T H E S I S

on

The Induction Motor and Performance Test

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<u>O R E G O N</u> <u>A G R I C U L T U R A L</u> <u>C O L L E G E</u>

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The Induction Motor and Performance Test.

The induction motor is essentially a transformer and is analagous to the direct current shant wound machine. In the transformer the primary and secondary are both stationary and the electrical energy alone is changed from one pressure to another as desired; while in the induction motor the stator or field windings, corresponding to the primary coil in the transformer, and the rotor, corresponding to the secondary, by virtue of their action on each other produce mechanical energy which is utilized. In other words a polyphase induction motor is equivalent to a stationary transformer with considerable magnetic leakage between primary and secondary coils. There is this difference, however, the rotor in which currents are induced is in many ways equivalent magnetically to that of a direct-current shunt-wound motor with a large amount of armature reaction.

The following discussion is confined mostly to that type of machine in which the squirrel cage revolving secondary is used. In its most primitive form it consisted simply of a disk-aramature as described by Baily in 1879 and due to Tesla (1888), of the fact that two, three, or more alternating currents of different phases combined produced a rotating field of magnetism. Later Ferraris in his experiments used a copper cylinder.

A conductor carrying current, when passing through a magnetic field is acted upon by a force which is both at right angles to the lines in such a field and to the direction of flow of the current. Hence for the best production of mechanical effects these currents must be led through strong fields of the proper polarity, that is they must follow a path under one pole in going one way and in returning follow a path crossing a field of opposite polarity to that of the one they followed in going the opposite way. It follows that the next step in the development of the induction motor was the introduction of slits running nearly the full length of the copper cylinder, or to simply build up a rotor of a number of bars joined to rings at the ends. This idea was first developed by Dobrowolsky under the name of Schluss-anker, in its several forms however no attention was paid to the insulation of those bars from the iron core. The resistance of the iron to the flow of induced currents was so high that although there was a strong magnetic field there was not sufficient induced currents to develope the desired torque. This difficulty was overcome by building up an iron core of annealed laminations and which was well insulated from the copper bars passing through slots in its surface. These precautions reduced the eddy currents which caused loss by expending power in heating effect, and they also caused the induced currents to flow along the desired bars or conductors. This brings us to the present form of rotor generally employed in small motors, a "Squirrel-cage" of copper strips or rods on an insulated core of laminated iron, the bars being short-circuited by copper rings at each end.

It may be said that the two essential parts of the induction motor consist of the stationary member designated as the stator and a moving one called the rotor. The windings of the stator are exactly the same as those of the polyphase alternator and are embedded, insulated from, and nearly enclosed in slots in the periphery of the laminated iron core. The rotor is built up as all ready described and gives the distinguishingname to this type of motor.

The operation of a polyphase machine of this kind depends upon the magnetic action before mentioned in connection with its discoverer. The alternating currents, differing in phase relationship with each other, circulating in the stator windings set up a rotating field. As the laminated iron core offers less resistance to the magnetic lines thus produced than the surrounding air, they pass through the iron and cause polarization. The rotating magnetic field induces a current in the short-circuited windings of the rotor which in turn causes a magnetic flux in the laminated iron core of that member. The action of the rotating magnetic field of the stator on the magentic flux of the rotor causes it to rotate with the polarity or magnetism of the stator. We might suppose then that the rotor would move with the same frequency as the field which is equal to that of the current divided by the number of pairs of poles, this however is not the case.

At this point will be briefly considered the induction motor in its frequency transformation action. It is apparent that unless the rotor is standing still the frequency of the current in the stator and that of the induced current in the rotor will differ. If the rotor were slowly turned in a backward direction the periodicity of its current would be greater than that flowing in the stator; at rest the frequency would be the same in both members; as the speed increased the alternations per second would grow less until if it ran in synchronism its frequency would be zero. It is on account of this low periodicity of rotor currents when running that the iron- losses in its teeth are almost negligible.

