GET-97D
Supersedes GET-97C

MANUAL OF

INSTRUMENT TRANSFORMERS

OPERATION PRINCIPLES AND APPLICATION INFORMATION

GENERAL ELECTRIC

FOREWORD

THIS manual is designed to give the reader a better understanding of the theory of operation and the application of instrument transformers. Because textbooks, in general, do not adequately cover the practical aspects involved in using instrument transformers, it was felt that such a treatise would be very helpful both to the practicing engineer and to the student.

Any person engaged in the fields of power generation, transmission, and application is faced with countless metering and relaying problems that can be solved only by the correct application of instrument transformers.

The manual is written with the intention of helping the reader apply standard transformers to his own needs rather than of making him an accomplished designer of instrument transformers. With this intention in mind, a general discussion of problems that are common to instrument transformers is presented. By making use of this information, the reader should be able to take full advantage of the many types of transformers now available as standard items.

It is suggested that the reader obtain for convenient reference a copy of USASI Standards for Instrument Transformers, USAS C57.13.

CONTENTS

CHAPTER ONE—FUNDAMENTALS

CHAPTER TWO—POTENTIAL TRANSFORMERS

CHAPTER THREE—CURRENT TRANSFORMERS

CHAPTER ONE
FUNDAMENTALS

INSTRUMENT transformers are essential parts of many electrical measurement systems and, as such, their qualities will affect directly the over-all accuracy and performance of such systems. Their place in the system is that of Auxiliary Means—Basic Elements that change the magnitude, but not the nature of a quantity being measured, to make it more suitable for the Primary Detector*. Thus, primary voltages or currents are transformed in magnitude to secondary values that are suitable for use with relays, meters, or other measuring devices that are rated usually at values of 120 volts or 5 amperes.

A second and equally important function of an instrument transformer is to provide insulation between the primary and secondary circuits, thus simplifying the construction of the measuring devices and providing safety for the personnel using those devices.

GENERAL TYPES

There are two general types of instrument transformers: instrument potential transformers, used in voltage measurements; and instrument current transformers, used in current measurement. Both types serve as insulators between the normally high-voltage primary and low-voltage secondary circuits.

The primary of potential transformers is connected either line to line or line to neutral, and the current that flows through this winding produces a flux in the core. Since the core links both the primary and secondary windings, a voltage is induced in the secondary circuit. The ratio of primary to secondary voltage is roughly in proportion to the number of turns in the primary and secondary windings and is usually that proportion which will produce 115 or 120 volts at the secondary terminals when rated voltage is applied to the primary.

The current transformer differs from the potential transformer in that the primary winding is designed for connection in series with the line. The ratio of primary to secondary current is, roughly, inversely proportional to the ratio of primary to secondary turns and it will usually produce five amperes in the secondary when rated current is flowing in the primary.

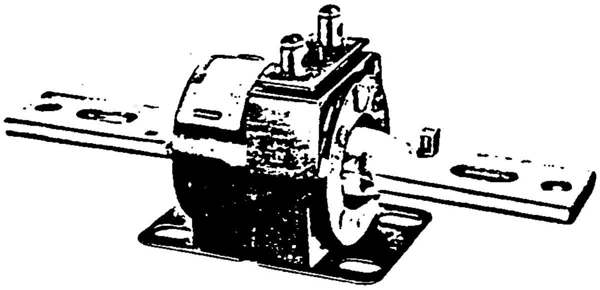


Fig. 1. Type JCT-0 instrument current transformer for indoor service; rated 600 volts

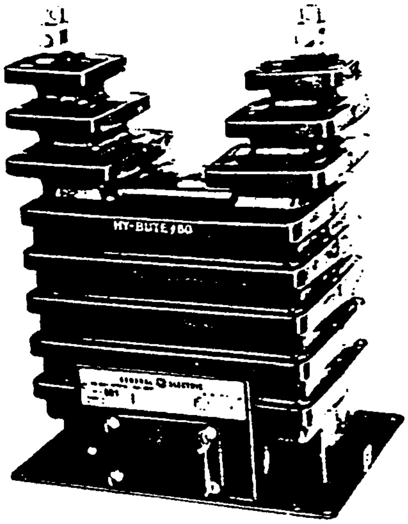


Fig. 2. Type JVW-5 instrument potential transformer for outdoor service; rated 15 kv

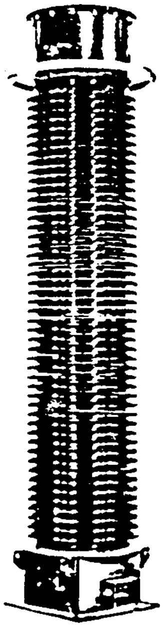


Fig. 3. Type EW-1300 cascade potential transformer for outdoor service; rated 345 kv

---

*For further information on classification of measurement systems see *Functional Analysis of Measurements* by I. F. Kinnard, *AIEE Transactions*, Volume 60, 1946, pp. 987-992.

INDOOR OR OUTDOOR SERVICE

To be suitable for use in a measurement system, an instrument transformer must not only be able to perform its function in the system, it must also fit the needs of the conditions under which it is to be used.

As many transformers are used indoors, a large number of transformers are made for this protected service. Many others, however, must be installed in the open; so an additional line of outdoor transformers is available.

In general, outdoor types for voltages of 69,000 or less are molded in specially compounded butyl called HY-BUTE/60® insulation. Transformers operating above the 69,000-volt level are normally liquid-filled and enclosed in weatherproof casings which also contain the insulating fluid.

ACCURACY

To be a useful part of a measurement system, instrument transformers must change the magnitude of the voltage or current that is being measured without introducing any unknown errors of measurement into the system. Their accuracy of transformation must, therefore, be either of a known value so that the errors can be included in the computation of the overall measurement, or the errors must be within the limits of a specified small value so that they may be disregarded safely.

Three factors affect this accuracy: (1) the design and construction of the transformer itself; (2) the circuit conditions such as voltage, current, and frequency; and (3) the burden imposed on the secondary circuit of the transformer. Consequently, for any specific transformer and circuit condition, the accuracy is dependent on the burden, and may be different for each burden. In general, the higher the burden, the greater the error; however, this relationship is often affected by the compensation, which will be described in later chapters.

In order that instrument transformers can be classified for accuracy, the USASI Standards for Instrument Transformers, USASI Standard C57.13, has specified various accuracy classifications for each of several standard burdens that cover the range normally encountered in service. In this way, any transformer or any particular types of transformers, all manufactured to the same design specifications, can be classified for accuracy at each of the standard burdens; thus, a standardized means of comparing the accuracy of various designs is available. This system of classification will be described in greater detail in later chapters.

INSULATION

It was stated before that an instrument transformer changed the magnitude of an electrical quantity to a value which is suitable for the measuring device used to measure that quantity. Since normal meters, instruments, and relays are suitable only for low-voltage service, the instrument transformer, whether current or potential, must insulate the high voltage and provide a secondary voltage above ground potential that is low enough to suit the measuring device. A potential transformer must accomplish this transformation accurately, but both potential and current transformers must insulate the End Device from the primary voltage. (An End Device can be defined as an assembly of measurement components that responds quantitatively to the quantity measured and performs the final measurement operation. An End Device performs the final conversion of Measurement Energy to an indication, record, or the initiation of control.)

Insulation for instrument transformers usually takes one of two forms: dry-type or liquid-filled.

With dry-type designs, one method of constructing insulation is to mold HY-BUTE/60 butyl insulation around the core and windings. (See Fig. 4.) Butyl is a synthetic flexible material which is injected into a mold containing the steel and copper parts of the transformer. The butyl fills the space around and between the windings, forming a homogeneous one-piece insulation and lending itself to a pleasing outside appearance. The use of HY-BUTE/60 insulation provides an insulation system suitable for operation under exposed outdoor conditions.

Another method of dry-type construction is to encase the core and windings in a HY-BUTE/60 insulation shell which is then filled with epoxy resin. This method makes use of the optimum qualities of both materials: HY-BUTE/60 insulation for its outstanding qualities of non-shattering ruggedness, non-creep-tracking, flame-retarding, and time-proven weathering; epoxy for its impregnating casting qualities, and dielectric and mechanical strength. The joining of these two materials has allowed the extension of dry-type insulation into higher voltage classes, previously requiring a liquid or gas insulation.

Liquid-filled designs have an outer casing, usually of metal and porcelain, which serves as a housing for the transformer and a container for the oil. In many cases, Pyranol®, a non-inflammable fluid, is used in place of the oil. This general type of insulation is used primarily for high-voltage transformers.

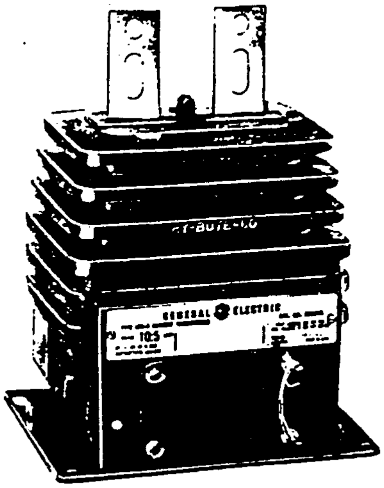


Fig. 4. Type JKW-3 butyl-molded instrument current transformer for outdoor service; rated 5 kv

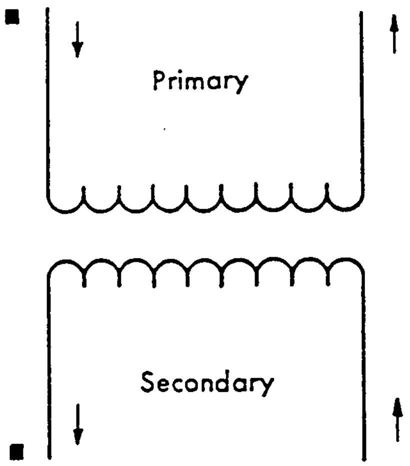


Fig. 5a. Relation of polarity marks to direction of current flow in instrument transformers

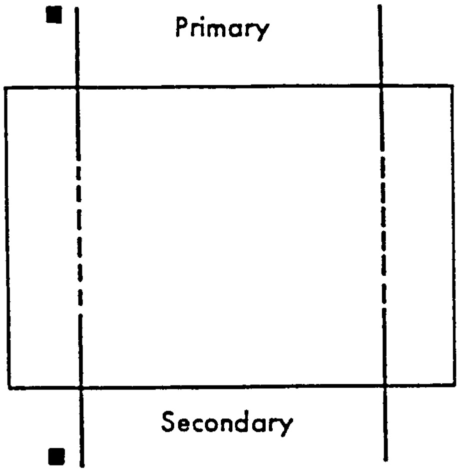


Fig. 5b. Simplified diagram of relation of polarity marks to direction of current flow in instrument transformers

Several tests are employed to insure that the insulation is adequate to protect both the measuring devices in the secondary circuit and the personnel using those devices. One of the most important of these is the impulse test which simulates the high-voltage surge condition encountered when a lightning stroke hits a power line and its associated equipment. Others include 60 Hz high-potential tests, ionization tests, and induced-voltage tests. The test values for low-frequency and impulse tests are specified by USASI Standard C57.13. A more complete discussion of this subject will be found in later chapters devoted to the subject of "Tests."

POLARITY

One primary and one secondary terminal of each instrument transformer is marked to indicate the relative instantaneous direction of primary and secondary currents. When current is flowing "in" at the marked primary terminal, current is flowing "out" at the marked secondary terminal. (See Fig. 5a.)

Either the marked or unmarked terminal of the primary winding of the current transformer can be connected to either the generator or load side of the line; likewise, either the marked or unmarked terminal of the primary winding of a potential transformer can be connected to either high-voltage line. Of course, there are exceptions to this rule such as single-bushing potential transformers that must be connected with the neutral-end terminal at ground potential. However, the *relative* polarities of the primary and secondary windings are important in all cases. *Considering direction of current only, connections can be made by assuming that the marked secondary line is a continuation of the marked primary line.* (See Fig. 5b.)

According to USASI Standards for power transformers, when marked primary and secondary terminals are connected together, the voltage between the unmarked leads is less than the voltage across the high-voltage winding. The same principle applies to instrument transformers; however, it must be remembered that "high voltage" refers to the voltage across the terminals of the winding, and in the case of current transformers, the secondary generally has a higher voltage between terminals than the primary. Yet the secondary is commonly called the low-voltage winding because, in speaking of the voltage of these windings, it is generally the voltage above ground that is involved.

TAPPED SECONDARY ARRANGEMENTS

Increasing use of tapped-secondary instrument transformers has developed considerable interest in the design details of these types.

In general, GE butyl-molded designs with secondary taps conform to USASI Standard C57.13 covering tapped instrument transformers. This Standard states:

> When taps are provided, each lead or terminal of an instrument transformer shall be marked with a letter and a number. The number shall be of the series 1, 2, 3, etc., the lowest and highest numbers indicating the full winding, and intermediate numbers indicating the taps in their relative order.

CURRENT TRANSFORMERS

On General Electric butyl-molded current transformers with center-tapped secondaries and three secondary terminals, such as Types JKM- and JKW-3, -4, and -5 and JKW-150 through -350, the higher ratio is usually obtained by using the full secondary winding X_1 and X_3 secondary terminals. The lower ratio is usually obtained by using the X_2 and X_3 terminals. (See Fig. 6a.)

Due to the compensation required to meet metering accuracy, the ratio correction factor of wound-primary-metering current transformers (Type JKM-3, -4, and -5 rated 10 through 800 amperes) will decrease about 0.0042 when using X_1 to X_2 instead of the correct connection, X_2 to X_3.

A similar change will occur using wound-primary switchgear current transformers (Types JKS-3 and -5) in 200/400- and 300/600-ampere ratings only. All other ratings of these types will have virtually no difference between the results obtained using either section of the winding.

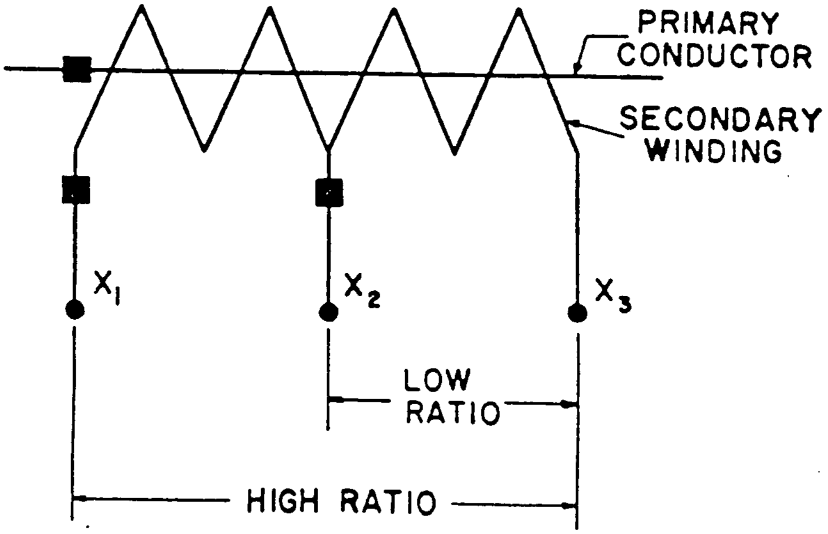


Fig. 6a. Typical wound-primary current transformer with tapped secondary and three secondary terminals

For greater ease of use, some manufacturers will provide four terminals and two separate terminal covers on mid-tapped transformers such as Types JAD-0, and JCP-0 for 600-volt insulation class and Types JCM- and JCW-3, -4, -5 and JCD- and JCB-3, -4, -5 for higher voltage. (See Fig. 6b.) With this construction, selection of the desired pair of terminals is simplified, and the unused pair may be sealed against accidental use.

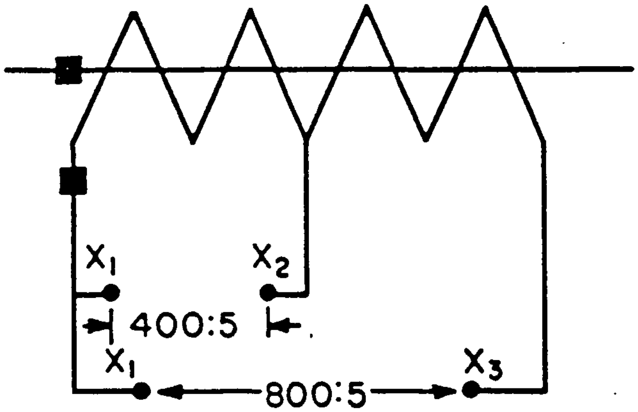


Fig. 6b. Typical window-type current transformer with four secondary terminals

On window-type current transformers rated 1000 amperes and above, the number of turns between X_1 and X_2 is usually the same as the turns between X_2 and X_3, and the accuracy using either pair would be very similar. On lower-ratio window-type units, there may be a significant difference in effective turns between X_1 and X_2 compared to X_2 and X_3 due to the effect of compensation.

For best accuracy, it is important that the correct pair of secondary terminals be used on metering-type current transformers. The correct terminals with respect to a particular ratio are invariably indicated on the transformer or the nameplate to eliminate any possible errors in making the correct connections.

POTENTIAL TRANSFORMERS

On tapped versions of butyl potential transformers, the higher ratio is obtained by using X_2 and X_3. (See Fig. 6c.) The lower ratio is obtained by using X_1 and X_3, the full secondary winding. A 2400/4800:120 JVM-3, for example, is actually a 4800:240 design with a secondary center-tap. On most butyl potential transformers, the results using X_2 and X_3 will usually be very similar to results with X_1 and X_2, as compensation is applied to the primary. (On ratios near or under 1:1, this may not always be true.)

The facts discussed above refer to standard designs. Odd ratios or special designs may not conform to these patterns.

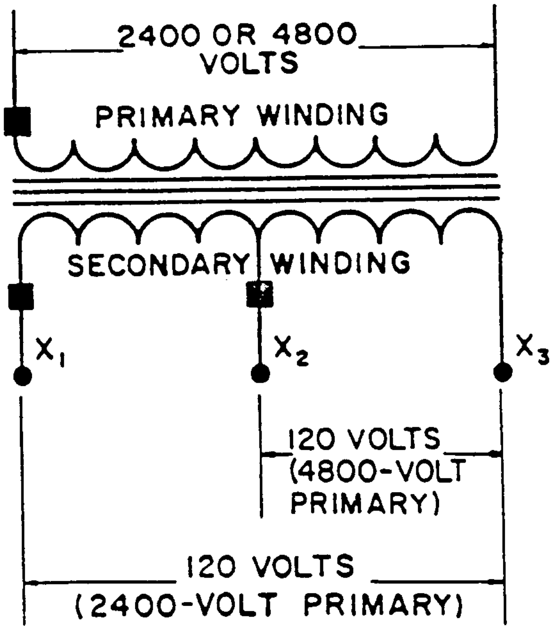


Fig. 6c. Typical potential transformers with mid-tapped secondary

CHAPTER TWO
POTENTIAL TRANSFORMERS

INSTRUMENT potential transformers are designed for connection line-to-line or line-to-neutral in the same manner as ordinary voltmeters. The secondary voltage bears a fixed relation with the primary voltage so that any change in potential in the primary circuit will be accurately reflected in the meters or other devices connected across the secondary terminals.

Potential transformers can be used with voltmeters for voltage measurements or they can be used in combination with current transformers for wattmeter or watthour meter measurements. They are used also to operate protective relays and devices, and for many other applications.

BASIC OPERATION

The user of a potential transformer normally seeks a safely isolated secondary voltage which is an exact proportionate representation of a higher primary voltage. The first of these objectives, isolation, is accomplished by well-designed and thoroughly tested insulation systems. The second objective of exact proportionality between input and output cannot be realized in practice. The degree to which this perfect state is approached is, however, a major factor in determining the quality of the transformer.

As stated on the preceding page, if standard polarity marks are observed, the secondary is in effect an insulated reduced direct extension of the primary. Perfect transformation could be expressed by $Vp = K \times Vs$, or primary voltage equals marked ratio K times secondary voltage. Assuming $K = 1$, phasor representation of this would be as in Fig. 7a.

Fig. 7a. Phasor representation

Vps—Primary voltage referred to secondary
Vs—Secondary voltage

Any transformer, whether loaded or not, will draw core-magnetizing current from the primary line. A constant error independent of burden results from this current flow, the magnitude of which depends directly on the quality of the core steel. The measured value of this error is recorded on a certificate of test furnished with General Electric butyl-molded transformers. Phasor representation of exciting current error is shown in Fig. 7b.

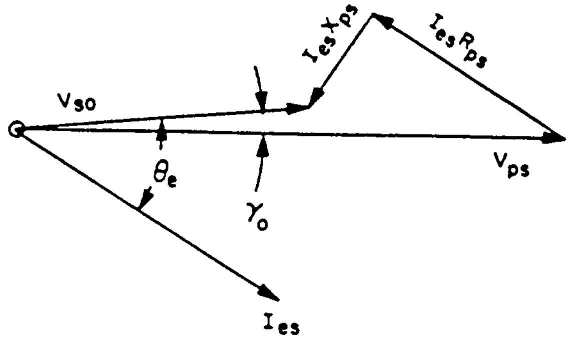


Fig. 7b. Phasor representation

Symbols for Figures 7b and 7c

Vps—Primary voltage referred to secondary
Vso—Secondary voltage with no burden
Rps—Primary resistance referred to secondary
Xps—Primary reactance referred to secondary
Ies—Exciting current referred to secondary
θe—Phase angle between Vso and Ies
γo—Phase angle between Vps and Vso
$\frac{Vps}{Vso} = RCF_o$ = Ratio correction factor with no burden

A variable error dependent on load or burden results from burden current flowing through the total effective transformer impedance. This burden error is independent of exciting current error. Phasor representation of these errors combined (Fig. 7c) determines the total error under any burden condition.

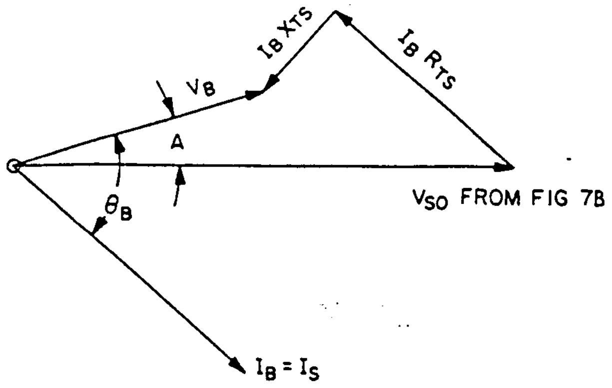


Fig. 7c. Phasor representation

Additional Symbols

V_B—Secondary voltage with burden
Rts—Total resistance referred to secondary
Xts—Total leakage reactance of transformer referred to secondary
I_B—Burden current $= I_S$—Secondary current
A—Phase angle between Vso and V_B
θ_B—Power factor angle of burden

Total error can now be expressed as the magnitude of V_B at an angle of $\gamma_o + A$ with respect to Vps. Measured error at stated burden unity power factor is recorded on the certificate of test furnished with General Electric butyl-molded transformers. From certificate data, calculations* can be made to determine transformer accuracy for any other burden within the rated value.

