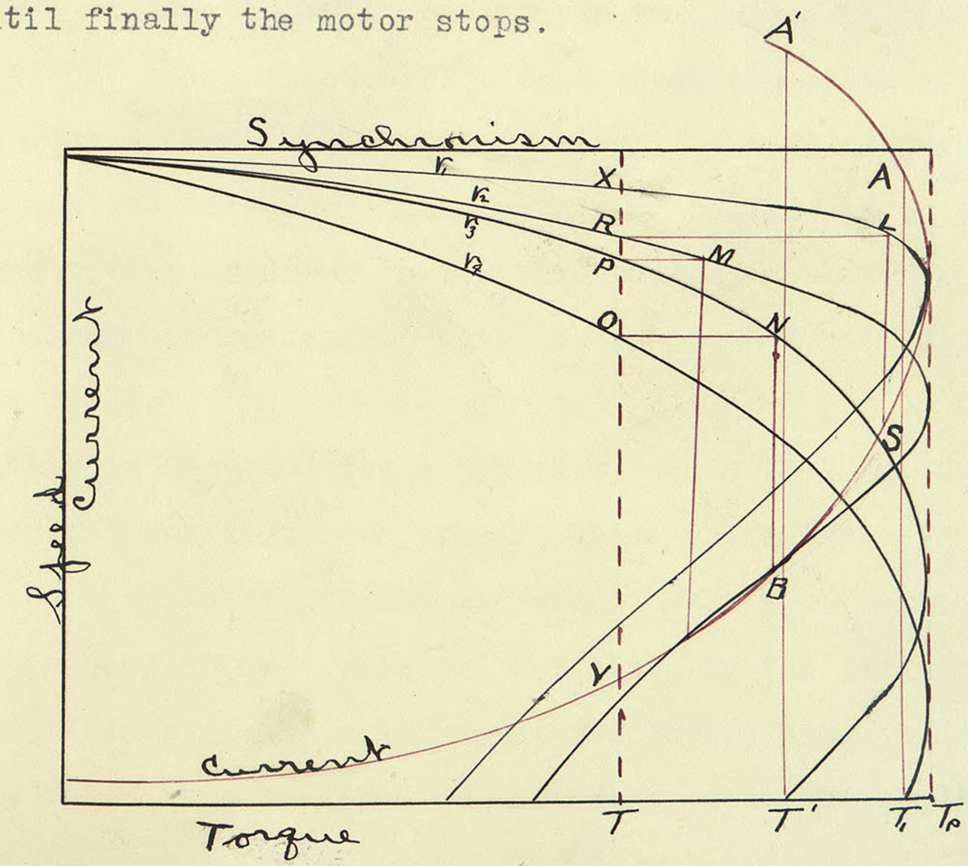
and P = pairs of poles.

This shows that the speed of a motor may be changed either by varying the frequency of the applied current or the number of poles, either of which requires complicated devices which make them more or less impracticable.

The speed can also be varied by altering the impressed voltage or the rotor resistances. These two methods depend for their operation upon the fact that inasmuch as the motor torque is proportional to the product of the stator flux and the rotor current for a given torque the product must be constant. Lessening the impressed voltage lessens the flux and also the rotor current if the same speed be maintained. The speed therefore drops until enough E. M. F. is developed to send sufficient current through the rotor to produce with the reduced flux the equivalent torque. Increasing the rotor resistance decreases the rotor current and requires a decrease in speed to restore its torque value.

The following curves show the relation between speed, rotor current and torque in an induction motor.

Due to magnetic leakage and inductance in the rotor the torque curve is not a straight line but has the form as shown in the figure. On account of magnetic leakage there is a maximum torque for any rotor which is constant regardless of the resistance of the rotor, and when the required torque becomes greater than this, the motor will stop. When this point, which is termed the "pull out" point, is reached there is a great rise in rotor current, meanwhile the torque decreases until finally the motor stops.



Let us examine the curves as shown and determine the conditions under which the motor is working. Let T_p be the "pull out" point, T the working torque; r_1, r_2, r_3 and r_4 the different resistances in the rotor. Then the starting current with the rotor resistance r_4 is "A" since it is working beyond the bend. With resistance r_3 the starting torque would be T' with current "A′". With resistances r_1 or r_2 the motor would not start with torque T since the torque for these resistances at a stand still is less than the required torque. From this we see that there is a maximum resistance for the rotor which will give the greater starting torque with a minimum starting current.

