THESIS

COMPARISON OF ELECTRICAL AND MECHANICAL METHODS FOR DETERMINING THE EFFICIENCY OF MOTORS

BY

R. P. KELLEY R. W. SHEEHAN

1917

Electric Motors, Induction

Copy I.

THESIS

Copy I

Electrical engineering

Comparison of Electrical and Mechanical Methods for Determining the Efficiency of Motors.

A Thesis Submitted to

The Faculty of

MICHIGAN AGRICULTURAL COLLEGE.

By

R.P. Kelley. R.W. Sheehan.

Candidates for the Degree of

Bachelor of Science.

June 1917.

THESIS

cop. 1

PREFACE.

The object of the tests on the Induction Motor was to obtain all of the data possible for the comparison of the different methods of determining the efficiency of this type of Alternating Current apparatus;and to become familiar with the different methods used commercially for testing the efficiency of motors.

Data was taken for the different tests and curves plotted from the calculated results.These curves furnish an easy and accurate method of comparing the relative merits of the different methods.

A study was made of the different kinds of brakes used for the Brake Test and the kind shown in our sketch was finally selected.We are indebted to Prof. Polson for advice on this subject. The main reason for selecting the type of brake used was that the length of the brake arm is constant at all conditions of load.

R.P.K.

R.W.S.

BIBLIOGRAPHY.

Experimental Electrical Engineering------Karapetoff

570- 584

561 - 564.

Standard Hand Book.-----------------------Sect.7

115 - 128

199 - 209.

Sheldon, Mason and Hausman----------------231 - 233.

Penders American Hand Book----------------1000 - 1005.

American Correspondence Schools-----------Volume 4.

360 - 364.

Steinmetz A.C. Phenomena------------------306 - 310.

LIST OF APPARATUS USED.

MOTOR:

G.E.Induction Motor # 183030.
Type: KT-65A- 1200 - Form C.
60 cycle,5 H.P., 1200 R.P.M.
13.2 Amperes, 220 Volts.

WATTMETERS:

Weston A.C. Wattmeters # 207 and # 208.
Model 310, Max. capacity 20 amperes.
High range in volts 300, low 150.
High range in watts 3000, low 750.

Weston Portable A.C. Wattmeter
Max. capacity 25 amperes.
High range in volts 300, low 150.
High range in watts 6000, low 3000.
Model 16, # 4995.

CURRENT TRANSFORMERS:

Weston Switchboard Current Transformers.
Model 236,Type I,# 330, # 325.
Amperes 25 - 5.
Line voltage 2200,Frequency 25 - 125.
Watts 5.

AMMETERS:

Weston A.C. Ammeters.
Model 155, # 8892, Range 5 amperes.
Model 155, # 8889, Range 5 amperes.
Model 155, # 16615, Range 25 amperes.
Model 155, # 16451, Range 50 amperes.

VOLTMETER:

Weston A.C. Voltmeter.
Model 156, # 4143.

BRAKE:

Rope Brake as shown in blue print.

SCALES:

Platform scales,Range on arm 10 #, Max. range 100

SPEED COUNTER.

BRAKE TEST.

The object of a brake test on any motor is to obtain the data for calculating the H.P. output and input of the machine.

To do this suitable electrical measuring instruments are placed in the line and their readings,multiplied by some constant,will the power input into the machine. The output is measured by means of the brake and from these two sets of readings the efficiency is determined.

The set up was made as shown in the wiring diagram consisting of two wattmeters with the current coils connected in the two outside leads and the potentialcoils connected across the middle lead and the line in which the current coil was connected. Ammeters were placed in the two outside lines and a voltmeter across the lines.

The voltage was held at the name plate value of the machine and simultaneous readings of all instruments were taken. The scale weight and the speed of the motor were recorded.

Using the formula:

$$\text{H.P. Output} = \frac{2\pi W\,l\,n}{33000}$$

Where W= Weight at end of the arm.

l= Length of the brake arm.

n= R.P.M. of the motor

the H.P. output was calculated for each point of the test and the efficiency of the motor determined from the formula:

$$\text{Efficiency} = \frac{\text{H.P. Output}}{\text{H.P. Input}} \times 100.$$

BRAKE TEST # I.

DATA.