The rotor, being swept by the passing lines of magnetism, has induced currents sep up in it, the mechanical reaction of these currents drive the rotor in the same direction. Even at no load, when the rotor attains its highest speed, it falls slightly short of synchronism, that is it does not actually run at the same speed as the invisible field of magnetism. When at full load it runs even slower, in practice from two to three per cent or in small machines as high as five and six per cent below that of the revolving field. This drop designated as the slip, is an essential feature of all such motors, and hence their name asynchronous, by which they are sometimes designated. It is in fact the slip which gives the driving forces, its necessity is apparent from the principles of induction. If absolutely no power were required to rotate the secondary there would be no slip; as the load comes on the amount of slip increases. If the rotor ran actually at full speed, that is in absolute synchronism there would be no relative motion between the fluxes and the secondary conductors and hence no electro-motive-forces induced, no rotor currents, and no driving forces. The effect of slip in cutting lines of force is the same as if the flux stood still and the rotor revolved backward at a speed equal to the slip. Therefore the slip being small the currents induced will be small; with increase of load there is increase of slip and consequently increase of driving-forces; or in other words the driving-forces are proportional to the slip and are automatically increased by it in proportion to the load. That is if we neglect copper losses and reactions in the motor the slip is directly proportional to the rotor losses.

From the relation of slip to the driving-power we see that it must also have a relation to the starting torque. The torque at starting must be in some cases from one and one fourth to one and one half that of full load, while the maximum for conditions running may vary approximately from two and one fourth to two and one half that of full load. In the constant-speed type of motors only an average starting-torque is required. If the speed only was to be taken care of the slip could be made much less. A heavy starting torque and low starting current require a greater amount of slip and dĕpend directly upon it.

The arguments in favor of the use of the induction motor are many. They require very little attention and can be operated by anyone. They are inexpensive, simple in construction, and efficient in operation. In mills and many other places where dust or explosive gases are prevalent and there is much danger from fire; since the rotor of the induction motor receives its current entireely by induction and not by conduction there is no necessity for commutator or brushes and resulting sparking and hence it is the ideal source of power for such places. In quarries where the dust or neglect would injure and give much trouble with other machines the induction motor is completely protected. Its simpleness of construction and operation; its high efficiency and the fact that it may be run in any place where a motor may be used for power, fully warrants its use, or at least due consideration before other kinds are installed.

PERFORMANCE TEST.

- The operating features of an induction motor may be best judged from a set of curves. All the data are plotted to horse-power output as abscissae; the three most important curves being those of efficiency, power factor, and speed. The curve of "true H. P. Input" is the volt-ampere input divided by 746. The ordinates of the power factor curve are the ratio of the true input to the apparent input. The performance curve shown on the sheet marked "I" were calculated from losses in the motor. The following is the experimental data taken from actual test and used in computations.

The machine used in this test was of the General Electric Co. make, type I, 110 volts and 52 amperes. Ten horse power rating, speed 1200, three phase. The rotor was of the "Squirrel Cage" type.

*	AMPERES			VOLTS			WATTS		MOTOR SPEED	IND. SLIP
	A	B	C	AB	BC	CA	A-AB	C-CB		
1	20	21.05	23.5	117	117	117	-170	320	1245	5
2	20	25.2	23.5	118	119	119	-175	290	1260	12
3	20	24	26	117	117	117	-30	430	1250	34
4	25	24	28	117	117	117	0	460	1250	44
5	25	24	27	117	117	117	20	470	1250	52
6	26	24	28	117	116	117	70	490	1250	57
7	30.5	29	33	116	116	116	220	640	1250	96
8	35	30	33	115	116	115	240	660	1240	106
9	33	30	35	115	115	115	250	700	1240	
10	35	38	40	114	114	114	280	840	1220	132
11	44	45	48	113	113	113	520	1000	1210	164
12	45	50	52	112	112	112	550	1100	1210	208

The column marked thus* contains numbers corresponding to the same lines in the table of computed values.

The following table of results is from the above experimental data. The electrical power-input of a three-phase motor being measured by the so-called two-wattmeter method, one of the line wires, sayB, is assumed to be the common return for the other two wires: The total watts is then the sum of the watts A-AB and C-CB but the two readings are only equal when the power factor is 100% and the load is balanced. The induction motor load is usually balanced but is always less than 100% power factor hence one wattmeter reading is always smaller than the other. When the power factor of the motor becomes less than 50% the wattmeters begin to give negative readings and the potential leads of the meter must be reversed and the difference of readings taken. A five to one current transformer was used with the wattmeter so that the readings must also be multiplied by five.

