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ACCURACY OF HIGH-RANGE CURRENT TRANSFORMERS

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ABSTRACT

The variations in ratio and phase angle of a current transformer caused by changes in the geometrical configuration of its primary circuit were determined experimentally for transformers of various makes and designs with primary current ratings from 1,200 to 7,500 amperes. A theoretical explanation of the results is given.

CONTENTS

I. INTRODUCTION

Commercial measurements of electric power and energy, in circuits carrying alternating currents of large value, are invariably made by the use of current transformers which supply, to the measuring instruments proper, secondary currents which are a replica to a reduced scale of the corresponding currents in the primary circuit. In important installations the proportionality factor or "ratio" of the transformer is obtained by an experimental comparison between the transformer in question and a standard transformer of known ratio. This comparison is usually made in the testing laboratory of the utility company concerned, while the standard transformer in turn is tested at suitable intervals by some "absolute" method usually in a large standardizing laboratory such as that of the National Bureau of Standards.

It is evident that the accuracy of the final results would be invalidated if the conditions under which either the working or the standard transformer is operated were allowed to differ to a significant extent from the conditions under which either transformer was tested. With ordinary care such conditions as frequency and secondary burden can be readily reproduced with sufficient fidelity, and the effect of changes in these conditions decreases in general with an increase in the current to be measured, and hence in the commercial importance of the measurement.

The variations in the magnetic effect of the primary circuit resulting from changes in its geometrical configuration, however, while negligible in multi-turn transformers of low current rating, tend to increase as the rated primary current increases. The arrangement of the primary circuit in the neighborhood of the working current transformer when in service is, of course, fixed by external considerations and the question arises as to how closely this arrangement must be duplicated in the testing laboratory if significant errors are to be avoided. Similarly, the closeness with which the circuits used with the standard transformer in the testing laboratory should be duplicated in the standardizing laboratory, becomes a matter for study and perhaps for standardization by mutual agreement.

The effect on the ratio and phase angle of a current transformer of changing the arrangement of its primary circuit has been studied by Price and Duff[1] on a number of transformers of ratings up to 1,600 amperes. In view of the extension in 1932 of the facilities at the National Bureau of Standards for testing current transformers up to 12,000 amperes, it seemed desirable to extend this study into the higher range where, presumably, the effects would be enhanced. Such a study would serve to bring out the precautions needed in this range of testing to fully utilize the precision available.

II. THEORY

The relation between the primary and secondary currents of a current transformer can be deduced by considering its magnetic circuit, provided all currents and fluxes are assumed to vary sinusoidally with time and their effective values are used as vectors. For simplicity, this relation will first be derived for the hypothetical case in which the air or other medium surrounding the current transformer core is assumed to have zero permeability. Under these conditions, for any arrangement of the windings, all of the magnetic flux produced by the primary and secondary ampere-turns will make a complete circuit in the core. An example is shown in figure 1A, in which

I_1 = primary current,
I_2 = secondary current,
n_1 = number of primary turns,
n_2 = number of secondary turns, and
ϕ = total flux at any section of the core.

The equation for the sum of the magnetomotive forces around the closed magnetic circuit a b c d a is:

$$I_1n_1+I_2n_2+I_en_1=0 \qquad (1)$$

All of the terms in this equation are vectors and I_en_1 represents the ampere-turns required to sustain the flux ϕ in the core.

The exciting ampere-turns, I_en_1, may be obtained experimentally as a vector function of the voltage induced in an exploring coil wound around the core (i. e., by using either the primary or the secondary winding as an exciting coil and measuring the components of the volt-

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[1] H. W. Price and C. K. Duff, *Through Type Portable Current Transformers*. Univ. Toronto, School Eng. Research Bul. 2, sec. 4, pages 202 to 210 (1921).

age induced in the exploring coil in time phase and in time quadrature with the exciting current for various values of exciting ampere-turns). Thus, if the voltage induced in the exploring coil is measured as a vector with respect to I_2 when the transformer is performing its normal function, $I_e n_1$ can also be obtained as a vector with respect to I_2 and then by use of equation 1 the vector relation between I_1 and I_2 can be computed, from which the ratio and phase angle of the transformer are readily obtainable.

For the practical case where the medium surrounding the core does not have zero permeability, the flux distribution will be about as shown in figure 1B, in which some of the flux occupies leakage paths through the air. Thus, the core flux and likewise the electromotive force induced in an exploring coil wound around the core are not constant for various sections along the perimeter of the core, and the $I_e n_1$ term in equation 1 cannot be obtained in the simple manner outlined for the hypothetical case. However, the equation for the sum of the magnetomotive forces around the closed magnetic circuit a b c d a will still be the same if the value of exciting ampere-turns, $I_e n_1$, is obtained by adding vectorially, for the entire core, the ampere-turns required to maintain the flux in each elemental length of the core.

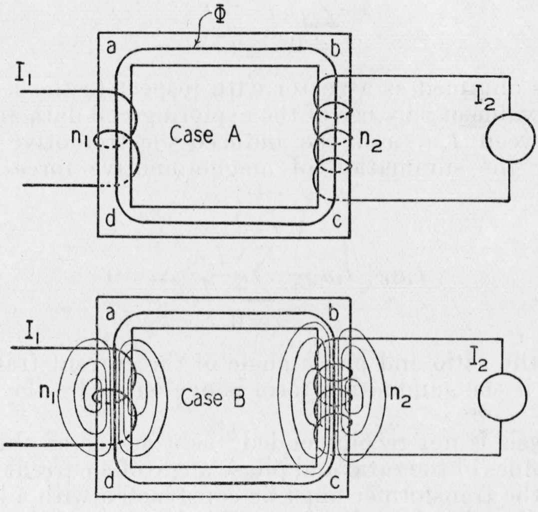

Figure 1

The summation of the exciting ampere-turns can be determined experimentally if the core flux is assumed to be uniform over any cross section and if all of the flux lines are considered to be perpendicular to the core cross section. In order to do this, a number of exploring coils must be wound on the core, spaced short distances apart along the core perimeter. Then, while the transformer is being used to measure a current of constant value, the electromotive force induced in each exploring coil and its phase relation with the secondary current are measured. These values are plotted against the distance along the core perimeter and by use of these curves the perimeter is divided into small lengths over which the induced electromotive force and its phase angle with respect to the secondary current are taken to be constant. The values of exciting ampere-turns and their phase angles with respect to the secondary current, for each small length of the core, are now obtained by use of the vector relation between the exciting ampere-turn and induced electromotive force. This relation is determined as outlined in the hypothetical case, except that the exciting turns must now be uniformly distributed around the core so that the core flux will be the same at different sections. The total exciting ampere-turns and their phase angle with respect to the secondary current are obtained by adding vectorially the values of exciting ampere-turns for each small section of the core. If x is the distance along the perimeter of the core from a fixed point to any other point, and if l is the total perimeter, the exciting ampere-turns for the entire core may be expressed as:

$$\sum_{x=0}^{x=l} \frac{I_e n_1}{l} \Delta x, \tag{2}$$

where $I_e n_1$ is obtained as a vector with respect to the secondary current for any value of x by use of the exploring-coil data and the vector relation between $I_e n_1$ and the induced electromotive force. The equation for the summation of magnetomotive forces around the core becomes

$$I_l n_l + I_2 n_2 + \sum_{x=0}^{x=l} \frac{I_e n_1}{l} \Delta x = 0 \tag{3}$$

from which the ratio and phase angle of the current transformer can be obtained if the summation term is evaluated by the method just described.

This analysis is not recommended[2] as a means of obtaining exact numerical values of the ratio and phase angle of a current transformer, because (1) the transformer must be constructed with a large number of search coils wound on its core, (2) the task of determining the electromotive force induced in these search coils for each value of secondary current is time consuming, and (3) the assumption that the flux density is uniform over any cross section of the core is never realized and in most cases the errors thus introduced will not be negligible. This analysis is, however, useful as a qualitative guide to an understanding of how changes in location of the primary conductors affect the ratio and phase angle of a current transformer.

