CONDENSER MOTOR WITH HIGH STARTING TORQUE AND LOW CAPACITANCE

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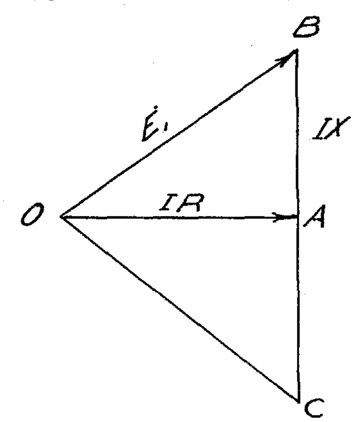
The theory of the condenser motor is the operation of a poly-phase motor on a single-phase source. If we consider the current in one phase of a two-phase motor the IR drop is in phase with the current I and the reactance drop is at right angles to it. The voltage OB across the phase is the vector sum of these two. Now if a condenser is connected in series with this phase the reactance drop across the condenser will be opposite to that in the winding. The voltage across the the condenser is BC and the total voltage across



the condenser and the phase in series with it is OC. This is the line voltage. If the other phase of a two-phase motor is connected directly across the line the two phases will have voltages impressed on them which are electrically displaced by the angle BOC. By assigning a proper value to the capacitance of the condenser this angle can be made equal to 90 degrees. The voltage OB, however, will not be equal to the line voltage unless the angle BOA is equal to 45 degrees, that is, the power factor of the phase must be 70.7 per cent. It is not necessary to design both phases of the motor for the same voltage so that this condition does not present any great difficulty.

The theory of the condenser motor is by no means new. On January 24, 1900 the late Dr. Charles P. Steinmetz read before the 39th meeting of the American Institute of Electrical Engineers his paper giving the theory and actual test data on such types of motors. The practical application to which the condenser motor is being subjected at the present time is, however, new for as far as one can determine no effort had been made in the past to utilize the advantages of the condenser motor.

This lack of interest in the condenser motor can readily be appreciated when one remembers that condensers then cost from two to three dollars per microfarad. To-day the price of condensers is only one eighth to one tenth of that amount.

Dr. Steinmetz considered two types of induction motors, the single-phase with tertiary winding and the three-phase motor. His method of changing the former into a condenser motor was rather odd since the tertiary winding, with its shunted condenser, was not electrically connected with the primary but only magnetically through the rotor. Hence the spacing between the primary and tertiary winding had to be less than ninety electrical degrees in order that the motor have the required starting torque. This design of a single-phase condenser motor seems rather awkward and one wonders why Dr. Steinmetz chose it. His use of a three-phase winding for a condenser motor is undoubtedly the mother of the present day condenser motor designs. By means of reactances he pr be obtained from a single-phase source the approximate three-phase relations for which the motor was designed.

Dr. Steinmetz also spoke of the need of a compensating transformer across the condenser, when the motor was operating at a low voltage (110), in order to reduce the condenser capacitance to a reasonable value.

In more recent times another paper on the condenser motor appeared. This paper was written by Prof. B. F. Bailey of the University of Michigan and was published in the March '28 issue of the Electrical World. Prof. Bailey's tests were for quarter horse power motors with tertiary windings and shunted condensers connected across the line. The advantage of a compensating transformer is also pointed out in this paper.

The goal of present day development seems to be the electrification of every possible operation. This calls for the introduction of small motors. In most places where the installation of a small motor is to be made the only available source of current is from single-phase A.C. lines. Up till the present this has limited the types of motor to be used to split-phase and repulsion motors.

The split-phase induction motor has a low starting torque, poor power factor, poor efficiency, and low pull-out torque. The repulsion motor has a higher starting torque, poor power factor, poor efficiency, and like the split-phase has only single-phase operation.

Due to the design of the repulsion motor the motor itself is quite complicated in construction.

Some small motor installations, such as fans etc., require a very low starting torque and in these it is possible to use a split-phase motor. However, a great many installations, such as electric refrigerators, air-compressors, oil-furnaces, etc. which are coming every day into wider application, require a high starting torque to overcome the static friction and start the attached load. Motors in such installations operate a great portion of the day and start and stop frequently and so it is advantageous to install motors with a fairly high efficiency.

The use of split-phase and repulsion motors is also objectionable from the standpoint of the central station. Considered individually the low power factor of either of these two motors is not alarming, but when it is remembered that to-day there are great numbers of such motors in operation and that every day the field is widening the matter of poor power factor is a problem of considerable importance. It requires that the central station maintain larger generators, larger transformers, etc. and due to the infeasibility of placing power factor meters in every home and store there does not appear to be any practical means of charging the customer with this additional expense.

All of these difficulties are eliminated with the introduction of the condenser motor. With reasonable values of capacitance it is possible to make a condenser motor with full load starting torque.

With this same capacitance value the pull-out torque is in the neighborhood of 150 to 160 per cent of full load torque. Such a motor also very closely approximates poly-phase efficiency. By a suitable choice of capacitance the motor power factor can be made unity. The condenser motor also gives the quieter operation of the poly-phase motor; this is a point in its favor in electric refrigeration installations where a quiet motor blends with the peace and tranquillity of domestic life.

In the condenser motor we are concerned with a circuit having inductance, resistance, and capacitance in series. To study the phase relations in this system the ordinary circle diagram was found inadequate (fig. 1). In the common diagram OO' represents the line voltage, OB' the

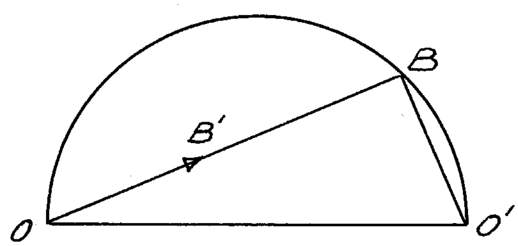
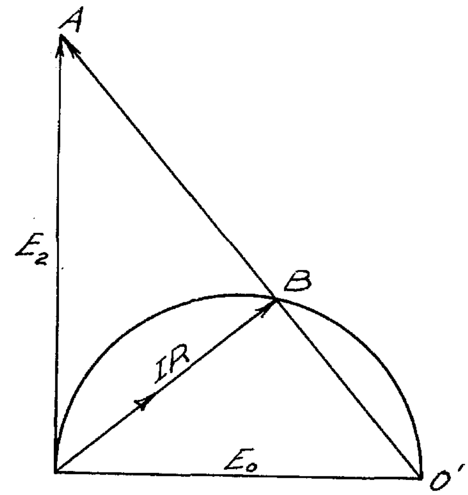


Fig. 1

current, OB the IR drop, and O'B the IX drop. The IX drop is equal to

$$IX_C - IX_L$$

where X_L is the inductive reactance and X_C is the condensive reactance. It was found desirable to make a diagram which showed both IX_L and IX_C. If we take the ordinary circle diagram and add the IX_L drop at right angles to the IR drop we then have the voltage E_2 across that phase of the motor. The drop across the condenser is AO'



$IR = OB$

$IX_L = BA$

$E_2 = OA$

$IX_C = AO'$

$Pf_2 = \text{Cos } \angle AOB$

OO' = Line Voltage

Fig. 2

The power factor Pf_2 of the current with respect to the voltage E_2 will be Cos $\angle AOB$.

If the power factor Pf_2 of the phase is kept constant and the capacitance of the condenser changed the point A will also change. If the path of point A is plotted then for each value of the capacitance $OA = E_2$, $BA = IX_L$, and $AO' = IX_C$. In this way the phase relations can be studied for all possible values of condenser capacitance. It can be shown that point A will describe a circle.

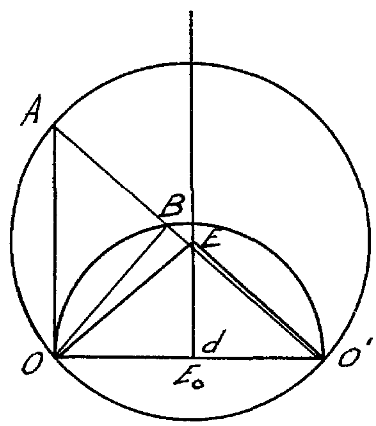


Fig. 3

If we draw the perpendicular bisector (fig. 3) of the line OO' and lay off the $\angle EOd$ equal to the power factor angle of the current with respect to the voltage across the phase and draw a circle around the point E with a radius EO, then the point A for the given power factor will follow this circle for all values of capacitance. By geometry

$$\angle O'EO = 2\angle OAB$$

$$\text{and} \quad \angle O'EO = 2\angle dEO$$

$$\text{hence} \quad \angle OAB = \angle OEd$$

$$\text{therefore} \quad \angle AOB = \angle EOd$$

$\angle EOd$ was made equal to the power factor angle. Since $\angle AOB = \angle EOd$ then $\angle AOB$ is the power factor angle, and the circle represents the true locus of the point A. These circles can be drawn for different values of the power factor.

The complete diagram is shown on Plate 1. The power factor circles are drawn for values of power factor from 25 to 100 per cent. Circles giving $OA = E_2$ for values from 50 to 150 per cent of line voltage are shown, also circles giving $O'A = IX$ for values from 50 to 200 per cent of the line voltage. For any power factor $OA = E_2$ the voltage across the motor winding

$$OB = IR$$

$$BA = IX_L$$

$$AO' = IX_C$$

$$\cos\angle AOB = Pf_2$$

$$OO' = \text{Line Volts}$$

If the resistance is constant OB will be proportional to the current. If the current is constant OB will be proportional to the resistance.

It is desirable to have the voltage across the condenser as high as safety permits, the voltage E_2 separated as nearly 90 degrees from the line voltage as possible, and as near that for which the motor is designed as possible.

We first considered locked rotor conditions. In the condenser motor the phase across the line will have constant voltage impressed on it while the voltage on the condenser phase will vary. A two phase test was made at locked rotor with normal voltage on one phase and variable voltage on the other. The results are shown on Plate 2.

With normal voltage on both phases

current per phase - - - - - - - - - - - - -	27 amps.
torque - - - - - - - - - - - - - - - - - - -	188% full load
Power factor - - - - - - - - - - - - - - -	65.5%
line volts - - - - - - - - - - - - - - - - -	110
frequency - - - - - - - - - - - - - - - - -	60

Let us see how nearly we can reproduce these conditions with condenser operation. We determine the point on the circle diagram where the 100% E_2 curve intersects the 65.5% power factor curve; this is point A. AO' the condenser voltage equals 151% line volts where the line voltage is 110

$$1.51 \times 110 = 166 \text{ volts}$$

$$I = \frac{E}{Z} \qquad Z = \frac{1}{2\pi FC}$$

$$I = 2E\pi FC$$

$$27 = 166 \cdot 2\pi 60C$$

$$C = 431 \times 10^{-6} \text{ farads} = 431 \text{ microfarads}$$

This capacitance of 431 microfarads would cost much more than the motor. If a 220 volt motor had been used the capacitance would have been one-fourth as great; this would still be too expensive to use.

For full load starting torque a voltage of 55% normal volts was required on the one phase.

current - - - - - - - - - - 13.4 amps.

power factor - - - - - - 67%

If we again determine the point A for 55% E_2 and 67% power factor we find that E_2 is about 110 degrees out of phase with the line voltage

$$110^\circ - 90^\circ \qquad 20^\circ$$

$$\frac{13.4}{\cos 20^\circ} = \frac{13.4}{.94} = 14.25$$

A current of 14.25 amperes is required with 110 degree phase angle. The condenser voltage is 134% line voltage

$$1.34 \times 110 = 147$$

$$C = \frac{14.25}{2\pi 60 \cdot 147} = 257 \text{ microfarads}$$

The capacitance in this case is still much too expensive. For 220 volts only 64 microfarads would be required.

