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EQUIPMENT FOR TESTING CURRENT TRANSFORMERS

By Francis B. Silsbee, Ray L. Smith, Nyna L. Forman, and John H. Park

ABSTRACT

The equipment and test procedure developed at the Bureau of Standards for measuring the ratio and phase angle of current transformers up to currents of 12,000 amperes at power frequencies are described in detail. Data are given to show the accuracy of the standard current transformer used in the higher ranges, and the effectiveness of the shaping of the heavy-current circuit so as to minimize errors from stray magnetic fields.

CONTENTS

I. INTRODUCTION

The steady and rapid increase in the use of electric power in recent years has involved a corresponding increase in the number and importance of the locations where large amounts of alternating-current power or energy must be accurately measured for purposes of billing or control. In such metering it has become universal practice to avoid connecting the measuring apparatus directly to the power circuits, and to use instead instrument transformers which serve to reproduce in their secondary circuits a replica on a reduced scale of the currents and voltages applied to their primary circuits. This practice offers the very great advantages of a reduction in life hazard, an economy in the cost and size of the measuring instruments proper and a very great increase in the flexibility and convenience in switchboard wiring and in protective relay operation. The instrument transformers, however, introduce an additional step in the measurement process and it becomes necessary in precise work to determine experimentally the exactness with which the current and voltage transformers reproduce to the proper scale the magnitude and phase relations of the primary currents and voltages, respectively.

As is the case with almost any kind of measurement, it is much easier to compare the ratio and phase angle of one transformer with those of another transformer of the same nominal ratio than it is to determine the ratio and phase angle of a single transformer directly.

Convenient types of apparatus for accomplishing the former comparisons have been on the market for some years and are now widely used by power companies to check the transformers installed for important metering work in terms of standard transformers of the same range. The testing of these standard transformers is done in turn at one of the more elaborately equipped laboratories maintained for the purpose by the larger power companies, by the transformer manufacturers, by public-utility commissions, or by the Federal Government.

The equipment and methods used for this purpose at the Bureau of Standards at Washington have been modified and enlarged from time to time to keep pace with the increasing demands in accuracy and range of the transformers to be tested. The object of this paper is to describe the equipment and methods [1] now in use at this Bureau in the hope that the data given may be of assistance to other laboratory workers who may wish to install apparatus for similar work.

The accuracy needed in this class of testing should, if possible, be so high that errors in the certified values will be negligibly small in comparison with the inaccuracy likely to occur in the next step in the measurement process; that is, in the comparison in the field between the standard transformer and the working transformer. A limit to the possible accuracy is, of course, set by the repeatability of the transformer under test. This limit is influenced by a number of factors, among which are changes in the magnetic condition of the core as a result of previous operation, uncertainties in the temperature of the transformer windings and hence in their resistance, and uncertainty in the exactness with which the burden used in the field is duplicated in the test. In the case of hole-type current transformers additional uncertainty arises because of differences in the position of the primary conductor in the hole, and in the position of the return lead. The magnitude of the changes in calibration resulting from these effects depends greatly upon the type of transformer, but may amount to several tenths of 1 percent.

The sensitivity of the present equipment is such that a change of 0.01 percent in ratio and 0.3 minute in phase angle is definitely detectable even at a secondary current as small as 0.5 ampere. Changes in the performance of the transformer under test are therefore often noted. The accuracy of the equipment, since it involves the calibration of resistance standards of widely different values with the additional liability to errors from skin effect and residual self-inductance, is, perhaps, not as high as the precision mentioned above would indicate. The accuracy limits printed on the Bureau's certificate form (viz, 0.1 percent in ratio and 3 minutes in phase angle) are, however, certainly very conservative. In reducing the observed values all corrections are normally carried to the nearest 0.005 percent and 0.1 minute and the resulting values are then rounded off in the certificate to the nearest 0.01 percent and 1 minute.

The present equipment is intended only for tests of transformers having the conventional 5-ampere secondary current rating. The measuring apparatus can be used for primary currents from 1 ampere to 12,000 amperes, but the ratings of the motor-generator sets available

[1] These developments have been the work of a very considerable number of individuals, both laboratory workers and mechanicians. In the former group mention should be made of P. G. Agnew, J. L. Fearing, J. M. Cork, F. M. Defandorf, and R. D. Wyckoff; in the latter, E. A. Baker, J. Ludewig, J. M. S. Kaufman, and E. A. Tibballs.

for energizing the circuits limit the testing to 6,000 amperes at 50 cycles, 7,500 amperes at 25 cycles, and 12,000 amperes at 60 cycles.

II. METHOD

The present equipment is based on the "resistance" method,[2] which is applied directly to the transformer under test for currents up to 2,500 amperes. For higher currents, use is made of a standard multiple-range transformer which is first calibrated by the resistance method on a low range and used on a higher range as a standard with which the transformer under test is then compared.

The essential circuits of the resistance method are shown schematically in figure 1. A current I_1 flows from the supply transformer through the primary of the transformer under test and through a fixed resistor R_1 of the 4-terminal type. The secondary current I_2

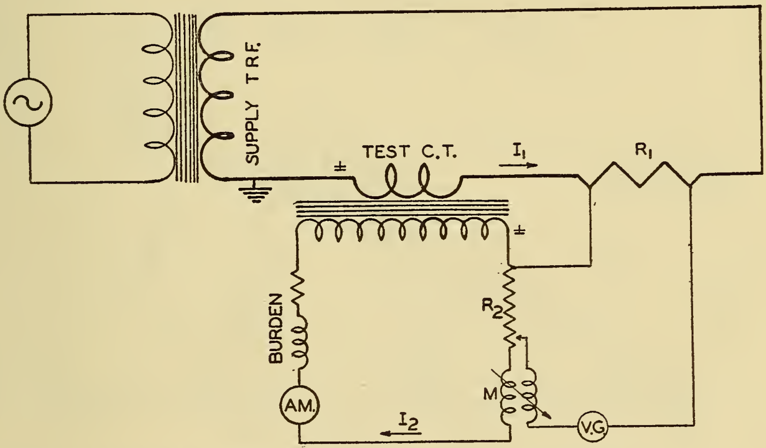

FIGURE 1.—*Circuits used in direct test of a current transformer by the resistance method.*

flows through an adjustable 4-terminal resistor R_2, through the primary winding of a mutual inductor M, and through an additional impedance, which is adjusted at the beginning of the test so as to make the resistance and the reactance of the entire secondary circuit, external to the transformer, equal to those of the burden with which the transformer is to be used in service.

Although the resistors R_1 and R_2 are made as noninductive as feasible, they have slight residual inductances L_1 and L_2, respectively. The impedance drops produced by the primary and the secondary currents are therefore I_1 $(R_1+j\omega L_1)$ and $I_2(R_2+j\omega(L_2-M))$, respectively, M being considered positive when its induced emf opposes $\omega L_2 I_2$. The two circuits are connected so that these two drops oppose each other and any net difference circulates current through the vibration galvanometer $V.G.$ The potential taps of the secondary standard resistor and the position of the coils of the mutual inductor are then adjusted until the galvanometer shows no deflection.

[2] For a discussion of various possible methods, see F. B. Silsbee, Trans. Am. Inst. Elec. Eng., vol. 43 p. 282, 1924.

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The vector relations existing when a balance is obtained are indicated[3] in figure 2, and, on equating the magnitude and the phase of the two opposing voltages give the two equations

$$\frac{R_1 I_1}{\cos\,\theta_1}=\frac{R_2 I_2}{\cos\,(\alpha-\theta_2)} \tag{1}$$

and

$$\beta+\theta_2=\alpha+\theta_1 \tag{2}$$

where

$$\tan\,\theta_1=\frac{\omega L_1}{R_1} \tag{3}$$

$$\tan\,\theta_2=\frac{\omega L_2}{R_2} \tag{4}$$

and

$$\alpha=\tan^{-1}\,\frac{\omega(M-L_2)}{R_2}+\tan^{-1}\,\frac{\omega L_2}{R_2} \tag{5}$$

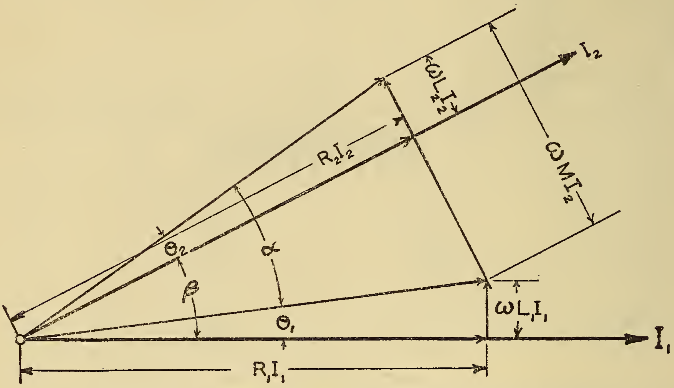

FIGURE 2.—*Vector diagram of resistance method.*

Equations (1) and (2) may be rearranged and put into more convenient form by introducing some approximations which, however, do not introduce errors of more than 0.01 percent in ratio or 0.1 minute in phase angle provided θ_1 and θ_2 do not exceed 5 minutes and 1 minute, respectively, and that β is not greater than 2 degrees. This process gives

$$n=\frac{I_1}{I_2}=\frac{R_2}{R_1}\cdot\;\frac{1}{\cos\,\beta} \tag{6}$$

$$\beta=\frac{\omega M}{R_2}+\theta_1-\theta_2 \tag{7}$$

In equation (7) if M is expressed in henries and R_2 in ohms, β, θ_1, and θ_2 should be in radians. Since 1 radian = 3,438 minutes, equation (7) may be written

$$\beta=\frac{0.003438\;M\omega}{R_2}+\theta_1-\theta_2 \tag{7a}$$

if M is in microhenries, R_2 in ohms and β, θ_1 and θ_2 are in minutes.

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[3] For the sake of clearness the phase angles are greatly exaggerated in figure 2. The current vectors are drawn to correspond to the arrows in figure 1 and not with regard to their magnetic effect on the transformer core.

