INSTRUMENT TRANSFORMERS

An instrument transformer (IT), like all ac transformers, consists of a ferromagnetic core on which a primary winding and a secondary winding are applied. The windings may be isolated from each other (double wound), or one winding may be a tapping off the other (auto wound). The basic difference between a power transformer and an IT is that the latter is used with little or no load connected to its secondary winding, and, as such, an accurate transformation of voltage or current can be attained.

In the electrical supply industry, ITs are widely used to extend the range of an instrument such as a voltmeter, an ammeter, a wattmeter, a watthour meter, or an item of protection or control equipment. In addition to its use as a range-extending device, a double-wound IT may also serve to isolate an instrument from a high-voltage circuit.

It is usually impractical to manufacture precision indicating instruments with voltage ranges above about 500 V, or current ranges above about 20 A. As the electrical supply industry is required to measure or detect voltages and currents very much higher than these values, a convenient way to do so is to use an IT to transform such voltages and currents down to measurable values. Also, an IT may be required to transform low voltages or low currents up to values which can be accurately measured on available indicating instruments.

TRANSFORMER RATIO

An IT used as a ratio standard is probably the most accurate and stable of all electrical ratio devices. To a first order of accuracy, the ratio is dependent only on numbers of turns wound on the ferromagnetic core.

In the case of a voltage transformer (VT), the external load (known as the *burden*) connected to the secondary terminals must be of high impedance. When this is so, a voltage applied to the primary winding causes a voltage to be induced in the secondary winding that is nearly equal to the applied voltage divided by the ratio of primary to secondary turns. In other words, the voltage on each winding is nominally proportional to number of turns.

In the case of a current transformer (CT), the external load connected to the secondary terminals must be of low impedance. When this is so, a current passed through the primary winding causes a current to be induced in the secondary winding that is nearly equal to the primary current multiplied by the ratio of primary to secondary turns. In other words, the current passing through each winding is nominally inversely proportional to number of turns.

USE OF INSTRUMENT TRANSFORMERS

When a VT is used to extend the range of a voltmeter or voltage circuit of a wattmeter, the voltage to be measured must

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be connected to the primary winding of the VT. A connection must then be made from the secondary terminals of the VT to the voltmeter. Where the VT is double-wound, it would be normal (for safety reasons) to connect an earth to one secondary terminal. Any exposed metal casing of the VT must always be earthed.

When a CT is used to extend the range of an ammeter or current circuit of a wattmeter, the circuit must be opened at the point where the current is to be measured, and the primary winding of the CT must be connected across this opening. A connection must then be made between the secondary terminals of the CT and the ammeter. Where the CT is double-wound, it would be normal (again for safety reasons) to connect an earth to one secondary terminal. For additional safety, a short-circuiting switch is usually connected across the secondary winding of a CT. This should be kept closed until all connections are complete. The reason for this is that if appreciable current is passed through a primary winding of a CT with an open circuit on its secondary, dangerously high peak voltages are likely to be induced in the secondary (see Fig. 1).

VOLTAGE TRANSFORMER CONSTRUCTION

A VT consists typically of a closed, oil-filled metal tank into which the core together with its windings have been inserted. The winding terminations are typically brought out to terminals through porcelain insulators which are secured to the top of the tank (see Fig. 2). In most parts of the world, the secondary-voltage rating is standardized at 110 V. A VT may have more than one primary- or secondary-voltage tapping if it is intended for multiple ratio use. VTs intended only for laboratory use may incorporate Bakelite or other plastic insulators; or, instead of being oil-filled, their whole assembly may be encapsulated in an epoxy molding. VTs rated at voltages below about 1 kV are rarely oil-filled or epoxy-encapsulated.

A VT may be designated according to international standards (1) as "unearthed," in which case two equal-size insulators (as in Fig. 2) will be used for its primary terminations. Such a VT will be suitable for connection between phases of a three-phase system. A designated "earthed" VT will be designed for one end of its primary winding to be suitable for connection to a potential close to earth only.

During manufacture, so as to grade the insulation most efficiently, it is most common to apply the lowest-voltage winding of a VT closest to the core and then work outwards to the higher-voltage windings.

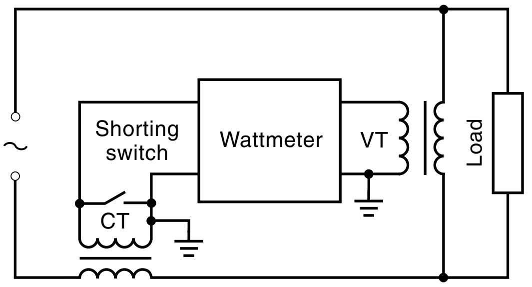

Figure 1. Use of instrument transformers to extend the range of a wattmeter. The voltage transformer and current transformer avoid the need to apply high voltages and currents to the wattmeter itself.

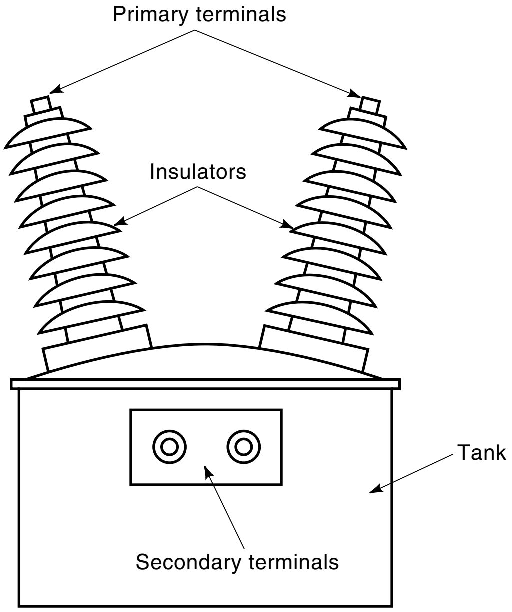

Figure 2. Typical voltage transformer in a metal tank, with outdoor-type primary-terminal insulators.