Since the performance of a current transformer is dependent upon the values of core flux at each cross section of the core along its perimeter, the location of the primary conductors will affect ratio and phase angle by affecting the values of core flux. However, in order to determine the qualitative effect on ratio and phase angle for a given change in arrangement of the primary circuit, further deduc-

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[2] It may be useful quantitatively in the case of a current transformer with a ring-shape core and uniformly distributed windings, since the core flux will then be the same at all cross sections of the core and one exploring coil measurement will be sufficient for each value of current.

tions are required. Price and Duff[3] have demonstrated that the flux at any cross section of the core may be thought of as divided into two components. One component is called the working or mutual flux. It makes a complete circuit in the core, linking all of the primary and secondary turns, and is the same at all cross sections of the core. The other component is called the leakage flux (primary leakage flux if produced by primary turns and secondary if produced by secondary turns). It does not make a complete circuit in the core but "leaks" out and completes its circuit through the surrounding medium. This component varies at different cross sections around the core and its magnitude depends upon the arrangements of the primary and secondary turns. Price and Duff separated the total flux at any cross section of the core into these two components by an experimental method. They supplied the primary winding and the secondary winding independently so that their values of ampere-turns were exactly equal and 180° apart in phase. For these conditions, equation 3 shows that the summation of the exciting ampere-turns around the core is zero. Also, the flux at various sections of the core is substantially the same as the leakage flux during normal operation of the transformer, and since the leakage flux is usually much larger than the mutual flux, especially in high-range current transformers with nonuniform distribution of primary windings around the core, the addition of the mutual flux will not greatly affect the magnetic condition of the core and the summation of the exciting ampere-turns required to produce the leakage flux in the core will still be zero. Therefore, the leakage flux will have no direct effect upon the summation term in equation 3. However, there will be an indirect effect, because the existence of the leakage flux will increase the flux density in the core and change its magnetic condition, thus changing the ampere-turns required to produce the mutual flux and, correspondingly, the ratio and phase angle of the current transformer. If the addition of leakage flux to mutual flux does not bring the total flux density at any cross section of the core above the value for maximum permeability, the number of ampere-turns required to produce the mutual flux will be decreased by the presence of the leakage flux. If the addition of leakage flux to mutual flux does bring the total flux density at any cross section of the core materially above the value for maximum permeability, the number of ampere-turns required to produce the mutual flux may be much increased. Thus, according to its magnitude, the addition of leakage flux may either increase or decrease the ratio and phase angle.

Leakage flux will also affect ratio and phase angle by causing a leakage reactance in the secondary winding. This leakage reactance may be defined as the integrated value per unit current of the linkages of secondary leakage flux with secondary turns minus the linkages of primary leakage flux with secondary turns. The contribution of secondary leakage flux is usually the larger, thus introducing a positive secondary leakage reactance, which has the same effect on ratio and phase angle as the addition of inductive burden, i. e., it decreases the phase angle and increases the ratio. However, for certain arrangements of primary circuit the contribution from the primary leakage flux will be the larger, thus making the secondary

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[3] *Effects of magnetic leakage in current transformers*, Univ. Toronto, Bul. 2, sect. 4, pages 167 to 191 (1921).

leakage reactance in effect negative. This will tend to make the phase angle larger and the ratio smaller. If the effective negative secondary leakage reactance is more than enough to balance the inductive reactance in the burden, it will make the secondary induced voltage (see fig. 2) lag the secondary current and the mutual flux lead the secondary current by less than 90 degrees. In extreme cases the exciting ampere-turns required to produce the mutual flux may also lead the secondary current by less than 90 degrees, thus making the ratio of primary ampere-turns to secondary ampere-turns less than one.

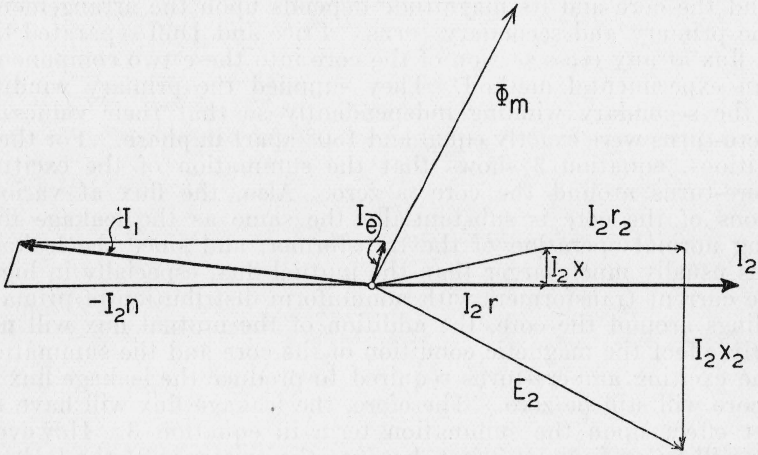

FIGURE 2.—*Vector diagram for a current transformer whose arrangement of primary turns is such that the secondary leakage reactance is negative in effect.*

I_1=primary current
I_2=secondary current
I_e=exciting current
E_2=secondary induced voltage
n=turn ratio

r=resistance of burden
x=reactance of burden
r_2=resistance of secondary winding
x_2=secondary leakage reactance
ϕ_m=mutual flux

A change in arrangement of primary circuit affects the performance of a current transformer by changing the leakage fluxes in and near the core. A change in the frequency of the current being measured or in the burden of the secondary circuit will not greatly affect the leakage flux. Therefore, for a given change in arrangement of primary circuit, the change in performance will be practically independent of the frequency and secondary burden, although the actual performance of the current transformer may change appreciably for different frequencies or secondary burdens.

III. TEST METHODS

In the present study, the ratio and phase angle of current transformers of each of the several main classes of design used in practice for measuring currents of 2,000 amperes or more, were determined with various arrangements of primary circuit. The equipment and methods regularly employed in testing transformers at the National Bureau of Standards [4] were used. The primary current circuit of this equipment, as shown by figure 3, consists of large copper slabs which connect the supply transformer, the transformer under test, and

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[4] *Equipment for testing current transformers,* BS J.Research **11**, 93 (1933) RP580.

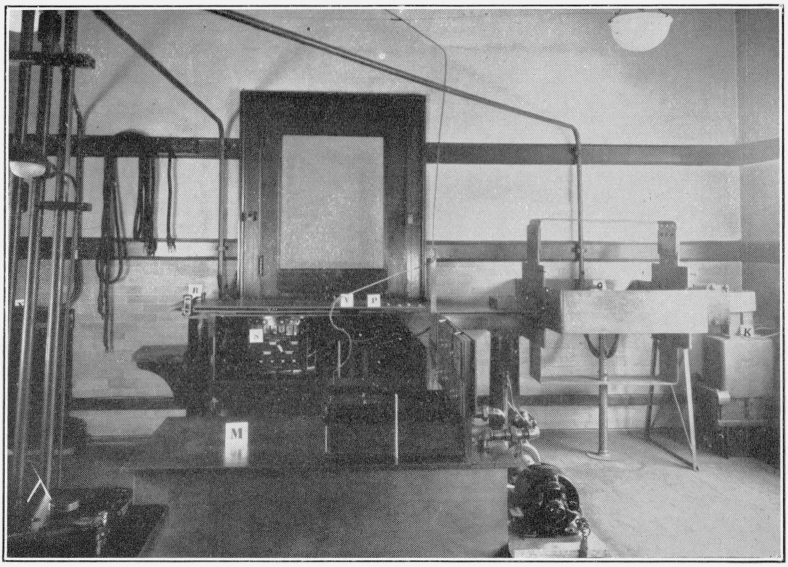


FIGURE 3.—*Primary circuit of equipment for testing current transformers, arranged as ordinarily used at the National Bureau of Standards.*

S, Standard current transformer; O, transformer under test; K, supply transformer; M, tank containing oil-cooled primary shunts.

the standard transformer or primary shunt in series. This circuit is so arranged that two copper slabs carrying current in opposite directions are face to face and close together throughout the entire circuit except where the transformer under test is connected. Here, a portion of the copper slab (called the inner conductor) carrying current in one direction is replaced by the primary of the transformer under test if it is of the busbar type; if it is of the hole type the copper slab is used as the conductor through its core window. The copper slab (called the return lead) carrying current in the opposite direction is close to the inner conductor up to two points 18 inches from the center of the transformer being tested. At each of these points the return lead is connected to a copper plate whose flat surface is perpendicular to the inner conductor. The circuit is completed by four copper slabs connecting these plates together. For the regular testing at the National Bureau of Standards, the arrangement of these slabs is as shown in figure 3. For the present study various numbers and location of these slabs were used. In order to arrange the primary circuit as a loop or loops around one or more sections of the core, flexible cables were used to construct the desired shape of primary circuit and these cables were then clamped to the heavy copper slabs at such a point that stray fields from the rest of the primary circuit would not affect the performance of the transformer. By using one or the other of these procedures for connecting the primary of the transformer under test, it was possible to obtain nearly any desired arrangement of primary circuit.

Exploring coils were wound on the cores of some of the experimental transformers and the electromotive forces induced in these coils, while the transformers were being tested at currents near their rated values, were measured by a separately excited voltmeter. From these measurements the core flux density at the location of each exploring coil was computed and the results show whether that section of the core was operating above or below the value of flux density for maximum permeability.

IV. RESULTS

Nearly all current transformers with a primary rating of 2,000 amperes or more have primary windings consisting of a single conductor passing through the opening of a single-window core and according to their design may be divided into the following groups: (1) transformers with cores of rectangular shape and secondary turns equally distributed on all four legs, (2) transformers with cores of rectangular shape and secondary turns in two equal sections on opposite legs, (3) transformers with cores of rectangular shape and secondary turns all on one leg, and (4) transformers with cores of ring shape and secondary turns uniformly distributed around the core. For all transformers of any one group, a given change in arrangement of primary circuit produces similar changes in ratio and phase angle, but the actual value of these changes depends upon the size and magnetic properties of the core and the rated primary ampere-turns. No attempt was made to obtain sufficient data so that the quantitative effect of changing the location of the primary conductors could be deduced for all transformers of various nominal currents and with cores of various sizes and magnetic properties. However, data were obtained on at least one current transformer of each of the above groups. These data are intended to show only the arrangements of primary conductor which are most likely to give the best performance for any transformer of each group, and approximately the order of magnitude of the changes caused by departures from these arrangements.