When the multiple-range transformer is used as a standard, the circuits are as shown in figure 3. It is evident that the impedance drop in the resistor R_3 plays the same role in this circuit that the impedance drop in the resistor R_1 does in that of figure 1. Also as a matter of definition, the secondary current I_3 of the standard transformer is related to the primary current I_1 by the vector relation.

$$I_3=\frac{I_1}{n_s}(\cos\beta_s+j\sin\beta_s) \tag{8}$$

where n_s and β_s are the ratio and phase angle, respectively, of the standard transformer. Substituting this value in the expression for the impedance drop in the fixed standard resistor having resistance R_3 and phase angle θ_3 gives

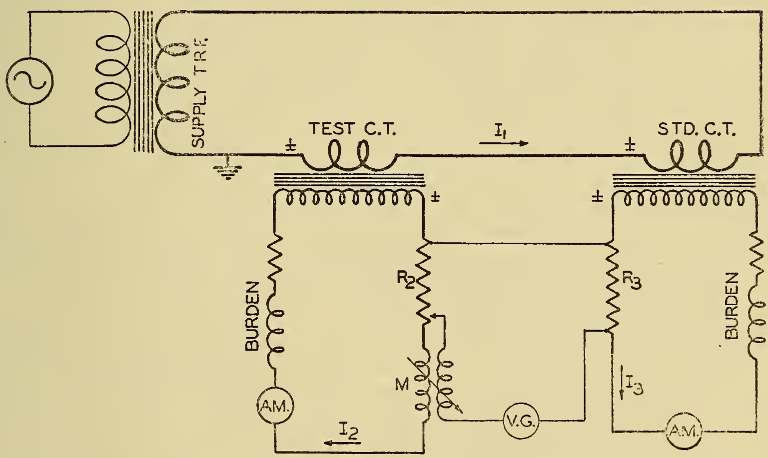

FIGURE 3.—*Circuits used in testing a current transformer by comparison with the standard current transformer.*

$$E_3=I_3R_3(1+j\tan\theta_3)=\frac{I_1R_3\cos\beta_s}{n_s}\left\{1-\tan\theta_3\tan\beta_s+j(\tan\theta_3+\tan\beta_s)\right\}$$
$$=\frac{I_1R_3}{n_s}\left\{1+j\tan(\theta_3+\beta_s)\right\}\ldots\ldots\ \text{approx.} \tag{9}$$

the approximation being very exact since θ_3 and β_s are very small angles (less than 1 minute and 5 minutes, respectively, in the present equipment). The corresponding drop in figure 1 is

$$E_1=I_1R_1(1+j\tan\theta_1) \tag{9a}$$

A comparison of (9a) and (9) shows that we need merely replace R_1 by $\frac{R_3}{m_s}$, and θ_1 by $\theta_3+\beta_s$ to obtain the final equations for the circuits of figure 3. This process yields for the ratio and phase angle of the transformer under test

$$n_x=\frac{R_2n_s}{R_3}\frac{1}{\cos\beta_x} \tag{10}$$

$$\beta_x = \frac{\omega M}{R_2} + \theta_3 + \beta_s - \theta_2 \tag{11}$$

When the standard transformer is connected for currents which can be carried by an available primary standard resistor, n_s and β_s can be directly observed by the resistance method. When the standard transformer is connected for ranges higher than those at which direct tests in terms of resistance can be made, the proper values of n_s and β_s must be determined by suitably modifying the results of tests at lower ranges.

The fundamental principle on which this determination can be based is that when the primary turns of a current transformer are changed from a series connection to a parallel one, the secondary winding, frequency, burden, and secondary current remaining the same, the phase angle will be unchanged and the ratio will be changed in inverse proportion to the number of series primary turns in use. It has been found experimentally without exception in a very great number of transformers tested at this Bureau that this principle holds to the same precision as that with which the transformer will repeat its performance if the connections are unchanged. The only combination of conditions which would be expected to cause the principle to fail is (1) that the impedance of the primary sections which are used in parallel shall differ so materially as to cause the currents which flow in each such section to be also materially different, and (2) that the mutual inductances of the sections in question on the secondary winding shall also be materially different.

In the multirange transformer used at the Bureau of Standards the secondary winding is distributed very uniformly around the ring core punchings so that there can be only very little difference in the mutual inductance between it and any conductor linking with the core, thus avoiding condition (2). Furthermore, any serious inequality in current distribution which might exist among the parallel paths in the primary winding would cause the net magnetomotive force to be different at different azimuths around the axis of the transformer. An exploring coil arranged to be placed in various azimuths at a constant radius from the axis of the transformer, serves as a convenient indicator of the distribution of leakage flux and hence of nonuniform magnetomotive force, and thus gives warning of the existence of condition (1).

A second principle which affords a partial check on the foregoing is that if the sections of the secondary winding are changed from parallel to series, and the impedance of the external burden is increased at the same time in proportion to the square of the ratio of the new to the old number of series secondary turns, the number of series primary turns remaining unchanged; then at the same frequency, and the same secondary ampere turns the phase angle of the transformer will be unchanged and the ratio will be increased in proportion to the increase in the number of series secondary turns.

A second and independent check on the validity of the stepping-up process is obtained by testing the multiple-range transformer on the higher range at low values of secondary current. The corresponding primary current will then not overload the primary standard resistors, and the values thus observed should agree with those inferred from the performance on the lower range at the same low secondary current. If such an agreement is observed, the transformer can then be used as a standard at higher currents with good assurance that the conditions required for the principle to be applicable are satisfied. The extent to which the standard transformer built for this work satisfies the conditions and exemplifies these principles will appear in a later section of this paper.

III. DESCRIPTION OF APPARATUS

1. GENERAL ARRANGEMENT

Figure 4 (p. 100) shows the general arrangement and figure 5 (p. 101) a wiring diagram of the equipment as installed at the Bureau of Standards in the spring of 1930. Two independent primary, or heavy-current circuits are provided; that at *XW* for transformers having ranges up to 500 amperes, and that at *KOS* for transformers of higher range. The secondary circuits of the transformer under test and of the standard transformer are located on the L-shaped table *BENG* at a considerable distance from *U* and *O* to avoid errors from the stray magnetic fields produced by the large primary currents. The leads *R*, connecting each of these circuits to its respective transformer, are formed of a length of no. 0000 A.W.G. stranded wire placed inside of a copper tube 1.5 inches in diameter and 0.0625 inch thick. This large cross section of conductor serves to keep down the resistance of the circuit, while the tubular construction gives good mechanical stiffness and incidentally makes all stray field effects in or from these conductors entirely negligible. The switchboard *T* furnishes a source of supply for the various circuits and also contains the terminals of trunk lines connecting the laboratory with the main distribution board of the Electrical Building.

For most tests power is obtained from one or another of several motor-generator sets located in another part of the building. These sets are driven by d.c. motors which are supplied by storage batteries, thus securing very constant frequency and current. Control of the fields of both motor and generator is obtained through a remote-control system,[4] outlets from which are provided on the switchboard. These motor-generator sets range in capacity from 3 to 15 kva at 120 or 240 volts, and can be overexcited to give an open-circuit voltage of over 300 volts. The wave form is very closely sinusoidal at excitations above one fourth of normal.

For currents exceeding 6,000 amperes at 60 cycles use is made of a 100 kva motor-generator set, normally used for the life testing of incandescent lamps. This machine is driven by a 60-cycle synchronous motor from circuits of the local power company. By its use currents up to 12,000 amperes are obtainable, but only at the fixed frequency of 60 cycles per second.

The 500-ampere primary circuit (*XW* in figs. 4 and 5) is supplied by two 3 kva 120/60 to 2/4 volt 60-cycle step-down transformers *Y*. The secondaries of these transformers are permanently connected in series with each other and with a rheostat. This consists of four fixed sections of 0.025 ohm each in parallel with a 3-dial rheostat section which has a minimum resistance of 0.025 ohm. The last-mentioned section is located under the table at *J* (fig. 4), where it is accessible to operator

[4] Agnew, P. G., Stannard, W. H., and Fearing, J. L., B.S. Bull., vol. 13 (S291), p. 581, 1916–17.

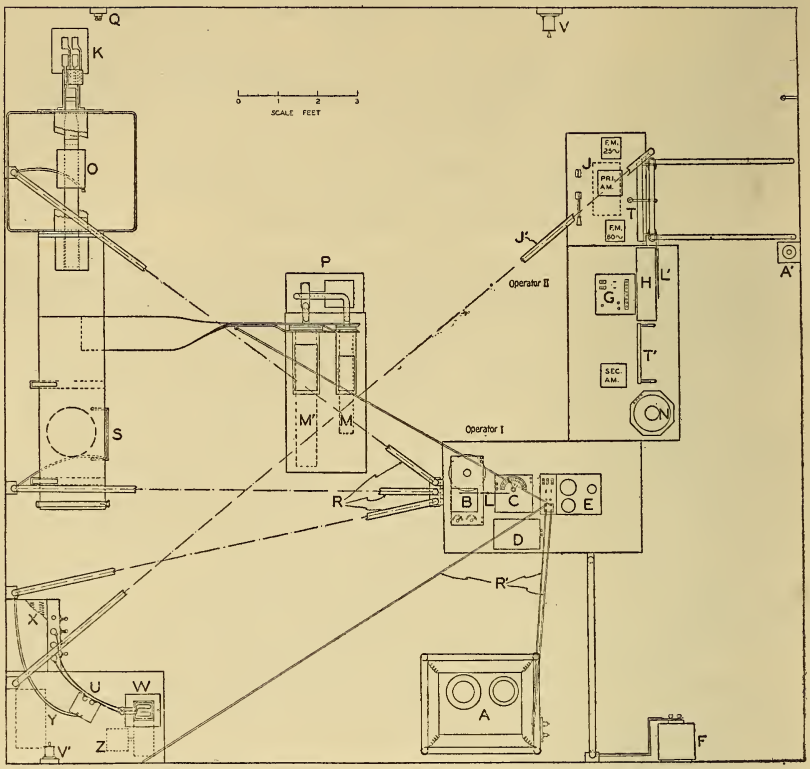

Figure 4.—*Arrangement of apparatus for testing current transformers up to 12,000 amperes.*

A, 25- and 60-cycle vibration galvanometers.
A', d.c. galvanometer.
B, mutual inductor.
C, secondary standard resistor for test transformer.
D, secondary standard resistor for standard transformer.
E, mercury cup selector switch.
F, air-core inductors.
G, adjustable resistance and d.c. galvonometer key panel.
H, Wheatstone bridge for measuring burden.
J, 3-dial rheostat for low-current primary circuit.
J', leads connecting *J* in parallel with *X*.
K, supply transformer for high-current primary circuit.
L, scale for vibration galvanometers.
L', scale for d.c. galvanometer.
M, 1,000-ampere oil-cooled standard resistor.
M', 2,500-ampere oil-cooled standard resistor.
N, variable inductor 10 microhenries.
O, transformer under test, range up to 12,000 amperes.
P, oil pump and motor.
Q, terminal board for primary of supply transformer.
R, secondary leads from transformers to measuring apparatus.
R', galvanometer circuit leads.
S, standard transformer.
T, supply panel.
T', secondary panel.
U, transformer under test range up to 500 amperes.
V, main supply switch.
V', low-current supply switch.
W, air-cooled standard resistor.
X, rheostat for low-current primary circuit.
Y, supply transformers for low-current primary circuit.
Z, blower for cooling standard resistor.

II. The fixed sections are located at X above the step-down transformers and can be connected in parallel with the 3-dial section by single-pole knife switches. For each test the primary circuit is completed through the transformer under test U and the primary air-cooled standard resistor W by flexible leads of dynamo brush cable.