Besides the economic consideration a large capacitance is not desirable at light load or at full load for several reasons. From a test on a one horse power, 220 volt, motor operating at light load it was found that at 50 microfarads the condenser voltage was 444 volts and the voltage across the condenser phase was 390 volts. The condensers used were rated at 385 volts continuous operation. The voltage of 444 is above this limit. The motor winding which was designed for 220 volts was operating at 390 volts. This caused high iron losses and circulating currents. Due to the high voltage on the condenser phase the counter-emf. of the standard phase was greater than the line voltage so that it was generating current. The standard phase was generating 500 watts while the condenser phase was carrying this load besides the motor losses, which were equal to 1200 watts. These losses were 162% of the motor rating.

The reason for this peculiar operation can be seen from the circle diagram. The power factor of the phase is low at light load and the current with two phase operation is also small. The current per phase is about 4.5 amperes. This would produce a drop across a 257 microfarad condenser of 46.5 volts which is 42.3% of line volts.

The voltage across the condenser phase tends to approach the line voltage but because the power factor is small the voltage on the condenser winding increases as the angle between E_2 and E_0 decreases. This increase in voltage causes the standard phase to act as a generator, thereby the load is placed on the condenser phase and increases its power factor. This increases the current in the condenser phase which in turn increases the drop across the condenser. A balance is reached when the increase in condenser drop and power factor offset the increase in voltage and current.

This condition also exists at full load but to a lesser degree. From a test on the same motor at full load with 50 microfarads condenser capacitance we have the following values:

condenser voltage	395 volts
condenser phase voltage	360 volts
condenser phase power	1480 watts
standard phase power	180 watts
line power	1670 watts
load	750 watts

The condenser phase voltage is still much too high and causes this phase to carry nearly all the load. At 3/4 full load the condenser phase was carrying all the load.

This motor operated most efficiently at full load with a condenser capacitance of 27.5 microfarads. This was about one-half the capacitance required for full load starting torque. With a capacitance of 27.5 microfarads the starting torque was less than one-third full load. In his article Prof. Bailey suggests the using of a relay to cut out the extra capacitance after the motor gets started. This method, however, requires the purchase of a relay and the extra capacitance. One-half of the condenser capacitance is idle when the motor is running. Since the cost of the condenser is a considerable portion of the total motor cost it is indeed a very important item.

If we again turn to the locked rotor test for the two-phase motor operation, Plate 2, we see that full load starting torque was obtained with 55% normal voltage on one phase,

volts	55%
power factor	67%
current	13.4 amperes

Referring to the circle diagram we see that E_2 is 90 degrees out of phase with the line voltage for a power factor of 67% when E_2 = 112% line voltage. When E_2 = 110% line voltage with 67% power factor it is still very nearly 90 degrees out of phase with the line voltage.

If we design the condenser phase for twice line voltage it would then have 55% normal voltage impressed on it when E_2 = 110%. The motor on which the tests were run was designed for 110-220 volts service, in fact it was for this reason that this motor was chosen. The coils of the condenser phase were connected in series while those of the standard phase were left in parallel. Let us now see what capacitance is required. The current with the coils in parallel was 13.4 amperes so that in series it would be 13.4 divided by two or 6.7 amperes. For 67% power factor and 110% E_2, E_c = 150%

$$150 \times 110 = 165 \text{ volts} = E_c$$

Hence $C = 108 \times 10^{-6}$. 108 microfarads are required for full load starting torque. For a 220-440 volt motor the capacitance would be 27 microfarads, which is a very reasonable value.

The motor was again connected for 110 volts for each phase and a two-phase performance taken (see Plates 3, 4, and 5). At full load

line current - - - - - - - - - - - 13.2 amperes

current per phase - - - - - - - - 6.6 amperes

power factor - - - - - - - - - - - 66%

For E_2 = 100% and 66% power factor, E_c = 149% or 1.49 x 110 = 164 volts.

$$C = 106 \times 10^{-6} \text{ farads}$$

106 microfarads are required. For 220 volts this would be 26.5. Hence the motor requires practically the same capacitance at full load with

the coils in parallel as it does to develop full load starting torque with the coils in series.

Let us see how closely these calculations compare with actual test values. Plate 6 gives starting torque for different condenser capacitances, Plate 7 condenser and condenser phase volts, Plate 8 power factors, Plate 9 currents, Plate 10 watts. From these curves we obtain the following values:

Condenser operation

locked rotor full load torque

	test	calculated
$\frac{\text{condenser volts}}{\text{line volts}}$	149.2%	150%
$\frac{\text{condenser phase volts}}{\text{line volts}}$	110%	110%
condenser phase p.f.	67%	67%
condenser phase current	6.6 amp.	6.7 amp.
condenser phase watts	525 watts	532 watts
microfarads	108	108

Now let us compare the calculated and the test values at full load. A capacitance of 110 microfarads was used. The test results are shown on the Plates 3, 4, 11, 12, 13.

Condenser operation

Full load

	test	calculated
capacitance	110	106
condenser phase current	6.6 amp.	6.6 amp.
$\frac{\text{condenser volts}}{\text{line volts}}$	146%	149%
$\frac{\text{condenser phase volts}}{\text{line volts}}$	100%	100%
condenser phase power factor	69%	66%

Considering the difference in the capacitances used these results agree very closely.

A comparison of two-phase operation and condenser operation is given on Plates 3, 4, and 5. The condenser operation compares very favorably with the two-phase operation.

Curves for light load operation are given on Plates 15 and 16. We see that the losses are lowest for low capacitances but the line current is high and the power factor poor. The power factor approaches unity and the current is a minimum for capacitances near 100 microfarads. This is about the same capacitance that gives the full load starting torque with the coils in series, and the best operation with the coils in parallel. If it were possible to start the motor with the coils in series and have it run with the coils in parallel we would have a very satisfactory motor. Since the starting current is about four times the full load current it is possible to build a relay which will connect the coils in series when the current becomes high and then connect them in parallel when the current decreases as the motor comes up to speed.

The diagram for the relay connection is shown in figure 4.

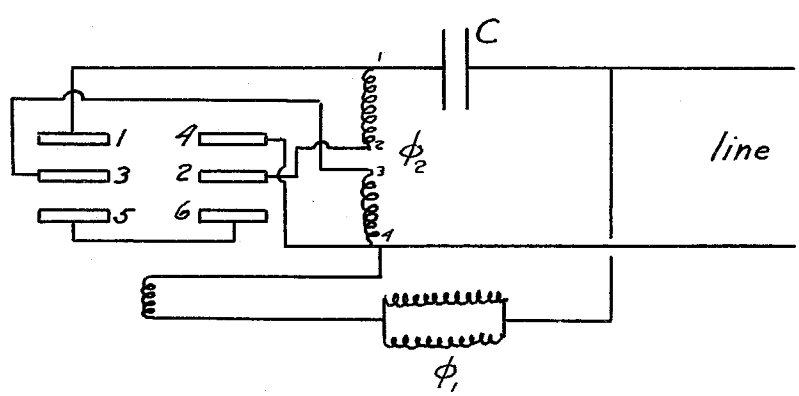


Fig. 4

The relay is energized by the standard phase current. When the motor starts the high current causes the relay to pull the contacts 3 and 5 and the contacts 2 and 6 together thereby connecting the coils in series. When the current decreases the contacts 3 and 1,and 2 and 4 close thereby connecting the coils in parallel. A relay was designed for this purpose, giving a fast break and a large separation. It was possible to adjust the relay very closely to the requirements of the motor. While the starting current was four times full load current it was possible to adjust the relay to a 10 to 7 ratio, making its operation certain and consistent. With locked rotor and under other severe test conditions the relay operated very satisfactorily. At present a Los Angeles motor concern is putting in test installations using this method. If field tests prove as successful as those in the laboratory have, they are prepared to go extensively into this field of motor design. This motor gives every indication of being a commercial success.

We wish to thank the U. S. Electrical Manufacturing Company for their cooperation and the use of their test facilities and equipment.