Let us now examine the speed relations. Starting with resistance "r_4" there is a torque T_1 which is greater than the required torque, therefore the speed will increase until the required torque is reached which would be at "O". As the speed increased the current decreased so that when the speed reached "O" the current had run down to "Y". If now the rotor resistance is changed to "r_3", the torque will be "n" and current will rise to B at the speed at which the motor is running . But this torque is larger than is necessary and the speed will be increased again until "P" is reached in the meantime the current having returned to Y. This process would be continued for every change in resistance until r_1 is reached, at which it would run at the speed X.

Thus we see that for a constant torque that the running current is constant for different speeds, which shows that at different speeds with the same rotor current different amounts of power can be obtained from the same motor. This is explained by the fact that changes in the resistance of the rotor cause a corresponding change in the losses in the rotor thus leaving for different resistances, different amounts of energy available for doing work. Thus by using different rotor resistances a variable speed may be obtained, but with a loss in efficiency and capacity of the machine. This is the principle utilized by the General Electric Co. in the construction of their variable speed Form M induction motor of which the following is a brief description.

The motor under test was rated at 5.5 HP. 220 volts 16 ampere 900 R. P. M. at 60 cycles. The stator is wound for a three phase circuited, eight poles with distributed windings. The rotor is form wound with distributed windings, the three leads being brought out to slip rings on the rotor shaft. These slip rings provide a way for inserting resistances in the rotor circuit, external to the machine. The rotor circuit is always open unless the rings are short circuited or the circuit completed through an external resistance.

The resistances to be used with the motor consist of cast iron grids, which are thrown into the rotor circuit, and controlled with a type T - 1 controller, which has eight different positions. The first position throws in a maximum resistance and the last position short circuits the rotor windings. When on this point the motor is running as a "squirrel cage" motor.

The controller is also provided with four contacts by means of which the motor may be reversed.

The following curves show the performance of a General Electric, Form M, Induction Motor with different resistances in the Rotor. They were taken for different running points on the controller which throws in the resistances in the rotor. The curves show quite different conditions at the various steps. Take for instance point (8) In this position all the outside resistance is cut out of the rotor, and the motor will run at its highest speed, for the rated frequency.

The slip is very small at this point, it being only about 7% at an output of 4.5 HP. As more resistance is introduced into the rotor the slip becomes greater with load. On no load the speed of the motor is nearly the same at all steps on the controller, as it takes very little torque to run the motor, and the slip need not be great to produce it. However on load it requires a certain torque to carry this load, and torque is proportional to Stator flux and Rotor current. Hence if the resistance in the rotor be increased, the slip must increase, that is, the rate of cutting flux by the rotor must increase in order to keep up the rotor current, and carry the load. Therefore the same load may be carried at a reduced speed by putting in resistance in the rotor. This is not an economical method of reducing the speed because the extra energy that might be used in carrying the load at the higher speed is now used up in the rotor resistances, and it takes practically the same motor input to carry the load either at low speed or full speed. Noting the efficiency curves it is seen that when running on point (8) the efficiency reaches 78% which is fairly good for an induction motor of this capacity, and on point (5) it is 59%, while on point (2) it is only 53%. When running on point (2) the slip increases to 45% when the "pull out" point is reached and the mtor will not carry the load but comes to rest. It will be noted also that at this step the "pull out" point occurs at a load of 1.4 HP. while on point (8) nearly 4.5 HP. was obtained and the "pull out" point had not yet been reached.

The Power Factor of the motor is quite low, which is nearly always the case in low speed motors, and those having a large number of poles. On point (8) it reaches .56, and on point (2) it is always less than .5, one wattmeter reading negatively throughout the test.

These tests show that while the "Form M" Induction motor is very convenient to use in any place where frequent changes of speed are necessary, yet it gives results that are far from desirable, both in Efficiency and Power Factor. However this Form may be started as readily as any induction motor with starting device, without a heavy draft of current from the line. The problem yet remains for the Engineer to devise a system of speed control which does not materially lower the value of the desirable characteristics of the Induction Motor.

DATA - Point (2).