1. TRANSFORMERS WITH CORES OF RECTANGULAR SHAPE AND SECONDARY WINDINGS EQUALLY DISTRIBUTED ON ALL FOUR LEGS

Current transformer A_1, a description of which is given in table 1, was tested with various arrangements of a single primary turn. The turn ratio, 1499:1, was used as the nominal ratio in the computations. The curves in figures 4 to 7 show the ratio correction factor (the quantity which multiplied by nominal ratio gives true ratio) and the phase angle (the angle by which the reversed secondary current leads the primary current) plotted against secondary current for various arrangements of primary circuit. Because of limitations in the source of power supply, it was not possible to test this transformer at the 5-ampere value of secondary current in all instances, but a test point was taken as near the 5-ampere point as possible and it was at least 4 amperes in all cases.

Curves 1 in figure 4 show the performance of transformer A_1 with a straight conductor through the center of the core window and the return lead in four sections, equally spaced around the inner conductor, parallel to it, and 20 inches from it. This arrangement of primary circuit is the one ordinarily used at the National Bureau of Standards in testing current transformers for 1,000 amperes or over; also, it is in effect equivalent to a single return lead at a great distance from the inner conductor. It will be called the normal arrangement in the present discussion, and on each figure, curves 1 represent the performance of the transformer with this normal arrangement of primary circuit. Curves 1 will thus serve as a basis of reference for judging the magnitude of the errors when other arrangements of primary circuit are used.

With the normal arrangement of primary circuit, very little of the primary leakage flux passes through the core or links any secondary turns, and as seen by curves 1 of figure 4, the performance of transformer A_1 is quite normal under these conditions. Curves 2 show the performance with the primary consisting of a loop (12 inches in diameter) of large cable around leg "a" of the core. Under these conditions a large amount of primary leakage flux passes through part of the core and links some of the secondary turns. At low currents this flux is not sufficient to bring the core flux density up to the value for maximum permeability, but it introduces a negative leakage reactance in the secondary winding, the effect of which was explained in the discussion of theory. In this case the negative secondary leakage reactance is sufficient to make the ratio of primary ampere-turns to secondary ampere-turns less than 1 from 0.5 to 1 ampere secondary current. For larger currents, measurements with the exploring coils showed that the leakage flux was sufficient to bring the core flux density above the value for maximum permeability. Thus, the exciting ampere-turns and hence the ratio and phase angle increase rapidly when the secondary current is raised above 3 amperes.

Curves 2 of figure 4 indicate that the performance for this arrangement of primary circuit differs from the performance with the normal arrangement by as much as 6 percent in ratio and 20 minutes in phase angle. These are probably the largest differences that can be obtained by changing the primary circuit of this transformer and they will rarely occur in practice, because a current transformer such as A_1 would usually have a primary circuit consisting of a straight conductor through the center of its core window and one or more return leads parallel to the straight conductor and at various distances from

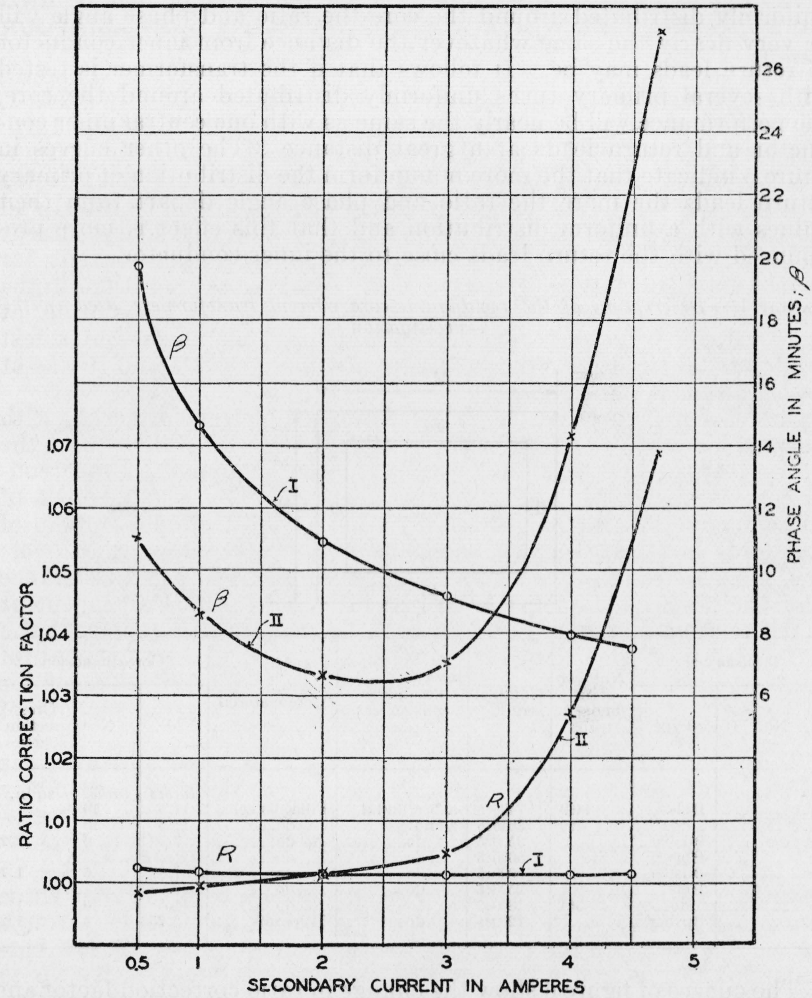


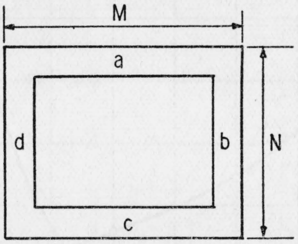
FIGURE 4.—*Performance curves for transformer* A_1

Nominal ratio $\frac{7495}{5}$. Burden 1.2 ohm and 2,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary circuit
1	Straight conductor through center of core window, one return lead opposite each leg of the core and 20 inches from center of the inner conductor.
2	A loop, 12 inches in diameter, of 2 large cables in parallel around leg "a".

it. The curves in figure 5 show the ratio correction factor and the phase angle for a number of possible arrangements of return lead. Curves 1 show the performance with the normal arrangement, which is the equivalent of a return lead at a great distance. Curves 2 are for data obtained with the four return slabs close to the transformer. A comparison of curves 1 and 2 shows that if the return leads are uniformly distributed around the core the ratio and phase angle will be very nearly the same whatever the distance from inner conductor to return leads may be. It follows that if the transformer is tested with several primary turns uniformly distributed around the core, the performance will be nearly the same as with one central inner conductor and return leads at a great distance. The other curves in figure 5 indicate that the more nonuniform the distribution of primary return leads the more the ratio and phase angle depart from their values with a uniform distribution and that this effect is more pronounced with the return leads close to the inner conductor.

TABLE 1.—*Description of the rectangular-core current transformers used in this investigation*



Transformer		Number of secondary turns	Nominal ratio	Secondary coils on legs	Core material	Core dimensions		
No.	Type					M	N	Cross-section area
						Inches	*Inches*	sq in.
A_1	Hole	1499	7495:5	a, b, c, and d	Silicon-steel	11.5	10	1
A_2	do	729	3645:5	a and c	do	11.5	10	1
B_2	Busbar		3500:5	do	do	7	6	2.25
C_2	Hole		5000:5	do	do			
D_2	Busbar		5000:5	do	do	7.87	6	1.75
E_2	Hole		2500:5	do	do			
A_3	do	364	1820:5	a	do	11.5	10	1
F_3	Busbar		1200:5	do	Hypernik	5.75	4	1.20

The curves of figure 6 show the change in ratio correction factor and phase angle when the inner conductor is displaced from the center of the core window. With the return leads uniformly distributed around the core, the inner conductor may be considerably off center without seriously affecting the performance. When the return leads are concentrated near one leg of the core, a displacement of the inner conductor from the center causes a considerable change in ratio for secondary currents over 3 amperes. Curves 1, 2, and 4 of figure 7 show the ratio correction factor and phase angle of transformer A_1 under the same test conditions as were used in curves 1, 2, and 4 of figure 6, except that a frequency of 60 cycles per second was used in place of 25. A comparison of these two groups of curves shows that the effect on performance of changing the position of the primary conductors is about the same at both frequencies. Curves 3 and 5