	Total Watts	Volt Amperes	Apparent H.P. In	True H.P. Input	H.P. Output	Power Factor	Efficiency	Torque	% Slip
* 1	750	4350	5.83	1.04	0	.172	0	0	.004
2	1075	4670	6.27	1.44	.4	.232	.315	5.53	.0095
3	2000	4725	6.34	2.68	1.68	.424	.626	21.64	.027
4.	2300	5200	6.98	3.09	2.05	.442	.665	26.3	.035
5	2450	5130	6.9	3.29	2.25	.478	.681	29.07	.0415
6	2800	5270	7.07	3.76	2.72	.53	.732	35.5	.0455
7	4300	6200	8.32	5.77	4.73	.695	.825	61.5	.0767
8	4500	6480	8.7	6.04	5.00	.695	.83	65.5	.0854
9	4750	6500	8.74	6.37	5.33	.73	.842	69.88	
10	6100	7400	9.94	8.2	7.16	.82	.875	92.5	.108
11	7600	8925	11.94	10.2	9.16	.85	.9	122.56	.135
12	8250	9500	12.71	11.05	10.01	.87	.9L	134.4	.17

These values are used in plotting curves on sheet marked "I".

Same Performance Curves from Circle Diagram.

The above performance curves and data may also be predetermined from a vector diagram(page marked "11"), as a "check" on the observed readings. The actual load tests are avoided, whenever possible, as they require considerable expenditure of energy, and special appliances to secure accurate results. For large size machines the waste of power and arrangements for load make actual tests impossible hence methods have been developed whereby the actual performance of the machine, under load conditions, may be determined from a few simple readings taken at no load.

The magnetizing current M in each phase of the stator winding is determined by driving the motor at no load, the value of M. effective is measured by an ammeter, and the phase difference, angle QOM, between E(for one phase) and M calaculated from the measured values of E and M and the wattmeter reading E M cosine angle QOM. The line OM representing the magnetizing current so determined, the point M is then one point on the circular locus of the stator current per phase.

Another point on the circle is found by measuring the current and power delivered per stator phase at any load or at standstill. Therefore, if the current and power per stator phase is measured at standstill, the line OP' representing this current may be laid off in the same way as explained above for OM.

11

Since the two points M and P' on the circle are known and that the diameter is a line at right angles to O E' passing through M, the line P' P" may be drawn at right angles to M P' and through the point M, thus the diameter M P' is determined and the circle may be drawn.

To use the circle diagram the resistance R' of each phase of the stator winding must be measured and what is called the equivalent resistance R" of the rotor per stator phase determined. Provided the rotor were wire-wound and had the same number of conductors in each phase as the stator, R" would equal the actual resistance of the rotor winding; the current per rotor phase would equal the load current I' in each stator phase and the $I^2R"$ loss of the rotor would be $qI^2R"$, where q is the number of phases. In any case the equivalent resistance of the rotor R" per stator phase is: Actual rotor I^2R loss equals qI^2R^2 q being the number of stator phases and I' the load current per stator phase.

R" is calculated from the measured current and power input per stator phase, R' having been measured, as follows. Input per phase minus E' times $\overline{Om}$ minus R' times $\overline{OP}'^2$, (see page marked "II") equals the rotor I^2R loss per phase at stand-still, this is then equal to $I'^2R"$ where I' is represented by MP'.