The precision resistors used in this primary circuit are of the air-cooled type[5] and range in resistance from 0.05 to 0.001 ohm. They

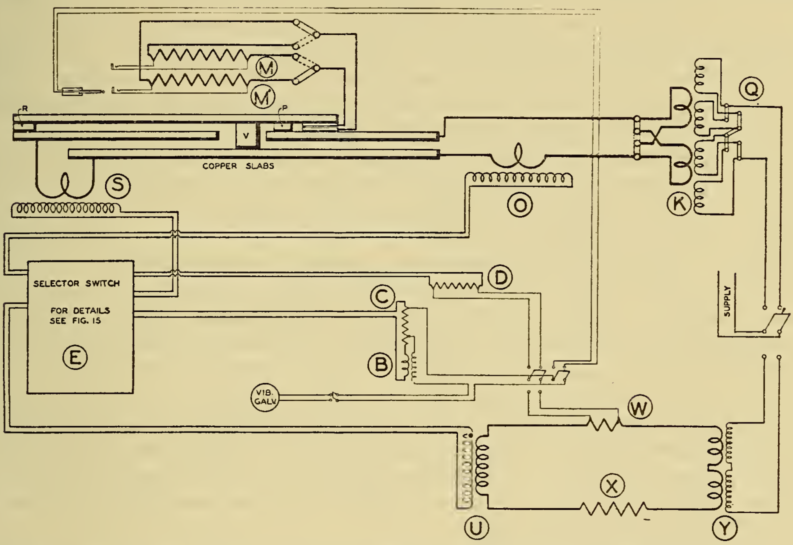

FIGURE 5.—*Wiring diagram of apparatus for testing current transformers up to 12,000 amperes.*

(Circled letters are the same as those shown in fig. 4.)
B, mutual inductor.
C, secondary standard resistor for test transformer.
D, secondary standard resistor for standard transformer.
E, mercury cup selector switch.
K, supply transformer for high-current primary circuit.
M, 1,000-ampere oil-cooled standard resistor.
M', 2-500-ampere oil-cooled standard resistor.
O, transformer under test, range up to 12,000 amperes.
Q, terminal board for primary of supply transformer.
S, standard transformer.
U, transformer under test, range up to 500 amperes.
W, air-cooled standard resistor.
X, rheostat for low-current primary circuit.
Y, supply transformers for low-current primary circuit.

are designed to operate with a voltage drop of 0.5 volt and at this load have a temperature rise of about 5° C. Cooling is provided by a blast of air from a motor-driven centrifugal blower Z, which is located under the table which supports the standard resistor and the transformer under test. The air stream from the blower passes up a duct and through a hole 4⁵⁄₁₆ inches (11 cm) square in the table top. The standard resistor is placed over this hole when in use.

The standard resistor M (figs. 4 and 5) has a resistance of 0.0005 ohm and at its rated current (1,000 amperes) has a drop between its

[5] For a more detailed description of these standard resistors see F. B. Silsbee, B.S. Jour. Research, vol. 4, (RP133), p. 91, January 1930.

potential terminals of 0.5 volt. The larger resistor M' is rated to carry 2,500 amperes and has two sets of potential terminals corresponding to resistances of 0.00025 and 0.00020 ohm. The total power dissipation in the larger resistor between its current terminals is about 2 kw. The transfer of this heat from the resistor metal itself is effected by a stream of oil which is forced through a narrow annular passage on each side of the resistor metal by a motor-driven centrifugal pump. Under normal conditions the speed of the pump is 1,800 rpm and the oil flow is 20 gallons per minute (1,200 cm^3 per second). Since the oil passages are about 5/32 inch (4 mm) wide, the oil velocity is about 2 feet (60 cm) per second and the temperature rise of the resistor metal above that of the outlet cooling oil is 11° C., at the normal rate of transfer of 1.7 watts per square inch (0.26 w/cm^2).

The inductance of these precision resistors is small and definite because the working metal has the form of a straight thin-walled circular cylinder of sheet manganin. The current returns through a copper cylinder which is inside of and coaxial with the manganin cylinder. The potential leads are attached to the outer surface of the resistor and are tied tightly against the tube. The disturbing effect of stray magnetic fields on the effective inductance of the resistor is minimized by using four complete sets of potential leads which are attached to the manganin cylinder along elements 90° apart[6] and which are connected, at suitable junction points, in parallel through equal resistances. The effective 4-terminal resistance can be adjusted as closely as desired to the nominal value by moving a tap lead along a single resistor of about 0.2 ohm, which is connected between such of these junction points as to place it effectively in parallel with a length of 3/4 inch (2 cm) of the tube.

The 12,000-ampere primary circuit includes the step-down supply transformer K (figs. 4 and 5) a "cage" in which the transformer under test, O, is located, the multirange standard transformer S, and the 2,500-ampere and 1,000-ampere primary standard resistors M′ and M.

The supply transformer is rated 480/240/120 to 4/2 volts, 25 cycles and has a 1-hour rated capacity of 20 kva. The primary windings can be connected in series, series-parallel, or parallel by a suitable arrangement of links on the terminal board Q. The secondary terminals are arranged for series or parallel connection by heavy copper terminal blocks and spacers. The greater voltage available with the series connection is needed only in tests of transformers of less than 1,000-ampere rating. At 60 cycles it is, of course, possible to operate this transformer at voltages considerably above the nominal rating and thus overcome the increased reactance offered by the circuit at the higher frequency.

The design of the primary circuit at the place where the transformer under test is located presented a rather difficult problem. Most transformers of the ranges tested in this circuit are used with a single primary turn, and in service are usually in a bus compartment at a considerable distance from the conductors carrying the return current in the other phases. Consequently it seemed desirable to have the return lead in the test circuit so placed as to have the least possible

[6] The resistances of these potential leads are checked periodically and before every important test in order to detect the development of any poor contact or an open circuit. For a more detailed description of these shunts see F. B. Silsbee, B.S. Jour. Research, vol. 4, (RP133), p. 91, January 1930.

effect on the transformer under test. On the other hand, the use of a wide primary loop would increase the kilovolt-amperes required from the motor-generator sets, and the resulting large stray magnetic field would constitute a potential source of error by reason of its effect in the primary standard resistors and the secondary mutual inductor. The distance from this inductor to the transformer under test was limited both by the size of the room and by the necessity of keeping down the resistance, and hence the length, of the leads connecting the transformer secondary with the inductor.

A fairly satisfactory escape from this dilemma was found in the construction shown just to the left of the supply transformer K in figure 6. The outgoing current passes through a conductor, not visible in the figure, which lies along the axis of the cagelike structure surrounding the transformer O under test, and after passing through the standard transformer or one of the standard resistors, returns through the 4 outer copper slabs which are connected in parallel by 2 vertical end slabs. The length of this "cage" is 36 inches and the "radius" approximately 20 inches. The reactance of this section of the circuit is about 190 microhms at 60 cycles and is a major part of the total impedance of the heavy current circuit. As is shown in appendix A, such a construction reduces the stray magnetic field at locations only a few feet away from the axis to a small fraction of that which would be produced by a single loop. Tests with an exploring coil at a distance of 40 inches from the axis of the cage showed a magnetic field of only 0.14 gauss with 1,000 amperes flowing. At the location of the mutual inductor the stray field was only 0.005 gauss per 1,000 amperes. At the same time the magnetic field at the core of the transformer under test is closely similar to that which would exist if the return conductor were at a very great distance.

Except in the neighborhood of the transformer under test, the heavy-current circuit is formed of wide copper slabs placed as close together as possible. For the circuit to the standard transformer which is designed for the full-rated current, these slabs are 20 inches wide by ½ inch thick and are spaced about 1 inch on centers. In the branch circuit to the oil-cooled resistors, which have a maximum rating of 2,500 amperes, the slabs are 10 inches wide by ¼ inch thick and are separated by only the thickness of a strip of varnished cambric. These slabs twist through an angle of 90° in a length of 2 feet in passing from the main slabs which are horizontal to the vertical terminals of the primary resistors. It was found feasible to bend the copper cold in this manner and thus avoid several joints.

The uppermost 20-inch slab is mounted on hinges so that it can be lifted back away from the other conductors. This gives access to the top of the standard current transformer and to the studs connecting its primary conductors to the upper transformer terminal. It is also possible by inserting either bakelite or copper spacers in the proper gaps at points R, V, P (figs. 5 and 6), to obtain any of the circuit combinations listed in table 1. A similar set of insulating or conducting spacers enables either or both standard resistors M and M' to be connected in series with the 10-inch slabs.

TABLE 1.—*Circuit combinations possible with primary circuit shown in figures 5 and 6*

Circuit combination	Between slabs at R	Between upper and lower slabs at V	Between upper and center slabs at P
Test transformer and standard resistor only	Bakelite	Copper	Bakelite.
Test and standard transformers only	Copper	Bakelite	Copper.
Test and standard transformers and standard resistors	do	do	Bakelite.

2. STANDARD TRANSFORMER

The standard transformer was designed so as to satisfy as completely as possible the requirements outlined above for having the same ratio factor and phase angle on different primary connections. The core is of silicon-steel ring punchings 12$\frac{1}{16}$ inches (20.7 cm) outside diameter, 7$\frac{13}{16}$ inches (19.8 cm) inside diameter, and 0.014 inch (0.36 mm) thickness. The core contains 36 pounds (17 kg) of this material and forms a stack 2$\frac{1}{8}$ inches (5.4 cm) thick. While the use of the newer nickel-iron alloys would have reduced the magnitude of the phase-angle and ratio errors, it was felt that they would not have been so small that corrections could have been neglected entirely. The mere reduction in the magnitude of the corrections was not considered a sufficient improvement to justify the very considerably greater cost of a core of nickel-iron alloy.

The secondary winding has a total of 2,400 turns of no. 12 A.W.G. single cotton and enamel covered wire. To minimize the danger of breakdown of insulation between turns, the winding is formed of 20 sectors each subtending an angle of 18° around the periphery of the core. Each sector is insulated from the core and from the adjacent sectors by at least two thicknesses of varnished cambric. Each of the sectors contains three separate coils, also carefully insulated, which have 96, 20, and 4 turns, respectively. The terminals of the 60 coils thus formed are brought to the outside of the secondary winding and there grouped to form 12 windings, of which 4 have 480 turns each, 4 have 20 turns each, and 4 have 100 turns each. In this grouping the five individual coils which are joined in series to form a winding are selected from sectors spaced 72° apart. Consequently the magnetomotive force produced by any one winding is distributed equally over five equidistant sectors of the core. Because 5 is not a factor of 24 (the number of primary turns), this spacing of the secondary sectors prevents any secondary winding from having a materially closer coupling to any one group of primary turns than to any of the others.

At the terminal board each 20-turn winding is joined in series between the 480-turn and the 100-turn windings which are located in the same set of five sectors. There are thus formed in effect 4 equal sections, each having a total of 600 turns with taps at 500 turns and at 480 turns. Links are provided for readily changing taps and also for connecting the four sections in series, series-parallel or parallel. It is thus possible to obtain a uniform turn distribution with 480, 500, 600, 960, 1,000, 1,200, 1,920, 2,000, or 2,400 turns. The resistance of the complete winding is about 4 ohms. The weight of the secondary copper is about 47 pounds (22 kg). The core and secondary

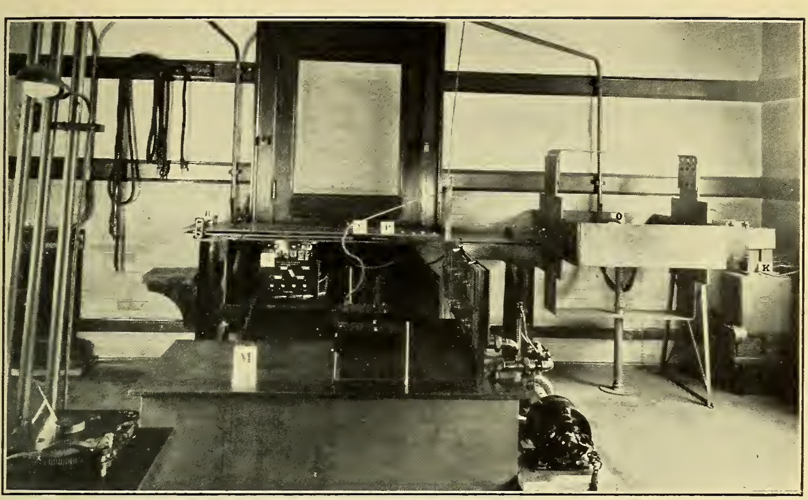

FIGURE 6.—*Primary circuit for testing current transformers, range up to 12,000 amperes.*

S, Standard current transformer; *O*, Transformer under test; *K*, Supply transformer; *M*, Tank containing oil-cooled standard resistors.