Wt.#	R.P.M.	Volts. AB	Amps. A	Amps. B	Watts AB	Watts. BC
0	I2I0	220	5.05	5.25	620	- 360
2	II95	220	5.I5	5.30	680	- 3I0
4	II85	220	5.I5	5.30	740	- 220
6	II80	220	5.35	5.45	840	- I80
8	II75	220	5.40	5.50	866	- I20
I0	II70	220	5.50	5.55	920	- 80
I5	II70	220	5.75	5.85	I060	+ 40
20	II70	220	6.I5	6.35	I200	+ I60
25	II70	220	6.65	6.85	I400	+ 320
30	II60	220	6.85	7.25	I490	+ 450
35	II50	220	7.65	8.00	I680	+ 600
40	II50	220	8.50	8.90	I870	+ 760
45	II55	220	8.90	9.30	2020	+ 880
50	II55	220	9.75	I0.I5	2220	I020
55	II55	220	I0.35	I0.50	2390	II90
60	II50	220	II.50	I2.25	2640	I380
65	II40	220	I2.90	I3.00	2800	I540

Radius of pulley plus I/2 thickness of rope = .344 ft.

Calculations for Brake Test.

$$H.P. = \frac{2\pi r}{33000} \times R.P.M. \times \text{load in pounds} = .0000656 \times RPM \times W$$

$$= .0000656 \times 1140 \times 65 = 4.85$$

BRAKE TEST # I.

(continued)

RESULTS.

Wt. #.	Total Watts Input.	H.P. Input.	H.P. Output.	Efficiency. %
0	260	.348	0.0	0.0
2	370	.495	.1565	31.6
4	520	.697	.315	45.2
6	660	.885	.465	52.6
8	746	1.00	.615	61.5
10	840	1.120	.766	69.0
15	1100	1.475	1.150	78.0
20	1360	1.82	1.530	84.0
25	1720	2.30	1.915	83.2
30	1940	2.60	2.26	87.0
35	2280	3.05	2.64	86.0
40	2630	3.52	3.01	85.5
45	2900	3.89	3.41	87.6
50	3240	4.34	3.78	87.0
55	3580	4.80	4.16	86.5
60	4020	5.37	4.51	84.0
65	4340	5.81	4.85	83.5

BRAKE TEST # 2.

The efficiency curves from Brake Test # I ,the Circle Diagram and the Loss method,while checking within 3 % at the full load point were over 5 % different at the quarter and half load points.Not being quite sure of our results from the first set of readings, we ran a second brake test on the same motor and under the same conditions.

DATA.

Wt.#.	R.P.M.	Volts AB	Amps. A	Amps. C	Watts AB	Watts. BC
0	I200	220	4.9	4.9	560	- 360
5	II95	220	4.95	4.95	680	- I90
I0	II93	220	5.I	5.I	820	- 30
I5	II80	220	5.55	5.5	960	+ I20
20	II80	220	6.I	6.0	II60	+280
25	II70	220	6.7	6.7	I320	+ 380
30	II65	220	7.3	7.3	I440	495
35	II60	220	8.0	8.0	I640	630
40	II55	220	8.7	8.75	I820	790
45	II50	220	9.5	9.6	2040	980
50	II45	220	I0.2	I0.3	2200	I080
60	II40	220	I2.0	I2.0	2560	I390
70	II30	220	I3.5	I3.5	2600	I640
80	II20	220	I6.0	I5.8	2400	I900

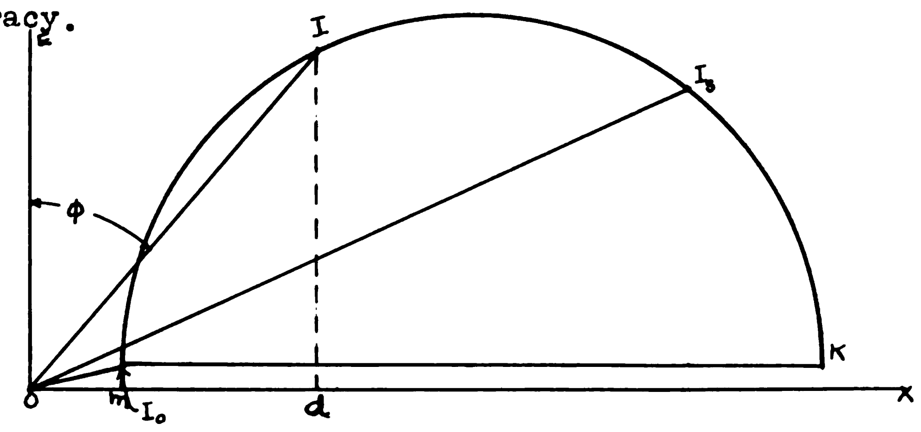
RESULTS.

Wt.#.	Total Watts Input.	H.P. Input.	H.P. Output.	Efficiency %
5	490	.656	.39I	59.8
I0	790	I.060	.78I	73.8
I5	I080	I.45	I.I6	80.0
20	I440	I.93	I.55	80.5
25	I700	2.28	I.92	84.0
30	I935	2.59	2.28	88.I
35	2270	3.04	2.67	87.7
40	26I0	3.50	3.02	86.4
45	3020	4.05	3.39	83.8
50	3280	4.40	3.75	85.2
60	3950	5.3	4.48	84.5
70	4240	6.69	5.09	88.8
80	4300	7.I	5.89	83.0

CIRCLE DIAGRAM.

