THE CONSTRUCTION AND CALIBRATION OF A PHASE-SHIFTER

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I. PREFACE

This thesis involves the construction and calibration of a phase-shifter as a permanent piece of apparatus for the Electrical Laboratory of the University of Tennessee.

The materials, which were furnished by the University of Tennessee, had been collected previously by students who had constructed the machine according to a somewhat different design.

The author wishes to acknowledge indebtedness to Professor J. G. Tarboux for the use of the Electrical Engineering Laboratory and its equipment. Acknowledgement is also made to Professor Tarboux and Mr. N. D. Martin for advise and services rendered.

August, 1935.

II. GENERAL SURVEY OF THE FIELD.

Phase-shifters are used whenever it is desired to alter the phase relationship between two voltages. Although machines for phase-shifting are manufactured by several different manufacturers of electrical equipment, no details as to their construction and operation were available. Very little information of any kind on phase-shifters could be found in the University Library.

III. USE OF PHASE-SHIFTERS.

Phase-shifters are used in the testing and calibration of wattmeters, watthourmeters, relays and other similar electrical instruments. In order to do this it is necessary to obtain several different power factors for the same electrical load.

There are several different methods of obtaining different power factors. Perhaps the most obvious method is that of properly combining resistances, capacities, and inductances, but this is too slow and laborious.

Another method which is somewhat widely used is that of connecting auto-transformers, equipped with center taps, in Delta. The big disadvantage of this is that the number of power factors obtainable is limited by the number of taps on the transformers.

The best method for phase-shifting is that of using such a phase-shifting device as has been the object of this thesis to construct. This machine not only overcomes the disadvantages of the other two methods, but also combines simplicity with compactness.

IV. GENERAL THEORY

The mechanical phase-shifter constructed for this thesis is comprised of a three phase stator, with an internal, concentric, single phase wound rotor. The stator of the machine is so designed as to give a synchronously revolving, magnetic field of constant strength in the air gap between the stator and rotor.

As this magnetic field rotates about the rotor the magnetic lines cut the conductors wound about the periphery of the rotor, producing an induced E.M.F. which is directly proportional to the number of turns on the rotor and of the same frequency as the voltage impressed upon the stator.

By rotating the rotor and changing the angular position, the phase of the secondary voltage can be adjusted to practically any value with respect to any one of the three phase supply voltages.

V. WINDING THE PRIMARY

The problem of this thesis was merely one of electrical design. The stator and rotor were formerly part of a 1/2 horsepower alternating current motor and were equipped with slots, and dimensions which it would hardly be feasible to alter. Wire for winding both the rotor and stator was already on hand. For the stator number 20, single cotton covered, enameled copper wire was used, and number 25 of the same kind of wire was used for the rotor.

The following data and dimensions for the stator were found:

Number of slots----------48

Length of slots----------2.125"

Diameter of slots----------5.75"

Since the number of slots was already determined, it remained only to determine the number of conductors per slot. This was readily calculated by the formula:

$$N = \frac{E \times 60 \times 10^8}{\Phi t \; n \; f_c \; Cw} \; *$$

Where: f_c= sin (P+90) = 1
Cw= 0.677 for three phase

A flux density of 43,000 lines per square inch was assumed for the air gap flux density, making, $\Phi t = 43000 \times 3.1416 \times 5.75 \times 2.125$

or $\Phi t = 1,650,616$

since the machine is of 2 pole 60 cycle design, the speed, $n = \frac{120 f}{P} = \frac{120 \times 60}{2} = 3600$ R.P.M.

*Design of Electrical Apparatus---Kuhlman

The windings were connected in "Y" making

$$E = \frac{110}{1.73} = 63.58 \text{ volts.}$$

From this

$$N = \frac{63.58 \times 60 \times 10^8}{1,650,616 \times 3600 \times 1 \times 0.677}$$

$N = 948.3$ turns in series per phase, or

$$\frac{948.343}{48} = 60 \text{ conductors per slot.}$$

Due to limited space at the ends some of the slots were not filled, since it was found that a current sufficient to produce enough flux and at the same time not endanger the windings could be applied to the slots filled and produce satisfactory results.