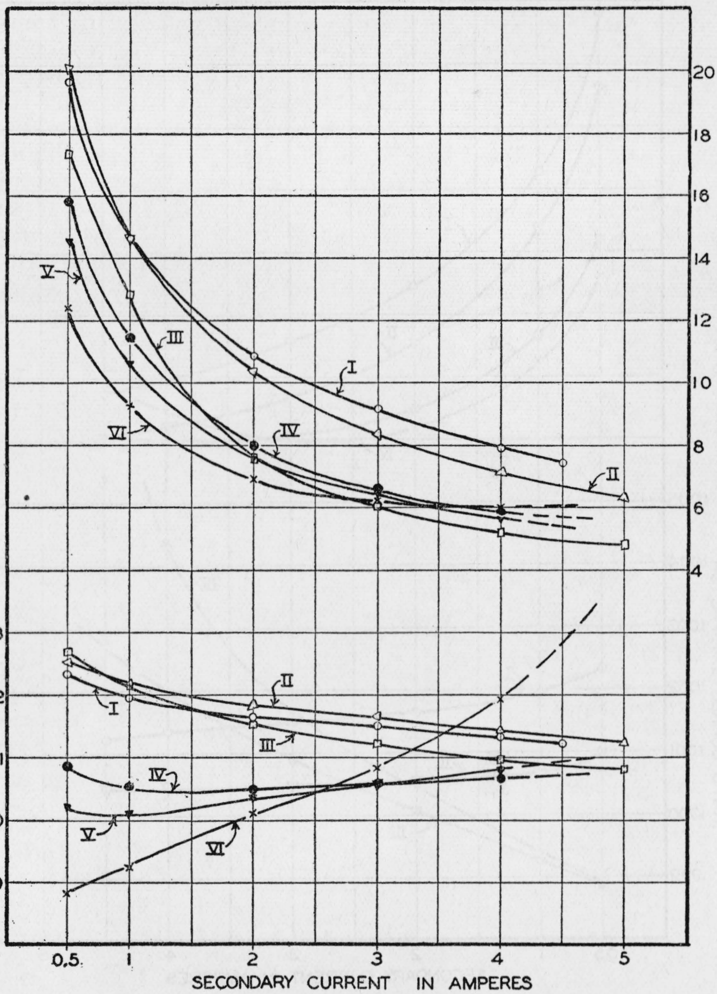


FIGURE 5.—*Performance curves for transformer* A₁

Nominal ratio $\frac{7495}{5}$. Burden 1.2 ohm and 2,000 microhenries. Frequency 25 cycles per second. Inner primary conductor in the center of the core window.

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from inner conductor.
2	One opposite each leg of the core and 8 inches from inner conductor.
3	One opposite each of legs "a" and "c" and 8 inches from inner conductor.
4	One opposite leg "a" and 26½ inches from inner conductor.
5	One opposite leg "a" and 15 inches from inner conductor.
6	One opposite leg "a" and 8 inches from inner conductor.

of figure 7 are for the same test conditions as curves 1 and 4, except that the secondary burden was much less. These curves show that the ratio and phase angle are slightly different for different burdens but that the change in performance for the same change in arrangement of primary conductors is the same at both burdens. These results check the predictions which were made in the theory.

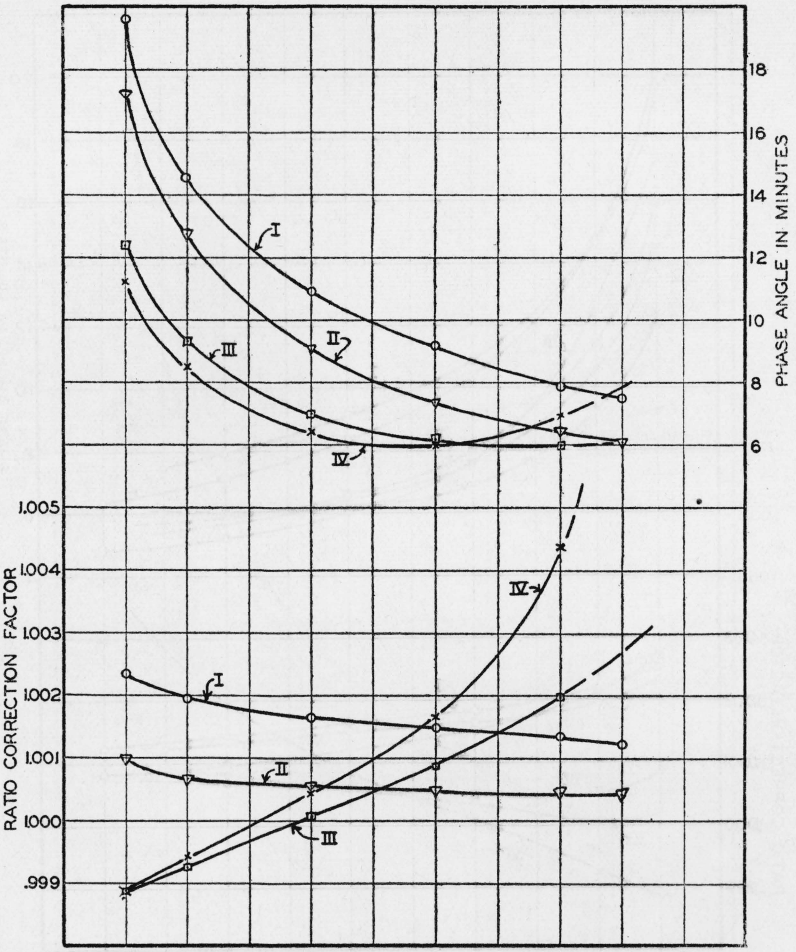


FIGURE 6.—*Performance curves for transformer* A_1

Nominal ratio $\frac{7495}{5}$. Burden 1.2 ohm and 2,000 microhenries. Frequency 25 cycles per second.

Curve	Location of inner primary conductor	Arrangement of primary return leads
1	Center of core window	One opposite each leg of the core and 20 inches from inner conductor.
2	Near leg "a"	Do.
3	Center of core window	One opposite leg "a" and 8 inches from inner conductor.
4	Near leg "a"	Do.

Since it is the change in performance of a current transformer for a change in arrangement of primary circuit which is of particular interest in this investigation, the results which follow are given for only one frequency and burden. The change in performance for a given change in arrangement of primary circuit would be nearly the same for any ordinary burden or usual power frequency.

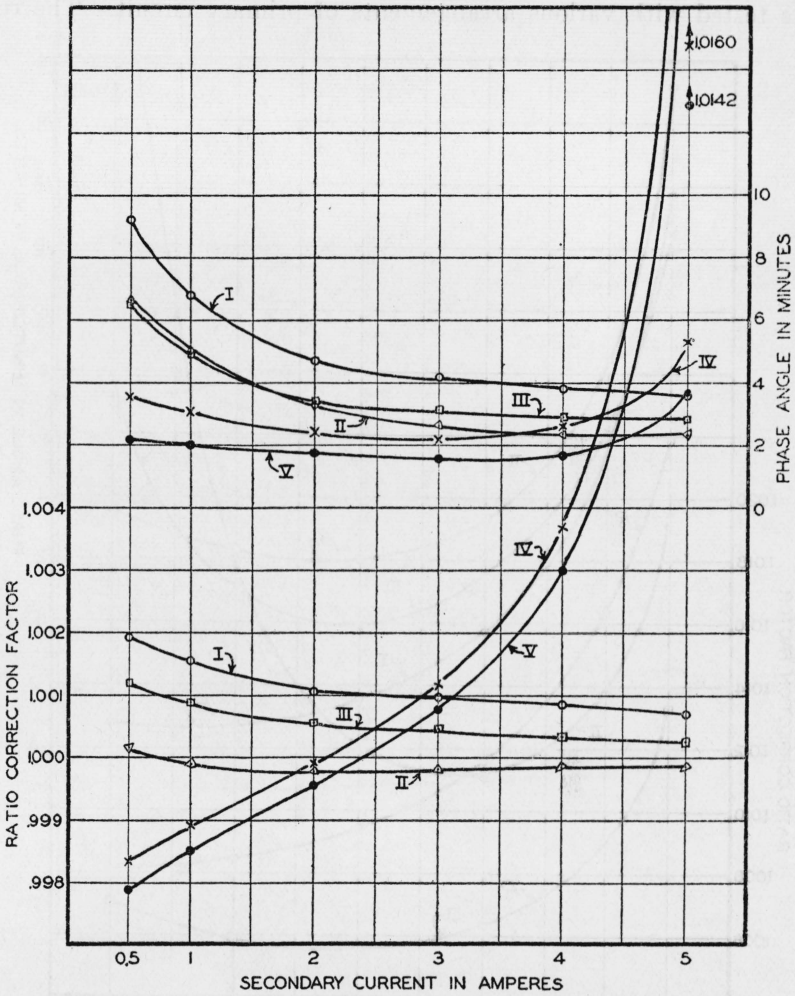


FIGURE 7.—*Performance curves for transformer* A_1

Nominal ratio $\frac{7495}{5}$. Frequency 60 cycles per second. "Burden C, 1.2 ohm and 2,000 microhenries." "Burden D, 0.26 ohm and 100 microhenries".

Curve	Burden	Location of inner primary conductor	Arrangement of primary return leads
1	C	Center of core window	One opposite each leg of the core and 20 inches from inner conductor.
2	C	Near leg "a"	Same as for 1.
3	D	Center of core window	Same as for 1.
4	C	Near leg "a"	One opposite leg "a" and 8 inches from inner conductor.
5	D	Near leg "a"	Same as for 4.