Most modern VTs, except those designed for special laboratory use, incorporate a ferromagnetic core made from cold-rolled silicon iron (also referred to as *grain-oriented silicon steel,* or GOSS). This ferromagnetic material is chosen because it is relatively cheap and has a high saturation flux density of about 1.8 T. The use of a more expensive, high-permeability, nickel-iron core could result in the VT having lower errors of transformation but, with a saturation flux density of only about 0.4 T, might cause the VT to be prohibitively large in size. A third alternative core material, known as *amorphous metal* or *glassy metal,* can be formulated to combine high saturation flux density with high permeability, but this material is usually too expensive for ITs.

The actual core construction of a VT typically consists of laminations as in a power transformer, with the windings applied on cylindrical formers through which the laminations pass. Such a construction is usually referred to as a "shell iron" VT.

Where specially high accuracy of transformation is required, a ring-type core might be used, where the core is wound up from a long length of strip as in a clock spring. Then the windings must be applied toroidally round the core. The advantage of such construction is that the windings are likely to be coupled more closely, and any component of error due to flux leakage will be minimized. Also, as the iron is used more efficiently, a lighter construction should result. Such construction (usually referred to as "toroidal") is more expensive than the use of laminations.

CAPACITIVE VOLTAGE TRANSFORMERS

VTs with voltage ratings greater than about 150 kV would often become too large and expensive to be manufactured by conventional means. In such cases it is common to use what is called a *capacitive voltage transformer* (CVT). Such a device is constructed in two parts. The first part consists of a capacitive divider with a low-voltage tapping at about 10 kV. The second part (known as the *electromagnetic unit*) consists of a conventional double-wound VT with its primary winding connected across the low-voltage tapping of the capacitive divider. An additional feature of the CVT is that the input inductance of the electromagnetic unit is arranged to resonate (at rated frequency) with the capacitive divider. This in turn enables the capacitive divider to be much smaller in size than would otherwise be the case for a given accuracy. A disadvantage of a CVT is that its errors are frequency dependent.

INDUCTIVE VOLTAGE DIVIDERS

A special type of VT, intended only for laboratory use, is known as an *inductive voltage divider* (IVD). An IVD is basically a step-down autotransformer with multiple secondary tappings arranged in decades. Intended for very high accuracy use, IVDs are made with the highest-permeability cores. Also, all windings of each decade are stranded together in a bunch or rope so that they are very well coupled with each other. A typical IVD has six decades so that the input voltage can be subdivided to a resolution of one part per million. IVDs are rarely made for an input voltage rating much greater than 100 V at 50 Hz.

CURRENT TRANSFORMER CONSTRUCTION

As the magnetizing forces (ampere turns) generated by the primary and secondary windings of a CT are nearly equal and are opposite in phase, the net ampere turns—and hence the working flux density—are normally very low. Also, as the permeability of cheap, silicon-iron cores drops away to almost zero at very low flux density, it is normal to construct CTs intended for accurate measurements with nickel–iron cores, which retain their high permeability down to very low excitation. However, protection CTs, where freedom from saturation of the core under overload conditions is more important than accuracy of transformation, usually incorporate silicon–iron cores.

Care needs to be taken when handling nickel–iron cores because mechanical shock is liable to greatly reduce their permeability. For this reason, many manufacturers will enclose their cores in a protective case so that the pressure of the windings themselves on the core do not cause loss of permeability.

In most parts of the world, the secondary-current rating for CTs intended for measurement use is 5 A, while for protection CTs it is 1 A. Laboratory standard CTs often have secondary tappings of both 1 A and 5 A, although the latter is more common.

The normal method of constructing a CT is to apply the secondary winding first, so that it couples the core closely. Thus, secondary-winding leakage-reactance is minimized. Although it is also desirable that the primary winding closely couples the core, leakage reactance in the primary, no matter how large, is simply in series with the wiring to the load and is of no consequence as far as errors of the CT are concerned.

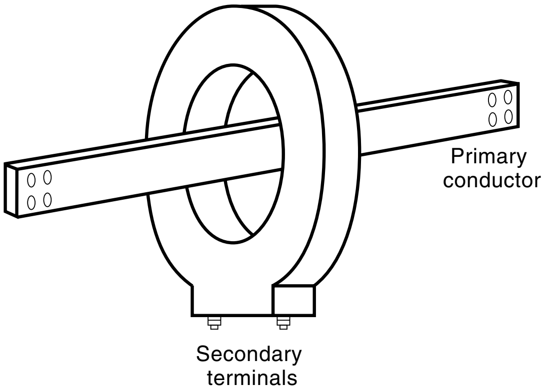

Figure 3. Typical current transformer for insertion onto a busbar, where the busbar itself forms a single-turn primary winding.

The most common type of CT encountered in the electricity supply industry is the "window" or "through" type, where a secondary winding is applied on a toroidal core, and the aperture of the core (the window) is left open so that one or more cables can be fed through it by hand to form the primary winding (Fig. 3).

When a window-type CT is used on a high-voltage transmission line, the clearance in the aperture must be large enough for there to be no possibility of a breakdown between the primary and secondary windings. Alternatively, solid insulation must be applied in the aperture.

In the highest-quality CT designs, terminals are made from plain copper, and all internal connections are soldered. Many manufacturers, however, use nickel- or chromium-plated terminals, often with detrimental effects. Research has shown (2) that the hard oxides on these plating materials can cause partial rectification at the contact faces, which in turn causes dc to flow in the windings. This component of dc will cause the permeability of the core to change or even cause saturation of the core. Plain, copper-to-copper connections, however, even when badly oxidized, rarely cause any trouble. Plain brass is a reasonable alternative metal to use for terminals, although when oxidized and poorly tightened, brass-to-copper connections can cause partial rectification.

TRANSFORMER ERROR

Due to various losses, the actual transformation ratio of an IT is never exactly equal to the ratio as defined by numbers of turns. Therefore, where the highest accuracy of measurement is required, the error in the transformation ratio must be determined and allowed for. The following are six effects which may give rise to errors in ITs, or which may cause the actual ratio to be unstable.

Effect of Loading

In a well-designed IT, the greatest contribution to error is that due to loading. The larger the volt-amperes delivered to the external burden connected to the secondary terminals, the greater will be the losses internal to the IT, and hence the greater the errors.