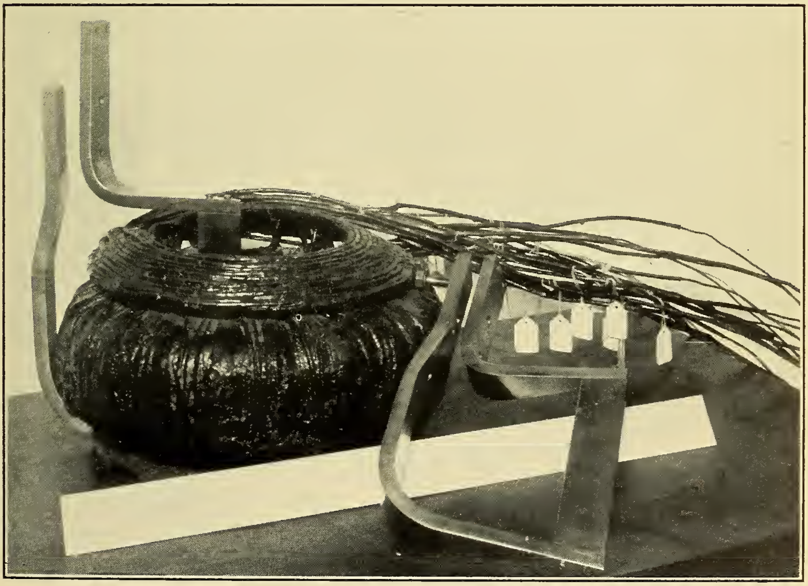

FIGURE 7.—*Completed wound core of standard current transformer showing the secondary winding and two primary turns, one in its normal position.*

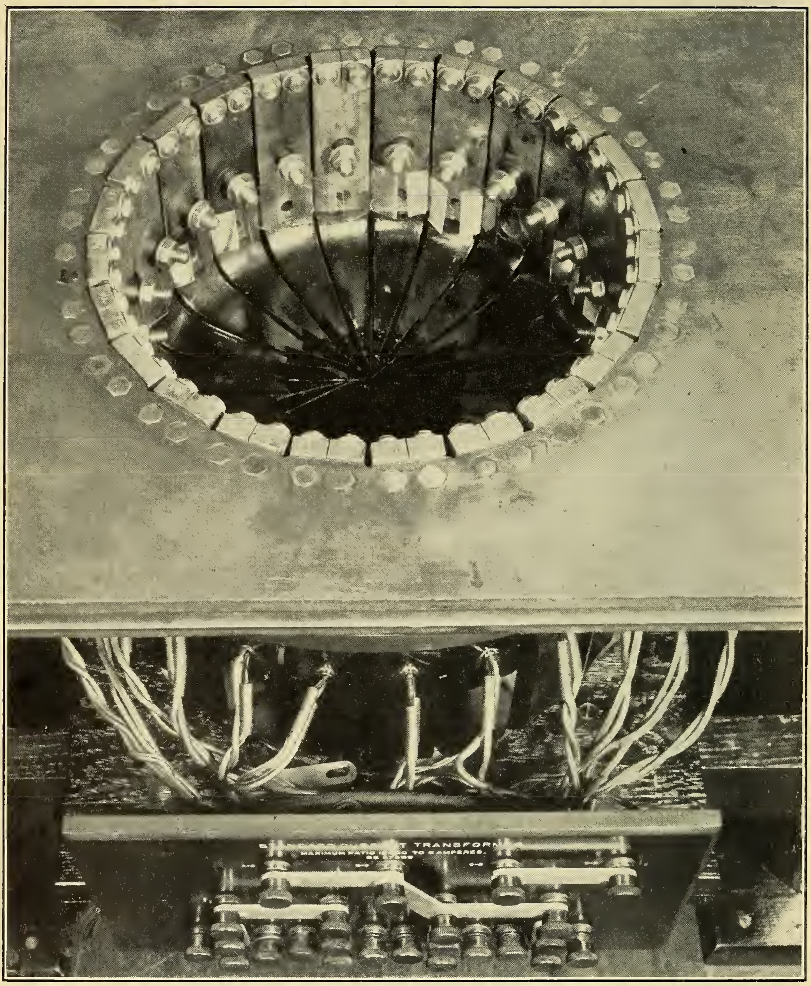

FIGURE 8.—*Completed standard current transformer in place.*

winding were vacuum impregnated[7] with insulating compound to form a very solid permanent unit. Figure 7 shows the completed secondary winding with the leads which connect the separate coils to form the windings.

As a further safeguard against failure of the secondary insulation, two safety spark gaps are provided. These are shunted around two of the 480-turn windings and break down at a potential difference of only a few hundred volts, thus short circuiting the winding and relieving it of electric stress in case the external secondary circuit should be accidentally opened.

Figure 8 shows the external appearance of the completed transformer as seen from above with the 24 primary turns which encircle the core and secondary winding connected in parallel to the upper terminal slab. Figure 9 shows a vertical cross section. The openings in the upper and lower terminal slabs (*D* and *E* in fig. 9) are machined to form regular polygons of 24 sides; that in the upper slab being observable in figure 8. Each primary turn consists of a sector-shaped bar which passes through the central opening in the transformer and two L-shaped pieces, such as *B* and *C* in figure 9. Two complete turns are shown in figure 7.

Each of the sector-shaped bars has a left-hand twist of 15° between its end faces. Because of this each outer bar *C* lies opposite that face of the polygon *F* which is next, in a counterclockwise direction (as seen from above), to the face which is opposite the inner bar *B* of the same turn. The result of this twist is that if a bolt is inserted at *b*, it pulls the *C* bar of one turn into contact with the *B* bar of the next turn, thus connecting the two turns in series. The upper L-shaped pieces, *B*, extend through an opening in the lower terminal slab *E*, and can be pulled into contact with the upper slab *D*, if desired by two ¼-inch cap screws. The lower L-shaped pieces *C*, extend only high enough to permit of connection to the cast copper flange *F* which in turn is bolted to the lower terminal slab *E*.

Removal of the cap screws and the insertion of a thin strip of insulating material at *e* serves to insulate this junction from either terminal of the transformer, the bar *C* springing enough if bolt *a* is absent to be held out of contact with flange *F*. As many adjacent turns as desired may thus be connected in series. Each group of such series turns is connected to the terminal slabs by screws at *a* and *e* at the end bars of the group, and is thus put in parallel with other similar groups. The number of series primary turns of the transformer may thus be made equal to any of the eight integral factors of 24.

The joints at *m* and *d* are silver-soldered. The joints *d* had to be soldered after the core and secondary winding were in place. It was found that the primary bars could be heated to the brazing temperature very conveniently by sending about 7,000 amperes through them. This electric heating avoided the risk of injuring the secondary winding which would have been incurred if the joints had been brazed with a gas flame.

The primary turns are insulated from the secondary windings by the ¼-inch bakelite ring *f* on which the secondary winding rests and by cylindrical shields of 1/32-inch sheet bakelite at *g* and *h*. The bars

[7] Through the courtesy of the General Electric Co., the impregnating process was carried out at their West Lynn works.

A are spaced apart by 1/32-inch bakelite strips, *j*, and are anchored symmetrically by the cap screws which fasten the bars *C* to the bakelite ring *k*.

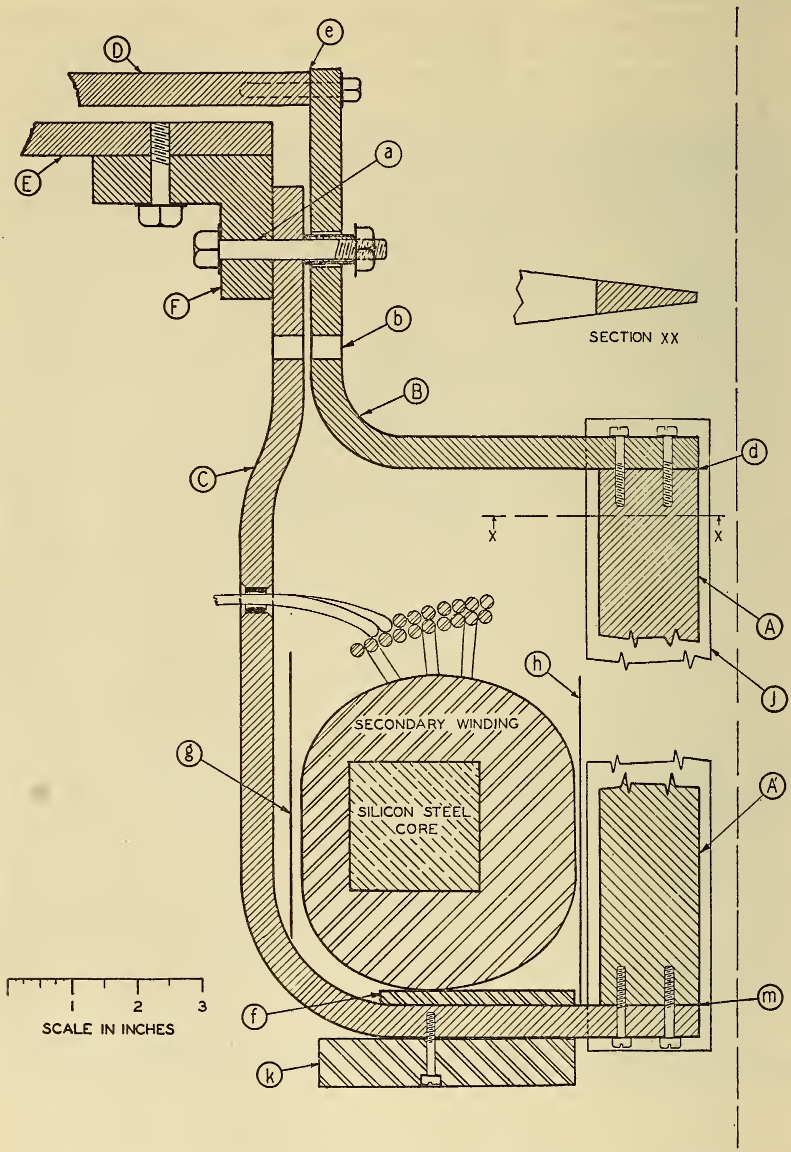

Figure 9.—*Vertical cross section of standard current transformer.*
(Bars *A–B* are part of the next turn adjacent to that formed by bars *A′–C*.)