W_1	W_2	A_1	A_2	V	R.P.M.	Weight
-620	900	11.5	11.5	222	868	0
-580	900	11.	11.	216	820	.875
-430	1050	11.5	11.5	216	743	2.
-390	1150	12.	12.	217	637	3.
-320	1270	13.	12.5	221	588	3.75
-280	1300	13.5	13.5	222	540	4.5
-240	1300	13.	13.	215	502	4.87
-160	1300	13.5	14.	218	434	5.69
-140	1300	13.5	14.	217	405	6.
-120	1300	14.	14.	219	405	6.12
-100	1310	14.	14.1	216	367	6.25

Input		Output	Efficiency	Cos Φ	Slip
Watts	HP.	HP.	%		%
560	.75	0	0	.127	0
640	.86	.41	47.7	.156	5.5
1240	1.66	.85	51.2	.288	14.4
1520	2.04	1.09	53.5	.337	26.5
1900	2.55	1.26	49.5	.390	32.2

DATA - Point (2) - Continued.

Input Watts	Input HP.	Output HP.	Efficiency %	Cos Φ	Slip %
2040	2.73	1.39	51.	.394	37.8
2120	2.84	1.4	49.4	.438	42.1
2280	3.05	1.41	46.4	.440	50.
2320	3.11	1.39	44.8	.449	53.3
2360	3.16	1.42	44.9	.445	53.3
2420	2.25	1.31	40.3	.461	57.7

Point #5.

W_1	W_2	A_1	A_2	V_1	V_2	Speed	Weight
-300	1300	12.5	12.5	222	222	790	3.5
-200	1300	12.	12.	222	222	780	4.375
- 50	1500	13.5	13.5	220	220	720	5.5
0	1525	14.	14.	221	221	710	6.125
+120	1625	15.	15.	210	210	680	6.75
300	1750	17.5	17.5	220	220	600	8.75
400	2300	22.2	22.2	218	218	460	11.25
600	2600	23.	23.	222	222	390	14.5

Input Watts	Input HP.	% Slip	Output	Efficiency	Cos Φ
2000	2.68	9.5	1.56	58.2	.36
2200	2.94	11.5	1.67	56.9	.41
2900	3.88	17.5	2.26	58.2	.48
3290	4.40	18.6	2.48	56.3	.53
3850	5.16	22.	2.62	50.7	.58
4100	5.5	31.2	2.99	54.3	.55
5400	7.23	47.3	3.28	45.3	.55
6400	8.57	55.3	3.23	38.	.56

DATA - Point (6)