Actual load tests on Induction Motors are avoided whenever it is possible because they involve a considerable expenditure of energy and require special appliances if accurate results are to be obtained. In machines beyond a certain size the waste of power and the arrangements for load make load tests practically impossible. Therefore methods have been developed for predetermining the performance of the machine under actual load conditions from a few simple readings taken at no load. One of these methods is by means of the circle diagram.

We will first explain the theory and the construction of the circle diagram and then give the proof of its accuracy.



Let OE in the figure represent the impressed voltage in one of the phases and OI the current in the same phase at a certain load. The angle Ø between the two then corresponds to the power factor of the motor at this load. Theory and experiment both show that, when the load is varied, the current changes in such a way that the locus of its vector is represented by a semicircle I_0IK

The current at no load is represented by the vector OI_o. The current is small and the phase angle EOI_o is large, the power factor being low. The no load current may be conside ered as consisting of a wattless component Om, which produces the magnetic flux, and a power component mO_o, which overcomes iron and friction loss in the motor. As the load increases, the point I_o moves along the circle, the value of the current increasing as well as the power factor. When the motor becomes overloaded the power factor decreases again, due to a more pronounced influence of the magnetic leakage. When the load is such that the motor stops, the c current it takes at standstill is represented by a certain vector OI_s. This current is called the short circuited current or the current with the armature locked. Thus if the circle has been determined for the motor, the power factor Cos $\emptyset$ may be measured from the diagram for any given value of the current input OI.

The proof of this can be verified by experiment with an accurate load test by plotting the vectors of current to the observed value of the phase angle $\emptyset$. It will be found that the load points lie on a semicircle.

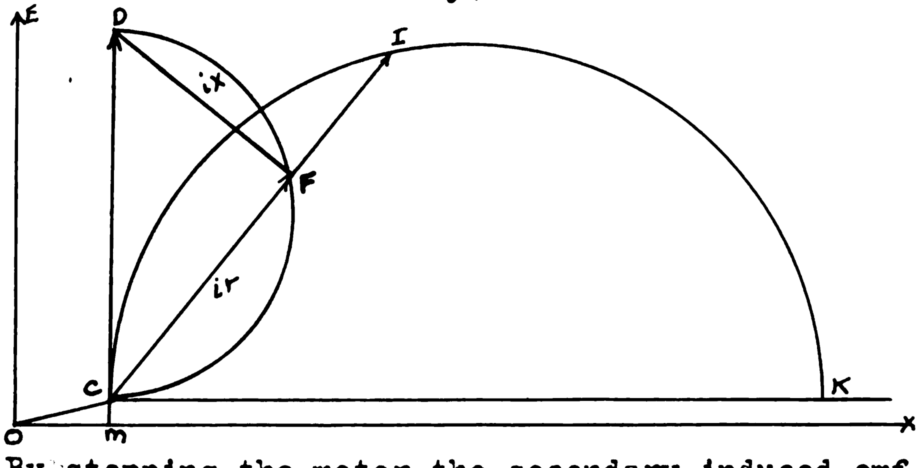
The circle may be constructed knowing only one point on it, if in addition, the position of the point I_o is known. As such a point, the point I_s is usually selected, the vector OI_s representing the current with the armature locked. No brake is really required in either case and the readings are both simple and accurate.

OI being the primary current, its component Id in phase with the voltage OE represents the working component of the current; therefore Id, multiplied by the voltage, gives true watts input per phase. The circle gives watts input and the value of the power factor for any given value of the primary current.

Output, torque, slip, efficiency, in fact all the data necessary for plotting the performance curves may be predetermined from the circle diagram.

PROOF OF THE CIRCLE DIAGRAM.

Instead of considering the rotor revolving and delivering mechanical power, it may be assumed as locked and loaded electrically on non-inductive external resistances. The same currents can be produced in the primary windings, by suitably varying the resistances, as if the rotor were revolving and were loaded mechanically.



By stopping the motor the secondary induced emf is increased $n_1 \div (n_1 - n_2)$ times, where n_1 is the synchronous speed of the motor, and n_2 is its actual speed. The revolving flux cuts the secondary conductors at a rate proportional to $(n_1 - n_2)$ when the rotor is revolving; with the armature locked the speed at which the conductors are cut by the flux is equal to n_1. The frequency of the secondary currents being thus greatly increased, the reactance of the secondary is thereby also increased the same number of times. By adding such an external resistance that the rotor resistance is is incresed $n_1 \div (n_1 - n_2)$ times, the same current and the same electrical relations are obtained in the secondary as with the rotor revolving; consequently the primary current will have the same value and the same power factor. Varying the external resistance is equivalent to varying the brake load with the armature revolving. In this way the Induction motor is reduced to a stationary transformer with an abnormal leakage and with a secondary load of non-inductive resistances , varying in value from 0 to infinity.