TERMS FOR EXPRESSING ERRORS

The ratio error is usually expressed as a *Ratio Correction Factor* (RCF) which is defined as the factor by which the marked ratio must be multiplied to obtain the true ratio. This is expressed as:

$$\text{RCF} = \frac{\text{True Ratio}}{\text{Marked Ratio}}$$

or: True Ratio = Marked Ratio × RCF.

The phase-angle error (γ) is the angle between the primary voltage vector and the secondary voltage vector reversed. It is usually expressed in minutes of angle. This angle is conventionally considered as positive when the reversed-secondary voltage vector leads the primary-voltage vector.

Thus, the ratio correction factor takes the form of a number, such as 1.004 or 0.998. The phase-angle error (γ) takes the form + 10 minutes or − 4 minutes as the case may be.

EFFECT OF BURDEN ON TRANSFORMER ERRORS

As shown in Fig. 7c, the error load or burden depends on both the magnitude of I_B and the angle between V_B and I_B. Therefore, the error is dependent on both the magnitude and power factor of Z_B, the external burden in the secondary circuit. Any change in the number or type of devices that are placed in the secondary circuit of the transformer will change R_B or jX_B, or both, and will affect the magnitude of the error due to burden.

If the power factor of Z_B is held constant, the magnitude of errors due to burden will vary linearly with burden VA, as shown in Fig. 8. As secondary voltage is essentially constant for this curve, note that increasing volt-amperes corresponds to increasing amperes and decreasing Z_B.

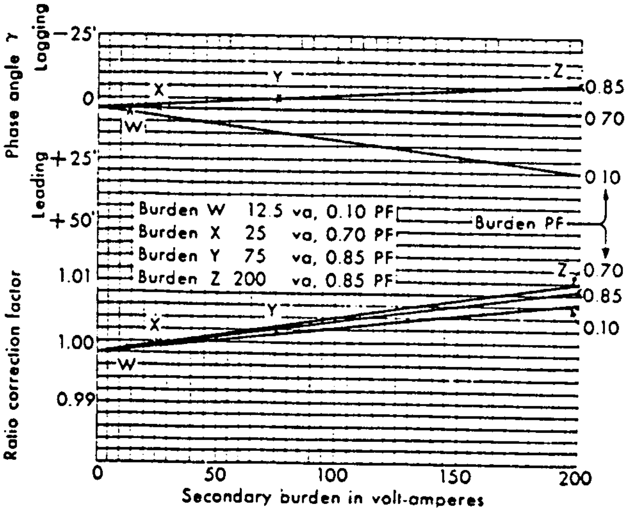


Fig. 8. Typical potential transformer characteristics

COMPENSATION

Most potential transformers are designed for the lowest practical exciting current and impedance of the windings. This means that the fundamental design is such that the errors are kept to a minimum. However, since the ratio error increases with an increase in the burden, the transformers are compensated to have the condition of zero ratio error with an average value of burden on the secondary, rather than minimum error at some extremely low burden. This is accomplished by making the actual turn ratio slightly

---

*Details derived and discussed in "Transmission & Distribution—Dec., 1959" article by F. R. D'Entremont entitled "How to use certificate test values to determine complete potential transformer accuracy characteristics."

different from that which is marked on the nameplate. This is shown on Fig. 8 by the fact that zero ratio error occurs at approximately 50 volt-amperes.

TEMPERATURE CHANGE

The accuracy of potential transformers is affected slightly by changes in temperature of the windings because the resistance of these windings varies as a result of the temperature change. This change in accuracy is usually under 0.1 percent for a 55 C change in temperature.

WAVE FORM

Voltage waves that contain third harmonics having a magnitude of as much as 25 or 30 percent of the fundamental will be reproduced in the secondary waves of most potential transformers with very little distortion, and the transformer errors will be changed very slightly. Waves that contain harmonics of a higher order than the third may not be generated as accurately because the amount of distortion increases as the frequency and magnitude of the harmonics increase. However, higher harmonics are usually of small magnitude, and in this instance, will cause little error.

VOLTAGE VARIATION

Potential-transformer errors are not affected by voltage variation unless the variation is of such magnitude as to change the ratio of exciting current to line voltage. Thus, voltages that are lower than rated voltage (nameplate rating) will not affect the accuracy appreciably, but those voltages higher than rated may cause saturation of the core—with resultant large errors and excessive heating. Most transformers will operate satisfactorily at 10 percent overvoltage, but values higher than this may cause increased errors and excessive heating.

FREQUENCY VARIATION

Normally, potential transformers are rated for use at one frequency only, although many designs are suitable for use on both 50 and 60 Hz circuits.

In general, an increase of as much as 100 percent above rated frequency will increase the errors only slightly, if at all. However, a decrease in frequency of more than 5 or 10 percent may lead to serious transformer errors, as well as excessive heating.

As the frequency is increased, the flux density in the core and the exciting current decreases, but the reactance of both the transformer windings and the burden increases. This increase in the reactance of the burden decreases the load current in the windings. Thus the increased reactance of the windings tends to increase the voltage drop in the windings; but at the same time, the decreased exciting current and load current tends to decrease the voltage drop. The net result depends on the design of the transformer in question and the circuit constants of the burden; but in general, only a very small increase in ratio and phase-angle errors will result from a considerable increase in frequency.

A decrease in frequency increases the flux density, the exciting current, and the load current, while it decreases the reactance. However, again depending on the design of the transformer, saturation of the core may be reached with a relatively small reduction in frequency. At this point, very large errors and considerable heating will take place.

EFFECT OF ERRORS ON INSTRUMENT READINGS

Both ratio errors and phase-angle errors are present in potential transformers. However, only the ratio error need be considered when potential transformers are used as part of a voltage measurement. The reading on the voltmeter will differ from the actual voltage to be measured by:

1. *The ratio of the transformer.* This is a desirable effect and is one of the principal reasons for using the transformer in the circuit. This ratio is marked on the transformer nameplate.
2. *The ratio error.* This is an undesirable effect. For high accuracy of measurement, this error must be taken into account when determining the actual primary voltage from the reading made in the secondary circuit. However, most potential transformers have a ratio error that is so small that it need not be considered in the usual measurement of voltage.

For measurements of power where the phase relationship between the voltage and current vectors enter the measurement (such as wattmeter readings), the phase-angle error must also be considered. Since an error in the voltage phase angle constitutes a shift in phase between the position of the voltage vector in the primary circuit and the corresponding voltage vector in the secondary circuit, the over-all result is to change the phase relationship between the voltage and current in the secondary circuit as compared to their relationship in the primary circuit. This will introduce an error in the wattmeter reading in addition to the ratio error. A graphical representation of this error is shown on Fig. 9. As with the ratio error, however, this phase-angle error is normally so small that it can be neglected in all but the most exacting measurements.

In general terms, a Ratio Correction Factor (RCF) greater than 1—for instance, 1.002—will cause the meters and instruments in the secondary circuit to read low (0.2 percent low for an RCF of 1.002).

A negative (lagging) phase-angle error will cause a wattmeter in the secondary circuit of a potential transformer to read high (for the normal situation of lagging line power factors). This results from the fact that a lagging potential phase-angle error decreases the power factor angle of the secondary circuit, over what it was in the primary circuit, by decreasing the angle by which the current lags the voltage as shown in Fig. 9. Since the watt reading results from the product of the voltage, current, and power factor (cosine of power-factor angle), a decreased angle gives an apparent higher power factor which makes the wattmeter read high.

STANDARD ACCURACY CLASSIFICATION

The USASI Standards for Instrument Transformers, USAS C57.13, has standardized on a method of classifying potential transformers as to accuracy. As the accuracy is dependent on the burden, standard burdens have been designated, and these are the burdens at which the accuracy is to be classified.

The standard burdens have been chosen to cover the range normally encountered in service and are listed by the letters W, X, Y, Z, and ZZ, as follows:

USASI STANDARD BURDENS FOR POTENTIAL TRANSFORMERS

Burden	Volt-amperes at 120 volts	Burden Power Factor
W	12.5	0.10
X	25.0	0.70
Y	75.0	0.85
Z	200.0	0.85
ZZ	400.0	0.85

NOTE—USASI Standards state that standard burdens for potential transformers shall have the same volt-ampere and power-factor values for all frequencies.

It should be pointed out that the burden of any specific meter or instrument may approximate, but seldom is the same as, any one of the standard burdens. The standard burden serves merely as a standardized reference point at which the accuracy of the transformer may be stated.

The accuracy classification as given by USASI is as follows:

USASI ACCURACY CLASSES FOR POTENTIAL TRANSFORMERS

Accuracy Class	Limits of Ratio Correction Factor and Transformer Correction Factor	Limits of Power Factor (Lagging) of Metered Power Load
1.2	1.012–0.988	0.6–1.0
0.6	1.006–0.994	0.6–1.0
0.3	1.003–0.997	0.6–1.0

The limits given for each accuracy class apply from 10 percent above rated voltage to 10 percent below rated voltage, at rated frequency, and from no burden on the potential transformer to the specified burden.

The *Ratio Correction Factor* (RCF) has been defined as the factor by which the marked ratio must be multiplied in order to obtain the true ratio.

The *Transformer Correction Factor* (TCF) represents a method of setting down in one number, the combined effect of the ratio error and the phase-angle error on wattmeter or similar measurements where the change in power factor from primary to secondary circuits enters the measurement. TCF is defined as the factor by which a wattmeter reading must be multiplied to correct for the combined effect of the instrument transformer ratio correction factor and phase angle. The limits of TCF, as indicated in the table above, have been set up by USASI for the range of load power factor set forth in the table. If the power factor of the primary circuit is outside this range, the TCF of the transformer also may be outside the limits specified, even though the transformer is correctly listed as one which will meet a certain accuracy class.

Since published data on potential-transformer characteristics, as well as the data given on transformer calibration certificates, are usually given in the form of ratio correction factor and phase-angle error, it is necessary to have a means of interpreting these data in terms of the accuracy classification given in the table. This is done as follows:

For any known ratio correction factor of a given potential transformer, the positive and negative limiting values of the phase-angle error (γ) in minutes may be adequately expressed as follows:

$$\gamma = 2600\ (\mathrm{TCF} - \mathrm{RCF})^{\dagger}.$$

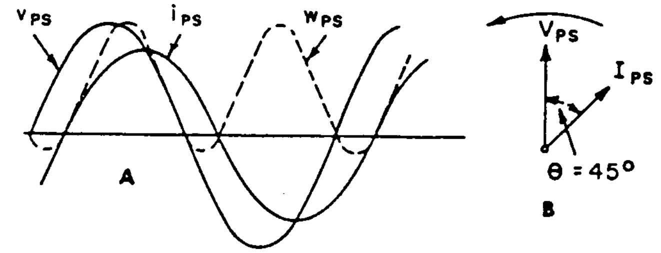
[†] The formula—$\gamma = 2600\,(\mathrm{TCF}\text{-}\mathrm{RCF})$—and the parallelograms of Fig. 10 derived from it are approximate only. The correct formula is: $\cos(53.13^\circ + \gamma) = 0.6\,\frac{\mathrm{RCF}}{\mathrm{TCF}}$. However, the approximate formula introduces very little error into the calculation and is entirely adequate for normal purposes.

PHASE RELATIONS IN INSTRUMENT TRANSFORMERS

The USASI Standards designate all leading transformer angles as positive. Based on this, the accompanying diagrams show graphically the phase relations in the primary and secondary circuits of a typical case and the derivation of the correction factor for that case.

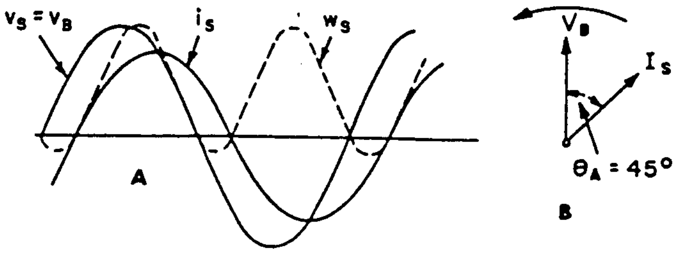
NOTES:

1. Curved arrows show direction of rotation of vectors.
2. In these diagrams, the length of vectors for effective values (for example, V_{ps} and I_{ps}) should be 0.707 times the peak of instantaneous values (for example, v_{ps} and i_{ps}).



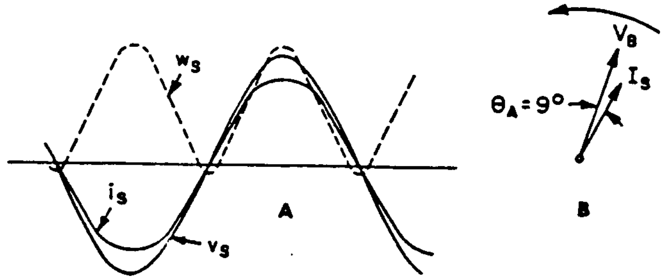
No. 1

Showing relation between current and voltage in the primaries of current and potential transformers respectively, the circuit having a power factor of 0.707, current lagging.



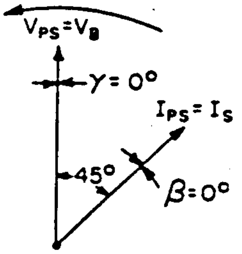
No. 2

Showing relation between current and voltage in the secondaries of current and potential transformers respectively, when both transformers have zero phase-angle error, and line power factor is 0.707, current lagging. θ_A is the apparent power-factor phase angle.



No. 4

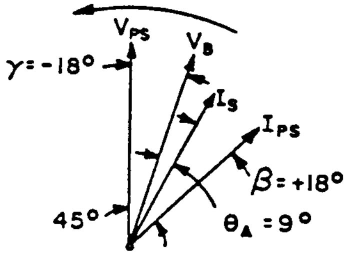
Showing same as No. 2, except that the current transformer has a −18-deg phase-angle error and the potential transformer has a +18-deg phase-angle error. (Exaggerated angles used to make effect visible.) Both these angles bring the secondary voltage and current vectors closer together than they are in the primary, thereby making the wattmeter read high.



No. 3

Showing B of No. 1 combined with B of No. 2. Phase-angle correction factor equals

$$\frac{\cos\theta}{\cos\theta_A} = \frac{\cos 45^\circ}{\cos 45^\circ} = \frac{0.707}{0.707} = 1.0$$



No. 5

Showing B of No. 1 combined with B of No. 4. Correction factor equals

$$\frac{\cos\theta}{\cos\theta_A} = \frac{\cos 45^\circ}{\cos 9^\circ} = \frac{0.707}{0.987} = 0.716$$

Fig. 9. Phase relations in instrument transformers

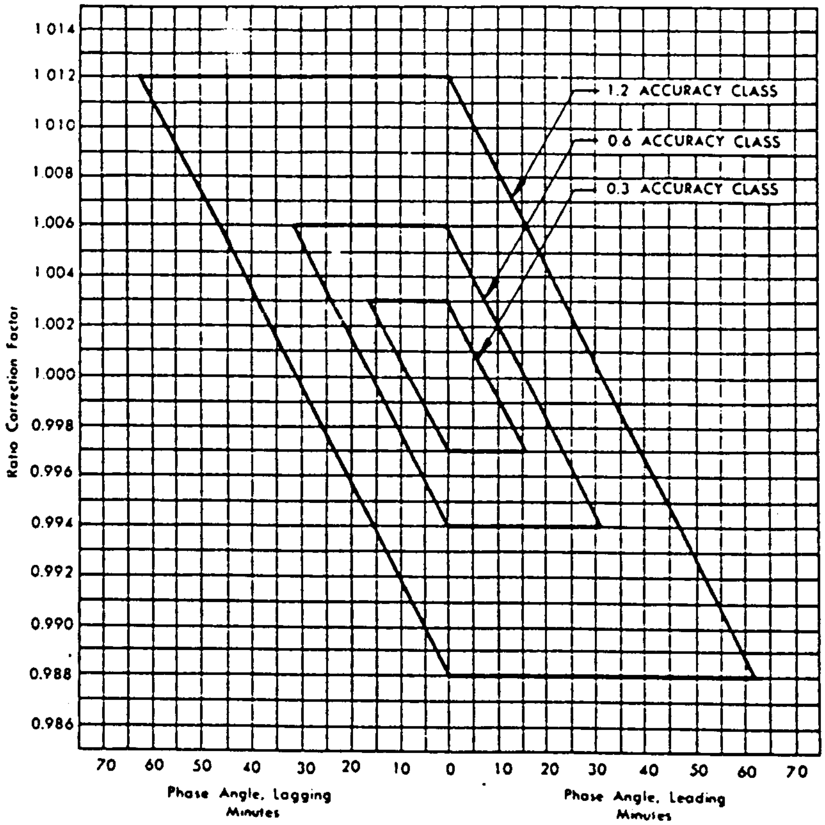


Fig. 10. Parallelograms showing graphical equivalent of USASI accuracy classes 0.3, 0.6, and 1.2 for potential transformers

TCF is taken in turn as the maximum and minimum values of transformer correction factor specified in the table, and RCF is the ratio correction factor of the potential transformer under the conditions that are being checked. This relationship is plotted for the various accuracy classes on Fig. 10.

By means of this USASI system, the accuracy of a potential transformer may be described by listing the best accuracy class which it meets for each burden.

Thus, a potential transformer may be accurate enough to be rated:

0.3 W, 0.3 X, 0.3 Y and 0.3 Z

while another may be:

0.3 W, 0.3 X, 0.6 Y and 1.2 Z

or still another:

0.3 W, 0.6 X and 1.2 Y.

In the last example, the omission of any reference to accuracy at the Z burden indicates that the error is greater than that specified for the poorest accuracy class at this high burden and, thus, no figure can be given.

It should be noted that the foregoing system provides a method of classifying transformers as to accuracy, but it does not give the specific error for any given transformer beyond the fact that it is within a certain range. Thus, for accurate measurements, the actual error of the transformer must be known and taken into account in the measurement. For high-accuracy measurements, this information may be obtained from a calibration certificate or other calibration result on the particular transformer in question. A reasonable approximation of the accuracy may be obtained also from the characteristic accuracy curves listed in the descriptive literature for all types of potential transformers.

THERMAL BURDEN RATING

It is not the usual practice to apply burdens on potential transformers in excess of their volt-ampere rating, as good accuracy of transformation will not be maintained under these conditions. However, an occasional application is encountered where some particular ratio or other feature of a potential transformer makes

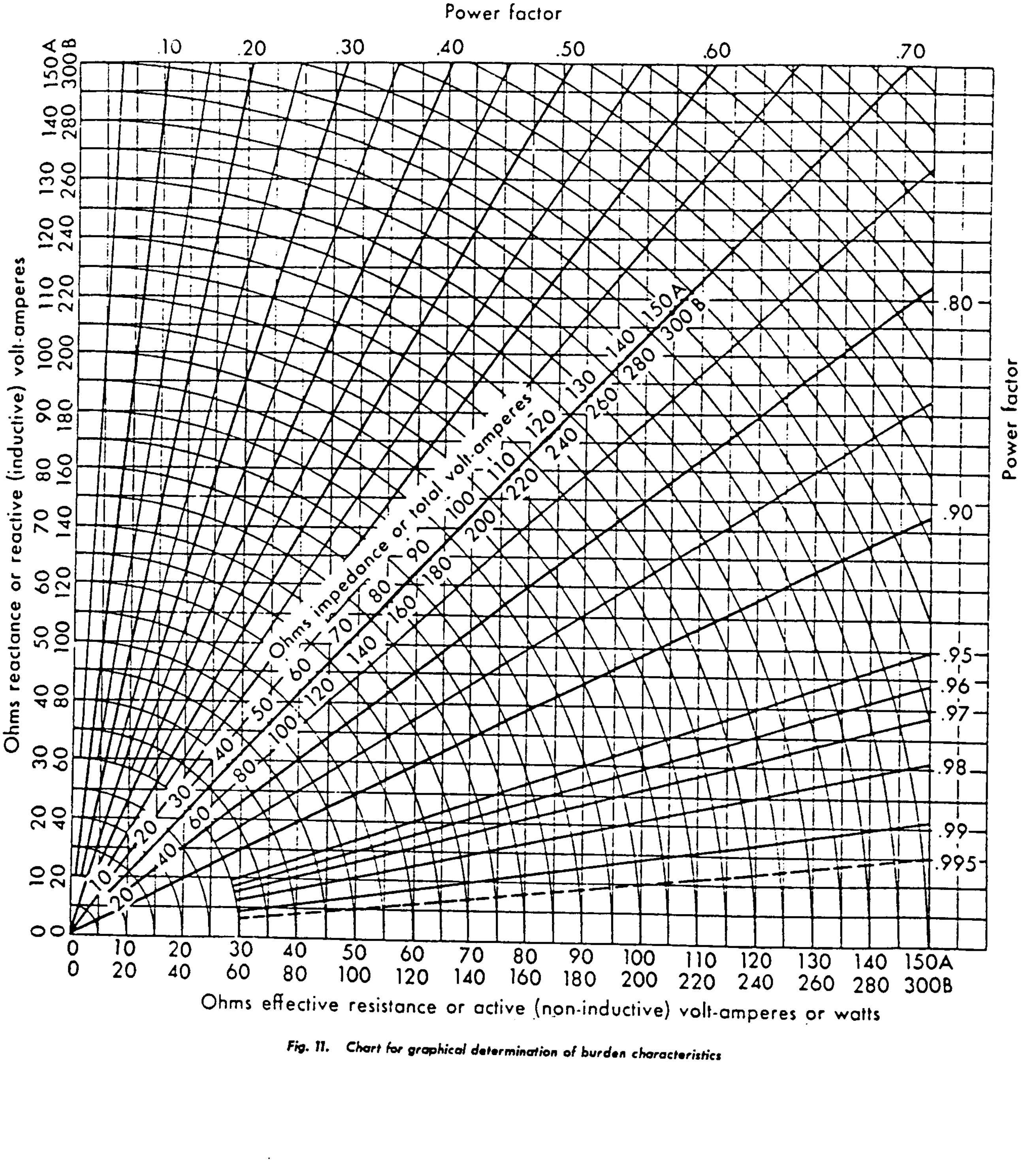


Fig. 11. Chart for graphical determination of burden characteristics

it desirable to use this type of transformer for supplying power, rather than for measurement purposes. In such situations, it is usually possible to place burdens which are considerably higher than the volt-ampere rating on the secondary circuit, without encountering excessive heating that would shorten the life of the transformer. The limit of such burden is called the *Thermal Burden Rating* of the transformer and is given in volt-amperes. Normally, this information may be found in the descriptive literature concerning each type of transformer.