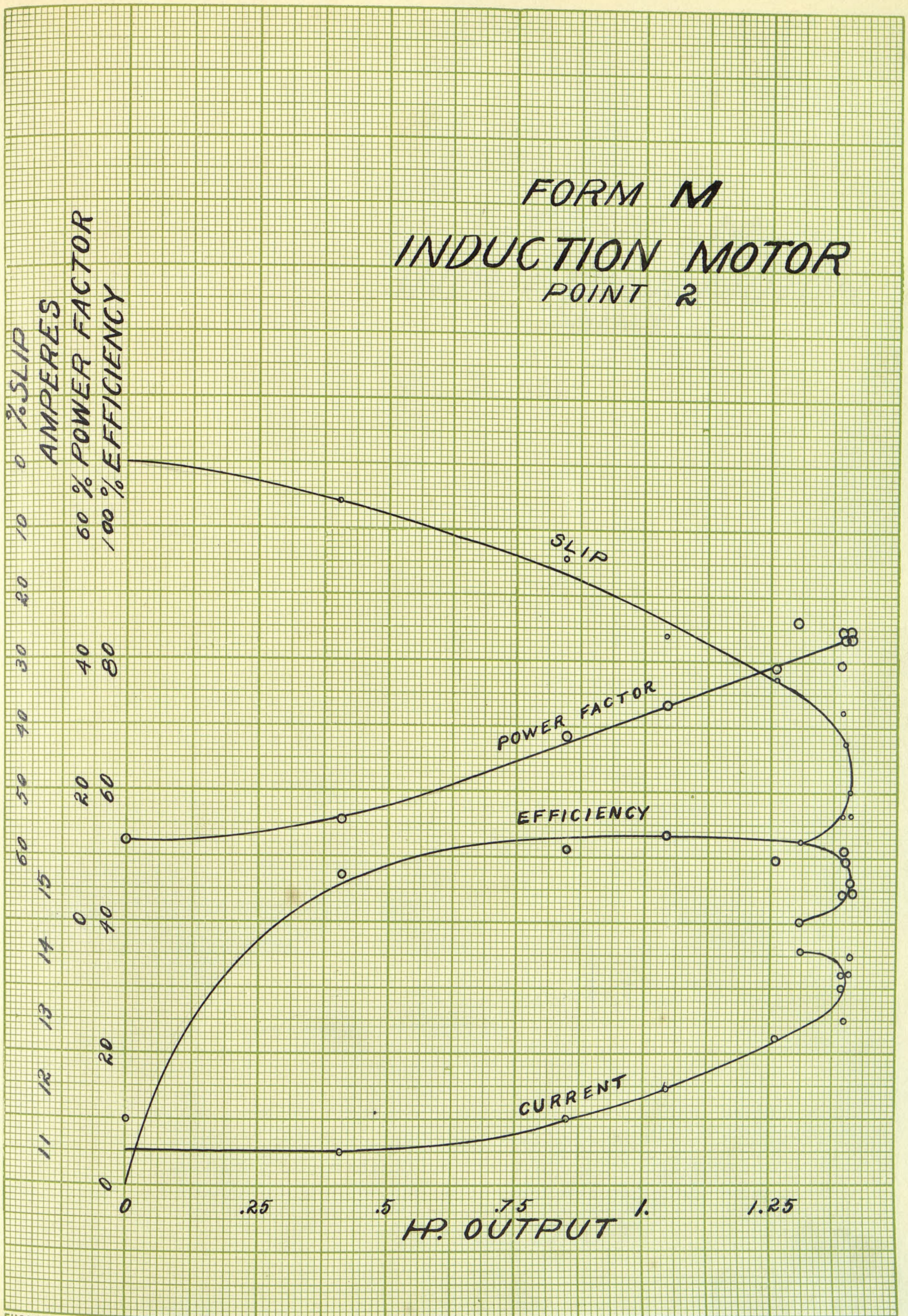
Input Watts	HP.	Speed R.P.M.	Weight #	Output HP.
580	.77	873	0	0
1010	1.35	864	1.125	.56
1060	1.42	854	1.833	.89
1606	2.15	854	2.833	1.38
2320	3.11	835	4.75	2.26
2540	3.40	820	5.25	2.45
2960	3.96	806	6.375	2.93
3400	4.55	796	7.5	3.41

Efficiency %	V x A.	Power Factor	Slip %
0	5192	.11	3.
41.4	5303	.19	4.
62.6	5192	.20	5.1
64.1	5550	.289	5.1
72.6	5940	.39	7.2
72.	5672	.44	8.8
73.9	6570	.45	10.4
74.9	6438	.52	11.5

DATA - Point (8)

W_1	W_2	A_1	A_2	V	Speed	Weight
750	-510	10.5	10.	222	878	0
810	-430	10.	10.	221	869	1.
900	-380	10.5	10.	222	878	1.875
1300	-280	12.	13.5	222	840	4.312
1450	-200	12.	14.	220	850	5.
1533	0	15.	15.	222	830	6.69
1540	0	15.	15.	222	830	6.81
1800	+450	16.	16.	216	840	9.

Input		Output	Efficiency	Cos Φ	Slip
Watts	HP.	HP.	%		%
480	.64	0	0	.122	0
760	1.01	.496	49.	.199	1.
1040	1.39	.94	67.6	.264	0 .
2040	2.74	2.07	75.6	.417	4.3
2500	3.32	2.42	73.	.505	3.2
3066	4.1	3.16	79.	.335	5.4
3080	4.12	3.25	77.2	.533	5.4
4500	6.04	4.33	72.	.752	4.3