Such a transformer can be replaced by an equivalent resistance and an equivalent reactance and the problem is then reduced to merely this;A non-inductive load is connected to a constant potential line, with some resistance and some inductance in series with it. The locus of the current vector when the load changes from zero to infinity is to be determined This can be solved by the use of the above figure.

CD represents the vector of the line voltage, which is constant; CI is the current at a certain load. CF, in phase with the current,represents the resistance drop. FD, perpendicular to the current vector represents the reactive drop; CD the geometrical sum of CF and FD is constant. As the latter two vectors are perpendicular to each other, the point F moves on a semicircle having CD for its diameter. The equivalent reactance being constant under all conditions of load, the vector FD represents the current to a certain scale and is proportional to it.

Thus when the load varies, the extremity of the vector of the current moves on a semicircle. This semicircle CIK, has its diameter perpendicular to the true position of the current x vector.This proof applies to the induction motor, since it has been demonstrated that the circuits in the two cases are electrically equivalent. The only difference is that in addition to the load current CI, the inductiom motor takes a magnetizing current Om and a small power component mC for overcoming iron loss and friction. This brings the total primary current to the value OI and this figure is identical with that of the circle diagram of the induction motor.

CIRCLE DIAGRAM TEST.

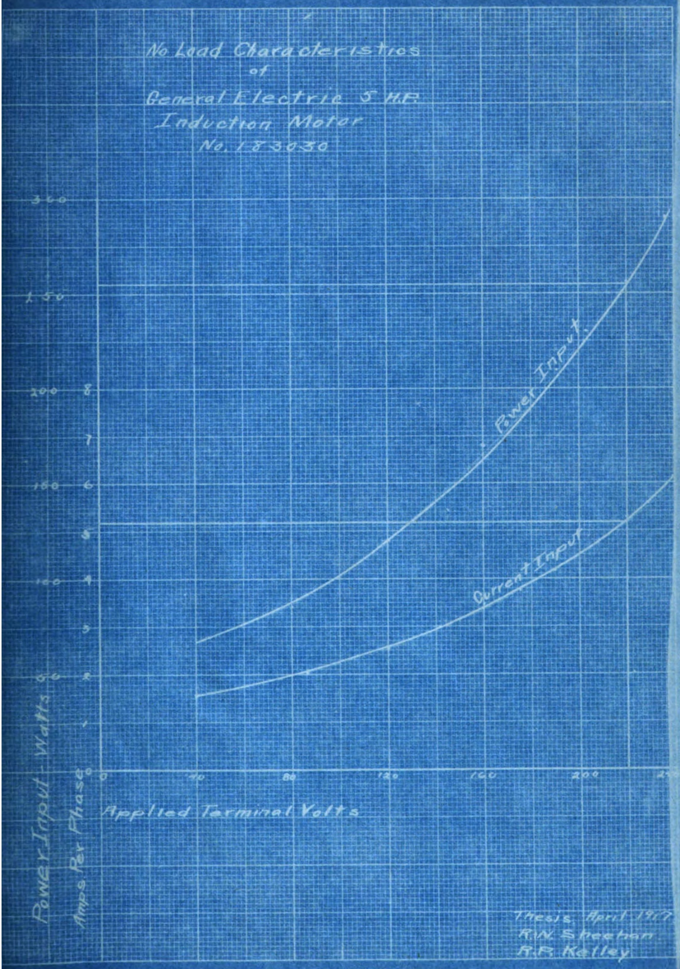
DATA.

EXCITATION TEST.

Volts. AB	Amps. A	Amps. C	Watts AB.	Watts BC.	Amps. Av.	Total Watts.
250	6.60	6.80	900	- 560	6.70	340
235	5.60	5.60	7I0	- 430	5.60	280
220	5.06	5.60	600	- 360	5.33	240
203	4.57	4.55	5I0	- 280	4.56	230
I90	4.I5	4.I5	430	- 2I0	4.I5	220
I75	3.7I	3.74	360	- I80	3.72	I80
I60	3.46	3.45	330	- I60	3.45	I70
I45	3.04	3.0I	250	- I20	3.02	I30
I20	2.52	2.55	I90	- 70	2.54	I20

RESULTS FROM EXCITATION TEST.

Rated Voltage.	Watts Input.	Amps. Input.
220	252	5.2


No Load Characteristics
of
General Electric 5 H.P.
Induction Motor
No. 183030
Power Input
Current Input
Power Input - Watts
Amps Per Phase
Applied Terminal Volts
0
40
80
120
160
200
300
250
200
150
100
50
8
7
6
5
4
3
2
1
0
Thesis April 1917
R.W. Sheehan
R.P. Kelley

CIRCLE DIA GRAM TEST.