SECONDARY BURDENS

It has been stated before that the burden on the secondary circuit of a potential transformer affects the accuracy of that device. Therefore, to predict the performance of a particular transformer that is to be used in a certain circuit, the burden of the various meters and instruments in the secondary of this circuit must be known. Burden data for General Electric Company apparatus are listed in Publication GET-1725 as well as in the descriptive literature for each class of apparatus.

It is often found desirable to connect several meters or combinations of devices in parallel on the secondary of potential transformers. In these cases, it is necessary to compute the total burden of such a combination of devices.

For many purposes, it is sufficiently accurate to add arithmetically the volt-ampere burden of the individual devices involved. In case the impedance burden only is known, the volt-ampere burden can be calculated from the relationship:

$$VA = \frac{V^2}{Z_b}$$

where E is the voltage drop across the burden and Z_b is the burden impedance.

This method is followed, for example, in determining whether or not a transformer will have excessive burden. In those cases where a calculation on this basis indicates too much total burden, it is advisable to recalculate, taking the power factor into account.

For convenience in combining burdens in those cases where it is necessary to consider the power factor of the impedance, the chart shown in Fig. 11 has been constructed. Thus, it is possible to readily work out burden combinations graphically, without using a comparatively complicated mathematical process.

The chart consists of a quadrant laid off in polar co-ordinates, superposed on rectangular co-ordinates. The radii of the polar plot are drawn at angles that correspond to even values of power factors. These radii are sufficient in number to permit the determination of power factor with reasonable accuracy. The radii of the polar plot and the ordinates and abscissas of the rectangular plot are laid off in ohms and volt-amperes to a common scale. Thus, a certain value of impedance or volt-amperes at a certain power factor determines a point in the polar plot. Reference to the same point on the rectangular plot gives the inductive component (reactance or reactive volt-amperes) as ordinate, and noninductive component (effective resistance or watts) as abscissa. Inductance in henrys equals reactance divided by $2\pi f$, when $f =$ frequency.

It should be noted that the chart has two distinct sets of scale values, and care must be taken to use corresponding scales on the two different plots. The set of values should be used that will locate the point farthest from zero. Also, it should be noted that the decimal point in the scales may be transposed to any desirable point, so long as it is moved correspondingly on both the polar and rectangular plots.

The chart can be used for the following purposes:

1. To determine the combined impedance and power factor of combinations of such devices (either potential or current) as are listed in Publication GET-1725, or other devices on which similar data are available.
2. To determine the components of an impedance for the purpose of determining the total (or equivalent) impedance of a combination. The power factor must be known.
3. To determine the total output required by a combination of devices whose volt-amperes and watts are known values.
4. To determine the components of the output required by separate devices for the purpose of determining the total output required by a combination.

An example of its application to the problem of combining potential-transformer burdens is as follows:

Required: To determine the total volt-amperes and power factor of the burden on a potential transformer to which are connected:

One Type I-50, 120-volt watthour meter,
One Type AB-18, 150-volt voltmeter, and
One Type AB-18, single-phase wattmeter.

From Publication GET-1725, burden data may be found as follows:

	Watts	Vars
Watthour Meter	1.1	8.2
Voltmeter	4.7	0.9
Wattmeter	2.1	0
Total	7.9	9.1

Using scales A (by multiplying the above values by 10), locate a point in the rectangular plot by using 7.9×10 as an abscissa and 9.1×10 as an ordinate. This point falls on the radius 0.66, which gives this value as the power factor of the total burden. Then, following the arc (imaginary) on which the point is located to the radius marked in total volt-amperes, 12.0×10 will be noted as the volt-ampere burden.

CORRECTION FOR ERRORS

The USASI accuracy classification of all GE potential transformers is listed in the descriptive literature for this apparatus. Some designs have the accuracy listed directly on the nameplate.

The accuracy classification indicates the performance levels of the various types of transformers. For many measurements, the maximum errors thus indicated are so small that they can be neglected without seriously affecting the over-all accuracy of the measurement. In other measurements, high accuracy is required, and corrections for potential-transformer errors must be made. In such situations, the USASI classification of errors is not suitable for making these corrections, so characteristic curves or test data must be used. Procedure for obtaining complete accuracy characteristics from certificate of test values furnished with General Electric butyl-molded potential transformers is contained in the Instrument Transformer Data Book Publication No. 220TD.

DETERMINATION OF ERRORS FROM CHARACTERISTIC CURVES

Characteristic curves for potential transformers are published in the descriptive literature in a form similar to that shown on Fig. 8. This curve lists the ratio correction factor (RCF) and the phase-angle error (γ), from zero to rated burden in volt-amperes, for each of the several burden power factors specified by USASI. In general, the accuracy of individual transformers of a given type will match the characteristic accuracy curves for that type within the following limits: ratio correction factor may vary ±0.002 and phase-angle error may vary ± 7 minutes from the curve values. Thus, an RCF of 1.004, as read from the curve, may be actually anywhere within the range of 1.002 to 1.006 for any specified transformer. A phase-angle error of +12 minutes may be actually +5 minutes or +19 minutes. Of course, this variation is for the general case; many designs have variations smaller than this, although very few individual transformers will exceed this range.

DETERMINATION OF ERRORS FROM TEST DATA

Correction data for potential-transformer errors may be obtained from test results on the particular transformer, as well as from characteristic accuracy curves. Such data are usually taken at the same burden and voltage at which the final measurement is to be made so that calculation of errors under other conditions is usually unnecessary; however, the general methods outlined in the Instrument Transformer Data Book 220TD may be employed.

The accuracy with which the test data are taken will, of course, affect the accuracy of the corrected final measurement. Certificates of Test for potential transformers, issued by the General Electric Company, guarantee the ratio correction factor to be within ±0.001 of the figure given and the phase-angle error to be within ±3 minutes. Correction of errors by this means gives the best accuracy for the particular potential transformer used.

RATIO ERROR

If no errors were present, the voltage that exists in a particular circuit would be the voltage measured in the secondary of a potential transformer connected in that circuit, multiplied by the marked ratio of the transformer. However, two errors may be present in such a measurement—an error in voltage in the voltmeter, and an error in ratio in the transformer. The error in the voltmeter may be corrected by applying the proper correction factor from a calibration curve or other data for that device. (See General Electric Company *Instructions* GEJ-121 for further information on instrument corrections.) The error in ratio can be corrected by multiplying the marked ratio by the ratio correction factor to find the true ratio. The primary voltage, thus, equals:

$$\text{Primary voltage} = \text{Corrected secondary-voltage measurement} \times \text{ratio} \times \text{RCF}.$$

The RCF may be found for the burden imposed on the transformer by reference to the characteristic curves or test data for the transformer.

PHASE-ANGLE ERROR

Potential-transformer phase-angle errors do not affect the accuracy of ordinary voltage measurements, but do introduce errors into wattmeters or other measurement devices where the power factor of the circuit to be measured enters into the measurement. This may be seen by reference to Fig. 9. For many purposes, these errors are too small to warrant correction. For other higher accuracy measurements, they must be considered to achieve the desired accuracy.

For such high-accuracy measurements, several errors in phase angle must be considered, including that introduced by the potential transformer. These errors are: (1) the phase-angle error of the potential transformer; (2) the phase-angle error in the potential circuit of the wattmeter, if one is used in the measurement*; and (3) the phase-angle error of the current transformer, which is often used in wattmeter measurements. Of course, the wattmeter scale correction, and ratio errors of both the potential transformer and current transformer, must also be considered.

TYPES OF POTENTIAL TRANSFORMERS

Potential transformers are, of course, made in many voltage ratings. In general, instrument transformers for use on circuits rated 25,000 volts and above are suitable for use out-of-doors. Transformers for circuits below this voltage are usually molded of specially compounded butyl that is suitable for outdoor service. Also, several specific indoor potential transformers are available to fulfill the requirements of certain service conditions.

Portable potential transformers are normally used for test purposes. They are equipped with handles, for convenience in transport, and they may be specially calibrated for high accuracy testing.

Phasing transformers are also available for use with wattmeters or watthour meters. These transformers operate by shifting the phase of the voltage applied to these end devices so that they can be used for measuring vars (reactive volt-amperes).

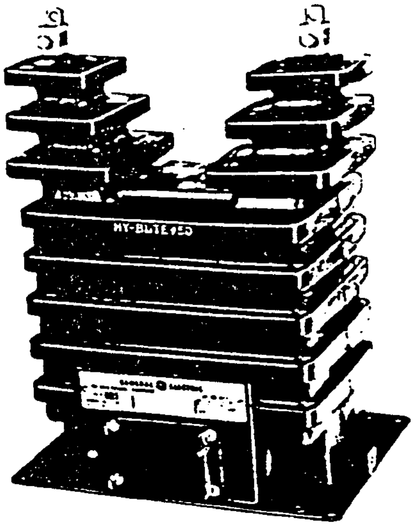


Fig. 13. Type JVW-4 butyl-molded instrument potential transformer for outdoor service; rated 8.7 kv

Outdoor potential transformers in the higher voltage range (generally 25,000 volts and above) are made in two distinct styles. One has two high-voltage primary bushings and is suitable for either line-to-line or line-to-neutral applications. The other has only one high-voltage primary bushing. The other end of the primary winding is brought out at a low-voltage bushing and grounded. See Fig. 14 and 15.

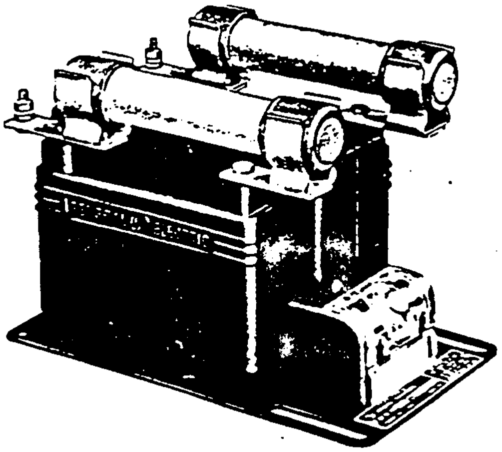


Fig. 12. Type JVM-3 instrument potential transformer for indoor service; two-fuse model; rated 5 kv

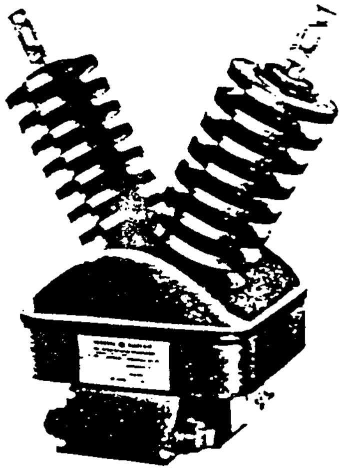


Fig. 14. Type JVT-200 SUPERϟBUTE† instrument potential transformer for outdoor service; rated 34.5 kv

---

* There is no corresponding error in a watthour meter.

† Trade-mark of General Electric Company.

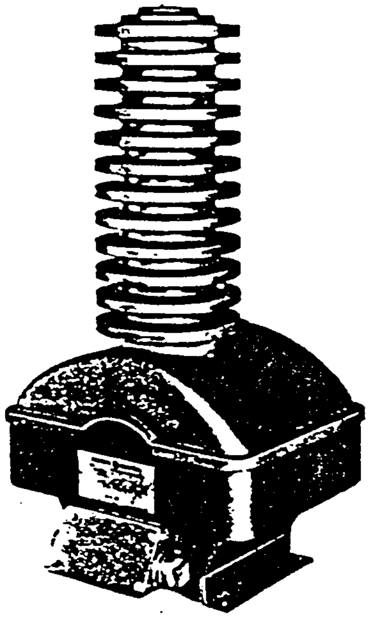


Fig. 15. Type JVS-350 SUPER⚡BUTE instrument potential transformer for outdoor service; rated 69 kv

Table I, below, lists the various standard ratings of potential transformers as set forth in USASI Standard C57.13.

APPLICATIONS

Potential transformers are used in many different types of circuits and for many different purposes. A typical connection of a voltmeter and potential transformer for the measurement of voltage is shown in Fig. 16. Other typical circuits, measured by various meters, instruments, and relays by the use of both potential and current transformers, are shown in Fig. 19 through 25 inclusive.

When applying potential transformers, consideration should be given to the particular type of system in which the transformer is to be placed to be sure that the transformer has the proper insulation for the system in question. Table I, reproduced from USASI Standard C57.13, lists the standard ratings for potential transformers and the types of circuits on which they can be used. Figure 26, reproduced from the same publication, gives typical examples of three-phase systems and the manner in which various potential transformers may be connected in these systems.

TABLE I
STANDARD INSULATION CLASSES, MARKED RATIOS, PRIMARY-VOLTAGE RATINGS, AND DIELECTRIC TESTS FOR POTENTIAL TRANSFORMERS

Nameplate Marking			Usual Circuit Voltage (Highest Standard Value Is Shown)	Permissible Transformer Connection	Dielectric Tests			
Insulation Class (Kv)	Marked Ratio	Primary-voltage Rating/ Rated Voltage Line-to-Line (Volts)			Low-frequency Test (Kv RMS)	Impulse Test		
						Chopped Wave		Full Wave (Kv Crest)
						Crest Voltage (Kv)	Min. Time to Flashover (Microseconds)	
Group 1: 1.2 to 15 Kv, full insulation, Y voltage limit equals $\sqrt{3}$ times Δ voltage limit								
0.6	1:1	120/208Y	120 208	Δ or Y Y only	4	12	—	10
	2:1	240/416Y	240 416*	Δ or Y Y only	4	12	—	10
	2.5:1	300/520Y	277 480	Δ or Y Y only	4	12	—	10
1.2	1:1	120/208Y	120 208	Δ or Y Y only	10	36	1.0	30
	2:1	240/416Y	240 416*	Δ or Y Y only	10	36	1.0	30
	2.5:1	300/520Y	277 480	Δ or Y Y only	10	36	1.0	30
	4:1	480/832Y	480 832*	Δ or Y Y only	10	36	1.0	30
	5:1	600/1040Y	600 1040*	Δ or Y Y only	10	36	1.0	30
5.0	20:1	2400/4160Y	2400 4160	Δ or Y Y only	19	69	1.5	60

* These system voltages are not listed in Standard Voltage Ratings for A-c Systems, USAS C84.

TABLE I (Cont.)

STANDARD INSULATION CLASSES, MARKED RATIOS, PRIMARY-VOLTAGE RATINGS, AND DIELECTRIC TESTS FOR POTENTIAL TRANSFORMERS

Nameplate Marking			Usual Circuit Voltage (Highest Standard Value Is Shown)	Permissible Transformer Connection	Dielectric Tests			
Insulation Class (Kv)	Marked Ratio	Primary-voltage Rating/ Rated Voltage Line-to-Line (Volts)			Low-frequency Test (Kv RMS)	Impulse Test		
						Chopped Wave		Full Wave (Kv Crest)
						Crest Voltage (Kv)	Min. Time to Flashover (Microseconds)	
Group 1: 1.2 to 15 Kv, full insulation, Y voltage limit equals √3 times Δ voltage limit (Cont.)								
8.7	35:1	4200/7280Y	4200*	Δ or Y	26	88	1.6	75
			7280*	Y only				
	40:1	4800/8320Y	4800	Δ or Y	26	88	1.6	75
			8320	Y only				
15 L	60:1	7200/12470Y	7200	Δ or Y	34	110	1.8	95
			12470	Y only				
	70:1	8400/14560Y	8320	Δ or Y	34	110	1.8	95
			13200	Y only				
15 H	60:1	7200/12470Y	7200	Δ or Y	34	130	2.0	110
			12470	Y only				
	70:1	8400/14560Y	8320	Δ or Y	34	130	2.0	110
			13200	Y only				
Group 2: 0.6 to 161 Kv, full insulation, Y voltage limit equals Δ voltage limit								
0.6	1:1	120/120Y	120	Δ or Y	4	12	—	10
0.6	2:1	240/240Y	240	Δ or Y	4	12	—	10
0.6	2.5:1	300/300Y	300	Δ or Y	4	12	—	10
0.6	4:1	480/480Y	480	Δ or Y	4	12	—	10
0.6	5:1	600/600Y	600	Δ or Y	4	12	—	10
2.5	20:1	2400/2400Y	2400	Δ or Y	15	54	1.5	45
5.0	40:1	4800/4800Y	4800	Δ or Y	19	69	1.5	60
8.7	60:1	7200/7200Y	6900	Δ or Y	26	88	1.6	75
15 L	100:1	12000/12000Y	12000	Δ or Y	34	110	1.8	95
	120:1	14400/14400Y	14400	Δ or Y	34	110	1.8	95
15 H	100:1	12000/12000Y	12000	Δ or Y	34	130	2.0	110
	120:1	14400/14400Y	14400	Δ or Y	34	130	2.0	110
25	200:1	24000/24000Y	24900	Δ or Y	50	175	3.0	150
34.5	300:1	34500/34500Y	34500	Δ or Y	70	230	3.0	200
46	400:1	46000/46000Y	46000	Δ or Y	95	290	3.0	250
69	600:1	69000/69000Y	69000	Δ or Y	140	400	3.0	350
92	800:1	92000/92000Y	92000*	Δ or Y	185	520	3.0	450
115	1000:1	115000/115000Y	115000	Δ or Y	230	630	3.0	550
138	1200:1	138000/138000Y	138000	Δ or Y	275	750	3.0	650
161	1400:1	161000/161000Y	161000	Δ or Y	325	865	3.0	750
Group 3: 25 Kv to 345 Kv, reduced insulation at neutral end, GrdY application only								
Not Specified by USAS C57.13	120 & 200:1	14400 for 25000GrdY	24900	GrdY only	Not Specified by USAS C57.13	Not Specified by USAS C57.13	Not Specified by USAS C57.13	Not Specified by USAS C57.13
	175 & 300:1	20125 for 34500GrdY	34500	GrdY only				
	240 & 400:1	27600 for 46000GrdY	46000	GrdY only				
	350 & 600:1	40250 for 69000GrdY	69000	GrdY only				
	480 & 800:1	55200 for 92000GrdY	92000*	GrdY only				
	600 & 1000:1	69000 for 115000GrdY	115000	GrdY only				
	700 & 1200:1	80500 for 138000GrdY	138000	GrdY only				
	800 & 1400:1	92000 for 161000GrdY	161000	GrdY only				
	1000 & 1700:1	115000 for 196000GrdY	196000*	GrdY only				
	1200 & 2000:1	138000 for 230000GrdY	230000	GrdY only				
	1500 & 2500:1	172500 for 287000GrdY	287000*	GrdY only				
	1800 & 3000:1	207000 for 345000GrdY	345000	GrdY only				
	2500 & 4500:1	Not Established	500000	GrdY only				

* These system voltages are not listed in Standard Voltage Ratings for A-c Systems, USAS C84.

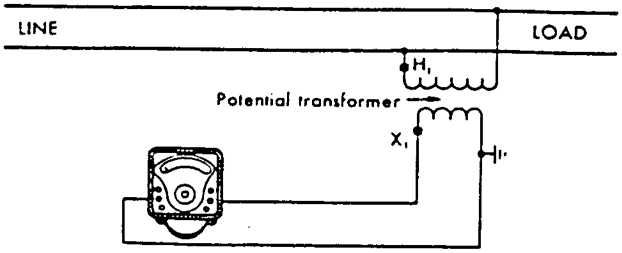


Fig. 16. Connection diagram of a voltmeter with potential transformer

YY-CONNECTED

It is often desirable to connect potential transformers with their primaries connected in Y and the secondaries connected either in Y or broken delta. For a typical example, see Fig. 27.

Such connections permit satisfactory operation on three-phase, four-wire, grounded-neutral systems, and on three-phase, three-wire systems if both the neutral of the circuit (the section to which the transformers are connected) and the neutral of the transformer primaries are solidly and permanently grounded.

However, special consideration should be given to such connection of potential transformers on isolated-neutral systems or on systems grounded through a high impedance. Excessive voltage and neutral instability may occur as a result of circuit faults, if grounded-neutral potential transformers are connected to such isolated-neutral systems. Most potential transformers are designed to withstand the higher voltage during emergency operation after circuit faults; however, the insulation will deteriorate rapidly during such operation. The neutral instability* may be avoided by the use of adequate noninductive secondary burdens. Thus the use of such circuits is possible, but special care is necessary.

FUSING

It is a general rule that fuses should be used in both the primary and secondary circuits of potential transformers. This is done to protect these devices from high currents due to circuit faults and, conversely, to protect the circuits from faults that may occur in the potential transformers or in the secondary circuits attached to them.

However, there are several exceptions to this rule. It is general practice to omit the fuses in the connections to grounded terminals of potential transformers. This practice is essential in the case of single-primary-bushing-type potential transformers. In addition, for certain applications involving regulators or protective relays, where the continuity of excitation to these devices is more important than the possibility of damage to the transformers, it is customary to omit the fuses.