2. TRANSFORMERS WITH CORES OF RECTANGULAR SHAPE AND SECONDARY WINDINGS IN TWO EQUAL SECTIONS ON OPPOSITE LEGS

Current transformer A_2, a description of which is given in table 1, was tested with various arrangements of primary circuit. The results of these tests are shown in figures 8 to 11. The curves in figure 8 show the performance with the normal arrangement of primary circuit and with the two arrangements causing the largest difference

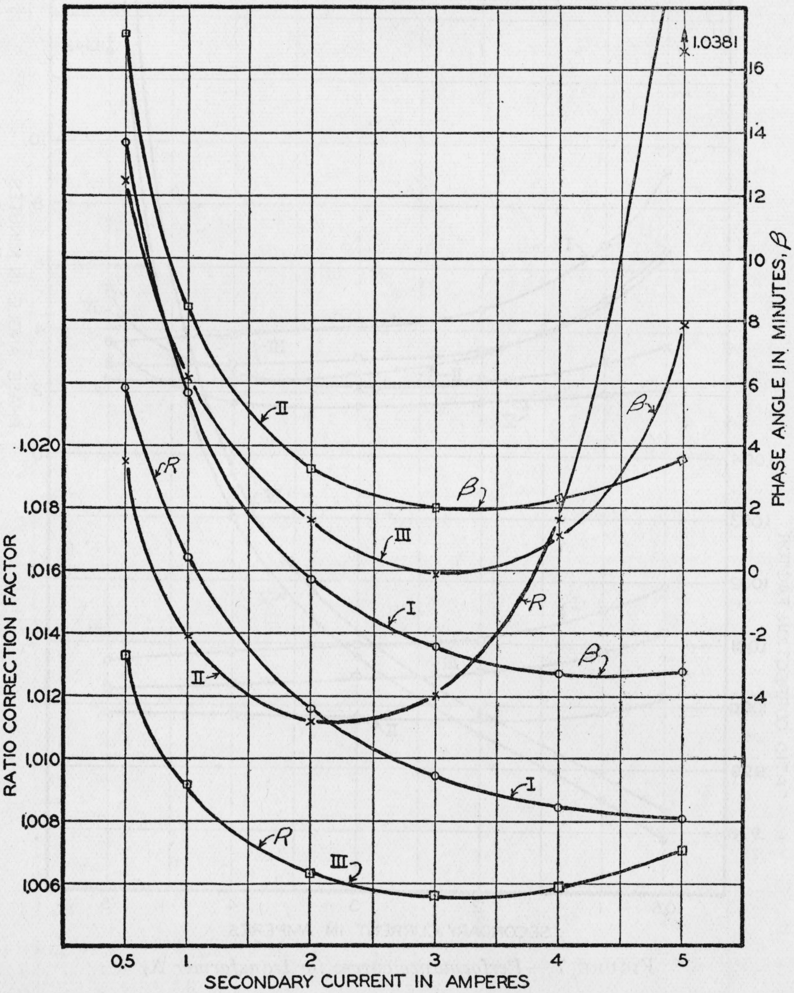


FIGURE 8.—*Performance curves for transformer* A_2

Nominal ratio $\frac{3645}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary circuit
1	Straight conductor through center of core window, one return lead opposite each leg of the core and 20 inches from inner conductor.
2	A loop, 12 inches in diameter, of large cable around leg "a".
3	A loop, 12 inches in diameter, of large cable around leg "d".

in ratio (a maximum of over 3 percent). These conditions are not apt to occur in practice and the results show the necessity of avoiding them.

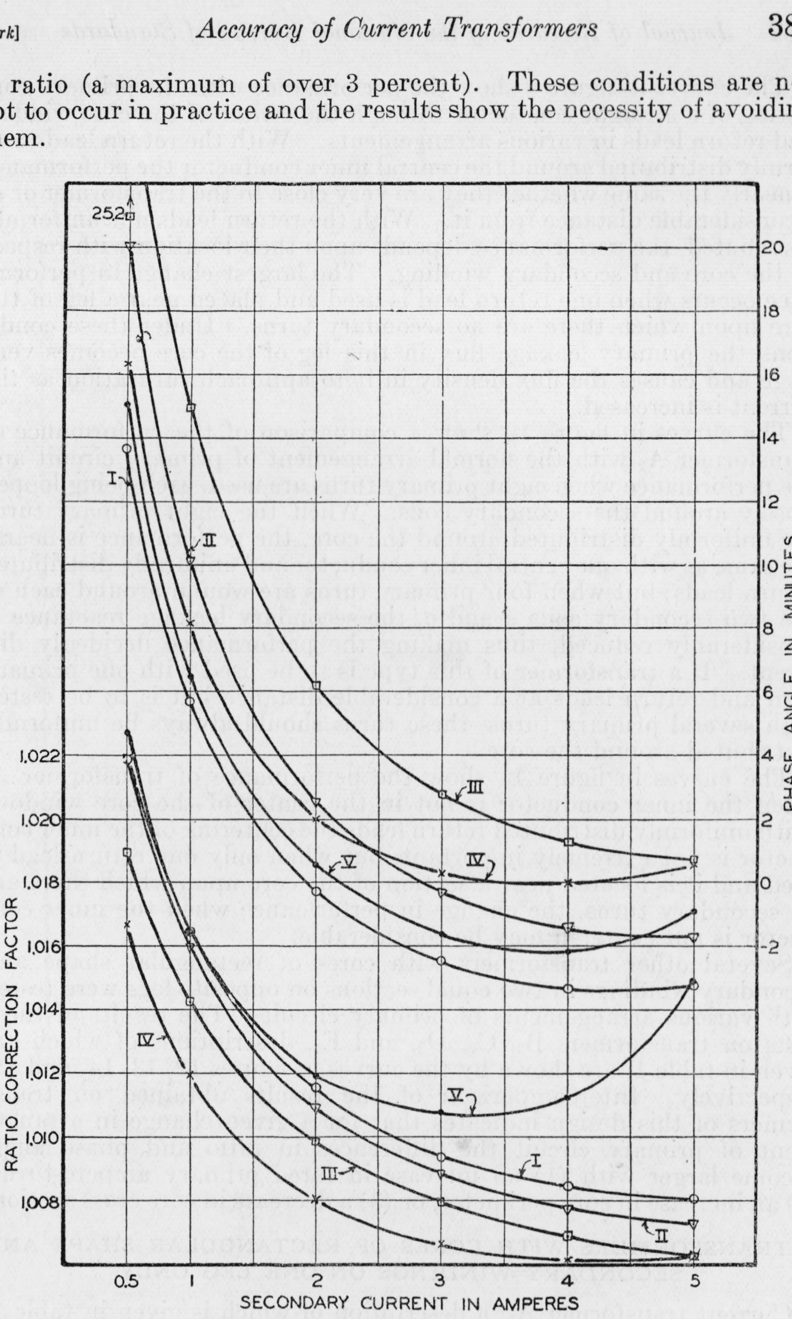


FIGURE 9.—*Performance curves for transformer* A_2

Nominal ratio $\frac{3645}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second. Inner primary conductor in the center of the core window

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from inner conductor.
2	One opposite each leg of the core and 8 inches from inner conductor.
3	One opposite each of legs "a" and "c" and 8 inches from inner conductor.
4	One opposite leg "a" and 8 inches from inner conductor.
5	One opposite leg "d" and 8 inches from inner conductor.

The curves in figure 9 show the performance with the primary consisting of a straight conductor through the center of the core window and return leads in various arrangements. With the return leads uniformly distributed around the central inner conductor the performance is nearly the same whether they are very close to the transformer or at a considerable distance from it. With the return leads not uniformly distributed, the performance depends upon their location with respect to the core and secondary winding. The largest change in performance occurs when one return lead is used and placed near a leg of the core upon which there are no secondary turns. Under these conditions the primary leakage flux in this leg of the core becomes very large and causes the flux density in it to approach saturation as the current is increased.

The curves in figure 10 show a comparison of the performance of transformer A_2 with the normal arrangement of primary circuit and the performance when eight primary turns are used, each being looped closely around the secondary coils. When the eight primary turns are uniformly distributed around the core, the performance is nearly the same as with one central inner conductor and uniformly distributed return leads; but when four primary turns are wound around each of the two secondary coils a and c, the secondary leakage reactance is considerably reduced, thus making the performance decidedly different. If a transformer of this type is to be used with one primary turn and return leads at a considerable distance but is to be tested with several primary turns, these turns should always be uniformly distributed around the core.

The curves in figure 11 show the performance of transformer A_2 when the inner conductor is not in the center of the core window. With uniformly distributed return leads the centering of the inner conductor is not extremely important, but when only one return lead is used and it is located near a section of the core upon which there are no secondary turns, the change in performance when the inner conductor is not centered may be considerable.