After completion the coils were well insulated from the frame in order to prevent the wires from becoming grounded and causing the phases to become unbalanced.

VI. WINDING THE SECONDARY.

The following data and dimensions were determined for the secondary, or rotor:

Number of slots----------69

Length of slots----------2.125"

Diameter of rotor----------5.75"

The rotor was to be wound for 110 volts, 60 cycle, single phase, it being desired to obtain approximately the same induced voltage on the rotor as was impressed on the stator.

It was assumed that there would be a 10% flux leakage thus causing the rotor to benefit by only 90% of the total produced flux.

By making the proper substitutions in the same formula that was used for the stator, namely; $N = \frac{E \times 60 \times 10^8}{\Phi t\ n\ f_c\ Cw}$ it was found that 30 conductors per slot would be satisfactory. It should be noted that E, Φt, f_c and Cw have all changed, being respectively 110, 1,495,554, 1, and 1.

The formula being,

$$N = \frac{110 \times 60 \times 10^8}{1,495,554 \times 3600 \times 1 \times 1}$$

or N = 1380 turns in series.

In order to make any corrections for poor assumptions, so that if the voltage was too low more turns could be added it was decided to use only about 2/3 or 46 of the slots. From this and the above calculations it was determined to wind 1380/46 or 30 conductors per slot.

As in the case of the stator the coils had to be carefully insulated against grounds in order to obtain a constant and uniform voltage.

VII. CALIBRATION OF THE DIAL.

In order to facilitate the calibration of the dial it was subdivided into intervals of five degrees each. Since the machine was designed for two poles one electrical degree is equal to one mechanical degree. A space of 180 degrees only was calibrated since the power factors would be respectively zero for both 90 degrees lagging and leading current, making a space of exactly 180 degrees between the 90 degree lag and 90 degree lead points. The dial was placed on the milling machine and by means of a dividing engine divisions were made at intervals of exactly 5 degrees. The rotor of the phase shifter was then rotated until the indicator of a wattmeter to which it was connected read zero. The dial was then placed so that one of its 90 degree marks coincided with the mark on the indicator.

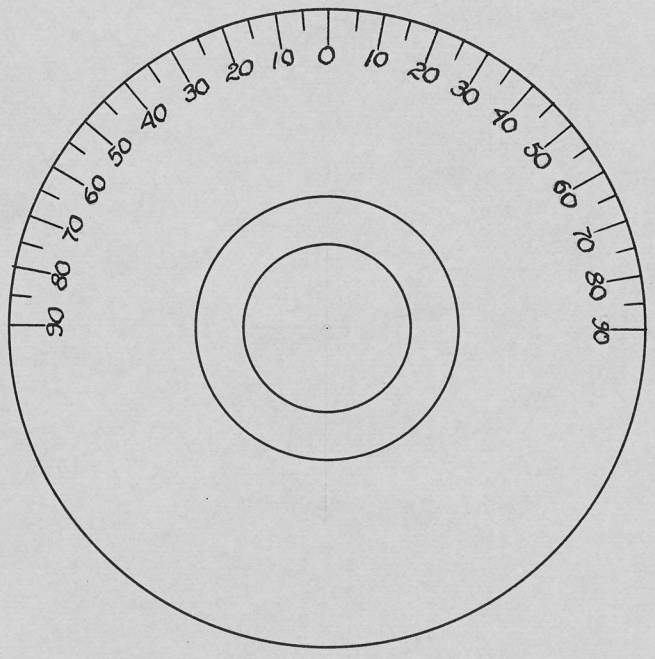


Fig. 1

VIII. OPERATION.

For simplicity of connection the phase-shifter has been equipped with a panel board which has been lettered to secure proper connections. The accompanying circuit diagram will make even more clear the correct connections.

The phase-shifter is connected to a three phase supply and a pure resistance load is connected to one phase of the supply. The current elements of a standard wattmeter, the meter to be tested, a phase angle meter and an ammeter are placed in series with one of the lines supplying the load. The potential elements of the meters are then connected in parallel to the voltage brought off of the rotor to jacks on the panel board.