Primary Fuses

Primary fuses must be so selected that they will perform the following functions:

1. Interrupt the maximum short-circuit current which may occur at the point of fuse installation.
2. Open the circuit if a short circuit occurs at

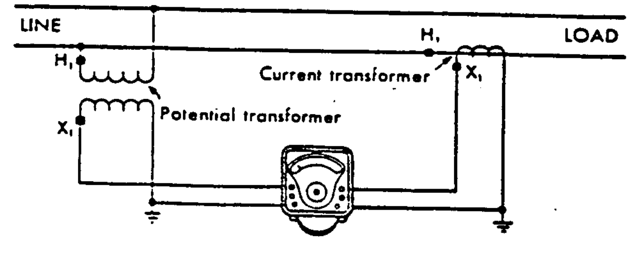


Fig. 17. Connection diagram of a wattmeter with current and potential transformers

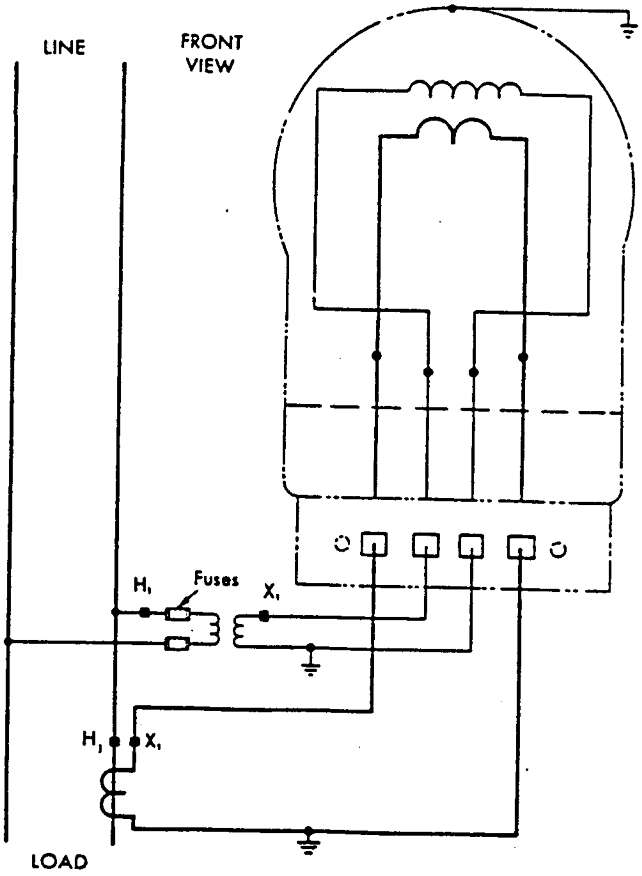
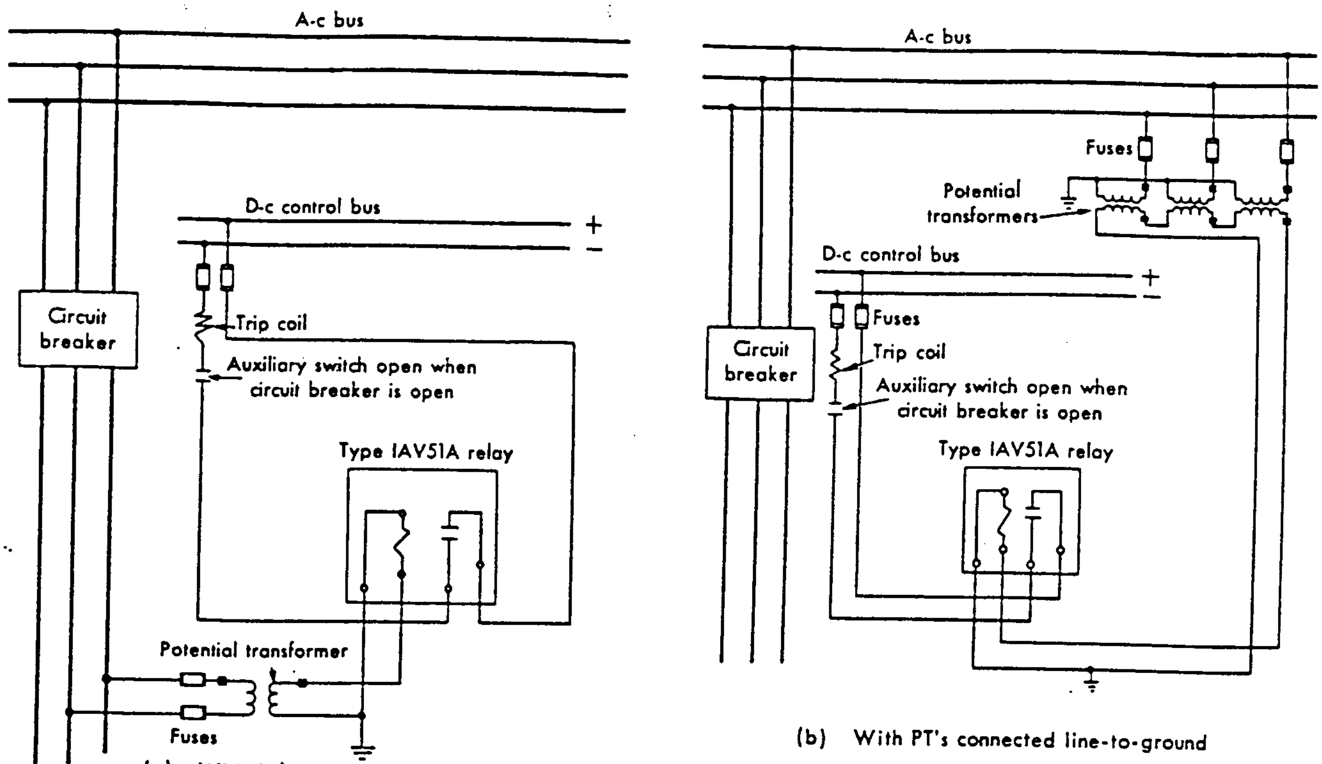


Fig. 18. Connection diagram of a watthour meter with current and potential transformers

---

*This general subject is discussed in the paper entitled *Criteria for Neutral Stability of Wye-Grounded Primary Broken-Delta-Secondary Transformer Circuits* by H. S. Shott and H. A. Peterson; *AIEE Transactions*, Vol. 60, 1941, pp. 997-1002.



(a) With PT's connected line-to-line

(b) With PT's connected line-to-ground

Fig. 19. Connection diagrams of overvoltage relays with potential transformers

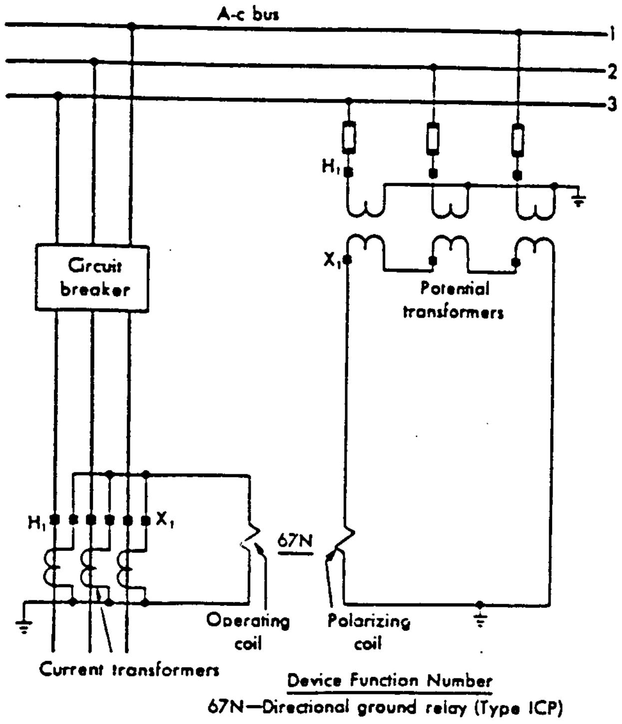


Fig. 20. Connection diagram of potential-polarized relay with current and potential transformers

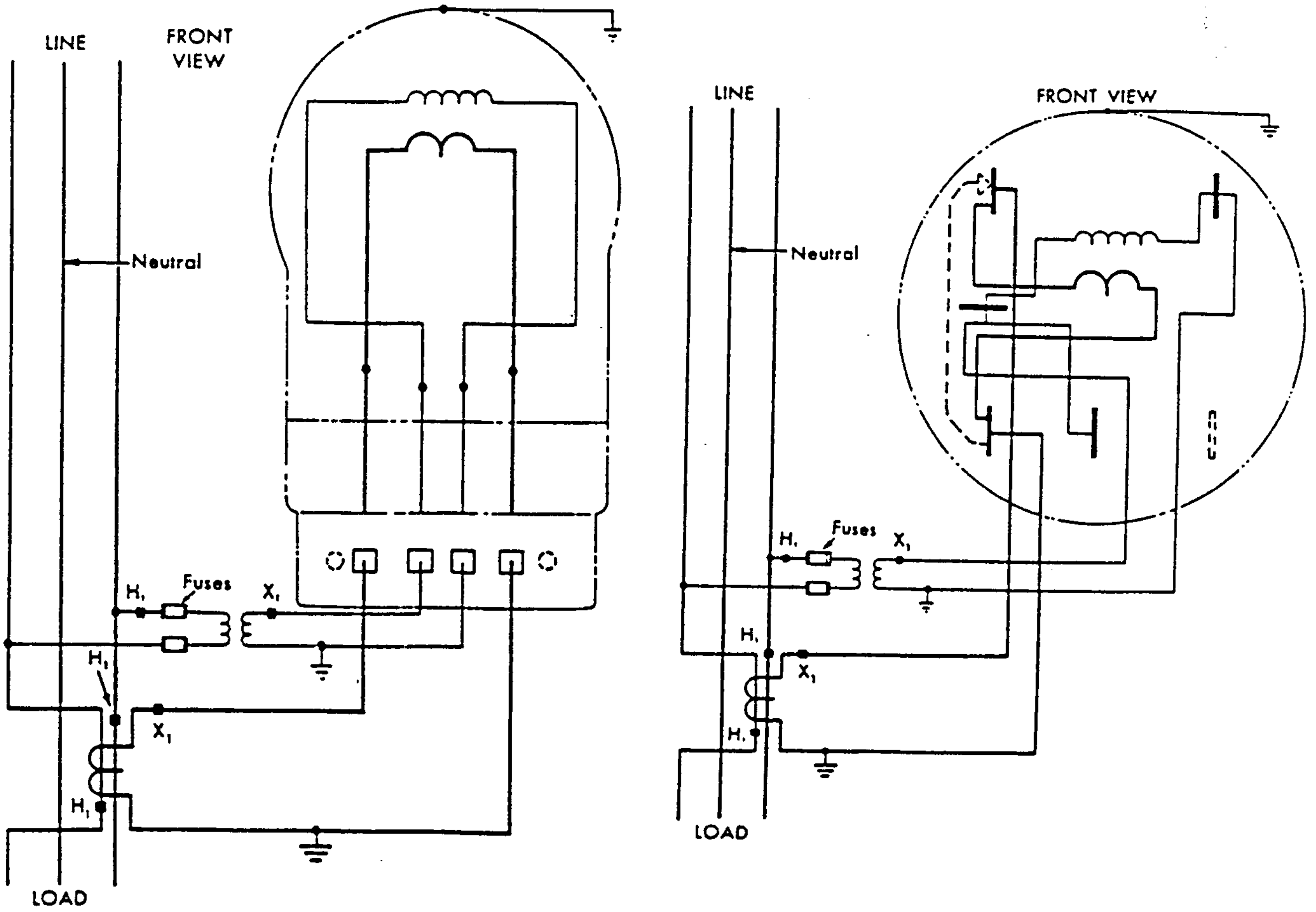
(or electrically close to) the potential-transformer-secondary terminals.

3. Maintain the circuit uninterrupted under the action of the inrush magnetizing current to the transformer, which occurs during switching operations.

The maximum short-circuit current may be calculated by assuming a zero impedance fault at the point of fuse installation. A current-limiting fuse (such as the GE Types EJ-1 and EJO-1) which has a voltage rating equivalent to the line-to-line voltage of the circuit, and an interrupting rating equal to or greater than the calculated short-circuit current, will interrupt this maximum current safely. However, other types of fuses are generally made with such low interruption ratings that they require a series resistance to limit the current to a value within the interrupting capacity of the fuse.

Faults which occur near the secondary terminals cause a primary current to flow, and this current will usually blow the fuse if the fuse is properly selected. However, if a fuse of too low a current rating is chosen, it will blow on the inrush current to the transformer during switching, which is, of course, undesirable.

As the heating effect (which actually melts the fuse link) of the maximum inrush current and of the primary current due to secondary short circuit at the

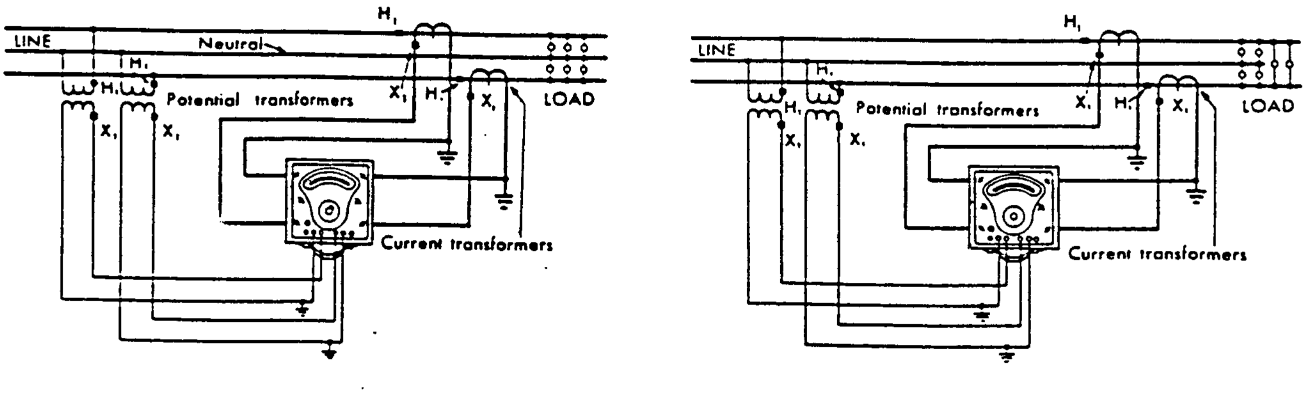


(a) Type I-50-A

(b) Type I-50-S

Fig. 21. Connection diagrams of single-phase watthour meters for 3-wire, single-phase circuits, showing use of 2-wire meters in 3-wire circuits by means of 3-wire current transformers

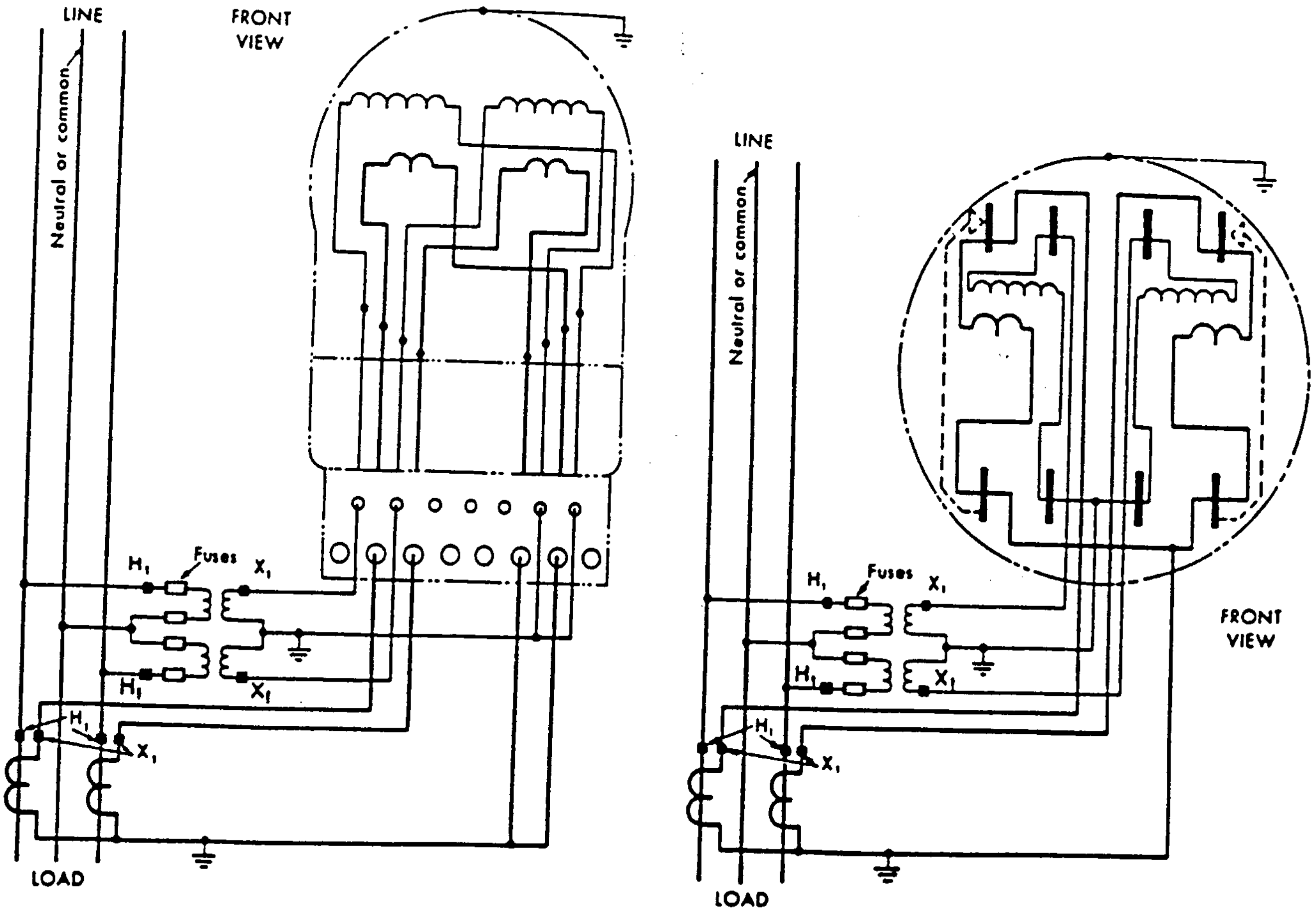
terminals are known quantities for any given transformer, the manufacturer is able to apply primary fuses to potential transformers. These fuses will give the maximum protection to both the circuit and the transformer, without causing unnecessary interruptions to the circuit. Thus the fuses supplied with fused potential transformers should be replaced, when necessary, with fuses of similar characteristics. In those situations where separately mounted fuses are employed to carry the primary current of more than one



(a) Two-phase, 3-wire circuit, balanced or unbalanced voltage or load

(b) Three-phase, 3-wire circuit

Fig. 22. Connection diagrams for a polyphase wattmeter with current and potential transformers



(a) Type V-63-A

(b) Type V-63-S

Fig. 23. Connection diagrams of watthour meters for 3-wire circuits with current and potential transformers

transformer, special consideration should be given to the selection of fuses. Assistance in ordering the correct fuse type may be requested from the nearest GE Sales Office.

Secondary Fuses

The selection of primary fuses represents, among other considerations, a current rating large enough to maintain the circuit during switching surges. Therefore, faults in the secondary circuit that are electrically distant from the terminals may not cause sufficient primary current to blow the fuses, because of the impedance in the secondary circuit.

Secondary fuses should be used to protect the transformer from such short circuits. The General Electric Company standard 10-ampere cartridge fuse may be used for such service, but special precaution and inspection should be employed to determine that the contacts between the fuse and its support do not introduce extra resistance into the circuit. This additional resistance would affect the accuracy of secondary measurements.

Errors Due to Fuses and Leads

The resistance of fuses and secondary leads affects the accuracy of indication of secondary intsruments and meters. This is due to the voltage drop, which depends upon the current and the resistance of the fuses, etc. If GE fuses are used, the error due to the drop in them need cause no concern. These fuses are so designed as to keep the voltage drop in them less than 0.1 percent up to rated output of the transformer. Secondary-lead resistance, however, cannot be neglected because in many instances, where long leads and heavy burdens are unavoidable, the voltage drop in the leads may be relatively large. This can be checked easily by a simple calculation, if the lead resistance and secondary burdens are known.

In those instances where corrections for ratio and phase angle are to be applied from certified tests, equivalent resistance should be included at the time of test. In other cases, these resistances will generally have only a negligible effect on the accuracy. However,

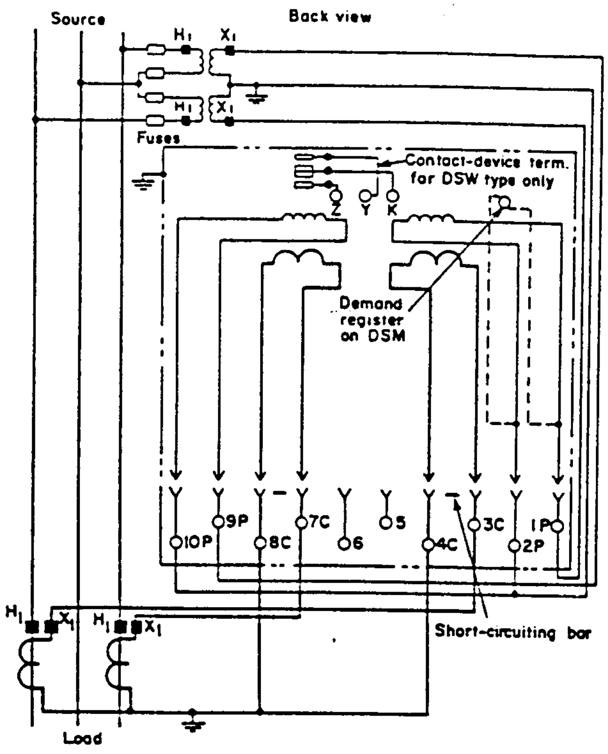


Fig. 24a. Connections for Types DS-63, DSM-63, and DSW-63 meters

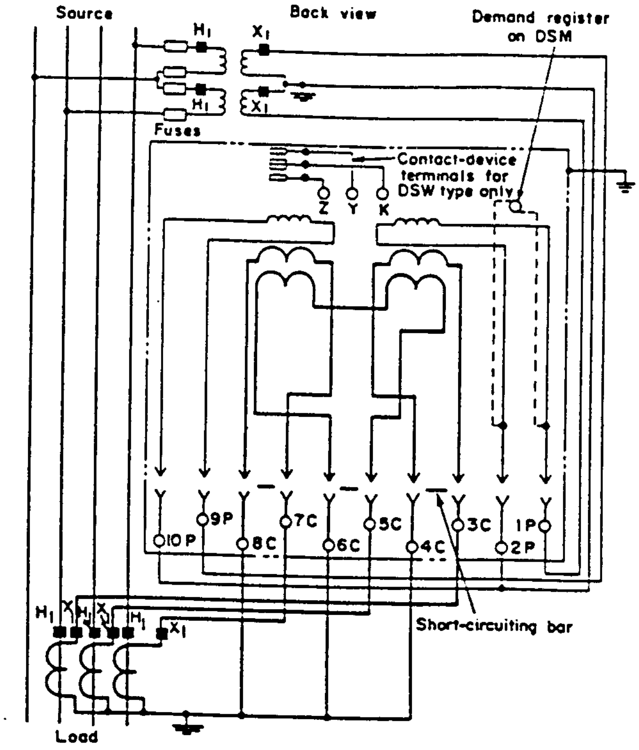


Fig. 24b. Connections for Types DS-65, DSM-65, and DSW-65 meters

it is best to check this point even when only approximate accuracies are involved, as the drop might deserve consideration in some such cases. For example, if the transformer is operating at 200 volt-amperes, and the secondary-lead resistance is 0.5 ohm (550 feet of No. 10 Awg copper wire), there will be a voltage drop of 0.87 volt, which is 0.75 percent of rated voltage.