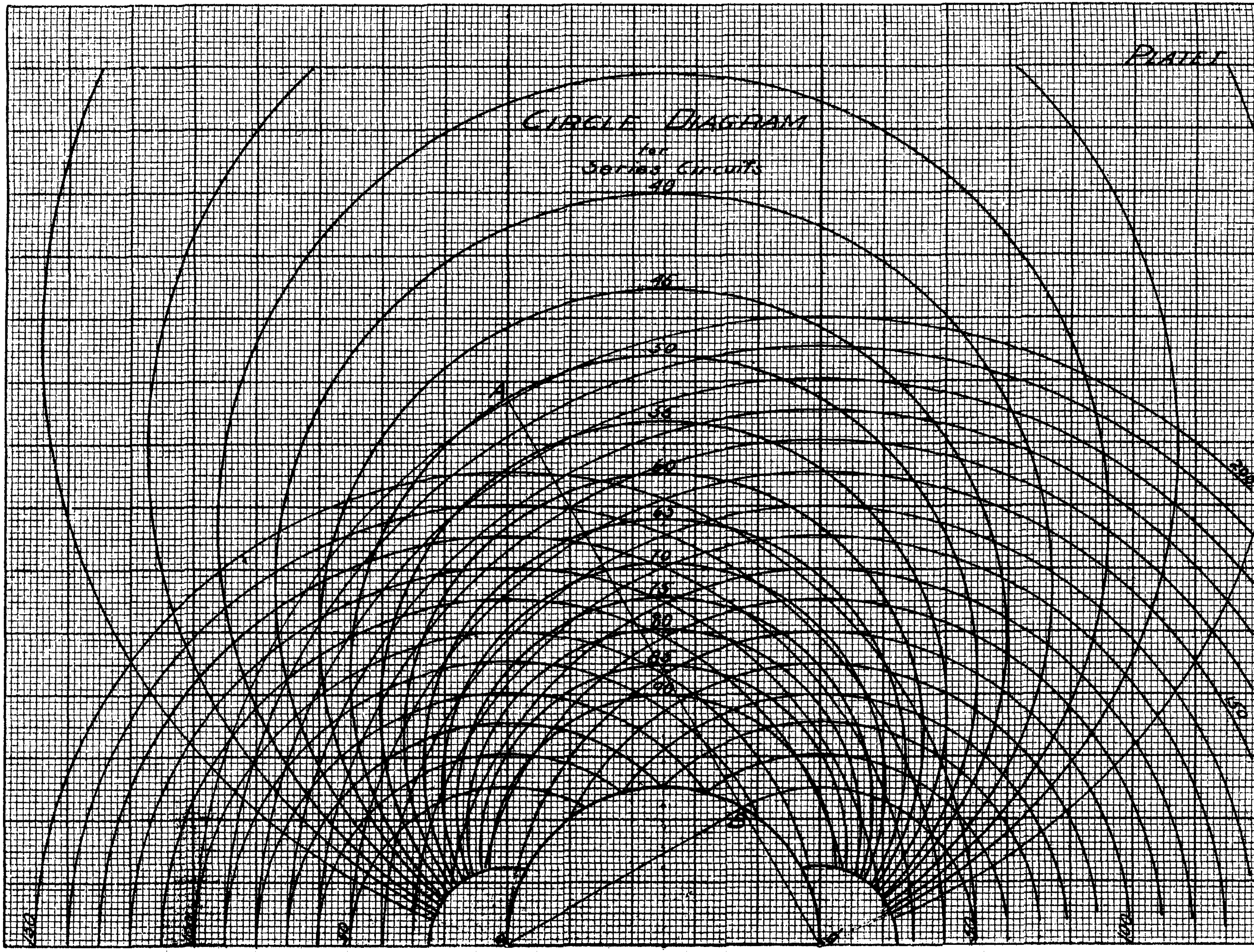
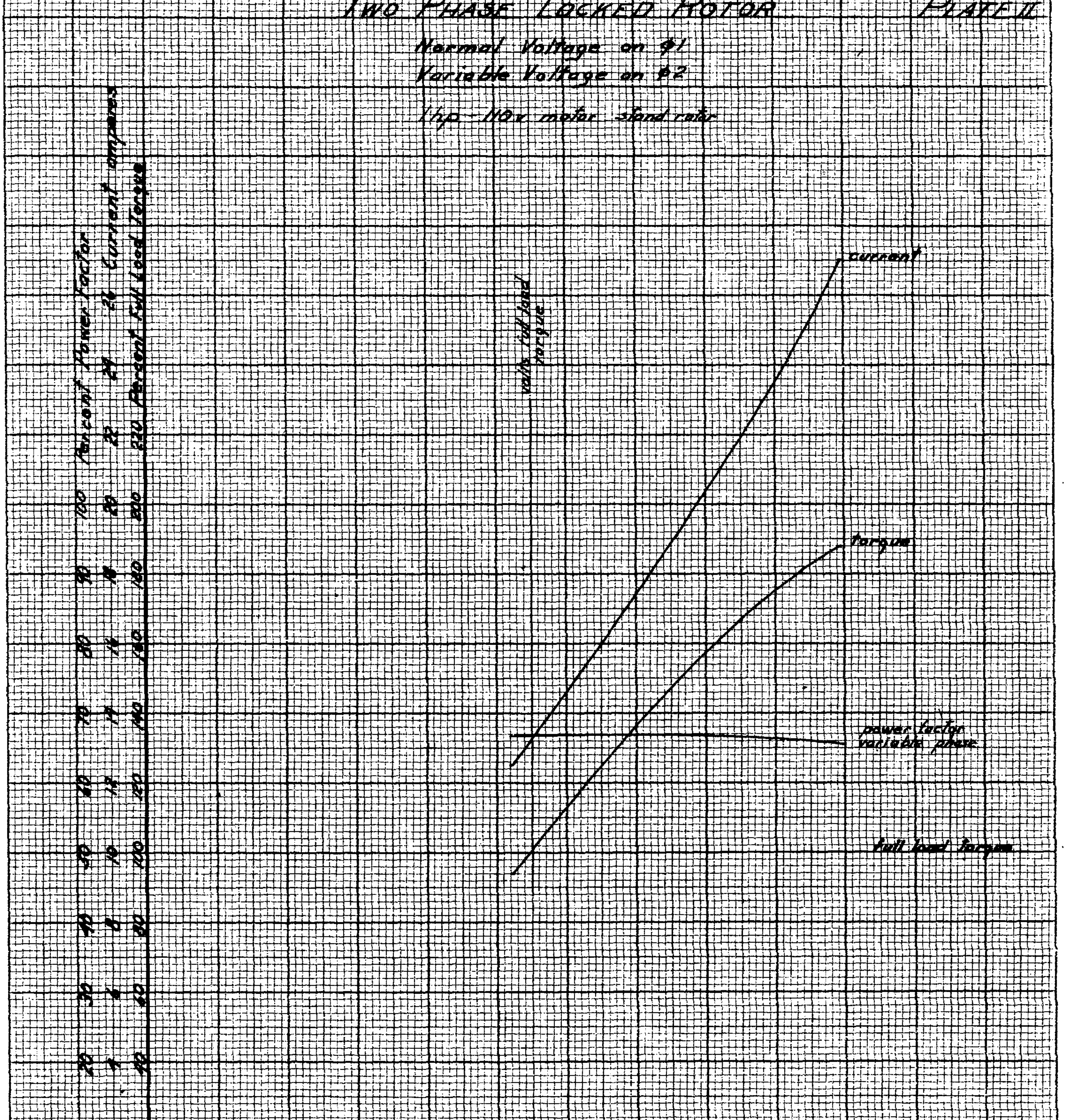
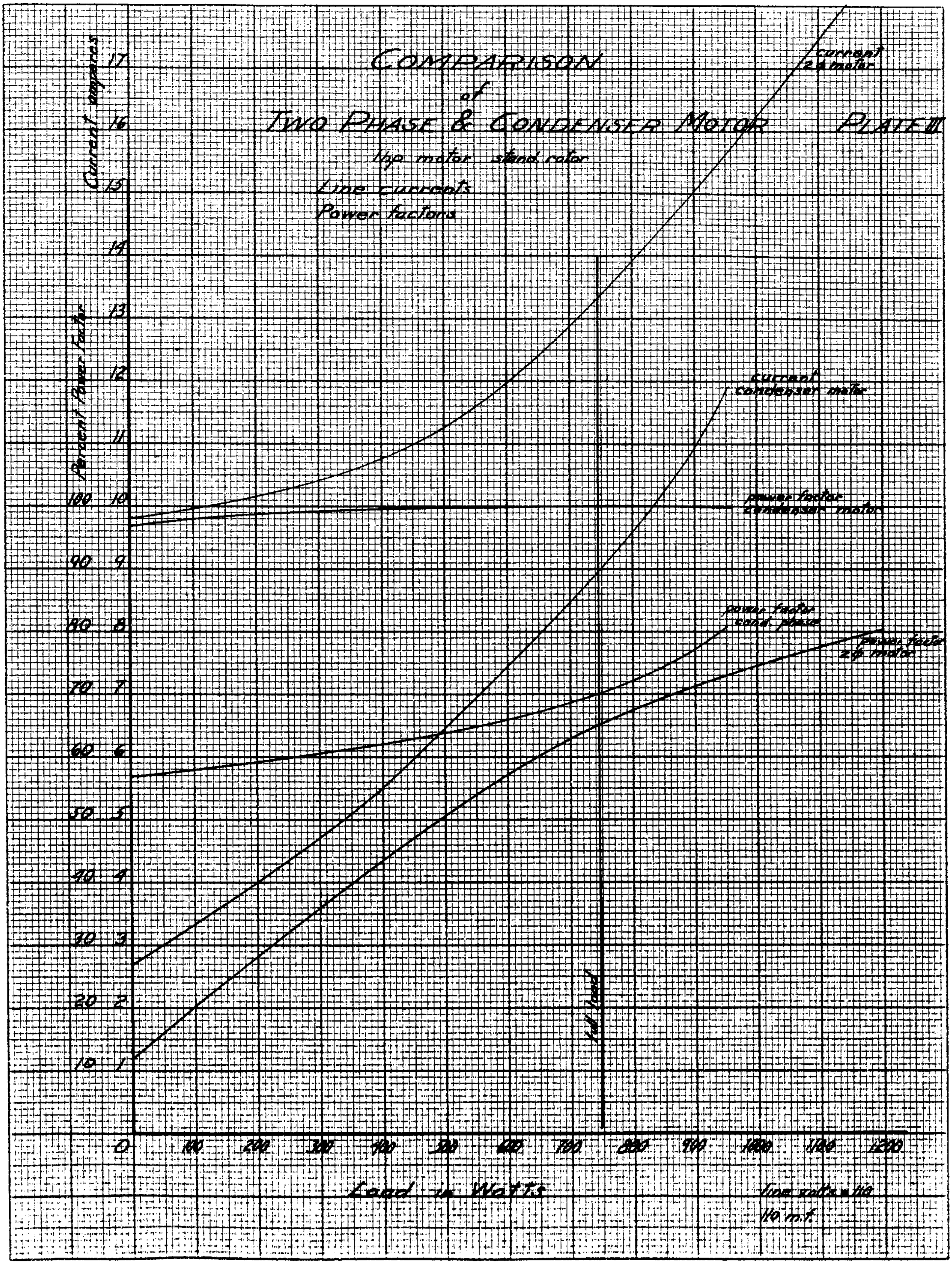
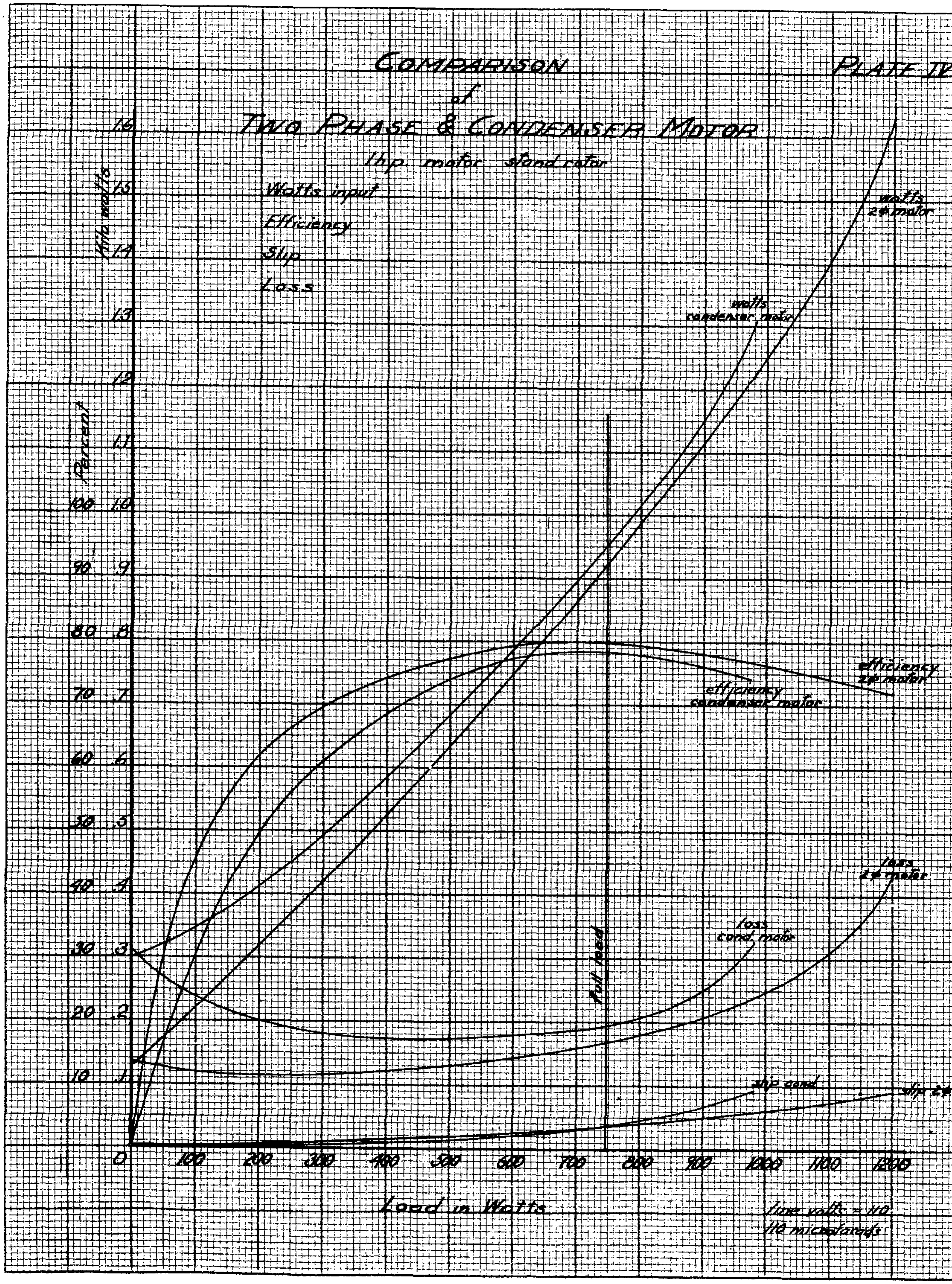