Several other transformers with cores of rectangular shape and secondary windings in two equal sections on opposite legs were tested with various arrangements of primary circuit. The results of these tests on transformers B_2, C_2, D_2, and E_2, descriptions of which are given in table 1, are shown by the curves in figures 12, 13, 14, and 15, respectively. Intercomparison of the results obtained on transformers of this design indicates that for a given change in arrangement of primary circuit the differences in ratio and phase angle become larger with (1) an increase in rated primary ampere-turns, (2) an increase in core perimeter, or (3) a decrease in core cross section.

3. TRANSFORMERS WITH CORES OF RECTANGULAR SHAPE AND SECONDARY WINDINGS ON ONE LEG ONLY

Current transformer A_3, a description of which is given in table 1, was tested with various arrangements of primary circuit. The curves in figure 16 show the results of the tests with the inner conductor at different locations in the window of the core and the return lead in four sections equally spaced around the inner conductor and 20 inches from it. Under these conditions the largest changes in performance are 8 percent in ratio (at 5 amperes secondary current) and 28 minutes in phase angle (at 0.5 ampere secondary current). For nonuniform distributions of return lead the changes are much greater.

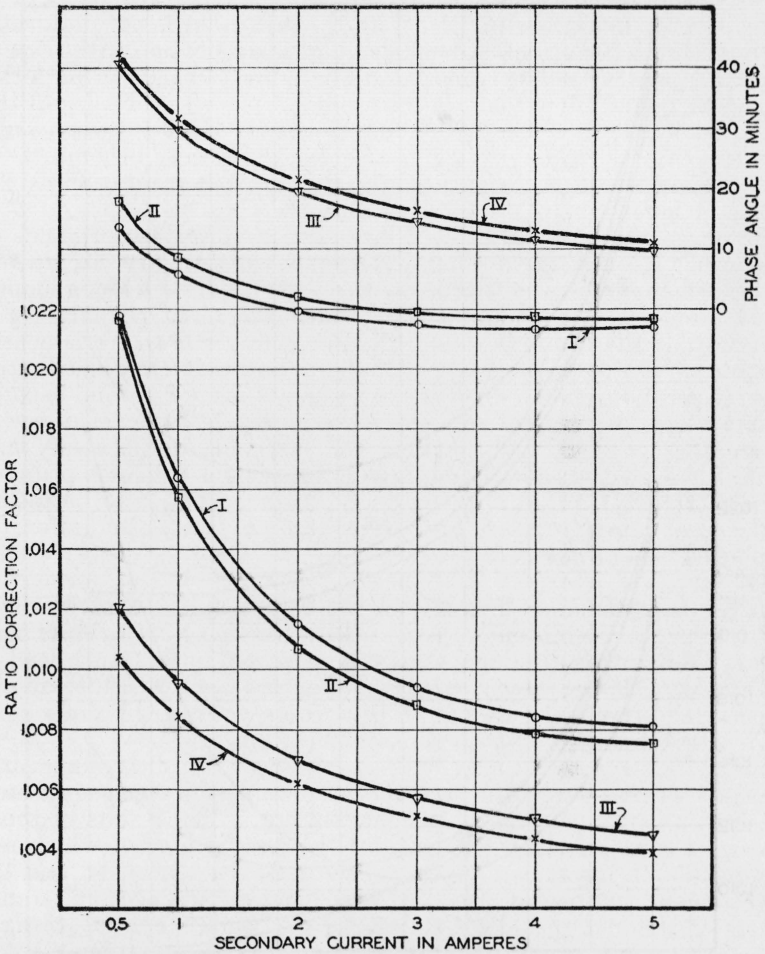


FIGURE 10.—*Performance curves for transformer* A_2.

Nominal ratio $\frac{3645}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary circuit
1	Straight conductor through center of core window, one return lead opposite each leg of the core and 20 inches from inner conductor.
2	Eight turns in series looped closely around the core, two on each leg.
3	Eight turns in series looped closely around the core, four around each of legs "a" and "c".
4	Eight turns in series looped closely around legs "a" and "c" in figures of eight.

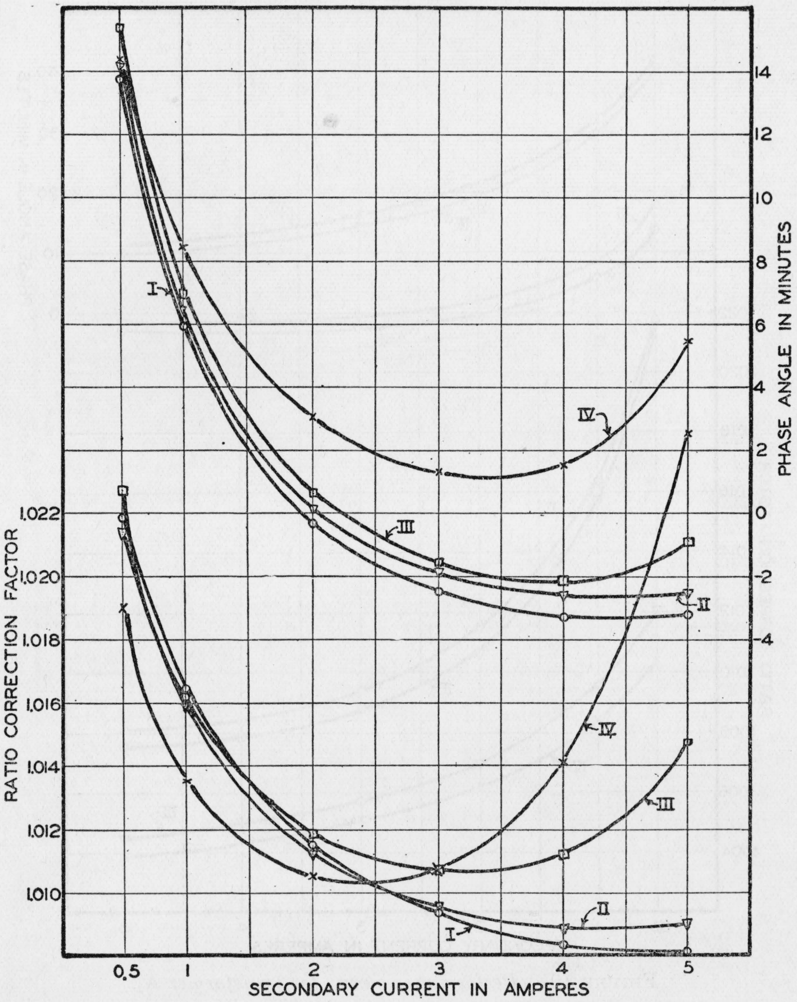


FIGURE 11.—*Performance curves for transformer* A_2.

Nominal ratio $\frac{3645}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Location of inner primary conductor	Arrangement of primary return leads
1	Center of core window	One opposite each leg of the core and 20 inches from inner conductor.
2	Near leg "d"	Same as 1.
3	Center of window	One opposite leg "d" and 8 inches from inner conductor.
4	Near leg "d"	Same as 3.

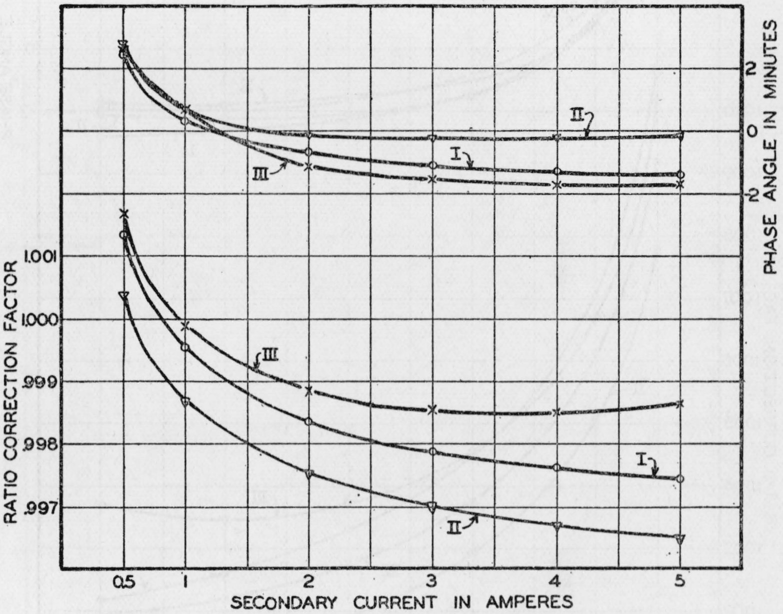


FIGURE 12.—*Performance curves for transformer* B_2.

Busbar type. Nominal ratio $\frac{3500}{5}$. Burden 0.45 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from central busbar.
2	One opposite leg "a" and 7 inches from central busbar.
3	One opposite leg "b" and 7 inches from central busbar.