It must be remembered also that not only the voltage drop itself must be considered, but also the effect of this drop on the phase of the voltage applied to the instruments and meters in the secondary circuit. In other words, it is only by vector solution that the effect of these resistances can be cared for correctly.

TESTS

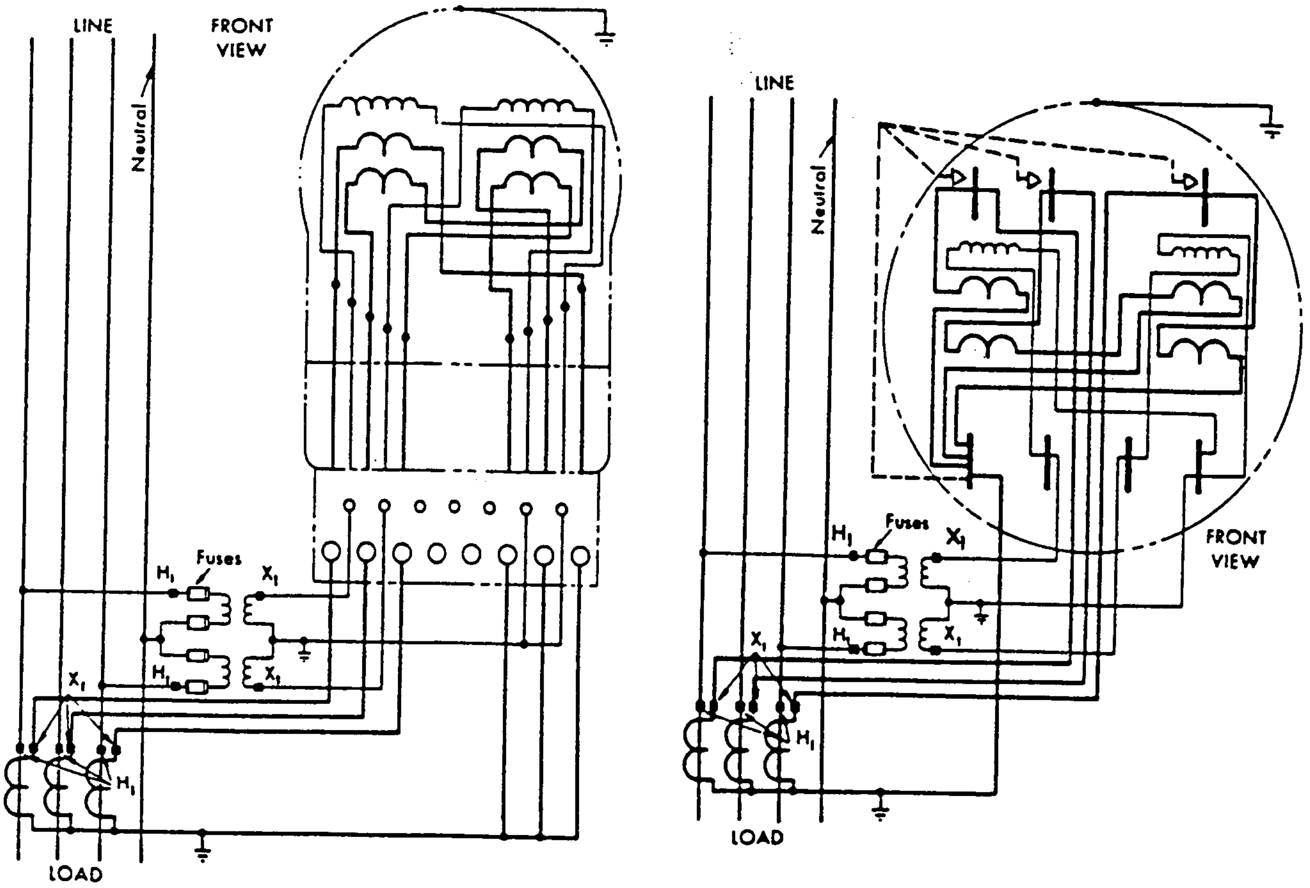
Various tests are made on potential transformers by the manufacturer to insure that the transformers meet the requisite specifications. Similar tests are made also by the user to insure that the devices continue to meet the specifications. A very brief outline of the various test methods that can be employed is explained in the following section.

ACCURACY

Voltmeter Method—This is the simplest method for determining ratio. With suitably rated voltmeters connected in the primary and secondary circuits, the ratio of the transformer is the ratio of the two voltages measured by these instruments. The range of this method is very limited because voltmeters rated over 600 volts are not available ordinarily. However, the range can be extended by using a calibrated potential transformer in the test circuit.

Resistance-potentiometer Method—This is the earliest precision method that was developed. A multi-rated resistance potentiometer, designed to minimize the effects of inductance and capacitance, is used to obtain a voltage—approximately 120 volts—which represents the voltage applied to the primary of the potential transformer undergoing test and which is compared with the secondary voltage through a suitable detector.

One method by which phase angle can be obtained is by comparing the same two voltages, using the two-wattmeter method with both instruments excited from the same source, so that the difference in deflection



(a) Type V-65-A

(b) Type V-65-S

Fig. 25. Connection diagrams of watthour meters for 4-wire, 3-phase circuits with current and potential transformers

represents the difference in phase between the two voltages. Another method uses a mutual inductor and a vibration galvanometer.

Capacitance-potentiometer Method—By substituting capacitors for resistors, the same method as that of the resistance potentiometer can be employed. The capacitance-potentiometer method provides a marked reduction in the floor space required and in cost because the resistances must be shielded and, thus, are large and expensive. The equipment operates like a Schering bridge and can be designed to be self-calibrating.

Comparison Method—This is a modification of the basic "potentiometer" method. Instead of reading the primary and secondary voltages, the secondary voltages of a calibrated "standard" transformer and the transformer undergoing test are compared with each other by using a null method. This null method is essentially the resistance-potentiometer method previously described. The comparison method, of course, requires the use of a "standard" potential transformer with a rating which corresponds to that of each potential transformer involved in calibrating.

POLARITY

Polarity is checked automatically in practically all ratio and phase-angle test methods or it may be determined by any one of several methods described below. The choice of the method will depend generally upon the apparatus available. However, it must be remembered that there is an element of danger in making polarity tests. This is dependent to some extent on the method used, the amount of potential applied, and the possibility of making a wrong connection.

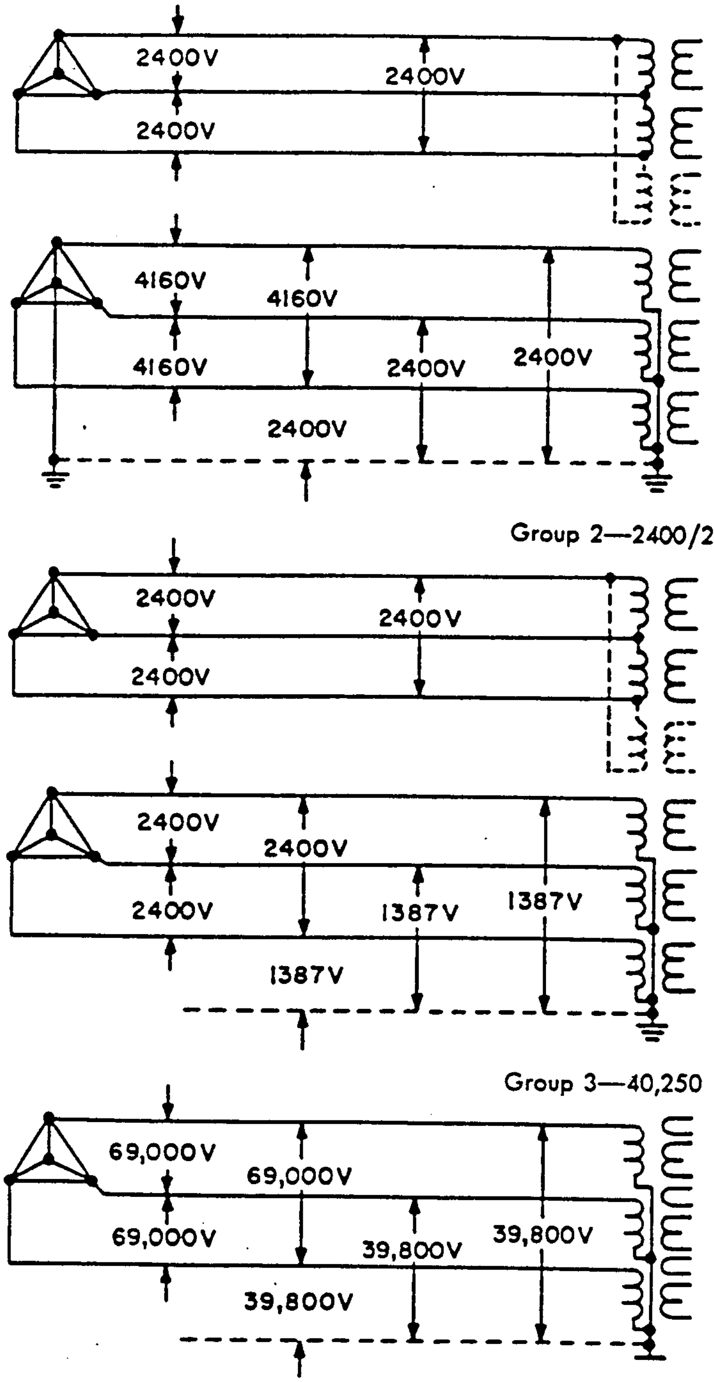
D-c Test

Connect a d-c permanent-magnet moving-coil-type voltmeter, preferably one with a 150-volt range, across the high-voltage terminals of the transformer, with the marked primary terminal of the transformer connected to the plus terminal of the voltmeter. Then connect two dry cells in series; the plus terminal of the battery to be attached to the marked secondary terminal of the transformer. Make an instantaneous contact between the negative terminal of the battery and the unmarked secondary terminal of the transformer.

A deflection or "kick" will be indicated on the voltmeter. If the initial "kick" (the one resulting from making, not breaking, the circuit) is in the upscale direction, the transformer leads are marked correctly. If the initial kick is downscale, the marking on the transformer is not correct.

NOMINAL 3-PHASE SYSTEMS

POTENTIAL TRANSFORMERS



Group 1—2400/4160 Y

2400-volt system—neutral grounded or ungrounded

4160-volt system—neutral grounded or 4 wire

The above transformers may be connected line-to-line on a 2400-volt system
OR
Line-to-neutral on a 4160-volt system

Group 2—2400/2400 Y

2400-volt system—neutral grounded or ungrounded

The above transformers may be connected line-to-line on a 2400-volt system but are limited by insulation
TO
Line-to-neutral connection on the same voltage (2400)

Group 3—40,250 For 69,000 Grd Y

69,000-volt system—neutral grounded or ungrounded

One primary terminal of each transformer is not fully insulated and must be connected to ground

NOTE TO GROUP 3: The double ratio for the transformers in Group 3 is obtained by two secondary windings, to provide the same rated voltage in the secondary from line to neutral as from line to line.

Fig. 26. Typical primary connections for potential transformers

A-c Tests

A-c Voltmeter Test—The relations existing between voltages, as explained in the USASI Standards, suggest another method for checking polarity; namely, to excite the transformer at a low voltage and compare the voltage across one winding with the voltage across both windings in series. For high ratios (say over 100:1), this method is not very practical because the difference between the two voltages being measured is too small to be observable with ordinary instruments. Furthermore, there is a potential hazard to be considered; that is, the possibility of exciting a low-voltage winding instead of a high-voltage winding, thereby producing dangerous voltage on the transformer.

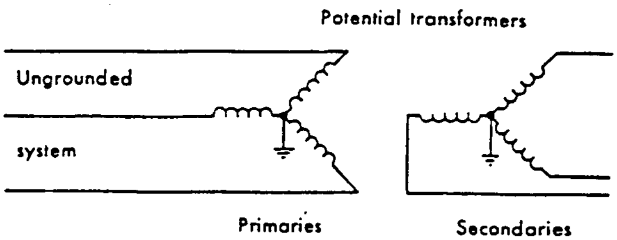


Fig. 27. Potential transformers connected Y-Y with grounded neutral on otherwise ungrounded system

Substitution Method—Another alternative is to use a substitution method, provided that a transformer of known polarity is available. One way of making this test is illustrated by Fig. 28. Connect the transformer with known polarity into this circuit, then, in place of this transformer, substitute the transformer of unknown polarity. If the wattmeter deflects in the same direction in both cases, the polarities of the two transformers are alike.

Differential Method—In this method of making a polarity test, as illustrated by Fig. 29, the primaries of both the "standard" and "test" transformers are excited simultaneously, and a voltmeter is used to make a differential measurement in the secondary circuits. The voltmeter should read V_{S1} and V_{S2} (arithmetical sum) when the polarities are in accordance with this illustration.

INSULATION

Both high-potential tests at 60 Hz and impulse tests are used to check the insulation of potential transformers. The test values specified by USASI for these tests are listed in Table I, page 18. A description of the requirements and test methods may be found in USASI Standard C57.13.

The test values listed in Table I are for factory dielectric tests that are designed to check the insulation and workmanship of individual transformers. All dielectric tests impose a severe stress on the insulation and, if applied frequently at a high value, may shorten the life of the insulation considerably. For this reason, the practice recommended by USASI for making periodic dielectric tests in the field is to limit the test values to 75 percent of the factory-test voltages listed in Table I.

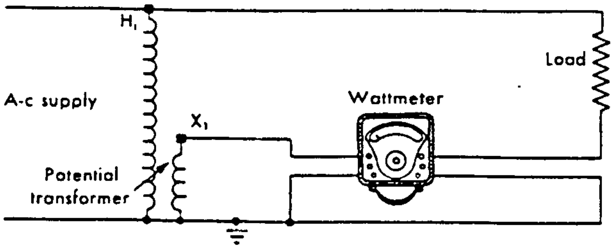


Fig. 28. Connection diagram of a potential transformer and the associated equipment used to determine the polarity of the transformer by the substitution method

High-voltage d-c (kenotron) testing is often employed on cables and other gear. If the circuit to be tested contains potential transformers, these should be disconnected before the voltage is applied, because the sudden application of d-c may cause transient voltages in the windings of a very high value which would overstress the insulation.

In addition, such transformers are often connected with one primary terminal at ground potential. If a d-c voltage were imposed from the other line to ground, a very high current would tend to flow in the relatively low-resistance (but high impedance) primary winding. In all probability the test set would not have sufficient capacity to supply this current, but if it did, the windings might become damaged.

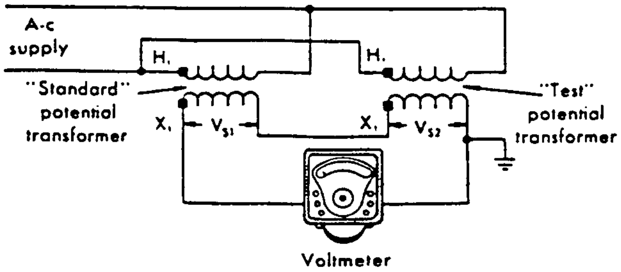


Fig. 29. Connection diagram of potential transformers and the associated equipment used to determine the polarity of one of the transformers by the differential method

CHAPTER THREE
CURRENT TRANSFORMERS

INSTRUMENT current transformers are designed for connection in series with the line in the same manner as that for ordinary ammeters. The secondary current bears a known relation with the primary current; consequently, any change in the primary current will be reflected in the meters or other devices connected in series with the secondary terminals of the transformer.

PRINCIPLE OF OPERATION

In general, the secondary current is inversely proportional to the ratio of turns as referred to the primary current. Like a potential transformer, this ideal transformation is never actually achieved. Small errors are always present because the current required to magnetize the core, and to supply the core losses, is not available as secondary current.

The relationship between the various voltages and currents in a potential transformer, as shown in Fig. 7a, 7b, and 7c are also applicable to current transformers. However, the operation of a current transformer can be seen more easily from a simpler diagram, i.e., Fig. 30. This illustration is for a 1:1 ratio transformer. The primary current can be considered as being made up of two components. One of these components (the exciting current which magnetizes the core and supplies the core losses) may be subtracted by phasor diagram from the primary current to find the amount remaining as secondary current. Therefore, on a 1:1 turn ratio basis, it is evident that the secondary current will be less than the primary current (except in the extremely improbable case of a highly capacitive secondary burden).

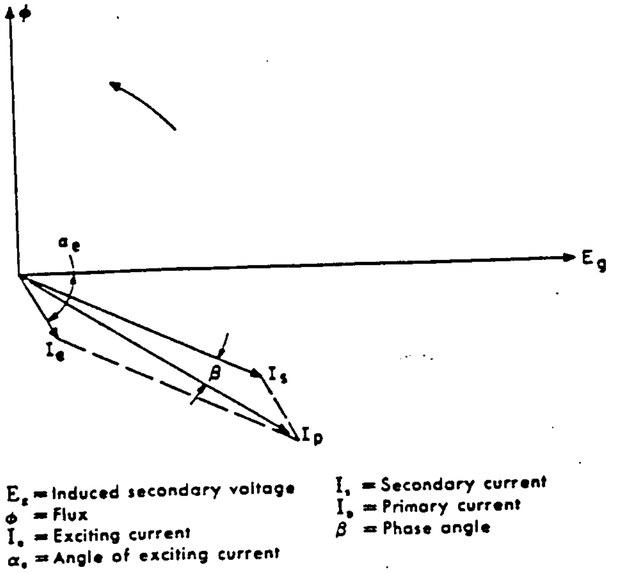


Fig. 30. Vector diagram illustrating the relation between current, voltage, and flux existing in a current transformer

Also, because of the differences in phase of the various quantities involved, the difference in phase between primary and secondary currents will be exactly 0 degrees only when the power factor of the total secondary burden (that is, the internal burden of the transformer itself, plus external burden of meters, leads, etc.) equals the power factor of the exciting current. For all other conditions, the angle will differ from 0 degrees by a small angle (β), which is called the phase-angle error of the current transformer.

TERMS FOR EXPRESSING ERRORS

Like the ratio error of a potential transformer, the ratio error of a current transformer is usually expressed as a ratio correction factor. This equals:

$$\text{RCF} = \frac{\text{True Ratio}}{\text{Marked Ratio}}$$

$$\text{or, True Ratio} = \text{Marked Ratio} \times \text{RCF}.$$

The phase-angle error (β) of a current transformer is also similar to that of a potential transformer. It is the angle between the primary current vector; this error is usually expressed in minutes of angle. This angle is considered as positive when the secondary-current vector leads the primary-current vector.

Since current transformers are often used with protective relays which must operate at high overcurrents, transformer performance under these conditions must also be known. The terms in which this performance is normally expressed, and the meaning of these terms, are explained in the next section.

OVERCURRENT ACCURACY

Current transformers are given standard accuracy-class ratings which define the performance at overcurrent values. These ratings are on the basis of the standard secondary-terminal voltage a transformer will deliver without exceeding a standard percent ratio error. Thus, transformers may be classified as:

2.5 (H or L) 200
or, 10 (H or L) 200.

The first term establishes a maximum percent ratio error; the second term (H or L) is determined by characteristics that are explained later; the third term is the secondary voltage which can be delivered at 20 times rated secondary current without exceeding the ratio error.

Standard percent ratio-error classes are 2.5 percent and 10 percent. Standard secondary-voltage classes are: 10, 20, 50, 100, 200, 400, and 800 volts.

For normal 5-ampere-secondary transformers, 20 times rated secondary current is 100 amperes; hence, the standard secondary voltage divided by 100 amperes gives the secondary-burden ohms. In the first example, 2.5 (H or L) 200, such a transformer could carry a 2-ohm burden without exceeding a 2.5-percent-ratio error from 5 amperes secondary to 100 amperes secondary. Similarly, in the second example, 10 (H or L) 200, the ratio error from normal to 20 times normal secondary current would not exceed 10 percent. Burdens used for overcurrent accuracy rating have the same power factor as the corresponding burdens used for normal accuracy rating.

Because of the steps in the classification series, the standard classes do not fully replace curves of transformer performance at overcurrent values. They do provide, however, a convenient means of specifying a desired level of performance within reasonable steps. It should be recognized that the classifications specify only the minimum secondary voltage at which the specified ratio error will not be exceeded. Thus the classification, 10 (H or L) 200, means that, at 200 volts, the ratio error is not more than 10 percent. By inference, it also means that the ratio error, at the voltage which corresponds to the next higher standard voltage (400), is more than 10 percent; otherwise, the classification would have been 10 (H or L) 400.

While the classification of overcurrent performance is primarily based on the ratio error at 20 times secondary current, it is often desirable to know something about the performance at lower values of current. Depending upon performance, current transformers can be broadly divided into two classes. The first class, designated by the letter H, will have a nearly constant-percentage ratio error when delivering a fixed secondary voltage over a wide range of secondary current. The other class, designated by the letter L, will have a nearly constant magnitude error (and hence a variable-percentage error) under similar conditions.

More precisely, the USASI Standards for Instrument Transformers defines an H-class transformer as one that is capable of delivering a secondary-terminal voltage equal to its voltage class at any secondary current from 5 times rated secondary current to 20 times rated secondary current without exceeding its classified ratio error. In other words, a transformer rated 10H200 would have a ratio error not exceeding 10 percent with a 2-ohm burden while it is operating at any secondary current between rated value and 20 times rated value. The 10 percent ratio error would not be exceeded with either a 4-ohm burden between normal and 10 times normal current or with an 8-ohm burden between normal and 5 times normal current.

An L-class transformer cannot be used with proportionately higher burdens at lower secondary currents without exceeding its classified ratio error.

EFFECT OF SECONDARY BURDEN ON ACCURACY

As is illustrated in Fig. 30, errors are present in current transformers because some of the primary current is required to magnetize the core and supply core losses and, thus, it is not available to contribute to the secondary current. The value of this exciting current (I_e), Fig. 30, depends upon the amount of flux (ϕ) it must produce. The amount of flux depends, in turn, upon the secondary voltage (E_g) that is required to force the secondary current (I_s) through the total secondary impedance. (Total secondary impedance comprises the impedance of the secondary of the transformer and the impedance of the secondary burden including leads.) Therefore, for any specific secondary current on a particular transformer, the exciting current (and consequently the errors) will increase as the impedance, or volt-amperes, of the secondary burden increases (neglecting the effect of the burden power factor).