Load is applied to the circuit by means of the resistance. In order to secure different power factors it is then only necessary to turn the dial until the fixed indicator coincides with the desired angle indicated on the dial. If it is so desired the adjustment may be very accurately made with the use of a small micrometer device attached to the phase-shifter.

CONNECTION DIAGRAM

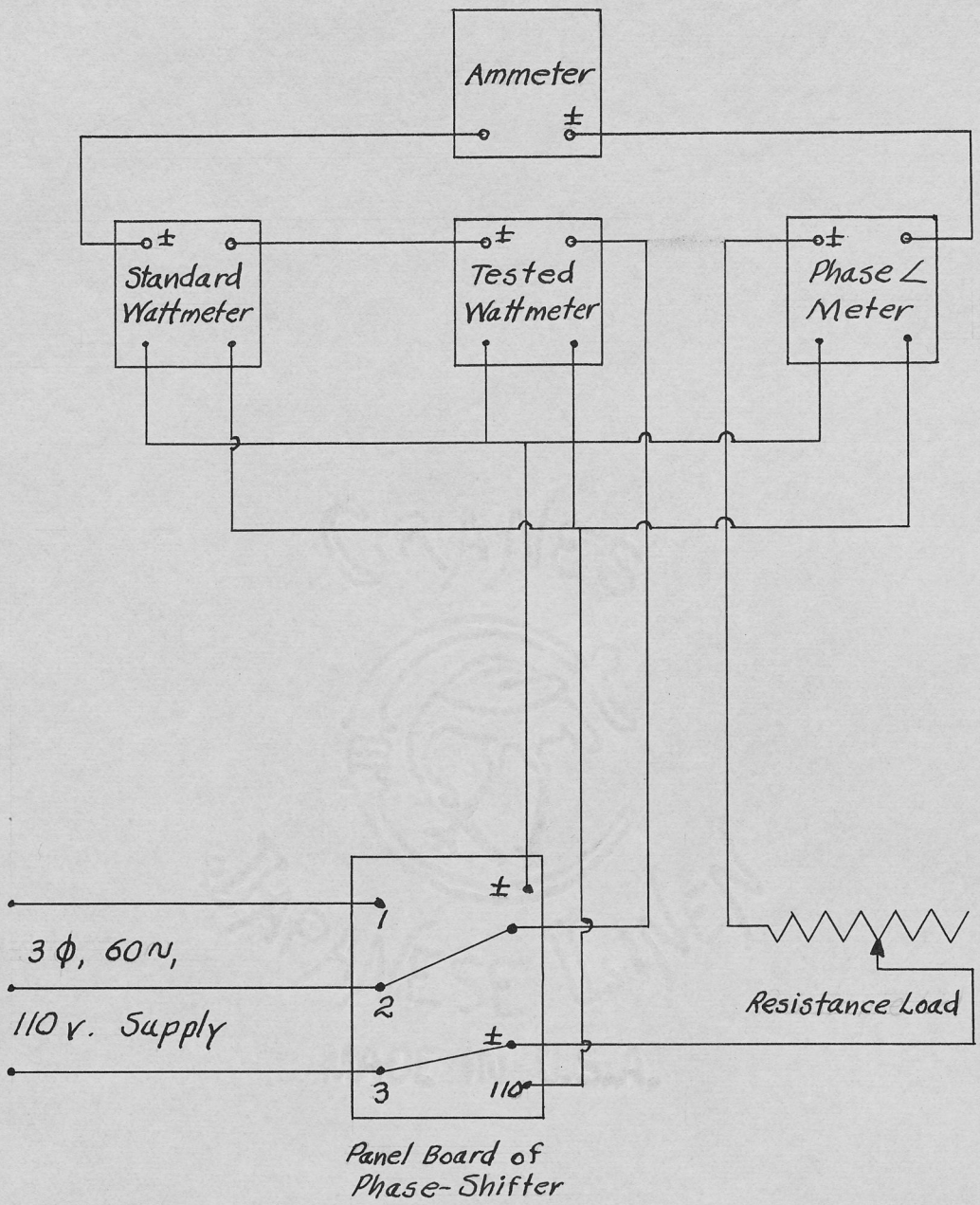


Fig. 2.