Effect of Insulation-Leakage Currents

In applications where the voltage applied to an IT is high, or where a high voltage is induced in one of the windings, insulation-leakage currents may contribute appreciably to the errors. ITs that fall into this category are VTs with voltage ratings above about 30 kV, CTs with current ratings below about 0.5 A, and ITs operating at high frequency. In most cases it is the capacitance of the insulation material that has the major effect. Up to a point, capacitance leakage can be a good thing, because this current tends to cancel out the magnetizing current, which in turn, particularly in a CT, can reduce the component of error due to loading. However, excessive capacitance leakage currents can become a serious liability as far as the errors of the IT are concerned.

Effect of Partial Coupling and Flux Leakage

When the turns of the primary and secondary windings do not closely couple each other, such as when one or both windings are not uniformly distributed around the circumference of the ferromagnetic core, some lines of magnetic flux generated by one winding will not link all turns of another winding. This in turn will fractionally change the effective turns ratio. In a VT, this effect usually gives rise to the secondary voltage being less than nominal, while in a CT it usually gives rise to the secondary current being greater than nominal. This effect is usually associated with VTs, where, for ease and cheapness of construction, the primary and secondary windings are not concentric with each other or with window-type CTs. This effect should not be confused with the circumstances which might arise in a window-type CT where leakage fluxes become so large that, in some regions of the core, local saturation occurs. This in turn will cause the secondary current to become much lower than nominal (3).

Turns Ratio Error

If, during manufacture, the number of turns on any winding is wrongly applied, this will give rise to an error in the actual ratio.

Bad Contacts

In an otherwise-well-designed IT, errors can occur due to bad contacts in the internal or external circuit. These errors are usually associated with CTs where partial rectification at contact faces of connections causes a small direct current to flow in one of the windings. This in turn causes the permeability of the core to change temporarily, and hence causes a change in the errors. The slow deterioration of bad internal connections of an IT can take tens of years before they start to cause serious instability.

Partial Discharges

As a result of air voids or bubbles that may be present in the insulating materials of an IT, ionization of the air in these voids can occur when high enough voltages are present. When the ionization voltage is reached, alternate breakdown and recovery of the air path in the void will rapidly occur. This effect is known as *partial discharges* (PDs). As a result of these PDs, a high-frequency voltage will be superimposed on the windings. Errors due to this effect are almost entirely associated with badly designed or constructed, high-voltage VTs. As often as not, the apparent error that these discharges cause is due to the behavior of the instrument connected to the IT and is not due to the IT itself, and therefore any calibration made of an IT exhibiting appreciable PDs could be meaningless. An additional effect that PDs can have on an IT is to degrade the insulation slowly with time and eventually cause its complete breakdown.

DEFINITIONS

Transformation Ratio

The transformation ratio of an IT (usually just referred to as “ratio”) is universally defined as the actual primary voltage or current divided by the actual secondary voltage or current. For this definition to have some useful meaning, the voltages or currents must be their root-mean-square (rms) values. This fact is not always made clear in definitions made by some standards organizations, although it will be assumed throughout this article.

In order to express the error in the ratio of an IT, some organizations define this as the quotient of “true ratio” (as defined above), divided by “nominal ratio” (as stated on the rating plate of the IT). Some organizations (particularly in the United States) refer to this quotient as the “ratio correction factor” (RCF). According to the above definition, a perfect IT would have an RCF of unity.

Turns Ratio

The turns ratio of a VT is universally defined as primary-winding turns divided by secondary-winding turns. Turns ratio of a CT is defined by some standards organizations as primary-winding turns divided by secondary-winding turns, but by others as the inverse of this. When using formulae quoted by standards organizations, metrologists should therefore be careful that they check on how the turns ratio of a CT is defined.

Voltage Error of a VT

According to international standards (1), the error in the ratio of a VT is defined as follows:

> The error which a transformer introduces into the measurement of a voltage and which arises when the actual transformation ratio is not equal to the rated transformation ratio. The voltage error, expressed in percent, is given by the formula
>
> $$\text{voltage error } \% = \frac{k_n U_s - U_p}{U_p} \times 100 \qquad (1)$$
>
> where
>
> k_n is the rated transformation ratio
> U_p is the actual primary voltage
> U_s is the actual secondary voltage when U_p is applied under the conditions of measurement.

According to the above definition, a perfect VT would have a voltage error of zero. Although not clearly stated in the above definition, U_p and U_s are the magnitude of their values (i.e., they are not vector quantities).

Current Error of a CT

According to the same international standards, the error in the ratio of a CT is defined as in Eq. (1) above except that the word "voltage" is replaced by "current" and the symbol *U* is replaced by *I*.

Phase Displacement

In some applications, particularly when an IT extends the range of a wattmeter or watthour meter not working at unity power factor, it is necessary to know the displacement in phase between the primary and secondary voltages or currents. According to international standards, phase displacement is defined for a VT as follows:

> "The difference in phase between the primary and secondary voltage vectors, the direction of the vectors being so chosen that the angle is zero for a perfect transformer. The phase displacement is said to be positive when the secondary voltage vector leads the primary voltage vector. *Note.* This definition is strictly correct for sinusoidal voltages only."

Substitute the word "current" for "voltage" in the definition of phase displacement for a CT. There are slight variations in wording between various world organizations in the definition of phase displacement (some organizations call it "phase angle" and others call it "phase error"), but numerically they are all the same.

Most standards organizations give the preference that phase displacement is expressed in centiradians because this unit is logically equivalent to voltage error or current error expressed in percent. Throughout the world, however, many electricity authorities still prefer to express phase displacement in "minutes" because this was the preferred unit used up until about 1970.

From the above, it is clear that IT errors are defined in polar coordinates. In circuit analysis and in technical papers, it is often more convenient to express IT error in rectangular coordinates in the form "$a + jb$". The definition of IT error in rectangular coordinates is identical to the definition of voltage error or current error above, except that the voltages or currents concerned must all be complex quantities.