The burden power factor will also affect the errors. As the power factor increases, the secondary current (I_s), Fig. 30, will be more nearly in phase with the voltage E_g; thus the phase-angle error (β) is increased, but the ratio error is decreased as I_p will more nearly equal I_s. Conversely, decreasing the burden power factor will decrease the phase-angle error, or even make it negative, but it will increase the ratio error. (The maximum ratio error will occur when I_s is in phase with I_e. After this point, the ratio error will decrease.)

While the fundamental errors of current transformers will be affected by the change in burden as described, the observed change in errors may differ somewhat because of the influence of the transformer compensation. The errors at different burdens on a typical compensated current transformer are illustrated in Fig. 31.

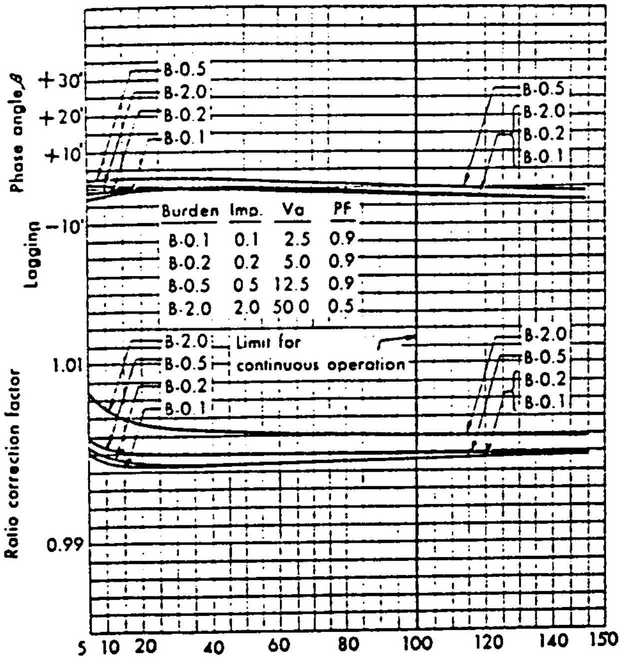


Fig. 31. Typical current transformer characteristics

EFFECT OF PRIMARY OR SECONDARY CURRENT ON ACCURACY

It has been pointed out before that the value of the exciting current (I_e), Fig. 30, depends upon the secondary voltage (E_s) which is required to force the secondary current (I_s) through the total secondary impedance. As the primary current decreases from the rated value for a specific transformer with a constant-impedance burden, the secondary current will decrease in approximately the same ratio, and the exciting current will also decrease. However, as current transformers are designed normally to operate at low flux densities in the core, below the point of maximum effective permeability, the exciting current will not decrease as rapidly as the secondary current.

Since the errors are dependent on the ratio of exciting current to secondary current, they will increase as the primary current, and thus the secondary current, decreases.

However, through the use of compensation, such changes in error will be reduced. The change in errors with the change in current for a typical compensated current transformer is shown in Fig. 31.

COMPENSATION

The general characteristic of a current transformer is such that the secondary current multiplied by the turn ratio will be less than the primary current by the amount of losses in the core. These losses are dependent on both the burden characteristics and the value of the secondary current. Therefore, the transformer may be compensated to give zero ratio error at some particular value of current and burden by making the turn ratio slightly larger than the marked ratio, thus increasing the secondary current the necessary amount.

This compensation is usually accomplished by reducing the number of secondary turns and is known as "turn compensation." The increment of change resulting per complete secondary turn removed is a small but inflexible quantity. More precise adjustment is possible by so called "split-turn compensation" providing fractional turn effect from 20 to 80% of a full turn (see Fig. 32). Two wires in parallel with different numbers of turns around the core constitute "split turn compensation." Difference in the size of the two wires gives additional precision.

Many other methods of compensation (such as D'ENTREMONT® Compensation) are possible depending on effects desired and complexity that can be justified. Detailed discussion of these methods may be found in material referenced in the bibliography.

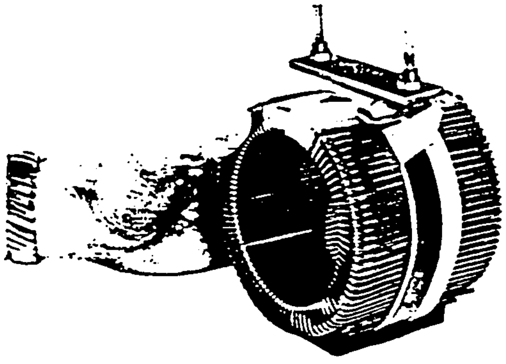


Fig. 32. Current transformer with split-turn compensation

FREQUENCY VARIATION

Current transformers can be used over a relatively wide range of frequency without appreciable effect on the performance. In general, the errors increase as the frequency decreases; and the reactance and the self-heating increase as the frequency increases. For this reason, the frequency limits that are stated for each design of current transformer should be followed.

Because the errors increase with a decrease in frequency, most current transformers are given a separate accuracy classification for each of the several standard frequencies on which they may be used. For instance, a transformer designed primarily for operation on 60 Hz may have a separate, and perhaps different, accuracy rating for 25, 50, or 400 Hz.

WAVE FORM

Current waves that contain third harmonics, having a magnitude as much as 50 percent of the fundamental, will be reproduced in the secondary wave of most current transformers with very little distortion, and the transformer errors will be changed very slightly—generally less than 0.1 percent.

Waves that contain higher frequency harmonics may not be reproduced as accurately, because the amount of distortion increases as the frequency and magnitude of the harmonics increase. However, higher harmonics are usually of small magnitude and, in this instance, will cause little error.

RETURN CONDUCTOR EFFECT

Conductors carrying large currents, such as those that might be used for return conductors on current transformers of 2000-ampere rating and above, produce a relatively large field, or flux pattern, about their axis. Therefore, if such conductors are placed too near to the current-transformer core, this flux may concentrate in the core, causing local saturation and, consequently, large errors.

EFFECT OF ERRORS ON INSTRUMENT READINGS

When current transformers are to be used in the measurement of current alone, only the ratio error need be considered. However, when wattmeter measurement or other measurements are made in which the phase relationship between the current and voltage is involved, the phase-angle error of the current transformer also must be considered. This is necessary because an error in the current phase angle constitutes a shift in phase between the position of the current vector in the primary circuit and the current vector in the secondary circuit. The over-all result is to change the phase relationship between the current and the voltage in the secondary circuit, as compared with the current and voltage relationship in the primary circuit, which introduces an error in the measurement. However, both the ratio and phase-angle errors of current transformers are normally so small that they can be neglected in all but the most accurate measurements.

In general terms, a ratio correction factor greater than one will cause the meters and instruments in the secondary circuit to read low.

A positive (leading) phase-angle error will cause a wattmeter connected in the secondary circuit to read high (for the normal case of lagging-line power factors). This is just the opposite effect of a similar error in a potential transformer. The effect of phase-angle errors of both current and potential transformers is shown in Fig. 9.

STANDARD ACCURACY CLASSIFICATION

The USASI Standards for Instrument Transformers, USAS C57.13, has standardized on a method of classifying current-transformer accuracy. As the accuracy is dependent upon the burden, standard burdens have also been designated. These are the burdens at which the accuracies are to be classified.

The standard burdens have been chosen to cover the range normally encountered in service and are listed in Table II.

The accuracy classifications for metering current transformers, as given by USASI, are listed in Table III.

Ratio correction factor (RCF) has been defined as the factor by which the marked ratio must be multiplied in order to obtain the true ratio.

Transformer correction factor (TCF) takes into account the combined effect of the ratio error and phase-angle error on wattmeters or similar measurement devices. It is defined as the factor by which a wattmeter reading must be multiplied to correct for the effect of instrument transformer ratio correction factor and phase angle. The limits of TCF, as indicated in Table III, have been established by USASI with the requirement that the power factor of the load being measured must be within the limits set forth in this table. If the power factor of the primary circuit is outside this range, the TCF of the transformer may also be outside the range specified.

For any known ratio correction factor of a specific current transformer, the positive and negative limiting values of the phase-angle error (β) in minutes may adequately be expressed as follows:

$$\beta = 2600\ (\mathrm{RCF} - \mathrm{TCF})^{\dagger}.$$

TCF is taken in turn as the maximum and minimum values of transformer correction factor specified in the table, and the RCF is the ratio correction factor of the current transformer under the conditions being checked. This relationship is plotted for the various burdens in Figs. 33 and 34.

---

† The formula—$\beta = 2600$ (RCF-TCF)—and the parallelograms of Fig. 33 and 34 which are derived from it are approximate only. The correct formula is $\mathrm{Cos}\ (53.13^\circ - \beta) = 0.6\ \frac{\mathrm{RCF}}{\mathrm{TCF}}$ · However, the approximate formula introduces very little error into the calculation, and it is entirely adequate for normal purposes.

By means of this USASI system, the accuracy of a current transformer may be described by listing the best accuracy class which it meets for each burden. Thus, a current transformer may be accurate enough to be rated:

0.3 B-0.1, 0.3 B-0.2, 0.3 B-0.5 and 0.3 B-2

For another transformer the error may be such that it can only be classified as:

0.3 B-0.1, 0.3 B-0.2, 0.6 B-0.5 and 1.2 B-2

or even . . .

0.6 B-0.1, 0.6 B-0.2 and 1.2 B-0.5

In the third example, the omission of any reference to accuracy at B-2 indicates that the error is greater than that specified for the poorest accuracy class at this high burden; hence no figure can be given.

THERMAL AND MECHANICAL RATINGS

Under conditions of circuit faults, current transformers can be exposed to short-circuit-current values which are considerably in excess of their normal current ratings. The maximum current in the circuit during fault conditions should be no greater than the ability of the current transformer to withstand this excessive current.

Short-circuit faults are usually cleared in a very short time, but extremely high currents may flow during this period. The first cycle is usually not only of the greatest magnitude, but it is often offset by a d-c component. As illustrated in Fig. 35, this d-c component may cause the first cycle to be fully offset.

TABLE II

USASI STANDARD BURDENS

Designation of Burden	Burden Characteristics		Secondary Burden at 60 Hz and 5-Ampere Secondary Current		
	Resistance (Ohms)	Inductance (Millihenrys)	Impedance (Ohms)	Volt-Amperes	Power Factor
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-1	0.5	2.3	1.0	25.0	0.5
B-2	1.0	4.6	2.0	50.0	0.5
B-4	2.0	9.2	4.0	100.0	0.5
B-8	4.0	18.4	8.0	200.0	0.5

TABLE III

USASI ACCURACY CLASSES FOR METERING CURRENT TRANSFORMERS

Accuracy Class	LIMITS OF RATIO CORRECTION FACTOR AND TRANSFORMER CORRECTION FACTOR				Limits of Power Factor (Lagging) of Metered Power Load
	100% Rated Current		10% Rated Current		
	Min.	Max.	Min.	Max.	
1.2	0.988	1.012	0.976	1.024	0.6–1.0
0.6	0.994	1.006	0.988	1.012	0.6–1.0
0.3	0.997	1.003	0.994	1.006	0.6–1.0

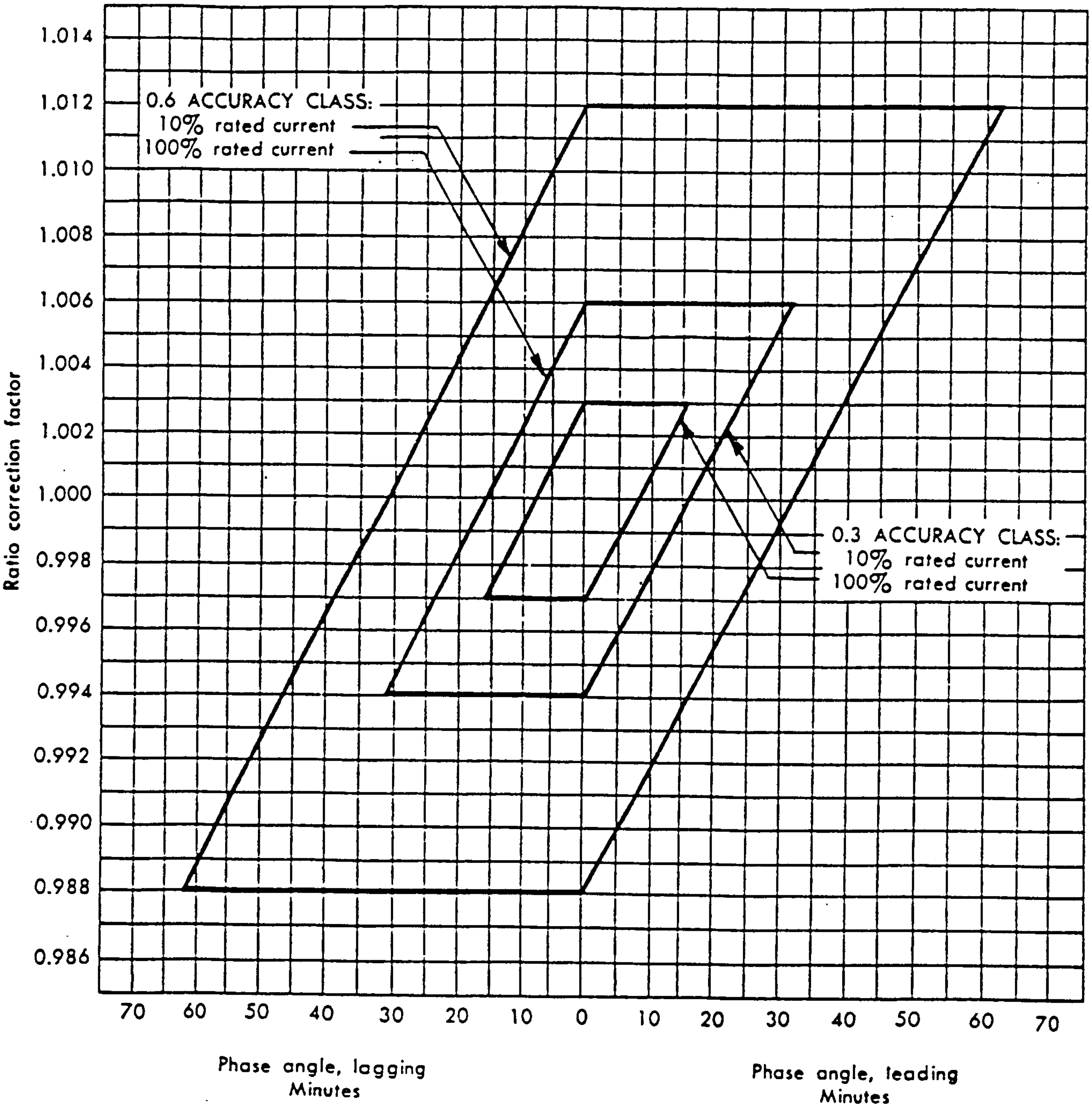


Fig. 33. Parallelograms showing graphical equivalent of USASI accuracy classes 0.3 and 0.6 for current transformers for metering service

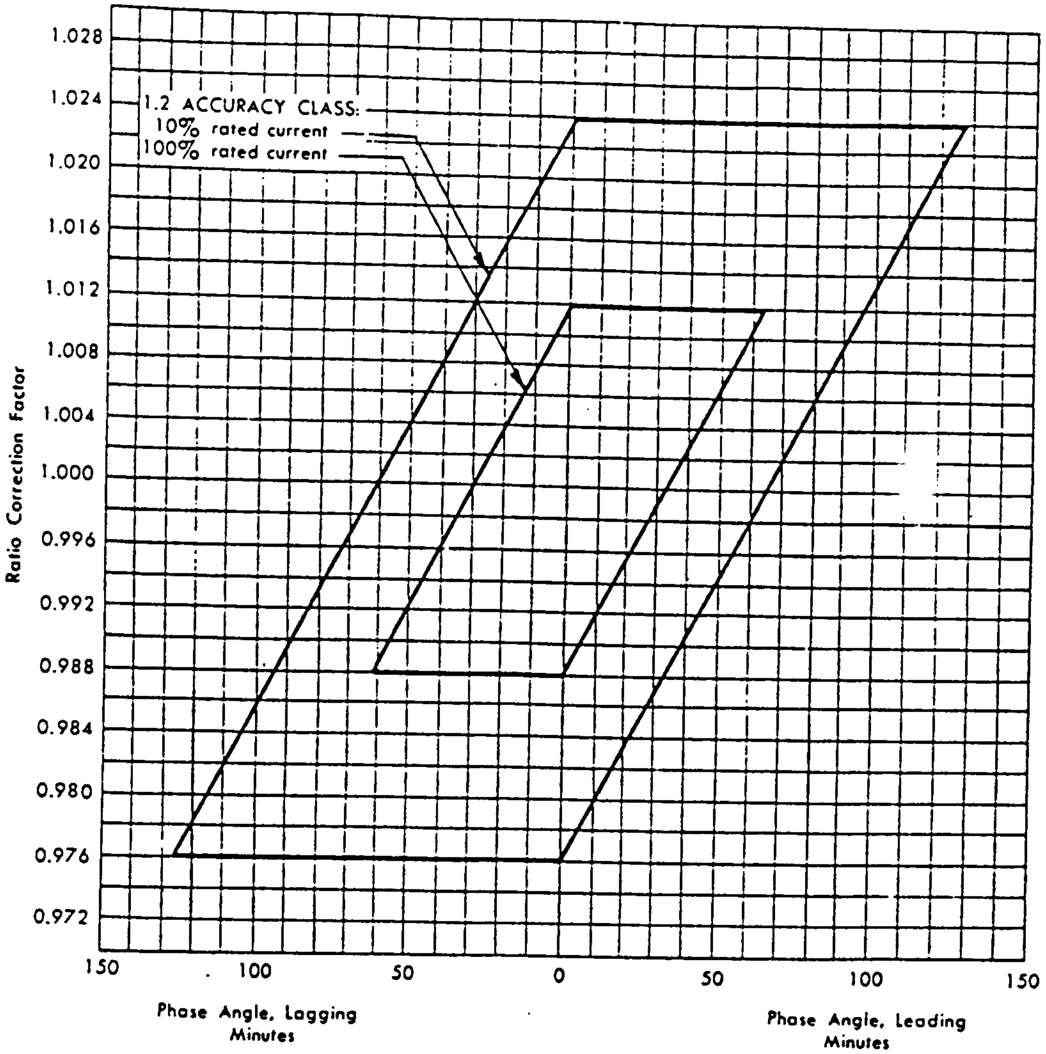


Fig. 34. Parallelograms showing graphical equivalent of USASI accuracy class 1.2 for current transformers for metering service

The ability of a current transformer to withstand the initial current caused by a short circuit is called its *mechanical rating*. By USASI definition, mechanical rating is expressed as the root-mean-square (RMS) value of the a-c component of a completely displaced primary-current wave which the transformer is capable of withstanding with the secondary short-circuited. Thus, a maximum completely displaced current within the rating of a transformer will not cause mechanical damage to the transformer—damage which is generally characterized by deformation of the windings.

In addition to the mechanical effect, the heating effect of the short-circuit current also must be considered. The ability of current transformers to withstand such heating is called the thermal short-time rating of the device. This rating is given as the RMS value of a steady current which the transformer can withstand without exceeding a maximum specified temperature—250 C for most designs—for a certain period of time, usually less than 5 seconds.

The mechanical and thermal ratings of various current transformers are listed in the published data which describe those devices. Concerning thermal ratings, it is usually given for one second, but it can be calculated for any period of time *up to five seconds* from the relation:

$$\text{Thermal Rating for Time } t = \frac{\text{Thermal Rating for One Second}}{\sqrt{t}}$$

where t is expressed in seconds.

Proper application of current transformers requires that transformers be selected with mechanical and thermal ratings higher than the corresponding

COMPARATIVE VALUES AT INSTANT OF SHORT CIRCUIT			
CURVE	RMS TOTAL CURRENT =100%	ENVELOPE A-C COMP =100%	RMS OF A-C COMP =100%
Curve of Major Peaks	163.3	200	282.8
RMS Total Current	100	122.5	173.2
D-c Component and Envelope of A-c Comp	81.6	100	141.4
RMS of A-c Component	57.8	70.7	100
Curve of Minor Peaks	0	0	0
Envelope of A-c Component	81.6	100	141.4

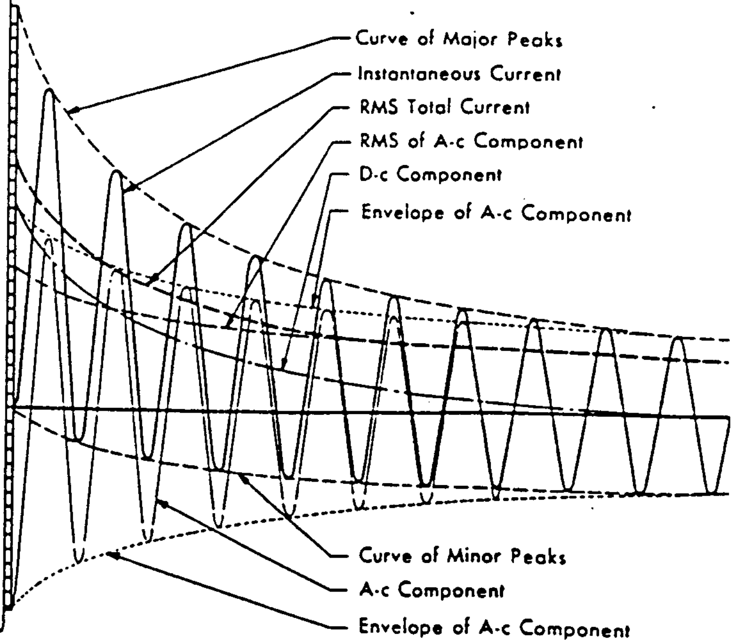


Fig. 35. Short-circuit current components

maximum currents reasonably expected on the circuit being measured.

SECONDARY BURDENS

As previously stated, the burden on the secondary circuit of a current transformer affects the accuracy of that device. Therefore, to predict the performance of a particular transformer used in a certain circuit, the burden* of the various meters, instruments, and relays in its secondary must be known.

It is often found desirable to connect several meters or combinations of devices in series on the secondary of current transformers. In these situations, it is necessary to compute the total burden of such a combination of devices.

For many purposes, it is sufficiently accurate to add arithmetically the impedance burden of the individual devices involved. In case the volt-ampere burden alone is known, the impedance burden can be calculated from the relationship:

$$Z_b = \frac{VA}{I^2}$$

where I is the current through the burden, and Z_b is the burden impedance.

This method is followed, for example, in determining whether or not a transformer will have excessive burden. In specific instances when calculation on this basis indicates too much total burden, it is advisable to recalculate, taking the power factor into account.