IX. CONCLUSIONS.

It is necessary that the phase rotation indicated on the panel board of the phase shifter be correctly followed. If this is not done the phase relationship will be rotated 120 degrees making it impossible for the machine to reach both 90 degree lag and 90 degree lead since the machine is equipped with a stop which allows it to turn through a range of only a little better than 180 degrees.

The author suggests the use of both an ammeter and phase-angle meter in the testing circuit, although their use is not absolutely necessary. Since the wattmeters will show very low power at the low power factors the ammeter is inserted in the circuit to indicate when the capacities of the current coils of the meters have been reached.

The phase angle meter should be inserted to determine whether the phase relationship is lag or lead. Although the indications could have been made on the dial, it was thought unwise to do so, since an incorrect connection would change the phase rotation and render the indications worse than useless.

X. BIBLIOGRAPHY

1. Design of Electrical Apparatus--Kulhman.

2. Construction and Calibration of a Phase-Shifter--
R. W. McEver, (Thesis, 1928)

3. The Construction and Calibration of a Phase-Shifter--
J. R. Wade and T. E. Braxton, (Thesis, 1931)

XI. APPENDIX

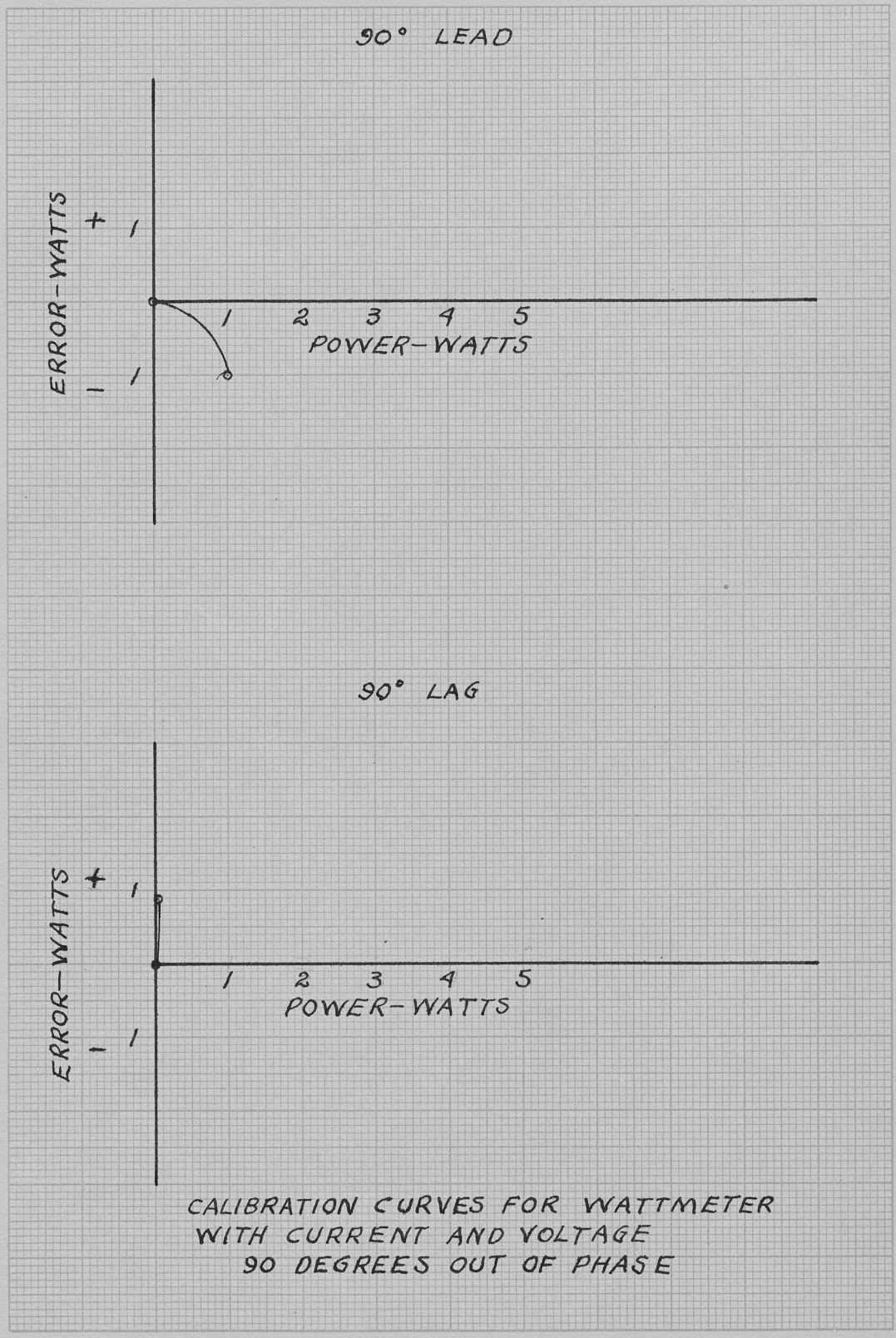
TABLE I

Results of a test made on a wattmeter.

Std., meter--G.E.--type PL-2; Tested, G.E.--type P-3

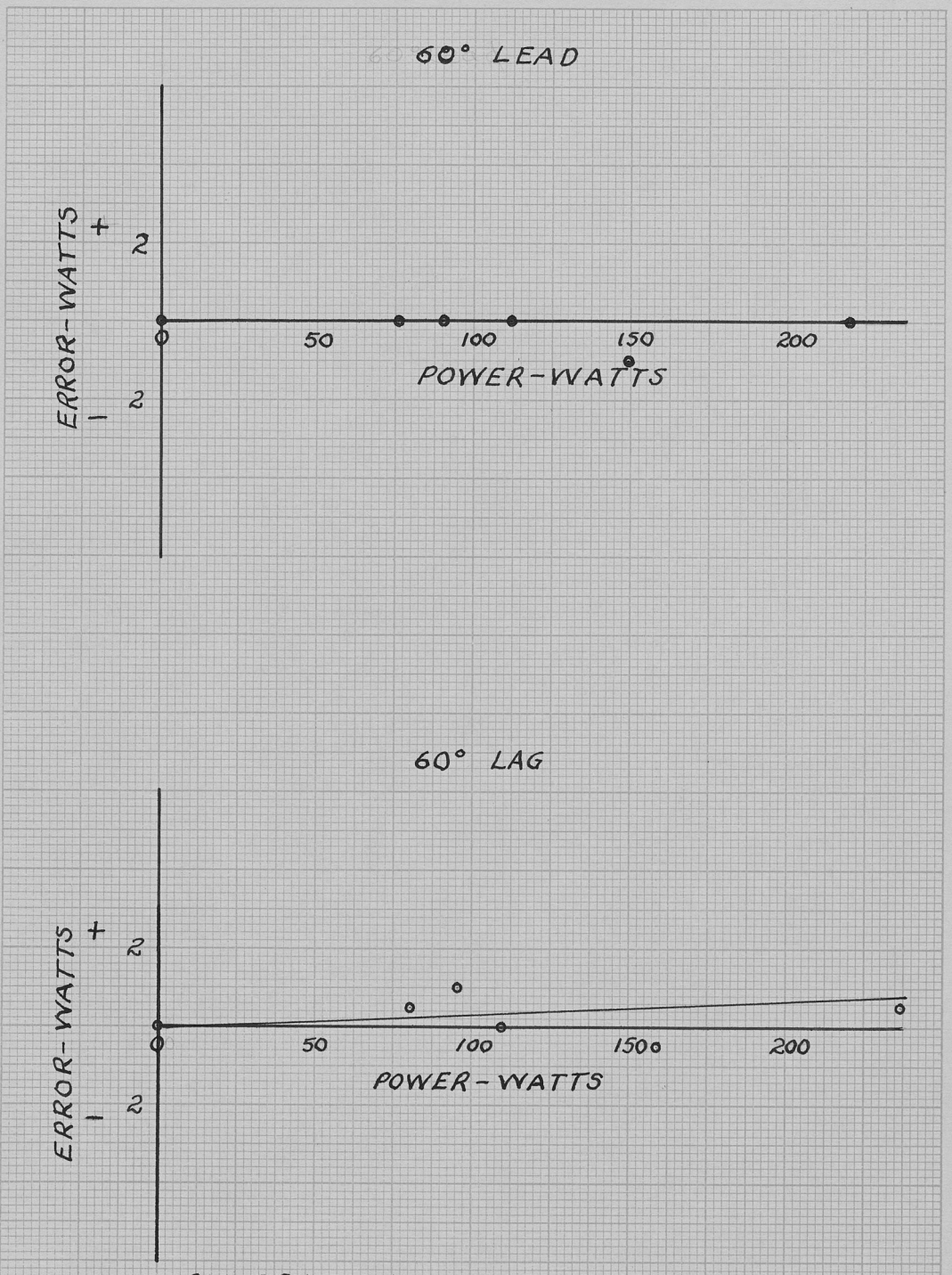
Std. Wm. Se.No.846460	Tested Wm. Se. No. 992345	Std. Wm. 846460	Tested Wm. 992345
90 Degrees Lead		90 Degrees Lag	
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
1.0	0.0	0.05	0.0
60 Degrees Lead		60 Degrees Lag	
76.0	76.0	80.5	81.0
90.0	90.0	96.0	97.0
112.0	112.0	120.0	120.0
149.0	148.0	159.5	159.0
219.0	219.0	237.0	237.5
30 Degrees Lead		30 Degrees Lag	
132.0	132.0	130.5	130.0
157.5	157.5	156.5	156.5
196.0	196.0	195.5	195.0
261.0	260.0	260.0	260.0
387.0	385.0	389.0	386.0