As will be noted from figure 9, there is a considerable clearance in a vertical direction between the secondary winding and the primary turns. This spacing was allowed to permit of soldering the upper joint without damage to the insulation, although it materially increases the primary leakage reactance. The reactance of the primary, when all 24 turns are in series and the secondary is short-circuited, is 7,400 microhms at 60 cycles, while the effective resistance is 2,360. The resistance computed from the dimensions of the bars and the resistivity of copper is 840 microhms and the losses in the short-circuited secondary may account for a resistance of perhaps 400. The excess of 1,120 microhms remaining is presumably mainly due to skin effect. All the contact surfaces both of the bars and of the faces of the two 24-sided polygonal openings in the terminal slabs are gold plated, with the result that the resistance of the average contact is only 2.5 microhms.

Of the two factors which might combine to introduce an error when the transformer is used on a higher range than that on which it was calibrated, the first (inequality in current distribution among the primary turns) has been studied in some detail. The variations in contact resistance among the various parallel paths ordinarily do not amount to more than 4 microhms, or about 4 per cent of the total resistance of a single primary turn. In order that the length of path and hence the resistance offered to the portions of current flowing to the several primary turns may be as nearly equalized as possible, the two terminal slabs are extended in opposite directions from the transformer, so that, at any instant, the current after passing through the primary winding flows away from the transformer in the same absolute direction as that in which it approached. As a result the system, as regards resistance, is symmetrical about a plane passing through the axis of the transformer at right angles to the axis of the terminal slabs. The transformer is, of course, also symmetrical about the plane containing its axis and that of the slabs. The result of this twofold symmetry is that the resistances of the current paths are the same for the four quadrants into which these planes divide the transformer. Unfortunately the current in the uppermost horizontal slab does not completely neutralize the magnetic effects of the currents in the two slabs below it, and the resulting voltages induced in the primary turns somewhat affect the current distribution.

Curve *A* of figure 10 shows the distribution of current among the various bars at 25 cycles per second, when all 24 were connected in parallel, as indicated by measuring the impedance drop on a length of about 7 inches of each bar by an a. c. potentiometer. The axis of the terminal slabs lies between bars 1 and 2 and between bars 13 and 14.

The use of an exploring coil (100 turns of 10 cm^2 area located 1 cm outside of the outer bars) gives a more convenient though less direct measurement of the distribution of current and magnetomotive force around the transformer. The coil is placed in succession opposite the center of each primary bar, the plane of the coil being radial so that the tangential component of the magnetic field is effective in inducing an electromotive force in it. This induced voltage is balanced by that induced in a mutual inductor carrying the secondary current of the transformer. The results are expressed as the leakage field intensity in gilberts per centimeter, per primary ampere turn.

In figure 10, curve *C* gives the result obtained when all 24 primary turns were connected in series and necessarily carried the same current. The fluctuations from bar to bar can be explained in part as resulting from slight inequalities in the location (both radially and tangentially) of the individual primary bars, and in part from similar inequalities in the spacing of the sectors of secondary winding. The small absolute magnitude of this stray field is made evident by the arrows which indicate that the maximum field intensity is less than 3 percent of that existing just inside of the primary turns.

Curve *B* was obtained when all 24 turns were in parallel. The differences between curves *B* and *C* are presumably the result of differences in the magnitude of the current flowing in the several bars and of the stray magnetic field of the loop formed by the terminal slabs at the top. To greatly exaggerate these inequalities curve *D* was obtained when 23 turns were connected in series, bar no. 2 being

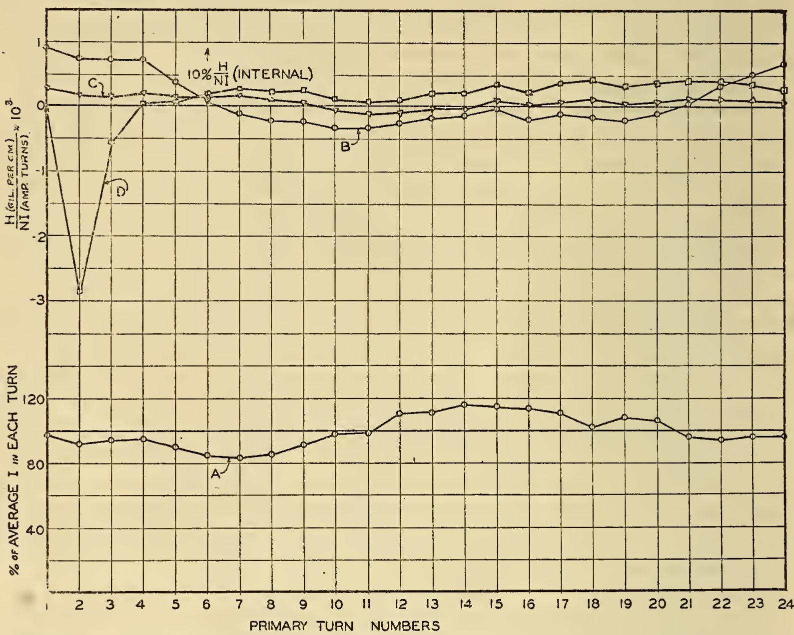

Figure 10.—*Current distribution in primary turns of standard current transformer and stray magnetic field around transformer.*

Curve *A*, percent of average current per turn in each turn when all turns are in parallel.
Curve *B*, tangential magnetic field outside at central plane of each turn when all turns are in parallel.
Curve *C*, tangential magnetic field outside at central plane of each turn when all turns are in series.
Curve *D*, tangential magnetic field outside at central plane of each turn when 23 turns are in series (turn no. 2 being disconnected).

omitted from the circuit. The stray field opposite this bar is seen to be six times the greatest difference between the normal curves *C* and *B*, yet the ratio factor and phase angle of the transformer as a whole were found to be the same as under normal conditions to within 0.01 percent and 0.1 minute.

The second factor (inequalities in the coupling between individual primary bars and the secondary winding) was checked experimentally by measurements of ratio factor and phase angle when only one primary turn was used. Under these conditions the transformer operates with only 500 ampere turns and has a correspondingly mediocre performance, but of the six representative primary turns measured there was no departure from the mean exceeding 0.03 percent in ratio factor or 2 minutes in phase angle. Since each primary turn only contributes one twenty-fourth of the total magnetomotive force, the slight inequalities in current distribution and coupling would not be expected to combine to make the ratio factor with turns in parallel differ appreciably from that with turns in series.

An alternative basis can be obtained from the following data for judging the degree to which this transformer satisfies the requirements outlined above as being necessary and sufficient for the correct extrapolation of its ratio and phase angle to higher ranges of current. When used with only 500 secondary turns the ratio and phase angle may be directly measured by the resistance method for all 8 combinations of primary turns. The results of such a series of measurements are given in tables 2 and 3 for ratio factor and phase angle respectively. The changes in these quantities with change in primary grouping are seen to be less than 0.02 percent and 1 minute respectively.

TABLE 2.—*Ratio factor of standard transformer with 500 secondary turns and burden of 96μh and 0.284 ohm*

Ratio	Secondary current in amperes					
	0.5	1	2	3	4	5
500/1	1.0001_6	1.0002_1	1.0002_4	1.0002_5	1.0002_2	1.0002_0
500/2	1.0001_4	1.0002_2	1.0002_1	1.0002_2	1.0002_3	1.0001_9
500/3	1.0001_9	1.0002_4	1.0002_6	1.0002_6	1.0002_6	1.0002_3
500/4	1.0002_1	1.0002_7	1.0002_9	1.0003_1	1.0003_1	1.0002_9
500/6	1.0002_5	1.0002_8	1.0003_1	1.0003_0	1.0003_0	1.0002_6
500/8	------------	1.0003_0	1.0003_2	1.0003_1	1.0003_0	1.0003_0
500/12	1.0003_2	1.0003_5	1.0003_8	1.0003_6	1.0003_3	1.0002_9
500/24	1.0002_7	1.0003_0	1.0003_2	1.0003_2	1.0003_2	1.0003_0

TABLE 3.—*Phase angle (in minutes) of standard transformer with 500 secondary turns and burden of 96μh and 0.284 ohm*

Ratio	Secondary current in amperes					
	0.5	1	2	3	4	5
500/1	$11._1$	$9._1$	$7._3$	$6._4$	$5._9$	$5._4$
500/2	$11._3$	$9._4$	$7._5$	$6._6$	$5._9$	$5._5$
500/3	$10._9$	$9._1$	$7._2$	$6._3$	$5._7$	$5._3$
500/4	$11._4$	$9._6$	$7._5$	$6._6$	$5._9$	$5._5$
500/6	$10._5$	$9._2$	$7._4$	$6._4$	$5._8$	$5._4$
500/8	---------	$9._3$	$7._5$	$6._6$	$5._8$	$5._5$
500/12	$10._7$	$9._4$	$7._5$	$6._5$	$5._9$	$5._5$
500/24	$11._0$	$9._5$	$7._6$	$6._6$	$6._0$	$5._5$

The agreement of the transformer with the second general principle set forth above is shown by figure 11, in which values of secondary ampere-turns are plotted as abscissas and values of ratio factor and phase angle as ordinates. Data were obtained for three different numbers of secondary turns and for each the external burden was kept proportional to the square of the number of secondary turns. It is seen that the observed points all lie on a common curve, thus strengthening the validity of the extrapolation to higher currents.

3. ADJUSTABLE STANDARD RESISTOR

The adjustable standard resistor used in the secondary circuit of the transformer under test is shown diagrammatically in figure 12. The general mechanical arrangement is indicated in (*a*) while the connections are shown schematically in (*b*).

The resistor consists of a closed loop of resistance alloy. Coarse adjustment (in steps of 0.01 ohm) is obtained by plugs (as at *EF*) which fix the points at which the current enters and leaves the loop (as in an Ayrton shunt); while two steps of fine adjustment are obtained by sliding the two potential taps on the opposite side of the loop.

Between *A* and *B* (shown at the bottom of figure 12(*b*)) is a strip of resistance alloy 0.78 inch (2 cm) wide, 0.01 inch (0.027 cm) thick, and 55 inches (139 cm) long. This has a resistance of about 0.118 ohm and carries the bulk of the secondary current. With the plugs

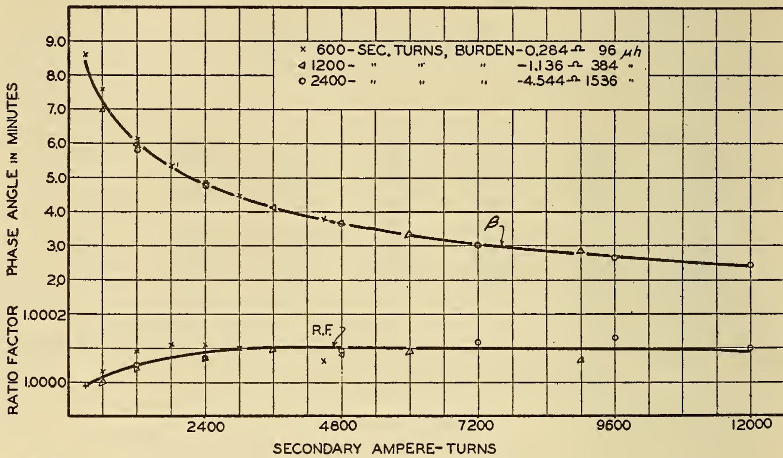

Figure 11.—*Ratio factor and phase angle curves of standard transformer, primary consisting of two groups of turns in parallel, each group having 12 turns in series.*

as shown, the current enters this strip at *E* and leaves at *F*. In parallel with *AB* is a second circuit GP_1P_2H which has a resistance of 10.7 ohms. One of the potential terminals P_1 is connected to a sliding contact on a 0.1 ohm slide "wire" [8] 21 cm long, which forms one end of this shunt circuit, while the other P_2 connects to the contact arm which runs over the set of 13 studs separated by 0.1-ohm coils which form the other end of the circuit GP_1P_2H. Between the slide wire and the studs is a fixed coil of 9.4 ohms.

