THE TESTING OF TRANSFORMERS

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THE general subject of transformer testing extends, with overlapping ranges, from research investigations through factory production testing to occasional, but at times essential, tests after installation. The author has included only such tests as the operating engineer might be called upon to make, and has described how they can be conducted without elaborate equipment. His article thus forms an instructive manual for which there has been great need.

Testing of Transformers

THE rapid growth of power systems has been paralleled, in fact, has been made possible, by the development of power units of increasingly large size and capable of performing under operating conditions that have become more severe and complex. Also, every few years the hitherto maximum voltage usable in commercial practice has been raised to a higher value, and these advances have exerted a similar progressive influence upon the selection of the sub-voltages. These factors in the evolution of the modern power system have brought about marked changes in most of the equipment involved. Of the power units, transformers have had to respond to all the new requirements—greater capacity, higher voltage, strenuous duty, and intricate performance. As the result we have to-day transformers of more than 80,000 kv-a. and others of 220,000 volts, transformers built to withstand not only the exacting demands of the load but also the unavoidable stresses of line short circuits and lightning discharges, and units that are no longer inflexible in ratio while under load.

The design, application, and operation of transformers have thus become of a new order, and in consequence the matter of testing has assumed an increased importance. To assist the user in becoming familiar with the details of up-to-date commercial testing practice, the writer has prepared this article in collaboration with a number of other engineers who are versed in the subject.

Tests

The following are general tests on transformers:

(*a*). Resistance, cold and hot
(*b*). Polarity and Phase Rotation
(*c*). Ratio
(*d*). Core or No-load Loss and Exciting Current
(*e*). Copper or Load Loss, and Impedance Voltage
(*f*). Full-load Heat Run
(*g*). High-potential Test
(*h*). Induced-voltage Test.

Sequence of the Tests

The cold resistance of the windings must obviously be taken before the transformer has been heated by any other test. The polarity and phase rotation, ratio, core loss and exciting current, copper or load loss, and impedance voltage tests should be made next, their sequence being left largely to the man making them. The full-load heat run, high-potential test, and induced-voltage test should be made last and in the order named.

RESISTANCE MEASUREMENTS

The resistance measurements are used for two purposes: for calculating the I^2R loss; and for determining the temperature of the windings at the end of the heat run. Several methods are in use for making these resistance measurements. The direct methods make use of such instruments as the Wheatstone bridge, the Thomson bridge (sometimes called "double bridge"), or their equivalents. The indirect method or "drop of potential method" is the recommended one and should be employed unless the rated current of the transformer winding is less than one ampere, in which case the Wheatstone bridge method may be used.

For the drop of potential method, direct-current ammeters and voltmeters of suitable range are required, simultaneous readings being taken on each. If the potential drop is less than one volt, a potentiometer should be used in place of the voltmeter. From these readings the resistance is calculated by Ohm's law:

$$R=\frac{E}{I}$$

The connections for measuring transformer resistance by this method are shown in Fig. 1, wherein the

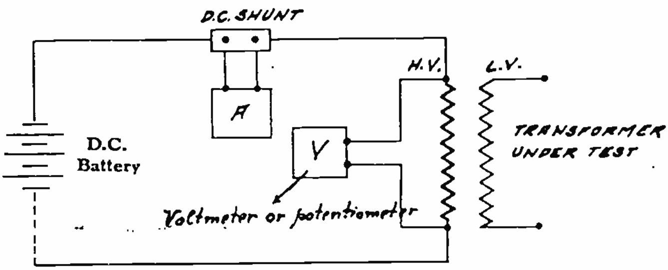


Fig. 1. Drop-of-potential Method of Connections for Making Either Cold or Hot-resistance Measurements of Transformer Windings; Here Applied to the High-voltage Winding

resistance of the high-voltage winding is being determined. The voltmeter leads should be attached to the terminals of the transformer in order to avoid including in the readings the voltage drop in the temporary connections.

Instruments of such capacity should be chosen that the deflections obtained are reasonably large in order to reduce the error of observation. Direct current should of course be employed and should be of sufficient amount to give a good deflection on the ammeter. However, the current should not be more than 15 per cent of the rated current of the winding because a larger value may heat the winding appreciably and thus cause the resistance determinations to be inaccurate.

Particular care should be taken when making the cold resistance test because this combination of temperature and resistance is the basis for the later calculations of temperature rise made at the end of the heat run. The temperature at the time of making the cold resistance measurement may be safely assumed to be the same as that of the transformer oil if this oil temperature has remained constant during several preceding hours while the transformer has remained idle.

POLARITY AND PHASE ROTATION

Polarity and phase rotation are of interest primarily on account of their bearing on the banking and parallel operation of transformers. Consequently if any doubt should exist regarding the correctness of the polarity markings of a power transformer, a check should be made.

In the past, considerable confusion existed because transformers of similar rating when built by different manufacturers did not have like polarity; but a uniform practice in transformer polarity has since been adopted by the N. E. M. A., as follows:

All power and distribution transformers . . . Subtractive polarity
  Except distribution transformers 200
    kv-a. and below with voltage ratings
    7500 volts and below . . . . Additive polarity.

Before proceeding to illustrate the methods used to test polarity, a brief digression into its origin in the transformer may prove useful.

When arranging transformers for parallel operation, attention need be given only to the vector relations of voltage because those of current do not determine either polarity or phase rotation.

In analyzing the voltage relations, the most logical procedure is to consider only the *induced voltages*.

Since the primary and secondary induced voltages are generated by the same flux, they must be in the same direction in each turn regardless of the manner in which the primary and secondary coils are wound.

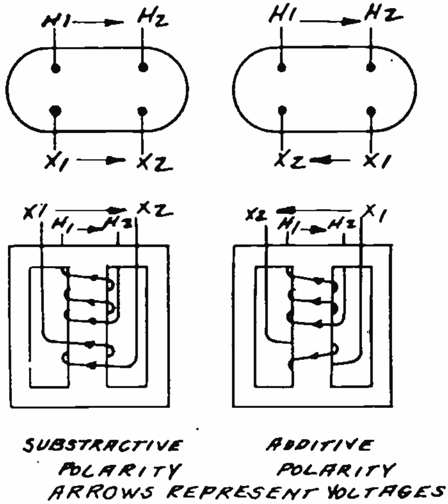


Fig. 2 Fig. 3

Fig. 2 and 3. Tank, Core, and Windings of Two Transformers Unlike Polarity

However, whether they will appear in the same direction as viewed from the terminals depends on the relative directions of the windings. Thus, in Fig. 2, voltages H_1, H_2 and X_1, X_2 are in the same direction; while in Fig. 3, they are in opposite directions.

The relative direction of the induced voltages, as they appear at the terminals of the windings, is dependent on the order in which these terminals are taken. It is necessary, therefore, that the designation "polarity," in order to have any certain meaning, be referred to a perfectly definite order in which the terminals shall be considered. By common usage, polarity refers to the voltage vector relations of the transformer leads as brought outside the case with both high-voltage and low-voltage leads being taken in the same order (from left to right or right to left) facing the same side of the transformer in both cases.

Thus referring to the sketch in Fig. 2, polarity is the relative direction of induced voltages from H_1 to H_2 as compared with that from X_1 to X_2, both being viewed in the same order (from left to right, facing the low-voltage side).

Additive and Subtractive Polarity

When the induced voltages of the high-voltage and low-voltage sides are in opposite directions, as in the sketch in Fig. 3, the polarity is said to be *additive;* and when the induced voltages are in the same direction, as in Fig. 2, the polarity is said to be *subtractive.* The reason for this nomenclature will be evident from the following: Referring to the tank sketch in Fig. 2, if a high-voltage lead be connected to the adjacent low-voltage lead, for instance H_2 to X_2, and the transformer be excited from either side, the voltage across the remaining leads H_1 to X_1 will be the difference of the voltages of the two sides. Following the voltage from X_1 through X_2 to H_2 and then to H_1 it is evident that the voltage H_2 to H_1 will oppose the voltage X_1 to X_2. Hence, the polarity is subtractive.

Referring now to the tank sketch in Fig. 3, which shows the primary and secondary induced voltages to be in opposite directions, if an H lead be connected to the adjacent X lead, for instance H_1 to X_2, and the transformer be excited, the voltage across the other leads, H_2 to X_1 will be the sum of the primary and secondary voltages, as can be deduced from the explanation given in the previous paragraph. Hence, the polarity in this latter case is additive.

In Fig. 4 are shown the standard markings for the leads of single-phase transformers of additive polarity and also those of subtractive polarity.

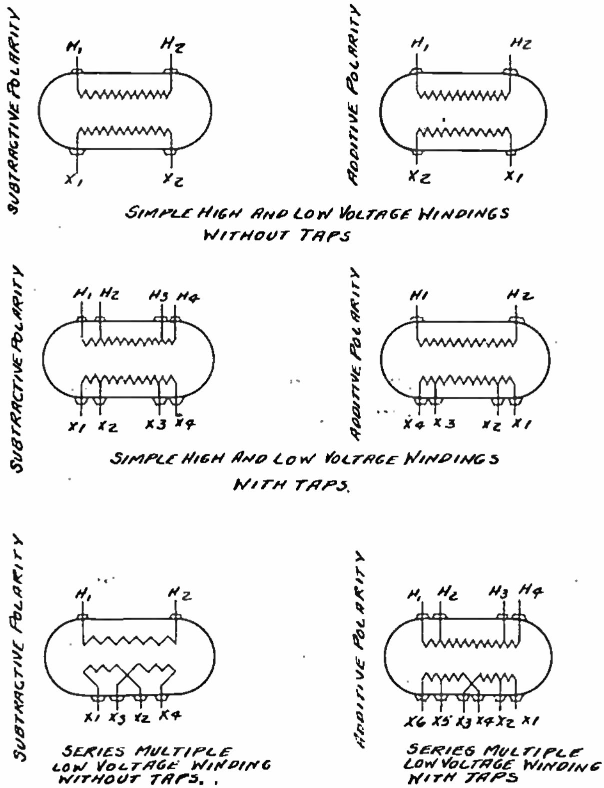


Fig. 4. Standard Polarity Markings for the Leads of Single-phase Transformers

Testing of Polarity

The three following methods are commonly employed for testing the polarity of transformers, and the method which is most convenient for a particular case should be chosen.

(1). When a standard transformer of the same rated ratio as the one under test is available, the polarity and ratio tests may be combined.

The high-voltage winding of the transformer under test should be connected directly in multiple with the high-voltage winding of the standard transformer, and the low-voltage winding of the transformer under test should be connected in series opposition with the low-voltage winding of the standard transformer through a voltmeter to indicate any difference in voltage. With these connections, the high-voltage winding should be excited at reduced voltage, and if there is no difference in voltage indicated by the voltmeter the polarity and ratio of the two transformers are identical.

If a small difference of voltage is indicated by the voltmeter, the polarity is correct but the ratio is not. If the difference in voltage is greater than that across the low-voltage winding of one of these transformers, the polarity is reversed.

(2). The polarity may be determined at the same time as the resistance by making use of direct current as follows:

With direct current passing through one winding, usually the high-voltage, connect a high-voltage voltmeter across the terminals of this excited winding so as to obtain a small positive deflection. Then transfer the two voltmeter leads directly across the transformer, *i.e.*, the lead from the right-hand high-voltage terminal being placed on the right-hand low-voltage terminal (facing the high-voltage side), and the lead from the left-hand high-voltage being placed on the left-hand low-voltage terminal. The direct-current excitation is then broken and the inductive kick in the voltmeter observed. If the needle swings in the *same* direction as before, the polarity is *additive*, otherwise it is subtractive.

(3). If neither a standard transformer nor a source of direct current is available, the polarity may be determined as follows:

With the primary and secondary in series, one primary lead being connected to the adjacent secondary lead (such as H_2 and X_2 in Fig. 2), the transformer is excited from an alternating-current source on either side and the voltages across the high-voltage winding and also that between the free primary and secondary

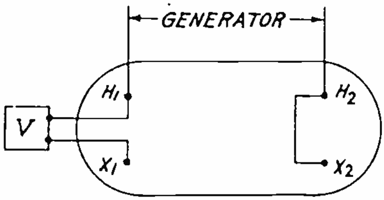


Fig. 5. Polarity-checking Connections for a Transformer the Primary and Secondary Voltages of which Are Greatly Different

terminals are measured. If the latter voltage is found to be *less* than that across the high-voltage winding, the polarity is *subtractive;* if more, the polarity is additive.