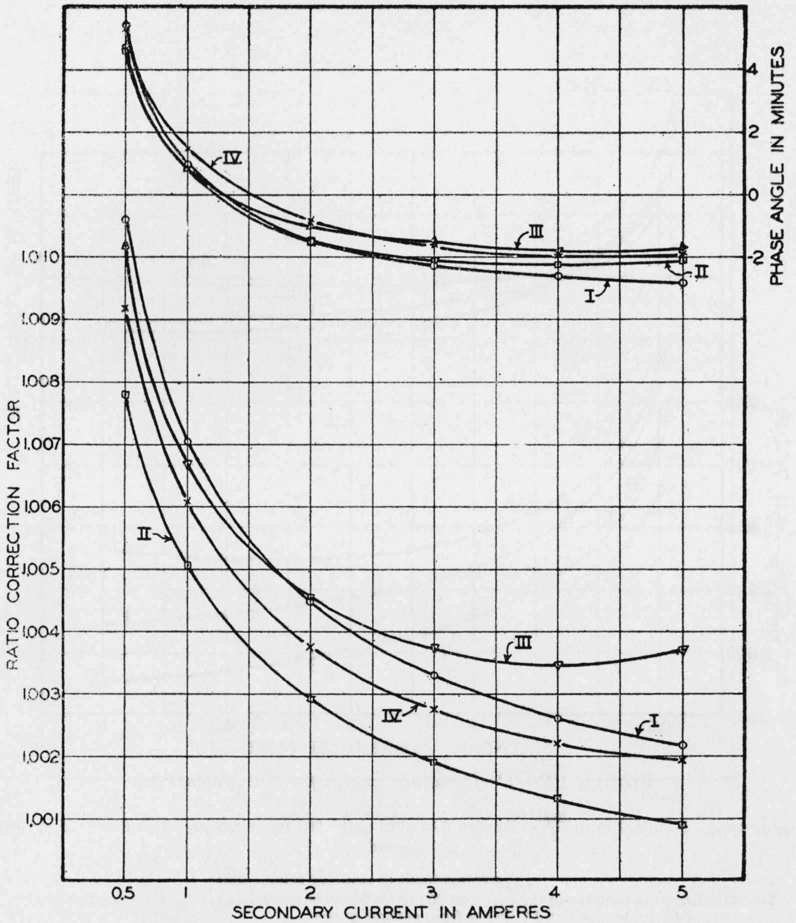


FIGURE 13.—*Performance curves for transformer* C_2.

Hole type. Nominal ratio $\frac{5000}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second. Inner primary conductor in center of core window.

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from inner conductor.
2	One opposite leg "a" and 7 inches from inner conductor.
3	One opposite leg "b" and 6 inches from inner conductor.
4	One opposite corner of legs "a" and "b" and 8 inches from inner conductor.

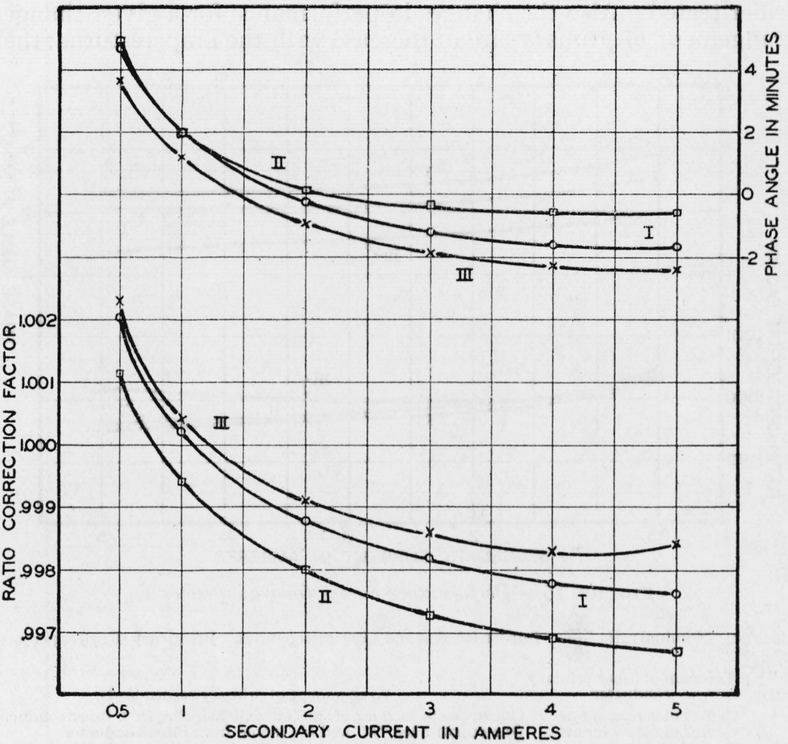


FIGURE 14.—*Performance curves for transformer* D_2.

Busbar type. Nominal ratio $\frac{5000}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from central busbar.
2	One opposite leg "a" and 5 inches from central busbar.
3	One opposite leg "b" and 5 inches from central busbar.

This transformer was constructed with a secondary coil on each leg, but only one secondary coil was used in this test. Thus, the perimeter of the core and consequently the change in performance for a given change in arrangement of primary circuit were much greater than they would be for a transformer with the same rated ampere-turns, designed with a secondary coil on one leg only. However, the ampere-turn rating of this transformer as tested was only, 1,820, and for larger current ratings the core perimeter of a transformer designed with only one secondary coil might approach that of the transformer tested. Also the changes in performance for a given change in arrangement of primary circuit increase with the ampere-turns; therefore, the results for this transformer may be considered to give a fair indication of the errors for transformers of this type when they are used for large primary currents, say 3,000 amperes or over.

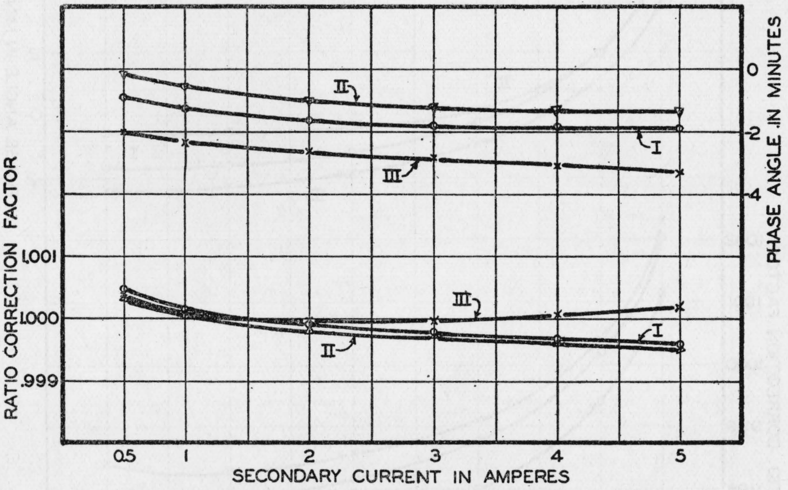


FIGURE 15.—*Performance curves for transformer* E_2.

Hole type. Nominal ratio $\frac{2500}{5}$. Burden 0.6 ohm and 1,000 microhenries. Frequency 60 cylces per second.

Curve	Location of inner primary conductor	Arrangement of primary return leads
1	Center of core window	One opposite each leg of the core and 20 inches from inner conductor.
2	Center of core window	One opposite leg "a" and 5½ inches from inner conductor.
3	Near leg "b"	One opposite leg "b" and 3½inches from inner conductor.

Current transformer F_3, a description of which is given in table 1, was tested with several arrangements of primary circuit. The curves in figure 17 show the performance of this transformer with the locations of return lead causing the largest changes in ratio and phase angle. These changes are quite small, and it may be concluded that transformers of this type are satisfactory for primary currents below 2,000 amperes if their cores are small in perimeter and large in cross-sectional area.

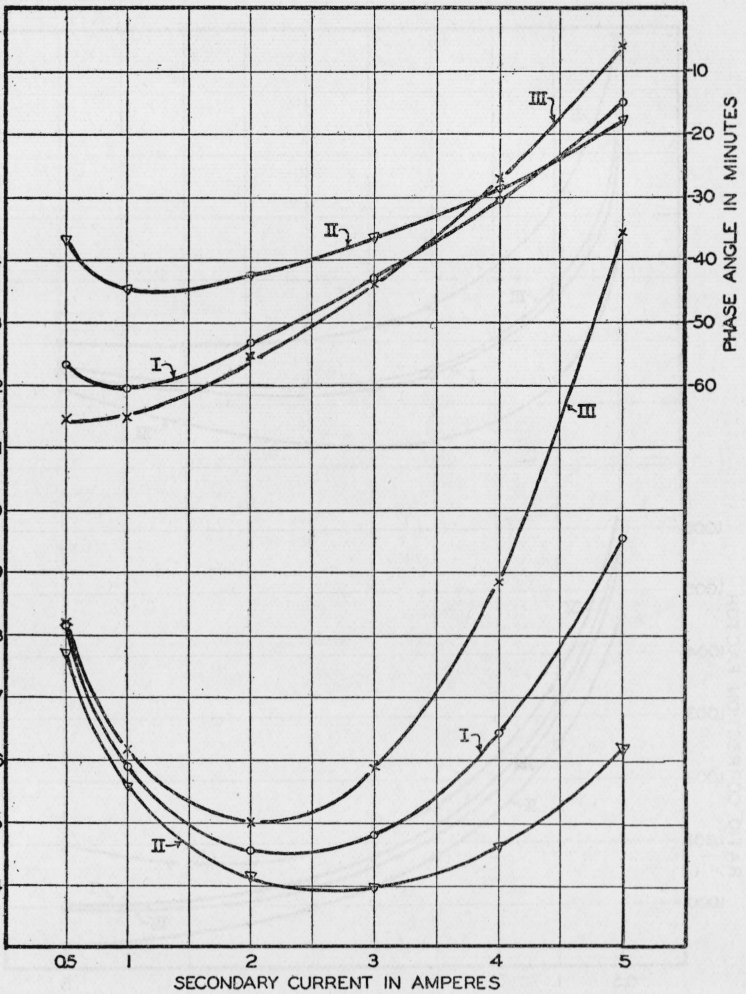


FIGURE 16.—*Performance curves for transformer* A$_3$.