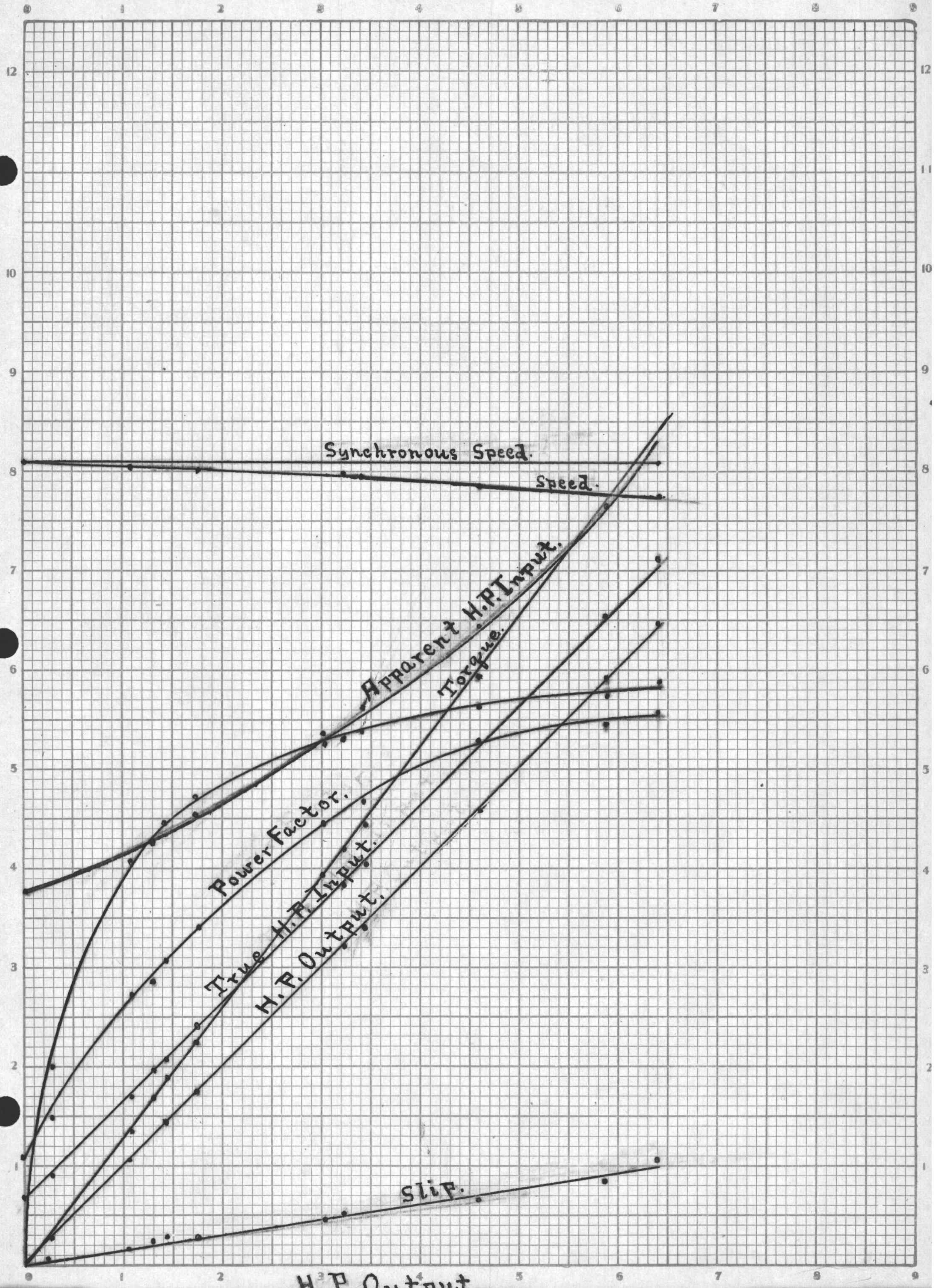
Use of diagram.--Having determined R' and R", performance curves are determined as follows: Take point

P at several positions on circular current locus and for each position calculate as follows: Motor intake equals $\overline{OQ}$ times E'Xq, where q is the number of phases. Power factor of motor equals cosine of angle POE'. Total power delivered to rotor equals ($\overline{mO}$ times E' minus R' times $\overline{OP}^2$) times q(Electrical power b developed in rotor equals R" times $\overline{NP}^2$ times q) Mechanical power developed in rotor equals a munus b. Motor slip is found from the equation b equals Sa, motor speed n can be found since synchronous speed is known. Efficiency equals b divided by motor intake. Torque is found from the equation 2π n T equals a; T is in watts per unit angular velocity,(watts per radians per second). If in terms of at is expressed in "synchronous watts" so called, or the power in watts that the torque would develop when driving the rotor at synchronous speed.