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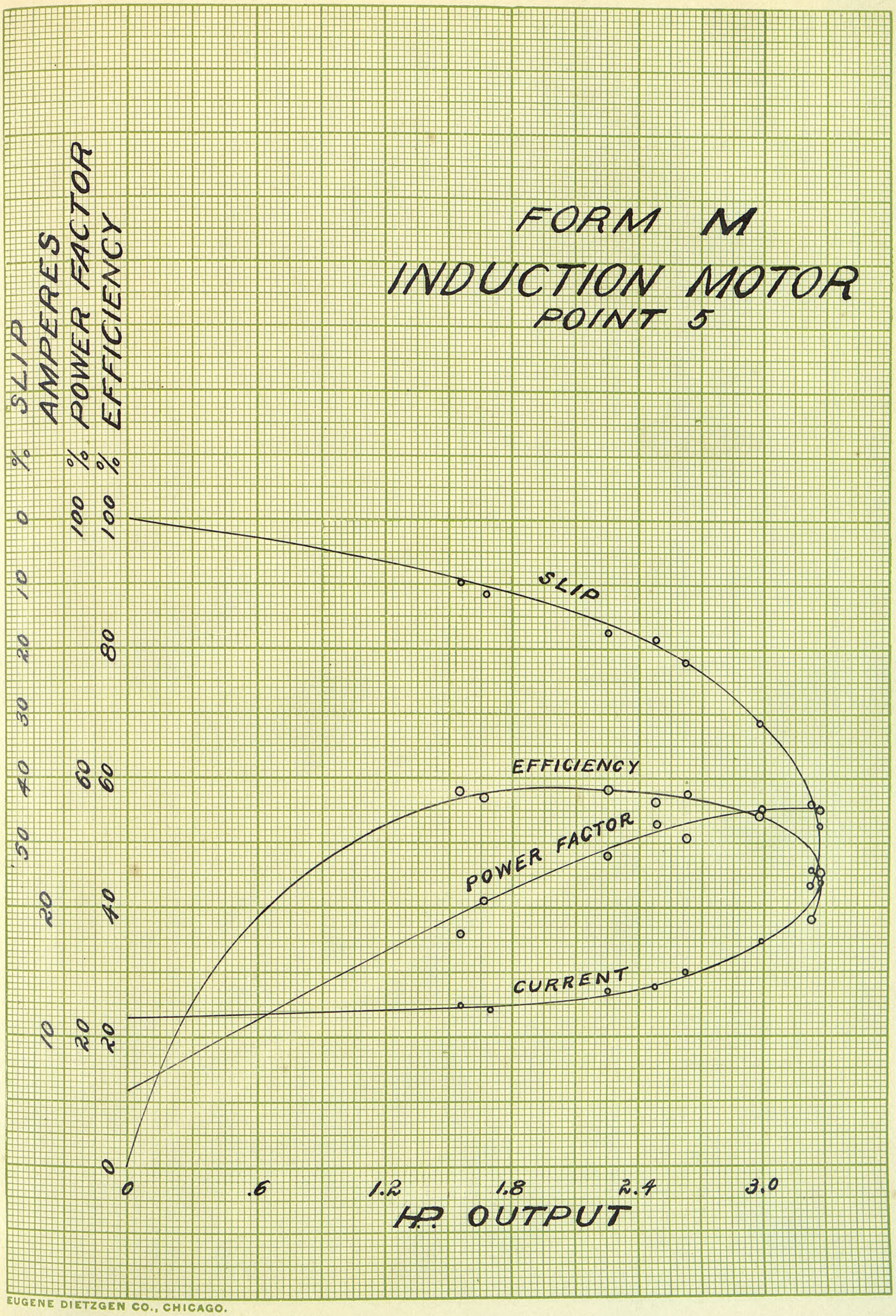