If R_p denotes the resistance of the branch *GH* between the potential taps P_1 and P_2, R_c the resistance of the branch *AB* between the plugs *E* and *F*, and *S* the total resistance of the entire closed loop of resistance material GP_1P_2HBFAG, the resistance of the two circuits in parallel between branch points *E* and *F* is given by $R_c(S-R_c)/S$. The fraction of this resistance which is spanned by the taps P_1P_2 is

[8] This slide "wire" is formed of an alloy strip 0.027 cm thick and 0.36 cm wide set on edge and bent into the form of a circular arc of 8 cm radius. The contactor touches the edge of the strip as shown in section at *XX* of figure 12.

$R_p/S - R_c$. Hence the effective resistance R_2 of the 4-terminal combination, using E and F (or C_1 and C_2) as current terminals and P_1 and P_2 as potential terminals, is

$$R_2 = \frac{R_p R_c}{S} \tag{12}$$

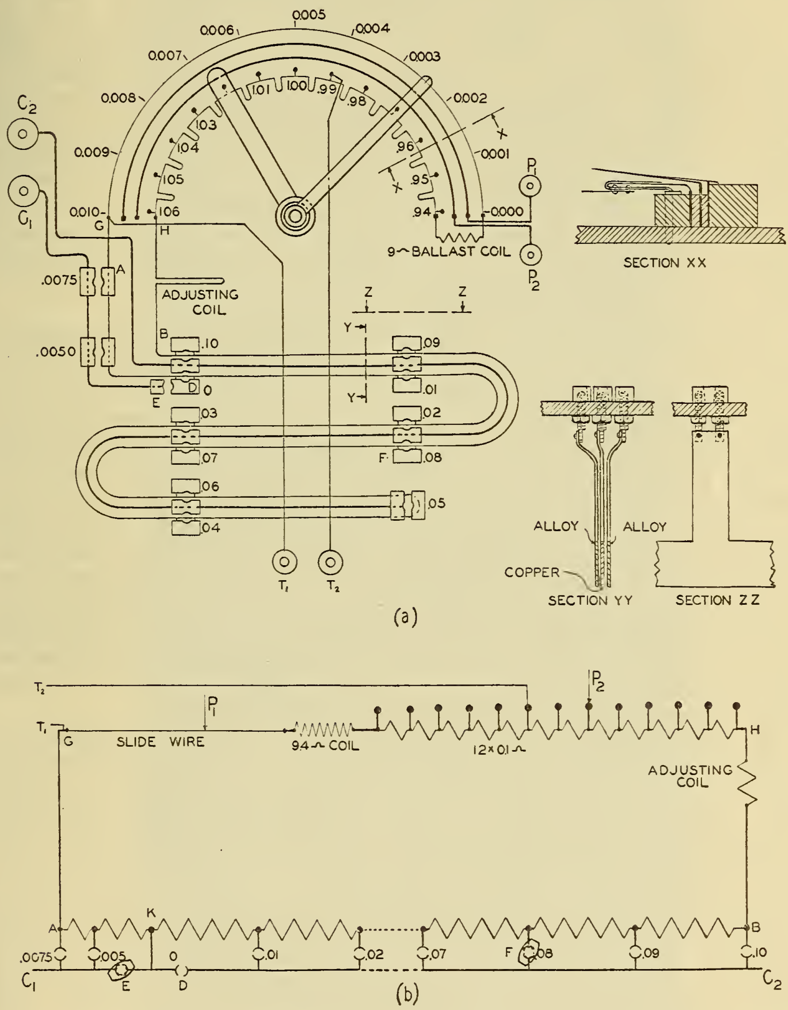

FIGURE 12.—*Standard resistor used in secondary circuit of transformer under test.*

Since S is independent of the settings of the plugs or sliders, the effective resistance for any given setting of R_c is proportional to the resistance R_p between P_1 and P_2. The inner end of the slide wire is marked "0" and the central stud is marked "1.00." The resistance of the branch circuit between these points is adjusted to be 10 ohms. Consequently each step of the contact arm P_2 changes

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R_p and hence R_2 by 1 percent. The entire range of the slider is also 1 percent, and as it is furnished with a 100-division scale, settings can be read to 0.1 division or 0.001 percent.

An adjusting coil of about 0.16 ohm is inserted between H and B and serves to make the total resistance S exactly 1,000 times the resistance (0.01097) of R_c between adjacent plug taps. When P_1 and P_2 are set to read 100 percent and, therefore, $R_p=10$ ohms, the effective 4-terminal resistance is by equation (12) exactly 0.01 ohm for each step between plugs E and F. The plug blocks marked 0.005 and 0.0075 to the left of E in figure 12 (b) allow of increasing the resistance above that corresponding to the plug at F by the fractional steps indicated. In use the plugs are so inserted that the nominal resistance is equal to the product of the resistance of the primary standard resistor multiplied by the transformer ratio. The settings of P_1 and P_2 then indicate directly the true ratio of the transformer in terms of its nominal ratio. This resistor has the additional merit that the resistance inserted in the secondary circuit of the transformer under test is only slightly greater (10 percent) than the effective 4-terminal resistance needed for the measurement.

A number of precautions have been taken to minimize the effective inductance of the apparatus. As shown in cross section at YY (fig. 12) the alloy strip is doubled back on itself and a copper strip constituting the lead DC_2 of figure 12 (b) is placed between the two alloy strips separated only by thin mica insulation. The inductance of this arrangment of conductors can be computed for each plug position, and the phase angle of the resistor is about 0.3 minute at 60 cycles. The 9.4-ohm coil and the 0.1-ohm steps in the high-resistance branch circuit are wound bifilar. As shown in the section on XX, the contact arms to the slide wire and to the studs serve merely to bridge across to one of the two copper arcs which connect to the potential binding posts. In this way, no loops of appreciable area are formed in the potential circuit for any position of the contact arms and the resistor is therefore not subject to inductive effects from stray magnetic fields.

To facilitate measuring its 4-terminal resistance by means of a Kelvin double bridge, additional potential terminals T_1T_2 are permanently soldered to the end of the slide wire and to the "0.99" stud. The use of these test terminals eliminates the four sliding contacts with their possible variations in resistance from the ratio-arm circuits of the double bridge. The initial calibration of the apparatus can be accomplished by the use of two potentiometers, by the Mathiessen-Hockin method, or, when the contacts are in good condition, by careful work with the double bridge, using the normal potential terminals. Periodic checks to verify the constancy of the effective resistance can then be made with the double bridge, using the test terminals.

The resistor has its maximum resistance at a temperature of 14° C. and decreases by 0.01 percent for a temperature rise of 13° C. above this point. For the most precise work it is therefore necessary to apply a correction for these resistance changes, allowing also for the temperature rise produced by the current, which is about 6° C. at 5 amperes.

FIGURE 13.—*Mutual inductor.*

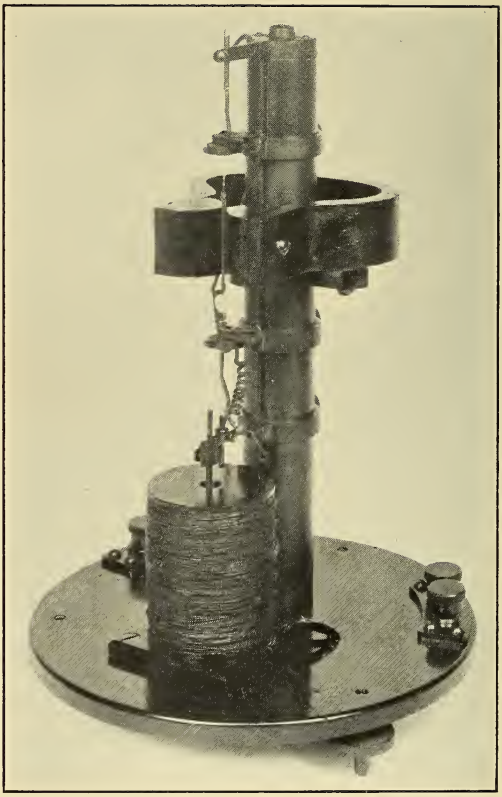

FIGURE 14.—*Vibration galvanometer used for 25-cycle tests, as equipped with solenoid for remote tuning.*

4. MUTUAL INDUCTOR

The mutual inductor (fig. 13) used to measure the phase angle of the transformer under test has a maximum value of 56 μh. The primary circuit has a resistance of 0.007 ohm and an inductance of only 2 μh. The burden thus imposed on the transformer under test is very small and can readily be allowed for in making up the total burden to any desired value. The secondary circuit is composed of three parts: (1) A set of 7 fixed sections each giving 6.6 μh, (2) a set of 7 fixed sections each giving 1.2 μh, and (3) an adjustable coil mounted so that it can be moved with respect to the fixed coils. The mutual inductance between this third section and the primary may be varied continuously from −1.0 μh through zero to +1.3 μh.

The arrangement of primary and movable secondary coils is, in general, similar to that described by Brooks and Weaver,[9] and the molded bakelite parts in which the coils are mounted are identical with those used in the Brooks inductometers regularly manufactured by the Leeds & Northrup Co. Because of the small number of turns needed for the low range of this instrument, and the space required for the fixed sections of the secondary winding, the primary turns do not occupy the entire winding space, and the scale law is not quite so linear as in a normal inductor.

The primary windings consist of four turns, one in each recess of the upper and lower plates. To minimize skin effect and eddy currents this winding is made of litzendraht wire having 189 strands (3 by 3 by 3 by 7) of no. 32 enamel-covered copper wire. The two turns in the lower plate lie against the outer wall of the recesses while those in the upper plate are located at the inner edge of the normal winding space.

The secondary winding on the movable disk consists of eight turns of no. 17 litzendraht wire. Four turns are wound pancake fashion in the central plane of each oval, the turns being spaced radially with heavy cord. The fixed sections are wound with a stranded conductor formed of seven no. 24 copper wires each insulated with enamel and silk. Each of the 7 strands forms 1 of the 7 steps of the appropriate section of the winding, and by reason of this construction the several steps differ in mutual inductance by less than one half percent. The small steps consist of 8 turns, 4 turns being wound outside of the single primary turn in each recess of the upper plate. The large steps consist of 40 turns, 20 turns being wound inside of the single primary turn in each recess of the lower plate.