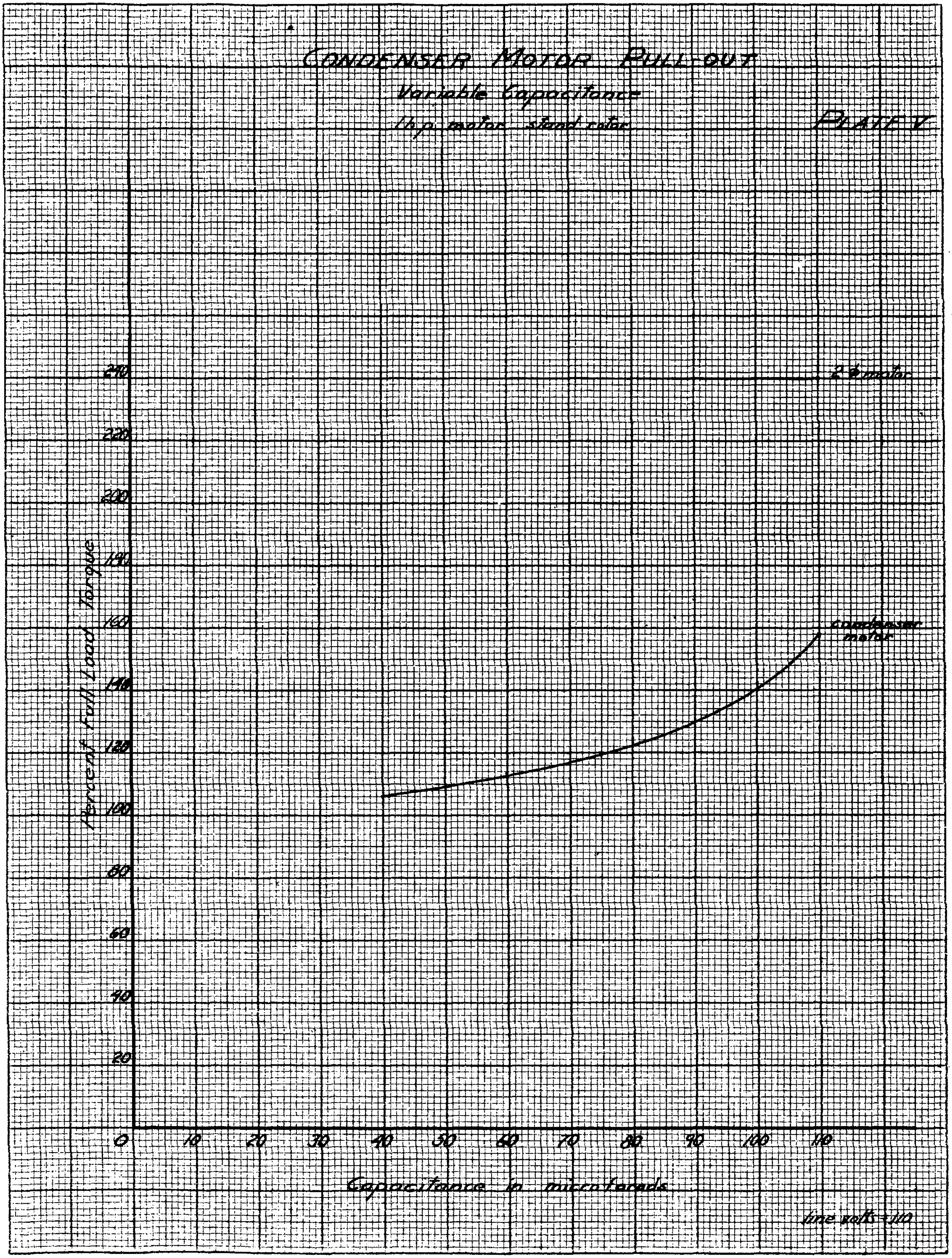
PLATE I
CIRCLE DIAGRAM
for
Series Circuits
40
45
50
55
60
65
70
75
80
85
90
A
B
200
150
100
50


TWO PHASE LOCKED ROTOR
PLATE II
Normal Voltage on Φ1
Variable Voltage on Φ2
1 hp - 110 v motor stand rotor
Percent Power Factor
Current amperes
Percent Full Load Torque
current
torque
power factor variable phase
full load torque
Percent Normal Volts
0
10
20
30
40
50
60
70
80
90
100


COMPARISON
of
TWO PHASE & CONDENSER MOTOR
PLATE III
1/4 hp motor stand rotor
Line currents
Power factors
Current amperes
Percent Power Factor
17
16
15
14
13
12
11
100 10
90 9
80 8
70 7
60 6
50 5
40 4
30 3
20 2
10 1
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
current 2φ motor
current condenser motor
power factor condenser motor
power factor cond. phase
power factor 2φ motor
full load
Load in Watts
line volts = 110
10 m.f.



COMPARISON
of
TWO PHASE & CONDENSER MOTOR
PLATE IV
1hp motor stand rotor
Watts input
Efficiency
Slip
Loss
Kilo watts
Percent
watts 2φ motor
watts condenser motor
efficiency 2φ motor
efficiency condenser motor
loss 2φ motor
loss cond motor
slip cond
slip 2φ
full load
Load in Watts
line volts = 110
110 microfarads



CONDENSER MOTOR PULL-OUT
Variable Capacitance
1 h.p. motor stand rotor
PLATE V
2 φ motor
condenser motor
Percent Full Load Torque
240
220
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
110
Capacitance in microfarads
line volts = 110