Hole type. Nominal ratio $\frac{1820}{5}$. Burden 0.3 ohm and 500 microhenries. Frequency 25 cycles per second. Primary return lead in four sections, one opposite each leg of the core and 20 inches from the center of the inner conductor.

Curve	Location of inner primary conductor
1	Center of core window.
2	Near leg "a".
3	Near leg "c".

4. TRANSFORMERS WITH CORES OF RING SHAPE AND SECONDARY WINDINGS UNIFORMLY DISTRIBUTED AROUND THE CORE

A 3,000-ampere hole-type current transformer with a ring-shaped core and secondary winding uniformly distributed around the core

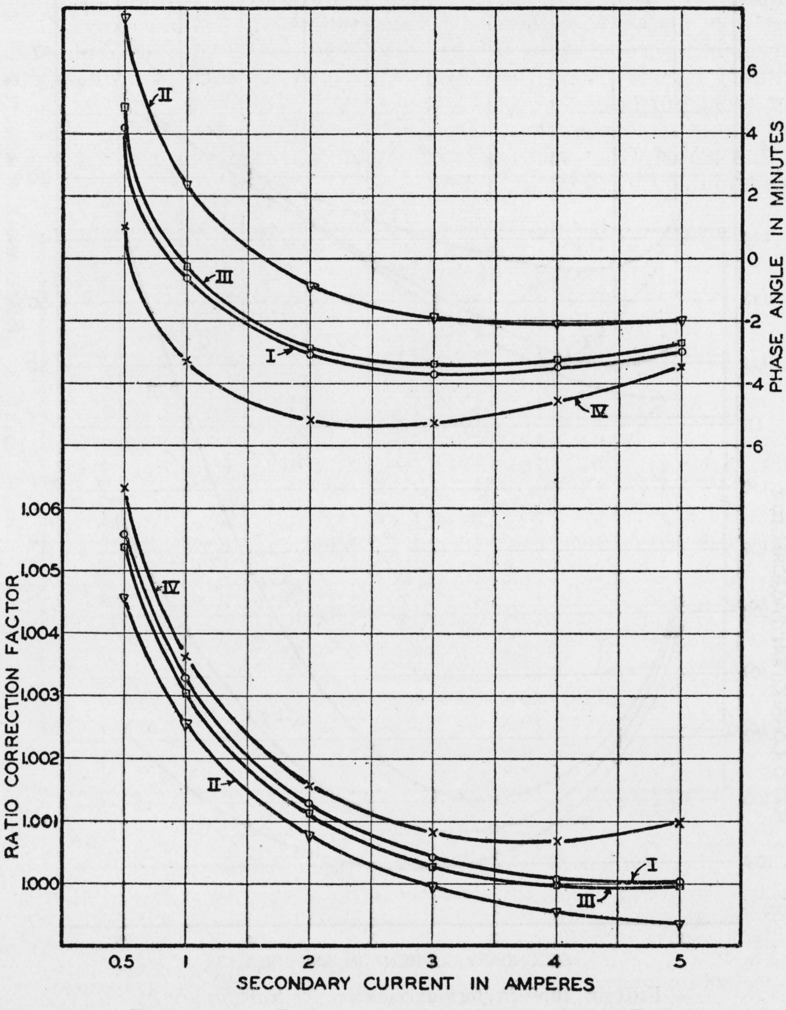


FIGURE 17.—*Performance curves for transformer* F_3.

Busbar type. Nominal ratio $\frac{1200}{5}$. Burden 0.3 ohm and 500 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary return leads
1	One opposite each leg of the core and 20 inches from central busbar.
2	One opposite leg "a" and 6 inches from central busbar.
3	One opposite leg "b" and 6 inches from central busbar.
4	One opposite leg "c" and 6 inches from central busbar.

was tested with its primary winding (1) uniformly distributed around the core and (2) concentrated on one section of the core. The differences in performance with these two arrangements of primary circuit were found to be less than 0.01 of 1 percent in ratio and 1 minute in phase angle. Therefore, the performance of this transformer was considered to be independent of the arrangement of the primary circuit. The core was made of a nickel-iron alloy and the diameter of the central opening was only 3 inches.

A 5,000-ampere hole-type current transformer, G_4, with a ring-shaped core and secondary winding uniformly distributed around the core was tested with several arrangements of primary circuit. The curves in figure 18 show the performance for the two arrangements of primary circuit giving the largest differences in ratio and phase angle. For most purposes these differences (0.07 of 1 percent or less in ratio and 4 minutes or less in phase angle) would be negligible. The core of this transformer was made of silicon steel and the central opening was about 6 inches in diameter.

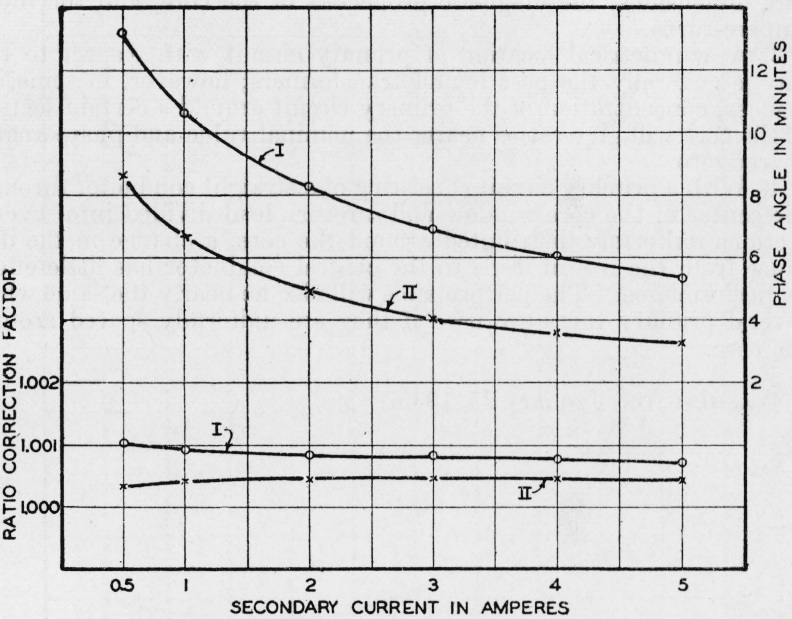


FIGURE 18.—*Performance curves for transformer* G_4.

Hole type. Circular core. Secondary winding uniformly distributed around the core. Nominal ratio $\frac{5000}{5}$. Burden 0.8 ohm and 1,000 microhenries. Frequency 25 cycles per second.

Curve	Arrangement of primary circuit
1	Straight conductor through center of core window, four return leads equally spaced around inner conductor and 20 inches from it.
2	A loop, 12 inches in diameter, of large cable around a section of the core.

The results of the experiments on these two transformers indicate that the performance of transformers of this design is nearly independent of the arrangement of the primary circuit. Arnold [5] has shown that this is not the case for certain transformers with cores made of a nickel-iron alloy, designed for 5,000 ampere-turns or over. With a concentrated primary winding these transformers showed very large errors, which could probably be materially reduced by the use of a

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[5] A. H. M. Arnold, Leakage phenomena in ring-type current transformers. J.Inst. Elec. Engrs. (London) 74, 413 (1934).

silicon-steel core, since silicon-steel reaches its maximum permeability at a much higher flux density than the nickel-iron alloys. However, it must be concluded from Arnold's paper, that for ring-core transformers of over 5,000 ampere-turns, the arrangement of the primary circuit may have an appreciable effect on performance.

V. CONCLUSIONS

1. The more uniformly the secondary winding of a current transformer is distributed around its core, the less will changes in arrangement of primary circuit affect the performance.

2. The actual changes in ratio and phase angle for a given change in location of the primary circuit depend not only upon the shape of the core and distribution of secondary winding, but also upon the core dimensions, the magnetic properties of the core, and the rated ampere-turns.

3. A symmetrical location of primary circuit with respect to the core is generally the best for all transformers; however, in some instances, concentration of the primary circuit around a certain section of the core will give ratios nearer the nominal value and phase angles nearer zero.

4. With a primary circuit consisting of a straight conductor through the center of the core window and a return lead divided into several sections uniformly distributed around the core, a change in the distance from the return leads to the central conductor has little effect on performance. The performance will also be nearly the same when several primary turns are used if they are uniformly spaced around the core.

WASHINGTON, January 25, 1935.