The terminals of the various sections of the secondary winding are brought to a terminal block mounted 8 inches away from the nearest point of any coil to avoid magnetic coupling between the connecting leads and the primary turns. Two dial switches serve to insert any desired number of the fixed steps in series with the movable coil. For purposes of calibration, links and plug sockets are provided by which the secondary electromotive force of the movable coil can be opposed in succession to that of each small fixed step, and also so that the movable coil, together with the first five small steps, can be opposed to each one of the large steps. In this way the relative values of mutual inductance of the steps and of the movable coil can be readily determined. The calibration of the scale of the movable coil relative

[9] Brooks, H. B., and Weaver, F. C., B.S.Bull. vol. 16 (S290), p. 569, 1916.

to some one scale point can be made by opposing its electromotive force to the resistance drop in a calibrated slide wire which is carrying a current in quadrature with that flowing in the primary of the mutual inductor. A single direct measurement of the mutual inductance, when all sections of the secondary are aiding, then completes the calibration of the apparatus.

The scale engraved on the movable disk is laid off in uniform divisions subtending 1° each, and is probably decidedly more accurate than would be the case if an attempt had been made to lay it off electrically to fit the scale law of the apparatus. Errors from parallax are minimized by using a special form of fiducial mark. A block of plate glass 0.5 inch (1.3 cm) thick is embedded in the upper plate of the inductor. The index mark consists of a fine radial line etched on the lower surface of this glass block which is close to the scale. A small "*X*" mark etched on the upper surface of the block directly above the index mark enables the observer to place his eye in line with these two marks and insures that his line of sight is always at the same definite angle with the scale.

5. VIBRATION GALVANOMETERS

The vibration galvanometers used to indicate the balance of alternating potential drops are of the moving-coil type. One of these, used for 25-cycle tests, was built in the instrument shop of the Bureau of Standards. The other galvanometer, which is used for tests at 60 and at 50 cycles, was built by Robert W. Paul, Ltd., but has been greatly modified to adapt it to the present work. The 25-cycle galvanometer is shown in figure 14. The moving coil of each galvanometer consists of 10 turns of no. 32 A.W.G. enameled wire stretched taut between suspensions of copper strip. Rough adjustment of the natural frequency of vibration of the coil is obtained by adjusting the distance between the clamps which hold the suspensions. The lower end of the lower suspension strip carries a small iron plunger which hangs inside a solenoid. Adjustment of the direct current flowing in this solenoid changes the pull exerted on the suspension and affords fine adjustment of the natural frequency of the instrument. Thus tuning for maximum sensitivity becomes a very simple process, for the solenoid current may be adjusted while the observer is watching the amplitude of the deflection.

The sensitivity of each galvanometer is about 0.3 mm/μv at its terminals with a scale distance of 1 m. The sensitivity drops to about one half of this value for a change of 8 percent in frequency. The resistance of each galvanometer is about 1 ohm.

The galvanometers are mounted on a special support to avoid disturbance from external mechanical shocks. This support consists of a large concrete block (12 by 16 by 25 inches) which is hung on four large helical steel springs. The natural frequency of oscillation of this system is very low and the small impulses of higher frequency which are transmitted to it are effectively absorbed by a layer of hair felt about 1 inch (2.5 cm) thick which is placed between the top of the concrete block and the board on which the galvanometers stand.

IV. TEST PROCEDURE

When a current transformer is received for test the insulation between primary and secondary windings is first tested with a 1,000-volt megger. Its primary terminals are then connected in series in the primary circuit (fig. 5) appropriate to the range of the transformer. A standard resistor capable of carrying the rated primary current of the transformer is also connected in this circuit. The value of secondary standard resistor to use is thus fixed as equal to the product of the resistance of the primary resistor multiplied by the ratio of the transformer. If the primary current exceeds 2,500 amperes, the primary shunt is not used, but the primary terminals of the standard transformer are so connected as to give it about the same primary current rating as that of the transformer under test. A 5-ampere resistor (R_3) of convenient value is connected to the secondary terminals of the standard transformer. The value of the standard resistor (R_2) in the secondary of the transformer under test is then determined from the equation $R_2 = R_3\ n_x/n_s$ where n_x is the nominal ratio of the transformer under test, and n_s is the nominal ratio of the standard transformer.

The resistance of the secondary circuit of the transformer under test is then measured with a Wheatstone bridge to make sure that it is definite and not abnormally high as the result of broken wires or poor contacts. In this measurement the bridge current is kept very small (less than 10 milliamperes) to avoid magnetizing the transformer appreciably.

The next step in the test is the adjustment of the secondary burden to duplicate that specified by the customer. The desired inductance is made up by including in the circuit the proper combination of air-cored reactance coils. A set of eight such coils wound with 0.162-inch square wire gives values of inductance up to 1,100 μh in steps of 10 μh, with a time constant ranging from 0.002_5 to 0.017 second. Other coils of somewhat lower time constant are available to give burdens up to 8,000 μh. Fine adjustment of the inductance is obtained by two inductors of the Brooks type which have ranges of 1,100 and 10 μh, respectively.

The resistance of the burden is adjusted by a set of fixed resistors connected to a set of contact plugs which give a range of 1.1 ohm in steps of 0.01 ohm. The smallest step can be bridged by a continuously adjustable resistor formed by a mercury column 0.12 inch (3 mm) in diameter and 8 inches (20 cm) long. An amalgamated copper wire forced down into the mercury effectively short-circuits any desired fraction of the mercury resistor. The resistance of the burden is adjusted experimentally to the desired value as shown by the Wheatstone bridge, thus allowing for changes in the resistance of the circuit resulting from temperatures changes. This adjustment is made to an accuracy of about 0.001 ohm. The mercury-cup selector switch (fig. 15) with its two sets of links provides a convenient means of making connections between either of the current transformer secondaries, the Wheatstone bridge, and the burden. The shunt S when applied to the bridge ratio arm A serves to make the total resistance of the arm XY, including the lead to Y, equal to the nominal value of A. Arms R and B are of much higher resistance so that the lead from Z to R has a negligible effect.

The secondary precision resistor, the primary winding of the mutual inductor and a certain amount of lead resistance are necessarily in the secondary circuit of the transformer under test. This minimum burden for a resistance setting of 0.05 ohm is 0.11 ohm. When the

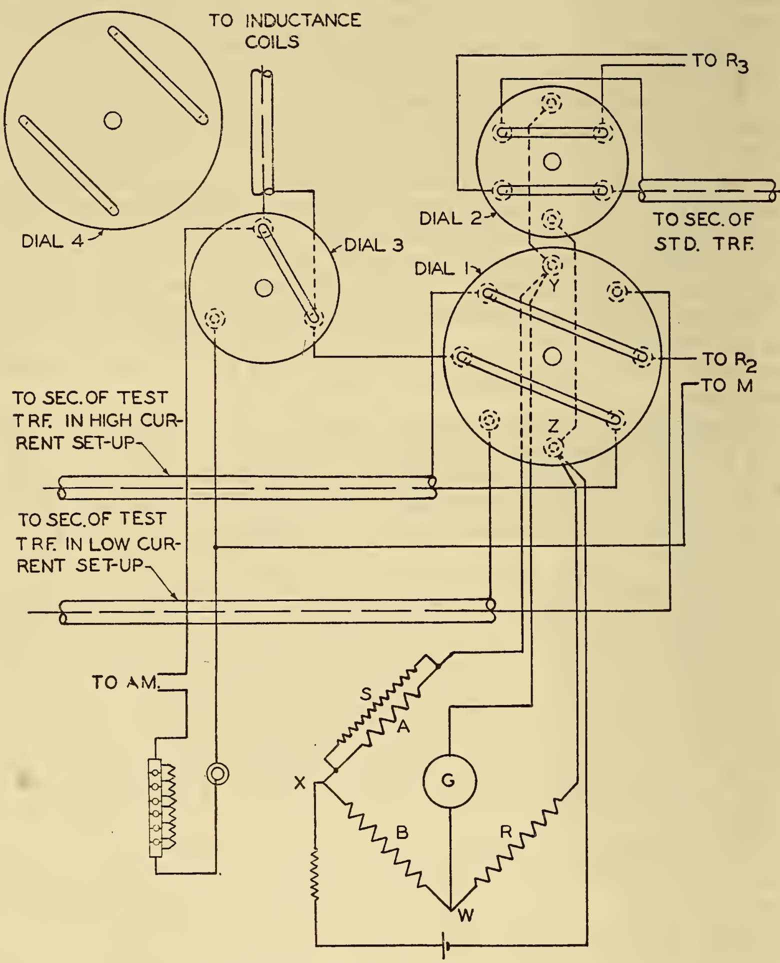

FIGURE 15.—*Mercury cup selector switches.*

Dial *1* as shown, secondary of high-current transformer to measuring circuit (consisting of adjustable mutual inductor and secondary resistor).
Dial *1* rotated 45° clockwise, secondary of high-current transformer to bridge.
Dial *1* rotated 90° clockwise, secondary of low-current transformer to bridge.
Dial *1* rotated 135° clockwise secondary of low-current transformer to measuring circuit.
Dial *4* replacing dial *1*, measuring circuit to bridge.
Dial *2* as shown, secondary standard transformer to its standard resistor.
Dial *2* rotated 60° clockwise, secondary winding of standard transformer to bridge.
Dial *2* rotated 120° clockwise, external secondary circuit of standard transformer to bridge.
Dial *3* as shown, burden inductors shorted.
Dial *3* rotated 120° clockwise, inductors and adjustable resistor shorted.
Dial *3* rotated 240° clockwise, adjustable resistor shorted.
Dial *3* left out, inductors and adjustable resistor in secondary circuit.

burden specified by the customer is less than this it becomes necessary to make two tests on the transformer, the first with the minimum feasible burden and the second with a burden greater than the minimum by an amount equal to the excess of the minimum burden over the specified burden. Using these two sets of data, linear extrapolation will give with reasonable certainty the ratio and phase angle which the transformer would have on the specified burden. As has been pointed out elsewhere [10] there is little gain to the user from specifying very low transformer burdens.

It is frequently feasible to use in the test the actual instruments which will later be used with the transformer. The resistance of the standard resistor, mutual inductor, etc., must then be allowed for by correspondingly reducing the test lead resistance below the customer's value. If this specified value is 0.1 ohm or more it is usually possible to make the test in this way. Other things being equal, it is, of course, desirable for the highest accuracy to use the actual secondary instruments because their impedance may depart slightly from the typical values stated by their maker. Furthermore, the inductance of most instruments changes somewhat with the position of the pointer and, if iron is present, with the frequency and the current. It is not practicable to duplicate these changes using simple air-cored inductors.

As a final preliminary step the transformer is demagnetized, usually by connecting the secondary circuit between the sliding contact and one end of a potentiometer-type slide-wire rheostat while the transformer primary is open. The voltage applied to the transformer is raised until a current of 5 amperes is reached, or until a rapid increase in current for a small increase in applied voltage indicates that the knee of the magnetization curve has been passed. The applied voltage is then reduced very gradually to zero, at first by the generator field control and later by the slide rheostat. In the case of transformers of very high range it is sometimes necessary to apply as much as 350 volts at 25 cycles to reach the desired flux density. In cases where the customer wishes to know the ratio and phase angle of the transformer in the condition in which it was used in some preceding measurements, this demagnetizing process and the measurement of secondary resistance are, of course, omitted.