In these definitions, the sign of the quadrature component of error in rectangular coordinates is the same as the sign of the phase displacement in polar coordinates.

TRANSFORMER CLASS

It is the practice among most manufacturers to assign an accuracy class to an IT. In its simplest form, this class designation consists of a number, which indicates the limits of voltage error or current error in percent and the limits of phase displacement in centiradians which should apply during normal use. The range of voltage or current levels, or range of burden levels over which the limits of error should apply, varies from one type of IT to another and also varies from one standards organization to another. Commonly, VTs are required to be within class between 90% and 110% of rated voltage; CTs between 10% and 125% of rated current; and all ITs between 25% and 100% of rated burden. Burden is usually expressed in "millisiemens" for a VT and in "ohms" for a CT, although before about 1970 it was normal to express burden for both VTs and CTs in volt-amperes (VA). It will therefore be noted that many older ITs have rated burden expressed in "VA" on their rating plate.

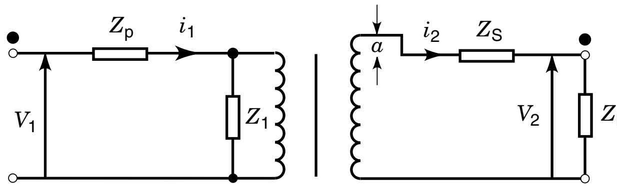

Figure 4. Equivalent circuit of an instrument transformer having a nominal ratio of unity.

In addition to a number, a class designation may also include one or more letters. These letters, for instance "L," mean that the IT is intended for laboratory use; "M" would mean that the IT is for measurement use in the field; while "P" would mean that the IT is for protection use. There are also many subclasses of protection ITs which are designated with additional letters or numbers.

The main difference between measurement ITs and protection ITs is that the latter need to maintain their accuracy at voltages or currents many times greater than their rated voltages or currents. This is particularly the case in protection CTs where their class designation may require them to perform satisfactorily at up to 20 times rated current.

EQUIVALENT CIRCUIT OF AN INSTRUMENT TRANSFORMER

If an IT is analyzed (from basic electrical principles) as two mutually coupled windings each having coupled and uncoupled impedance, the equivalent circuit of Fig. 4 can be derived. For simplicity, this equivalent circuit shows an IT with a nominal ratio of unity.

In Fig. 4, the combined effect of less-than-perfect coupling between primary and secondary windings and the effect of turns-ratio error are shown as a tapping "*a*" off the secondary winding. Some texbooks like to show the effect of less-than-perfect coupling as an additional reactive impedance in series with one of the windings.

In reality, if no local saturation of the core occurs, it is rare for the effects of less-than-perfect coupling to directly cause errors greater than 0.01% or 0.01 crad at 50 Hz, even when the primary and secondary windings are concentrated in different regions of the core circumference. When a situation is reached in a window-type CT where the ampere-turns become so unbalanced that local saturation of the core occurs, errors are likely to become as high as 10% and 10 crad. At the other extreme, however, when high-permeability toroidal cores are used with uniformly distributed windings, the effect of less-than-perfect coupling would not be expected to cause errors much greater than one part per million at 50 Hz.

The circuit of Fig. 4 does not take into account insulation leakage effects. However, for most practical purposes, particularly for CTs, this can be represented by a single impedance shunting the primary terminals.

TERMINAL MARKING CONVENTION

The universally accepted polarity convection for currents and voltages in an IT is shown in Fig. 4. When the instantaneous directions of the voltages and currents are as shown, the heavy dots represent a similarly marked terminal.

CALIBRATION OF INSTRUMENT TRANSFORMERS

The most common method of calibrating ITs is to compare them in a differential circuit with a standard IT of the same nominal ratio and of known error.

Voltage Transformer Testing Circuits

A basic circuit for the intercomparison of two VTs is that of Fig. 5. In this circuit, "V1" represents an ac instrument which indicates (in terms of V2) the magnitude and phase of the difference in voltage between the secondaries of the standard VT and the VT under test. An instrument designed to compare one VT with another is commonly called a *voltage transformer testing set* (VTTS).

The earthing arrangement should be specially noted in Fig. 5. For safety reasons, one of the secondary terminals of both VTs must be connected to earth. This means that there is no choice but to have the measuring circuit (V1 in Fig. 5), floating up at the secondary voltage of the VTs unless an isolating VT is connected between the "high" ends of the two secondary windings. The alternative of measuring the difference voltage between the "low" ends of the two secondary windings could lead to a large systematic error in the measurement. This is because any insulation leakage currents between the primary and secondary windings of one of the VTs, driven by the full primary voltage, will flow to earth through the measuring circuit. In most test circuits (except where two designated "unearthed" VTs connected between phases of a three-phase system are being compared), it will also be necessary to earth one primary terminal of both VTs.

Current Transformer Testing Circuits

A basic circuit for the intercomparison of two CTs is that of Fig. 6. In this circuit, "A1" represents an ac instrument which indicates (in terms of A2) the magnitude and phase of the difference in current between the secondaries of the standard CT, and the CT under test. An instrument designed to compare one CT with another is commonly called a current transformer testing set (CTTS).

The earthing arrangement of a CT testing circuit is not as critical from the safety point of view as that of a VT testing circuit. In order to minimize measurement errors, however, it is important that one point on the primary circuit and one point on the secondary circuit are earthed. Figure 6 shows the common secondary terminals as earthed. This not only defines the potentials of both CT secondaries, but also eliminates any errors due to the measuring circuit not being at earth potential.

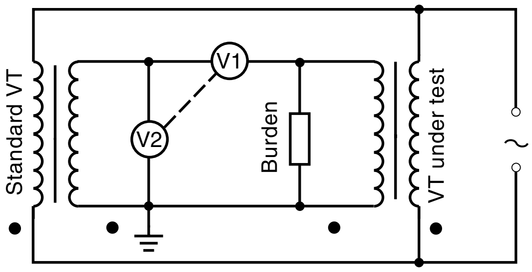

Figure 5. Differential circuit for intercomparing two voltage transformers. The same voltage is applied to both primary windings, while voltmeter V1 simply reads the difference between the two secondary voltages.