The polarity test may be satisfactorily made in this manner if the ratio of primary to secondary voltages is low: *e.g.*, with a transformer rated 110,000/66,000 volts. Thus, referring to Fig. 5, with the application of low alternating voltage, say 110 volts across H_1 and H_2, the difference between $110-66$ and $110+66$ volts will be easily discernible on the scale of a 150-volt meter. If, however, the transformer were rated at say 110,000/110 volts, such as a standard potential transformer, it is obvious that with the same connections and applications of 110 volts to the H_1 and H_2 terminals the difference of $110-0.1$ and $110+0.1$ will not be so readily apparent on the scale of a meter. Under these conditions, the polarity should be checked by the direct-current method already described.

Three-phase Transformers

In single-phase transformers, the primary and secondary voltages are either in phase or in opposition; and this is completely specified by the polarity or the lettering of the leads.

In polyphase units, however, these vector relations are more complicated and are represented by voltage diagrams because the mere lettering of the leads does not indicate the relations completely. Furthermore, polarity alone is inadequate to represent the vector relations in polyphase connections as the angular phase relation between the high and low-voltage windings is also involved. The phase relation is called "Angular Displacement" and is defined in the A. I. E. E. Standardization Rules as the angle between the lines H_1—N and X_1—N (N being the neutral point of the diagram). The location of the H_1 lead for single-phase units is defined as being on the right-hand side when the observer is facing the high-voltage side. The location of the X_1 lead is fixed so as to make the diagram fall under one of the standardized groups (Figs. 8 and 9) to be described later. Under these conditions, the angular displacement in Fig. 6(b) is zero and that in Fig. 7(b) is 180 deg.

To Obtain Voltage Diagrams by Test

If desired, the voltage diagrams can be determined by the following method which neglects the polarity and phase-rotation tests. Connect one of the high-voltage leads to one of the low-voltage leads, excite the transformer at a voltage that is safe for the low-voltage circuit, measure the voltages between all the other high and low-voltage leads, and plot them to scale. For instance, referring to Fig 6(a), if H_3 be connected to X_3 and the voltages between each pair of terminals measured, a diagram like that in Fig. 6 (c) would be obtained; or referring to Fig. 7 (a) a connection from H_3 to X_3 would result in a diagram like that in Fig. 7 (c).

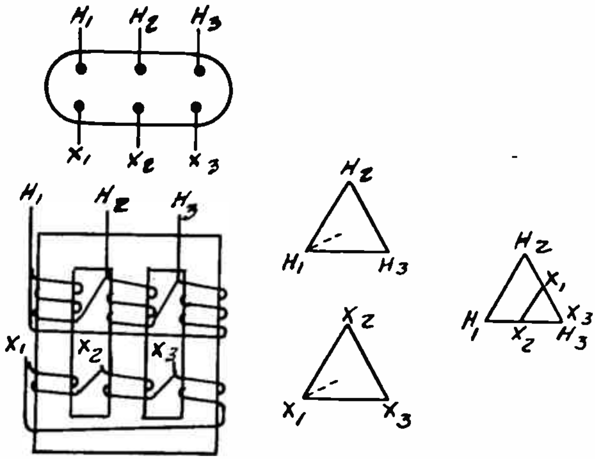


Fig. 6(a) Fig. 6(b) Fig. 6(c)

Fig. 6. Three-phase Transformer, Angular-displacement Diagram (Displacement Zero), and Voltage-vector Diagram

If this test were applied to Y-Y-connected units of the same polarity the same diagrams as in Fig. 6(c) and 7(c) would be obtained. Thus, such a test will not determine whether the internal connection is delta-delta or Y-Y. However so far as parallel operation is concerned, the distinction is unnecessary. The test will indicate the "angular displacement" between the high and low-voltage circuits but cannot distinguish between connections that belong to the same group, *i.e.*, between the connections of windings that can be paralleled with each other.

It will be evident that obtaining voltage diagrams by such measurements becomes difficult when the voltage rating of one side is very small compared to that of the other.

If the voltage diagrams of transformers which are to operate in parallel are available, it is then only

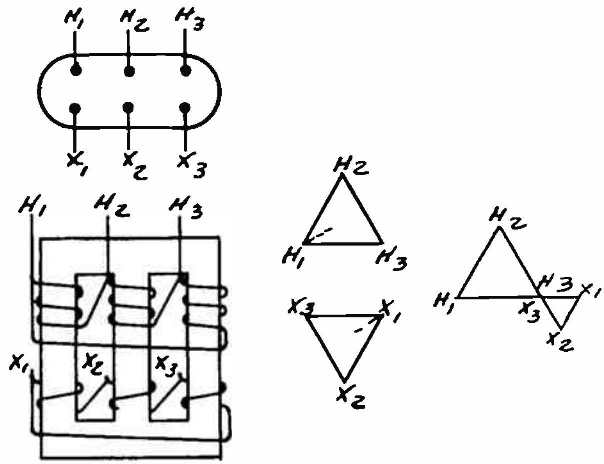


Fig. 7(a) Fig. 7(b) Fig. 7(c)

Fig. 7. Three-phase Transformer, Angular-displacement Diagram (Displacement 180 Deg.), and Voltage-vector Diagram

necessary that these diagrams coincide and the corresponding terminals can be connected together.

It is entirely unnecessary then to question the polarity and phase rotation, because when the voltage diagrams coincide the leads which are to be connected together will have the same potential, this being the basic requirement for parallel operation whereas tests of polarity, phase rotation, etc., merely furnish the means to arrive at this condition. When voltage diagrams coincide, polarities and phase rotations must necessarily agree, although the converse is not necessarily true.

Phase Rotation

In addition to the polarity tests, it is necessary to check the phase-rotation of three-phase and six-phase transformers.

The phase-rotation meter (a small three-phase induction motor may be used) should be connected to the *high-voltage* side of the transformer, and a relatively low voltage applied to the high-voltage side. This voltage should be only sufficient to cause the meter to rotate, and the direction of rotation should be noted. Then the leads from the meter should be transferred straight across the transformer to the low-voltage terminals. The transformer again should be excited from the high-voltage side with voltage sufficient to cause the meter to rotate, and the direction of rotation noted. The phase rotation of the transformer is standard if the meter revolves in the same direction as before. In three-phase transformers which have been marked according to the A.I.E.E. rules, phase rotation is the same in the sequence X_1 X_2 X_3 as in H_1 H_2 H_3, and therefore a check may be made by transferring the leads of the phase-rotation meter from H_1 to X_1, from H_2 to X_2, and from H_3 to X_3.

In three-phase six-phase transformers which do not have a permanent neutral, the coils should be connected in a three-phase connection, and phase rotation taken as described for three-phase transformers. If the neutral connection is permanently made, the phase rotation should be taken by shifting the lines from H_1 H_2 H_3 to X_1 $X_3 X_5$ respectively, then to $X_2 X_4 X_6$ respectively. The rotation should be the same in each case.

Three-phase Transformer Groups

Three-phase transformers utilizing the common connections may be divided into three groups based on their angular displacements, as shown in Fig. 8.

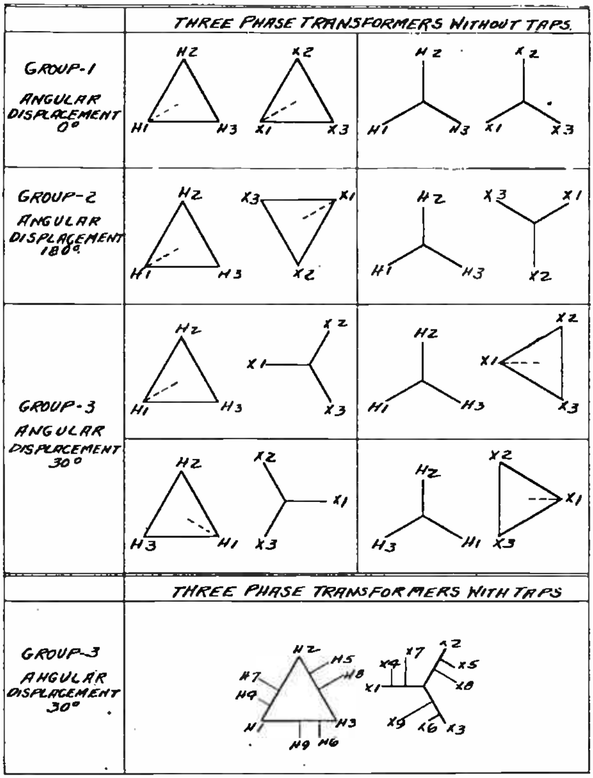


Fig. 8. Group Classification of the Polarity, or Lead Markings, and the Voltage-vector Diagrams for the Usual Three-phase Transformer Connections

Four of the normal three-phase to six-phase diagrams are shown as Groups 4 and 5 in Fig. 9.

To operate in parallel, transformers must belong to the same group. No interchange of external leads can change one group into another. Thus, two delta-delta transformers, one of Group 1 and the other of Group 2, cannot be operated in parallel. If the high-voltage diagrams be superposed, the low-voltage diagrams will not coincide. All Y-delta or delta-Y transformers, however, can be reduced to the same

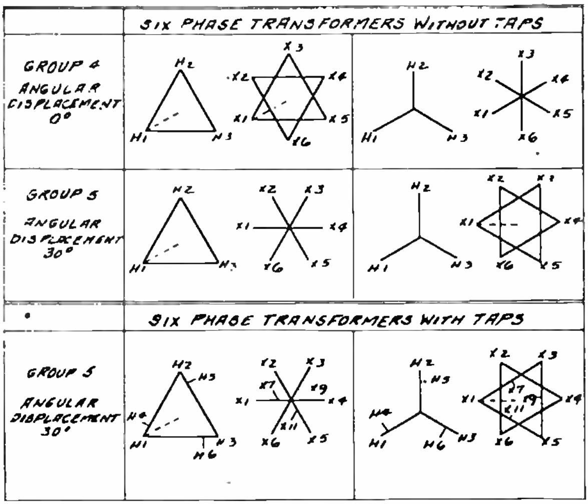


Fig. 9. Group Classification of the Polarity, or Lead Markings, and the Voltage-vector Diagrams for the Usual Six-phase Transformer Connections

diagrams, and therefore they are classed in only one group.

RATIO

The ratio of a transformer is the numerical relation between the no-load primary and secondary voltages.

In large power transformers, on account of their comparatively small number of turns, this test does not offer any special difficulties. Great care, however, must be used in order to obtain the correct ratio of small high-voltage transformers.

During the ratio test the transformer should be operated at normal frequency or higher, and at normal voltage or lower. An abnormally low frequency or high voltage would tend to make the core density and exciting current abnormally large. Such a high voltage would also place an unnecessary strain on the insulation. Transformers having capacities of 500 watts or less and having an exciting current of more than 10 per cent should be tested only at normal voltage and frequency. For other transformers, as low as 10 per cent of the rated voltage may be used, but, on account of the fact that at the lower densities the exciting current does not diminish as fast as the voltage, there will be tendency for a little ratio error to creep in by the leakage impedance drop caused by the exciting current.

Test Methods

The common methods of measuring voltage ratio are:

(1). Voltmeter Method

(2). Standard Transformer Method

(3). Resistance Balance Method.

(1). Ratio by Voltmeter Method

This method is the one usually employed for power transformers. In using it, approximately rated frequency should be applied. Two voltmeters are used (with potential transformers if necessary), one to read the voltage of the high-voltage winding and the other to read the voltage of the low-voltage winding.

Holding say, 90, 100 and 110 per cent voltage successively on the voltmeter that is connected to the winding to which potential is applied, simultaneous readings should be taken of the voltage induced in the other winding. Then the meters should be interchanged and the readings repeated, holding the same voltages on the same winding as before.

The ratio of the average of the six high-voltage readings to the average of the six low-voltage readings should check the nameplate ratio within one per cent. If the error is more than one per cent, the ratio should be rechecked with different meters.

It is essential that such potential transformer ratios be chosen as will render the readings of the two meters approximately the same, otherwise the meter errors will not compensate and it will be necessary to apply meter corrections.

If the transformer has ratio adjusters, ratio measurements should be taken (as previously explained) on the full-winding position. On each of the other positions of the adjusters, two sets of readings should be taken—one set with the meters interchanged.

If the transformer does not have ratio adjusters but has taps brought to a terminal board, the same method should be used to determine each tap ratio.