For those situations in which it is necessary to consider the power factor of the impedance, a graph, illustrated by Fig. 11, has been prepared for combining burdens in a convenient manner. From this curve, burden combinations can be readily worked out graphically without using a comparatively complicated mathematical process.

The explanation of the chart and its use is given under section "Secondary Burdens," page 15. An example of its application to the problem of combining current-transformer burdens is as follows:

Required: To determine the total impedance and power factor of the burden on a current transformer to which are connected:

One Type I-50, 2.5-ampere watthour meter,
One Type AB-14, 5-ampere ammeter,
One Type AB-14 single-phase wattmeter, and
Two 25-foot leads made of No. 10 Awg copper wire (50 feet of wire).

---

*Burdens for GE apparatus are listed in Publication GET-1725 entitled *Instrument Transformer Burden Data*, as well as in the descriptive literature for each class of apparatus.

From Publication GET-1725, burden data can be found as follows:

Device	Effective Resistance (Ohms)	Inductance (Microhenrys)	Reactance (Ohms)
Watthour Meter	0.013	44	—
Wattmeter	0.023	260	—
Ammeter	0.055	270	—
Leads	0.050	0	—
Total	0.141	574	0.217*

---

* Reactance = 2πfl, where f = frequency (60), and l is inductance in henrys.

Using scales B (Fig. 11), locate a point on the rectangular plot by using 0.14 × 1000 as an abscissa and 0.22 × 1000 as an ordinate. This point falls on the radius 0.53 which gives this value as the power factor of the total impedance. Following the arc (imaginary), on which this point is located, to the radius marked in total impedance, 0.26 × 1000 will be noted as the total impedance.

INTERCONNECTION OF BURDENS ON THREE-PHASE CIRCUITS

There are three common types of interconnection used with current transformers on three-phase systems. They are:

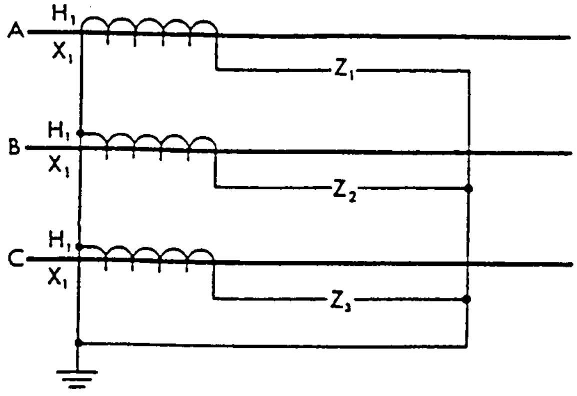
1. Y connection (three transformers).
2. V or "straight" connection (two transformers).
3. Reversed-V or "cross" connection (two transformers). These are illustrated in Fig. 36, 37, and 38, respectively.

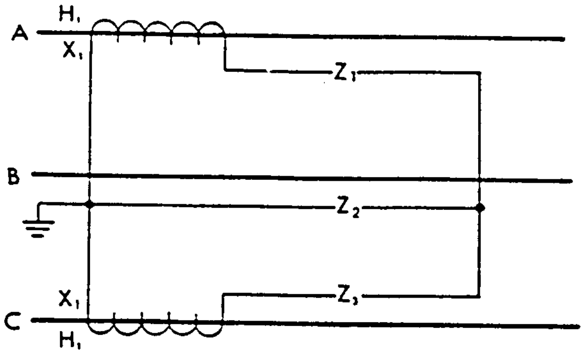
The following rules for computing secondary burdens in these three examples will be found convenient and are sufficiently accurate for most commercial purposes. Where the highest accuracy is required, the burdens should be determined by vector analysis as described on page 37.

Y Connection

With the 4-wire Y connection (Fig. 36), the burden is Z_1, Z_2, and Z_3 on CT_A, CT_B, and CT_C, respectively.

With the 3-wire Y connection, the burden on any transformer is one-third of the total secondary burden on all transformers, except for highly unbalanced burdens.





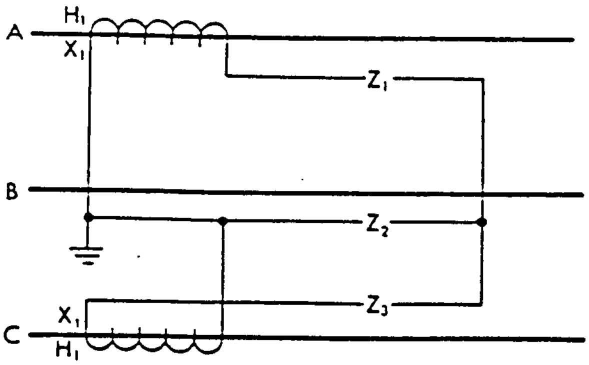


Fig. 38. Three-phase reversed V or "cross" connection of current-transformer secondaries

V or "Straight" Connection

With the V connection, Fig. 37, the burden on a specific transformer depends on the ratio of the impedance in the secondary line that has no current transformer to the impedance in the line connected directly to the secondary of the transformer considered.

1. When this ratio is greater than 3.2:1, the equivalent burden on the transformer equals the impedance directly connected to its secondary plus the impedance in the secondary line without transformer.
2. When this ratio is less than 3.2:1 and greater than 0.4:1, the equivalent impedance on the transformer equals the impedance in the line that is directly con-

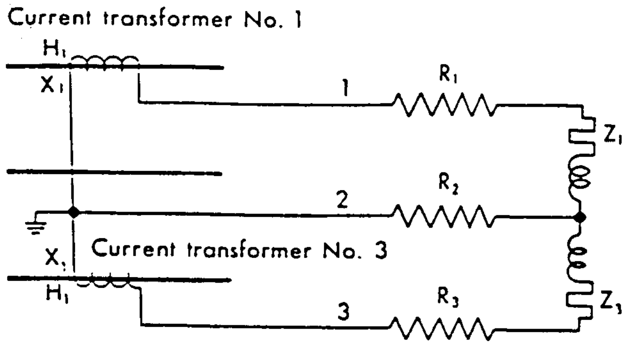


Fig. 39. Typical example of open-delta interconnection of current-transformer secondaries

nected to its secondary, plus three quarters of the impedance in the secondary line without transformer.

3. When the ratio is less than 0.4:1, the equivalent impedance on the transformer equals the impedance in the line that is connected directly to its secondary, plus one-half of the impedance in the secondary line without transformer.

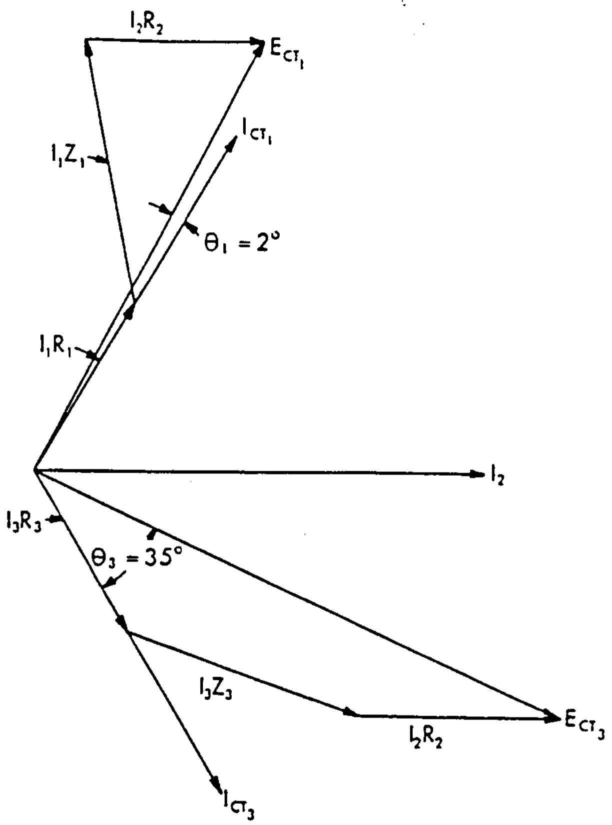
Reversed-V or "Cross" Connection

With a reversed-V or "cross" connection, Fig. 38, the equivalent impedance on each transformer equals the sum of the impedance (volt-amperes) connected directly to it, plus 1.5 times the impedance in the middle leg; thus, $Z_1+1.5Z_2$.

VECTOR SOLUTION FOR INTERCONNECTION OF BURDENS

In specified cases where the highest accuracy in the computation of three-phase current-transformer interconnection is desired, or where leads carrying the secondary current from more than one current transformer have high resistance, a vector solution of the total burden imposed on each transformer should be employed. When the portion of the circuit that is common to two such interconnected transformers is merely a short lead of relatively low impedance, the effect of the interconnection on the accuracy of either transformer is generally inappreciable. However, if the common portion is a long lead or a device of appreciable impedance, the outputs from the current transformers may reach unexpected conditions of power factor and unbalance.

A typical example of the common "straight" or "open delta" interconnection, in which moderate unbalancing is produced, is given in Fig. 39. As shown in this illustration, two wattmeter elements are connected to two current transformers through three leads, with one of the leads being common to both circuits and carrying a current equal to the vector sum of the currents in the other two leads.



From Fig. 39, the outputs from the transformers are found to be:
CT_1 = 1.32 volts × 5 amp (at 2°) = 6.6 va at 1.00 pf
CT_3 = 1.60 volts × 5 amp (at 35°) = 8.0 va at 0.82 pf

Fig. 40. Vector solution for the burdens imposed on the current transformers shown in Fig. 39.

Figure 40 indicates graphically that, although the secondary connected devices are apparently equal and symmetrically arranged, the output from current transformer No. 1 is at unity power factor, while that of No. 3 is at 0.82 power factor (current lagging). This means that different ratio and phase-angle corrections apply for each transformer. However, no particular difficulty is presented, since the accuracies of the transformers for such ranges of output are ordinarily either directly available or readily estimated from the calibration data furnished with the transformer.

Certain situations should be guarded against; that is, those in which the power-factor unbalance may be sufficient to cause the output from one of the transformers to assume some unusual value for which the accuracy of the transformer is unknown or cannot be readily estimated. For instance, it can be shown from a solution similar to Fig. 40 that, had the lead resistances, R_1, R_2, and R_3, been assumed slightly greater, there would have been a "leading" current output from transformer No. 1. It will also be found that, with highly inductive burdens of even moderate impedance connected in lines 1, 2, and 3, the output from transformer No. 3 may drop to zero power factor. The determination of the accuracy characteristics of interconnected transformers, when leading currents or currents lagging by 90 degrees or more are being delivered, is ordinarily impossible unless data are available from special 3-phase calibration tests which have been made under identical conditions of secondary interconnection.

CORRECTIONS FOR TRANSFORMER ERRORS

The USASI accuracy classification of all GE current transformers is listed in the descriptive literature. In addition, standard test data is provided on the certificate of test. Some designs have the accuracy listed directly on the nameplate. Since corrections, normally, are not made for the errors of current transformers at overcurrents, the overcurrent-accuracy classification will not be discussed.

The accuracy classification at normal currents indicates the performance levels of the various types of transformers. For many measurements, the maximum errors thus indicated are so small that they can be neglected without seriously affecting the over-all accuracy of the measurement. In other measurements, high accuracy is required, and corrections for current-transformer errors must be made. In these specific instances, the USASI classification of errors is not suitable for making such corrections, so characteristic curves or test certificate data must be used.

ERRORS FROM CHARACTERISTIC CURVES

Descriptive literature for current transformers include transformer characteristic curves published in a form similar to that shown in Fig. 31. This curve lists the ratio correction factor (RCF) and phase-angle error (β) from 5 percent to 100 percent (or more) of rated current, at each of the several standard burdens. The variation in accuracy of individual transformers of a given type from the characteristic curve for that type depends, in some measure, on the fundamental error of the transformer. Thus, the higher the error, the greater the possible variation in error from the characteristic curve. However, the fundamental error is often not the observed error of the transformer, because of the effect of the compensation. Thus, no numerical significance can be given to the variation in error in terms of the error itself, although a general classification of this variation (such as is represented by the following table), will give a good indication of the limits of such variation. Since, for a specified USASI accuracy classification, the observed error at 10 percent of rated current may be double that of the error at 100-percent current, the expected variation in error is given at each of these two points:

Accuracy Classification at Burden Under Consideration	Variation in Error from Characteristic Curve Values			
	Ratio Correction Factor		Phase-angle Error	
	10% Current	100% Current	10% Current	100% Current
0.3–0.6	±0.004	±0.002	± 10 min.	± 7 min.
1.2	±0.005	±0.003	± 15 min.	± 10 min.

The variation indicated by this table is for the general case; many designs have variations smaller than this, although very few individual transformers will exceed this range.

ERRORS FROM TEST DATA

Correction data for current-transformer errors may be obtained from test results on the particular transformer, as well as from the characteristic accuracy curves. Certificates of Test for current transformers, issued by the General Electric Co., guarantee the ratio correction factor to be within ±0.001 of the figure given and the phase-angle error to be within ±3 minutes. Correction of errors by this means gives the best accuracy for the particular current transformer used.

TYPES OF CURRENT TRANSFORMERS

Current transformers are made in many different current ratios. In addition, various designs are insulated for use on different voltage circuits. Thus, the circuit voltage is as important a consideration in the selection of current transformers as it is for potential transformers. In general, instrument transformers for use on circuits rated 25,000 volts and above are suitable for use out of doors. The same transformers, however, may be used indoors, if desired. Transformers for circuits below this voltage are usually made in two distinct types: one for outdoor service, and the other for indoor use.

WOUND-PRIMARY TYPE

Current transformers, other than 600-volt window and bar types, for current ratings of 800 amperes and below are usually of the wound-primary type. In this range of ratings, more than one primary turn is fre-

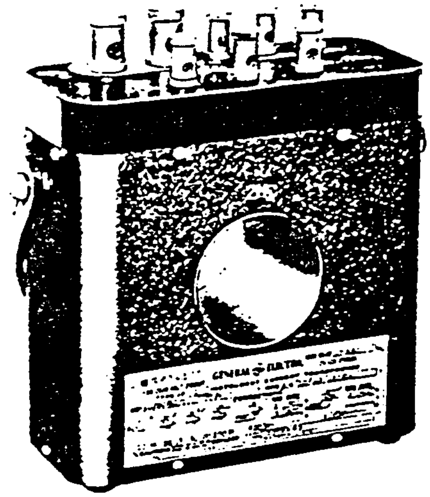


Fig. 41. Type JP-1 portable-type instrument current transformer

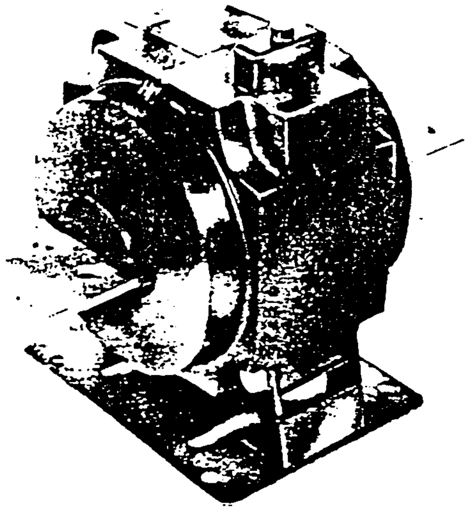


Fig. 43. Type JCM-3 instrument current transformer for indoor service

quently required to obtain low exciting current and high accuracy.

BAR-PRIMARY TYPE

Current ratings of 1200 amperes and above permit sufficient ampere-turns for good design with only one effective turn in the primary. In most designs, the primary consists of a straight bar extending through the core and secondary winding.

This type of construction is particularly suited to withstand the stresses of heavy overcurrent; there is no tendency for the primary winding to assume a circular shape, as is the case with wound-primary-type transformers. However, these transformers must be mounted with proper relation to adjacent conductors so as to avoid magnetic stresses which might be sufficient

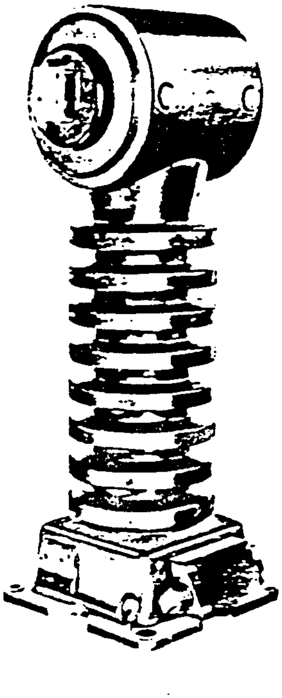


Fig. 42. Type JKW-200 SUPER✈BUTE instrument current transformer for outdoor service

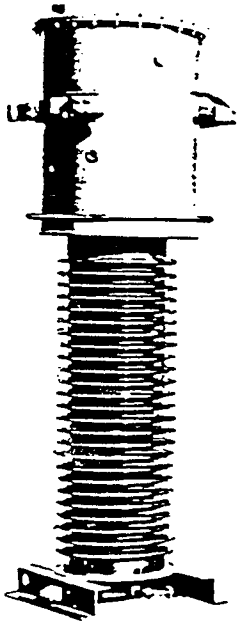


Fig. 44. Type KW-900 instrument current transformer for outdoor service

to distort the buses and, thus, damage the transformers. (See section entitled, "Return Conductor Effect," page 31.)

WINDOW TYPE

High-current transformers similar to the bar-primary types may be had with no primary at all. These so-called "window types" have an insulated hole through the core and secondary winding, through which the user can place his own conductor. This conductor then becomes the primary of the transformer, and no other primary connections are necessary. By adding insulation to this conductor, the user can increase the over-all insulation of the transformer.

TRIPPING TRANSFORMERS

There are several types of small and inexpensive current transformers which are manufactured especially for protective and control purposes. These transformers are not designed to meet the same accuracy specifications as those instrument current transformers which are intended for use with instruments and meters; but, in some cases, they will be found sufficiently accurate for operating instruments.

BUSHING TYPE

The bushing-type transformer consists of a secondary winding on a circular core which is designed to fit on the bushing of a power transformer, oil switch, or other device. The conductor in the bushing acts as the primary "winding" of one effective turn. It is, therefore, evident that the ampere-turns equal the primary amperes. For this reason and the fact that accuracy depends on ampere turns as well as core size and other factors, not all bushing transformers of a given size have the same accuracy for all current ratings; in short, the lower the rating, the poorer the accuracy.

Most of the bushing-type transformers are used for relaying purposes, where accuracy at normal current values is not extremely important. However, by means of special compensation, such transformers can be supplied with sufficient accuracy, even at primary currents as low as 300 amperes, for normal metering purposes. Burdens placed on such transformers must be kept low, however.

COMBINATION TYPES

Metering outfits (Fig. 46) combine one or more current elements with one or more potential elements in a single tank assembly. Complete metering facilities are thus provided in minimum space.

Fig. 45. Type JKW-5 instrument current transformer for outdoor service

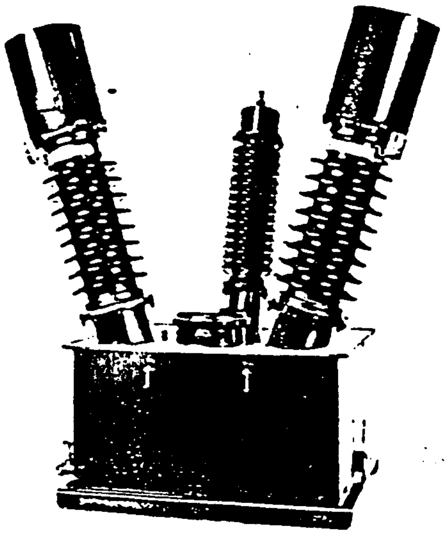


Fig. 46. Type MC-350 metering outfit for outdoor service

PORTABLE TYPE

Portable current transformers, for use in making tests, are available in several styles to meet various application requirements such as accuracy, weight, and other features. These devices usually incorporate a number of primary windings so that a considerable range of current can be covered.

DOUBLE-SECONDARY TYPE

The majority of standard single-secondary current transformers have sufficient capacity to carry the usual burdens, including relays, without exceeding ordinary accuracy limits. When the occasion demands, however, transformers with more than one secondary can be furnished. These designs permit instruments and other devices to be separated; that is, either to limit the maximum burden on any secondary or to isolate some particularly important device, such as a differential relay.

A double-secondary transformer is actually two transformers, each transformer having its own core. Less space is required for this type of construction than for two transformers in series.

THREE-WIRE, SINGLE-PHASE TYPE

For measurement purposes on three wire, single-phase circuits, double-primary-type current transformers of the required construction are available. With this type of transformer, a normal single-phase instrument or meter can be used for three-wire circuit measurements.

SPLIT-CORE TYPE

Window-type transformers are available and are designed with hinged cores which permit them to be assembled on buses without breaking the circuits. A transformer of this type should be used with discretion, as errors and mechanical difficulties might result from the use of such a core, unless it has been specifically designed to provide the required degree of accuracy.

AIR-GAP-CORE TYPE

High overcurrents during fault conditions, particularly overcurrents during which long d-c transients occur, tend to saturate the cores of ordinary current transformers and cause high errors that vary with the current. Such errors are not easily accounted for in differential-protection circuits. For such conditions, air-gap-core transformers* are available in designs which have relatively constant errors over a wide range of overcurrents and transient conditions.

AUXILIARY TRANSFORMERS

Totalizing transformers are designed for connection in the secondary circuits of standard current transformers. They provide a practical means for totalizing the power output of several individual circuits. This method is often employed when it is impractical to connect the secondaries of current transformers in multiple; that is, when all current transformers are not of the same ratio. (See section entitled "Totalizing Transformers," page 45.)

APPLICATIONS

Current transformers are used in many different types of circuits and for many different purposes. A typical connection of an ammeter and a current transformer for the measurement of current is shown in Fig. 47. Other typical circuits, which are measured by various meters, instruments, and relays by the use of both current transformers and potential transformers, are shown in Fig. 17 through 25, and for current transformers alone, in Fig. 48.