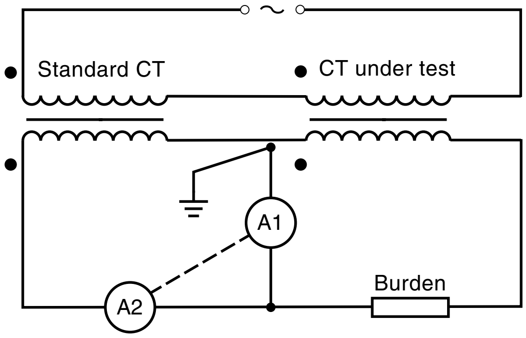

Figure 6. Differential circuit for intercomparing two current transformers. The same current is passed through both primary windings, while the ammeter A1 simply reads the difference between the two secondary currents.

There is no best position for the earth on the primary circuit, however. This is because if one side of the supply is earthed, the primary winding of one or other of the two CTs will be floating above earth, which might cause its errors to change. If the common primary terminal is earthed, any leakage currents between one side of the supply and earth will cause the primary currents of the standard CT and CT under test to be unequal. In order to estimate systematic errors due to earthing arrangements in a CT testing circuit, it is necessary for the metrologist to investigate changes in error with all possible earthing arrangements for each individual CT under test and, from these, assign a component of uncertainty. When the highest accuracy of measurement is required, changes in errors due to different earthing arrangements can be eliminated by employing electrostatically screened standard CTs (4).

Coordinate Systems

There are basically two types of instrument transformer testing sets (ITTSs). The first is where the difference voltage or current is balanced manually against a voltage or current derived from an ac potentiometer. In this method, the out-of-balance voltage or current is displayed on a galvanometer or amplifier-driven cathode ray tube, and, at balance, the error quantities are read on the balancing dials. In the second type, the difference voltage or current is fed into a microprocessor-driven circuit which outputs the error measurement as a digital readout. In practically all commercial ITTSs, the circuitry is such that the difference voltage or current is resolved into rectangular components.

Provided that the error being measured is within about 0.1 % and 0.1 crad, the difference in indication between the measured quantity in rectangular coordinates and the defined quantities in polar coordinates, is insignificantly small. If larger errors than these are indicated, corrections can be applied to convert from rectangular to polar coordinates according to the following formulae (5).

$$C_R = \sqrt{(1+a)^2 + b^2} - (1+a) \tag{2}$$

$$C_P = \left[\tan^{-1}\frac{b}{(1+a)}\right] - b \tag{3}$$

where

C_R is the correction to the indicated voltage error or current error in per unit
C_P is the correction to the indicated phase displacement in radians
a is the indicated voltage error or current error in per unit
b is the indicated phase displacement in radians

For all practical purposes, these formulae may be approximated to the following:

$$C_R \approx \tfrac{1}{2}b^2 \tag{4}$$

$$C_P \approx -ab \tag{5}$$

Some manufacturers of ITTSs do not indicate in their literature whether or not these corrections must be applied. With the microprocessor-controlled type of ITTS, it is common for these rectangular-to-polar coordinate corrections to be applied automatically as part of the software.

Calibration Procedure

As a preliminary procedure before calibrating CTs, both the standard CT and CT under test should be demagnetized. This is necessary because during previous use, one of the CTs might have been subjected to switching surges or a component of dc in one of its windings, either of which might polarize the core. This in turn will change the magnetizing current and hence change the errors. Demagnetization can be achieved by applying a voltage to the winding with the highest number of turns with all other windings open circuited. The voltage should be obtained from a variable-voltage source and raised slowly until saturation of the core occurs. Saturation can be detected on an ammeter in series with the winding to which the voltage is applied. Before saturation, little or no current will be seen to flow, but on the inception of saturation a sudden increase of current will occur. The voltage should then be lowered slowly to zero again. It is extremely important that demagnetization is not obtained by applying voltage to the winding with fewest turns, because if it is, then high peak-voltages might be induced in the winding with the highest turns. This in turn could break down insulation or cause electric shock.

The primary voltage or current in an IT testing circuit should never be fed directly from a voltage-regulating device or electronic amplifier. Small components of dc are likely to emanate from either such device which will change the characteristics of the ITs in the test circuit. To block such currents from the test circuit, an isolating transformer should always be used as a buffer.

It is rarely necessary to demagnetize VTs before a test because the very action of applying rated voltage to their primary winding is enough to eliminate any residual polarization that might be present in the core.

When calibrating ITs using a differential circuit, first apply a minimal amount of voltage or current while checking that polarities are correct. If full-load excitation is applied with incorrect polarity on one of the ITs, double full-load voltage or current will be applied to a measuring circuit, and this could cause a lot of damage. If all is well with polarities, then momentarily apply full-load excitation (without taking any readings) to eliminate any remaining polarization of the core.

If the calibration is to be made over a range of voltages or currents, start from the lowest excitation required, and finally, after working upwards to the highest excitation, repeat the reading at the lowest excitation. The difference in readings between the first and last settings will then be an indication of any component of uncertainty due to instability.

When calibrating VTs using a manually balanced VTTS, it may be discovered that when the excitation reaches a certain value, instability is detected on the balance-indicating device. If this instability becomes worse as the excitation is raised further, it is a probable sign that PDs are present either internally to one of the VTs, or externally to the VTs in the form of corona. In either case, if the effects cannot be eliminated, the ITTS's readings may have little useful meaning.

When calibrating CTs, it may be discovered that when a certain excitation is reached, the CTTS's reading slowly drifts with time. If this instability becomes worse as excitation is raised further, it is a probable sign that a small component of dc has entered into the circuit due to bad contacts. Upon detecting such instability, it will be necessary to check the tightness of all contacts and demagnetize all CTs in the circuit again; otherwise the readings may have little useful meaning. If the effect recurs, it will be necessary to search for nickel- or chromium-plated terminals in the circuit and, in extreme cases, remove the plating from the actual contact faces.