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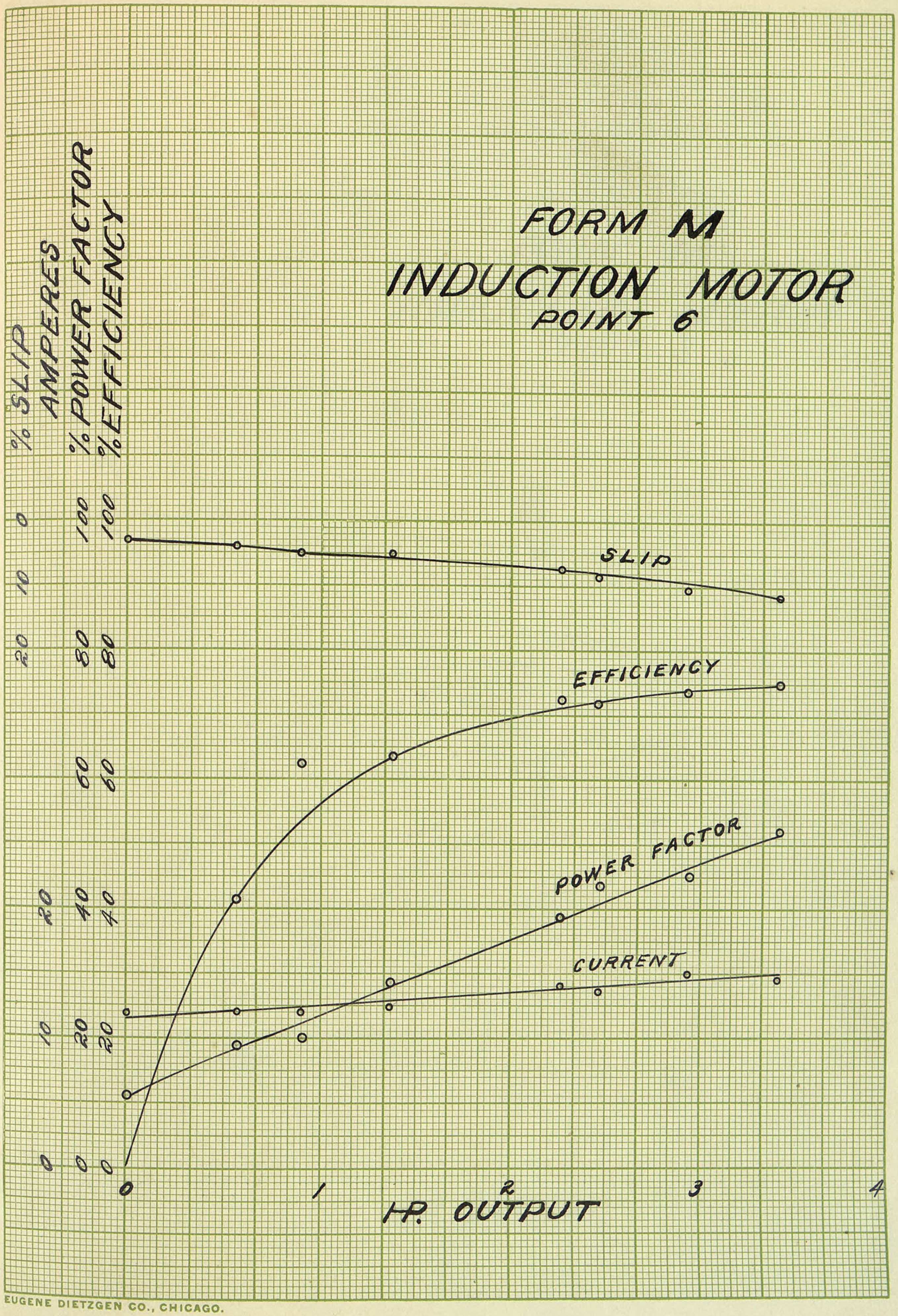
FORM M
INDUCTION MOTOR
POINT 6
% SLIP
AMPERES
% POWER FACTOR
% EFFICIENCY