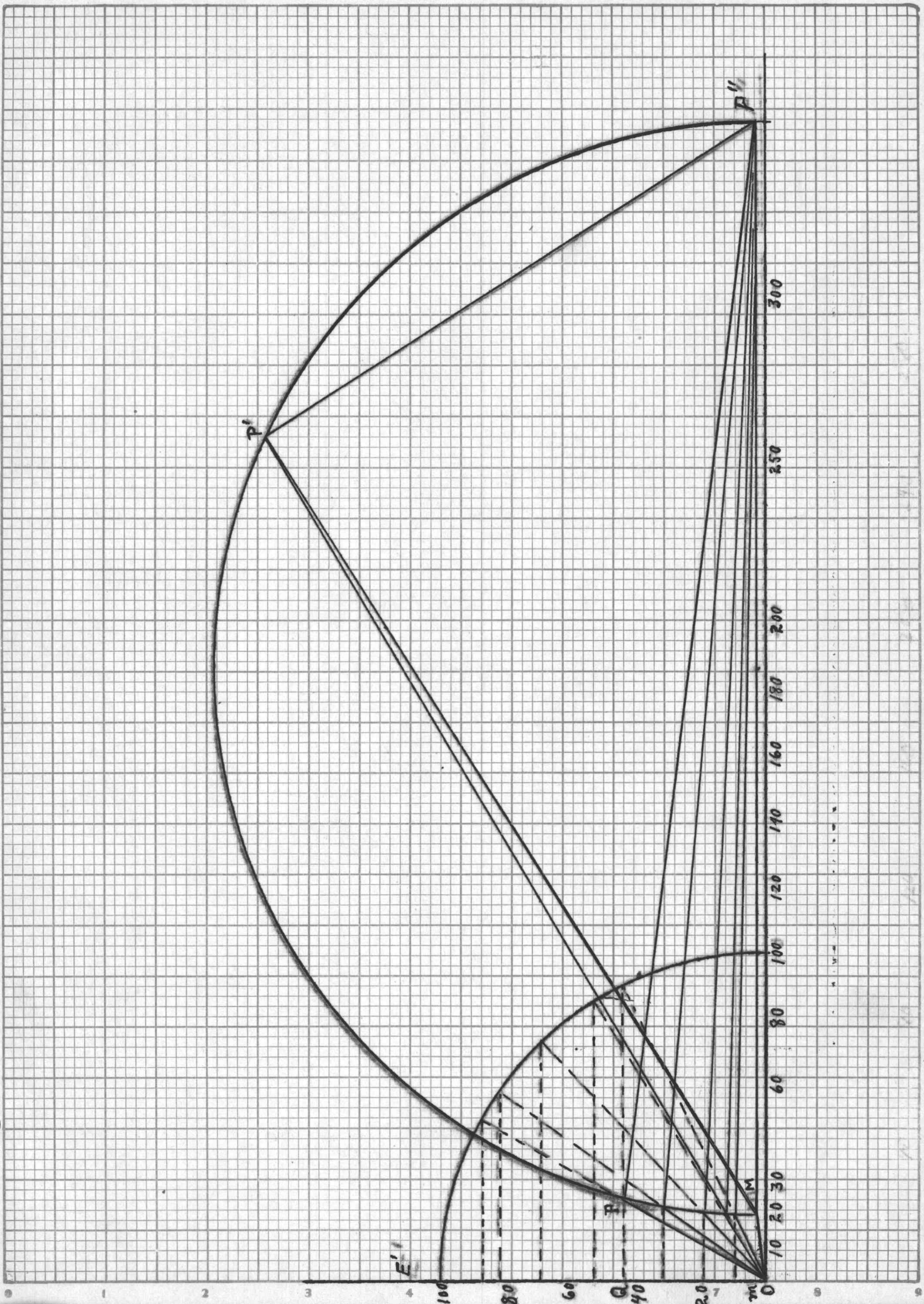
The following is a table of results obtained from the circle diagram (page "I") resistance of stator R' being .046.