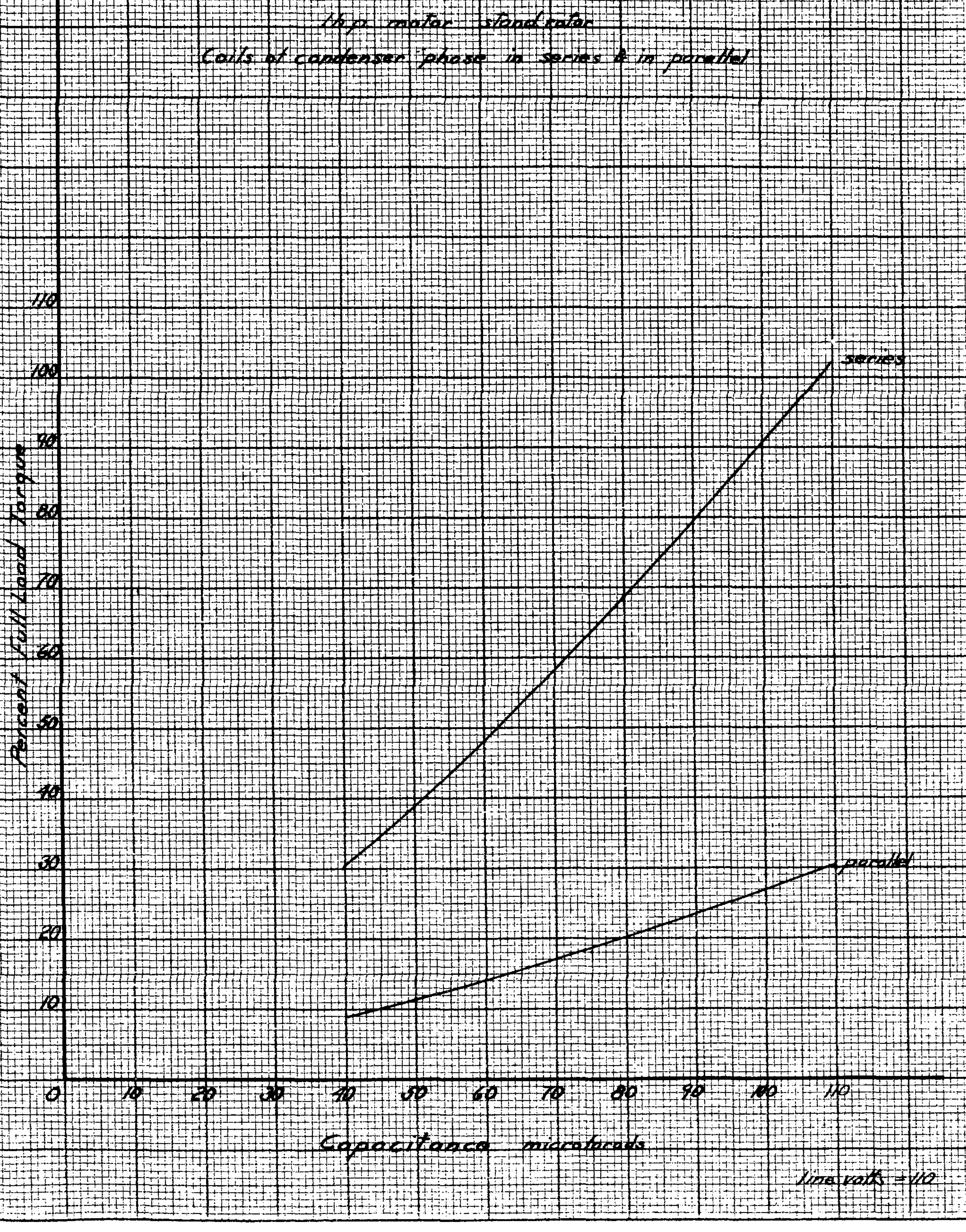
CONDENSER MOTOR

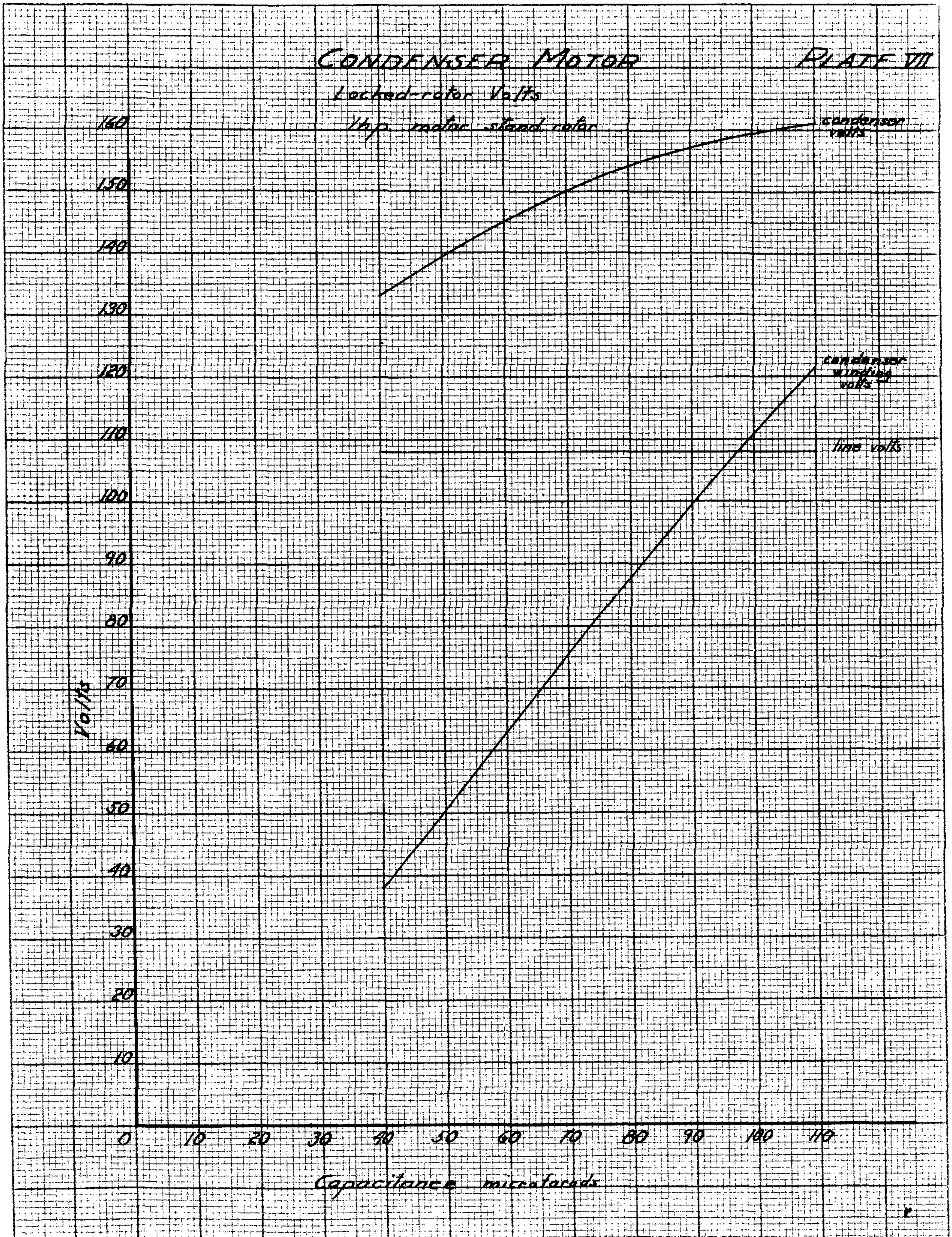
PLATE VI

LOCKED TORQUE

¼ h.p. motor stand. rotor

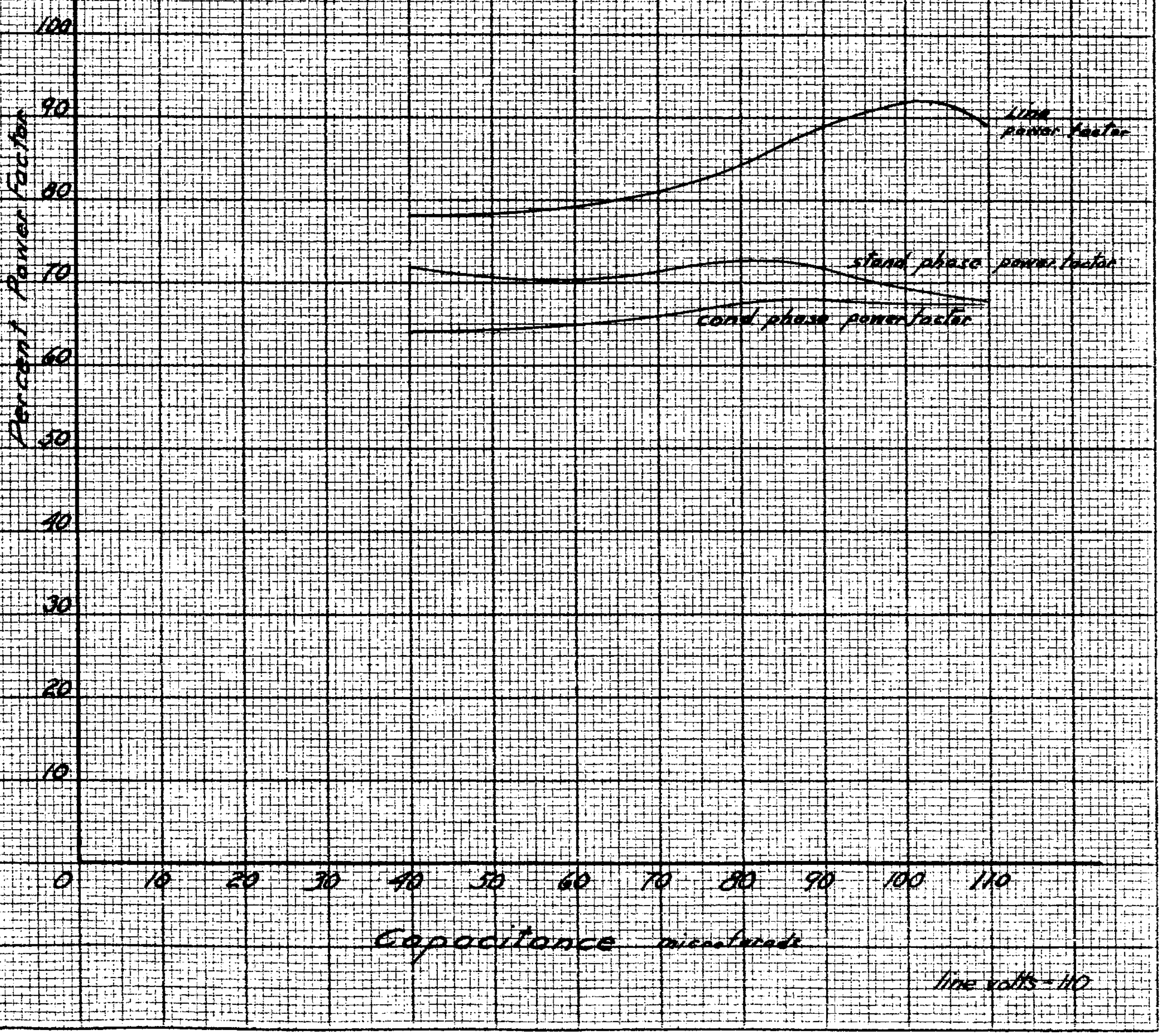
Coils of condenser phase in series & in parallel

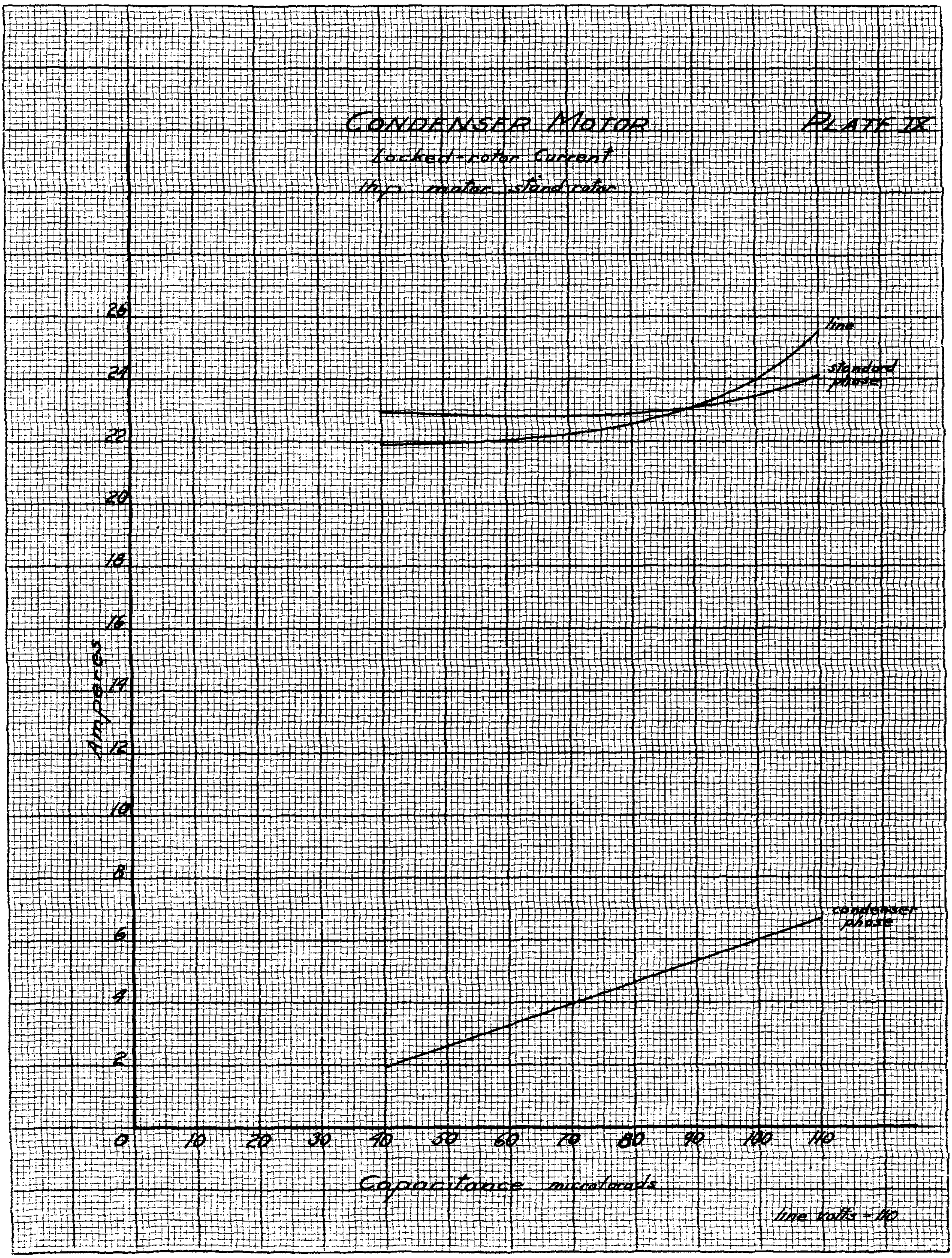



CONDENSER MOTOR
PLATE VII
Locked-rotor Volts
¼ hp. motor stand. rotor
condenser volts
condenser winding volts
line volts
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
Volts
0
10
20
30
40
50
60
70
80
90
100
110
Capacitance microfarads