For three-phase transformers the ratio test should be applied to all three phases as explained for single-phase transformers, with the exception that the six readings called for on the full winding of single-phase transformers need be taken on only one phase of the transformer. On the other phases, one set of readings, and another with the meters interchanged, are all that are required.

When each phase of a transformer is independent and accessible, single-phase power may be used, but it is preferable to employ three-phase power. In all other cases, three-phase power must be used.

Transformers that have Y-diametric connections but do not have the neutral of the Y brought out are tested for ratio with three-phase power. Any inequality in the magnetizing characteristics of the three phases will then result in a distortion of the neutral thereby causing unequal phase voltage. When such inequality is found, the diametric connection should be changed to a Y connection and the phase voltages measured. If these are found to be equal and of proper value (1.73 times the diametric voltages) the ratio is correct.

(2). *Ratio by the Standard Transformer Method*

When measuring the ratio of distribution transformers by voltmeters in the ordinary way, it is neces-

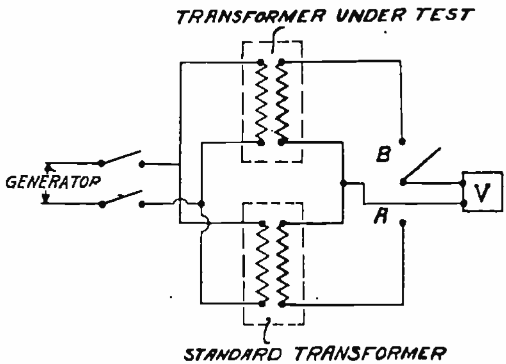


Fig. 10. Connections for Determining the Ratio of a Transformer by Comparison with a Transformer of Known Ratio

sary to apply practically normal voltage to obtain accurate results. If only a small percentage of normal voltage be used, the drop due to the load of the measuring instrument may introduce an appreciable error.

The most satisfactory way of measuring the ratio of such a transformer is by paralleling it with another transformer which is of known ratio and which has been specially designed with a large number of taps covering a wide range with very small steps. This latter transformer is used as the standard of comparison.

The test connections are shown in Fig. 10. The primaries being connected in multiple, the secondary voltage across the standard transformer and that across the transformer under test may be read, in turn, by throwing the voltmeter switch down to *A* and then up to *B*. The reading of the voltmeter with the switch at *A*, multiplied by the ratio of the standard transformer, is the impressed voltage on the primary of the transformer under test. From this value, and the reading of the voltmeter with the switch at *B*, the ratio of the transformer under test can be readily determined.

CORE, OR NO-LOAD, LOSS AND EXCITING CURRENT

When a transformer is connected to a source of alternating current, a loss of energy due to the cyclic reversals of the magnetic flux takes place in the iron. This loss of energy is known as the "core loss," and—together with the magnetic induction in the core—is supplied to the transformer by the exciting current.

The correct measurement of this loss is essential, as the loss is in most cases constant or continuous and therefore has a material bearing on the operating costs.

The core loss is a function of the frequency, the voltage, and the voltage wave form.

The frequency and voltage are easily determined with the aid of ordinary instruments; but unless the wave form of the applied voltage is a sine wave, the results will be greater or less than the sine-wave value, which is standard for the correct value. A peaked wave (form-factor greater than 1.11) gives lower losses, while a flat wave gives higher losses than would a sine-wave voltage.

In general, voltage waves are peaked due to the nature of the load on the generator, as explained later, and the measured loss will be less than that corresponding to the sine-wave voltage. Measured losses as much as 20 per cent below the correct values have often been observed.

The most serious discrepancy is that caused by the distorted wave shape of the exciting current. The generator e.m.f. is made up of two parts, one of which is balanced by the e.m.f. induced by the changing flux, while the other produces the exciting current for the transformer. If the flux be sinusoidal, the e.m.f. induced by it is also sinusoidal. But since the permeability of the material varies with the magnetic induction, the magnetizing current cannot be sinusoidal. The component of the e.m.f. producing current has the same wave form as the current, and it, therefore, cannot be sinusoidal. The total e.m.f. of the generator, then, is made up of one component which is sinusoidal and one which is not. Hence it is not sinusoidal. Its shape must vary with conditions and thus it would be useless to attempt to secure a sine-wave voltage in the generator e.m.f. It is evident that the distortion will be less if the iron be magnetized in the region of maximum permeability and the distortion is sure to become appreciable if the flux density is carried too high.

Obviously, therefore, it is impracticable to obtain sine-wave voltage for the commercial no-load tests of transformers, especially for very large transformers, and consequently suitable methods should be used for the reduction of the tests to a sine-wave basis.

Since wave-shape distortion increases with the degree of loading of the generator, the principle has been recognized that the transformer exciting kilo-volt-amperes should be a small fraction of the capacity of the generator used to furnish the excitation; in other words, the generator rating should be of the same order of magnitude as that of the transformer under test.

The general principle of using sufficiently large generators, though good, is impracticable for large units. For example, to test a 20,000-kv-a. transformer would require a 20,000-kv-a. generator; to test a 60,000-kv-a. transformer would require a 60,000-kv-a. generator, and so on.

Reduction of Core Loss to Sine-wave Basis

For the reduction of core loss to a sine-wave basis the following method may be used:[(1)]

A small "standard" transformer the core loss of which has been calibrated on pure sine-wave voltage, is usually excited through potential transformers in parallel with the power transformer under test. The voltage is set by a conventional-type (r.m.s.) voltmeter and the actual losses in both the power transformer and the standard transformer are observed. The factor which would convert the observed core loss of the standard unit into its sine-wave value (known from its calibration curves) is used to convert the observed loss of the power transformer to the sine-wave basis.

To secure accuracy by this method it is necessary:

(*a*). That the standard cores have the same kind of steel-sheets as the transformer core, and be excited at approximately the same flux density.

(*b*). That the potential transformers be of sufficiently large capacity and low impedance to avoid introducing distortion due to the exciting current of the standard core.

Reduction of Exciting Current to Sine-wave Basis

The exciting current may be corrected for wave shape by carrying the core-loss test a little further.

(1) For an alternate method, see "A Flux Voltmeter for Magnetic Testing" by G. Camilli, *Trans. A.I.E.E.*, Oct., 1926, and GENERAL ELECTRIC REVIEW, July, 1926.

After the core-loss correction has been determined, the voltage should be raised until the measured loss is equal to the correct loss. The exciting current read at this voltage is approximately the true sine-wave value. (2)

Connections

On distribution transformers having series-multiple windings, the series connection should be used during the test. If the transformer has taps on the excitation side, care should be taken to include the full winding.

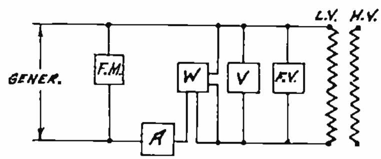


Fig. 11. Core-loss and Exciting-current Testing Connections for Single-phase Transformers. Instruments connected directly in the main circuits

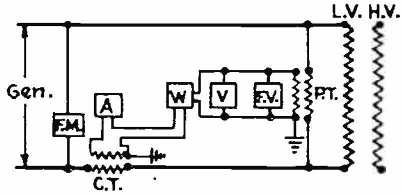
In connecting the instruments, the voltmeter should be connected nearest the load, the ammeter nearest the supply, and the wattmeter between the two with its potential coil on the load side of the current coil, as shown in Fig. 11 and 12.

The watts and volts should be read simultaneously. Theoretically, the amperes should be read with the potential circuit of the voltmeter and wattmeter open, but ordinarily the difference is not appreciable. The load should then be disconnected and the "tare," *i.e.*, the I^2R losses of the two pressure coils, read on the wattmeter. These losses should be subtracted from the previous wattmeter readings in order to obtain the true no-load loss of the transformer.

(2) For an alternate method, see "Reduction of Transformer Exciting Current to Sine-wave Basis," by G. Camilli, *Jour. A.I.E.E.*, Sept., 1927.

Use of Current and Potential Transformers

In case the current and voltage of the circuit are beyond the direct range of the instruments, current and potential transformers may be employed as shown in Fig. 12. Instead of potential transformers, multipliers may be used in series with the potential coil of the wattmeter. Power transformers are not suitable for making measurements because they introduce an erroneous tare as potential transformers and large ratio and phase-angle errors as current transformers.



V: Voltmeter
A: Ammeter
W: Wattmeter
P.T.: Potential transformer
C.T.: Current transformer
F.V.: Flux voltmeter
F.M.: Frequency meter

Fig. 12. Connections Similar to Those Shown in Fig. 11. Except for the Inclusion of Instrument Transformers

Core Loss of Three-phase Transformers

In measuring the core loss of three-phase transformers, it is advisable to take three entirely separate sets of readings by the two-wattmeter method, using each of the three lines in succession as the common. The average value of the three sets of readings should be recorded as the true no-load loss. In using the two-wattmeter method, great care should be exercised in reading the wattmeters because the load power-factor is usually very low (always less than 50 per cent) and therefore the two readings one of which is to be subtracted from the other may be nearly equal. This fact may lead to large errors in the net results (the difference between the two readings). Greater accuracy may sometimes be obtained by making the measurements from each line to the three-phase neutral and adding them together. This neutral may be either actual or artificial, as in Fig. 13 and 14.

Use of Low-power-factor Wattmeters

Losses in transformers should be measured preferably by low-power-factor wattmeters. The desirability of employing this type of instrument arises from the fact that power-factors of the order of 5 per cent are not unusual in core-loss tests, and power-factors as low as 2 per cent may be met in load-loss measurements. Under these conditions ordinary wattmeters would give very small deflections.

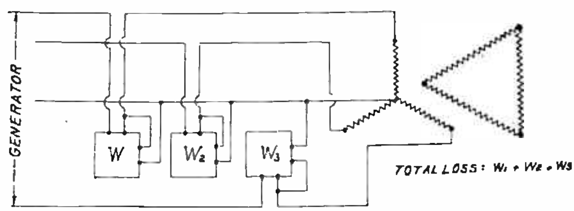


Fig. 13. Three-wattmeter Method of Connections for Determining the Core-loss of a Three-phase Transformer Having an Actual Neutral Available

Frequency Measurements

The frequency has such a great influence on the losses at low power-factors that correct measurement of frequency is essential. Good frequency-meters are available in the market. In the absence of one, a good tachometer recently calibrated may be used on the testing generator.

Core Loss Correction for Temperature

Any increase in the core temperature reduces the eddy-current loss: this loss is a true I^2R loss in the core-sheets and is subject to the same laws as govern I^2R losses in conductors. Since the flux in the core and therefore the induced voltage are constant, the eddy-current loss decreases with increasing resistance due to increasing temperature.

The temperature coefficient of the resistivity of silicon steel is about 0.001. In other words, the eddy-current loss may be reduced one-tenth of one per cent

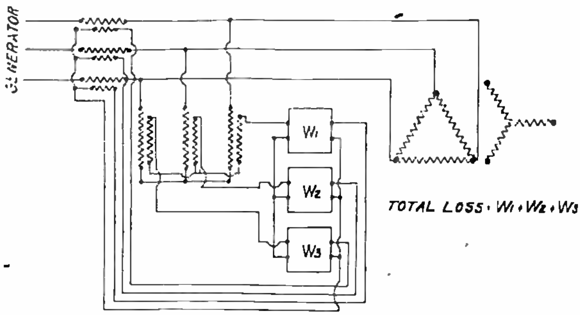


Fig. 14. Connections Similar to Those in Fig. 13, Except for the Introduction of Instrument Transformers to Create an Artificial Neutral Where an Actual Neutral is Lacking

for every degree increase of temperature. But the eddy-current loss constitutes only about one-fifth to one-third of the total core loss so that the correction on the total loss will be about one per cent for every 30 to 50 deg. rise in temperature.

Theoretically, the reduction in eddy currents will lower the exciting current also, but the percentage reduction in the exciting current will be far less than that in the watt loss because this loss has only two components, *viz.*, hysteresis and eddy-current components, while the exciting current has three components, *viz.*, the magnetizing current, the hysteresis component, and the eddy current—the magnetizing current predominating. The eddy-current component is about one-fifth of the hysteresis component and the hysteresis current is between one-fifth and one-tenth of the magnetizing current. Furthermore, the hysteresis and the eddy-current components are in quadrature with the magnetizing current. As a consequence, 10 per cent or even 15 per cent change in the eddy-current component will not be noticeable in the total exciting current. For this reason no temperature correction need be applied to the exciting current.

COPPER, OR LOAD, LOSS AND IMPEDANCE VOLTAGE

The load loss of a transformer is the loss occasioned by the current drawn from the transformer while under load and includes a number of items:

(1). The I^2R loss.