AUTOMATIC INSTRUMENT TRANSFORMER TESTING SETS

There is at least one serious shortcoming with all automatically balancing, digital-readout ITTS. That is, any instability that might be present in either the standard IT or IT under test, such as the inception of partial discharges, will not be evident (as it would be on a testing set balanced with the use of a galvanometer or cathode ray tube), and, as a result, a false indication may occur. Users of such ITTSs should therefore make alternative arrangements to detect instabilities, such as connecting a cathode ray oscilloscope across the secondary terminals.

APPLYING CORRECTIONS FOR INSTRUMENT TRANSFORMERS

Standard Transformers

When an IT is calibrated by comparing it with a standard IT, the errors of the standard, in both magnitude and phase, must be added to the indicated errors to obtain (within the uncertainties) the true errors of the IT under test.

Transformers Used in Wattmeter Circuits

When a VT and CT are used to extend the range of a wattmeter or watthour meter, corrections must be made to the indicated value of watts or watthours for the errors of the ITs. These corrections are according to the following formula:

$$\text{Correction} = -(a + b) + (\beta - \alpha)\tan(\cos^{-1} pf) \tag{6}$$

where

a is the voltage error of the VT in per-unit
b is the current error of the CT in per-unit
α is the phase displacement of the VT in radians
β is the phase displacement of the CT in radians
pf is the power factor

Note that all the terms in Eq. (6) are algebraic quantities including power factor. When the power factor is leading, the sign of the power factor (from the point of view of this formula) is positive; and when the power factor is lagging, the sign of the power factor is negative. Note also that this formula is correct for sinusoidal quantities only.

Some organizations use a convection where a positive sign is assigned to the value of a lagging power factor. Therefore metrologists should be careful that the power-factor sign convention is stated before they use any formulae given for wattmeter corrections. In ITTSs, however, the universally adopted convention is for a positive sign to be synonymous with a leading phase displacement and vice versa.

UNCERTAINTIES IN THE ERRORS OF INSTRUMENT TRANSFORMERS

The errors of an IT will change by small amounts with small changes in excitation level, frequency, burden, and temperature. Therefore when calibrating or using an IT, separate investigations should be made to ascertain the coefficients for these parameters so that components of uncertainty can be applied for whatever arbitrary limits are to be assigned to likely changes in these parameters. As a guide, these components of uncertainty can be estimated as follows.

Excitation Level

If the calibration is made over a range of different voltages or currents, a curve of error against excitation level can be plotted; and from the slope of the curve at any excitation, a component of uncertainty can be estimated. In most cases it will be found that the slope of the curve is greatest at the lowest excitation; and therefore from simple inspection of the figures at the two lowest levels of excitation, a component of uncertainty can be estimated. An exception to this rule might occur in an IT which is so constructed that at the highest level of excitation, the core flux density is close to saturation. In such cases it will be found that the errors (particularly the phase displacement) will change very rapidly as full excitation is reached. With such an IT, a separate uncertainty may need to be given for different excitation levels.

When an indicating instrument in the secondary circuit is used to set the voltage or current in the primary circuit, care should be taken (when doing so) to take into account the error in ratio of the IT. If this is not done, an additional uncertainty will result.

Frequency

Most electricity authorities in Western countries guarantee their frequency to be within ±0.2 % of nominal at all times except under fault conditions, so this is a good starting point for estimating a component of uncertainty for frequency. It is not usually convenient or even possible to make deliberate changes in frequency so as to estimate a frequency coefficient of the IT. Theory states, however, that the change in error due to change in frequency in a VT will be the same as for the same percentage change in voltage level. Similarly in a CT, the change in error with change in frequency will be the same as for the same percentage change in total burden. Note that total burden of a CT is an impedance equal to the externally connected burden plus the internal resistance and leakage reactance of the secondary winding. For the purpose of estimating the internal burden of a CT, the dc resistance can usually be taken, because the leakage reactance should be negligible.

Burden

The greatest component of uncertainty during both the use of an IT and during its calibration is usually that due to errors in applying its correct burden. It is usually easy to make a deliberate small change in burden during calibration to ascertain the IT's burden coefficient.

Temperature

It is not usually convenient or possible to change the temperature of an IT during calibration to ascertain its temperature coefficient. However, calculations can be made of the temperature coefficient from measured internal-circuit parameters of the IT and certain assumptions. These assumptions are as follows:

1. Winding resistances changes by +0.4% per °C.
2. Excitation reactance changes by −0.1% per °C.
3. Excitation resistance does not change with temperature.
4. Leakage reactances are negligible compared with winding resistances.

Other Components of Uncertainty

Other components of uncertainty that should be considered during the calibration of an IT are as follows:

1. The uncertainty in the standard IT against which the IT under test is calibrated.
2. The uncertainty in the ITTS's indication.
3. Uncertainties due to rounding off of both the reported errors and the reported uncertainty.
4. The effect of different earthing arrangements.
5. The effect of primary conductor configuration in a window type CT.
6. Possible change in errors due to self-heating (usually negligible).
7. Instabilities.

VOLTAGE TRANSFORMERS CONNECTED PHASE-TO-PHASE

A standard VT is normally calibrated with one of its primary terminals at earth potential. However, if such a VT needs to be used with its primary winding connected between phases of a three-phase system, the additional errors that will result can be estimated. These additional errors are based on the assumption (verified from practical experiment) that a VT has a component of error proportional to the voltage (in magnitude and phase) of the midpoint of its primary winding above earth.