CONDENSER MOTOR — PLATE VIII

Locked-rotor Power Factor
1 h.p. motor stand. rotor





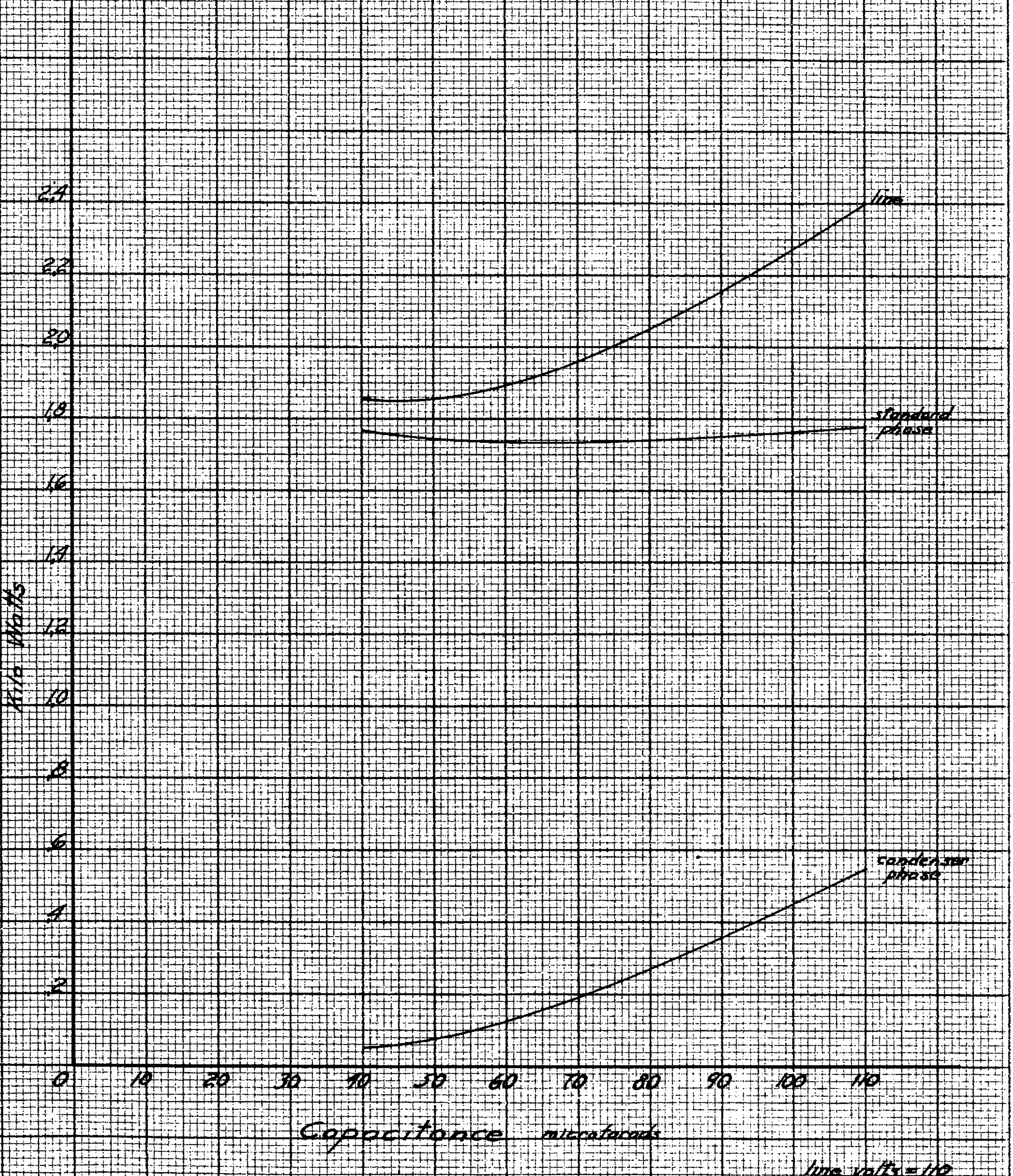
CONDENSER MOTOR
PLATE IX
Locked-rotor Current
1hp motor stand rotor
line
standard phase
condenser phase
Amperes
26
24
22
20
18
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80
90
100
110
Capacitance microfarads
line volts - 110