(2). The eddy-current losses in the conductors caused by the leakage flux in the conductors.

(3). The hysteresis and eddy-current losses in the tank, clamps, and core of the transformer, caused by the leakage flux cutting them. These losses are usually grouped under the term "stray losses."

The impedance voltage drop of a transformer should also be carefully measured for the following reasons:

(1). Transformers operating in parallel divide the load inversely as their impedance voltages, *i.e.*, the one having the higher impedance will take the smaller share of the load and vice versa. When transformers of different types are operating in parallel, the impedance of one transformer must sometimes be increased by introducing a reactor into the circuit. Therefore it is necessary to know the amount of the impedance voltage.

(2). The efficiency of a transformer is based on tested impedance watts, not on the calculated I^2R loss, and therefore it is essential that the impedance watts be measured.

The impedance ohms of a transformer may be considered as constant at all loads. The value is generally determined at full-load current, and the impressed voltage is then known as the "impedance volts," or when expressed in per cent of the normal rated voltage of the transformer it is termed the "per cent impedance drop."

Test

The copper, or load, loss and impedance-voltage tests are made simultaneously. The total copper, or impedance, loss of a transformer is determined by short circuiting either the primary or the secondary winding, and exciting the other winding at such a voltage as will cause a circulation of full-load current in the transformer. The voltage that is necessary to circulate this current is the impedance voltage of the transformer.

The current should preferably be measured in the excited winding; this applies also to the current for the wattmeter. However, no appreciable difference will be found between the percentage values of the two currents in the excited and short-circuited windings because the voltage across the excited winding is very small and the exciting current varies faster than the square of the voltage. With transformers having as high as 10 per cent magnetizing current at normal voltage, 10 per cent impedance volts would call for an exciting current much less than one per cent, which would therefore be negligible.

Although measuring the current in the exciting winding introduces a slight theoretical error due to the exciting current, measuring the current in the short-circuited winding would also involve a small error by introducing into the short circuit the impedance of the current transformer and meters. For this reason it is common practice to make the short-circuit complete and to observe the current in the excited winding.

The test is applied in the following manner:

(1). Determine the approximate impedance voltage and current of the winding to be excited.

(2). Short-circuit the other winding of the transformer.

(3). Connect the instruments as shown in Fig. 15. Connect the transformer leads to the source of power through a circuit breaker.

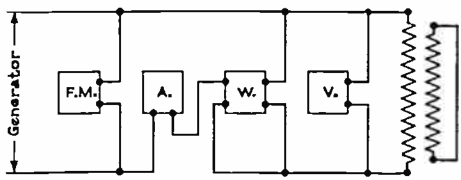


Fig. 15. Copper-loss (Load or Impedance-loss) and Impedance-voltage Testing Connections for a Single-phase Transformer. Instruments connected directly in the main circuits

(4). Adjust the voltage to give full-load current in the transformer, then make simultaneous readings of the voltmeter, ammeter, wattmeter, and frequency meter. Take several successive readings of the instruments to minimize errors.

The frequency should be checked by the frequency meter. In addition to the full-load current readings of volts, amperes, and watts, readings should be made of the temperature and the tare, and if instrument transformers are used their ratios should be recorded.

The tare reading is a measurement of the losses in the meters and instrument transformers themselves. This reading should therefore be taken with the same circuit connections as those employed for making the power readings, with the exception that the main lines are disconnected from the transformer under test when taking the tare reading. Also, the voltage and frequency should be the same as held when taking the power readings. An effort should be made to read to tenths of a scale division.

Load-loss Temperature Correction

The load-loss as obtained by test may be corrected to the specified temperature (75 deg. C.) by dividing it into its I^2R and stray-loss components, as the ohmic loss increases with the temperature while the stray loss decreases with increasing temperature.

The correction for the I^2R loss is then:

$$\frac{I^2R \text{ loss at temperature } T}{I^2R \text{ loss at temperature } T_o} = \frac{234.5+T}{234.5+T_o} \qquad (1)$$

And the correction for the stray loss is:

$$\frac{\text{Stray loss at temperature } T}{\text{Stray loss at temperature } T_o} = \frac{234.5+T_o}{234.5+T} \qquad (2)$$

where

T = temperature to which the losses are to be corrected

and

T_o = temperature at which the losses are measured.

Equation (2) is correct if all the stray losses are in the conductors but not if a considerable proportion of these losses is in the iron, because the temperature coefficient of resistivity of iron is not the same as that of copper Under the latter circumstances, the temperature correction for the stray losses will be greater than that given by Equation (2).

DETERMINATION OF TRANSFORMER LOSSES BY CALORIMETRIC METHOD

In some cases, it is desirable to measure losses approximately, or to check those obtained by the wattmeter method. For water-cooled transformers, a calorimetric method may be used, in which the heat carried away by the cooling water is measured and converted into watts loss. The procedure is the same as that for a heat run on any water-cooled transformer. However, in order that the heat carried away by the cooling water may represent as accurately as possible the total heat dissipated in the transformer, it is desirable to blanket the tank and cover heavily with paper or other suitable material.

The amount of water flowing through the cooling coils must be kept constant, and at such a value (measured accurately) that the difference in temperature between the ingoing and outgoing water is about 10 degrees C. Twenty degrees C. rise, however, is permissible for measurements with excitation only, or for very light loads in order that the error in water temperature readings will be a small percentage of the total rise. The excitation or load conditions should remain constant until the thermal conditions are constant, that is, until the top oil temperature and the temperature rise of the cooling water do not change over a period of two hours. The voltage connections of the transformer should be noted and the readings of voltage, current, air temperature, as well as thermal data, should be taken hourly and recorded.

The average gallon-degrees (gallons of water per minute times the temperature rise of the cooling water in degrees centigrade) multiplied by 264 watts (equivalent in watts of one gallon-degree) will give the losses dissipated by the cooling water, which are approximately the total losses of the transformer.

Segregation of Losses

When it is desired to obtain the segregated losses without removing the transformer from the line, a time should be chosen such that the load will remain constant, or nearly so, or fluctuate about some value which may be taken as average over a period of three or four hours. Since the core loss may be assumed constant, for reasonably constant voltage conditions, it will be necessary to take readings at only two different loads, in order to segregate the core loss and obtain two equations from which to calculate the total losses for any load.

Equation 1 (Load condition 1)

Core loss + $(a)^2$x Impedance losses at full load = L_1

Equation II (Load condition 2)

Core loss + $(b)^2$x Impedance losses at full load = L_2

where

a = fraction of full-load current for load 1

b = fraction of full-load current for load 2

L_1 and L_2 = losses as determined from water rise

Subtracting equation II from equation I:

$$\text{Impedance losses at full load} + \frac{L_1 - L_2}{(a)^2 - (b)^2}$$

The core loss and losses at other loads may be found directly by substitution.

When it is desired to obtain the segregated losses of a water-cooled transformer which is disconnected from the line, voltage or current should be applied in a manner to give the losses required, that is, open circuit for core loss, short circuit for impedance loss, or opposition method for total losses. (See HEAT RUNS.)

HEAT RUNS

As in most electrical machines, the safe operation of a transformer depends essentially on the maximum temperature to which it is heated when under load.

Temperature is of even more concern in a transformer than in other kinds of electrical machinery on account of its higher voltage of operation. An insulation which can withstand a considerable over-potential at ordinary temperature may break down when at a high temperature.

A transformer heats up in operation because of the losses in its core and windings. The core loss depends on the flux in the iron, or what is the same thing (for a given frequency) on the applied voltage, and is practically independent of the load. The copper loss is directly proportional to the square of the current flowing through the windings. Therefore, in order to determine the temperature rise in a transformer, the unit must be subjected to its full rated voltage and full-load current simultaneously. Various methods of loading are used, of which the most common are:

(a). Dead Load

Small-capacity transformers may be tested under actual load conditions by loading on a lamp bank, water box, rheostat, etc. This method is expensive when a large amount of power is required.

(b). Loading Back

When two similar transformers are available, one transformer can be loaded on the other and the second connected back to the source of supply. By this method the only power required is that necessary to supply the losses in both transformers.

This so-called "loading back," or more appropriately designated "stray power" or "opposition," method is the one used in testing not only transformers but generators and motors. The method may be used with any size of transformers.

The connections for an opposition heat test on two transformers are shown in Fig. 16 in which either *A* or B or both are the transformers under test. Their low-tension windings are connected in parallel to the power supply and their high-tension windings are connected in opposition to each other. If the transformers are identical, the excitation from this power source causes no current flow through the high-tension windings.

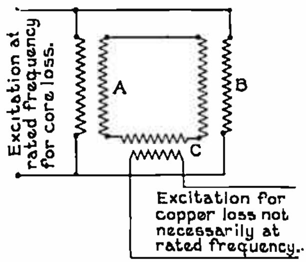


Fig. 16. Full-load Heat-run Connections for the Opposition Method of Testing Two Single-phase Transformers (*A* and *B*). The core loss of both transformers is supplied from one source, and the copper loss from another

If now a full-load current should be made to circulate in the windings, the transformers will be under heating conditions that are identical to those of full load. As this circulating current gives rise to copper loss only, the current need not be absolutely of the rated frequency of the transformer. Even a direct current (in both windings) may be used for the purpose, provided the eddy-current and stray losses of the transformer are not appreciable. However, on account of the fact that practically all power transformers have appreciable eddy-current and stray losses, it is desirable to hold the load current at approximately rated frequency when making heat runs. A convenient method is to open one of the circuits, and to introduce there a comparatively low-voltage source of alternating current of about the rated frequency.

This auxiliary source is shown in Fig. 16 in the form of a transformer *C*.

By adjusting the voltage of this source, full-load current can be made to flow in the primaries of the transformers under test; this current induces full-load current in the secondaries which therefore need not be opened for separate loading. This method is

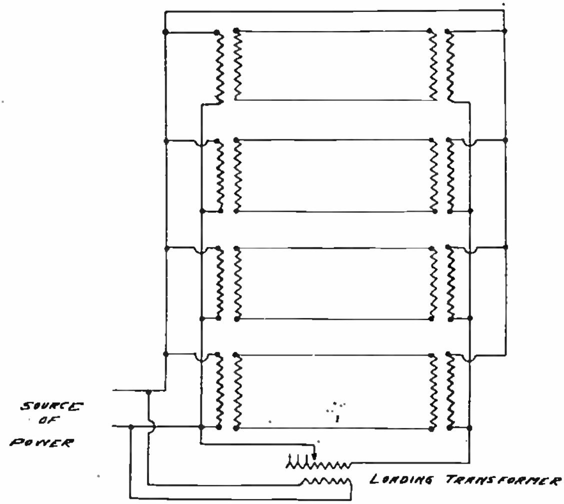


Fig. 17. Full-load Heat-run Connections for an Even Number of Small Similar Transformers Arranged in Two Opposing Groups; Here, Four Against Four

particularly convenient to apply to transformers that are wound for comparatively high voltage.

In this test the transformers are under actual load conditions as far as the losses and heating are concerned and, at the same time, the testing operation draws from the source of supply only that amount of energy which is sufficient to overcome the losses.

A transformer should always be interposed between the supply alternator and the transformers under test in order to avoid high potential on the switchboard and to prevent the possible breaking down of the insulation of the alternator.

Where a large number of small similar transformers are to be loaded at the same time, their primary windings may be connected in parallel and their secondaries may also be connected in parallel, or (as in Fig. 17) the secondary of one transformer in a

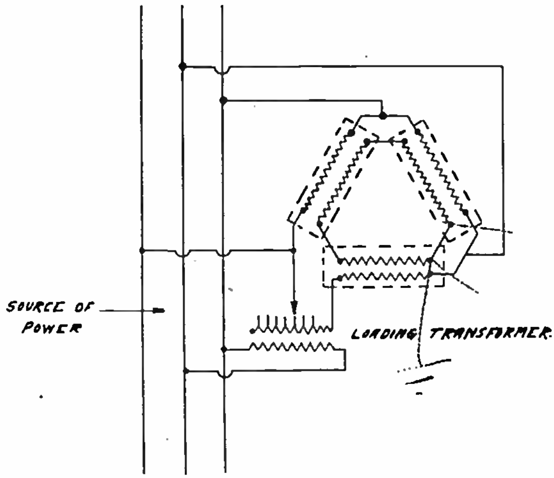


Fig. 18. Full-load Heat-run Connections for Testing Three Single-phase Transformers by a Method Employing Three-phase Excitation and Single-phase Loading. The diagram applies also to the heat-run test of a delta-delta three-phase transformer by the open-delta method

group may be paired with that of one of the opposition group independently of the secondaries of the other transformers in the same group.