SHORT CIRCUIT TEST.

DATA.

Volts. AB.	Amps. A.	Amps. C.	Watts AB.	Watts BC.	Amps Av.	Total Watts.
48	11.9	12.0	370	5	12.	375
50	16.0	16.0	640	20	16.0	660
56	18.0	18.1	890	25	18.05	915
62.5	21.5	21.5	1300	45	21.5	1345
80	25.5	25.8	1830	85	25.6	1915
102.5	32.5	32.8	2960	200	32.7	3160
122.0	39.5	40.0	4360	370	39.7	4730
140						6180
160						8210
180						10410
200						13000
210						14300
220						15775

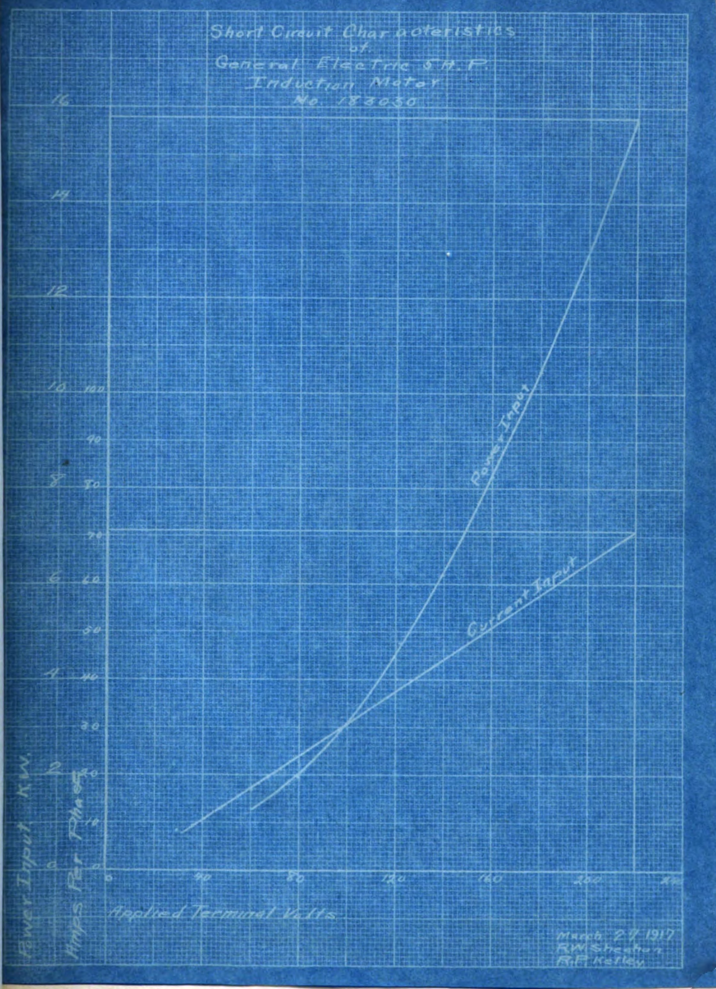
The last six values of the total watts were calculated from the power component.

RESISTANCE OF STATOR WINDINGS

BY

DROP OF POTENTIAL METHOD.

Phase	Amperes.	Volts Drop	Resistance. ohms.
AB.	14	13	.93
	12	12	1.00
	17	17	1.00
Mean			.99
BC	7	7	1.00
	11	11	1.00
	17.5	17.0	.97
	15	14.5	.98
Mean			.99
CA	17.5	17.0	.97
	12.0	12.0	1.00
	9.5	9.5	1.00
	7.0	7.0	1.00
Mean			.99



Short Circuit Characteristics
of
General Electric 5 H.P.
Induction Motor
No. 183030
16
14
12
10
8
6
4
2
0
100
90
80
70
60
50
40
30
20
10
0
Power Input
Current Input
0
40
80
120
160
200
240
Applied Terminal Volts
Power Input K.W.
Amps Per Phase
March 29 1917
R.W. Sheehan
R.P. Kelley

CIRCLE DIAGRAM TEST.

COMPUTATIONS.

App. H.P. input with Armature locked = $i_s E\sqrt{3} / 746$

i_s = Current at rated voltage = 7I amperes.

E = Rated voltage = 220

H.P. = $7I \times 220 \times \sqrt{3} / 746 = 36.25$

% Power factor= $\dfrac{\text{True power input}}{\text{Apparent power input.}} \times I00$

$= \dfrac{\text{Watts}}{i_s E\sqrt{3}} \times I00$

$= \dfrac{I580}{7I \times 220 \times \sqrt{3}} \times I00 = 58.4$ %

App. H.P. input with no load = $i_o E\sqrt{3}/ 746$

i_o= Current input at 220 volts, no load.