After these preliminaries are completed, the transformer secondary is connected to the burden circuit by the links at the mercury-cup selector switch. The supply switch is closed and the generator voltage raised by the field control until a secondary current of 5 amperes is reached. Operator II (fig. 4) adjusts frequency and current to the proper values and operator I adjusts the secondary standard resistor and the mutual inductor until a balance is obtained on the vibration galvanometer. The settings are recorded, operator II reduces the current to 4 amperes, and another setting is made. Further successive settings are then made with the secondary current at 3, 2, 1, and 0.5 amperes. Because of the small deflection produced by 0.5 or 1 ampere in a 5-ampere ammeter, the adjustment of current for these points is usually based on the indication of an ammeter of suitable range inserted in the primary circuit and short-circuited during the remainder of the test. After the balance has been obtained at the 0.5-ampere point, the operators exchange places and make a second set of balances at increasing values of current. Any differences exceeding 0.02 percent or 0.5 minute between the two sets of results indicate the need for a repeat test to locate the origin of the differences.

[10] Silsbee, F. B., Elec. World, vol. 81, p. 1082, May 12, 1923.

After the series of alternating-current balances has been satisfactorily completed, the resistance of the burden is again measured to make certain that it has not changed appreciably. If a gradual drift in the ratio has been noted, the resistance of the secondary winding may be measured again to obtain a basis for estimating its temperature rise during the run.

The computation of the results includes the averaging of the two settings at each value of current; the correcting of the apparent ratio factor, as read from the dials of the precision resistor in the secondary, by the calibration correction to the primary and secondary resistors and by the effects of room temperature and current in further changing their resistance. The phase angle is computed by equation (7a) from the mutual inductance as read from the calibration curve, the frequency and the setting of the secondary resistor.

The computations as made by one observer are checked independently by the other. The values of ratio and phase angle are then plotted as ordinates against secondary current as abscissas to make certain that they yield a smooth curve of normal shape. As a further check against errors, the results are carefully scrutinized independently by a third member of the staff, familiar with current-transformer performance, and when possible are compared with the old records of data obtained in the course of any previous test of the same transformer. The formal certificate is then prepared and proof read twice against the original data sheet before issuance.

V. CONCLUSIONS

Experience with the various parts of the equipment here described has led to the following general conclusions:

1. The resistance method for the absolute measurement of the ratio and phase angle of current transformers is readily capable of giving sufficient accuracy for present-day purposes, at least up to 2,500 amperes.

2. The design of suitable primary resistance standards is the limiting factor in the method and has become difficult and expensive when the range of currents has reached 1,500 amperes.

3. The use of a standard multirange transformer, tested with its primary turns in some groupings and used as a standard with its primary turns in other groupings of higher range, is feasible and accurate, and is preferable to the resistance method for currents above 1,000 amperes.

4. The uniformity of secondary winding which can be obtained with a ring core is the main factor in securing good performance in such standard transformers. Because of this excellent uniformity, the need for equality of current distribution in the primary is less necessary than might be anticipated. This is fortunate because contact resistance and the inductive action of the current in the terminal slabs prove to be serious obstacles to obtaining uniformity of primary current.

5. The number of primary sections (24) in the present transformer is probably larger than is necessary for most purposes, and with fewer turns the difficulties of construction would be materially decreased.

6. The arrangement of the primary leads is of increasingly great importance with increasing current rating in certain types of current

transformer, and an arrangement, such as the present "cage", which eliminates the effect of the return lead, would seem to be the logical form to use with standard transformers in testing laboratories.

APPENDIX A—CALCULATION OF THE MAGNETIC FIELD AROUND THE TEST TRANSFORMER "CAGE"

Figure 16 shows in cross section four infinitely long straight linear conductors, A, B, C, and D, connected in parallel to constitute the return for the single lead O. This structure approximates the "cage" in which the current transformer is placed for test. Three features

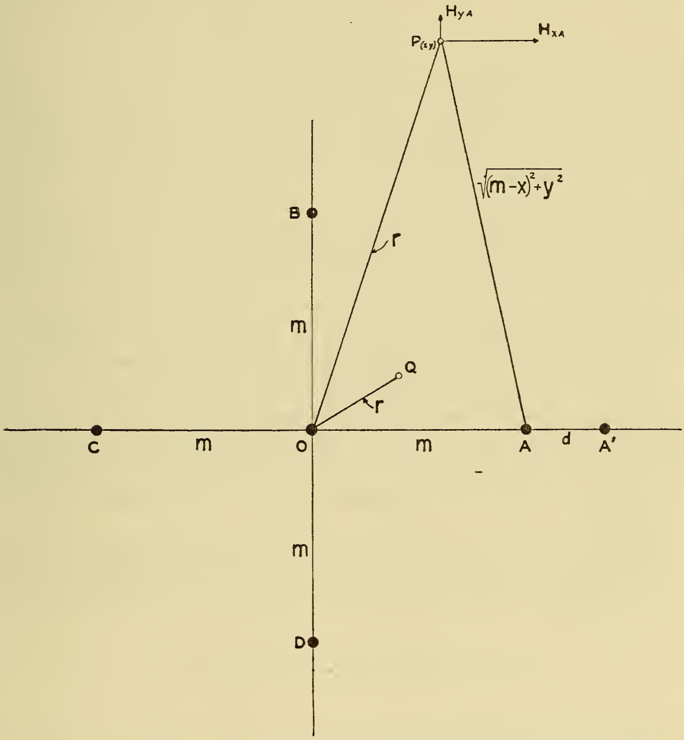

FIGURE 16.—*Diagrammatic cross section of test transformer "cage".*

of the magnetic field produced by such a structure are discussed below:

1. When a current I flows outward from the plane of the paper in conductor O, what is the magnetic field at a point P distant from the central conductor by an amount r, which is much greater than the distance m between each return conductor and O?

From the Biot-Savart equation for the field due to a long straight conductor, $H=2I/r$, we may immediately write down the contributions to the X and Y components of H produced by each of the five conductors. Thus for conductor A carrying a current $I/4$

$$H_{XA}=\frac{+Iy}{2[(x-m)^2+y^2]} \text{ and } H_{YA}=\frac{-I(x-m)}{2[(x-m)^2+y^2]} \tag{1A}$$

Summing up these contributions, including terms of the fourth order in $\frac{m}{r}$, gives

$$H_x = \frac{-2Iym^4}{r^6}\left[3+4\frac{y^2}{r^2}-8\frac{(x^4+y^4)}{r^4}\right] \tag{2A}$$

$$H_y = \frac{2Ixm^4}{r^6}\left[3+4\frac{x^2}{r^2}-8\frac{(x^4+y^4)}{r^4}\right] \tag{3A}$$

and for the resultant field from this total current I

$$H=\sqrt{H_x^2+H_y^2}=\frac{2Im^4}{r^5} \tag{4A}$$

Terms of lower order in m/r vanish completely, and it is interesting to note that the intensity of the resultant field is (to fourth-order terms) independent of the direction in which point P lies with respect to the axes, but varies as the inverse fifth power of the distance from the origin. The direction of the resultant field will be radial at points where $H_x/H_y=x/y$. On inserting the values from equations (2A) and (3A) in this condition, we find that the field is radial for $x=\pm(\sqrt{2}+1)y$ or $x=\pm(\sqrt{2}-1)y$. These conditions correspond to lines making an angle of 22.5° with the coordinate axes through the side conductors. Conversely the field is tangential if $H_x/H_y=-y/x$, which corresponds to cases when the point P lies on the coordinate axes or on lines making an angle of 45° with these axes.

The effectiveness of this arrangement in reducing stray field appears from equation (4A) which indicates that at a distance $r=5$ times m from the axis, the field is only 0.16 percent of that which would be produced by the central conductor alone, the return lead being at a great distance.

For comparison we may consider the field produced if the entire current I returned in conductor A. Combining the contributions from O and A gives to second order terms

$$H_x=\frac{4I_mxy}{r^4} \qquad H_y=\frac{2I_m(y^2-x^2)}{r^4}$$

and the resultant field $H=\frac{2Im}{r^2}$

In this case at $r=5$ times m we have a field 0.2 of that due to the central conductor alone, and hence 125 times as great as that produced by the 4-conductor arrangement.

2. With a total current I flowing in the outer four conductors only (assuming it equally divided among them and returning at an infinite distance) what is the magnetic field at a point Q located so near the origin that r is much less than m? The contributions of the four conductors may be tabulated as before, expanded in terms of r/m, and on summing these contributions, we get to terms of second order in r/m

$$H_x=\frac{2Iy}{m^4}(3x^2-y^2) \tag{5A}$$

$$H_y = \frac{2Ix}{m^4}(x^2 - 3y^2) \tag{6A}$$

The resultant field is then

$$H = \frac{2Ir^3}{m^4} \tag{7A}$$

and is, to this approximation at least, independent of the direction of Q from O. An analysis similar to that of case I shows that the resultant field of the four outer conductors is tangential when Q is on the coordinate axes or on lines at 45° from these, while the field is radial at points half-way between.

The intensity of the field at the center is zero and, at a distance r from the axis, the ratio of the field due to the four outer conductors only to that due to the same current flowing in a central conductor, is r^4/m^4. Since the radius, m, of the cage used is about four times that of the usual current transformer, the field intensity at the point where the core is placed, due to the return bars, is less than 0.4 percent of that of the central conductor. Of course, the line integral of this field around the core is rigorously zero with any configuration of return conductors not passing through the opening in the core.

3. When it is desired that the assemblage of return leads shall produce a magnetic field at the axis equal to that which would be produced by a single return conductor at a given large distance R from the axis, what should be the location A' of one of the bars? Since equal currents in A, B, C, D combine to give zero field at O, the field at O due to equal currents in A', B, C and D will be the same as that due to a current in A' returning in A only. This field is for a current $I/4$

$$H_{A'} = \frac{2I}{4}\left(\frac{1}{m} + \frac{1}{m+d}\right) \tag{8A}$$

The desired field is

$$H_D = \frac{2I}{R} \tag{9A}$$

Hence d can be found by equating these values, which yields

$$\frac{1}{m+d} = \frac{1}{m} + \frac{4}{R} \tag{10A}$$

If A' lies farther from the axis than A as shown, d is positive and R is negative; that is, the equivalent single return is on the opposite side of the axis from A. For the cage used m=50 cm and d can be adjusted from +10 to —30 cm. The effective range of R is therefore from —1,200 through infinity to +133 cm.

If conductors B and D are removed equation (8A) becomes

$$H_{A'} = \frac{2I}{2}\left(\frac{1}{m} + \frac{1}{m+d}\right) \tag{11A}$$

and (10A) becomes

$$\frac{1}{m+d}=\frac{1}{m}+\frac{2}{R}$$

The minimum value of R is thus brought down to 67 cm and by using one conductor A' only, still smaller values can be obtained.

The field at points near but not on the axis is, of course, not exactly the same when the cage is in use as when a real distant single return conductor is present. The difference is, however, not very great and the resulting differences in the performance of a current transformer are probably negligible.

WASHINGTON, May 15, 1933.