When there are three single-phase transformers to be tested, a scheme employing three-phase excitation with single-phase loading may be used (Fig. 18).

(c). Cascade Loading

If two switchboards excited from a common bus of proper voltage are available and one of the boards is equipped with an induction or other type of regulator, one or more transformers may be connected between them and a flow of normal load current obtained by adjusting the regulator. This method can be used only within the capacity of the regulator.

(d). Compromise Load

Owing to possible limitations of available apparatus for making the heat test, and on account of the peculiarity of some designs, it may be found impracticable to imitate actual load conditions. When such conditions exist, the following method of loading may be used for testing oil-immersed transformers.

With normal cooling medium conditions, short-circuit one winding and circulate sufficient current at normal frequency through the other winding to produce losses in the windings under this condition which will equal the full-load loss (no-load loss plus load loss at rated voltage and frequency). Continue heat-run until conditions become constant and observe top oil rise over ambient temperature. Then reduce the current in the windings to normal rated current. After the rise of windings over top oil has become constant, generally in about two hours, it should be measured in the usual manner by taking the temperature by resistance and correcting it back to shut-down.

The sum of the top oil rise over ambient from the first run and the winding rise over top oil from the second run gives the true winding rise over ambient temperature.

Choice of Method

Single-phase Transformers

When only one transformer is available. Method (a) or (c) may be used.

When two transformers are available. In general, method (b) should be used.

Three-phase Transformers

When only one transformer is available and it has delta-delta windings. Method (a) or (c) may be used on small-capacity transformers.

Modification of Method (b)

A three-phase transformer may be loaded by using method (b) when the high-voltage and low-voltage

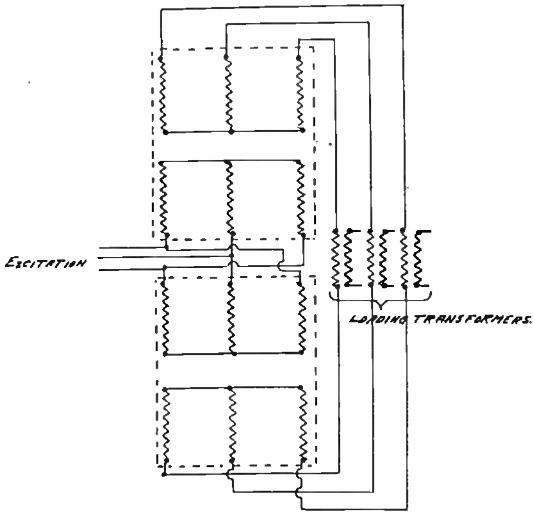


Fig. 19. Full-load Heat-run Connections for Testing Two Y-Y Three-phase Transformers by the Opposition Method

windings are capable of being connected delta-delta. One of the deltas must be opened (see Fig. 18) and a suitable single-phase current introduced at that point, while three-phase excitation is applied to either one of the groups of windings in order to supply the no-load loss and the exciting current. The load current circulates within the delta and is entirely independent of the three-phase excitation.

When testing three-phase, core-type transformers by this method, the correct impedance watts should be held instead of rated current. This is due to the fact that when single-phase current is circulated through the three phases in series, the leakage flux is in the same direction in all three core legs and excess loss may be obtained, particularly in the tank.

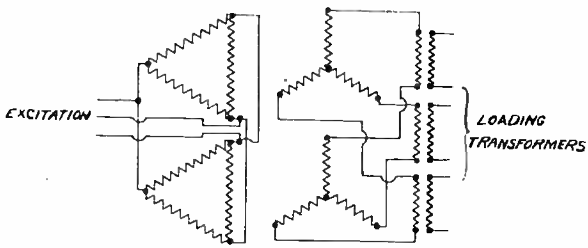


Fig. 20. Heat-run Connections for Two Delta-Y Three-phase Transformers in which the Load Current Supply is Impressed on the Y Windings

Delta-Y or Y-Y Transformers

Whenever possible, the neutral of a Y connection should be disconnected and the transformer loaded by using the connections just described.

Where this is not possible, Fig. 19 shows a method of three-phase excitation and three-phase loading that is very convenient. This method, although not very often used, is the most accurate method of loading for it gives balanced load and voltage conditions as in service.

If in this method it is found necessary to apply excitation and load current to the same windings, the excitation should be applied to the midpoints of the loading-transformer windings so as to maintain balanced conditions on the transformers under test.

The advantages of this method are:

(1). No temporary internal connections required

(2). Service voltage conditions duplicated

(3). Balanced loading of the two transformers accomplished.

The disadvantages are:

(1). Complex connections

(2). A three-phase loading transformer is required.

In Fig. 20, 21, and 22 are illustrated other more frequently used methods for testing delta-Y transformers. In that of Fig. 21 the high-tension delta windings of the two transformers are first opened and then con-

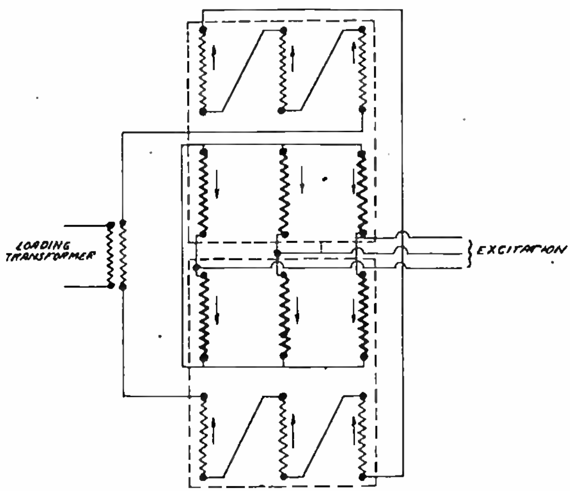


Fig. 21. Heat-run Connections for Two Delta-Y Three-phase Transformers in which the Delta Windings Are Opened at One Point and Then Connected in Series with Each Other and the Loading Transformer

nected in series with each other and the loading transformer. This method is not suitable for transformers of high reactance owing to excessive load losses. For transformers of the latter type, the method in Fig. 22 must be used in order to obtain balanced service conditions. It is sometimes found necessary to excite the same side as that into which the load is introduced, in which case the excitation should be applied to the mid-points of the loading transformer in order to maintain balanced conditions on the two transformers.

The scheme of connections for a heat run on standard Y-Y transformers is shown in Fig. 23. This method entails the opening of the Y connection of the high-voltage side and the reconnecting of the windings in series. The method gives satisfactory results and is very commonly used. The advantages are simplicity

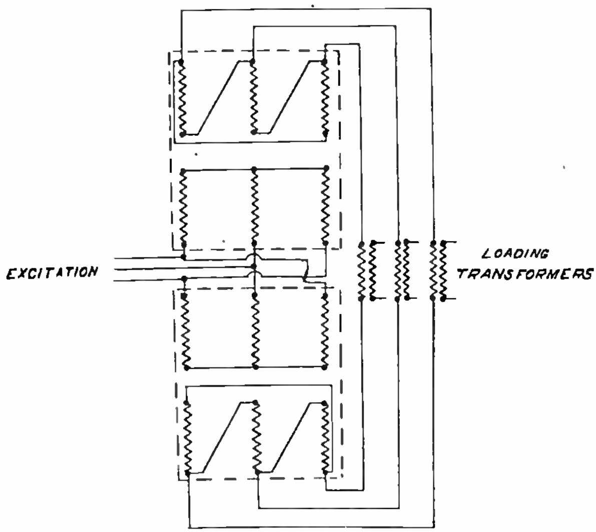


Fig. 22. Heat-run Connections for Two Delta-Y Three-phase Transformers in which the Delta Connections Are Retained and Three Separate Transformers Employed to Circulate the Current Load

of connections, balanced conditions of the two transformers, single-phase loading, and three-phase excitation. If the transformers have high impedance, the method has the disadvantage that the voltage across the loading transformers will be high, being approximately equal to the sum of the impedance voltages for the six legs. There is also the disadvantage of temporary internal connections. Furthermore, the method is not suitable for transformers of high reactance owing to excessive load losses (eddy-current losses in the conductors) which, owing to the series method of loading, will be higher than the true losses. In such cases it is much better to use the scheme in Fig. 19.

Methods of Temperature Determination

The fundamental methods of measuring tempera-

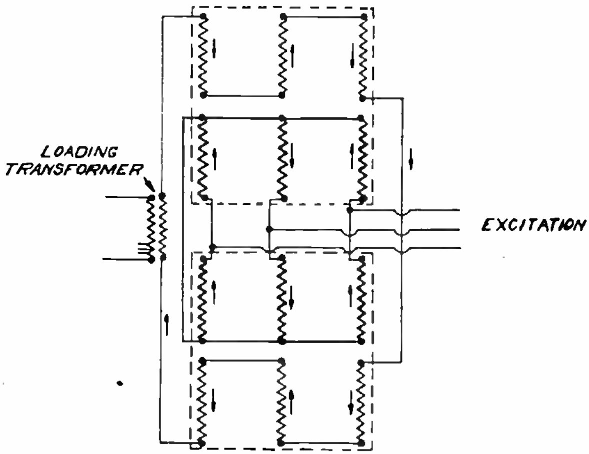


Fig. 23. Heat-run Connections for Testing Two Y-Y Transformers by an Opposition Method in which the Windings of Each Y Are Disconnected and Arranged in Series for Loading

ture are. (1). The thermometer method. (2). The resistance method.

The Thermometer Method

Because mercury is a metal, thermometers of the mercurial type should not be used inside of transformers or anywhere that they invite a short circuit or a breakdown in the insulation by reason of their presence, intact or broken. For this reason all temperature measurements by thermometer, except those of outside tank temperature, etc., should be made by thermometers of the alcohol type.

The surface temperature of iron or alloy parts surrounding or adjacent to leads carrying large current, and the temperature of the caps of the terminals or of the leads carrying this current, should be read at the end of the heat run immediately after shutdown. Top-oil temperature should be read every hour by a thermometer which has the bulb immersed two inches in the oil.

When it is not convenient to read a thermometer each hour, a thermocouple may be placed in the oil near the thermometer and the thermocouple read every hour. In such cases, however, the thermometer should be read every three hours and also at the end of the heat run. Also, the thermometer and thermocouple readings should approximately check each other.

The Resistance Method

This method consists in calculating the average temperature of the windings from measurements of the increase in resistance of the windings as determined by readings of voltage drop across them, when cold and hot, for the same direct-current flow.

The necessary measurements may be made in either of two ways:

(1). Potentiometer method

(2). Voltmeter-ammeter method.

Of these two, the first is generally used when the drop to be measured is one volt or less. When using the second, the current to be measured should be high enough to give a good reading on the voltmeter, but in any case should not be more than 15 per cent of the rated current of the winding. For very low resistances, the voltmeter-ammeter scheme is not desirable because of the very large current required to produce a voltage that can be accurately measured.

The Wheatstone bridge is not suitable for such an application because its resistances include leads and contacts which are a large proportion of the total resistance. The potentiometer avoids these errors and it is therefore preferable for measurements of low resistances.

In using the voltmeter-ammeter method, care must be taken to avoid including the resistances of leads and contacts. This can be done by carrying separate leads to the voltmeter and to the ammeter from the transformer terminals.

When applying the direct current, an induced counter-e.m.f. lowers the voltmeter reading for a time. This e.m.f. gradually disappears but is objectionable because it delays the taking of the voltmeter readings. It can be made to decrease more rapidly by first raising the current to a value about 10 or 15 per cent in excess of that desired and then bringing it down slowly.

The fundamental relation between the rise of temperature and the increase of resistance of copper may be expressed thus:

$$R_h = R_c \left\{ 1 + a\ (t_h - t_c) \right\} \qquad (3)$$

where

R_h = hot resistance (at temperature t_h deg. C.)

R_c = cold resistance (at temperature t_c deg. C.)

a = temperature coefficient at zero deg. C. = 0.00427

For use in slide-rule calculation the following formula is more convenient:

$$\frac{R_h}{R_c} = \frac{234.5 + t_h}{234.5 + t_c} \qquad (4)$$

Measurement of the Cooling-medium Temperature

The following types of transformers require consideration:

(1). Self-cooled transformers
(2). Water-cooled transformers
(3). Air-blast transformers.
(4). Forced oil transformers.