CONDENSER MOTOR

PLATE X

Locked-rotor Watts

1 h.p. motor stand. rotor

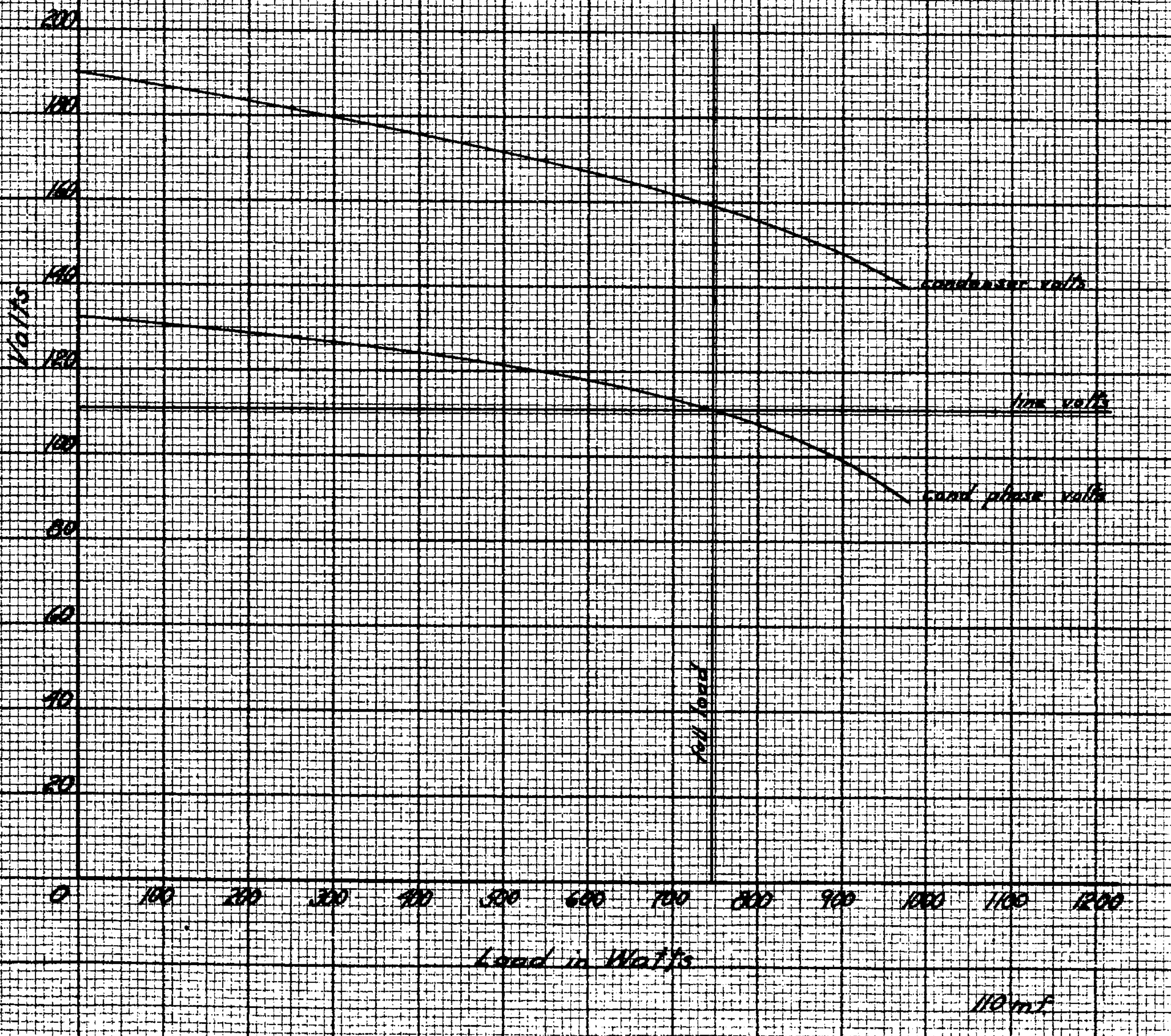


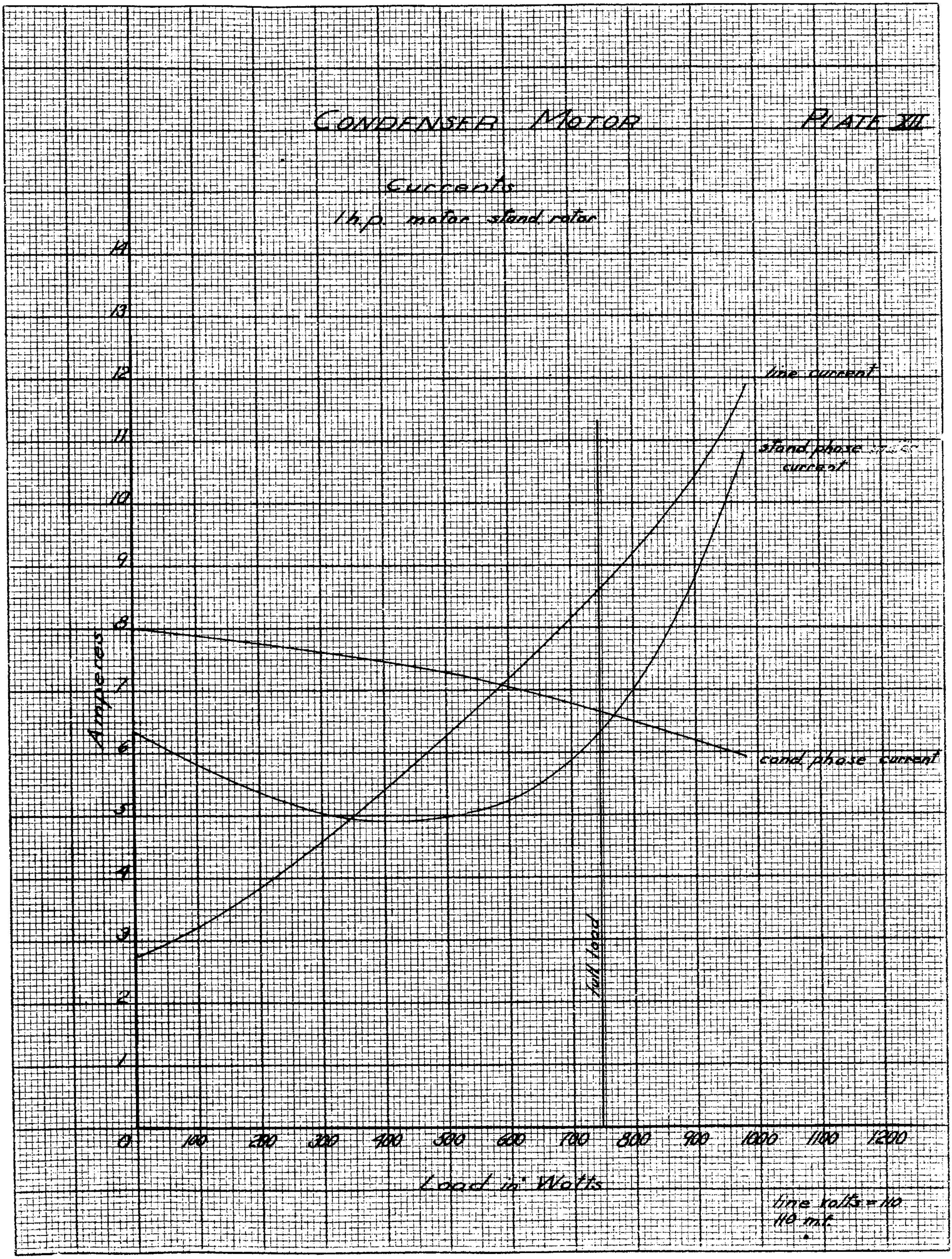
CONDENSER MOTOR

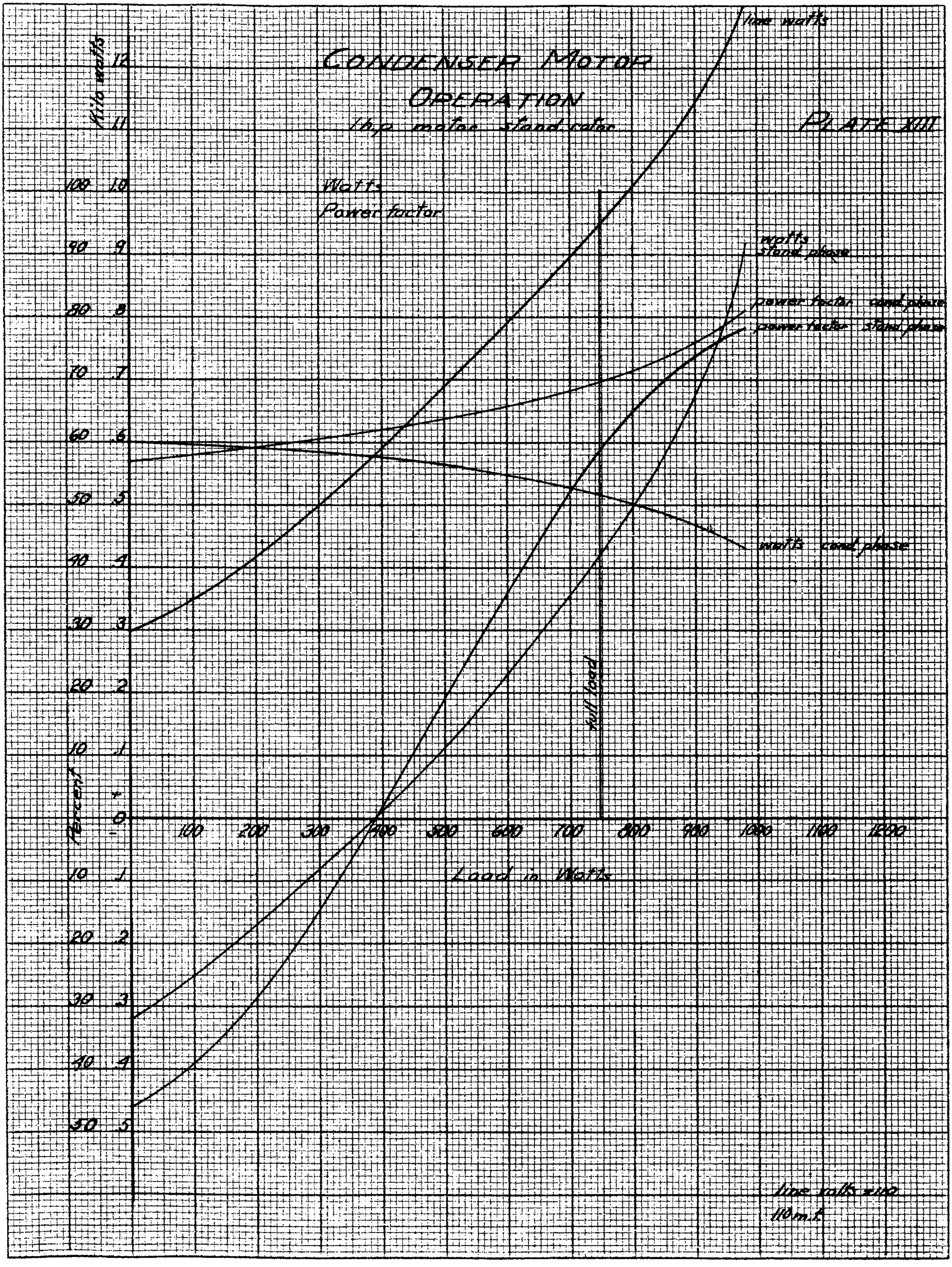
PLATE XI

Operating Voltage

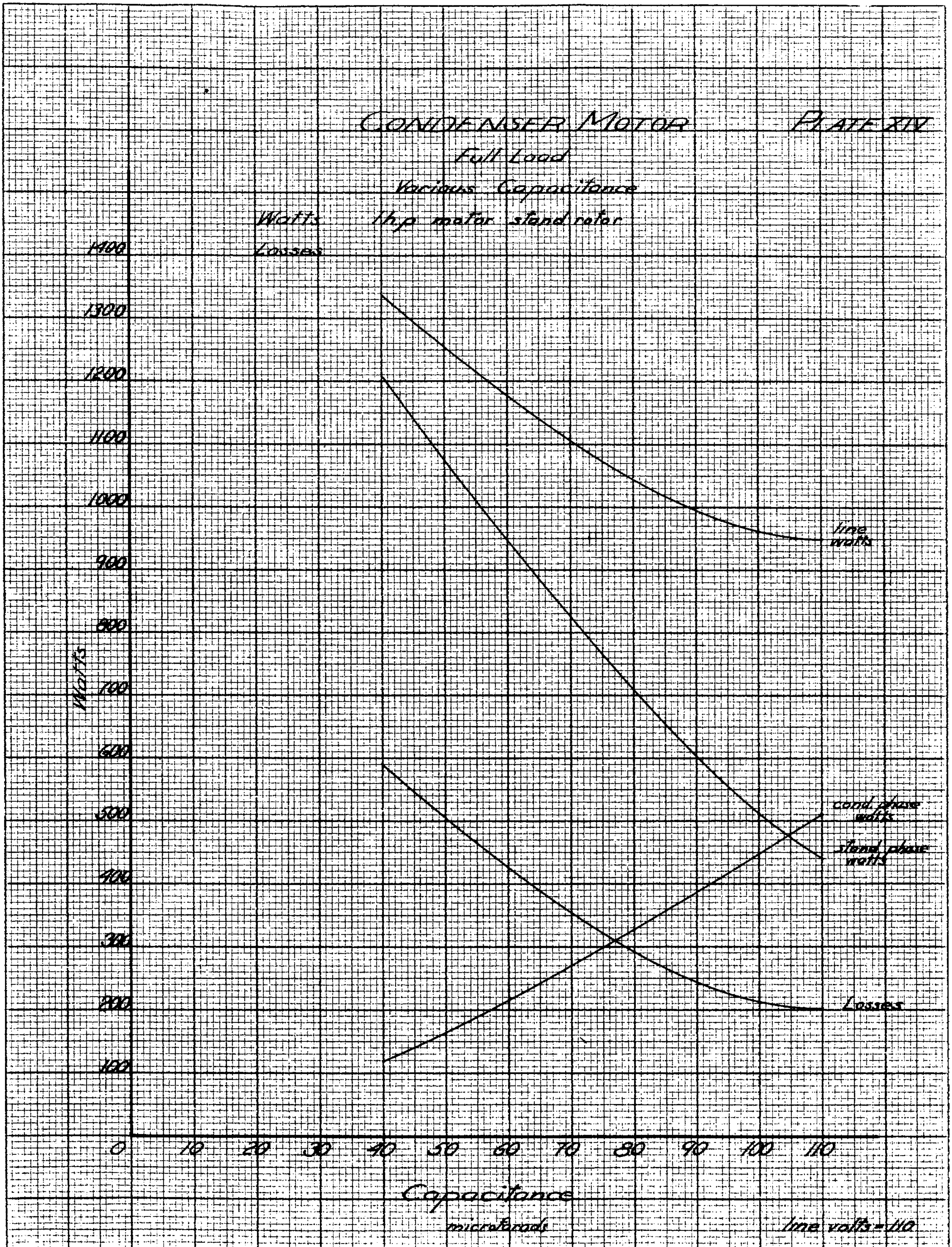
1 h.p. motor stand rotor



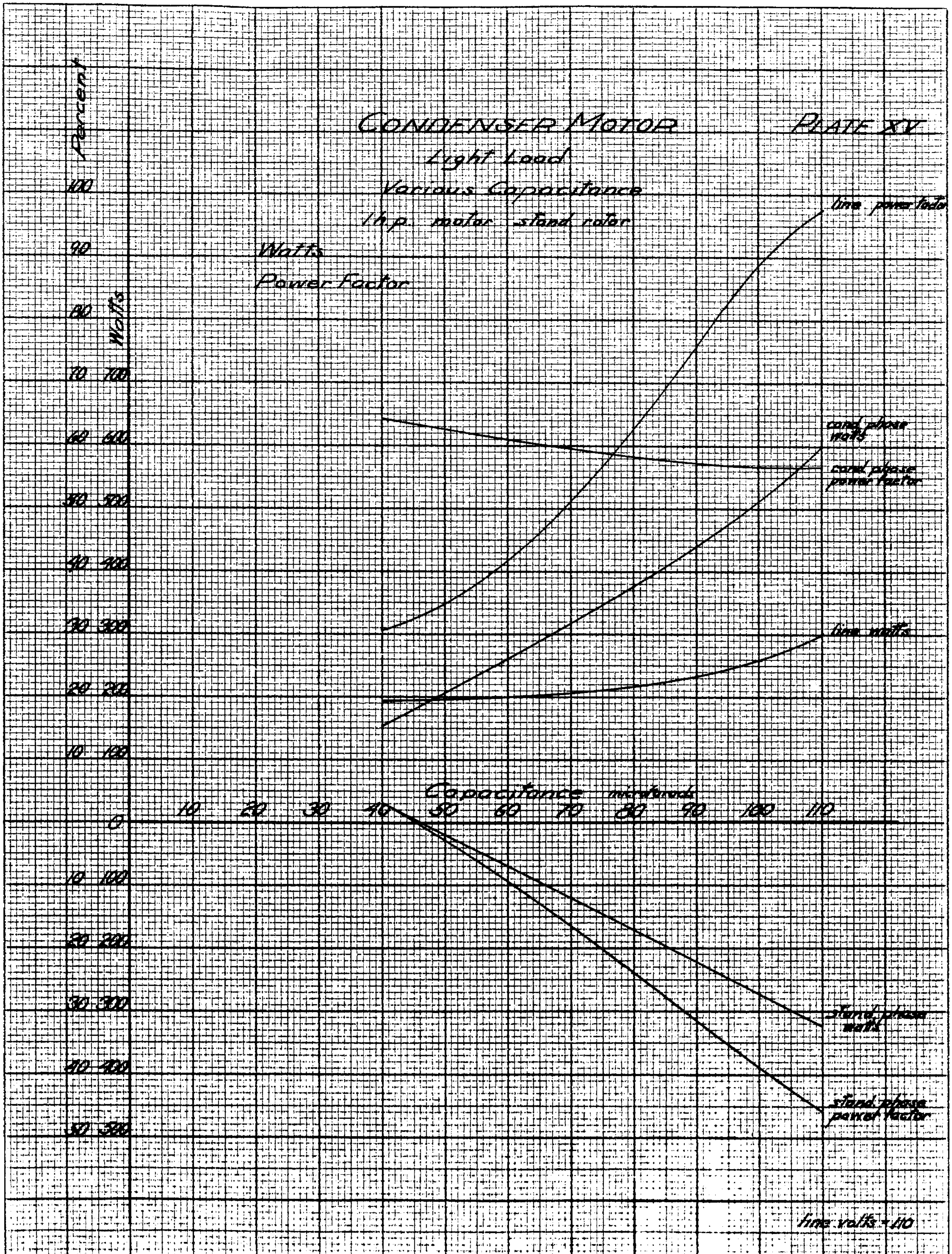

CONDENSER MOTOR
PLATE XII
Currents
1 h.p. motor stand rotor
line current
stand phase current
cond phase current
full load
Amperes
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
100
200
300
400
500
600
700
800
900
1000
1100
1200
Load in Watts
line volts = 110
110 m.f.