$i_o = 5.2$

H.P. $= \dfrac{5.2 \times 220 \times \sqrt{3}}{746} = 2.65$ H.P.

% Power factor = $\dfrac{\text{Watts}}{i_o E\sqrt{3}} \times I00$

$= \dfrac{252}{5.2 \times 220 \times \sqrt{3}} = I2.7$ %

CIRCLE DIAGRAM TEST.

RESULTS.

H.P. Output	H.P. Input	% Efficiency.
.5	.91	55.0
1.0	1.51	66.2
1.5	1.94	77.4
2.0	2.50	80.1
3.0	3.60	83.4
4.0	4.76	84.2
5.0	5.95	84.0
6.0	7.21	83.4

EFFICIENCY FROM LOSSES.

The losses in an Induction Motor consist of copper loss in the stator and copper loss in the rotor;friction and wind age. The rotor copper loss is proportional to the slip and is expressed in per cent of the slip.

No load current = I_n

No load power = W_n

Primary resistance per phase = R_p

Primary no load copper loss = $I_n^2 R_p \times 3/2 = W_{pn}$

Iron and friction loss = No load power.

Input - no load primary copper loss = $W_n - W_{pn} = W_{FI}$

Power input at any load W_x, Current = I_x

Primary copper loss = $I_x^2 \times R_p \times 3/2 = W_{px}$

Output + Sec. copper loss $W_x - (W_{px} + W_{FI}) = W_s$

Input into the secondary.

Secondary copper loss = $W_s \times$ Slip / 100 = W_1

Output = Secondary input - Secondary copper loss

$= W_s - W_1 = W_o$

Efficiency = W_o / W_x

METHOD.

The motor was loaded by means of a brake and the following readings taken for different loads;- Volts, amperes, watts and speed. Readings were also taken at no load and the resistance of the windings measured by the drop of potential method.

EFFICIENCY BY LOSSES.

DATA.

R.P.M.	Volts. AB	Watts. AB	Watts. BC	Amps. A	Amps. C
I2I0	220	620	- 360	5.05	5.25
II95	220	680	- 3I0	5.I5	5.3
II85	220	740	- 220	5.I5	5.3
II80	220	840	- I80	5.35	5.45
II75	220	866	- I20	5.40	5.5
II70	220	920	- 80	5.5	5.55
II70	220	I060	+ 40	5.75	5.85
II70	220	I200	I60	6.I5	6.35
II70	220	I400	320	6.65	6.85
II60	220	I490	450	6.85	7.25
II50	220	I680	600	7.65	8.0
II50	220	I870	760	8.5	8.9
II55	220	2020	880	8.9	9.3
II55	220	2220	I020	9.75	I0.I5
II55	220	2390	II90	I0.35	I0.5
II50	220	2640	I380	II.5	I2.25
II40	220	2800	I540	I2.9	I3.0

EFFICIENCY BY LOSSES.

RESULTS.

Watts Input.	Current Amps.	Primary I^2R loss.	% Slip.	Input To sec.	Secondary Copper loss.
252	5.20	40.2	0.I8	0.0	0.0
370	5.22	77.5	I.24	80.7	I.0
520	5.23	77.7	I.65	230.5	3.8
660	5.40	80.2	2.06	368.0	7.6
746	5.45	8I.0	2.48	453.2	II.2
840	5.52	82.0	2.89	546.2	I5.8
II00	5.80	86.I	2.89	802.I	23.2
I360	6.25	93.0	2.89	I055.2	30.5
I720	6.75	I00.I	2.89	I408.I	40.7
I940	7.05	I04.9	3.82	I683.3	64.4
2280	7.85	II6.5	4.55	I95I.2	89.0
2630	8.70	I29.0	4.55	2289.2	I04.0
2900	9.I0	I35.0	4.30	2553.2	I09.5
3240	9.95	I48.0	4.30	2880.2	I24.0
3580	I0.42	I55.0	4.30	32I3.2	I38.0
4020	II.87	I78.0	4.55	363I.2	I65.0
4340	I2.50	I86.0	5.36	3942.2	2I2.0

Watts Output.	Efficiency.
0.0	0.0
79.7	22.0
226.7	43.5
360.4	54.6
442.0	59.4
530.4	63.0
778.9	70.6
I024.7	75.5
I367.4	79.5
I6I9.0	83.3
I862.7	8I.7
2I85.0	83.2
2444.0	84.5
2776.0	85.5
3075	86.0
3466	86.2
3730	86.0