Self-cooled Transformers

If the room temperature is kept constant throughout a heat-run, its actual temperature is the effective reference base. Mercury thermometers placed in the air or in small oil cups are satisfactory for the determination of this temperature.

In case of small changes in room temperature it is not satisfactory to use the actual air temperature. It is permissible to use the temperature of an idle unit of similar capacity or nearly so for the ambient temperature. This temperature should be determined from thermometers on the tank of the idler. It is also permissible to use the reading of a thermometer in an oil cup at least 1 inch in diameter and 2 inches high.

In case of large changes in room temperature, a reliable heat run cannot be made; it is necessary to wait until the room temperature becomes more nearly constant.

Water-cooled Transformers

The case of water-cooled transformers presents two cooling mediums for consideration. However, since the amount of heat taken away by radiation and convection from the surface of the tank is negligible compared with that removed by the cooling water, no correction need be applied for the difference between the temperature of the surrounding air and that of the cooling water. In any case it is nevertheless desirable that the water temperature be within

5 deg. of the room temperature, and at 25 deg. C. if possible, the temperature being measured at the intake of the cooling coil.

Air-blast and Air-cooled Transformers

These types of transformers follow changes in air temperature much more closely than do the oil-immersed types, because their thermal capacities are much smaller. The ingoing air temperature is measured directly and is taken as the effective base, precautions being taken to guard against sudden fluctuations.

Forced Oil Transformers

These may be of the water-cooled type or of the air-cooled type.

In either case the reference temperature base is that of the cooling medium, *i.e.*, the temperature of either the ingoing cooling water or that of the cooling air.

Measurement of Cold Resistance

Thermometers should be placed in direct contact with the windings or coils, or in the ducts between the coils, at least one-half hour before the first readings of resistance are taken. Sufficient readings of temperature and resistance should be taken to determine their exact value.

In making resistance measurements, the readings should be taken as quickly as is consistent with accuracy and the current should be small enough to avoid any appreciable heating of the windings.

The resistance to be measured is generally known approximately, so that the potentiometer can be set fairly close to the correct point beforehand. The time taken to adjust to the correct settings can therefore be made very short, which is quite necessary when measuring the resistance at the end of the heat run.

When an idle unit is used the *cold resistance* R_c of the *hot transformer* should be determined as follows:

$$R_c = R_f \frac{T_s}{R_s}$$

in which

R_f = resistance of idle unit at the end of the heat run

R_s = resistance of idle unit before the heat run.

T_s = resistance of hot transformer before the heat run.

The ratio $\frac{T_s}{R_s}$ should be based on the same temperature.

Measurement of Hot Resistance

The hot resistance measurements should be made by the same method as described for the cold resistance measurements.

The resistance of the high-voltage winding should be measured as soon as possible after shutdown. That of the low-voltage winding should be measured as soon as possible after taking the readings on the high-voltage side. If all the resistance readings cannot be completed within five minutes the heat run should be resumed until normal temperatures are again obtained, after which the remainder of the readings should be taken.

Both the values of resistance and time required to take each reading after shutdown should be recorded in order to calculate the maximum value of temperature reached by the windings.

The thermal capacity of the coils being much less than that of the other parts, the windings cool initially much faster than the other parts of the transformer.

Correction for Cooling of Winding After Shutdown (4)

Since a drop in temperature occurs in a winding between the instant of shut-down and the time of measuring the hot resistance, a correction should be applied to the temperature determined from this measurement so as to obtain as nearly as practicable the temperature at the instant of shut-down. This correction may be determined approximately by making a series of resistance measurements and, from these, calculating and plotting a time-temperature curve which is extrapolated back to the instant of shutdown.

Other permissible simplified methods of determining the correction factor are:

For Oil-immersed Apparatus. When the copper loss, as determined by wattmeter measurement, does not exceed 30 watts per pound, the correction in degrees may be taken as the product of the watts loss per pound of copper for each winding multiplied by a factor that depends upon the time elapsed between the instant of shutdown and the time the resistance measurement is taken as given in the following table:

Time in Minutes	Factor
1	0.19
1½	0.26
2	0.32
3	0.43
4	0.50

For intermediate times the values of the factor may be obtained by interpolation.

When the copper loss, measured by wattmeter, does not exceed seven watts per pound, an arbitrary correction of 1.0 deg. C. per minute may be used, provided the time elapsed between the instant of shutdown and the measurement of the hot resistance does not exceed four minutes.

(4)Taken from A.I.E.E. Standard Rules No. 13-224.

For determining the copper loss in watts per pound, the total loss in both windings as measured by wattmeter shall be apportioned between high and low-voltage windings in the ratio of their respective I^2R losses.

For Air-blast Transformers. Whenever the temperature is measured by thermometers a correction of 1 deg. C. per minute up to four minutes should be made for the time elapsed between the instant of shutdown and the reading of the thermometers.

The rate of cooling of windings in air-blast transformers is lessened considerably if the air is shut off simultaneously with the load.

In fact, it is quite often found that the thermometers on the coils indicate an increase in temperature for the first few minutes. This change probably results from the shutting off of the air supply leading to an equalization of temperature throughout the coils, thus reducing the higher and increasing the lower temperatures.

Exploring Coils and Temperature Indicator

The rise by resistance of the winding shows only the average temperature of the winding. It is sometimes considered desirable to ascertain the temperatures at points where it is suspected that the values will be considerably above the average. This can be done by means of small exploring coils.

It is also desirable in some cases to determine the temperature of the windings without disconnecting the load. This may be accomplished by means of a small exploring coil which measures a local temperature or by means of a resistance coil located in the upper part of the transformer winding. When desired, transformers up to 30,000 volts can be furnished with such a resistance unit wound in it so that the internal temperature of the winding may be very closely determined by means of a temperature indicator, the scheme of connections being as shown in Fig. 24.

Details That Should be Observed in Performing a Heat Run

Self-cooled Transformers

If the transformer has a conservator, this should be filled to the proper level.

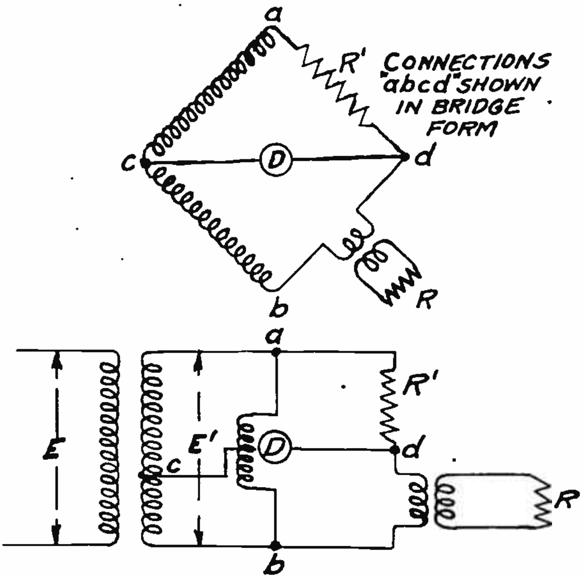


Fig. 24. Simplified Connections of Alternating-current Temperature Indicator for Use in Conjunction with Exploring Coils

For reading top-oil temperature, a thermocouple is passed under the manhole cover so as to project about four inches below the edge of the manhole. Tape should be wrapped around the thermocouple lead where it passes over the edge of the manhole to prevent the lead being cut when the manhole cover is bolted down.

The readings are to be taken each hour.

If there is a third transformer, it is used as an idle unit for measurement of the base temperature. It should be filled to the same level as the test units and should be placed at least three feet from any source of heat.

Two thermometers should be placed on opposite sides of the outside surface of the tank of the idle transformer in a position approximately midway between the top and bottom of the coil stacks. During the heat run, the lines used for resistance measurement should be left connected to the high-voltage winding of the idler, as it is desirable to check the idler resistance during the heat run.

If a third unit is not available for an idler, any transformer or spare tank of approximately the same dimensions as the transformers being tested may be filled with oil and used as the idler. Any unit that is used for an idler should be located at the same level as the units on the heat run.

Small self-cooled transformers are usually started with a small overload to increase the rate of heating. When the oil rise is within one degree of the expected rise, the load should be reduced to normal.

Water-cooled Transformers

No idler is necessary in connection with heat runs on water-cooled units.

The top-oil temperature is read by a thermocouple. If the transformers have conservators, they need not be filled into the conservator for the heat run but should be filled to within three inches of the cover.

The oil temperature rise is the difference between the top-oil temperature and the ingoing-water temperature.

Heat runs on this type of unit should be started without flow of cooling water to increase the rate of heating temporarily. The water should be turned on however when the oil rise is within five degrees of the expected value.

The water flow in each pipe should be kept so adjusted that at all times a temperature difference of 10 deg. C. is maintained between the ingoing and outgoing water.

After the heat run is completed, a pressure gauge should be inserted at the transformer inlet water valve and readings taken of the pressure necessary to force through the cooling pipes the same amount of water as was recorded in the final reading for the heat run. At the same time the water flow of *each* pipe should be measured with a measuring can. A record should be made of the water pressure and the time required to fill the measuring can and from these data the total flow for all pipes should be calculated.

Air-blast Transformers

The wiring for the test should be arranged as explained in the general description of the heat run.

Mercury thermometers are to be placed at the top, middle, and bottom of each joint in the core laminations on one end and one side of the transformer.

At least one spirit thermometer should be placed in each high-voltage and in each low-voltage group of coils. If the coil group is of more than four coils, several thermometers should be placed in it. The thermometers should be located so that the bulbs will be down in the air ducts and touching the coils.

During the first few hours of the heat run, the location of the coil thermometers should be changed from time to time in an endeavor to locate them finally at the hottest portion of the coil groups.

The ingoing and outgoing air temperatures should be read by several thermometers located at various places directly in the air path, and the average readings recorded.

The specified pressure and volume of air should be maintained during the test.

Final Temperature

When the heat run is shut down for resistance measurements, the coil thermometers and the temperature indicator coils (if any) should be read continually in rotation until the temperature begins to fall. The highest temperatures are then to be recorded as the final temperatures.

Temperature Rise

By temperature rise is meant the final observed temperature reached in the heat run minus the reference or ambient temperature.

Temperature Rise Corrections

Corrections should be applied to the observed temperature rise under the following conditions:

(1). When the guarantee is based on the rise at the instant of shutdown.

(2). When the observed rise is based on an ambient temperature different from the standard of reference.

(3). When the guaranteed temperature rise is based on an altitude which is appreciably different from that at which the test is made.

Unless a given guarantee is for a special ambient temperature, the desired ambient temperature should be 25 deg. C. for water-cooled transformers and 40 deg. C. for self-cooled transformers.

Correction of Observed Temperature Rise for an Ambient Temperature Different from That of the Standard of Reference

Air-blast Transformers. Air-blast transformers shall have a correction applied to the observed-temperature rise of the windings, when the temperature of the ingoing cooling air differs from 40 deg. C. because of the difference in resistance. This correction should be applied as follows: Corrected Temp. Rise = Observed Temp. Rise $\times \frac{274.5}{234.5+\theta}$ where θ is the ingoing cooling air temperature.

Oil-immersed Transformers. Unless the ambient temperature is specified, the desired ambient temperature is assumed to be 25 deg. C. for water-cooled transformers and 40 deg. C. for self-cooled transformers.

The decrease in viscosity of the oil at higher ambient tends to decrease the temperature rise, as does also the increase in radiation loss in self-cooled apparatus. This decrease in rise is opposed by the increase produced by larger losses due to higher resistance at higher ambient temperatures. The net effect of changing the ambient temperature is very small and no correction should be made to the rise of oil-immersed transformers on account of an ambient temperature differing from the standard ambient temperature. However, higher ambients obviously mean higher total temperatures, and full-load operation at ambients appreciably above the standards should be avoided.

Correction for Altitude

When the guaranteed temperature rise is based on operation of transformers at altitudes higher than 1000 meters (3300 ft.), the correction should be made in accordance with Section 13 of the 1925 A.I.E.E. rules, quoted as follows:

Altitude (*a*). Standard apparatus tested at an altitude not exceeding 1000 meters: Apparatus rated in accordance with these standards may be tested at any altitude not exceeding 1000 meters (3300 ft.) and no correction shall be applied to the observed temperature rise.