SLIP
EFFICIENCY
POWER FACTOR
CURRENT
0
10
20
40
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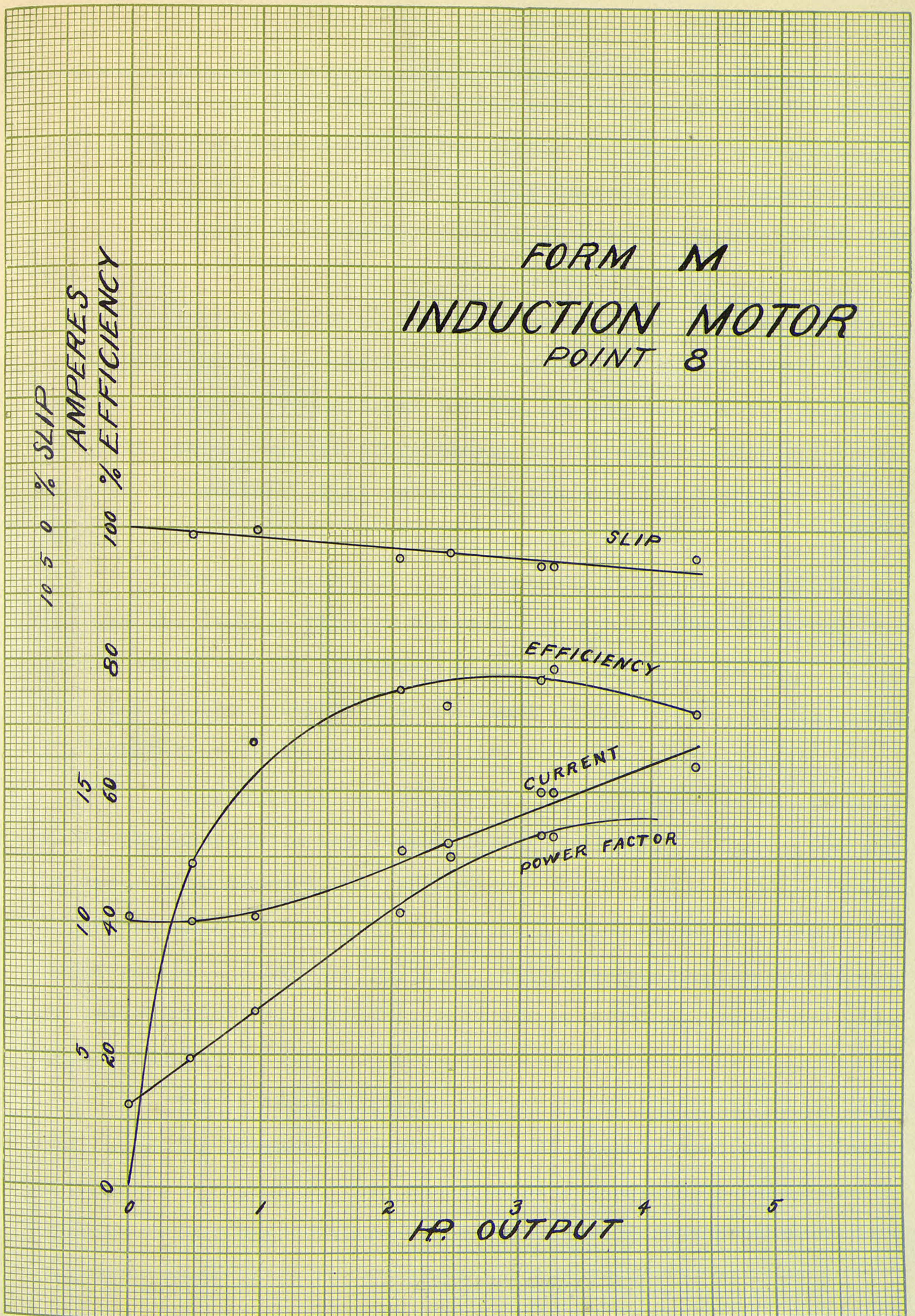
4
H.P. OUTPUT