A VT intended for use with its primary winding connected between phases of a three-phase system can be calibrated as follows. First calibrate the VT with one of its primary terminals earthed (say the "A" terminal), and then repeat the calibration with the other terminal earthed (say the "B" terminal). The formulae below can then be used to calculate the additional errors (from those measured with the "A" terminal earthed) for the case where the VT is connected between phases of a three-phase system of phase sequence A–B–C.

$$\Delta VE = -\frac{(VE_{\mathrm{A}} - VE_{\mathrm{B}})}{2} - \frac{(PD_{\mathrm{A}} - PD_{\mathrm{B}})}{2\sqrt{3}} \tag{7}$$

$$\Delta PD = -\frac{(PD_{\mathrm{A}} - PD_{\mathrm{B}})}{2} + \frac{(VE_{\mathrm{A}} - VE_{\mathrm{B}})}{2\sqrt{3}} \tag{8}$$

where

ΔVE is additional voltage error (in per unit)
ΔPD is additional phase displacement (in radians)
VE_{A} is voltage error (in per unit) with terminal "A" earthed
VE_{B} is voltage error (in per unit) with terminal "B" earthed
PD_{A} is phase displacement (in radians) with terminal "A" earthed
PD_{B} is phase displacement (in radians) with terminal "B" earthed

Corrections for the above additional errors are difficult to apply with confidence, particularly because the phase sequence of the supply must be known with certainty. If the phase sequence is the reverse of A–B–C, the signs of the second terms in Eqs. (7) and (8) must also be reversed. As the additional errors are usually no more than a few parts per million, it is probably safer to apply them as an additional component of uncertainty rather than risk applying the wrong sign to a correction.

CALIBRATION OF THREE-PHASE VOLTAGE TRANSFORMERS

When one phase of a three-phase VT is calibrated against a single-phase standard VT, all three phases must be energized during the calibration; otherwise a systematic error will be introduced. Experience has shown that this is necessary even if the three-phase VT consists of three single-phase VTs mounted in the same tank. Also, the phase sequence of the supply must be noted as part of the calibration, because if the phase sequence is reversed, significant changes in the VT's errors are likely to occur.

ABSOLUTE CALIBRATION OF INSTRUMENT TRANSFORMERS

When it is not appropriate to calibrate an IT by a differential method against a standard IT, such as in a laboratory that is the highest authority in a country, an absolute method must be used.

Most absolute methods of VT calibration involve comparing a VT with a capacitance divider in a bridge circuit, with either (a) the capacitors themselves being calibrated by some other absolute method or (b) the relative values of the capacitors being calibrated by a "buildup" method (6). In the United States and some other countries, the term "bootstrap" tends to be used instead of the term "buildup." A capacitance buildup usually involves measuring a number of three-terminal capacitors individually against one arbitrary reference capacitor and then reconnecting one or more of these capacitors in parallel in each arm of a bridge.

A method for the absolute calibration of VTs or CTs is to construct a special IT with a primary winding made up of sections which can be connected in various series–parallel arrangements. If one of the winding arrangements results in a ratio of unity, which can be calibrated absolutely in a differential circuit by comparing the primary directly with the secondary, it could be assumed that all the other ratios will have the same errors. Such an assumption would be conditional that errors due to insulation leakage currents had been eliminated, as would errors due to imperfect sharing of currents when the winding sections are connected in parallel.

An extension of the above can be used in the absolute calibration of CTs where two CTs of known errors, connected with their primaries in parallel and their secondaries in series, are used to obtain a known, composite CT of higher ratio (7).

An extension of either of the above can be used in the absolute calibration of CTs where a window-type CT is calibrated with multiple inserted primary turns and then assumed to have the same errors with fewer primary turns. For this assumption to be valid, it would be necessary to know that the CT is insensitive to primary-turns configuration.

COMPENSATED INSTRUMENT TRANSFORMERS

Compensation methods may be divided into the categories of (1) simple passive methods, (2) amplifier aiding, and (3) two-staging. Also, any combination of the three categories might be used together.

Simple Passive Compensation

The simplest and most common method of compensation used in measurement-class ITs is what is termed "turns compensation." For example, if the component of voltage error or current error (at rated burden) due to loading is -1%, all that is needed is to make the secondary turns 1% greater than nominal in a VT or 1% fewer than nominal in a CT for the error in ratio to be minimized. Of course, the amount by which the errors change with change of burden will not be improved, while the phase displacement will not be improved at all. Therefore this method of compensation is only efficient for those ITs used in the measurement of voltage or current, or in the measurement of watts where the power factor is close to unity.

Other methods of simple passive compensation (8,9) effectively supply the IT with a negative burden from a separate, adjustable source which cancels out the positive burden supplied to the load.

Amplifier Aiding

There have been large numbers of circuits devised where electronic amplifiers are used to reduce the errors of ITs. Basically, most amplifier aiding methods incorporate a unity-gain buffer amplifier on the output of the IT so that the IT itself is supplying zero burden and the amplifier is supplying the load (10); or the amplifier acts separately to supply the magnetizing current, and hence reduces the voltage drop in the windings (11). Few, if any, of the amplifier-aiding methods compensate for errors due to less-than-perfect coupling between windings, or turns-ratio errors, while most do not compensate for errors due to insulation leakage. A disadvantage of amplifier aiding is that a separate supply must be brought into the IT to power the amplifier.

Two-Staging

The theory behind the two-stage IT was first proposed by Brooks and Holtz as early as 1922 (12). Two-staging involves an IT with two cores, although not all two-core ITs are two-stage ITs. Basically, the primary and secondary windings of a two-stage IT are applied equally to both cores, and an auxiliary winding (often called the *magnetizing winding*) is applied to just one of the cores (Fig. 7). In a two-stage VT, the auxiliary winding has the same number of turns as the primary winding and is connected in parallel with the primary. In a two-stage CT, the auxiliary winding has the same number of turns as the secondary winding and is connected in parallel with the secondary. Toroidal cores are usually used in two-stage ITs. After the auxiliary winding is applied to the first core, the two cores may be stacked together axially before the main windings are applied. Alternatively, the second core may be constructed in such a way that it totally encloses the first core. If the latter core configuration is used, the second core is often referred to as a *magnetic shield.*

Mathematically, it can be shown that the errors of a two-stage IT can be reduced almost to zero at zero external-burden. This will be so no matter what the internal winding impedance. If the external burden connected to an IT is not zero, or at least is not small, the application of two-staging will result in an IT with larger errors than would have resulted if the same amount of iron and copper had been used in a single-stage IT. Two-staging does not reduce components of error due to insulation leakage impedance, turns-ratio error, or less-than-perfect coupling between the windings.

From the above it might appear that two-staging would be of very little practical use. However, by various circuit additions, good use can be made of the low-error potential of a two-stage IT. For example, in a two-stage VT, an unloading addition to the circuit can be added as described in Ref. 13.