Std. Wm.	Tested Wm.
0 Degrees Lag	
155.0	155.0
185.0	185.0
231.0	231.0
307.0	307.0
456.0	454.0



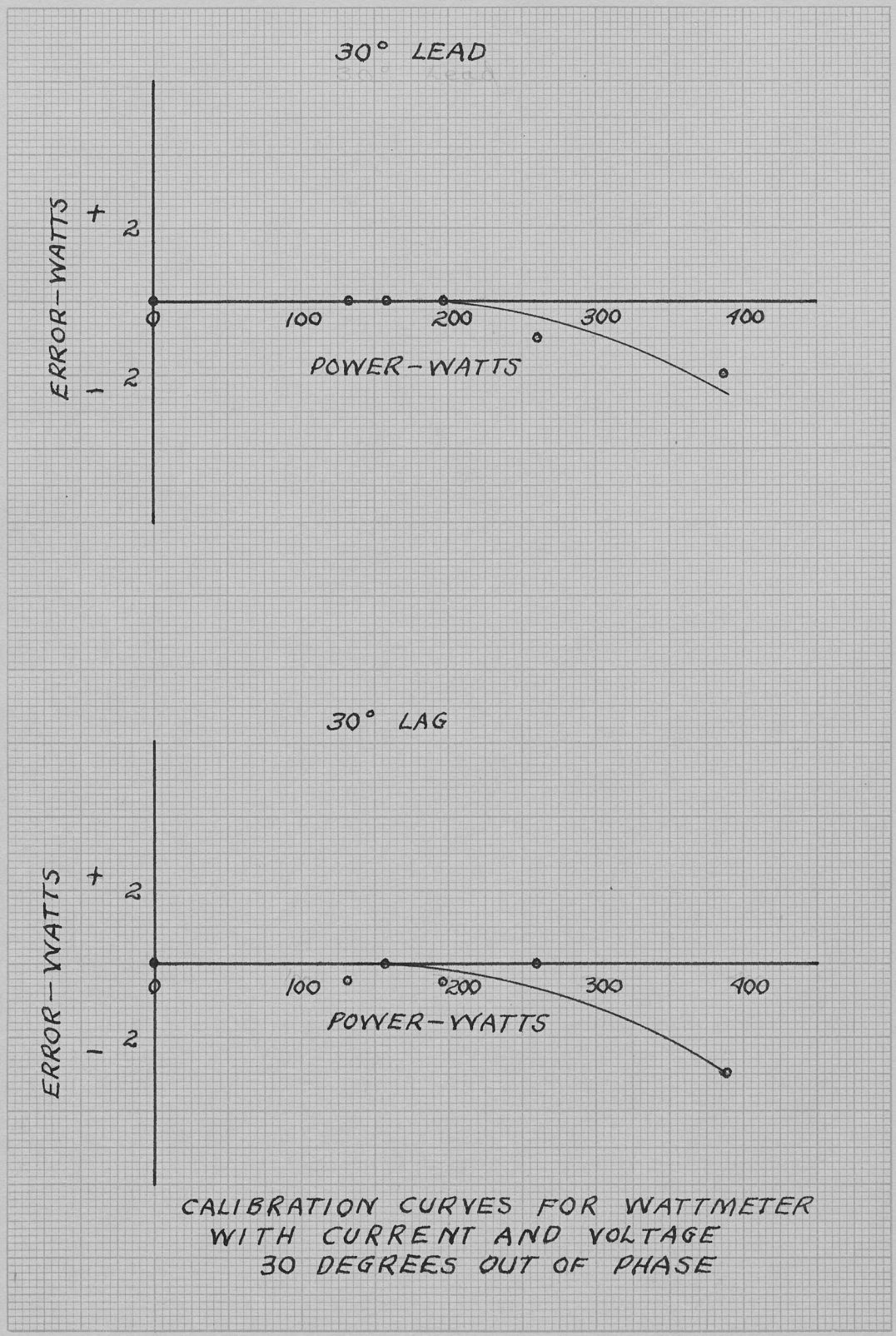
CALIBRATION CURVES FOR WATTMETER
WITH CURRENT AND VOLTAGE
90 DEGREES OUT OF PHASE