(*b*). Standard air-cooled apparatus tested at an altitude greater than 1000 meters: If the test is made at an altitude greater than 1000 meters it shall be assumed that the temperature rise at any altitude less than 1000 meters will be the temperature rise observed at the higher altitude reduced by 4/10 of one per cent in the case of oil-immersed or natural-draft apparatus and by one per cent in the case of air-blast apparatus for each 100 meters (330 ft.) by which the altitude at which the apparatus is tested exceeds 1000 meters.

NOTE.—The term "temperature rise" here applies to the rise of temperature of the windings as measured by resistance. The term "oil-immersed apparatus" refers only to self-cooled types. No correction is required in the case of water-cooled transformers.

Example: Assume that self-cooled transformer tests 55 deg. C. winding rise at 19,800 ft.

$$\text{Correction} = \frac{19{,}800 - 3300}{330}\ (0.4\ \text{per cent}) = 20\%$$

At Pittsfield (altitude 1010 ft.), it would test $55\left(1-\frac{20}{100}\right)=44$ deg. C.

Conversely, if it tested 44 deg. C. at Pittsfield it would test $\frac{44}{\left(1-\frac{20}{100}\right)}=55$ deg. C. at 19,800 ft. altitude.

HIGH-POTENTIAL TEST

The insulation of transformers should be tested: (a) between windings, and also between windings and ground, by a high-potential test; and (b) between turns by an induced-voltage test.

In determining the voltage to be applied, the standardization rules of the A.I.E.E. should be followed except where the manufacturer has guaranteed that the transformers will stand greater voltage.

The high-potential test should be applied when the insulation is in its weakest condition, *i.e.*, at full-load temperature, so that the test should follow immediately after the hot-resistance measurements, except that for oil-immersed transformers a sample of the oil should first be taken for test as specified later. If the oil in the transformer has to be replaced for any reason, the transformer, after refilling, should be allowed to stand one hour for each 50 kv. of the test voltage but not longer than four hours, this in order to drive out the possible entrapped air in the windings of the transformer.

When no heat run is made, the high-potential test should not be applied to oil-immersed transformers until they have stood for a time varying from one or two hours for medium size low-voltage transformers to five or six hours for very large high-voltage transformers.

Quality of Oil

No tests should be made with any oil that has a dielectric strength less than 22 kv. when tested between one-inch disks 0.1 in. apart. Regardless of the test voltage, a sample of the oil should be taken from the bottom of the transformer immediately before test and its dielectric strength determined.

Duration of Test

The high-potential test should be of one-minute duration unless otherwise specified.

Preparation of the Transformer

The transformer should be filled to the marked oil level. Sometimes transformers are provided with adapters between the bushing and the tank, in which case these also should be filled with oil. To make sure that the adapters are filled, see if oil will flow from the small valves at their top.

Short-circuiting Terminals

The terminal ends of the winding under test should be joined together and to the line terminal of the testing transformer. All other terminals and parts (including core and tank) should be well connected to ground and to the other terminal of the testing transformer.

Cable or Wire to be Used for Connections

All the testing cables should be of at least ¼-in. overall diameter and should be provided with suitable connections for making as good a mechanical joint with the transformer terminals as possible without forming sharp corners or points.

Small bare wire may be used, but much care should be exercised to keep the wire on the high-voltage side well away from ground.

Resistance and Reactance

No resistance should ever be placed between the testing transformer and the one under test, otherwise a voltage drop will occur over this resistance because of the flow of charging current. It is permissible, however, to use reactive coils at or near the terminals of the testing transformer.

Source of Power

A sine-wave generator should be used if available. For tests of 50 kv. or less, any 60-cycle circuit which has approximately a sine wave may be used. For higher voltage tests, a sine-wave 60-cycle generator with no other load should be used.

Control of Voltage

Method of Control

(1). Resistance:

The voltage may be regulated by means of resistance in series with the low-voltage side of the testing transformer. A fixed resistance should be connected in multiple with this low-voltage winding and so set as to allow a flow of current of at least five times the exciting current of the transformer under any condition. The purpose of this arrangement is to maintain a smooth wave-shape.

(2). Induction Regulator:

Regulation may be obtained by means of an induction regulator in the low-voltage circuit of the testing transformer. This method may be used for any test voltage.

(3). Alternator.

Regulation may be obtained by variation of the alternator field strength. That generator connection should be used which will require approximately normal excitation. This method also may be used for any voltage.

Limits of Control

(1). Tests above 125 kv.

First adjust the sphere-gap and its series resistance to the setting for the desired testing voltage, according to the instructions given later in the sections "Use of Sphere Gap" and "Sphere-gap Sparking Distances." As stated in the later section "Application of Voltage," increase the voltage until the gap breaks and note the voltmeter reading at that instant. Break the gap in this manner three times and record the average voltmeter reading.

Then set the gap for a 20 per cent higher breakdown value and again raise the voltage, as instructed in "Application of Voltage," until the voltmeter shows the reading that was determined as the average value in the test described in the preceding paragraph. Hold this voltage for the specified length of time and then reduce it slowly to zero.

If the sphere-gap arcs over during this final test, a careful inspection should be made to discover the cause, such as loose contacts, sharp points from which a spark might pass to the tank, etc.

(2). Tests of 125 kv. and less:

Either the method described under "Tests above 125 kv." or the following may be employed.

Set the sphere-gap with resistance in series at 20 per cent above the voltage desired.

Raise the voltage, as instructed in "Application of Voltage," until the voltmeter coil in the testing transformer indicates the proper test value. Hold this reading for the specified length of time and then reduce the voltage slowly to zero.

The following exceptions are allowable:

(a). For transformers of 100 kv-a. and less to be tested at 50 kv. or less, it is permissible to depend on the ratio of the testing transformer to indicate the proper test voltage.

(b). For transformers of 100 kv-a. and less to be tested at 15 kv. or less, it is in addition permissible to omit the spark-gap.

Application of Voltage

In order to drive out entrapped air before the full test voltage is applied, all transformers which receive a high-potential test of over 100 kv. are as a general rule subjected to the so-called "bubble-run," which is essentially an 80 per cent high-potential test. The voltage should be brought up to 80 per cent of the high-potential test value by the method to be described, held for one minute, and then slowly reduced to zero. The transformer should then be allowed "to rest" for at least two minutes before applying the 100 per cent high-potential test.

The high potential should be applied at one-quarter or less of the final value, and then brought up at the rate of about 100 kv. per minute. The length of time required for raising the voltage should never be less than one-half minute or more than one and one-half minutes. This will necessitate raising the voltage at a higher rate than 100 kv. per minute on some high-voltage transformers. The current should never be interrupted by fuses or switches except at the minimum voltage.

Use of Sphere-gap

Position

When a sphere-gap is used, it should be placed as near as possible to the transformer under test and certainly not more than 30 ft. away.

Series Resistance

To prevent high-frequency oscillations in the case of a discharge across the sphere-gap, and to limit

TABLE 1

SPHERE-GAP SPARK-OVER VOLTAGES

(At 25 deg. C. and 760 mm. barometric pressure)

Sinusoidal (e.s.m.) Kv.	SPARKING DISTANCE IN MILLIMETERS					
	20-mm. Spheres		62.5-mm. Spheres		125-mm. Spheres	
	One Sphere Grounded	Both Spheres Insulated	One Sphere Grounded	Both Spheres Insulated	One Sphere Grounded	Both Spheres Insulated
10	3.85	3.85	4.1	4.1		
12	4.75	4.75				
14	5.70	5.60				
16	6.65	6.50				
18	7.65	7.50				
20	8.90	8.55	8.9	8.9		
22	10.15	9.65				
24	11.75	10.85				
26	13.55	12.05				
28	15.60	13.40				
30	18.10	14.80	14.1	14.1	14.1	14.1
40			19.6	19.5	19.5	19.5
50			25.6	25.3	25.1	25.0
60			33.3	31.8	30.9	30.7
70			45.3	39.6	37.0	36.6
80			62.3	49.1	43.6	42.8
90				61.3	50.7	49.4
100					58.9	56.3
120					79.5	71.5
140					108.2	89.1
160					148.7	111.1
180						138.9

TABLE 1 (Continued)

Sinusoidal (e.m.s. Kv.	SPARKING DISTANCE IN MILLIMETERS					
	250-mm. Spheres		500-mm. Spheres		750-mm. Spheres	
	One Sphere Grounded	Both Spheres Insulated	One Sphere Grounded	Both Spheres Insulated	One Sphere Grounded	Both Spheres Insulated
60	29.7	29.6				
70	35.3	35.1				
80	41.1	40.7	40.4	40.2		
90	47.1	46.5	45.8	45.6		
100	53.3	52.5	51.3	51.0	49.5	50.0
120	66.4	65.0	62.4	61.8	60.0	60.7
140	80.4	78.2	73.6	72.8	71.0	71.4
160	95.5	92.3	85.1	83.8	81.9	82.3
180	111.9	107.4	96.8	94.9	93.0	93.4
200	129.9	123.4	108.6	106.4	104.5	104.5
220	150.5	140.8	120.9	118.3	116.0	116.0
240	175.1	159.8	134.0	130.6	128.4	127.5
260	209.0	180.2	148.0	143.6	140.5	139.5
280	255.5	203.1	162.8	157.3	152.5	152.0
300		230.5	178.5	171.8	165.2	164.5
320		263.1	195.4	187.2	178.1	177.5
340			213.7	203.2	191.8	190.7
360			233.2	219.9	206.0	204.3
380			253.9	237.4	220.5	218.2
400			276.4	255.7	235.5	232.5
420			300.7	274.8	250.5	247.0
440			327.2	294.5	265.8	261.5
460			355.5	314.8	282.3	277.0
480			385.6	335.9	299.6	293.0
500			417.7	357.7	317.5	309.5
520					336.5	326.3
540					356.0	343.5
560					377.0	361.0
580					399.0	378.0
600					422.0	396.0
620					445.0	413.5
640					469.2	435.2
660					495.5	457.0
680					525.0	479.0
700					555.8	501.5
720					588.0	524.5
740					621.5	548.0
760					659.0	572.0
780					701.0	597.0
800					747.0	623.5
820					795.5	651.2
840						680.0
860						709.5
880						742.0
900						776.0

resultant current, a non-inductive resistance of about one ohm per volt of the test voltage should be inserted in series with gap.

If the test is made with one terminal grounded, the entire resistance should be inserted in series with the non-grounded electrode. If neither terminal is grounded, one-half of the resistance should be inserted in series with each electrode. In either case, this resistance should be as near to the sphere-gap as possible. A water tube is the most suitable form of resistor for the purpose. Carbon rods of approximately ¾-in. diameter and approximately 8 in. long, having a resistance of not more than 4000 ohms per unit, may be used. (Carbon resistors of high specific resistance should not be employed because their resistance may become very low at high voltage.)

Sphere-gap Sparking Distances

Table I gives sparking distances between spheres for various r.m.s. values of sinusoidal voltage.

Effect of Air Density on Spark-over Voltage

The spark-over voltage, for a given gap, decreases with decreasing barometric pressure and increasing temperature. This variation may be considerable at high altitudes. When the elevation above sea-level is not great, the relative air density may be used as the correction factor. When the altitude is great, or greater accuracy is desired, the correction factor corresponding to the relative air density should be taken from Table II, in which

$$\text{Relative air density} = \frac{0.392\, b}{273 + t}$$

where

b = barometric pressure in mm.

t = temperature in deg. C.

Correction curves may be plotted for any given altitude if desired. It will be noted in Table II that for values of relative air density above 0.9 the correction factor does not differ greatly from the relative air density.

Correction of Gap Spacing for Air Density

To determine the gap spacing for a required spark-over voltage, divide the required voltage by the correction factor obtained from Table II and use the new voltage thus obtained to find the corresponding spacing from Table I, using a graph of the latter if more convenient.

Correction of Voltage for Air Density

To determine the spark-over voltage for a given gap spacing, multiply the voltage corresponding to the gap spacing obtained from Table I by the correction factor from Table II.