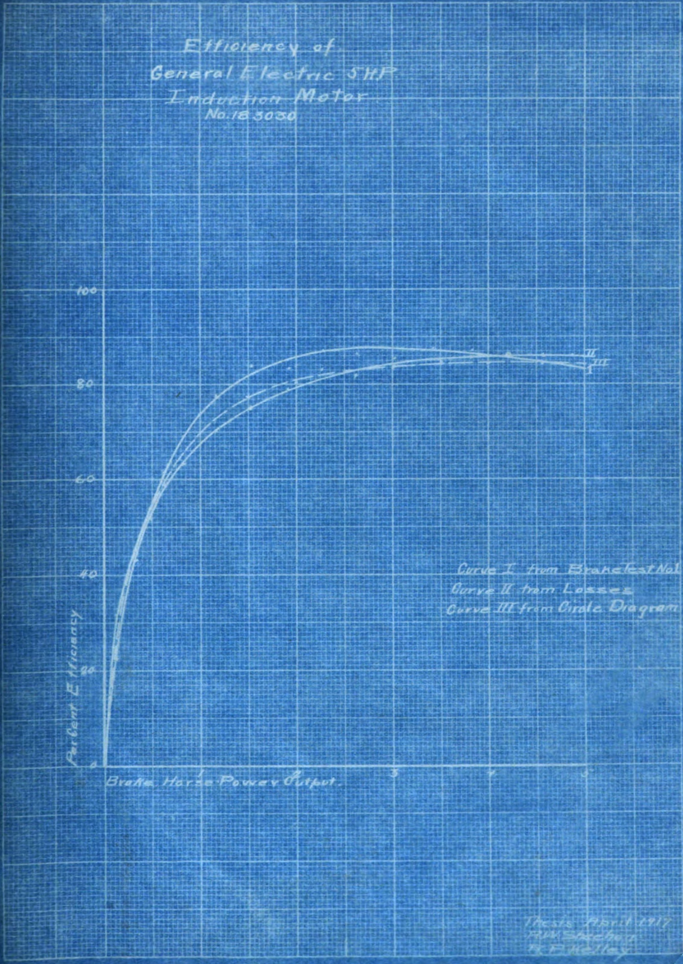
Resistance of one phase = .495 ohms.

Primary no load copper loss = $I^2R \times 3/2$

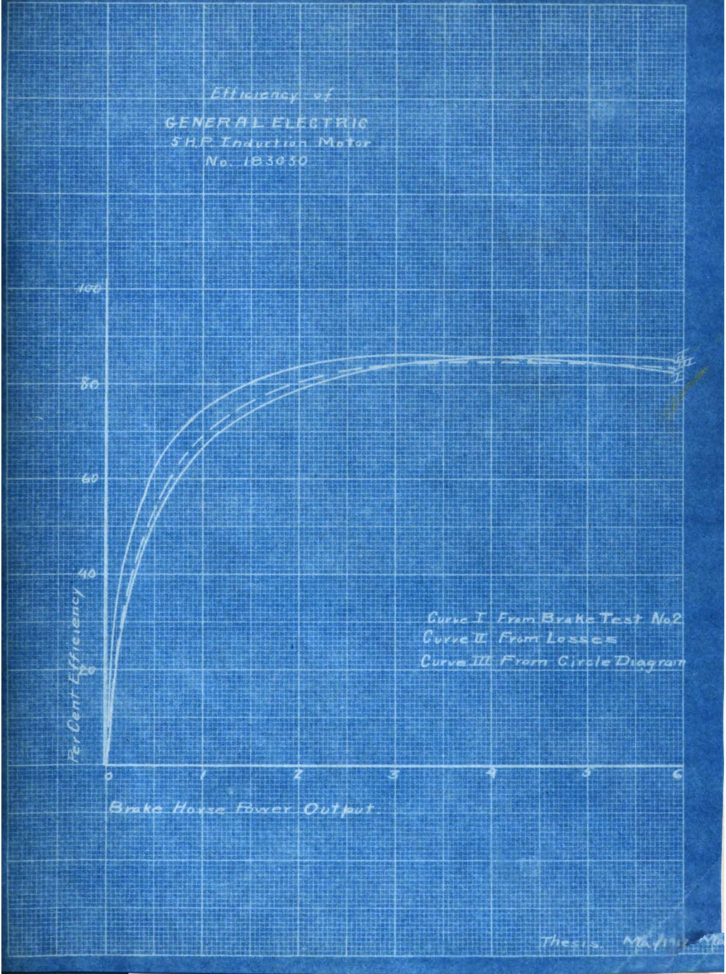
$$= 5.20^2 \times .99 \times 3/2 = 40.2 \text{ Watts}$$

Irom and friction loss = No load input - no load copper loss.