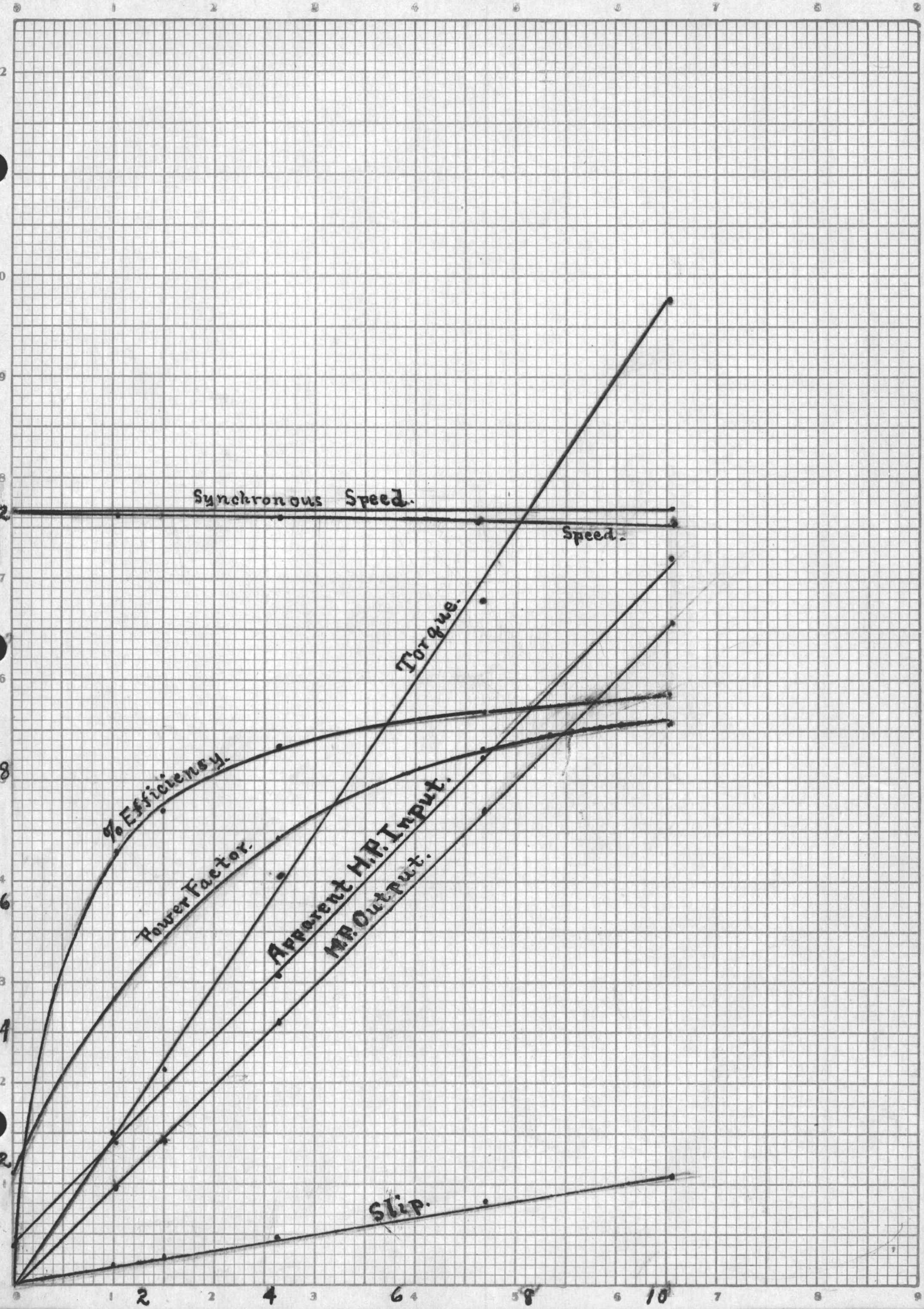
P.F.	Amp. Input per phase	Volt	App. P. Input	A Power Dev Rotor	b. E. P. in Rotor	Mech. P. Dev. to rotor	% Slip	Speed	% Eff.	Torque
.17	20.	110	.56	0	0	0		1200	0	0
.44	22.2	110	2.3	1.55	.0044	1.546	.0032	1196	67.2	6.81
.53	24	110	3.09	2.29	.01	2.28	.0043	1195	73.7	10.07
.69	28.2	110	4.85	4.06	.03	4.03	.0074	1191	83.1	19.29
.83	39.	110	8.17	7.3	.1	7.2	.0137	1184	88.1	31.05
.87	50	110	11.2	10.25	.17	10.08	.0166	1180	90.9	45.54

The performance curves on sheet "III" are plotted from this data. By comparison of this table with preceding ones and with the curves thus obtained it may be seen how nearly the motor in actual practice comes to the theoretical or predetermined conditions.


Synchronous Speed.
Speed.
Apparent H.P. Input.
Torque.
Power Factor.
True H.P. Input.
H.P. Output.
Slip.
H.P. Output

II




Synchronous Speed.
Speed.
Torque.
% Efficiensy.
Power Factor.
Apparent H.P. Input.
H.P. Output.
Slip.
12
8
6
4
2
2
4
6
8
10