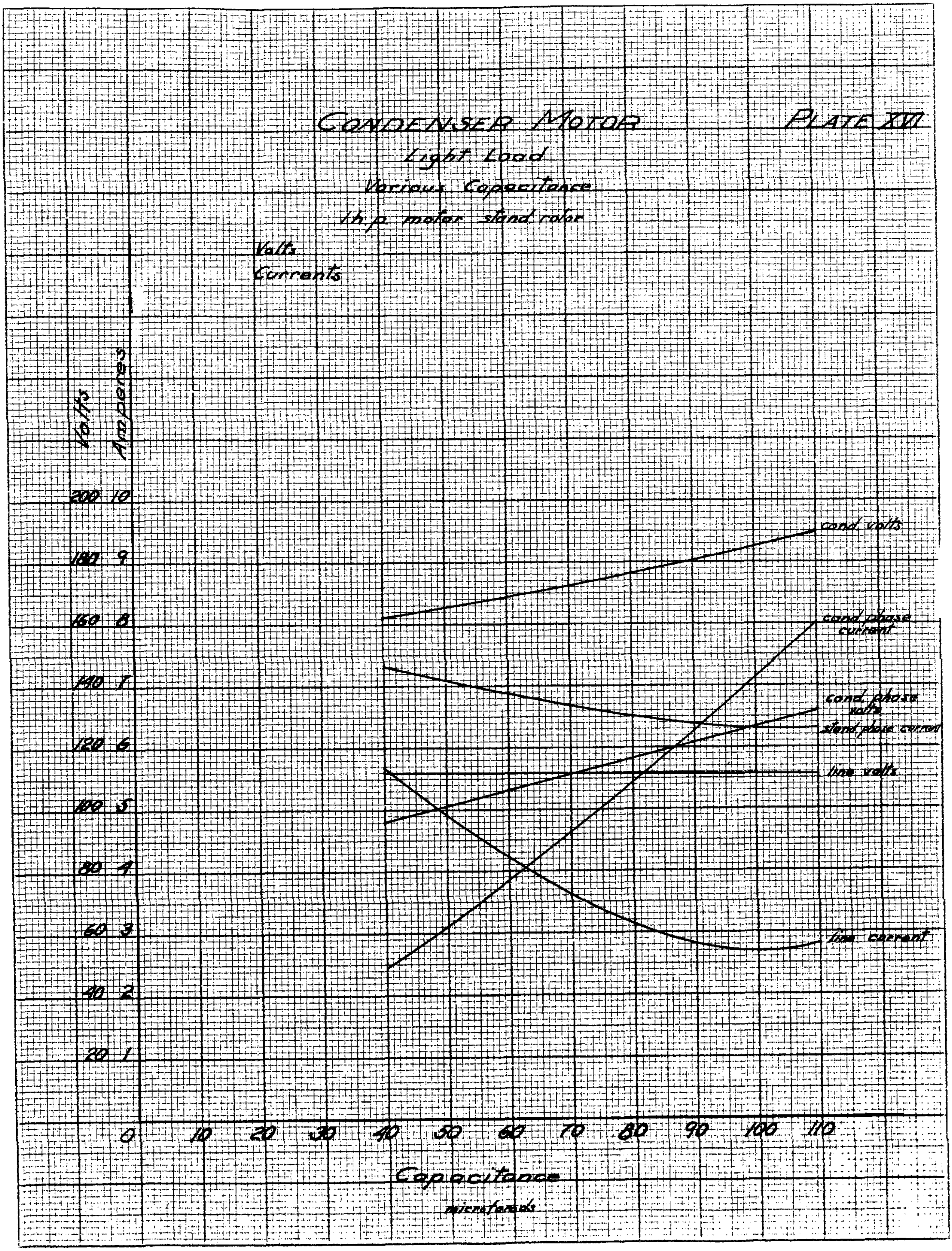
CONDENSER MOTOR
OPERATION
1 h.p. motor stand. rotor
PLATE XIII
Kilo watts
Watts
Power factor
line watts
watts stand. phase
power factor cond. phase
power factor stand. phase
watts cond. phase
full load
Percent
Load in Watts
line volts = 110
110 m.f.



CONDENSER MOTOR
PLATE XIV
Full Load
Various Capacitance
Watts
1 h.p. motor stand rotor
Losses
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Watts
line watts
cond. phase watts
stand. phase watts
Losses
0
10
20
30
40
50
60
70
80
90
100
110
Capacitance
microfarads
line volts = 110

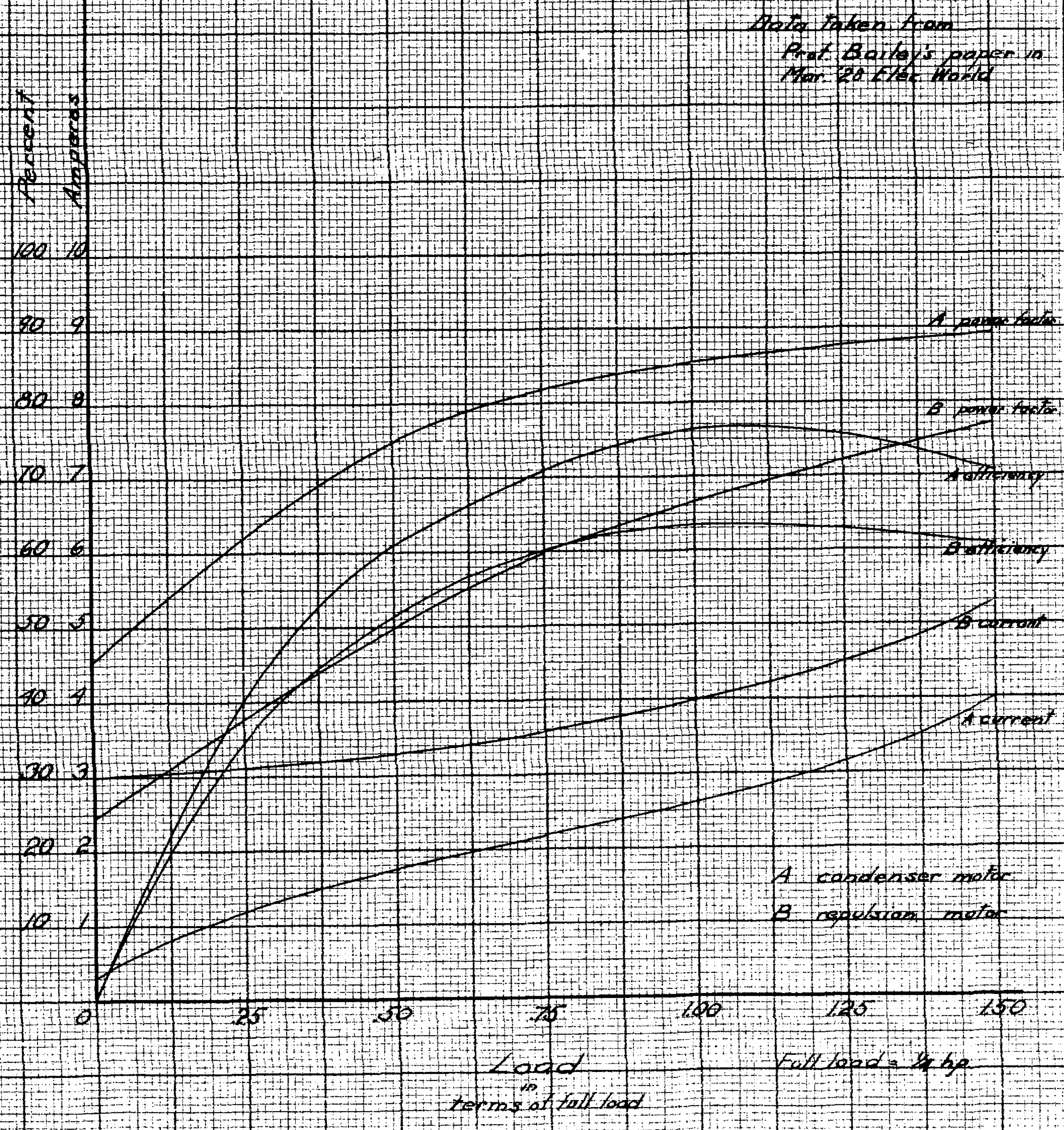


CONDENSER MOTOR
PLATE XV
Light Load
Various Capacitance
1 h.p. motor stand rotor
Watts
Power Factor
Percent
Watts
100
90
80
70 700
60 600
50 500
40 400
30 300
20 200
10 100
0
10 100
20 200
30 300
40 400
50 500
Capacitance microfarads
10
20
30
40
50
60
70
80
90
100
110
line power factor
cond phase watts
cond phase power factor
line watts
stand phase watts
stand phase power factor
line volts = 110


CONDENSER MOTOR
PLATE XVII
Light Load
Various Capacitance
1 h.p. motor stand rotor
Volts
Currents
Volts
Amperes
200 10
180 9
160 8
140 7
120 6
100 5
80 4
60 3
40 2
20 1
0
10
20
30
40
50
60
70
80
90
100
110
cond. volts
cond. phase current
cond. phase volts
stand phase current
line volts
line current
Capacitance
microfarads

Comparison of Repulsion & Condenser Motors

Plate XVII



LOCKED ROTOR VOLTS
against
VARIOUS CAPACITANCE
1 h.p. motor 110 v. stand rotor
Circle Diagram

PLATE XVIII

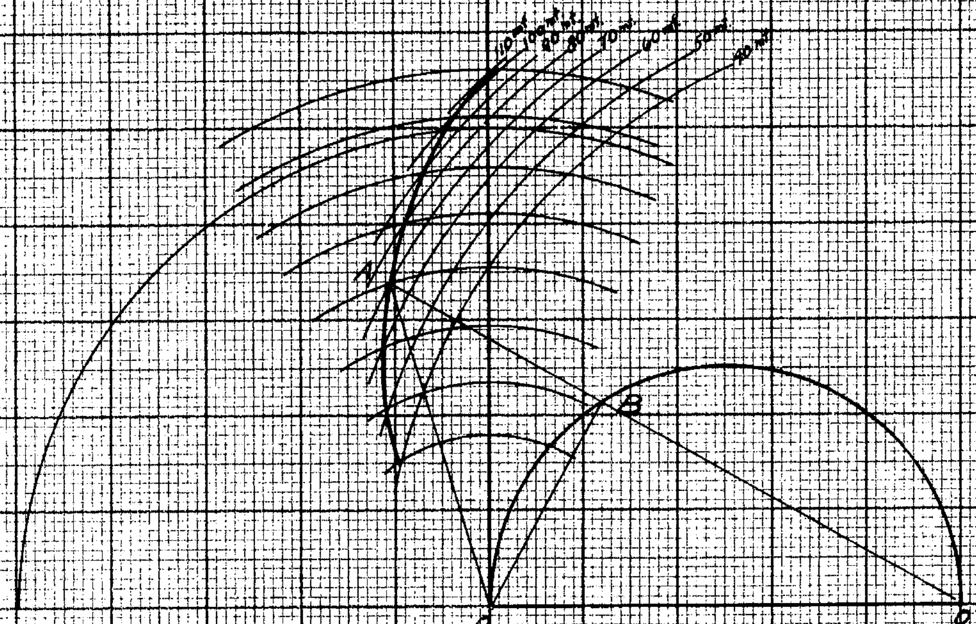


PLATE XIX

VOLTAGE RELATIONS vs LOAD

on

Circle Diagram

1hp 110v motor stand rotor