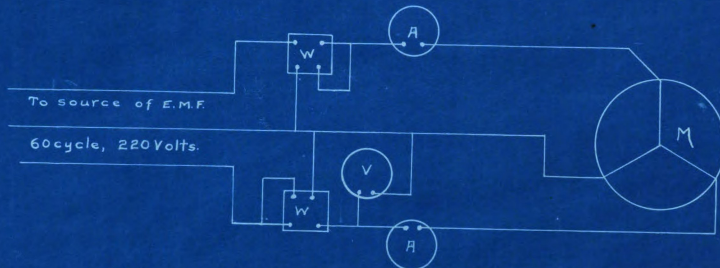
$$= 252 - 40.2 = 2II.8 \text{ Watts.}$$



Efficiency of
General Electric 5 H.P.
Induction Motor
No. 183030
100
80
60
40
20
0
Per Cent Efficiency
Brake Horse Power Output
3
4
5
II
III
I
Curve I from Brake Test No 1
Curve II from Losses
Curve III from Circle Diagram
Thesis April 1917
R F Kelley



Efficiency of
GENERAL ELECTRIC
5 HP Induction Motor
No. 183030
100
80
60
40
20
Per Cent Efficiency
0
1
2
3
4
5
6
Brake Horse Power Output
I
II
III
Curve I From Brake Test No. 2
Curve II From Losses
Curve III From Circle Diagram
Thesis.



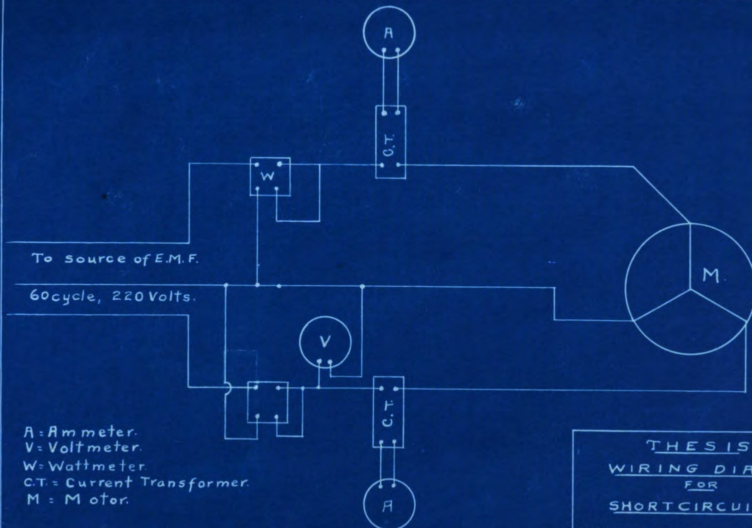
KEY

A = Ammeter.
V = Voltmeter.
W = Wattmeter.
M = Motor.

THESIS

WIRING DIAGRAM.
FOR
NO LOAD AND BRAKE TESTS

R.P. KELLEY   R.W. SHEEHAN
1917.



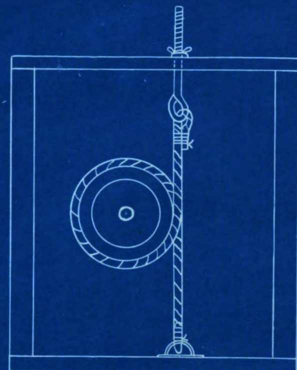
A = Ammeter.
V = Voltmeter.
W = Wattmeter.
C.T. = Current Transformer.
M = Motor.

THESIS.

WIRING DIAGRAM.
FOR
SHORTCIRCUIT TEST.

R.P. KELLEY   R.W. SHEEHAN.

1917.



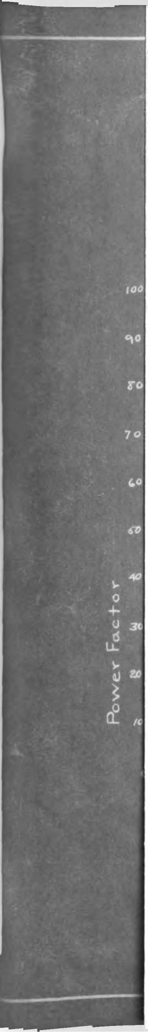
Brake sets on Platform Scales.

THESIS

TYPE OF BRAKE USED.

R.P. KELLEY R.W. SHEEHAN.

1917.



t.

nt

CONCLUSION.

In summarizing this thesis the following features and characteristics have been shown:-

The circle diagram method of testing for the efficiency of Induction Motors is much to be preferred to the brake test. With the latter method, vibration makes accuracy with a light load practically impossible. With the circle diagram method only a few readings need be taken and the method is very accurate.

The Loss method while giving results very close to those obtained from the circle diagram; possess the same disadvantages as the brake test. The difficulty of holding the load constant while taking the speed and the waste of power are the principal disadvantages.

At full load the efficiencies as computed by the different methods agree within 3 %.

In closing we hope that the data and results contained in this thesis may be of much value to the Electrical Engineering Department at M.A.C.