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One of the most useful diagrams in determining the performance of an induction motor is the circle or Heyland diagram which is shown in the figure. By means of this diagram the efficiency, torque, output, slip and power factor for any load on the motor may be determined.

In the figure OQ represents the applied voltage, PQ the drop in voltage due to the resistance of the stator windings and OP the effective voltage. The current for any load in the stator is represented by OA_1 which is also proportional to the ampere turns and hence the flux in the stator. B_1A_1 represents the magnetic leakage in the stator.

The corresponding current in the rotor is represented by OA_2 and the leakage flux of the rotor by A_2B_2. Then the total flux in the stator is the resultant of OA_1 and OB_2 which is OC_1. Likewise the flux in the rotor is the resultant of OA_2 and OB_1 or OC_2. Then the total flux in the air gap is OC_0.

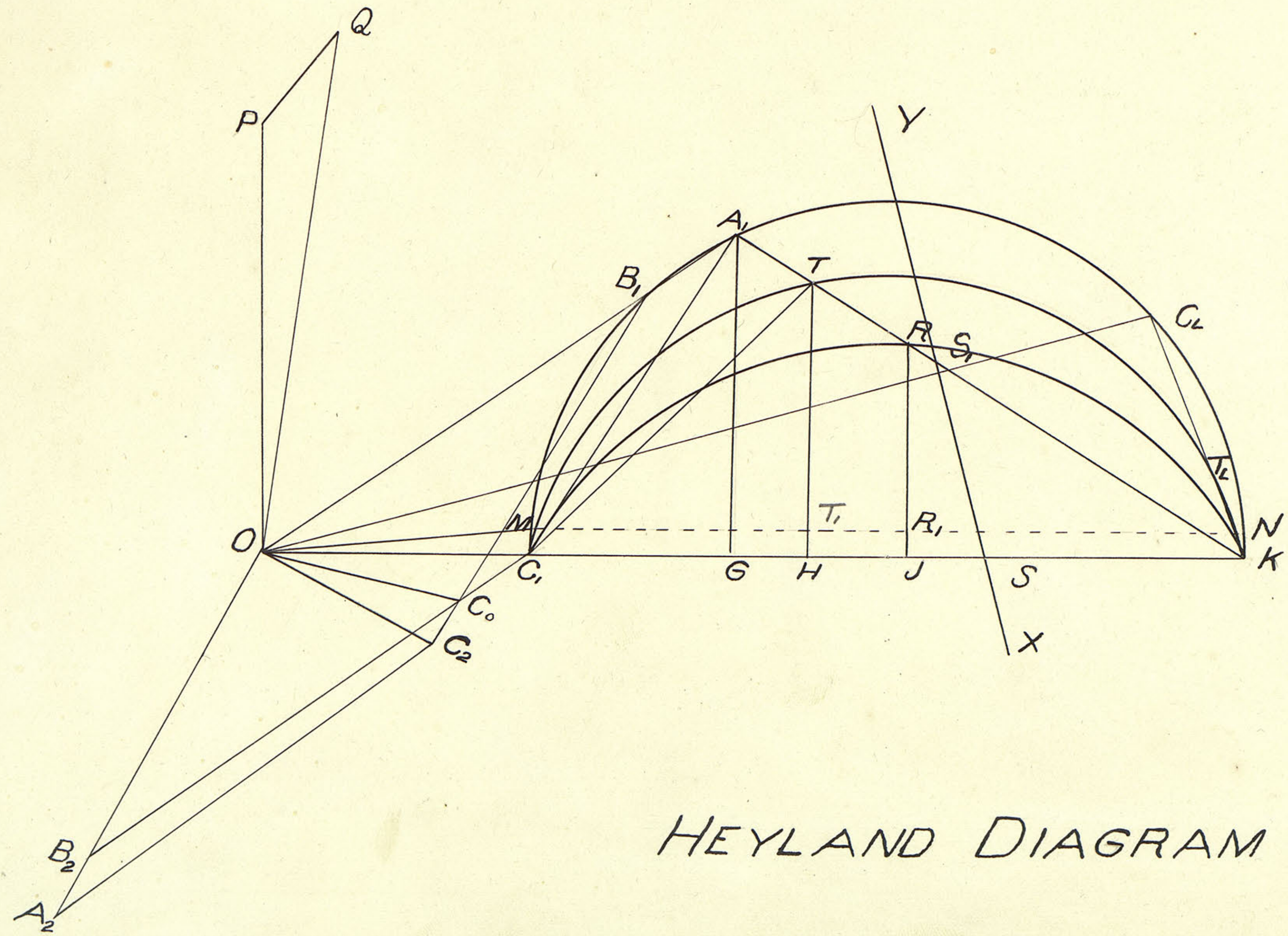
In constructing the diagram lay off the line OA_1 proportional to the amperes in the stator making angle QOA_1 equal to the angle of lag. Then A_1G will be proportional to the motor input. It can be proven that the locus of the point A_1 lies on an arc of a circle, which passes through the point C_L, which represents the conditions at locked armature, similarly laid off as point A_1, and whose diameter KC_1 is constant.

Due to the resistance of the stator the total input is not available for torque. Lay off on AK, AT proportional to the drop of voltage in the stator, then the circle of torque C_1TK will pass through T_1. Of the total torque TH TT_1 only is available the remaining T_1H being used up in the constant no load losses of the motor.

Due to the resistance of the rotor there is a drop, which when reduced to the equivalent primary drop is represented by TR. Then the circle of output passes through the point R, and the output is proportional to RR_1.

The slip is represented by the line xy. This line is drawn so that angle YSK = angle C_1TK. Then the slip is proportional to the segment SS_1 of xy.

This diagram is very practical in determining the performance of large induction motors or any other induction motors where it is impracticable to make a complete brake test. By taking the measurements while running light, on locked armature and on intermediate load, complete data may be worked out for any load, when the resistances of the stator and rotor are known. In large motors full voltage cannot be thrown upon the stator in the locked armature test, but due to the low magnetic density at which induction motors are worked, the current at reduced voltage may be reduced to the value at rated voltage as the current is proportional to the impressed voltage.



HEYLAND DIAGRAM