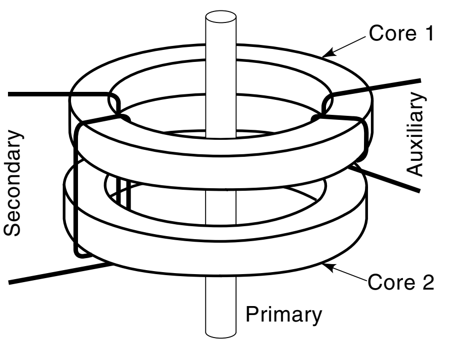

Figure 7. Winding arrangement of a two-stage current transformer.

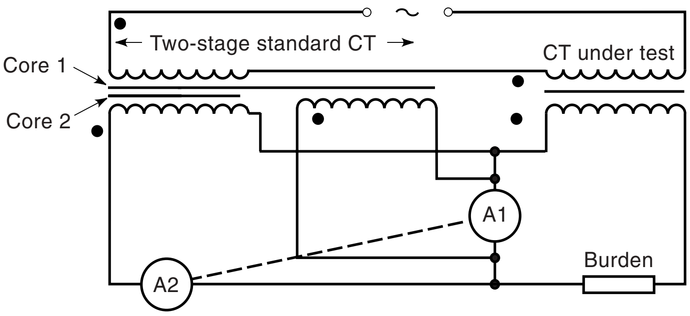

Figure 8. Two-stage current transformer in a differential calibration circuit. The two-core standard is in effect two current transformers, where that on core 2 does the work, and that on core 1 compensates for the errors.

In a two-stage CT, a unit-gain buffer amplifier can be connected between the auxiliary-winding output and the secondary terminals. With such a system, the component of error due to loading would remain negligible for any external burden up to the limit of output of the amplifier. Also of note is that the amplifier would only need to cope with the small error component of current whereas a single-stage, amplifier-aided CT would require the amplifier to cope with the full secondary current. Some manufacturers make two-stage laboratory-standard CTs amplifier-aided as described above.

Another practical example of the use of a two-stage CT is in a differential calibration circuit (14). If the auxiliary winding is connected directly into the difference current part of the circuit as shown in Fig. 8, the burden applied to the auxiliary winding is practically zero, and the same reduction in error will be obtained as with amplifier aiding.

A special example of a two-stage CT in a differential calibration circuit is the so-called "current comparator" (15). With such a system, ammeter A1 in Fig. 8 is replaced by a current injection circuit derived from A2, and the magnitude and phase of this injected current is adjusted until zero flux is detected in the core to which the auxiliary winding is applied. This zero flux is detected by measuring zero voltage across an open-circuited winding (Fig. 9).

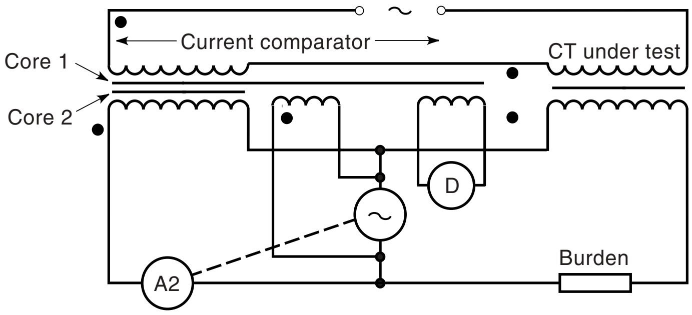

Figure 9. Basic circuit of a current comparator. This is fundamentally the same as the circuit of Figure 8, with the additional feature that the flux in core 1 is forced to be zero.

It should be emphasized that the very small error potential of the standard CTs shown in Figs. 8 and 9 will not be realized if the CT is taken out of the differential circuit.

OTHER SPECIAL DESIGNS OF INSTRUMENT TRANSFORMERS

Balancing Windings

In window-type CTs with ampere-turn ratings greater than about 2000, the magnetizing forces of the primary and secondary windings are very large. Although these forces are almost equal and opposite, and almost cancel each other out where both windings are uniformly distributed around the core circumference, any small imbalance of primary conductor configuration will cause large leakage fluxes to flow across air paths (3).

A method of reducing these leakage fluxes, and hence making the CT insensitive to the primary-conductor configuration, is with the use of balancing windings. Such windings consist of a number of equal sections (usually at least eight) all with the same number of turns, each occupying a separate sector of the core circumference, all of them open circuited, and all of them connected in parallel. The effect of these windings is that any imbalance of ampere turns around the core circumference will cause circulating currents to flow between the balancing-winding sections. This in turn will decrease the flux in those regions of the core where the magnetizing forces are greater, but will increase it where the forces are lesser.

For these balancing windings to be effective, there must be little voltage drop in the windings themselves. In order to achieve this aim, practical experiment has shown that the sum of the weight of copper in all the balancing-windings sections should be at least equal to the weight of copper in the secondary winding. Also, the resistance of the paralleling links should be no more than one-tenth of the resistance of any of the balancing-winding sections.

Another way of achieving ampere-turn balance is to enclose the whole of the core and winding assembly in a toroidal, conducting metal envelope made in such a way that it does not form a short-circuited turn. This in effect is an infinite number of single-turn open-circuited windings connected in parallel. Such an arrangement is often referred to as a "magnetic shield," although this is not the same thing as a magnetic shield already described as used in a two-stage IT. Magnetic shields as described above are usually made from copper or aluminum, and again their weight should be at least equal to the weight of copper in the secondary winding.

Transformer Windings with Large Numbers of Turns

When the number of turns on the primary winding of an IT is greater than about 2000, insulation leakage currents between winding layers are likely to contribute a major component of error in the IT. A method of reducing this component of error could be to increase the insulation between winding layers, but a more efficient method is to divide the winding in question into series-connected sections, with each section confined to a separate sector of the core circumference. By so doing, this component of error can be reduced by a factor of up to n^2, where n is the number of sections (13,16). In order to gain the full effect of this winding method, however, extra insulation must be applied between the winding in question and any other winding or electrostatic screen.

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