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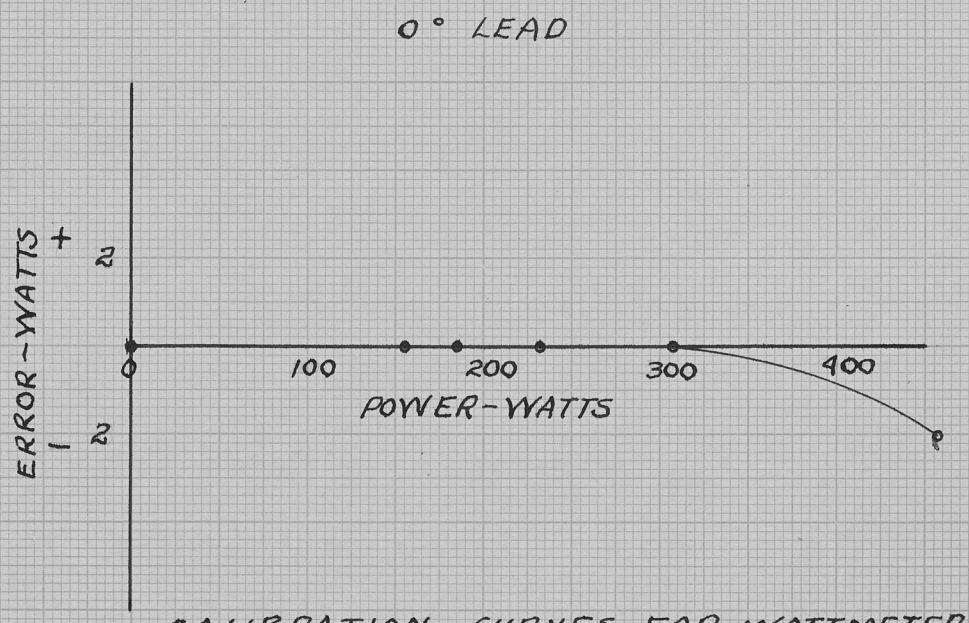
CALIBRATION CURVES FOR WATTMETER
WITH CURRENT AND VOLTAGE
60 DEGREES OUT OF PHASE

Published by The H. Cole Co., Columbus, Ohio. No. 290 G.



CALIBRATION CURVES FOR WATTMETER WITH CURRENT AND VOLTAGE 30 DEGREES OUT OF PHASE

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CALIBRATION CURVES FOR WATTMETER WITH CURRENT AND VOLTAGE IN PHASE

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APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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