TABLE II

AIR DENSITY CORRECTION FACTORS FOR SPHERE GAPS

Relative Air Density	DIAMETER OF STANDARD SPHERES IN mm.					
	20	62.5	125	250	500	750
0.50	0.573	0.547	0.535	0.527	0.519	0.517
0.55	0.617	0.594	0.583	0.575	0.567	0.565
0.60	0 661	0.640	0.630	0.623	0.615	0.613
0.65	0.705	0.686	0.677	0.670	0.663	0.661
0.70	0.748	0.732	0.724	0.718	0.711	0.709
0.75	0.791	0.777	0.771	0.766	0.759	0.757
0.80	0.833	0.821	0.816	0.812	0.807	0.805
0.85	0.875	0.866	0.862	0.859	0.855	0.854
0 90	0.917	0.910	0.908	0.906	0.904	0.903
0.95	0.959	0.956	0.955	0.954	0.952	0.951
1.00	1.000	1.000	1.000	1.000	1.000	1.000
1.05	1.041	1.044	1.045	1.046	1.048	1.049
1.10	1.082	1.090	1.092	1.094	1.096	1.097

TABLE III
INDUCED VOLTAGE TEST

Class	Type	Description	Test
1	1-phase	Kv-a. $\leqq$ 100 Voltages $\begin{cases} LV < 2500 \\ HV < 2500 \end{cases}$	4 × operating volts per turn
2	1-phase	Kv a. $\leqq$ 100 Voltages $\begin{cases} LV < 2500 \\ 2500 < HV < 3300 \end{cases}$	3 × operating volts per turn
3	1-phase	Kv-a. $\leqq$ 100 Voltages $\begin{cases} LV < 2500 \\ 3300 < HV < 4000 \end{cases}$	2.5 × operating volts per turn
4	1-phase	When voltage $\geqq$ 66 kv. grounded, for Y Y connection	3.46 × leg voltage + 1000 from line to ground
5	1-phase	When voltage $\geq$ 66 kv. grounded, any connection except Y Y	2.73 × leg voltage + 1000 from line to ground
6	3-phase	When voltage $\geqq$ 66 kv. grounded	3.46 × leg voltage + 1000 (between lines) 2.73 + leg voltage + 1000 (from line to ground)
7	1-phase 3-phase	All else	2 × operating volts per turn

Test Voltages

Transformers

In determining the value of voltages to be applied, the A.I.E.E. Rules should be followed.

Autotransformers

Since the high- and low-voltage windings are connected together, the total winding should be tested at a voltage corresponding to the high-voltage winding.

Permanently Grounded Transformers

Transformers with neutral or one end of a winding permanently grounded to the core require no high-potential test of that winding; transformers of 66 kv. and above, however, should be given a special induced voltage test.

INDUCED-VOLTAGE TEST

The last test to be made on all transformers is the induced-voltage test. It is applied in order to test the insulation between turns and between sections of the winding, and to determine if the preceding high-potential test had caused any damage to the windings.

The voltage to be applied for this test ranges from two to four times normal, the specific values being given in Table III.

The source of power should have an approximately sine-wave form, and a frequency such that the exciting current of the transformer under test will not exceed about 30 per cent of the normal rated current of the excited winding. Ordinarily this limitation of the current will necessitate the use of a frequency of 120 cycles or more when testing 60-cycle units. When frequencies higher than 120 cycles are used, the severity of the test is abnormally increased, and for this reason the time of applying such frequencies must be reduced to the equivalent cycles of a 120-

cycle one-minute test. According to the A.I.E.E. Rules, these equivalents are as follows:

Frequency in Cycles	Duration in Seconds
120	60
180	40
240	30
360	20
400	18

Control of Voltage

The voltage should be started at one-quarter or less of the full value and be brought up steadily to full value in not less than 15 sec. After being held for the duration of time specified in the preceding paragraph, it should be reduced slowly (in not more than 5 sec.) to one-quarter of the maximum value or less before the circuit is opened.

Transformers which have one winding grounded for operation on a grounded-neutral system should receive special care to avoid high electrostatic stresses between the windings and ground. To prevent such stresses in single-phase transformers that have one end of the high-voltage winding solidly grounded, a ground should be placed on the low-voltage winding during the induced-voltage test. If the maximum test voltage across the low-voltage winding exceeds 10,000 volts, this ground must be made at the middle of the winding itself or at the middle of the winding of a step-up transformer which is used to supply the voltage or which is merely connected for the purpose of furnishing the ground. If the maximum test voltage across the winding does not exceed 10,000 volts, the ground may be made on the end of the winding of the same polarity as the grounded end of the high-voltage winding.

Three-phase transformers having the neutral of the high-voltage winding solidly grounded should have a ground made on the low-voltage winding during the induced-voltage test. If the low-voltage winding is Y-connected, the neutral should be grounded. If the low-voltage winding is delta connected, the ground should be made on the neutral of the Y-connection of an intermediary step-up transformer. In the case of a delta-connected secondary having a voltage rating less than 7500 volts, it is permissible to ground one of the three corners of the delta.

If there is a third winding this should also be grounded.

The increased charging current, corresponding to the higher testing frequency, and the higher potential of the induced-voltage test may produce a large voltage rise through the increased reactance of the transformer at the higher frequency. Therefore, with sine-wave voltage impressed, and with one end of every winding grounded, the voltage induced in the high-voltage winding may be greater than that corresponding to the turn ratio. For this reason a sphere-gap should be connected across the high-voltage winding and used to limit the voltage to be held.

When another transformer is used to step-up the voltage for the induced-voltage test, the step-up ratio should not be trusted. The voltage should be determined either by a sphere-gap across the high-voltage winding or by the reading of a potential transformer connected across the low-voltage winding of the transformer under test. The sphere-gap method is preferable when but one means is to be used, but whenever possible both methods should be employed. After the proper voltage has been determined by the sphere-gap, the gap should be widened to a 10 per cent higher value and left connected in the circuit as a protection against over-voltages.

REGULATION

Calculation of Regulation

According to the A.I.E.E. Rules, the regulation of a constant-potential transformer "is the difference between the no-load and the rated-load values of the secondary terminal voltage at the specified power-factor (with constant primary impressed terminal voltage), expressed in per cent of the rated-load secondary voltage, the primary voltage being adjusted to such a value that the apparatus delivers rated output at rated secondary voltage."

Regulation may be determined by loading the transformer and observing the rise in secondary voltage when the load is disconnected. This method is seldom satisfactory because of the expense of making the test, and the small difference between the no-load and full-load secondary voltages.

Much greater reliance can be placed on results calculated from separate measurements of impedance watts and voltage than on an actual measurement of regulation.

Let P = Impedance watts, as measured in the short-circuit test and corrected to 75 deg. C.

E_z = Impedance volts, as measured in the short-circuit test

I = Rated primary current

E = Rated primary voltage

$\%IR$ = Per cent effective resistance drop of the transformer, *i.e.*, per cent impedance watts, at guaranteed load, corrected to 75 deg. C.

$$\%IR = 100 \times \frac{P}{EI}$$

$\%IX$ = Per cent reactance drop between the primary and secondary windings. This is independent of temperature.

$$\%IX = 100 \times \frac{\sqrt{E_z^2 - \left(\frac{P}{I}\right)^2}}{E}$$

p = Power-factor of the load. This is always positive.

q = Reactive-factor of the load. This is positive for lagging loads; negative for leading loads. Its value is equal to $\sqrt{1-p^2}$. Some pairs of corresponding values of power-factor (p) and reactive-factor (q) are:

p	q	p	q
1.00	0.00	0.65	0.76
0.95	0.312	0.60	0.800
0.90	0.436	0.50	0.866
0.85	0.527	0.40	0.916
0.80	0.600	0.30	0.954
0.75	0.661	0.20	0.980
0.70	0.714	0.00	1.000

Then:

For unity power-factor load:

$$\text{Per cent regulation} = \%IR + \frac{(\%IX)^2}{200}$$

For other power-factors:

$$\text{Per cent regulation} = p\times\%IR + q\times\%IX + \frac{(p\times\%IX - q\times\%IR)^2}{200}$$

Autotransformers

For autotransformers, $\%IX$ and $\%IR$ should be calculated in the same manner as for transformers. These values should be multiplied by the co-ratio

$$\frac{\text{Rated voltage (H-v. winding)} - \text{Rated voltage (L-v. winding)}}{\text{Rated voltage (H-v. winding)}}$$

after which they should be used in the preceding formulas given for transformers.

EFFICIENCY

Calculation of Efficiency

The efficiency of a transformer is the ratio of the useful power output to the total power input.

According to the A.I.E.E. Rules, the following conventional method of determining efficiency is recognized as standard:

The efficiency is obtained from the component losses and it is the ratio of the power delivered by the machine to the power received by it. Thus

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{total losses}}$$

wherein the output and losses are both expressed in watts or kilowatts. This formula may be written:

$$\text{Eff.} = \frac{1}{1 + \frac{\%\ \text{total losses}}{100}}$$

Normal Conditions of Efficiency Determination by A.I.E.E. Standards

Voltage, Current, and Frequency: The efficiency shall be determined for the rated voltage, current, and frequency.

Temperature of Reference: The efficiency of apparatus at all loads shall be corrected to a reference temperature of 75 deg. C.

Efficiency at Fractional Loads and at a Power-Factor Different from Unity

In this case efficiency can be more readily and accurately obtained from the following formula:

$$\text{Efficiency} = 1 - \frac{\%P_i + \%P_c\,F^2}{100\,pF + \%P_i + \%P_c\,F^2}$$

where:

P_i = Core loss in per cent of the kv-a. rating

P_c = Impedance watts in per cent of the kv-a. rating

p = Power-factor
F = Fraction of load.

The usual values of F and F^2 are the following:

Kv-a. Load	F	F²
1½	1.5	2.25
1¼	1.25	1.562
Full	1	1
¾	0.75	0.5625
½	0.5	0.25
¼	0.25	0.0625

Example

P_i = Core loss = 0.8 per cent
P_c = Impedance loss = 1.65 per cent
p = Power-factor = 0.80
F = Fraction of load = 0.75

Efficiency

$$= 1 - \frac{0.8 + 1.65 \times 0.5625}{100 \times 0.8 \times 0.75 + 0.8 + 1.65 \times 0.5625} = 0.972$$

Efficiency calculations can be considerably simplified by the use of a suitable chart, especially when calculations have to be made for several load conditions.

Fig. 25 shows such a chart arranged for direct reading for unity power-factor conditions. By expressing the losses as a percentage of the kilowatt output, the chart can be made to serve for any power-factor conditions. This is done by dividing the per cent loss at unity power-factor by the power-factor under consideration.

ACCURACY OF MEASUREMENTS

As was mentioned on page 5, the writer has attempted to describe the testing of transformers in such a manner that the work can be done with the facilities that the operating engineer is likely to have at hand.

While measurements that approach laboratory accuracy may be made in the field, such a degree of precision is seldom required in the field. Nevertheless, the conduct of a field test requires the display of considerable resourcefulness in collecting suitable testing paraphernalia and much constructive thought in its set-up, if credence is to be placed upon the results of such a test. Also, for the sake of accuracy, as well as safety, the instruments, etc., should be carefully examined before use to make sure that they are in satisfactory operating condition, for in such service they necessarily encounter more rough handling than does similar equipment in a laboratory or in a manufacturer's testing department.

When collecting measuring equipment that will be suitable for his purpose, the operator's testman should aim to select instruments (and instrument transformers if needed) that are of such ratings as will cause the readings to come within the central or the upper section of the instrument scales, for such readings will be more accurate than those toward the zero end of the scales.

If instrument transformers are necessary, either to act as multipliers for the instruments or to insulate them from high-potential circuits, the potential transformers should be chosen of such a ratio that their secondaries will deliver approximately 75 to 125 volts under the condition of the test and the current transformers of a ratio that will cause them to deliver about 1.5 to 5 amp. secondary. These ranges correspond to standard potential transformers having a rating of 110 volts secondary and to current transformers of 5-amp. secondary.

If the instruments and instrument transformers in such a combination are of modern design, and of a universally accepted make and undamaged, it is possible in many cases to neglect the instrument and instrument transformer corrections and still obtain results that will be reasonably accurate for the purpose of a field test. This may be due either to the errors being of negligible magnitude or to the fact that the errors of the instruments and the instrument transformers may partially compensate each other.

However, if the assurance of greater accuracy is desired, particularly when the power-factor is in the neighborhood of 20 per cent or less, corrections should be made for scale errors in the voltmeters, ammeters, and wattmeters, for phase-angle errors in the wattmeters and instrument transformers, and for ratio errors in the instrument transformers. The corrections for scale errors of the instruments may readily be made if calibration curves of the instruments are available. Accounting for the remaining errors is not so simple a matter and does not fall wholly within the province of this article. For these operations reference may be made to the books, "Instructions for Testing Electrical Apparatus," and "Instrument Transformers," which are identified by the designations GET-7 and GET-97 respectively, and published by the General Electric Company, and to the article, "Revised Tables of Phase Angle Correction Factors for use in Power Measurements," by C. T. Weller, which appeared on page 202 of the March, 1925 issue of the General Electric Review.

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