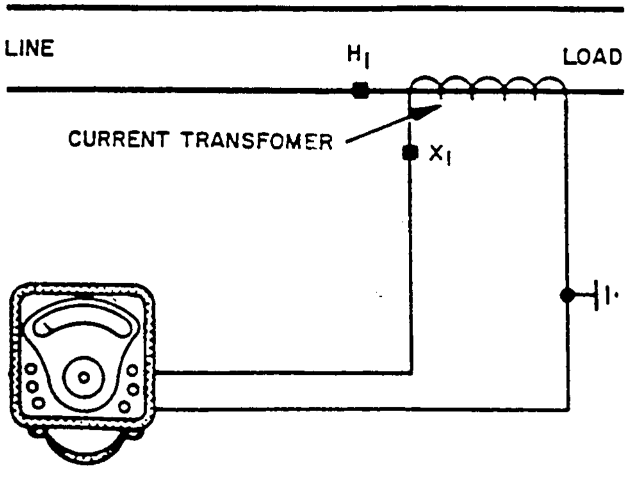
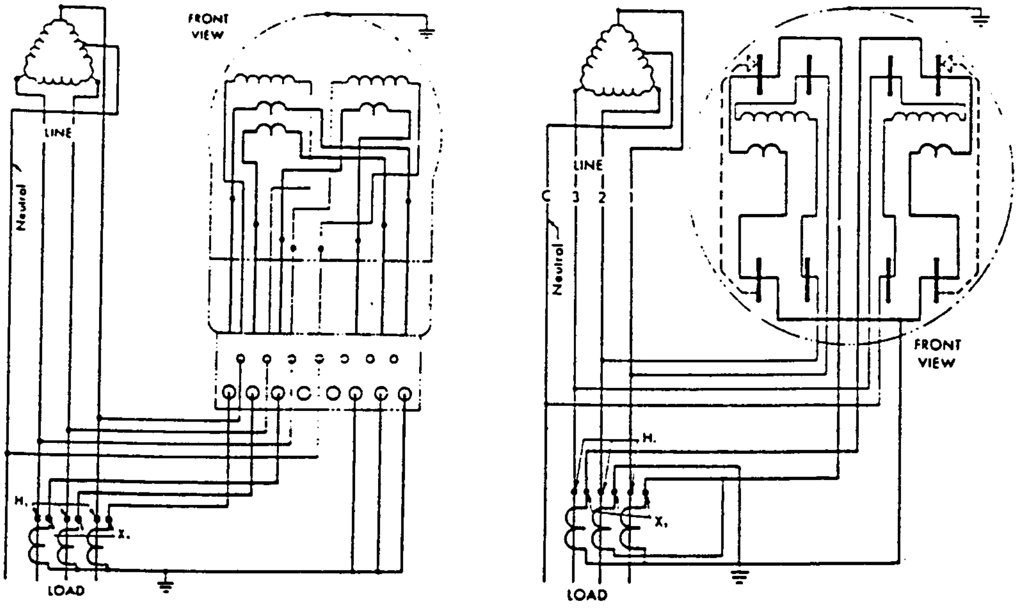


Fig. 47. Connection diagram of an ammeter with current transformer

---

*A detailed description of this type of transformer may be found in the article entitled *New Current Transformer for Bus Differential Protection* by L. F. Kennedy and A. T. Sinks, *AIEE Transactions*, 1941, Vol. 60, pp. 1180–1187.



(a) Type V-66-A (b) Type V-63-S

Fig. 48. Connection diagrams of watthour meters for 4-wire △, 3-phase circuits, with current transformers

TABLE IV

STANDARD INSULATION CLASSES AND DIELECTRIC TESTS FOR CURRENT TRANSFORMERS

Insulation Class (Nameplate Rating in Kv)	Maximum Line-to-neutral Voltage (Kv)	Dielectric Tests			
		Low-frequency Tests (Kv RMS)	Impulse Tests		
			Chopped Wave		Full Wave (Kv Crest)
			Crest Voltage (Kv)	Minimum Time to Flashover (Microseconds)	
0.6	0.380	4	12	1.0	10
1.2	0.762	10	36	1.0	30
2.5	1.59	15	54	1.5	45
5.0	3.18	19	69	1.5	60
8.7	5.52	26	88	1.6	75
15 L	9.53	34	110	1.8	95
15 H	9.53	34	130	2.0	110
25	15.9	50	175	3.0	150
34.5	21.9	70	230	3.0	200
46	29.2	95	290	3.0	250
69	43.8	140	400	3.0	350
92*	Not specified by USAS C57.13	185	520	3.0	450
115		230	630	3.0	550
138		275	750	3.0	650
161		325	865	3.0	750
196*	Not specified by USAS C57.13	395	1035	3.0	900
230		460	1210	3.0	1050
287*		575	1500	3.0	1300

---

* These system voltages are not listed in Standard Voltage Ratings for A-c Systems, USAS C84.

When applying current transformers, consideration should be given to the voltage rating and other characteristics of the particular system in which the transformer is to be placed, in order to be sure that the insulation of the transformer is adequate. The standard insulation classes, along with the maximum system voltage and dielectric tests for current transformers, as specified by USASI Standard C57.13, are reproduced at left in Table IV.

PROTECTION AGAINST VOLTAGE SURGES

The reactance of a current transformer acts as a choke coil so that, when a surge occurs, a voltage builds up which may involve danger to the apparatus. This fact has special significance in the case of high-voltage transformers which have large primary coils and low-current transformers which have a large number of primary turns; both of these tend to give relatively high transformer impedances. Furthermore, the voltage across the primary terminals is influenced by the amount of secondary burden.

Thyrite® By-pass Protection

It is standard practice to equip current transformers for high-voltage circuits with Thyrite by-pass protectors. With normal voltage, the resistance of the protector is high enough to have negligible effects on the transformer operation; however, when high-frequency, high-voltage surges occur, the characteristic of the Thyrite is such that an appreciable part of the surge current is by-passed through the protector, thereby preventing damage to the transformer insulation.

Operation of Gap-type Protection on SUPER⚡BUTE Current Transformers

Primary Winding Arrangement—SUPER⚡BUTE transformers have 24 conductors evenly distributed through the core window. They also have 48 conductors evenly distributed around the outside of the core, brazed together under the end bell. See Fig. 49.

The termination point is a large copper horseshoe having a large cross-section. This horseshoe, which is attached to the copper end bell, provides a large potential heat sink for rapid dissipation of any heat that might be generated by arcing. The gaps are located between the copper horseshoe and the primary conductor as it passes over the horseshoe. Each conductor has a minimum of two gaps in series (there is a copper horseshoe at each end of the transformer).

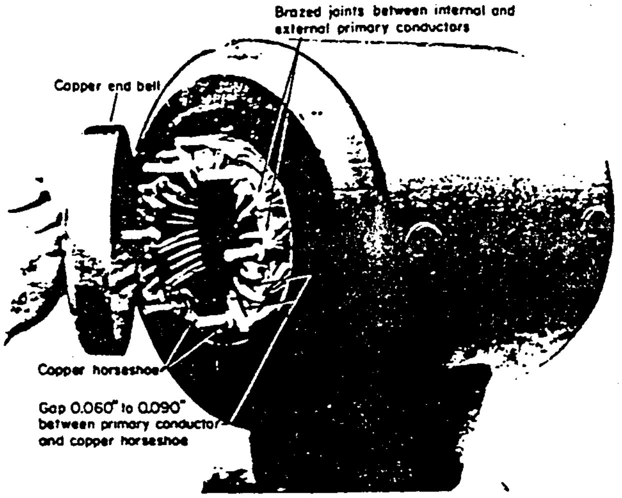


Fig. 49. Primary winding arrangement on SUPER⚡BUTE current transformers

When a high-voltage surge occurs on the line, these gaps will fire, by-passing the current through the outside conductors of the transformer because this is the lowest impedance path. There is a minimum of two conductors outside the core as compared to one through the core window. The gaps are set between 0.060 in. and 0.090 in., with at least two gaps on the same conductor set at 0.060 in. at each end. It takes 5000 to 7500 crest volts to fire the gap. This is far below the internal turn-to-turn strength of primary conductors, which is in excess of 30,000 volts to breakdown.

Gap Operation—When the gaps fire, there is a 48-volt drop across each gap or 96-volt drop in any one conductor which is gapped at each end of the transformer. If the voltage is insufficient to fire the gaps in the first turn, it has the opportunity to fire on each successive turn as the voltage builds up, because each turn is gapped as it crosses the copper horseshoe. When the first two gaps fire, they immediately trigger more gaps.

As the current increases, so does the number of gaps that fire. The electrical arc in the gap is a vapor path which becomes conductive, dissociating the gas into ions and electrons which is called a plasma. It is this plasma under the end bell of the transformer that causes the other gaps to fire. This dissipates the electrical energy over many gaps and greatly reduces the amount of current any two sets of gaps are required to carry.

The most adverse possible conditions the transformer would experience in the field would occur under fault conditions where the transformer was subjected to a high-voltage surge simultaneously with short-circuit currents. The SUPER✗BUTE current transformers with their gap protection will clear this condition in the first ½ cycle. The gaps fire, by-passing the surge and carrying maximum short-circuit current for the first ½ cycle, but then the arc is starved as it approaches current zero. See Fig. 50. The electrical energy being poured in at the end of the first ½ cycle is decreasing at a rapid rate. To maintain the arc requires a current flow of 1000 to 2000 amperes. The arc is starved because the conductivity of the arc drops, since it is being cooled by the large available heat sink in the copper horseshoe. Thus, the heat cannot be readily stored to maintain the conductivity of the arc, and the arc extinguishes itself.

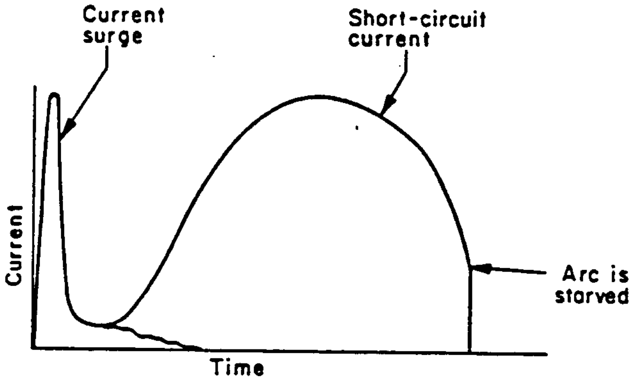


Fig. 50. Curve showing fault condition

Due to the nature of the transformer design, both primary and secondary windings are well distributed, and the leakage reactance is small. Thus, the restrike voltage (voltage drop across the primary gaps) is less than sufficient to re-establish the arc as the by-pass gaps regain their insulation strength.

Protection of Secondary Circuits

In some other circumstances, it is good practice also to protect the secondary circuit of the transformer with suitable protectors. In particular, the switching in a circuit which contains primary capacitors, such as individual surge capacitors for a-c motors or arc-furnace transformers or capacitor banks for voltage or power-factor correction, may result in high transient voltages across the instrument transformers associated with these capacitor circuits. Secondary protection should be used in such situations.

OPEN-SECONDARY CIRCUITS

Current-transformer secondary circuits must not be open while primary current flows. Breaking the secondary circuit while primary current is flowing is especially to be avoided.

Under such conditions, the entire primary current becomes the exciting current which raises the core density to saturation and induces a high voltage in the secondary; in short, human life as well as connected apparatus and leads are endangered by this situation. Another explanation is that the open-circuit impedance is many times the closed-circuit impedance; hence, the voltage across the transformer is much greater when the secondary is open. Therefore, those working with current-transformer circuits should *always make certain that the secondary winding is either closed through the instrument circuit or that it is short-circuited at the terminals.*

Although the insulation of most transformers will, in general, withstand open-circuit conditions, the resulting voltages are dangerous. Therefore, if it should be necessary to change secondary connections while primary current is flowing, the secondary terminals must be short-circuited while the change is being made. Furthermore, it is recommended that the secondaries of all current transformers be kept short-circuited at all times when not in service, that is, while held in stock, during transportation, etc.

PARALLEL CIRCUITS

Totalization of the load on several different circuits is often desirable, particularly in metering and measurement of demand. One simple and effective method of accomplishing this is by the paralleling of the secondary circuits of current transformers in each line to a single measuring device. The connections for such a scheme are shown in Fig. 51.

To accomplish this totalization without introducing excessive error in the measurement, several conditions must be fulfilled. These are:

1. All of the transformers must have the same ratio, regardless of the anticipated current flow in the circuits in which they are connected.
2. For polyphase circuits, all transformers which have their secondaries paralleled must be connected in the same phase of the primary circuits.
3. The feeders or lines must have a common voltage and frequency as, for example, those instances in which they terminate in one set of bus bars.

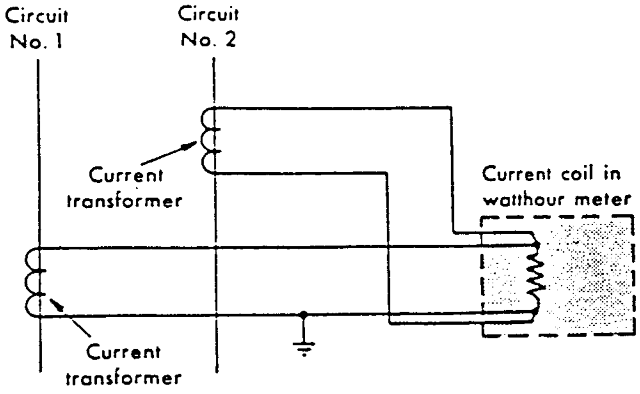
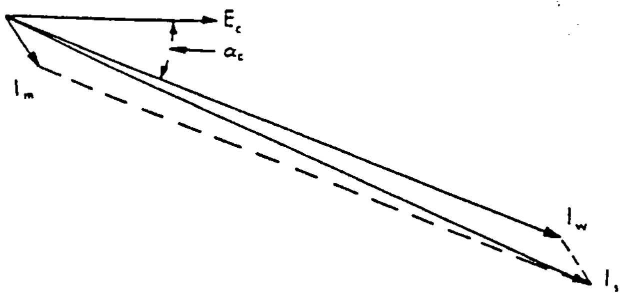


Fig. 51. Connection diagram for paralleled connections of current-transformer secondaries

It is also desirable to keep the common secondary burden on the transformers as low as possible. The importance of this may be seen from the fact that the addition of each transformer results in an additional volt-ampere burden, even though the impedance of the common burden remains unchanged. This is because the total of all the current from all transformers passes through the common burden; thus, the volt-ampere burden is raised even though the impedance remains unchanged. Of course, this total burden is divided among all the transformers in the system. However, for a given burden impedance, the volt-ampere burden is proportional to the current squared; thus, the burden on each individual transformer will be more with paralleled secondaries than with the same impedance burden on one transformer alone.

Because of the necessity for keeping the common burden as low as possible, it is desirable also to parallel the secondary leads at the measuring devices, rather than at the transformers, since the leads then become a burden on an individual transformer only.

The possibility of additional error when one primary circuit carries no current must also be considered. In this situation the "dead" transformer acts as a shunt across the measuring device; the current shunted through it is the magnetizing current for the "dead" transformer. The relation of this current to the current flowing through the measuring device is shown in Fig. 52. The errors are functions of the magnitude of the magnetizing current and the phase angle of the common burden. For a common burden with a power factor close to unity, most of the transformer error occurs as phase-angle error. As the power factor decreases, the ratio error increases; but the phase-angle error decreases. For a low burden and with high-quality current transformers, the magnitude of the errors due to this cause will be small.



E_c—Voltage across meter current coil
α_c—Phase-angle of meter current coil
I_s—Totalized secondary current
I_w—Current through meter current coil
I_m—Magnetizing current for dead transformer

Fig. 52. Vector diagram showing magnetizing current to a "dead" current transformer

Another reason for keeping the burden low is that it is difficult to apply corrections for the transformer errors because the volt-ampere burden on any one transformer is a function of the amount of current flowing in each of the other transformers. Thus, the volt-ampere burden on any transformer is not constant, and only an average value of secondary burden can be assumed in making corrections. The error in such a procedure is much less with low burdens.

CAUTIONS: Several precautions also should be recognized in using paralleled secondaries. During the servicing of the equipment in the secondary circuits, it is customary to short-circuit the secondary terminals of the current transformers. Care must be exercised to make sure that ALL transformers are shorted while work is progressing on the associated equipment and, on the completion of the servicing, that ALL shorts are removed. A short-circuited secondary is equivalent to a low-resistance shunt across the measuring device, which will cause large errors.

Paralleling the secondaries of potential transformers should be avoided, because this may create a serious hazard on the primary side. For example, one circuit may be disconnected from the line on the primary side; yet, this circuit might continue to be energized from another line through the paralleled secondaries of the potential transformers.

TOTALIZING TRANSFORMERS

If, for some reason, it is impossible with a paralleled secondary circuit to employ current transformers that have the same ratio, it may still be possible to employ the method of totalization that uses totalizing transformers. Such transformers are connected in the

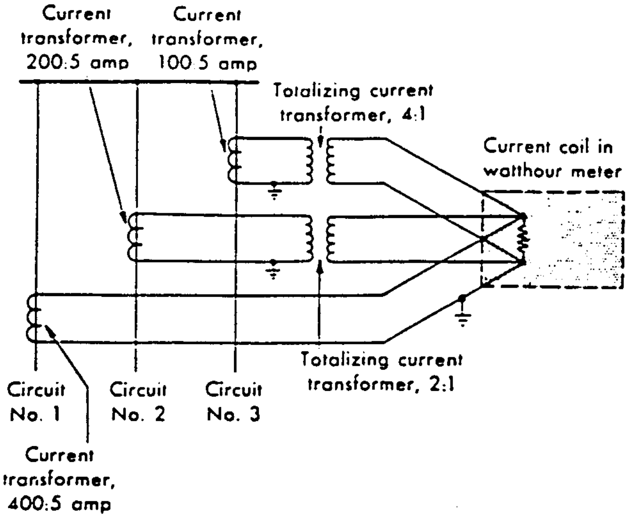


Fig. 53. Connection diagram showing use of totalizing current transformers

secondaries of the original current transformers to step down the secondary current and, thus, provide an over-all ratio which is the same as that of the other transformers in the circuit. The use of these transformers is illustrated in Fig. 53. In all cases, the use of step-up totalizing transformers should be avoided, as the effective burden impedance on the main transformer is increased by the reciprocal of the ratio of the totalizing transformer.

Because of the added burden of the totalizing transformers themselves, the use of totalizing transformers also increases the total burden on the main current transformers very materially. In addition, the errors in these secondary transformers must be added to the errors in the original current transformers. For these reasons, the use of totalizing transformers should be avoided wherever possible; however, if applied, the total errors resulting from such a scheme should be fully recognized.

INTERCONNECTION OF SECONDARIES ON POLYPHASE CIRCUITS

The practice of interconnecting secondary circuits is common. However, it is seldom realized that such interconnection introduces special errors and complications which are undesirable in certain cases. By interconnection is meant any connection which results in one wire or one device carrying the combined currents of two or more transformers in either the same or different phases.

There are, of course, many situations where interconnections are permissible and, in such, it is advantageous because it results in simplicity and economy in wiring. For example, in determining the accuracy of an installation from the characteristic curves of the individual transformers involved, and under conditions of burden determined by the impedance of instruments, leads, etc., directly connected to the respective transformers, no allowance is made ordinarily for the errors which are likely to result from interconnection.

This procedure is usually satisfactory as, in the majority of cases, the effect of the interconnection is negligible for one or both of the following reasons:

1. The burden may be such as to introduce no special errors or to add no difficulties in correcting for such special errors, if they should exist.
2. If special errors do occur, the magnitude may be small compared with the errors that can be tolerated.

However, it is advisable to avoid interconnection in certain instances, at least when it is intended to make accurate correction for the transformer errors from laboratory tests. The main reason for this is that it is often quite impractical to try to apply corrections accurately when secondaries are interconnected, because:

1. The effective burden often assumes unexpected values which cannot be determined by any simple rule of calculation, but must be found by a vector analysis as illustrated in Fig. 40.
2. The effective burdens do not remain constant, except for the particular condition of primary voltage or current balance (or unbalance) for which they are determined.

It is evident, therefore, that where it is desired to obtain the highest degree of accuracy, each phase of the polyphase circuit should be connected, measured, and corrected as a single-phase circuit (using single-phase instruments or meters and two wires per transformer), and the three-phase power or energy determined from simultaneous readings on the different phases. This method is often used, for example, in making water-rate tests on turbine-generators.

Some of these difficulties also will be encountered in certain types of interconnections that are used on single-phase circuits. (See section entitled "Parallel Circuits," page 44.)

Hence, accuracy statements derived from the results of single-phase tests and approximate rules for interconnected combinations can be considered as applicable only under reasonable conditions.

SUPERIMPOSED DIRECT CURRENT

Transformers are operated occasionally in circuits where direct current may be superimposed on the alternating current. The direct current will naturally tend to saturate the core and, therefore, adversely affect the accuracy. This necessitates special consideration to such applications and, often, the use of transformers designed particularly to meet such conditions.

There are also a few instances where the current transformer may be subjected to direct current when no alternating current is flowing. The effect in such instances is not so great as when both currents flow simultaneously, and can be easily remedied. (See following section on "Magnetic Bias.")

MAGNETIC BIAS

Sometimes current-transformer cores get into a condition referred to as "magnetized." As any transformer core is magnetized whenever it is excited under either normal or abnormal conditions, the phenomenon referred to might rather be called "magnetic bias." This may result from either of the following: (1) the passage of direct current through one winding; the passage of alternating current through one winding while the other (or others) is open-circuited; (2) the application of a high overcurrent, especially if a circuit breaker interrupts a high instantaneous value of current. This produces a bias which increases the density at which the core operates; therefore, the exciting current increases and, consequently, affects the accuracy. The resulting error can be neglected in many cases; but where the best accuracy is required, especially in cases where corrections are to be made for transformer errors, the condition should be remedied.

To remove this bias, the flux density should be raised to saturation and gradually reduced to zero. This can be accomplished by inserting suitable resistance in the secondary circuit and reducing it to zero in small steps while current is flowing in the primary. The amount of resistance which is necessary is not always the same, but a 50-ohm rheostat will be satisfactory for most transformers if rated current at 60 Hz flows in the primary. Some transformers will require more resistance.

Another method is to excite the core to a fairly high density by exciting the secondary while the primary is open and gradually reducing the excitation to a low value.

PERMEABILITY DRIFT

Somewhat associated with magnetic bias is another phenomenon known as "magnetic drift." This is the tendency of a core to change in permeability from one condition of magnetic equilibrium to another; the equilibrium is not always the same, as it depends upon excitation.

It is common practice to remove any bias (formerly called demagnetizing) from a current transformer before the transformer is tested for ratio and phase-angle errors. If the transformer is left unexcited after being tested, its permeability shifts to the stable state for zero excitation. Then, when put into service, it seeks a new state of equilibrium for whatever excitation is applied. For all but very low values of excitation, the new state of stability would be the same as that under which the transformer was tested. For this reason and because the phenomenon is of a transient nature that has a negligible effect after about one hour, its effect on a meter, which is read monthly or even weekly, would be completely lost.

While the effect of this phenomenon may sometimes be noticeable in accurate testing, it is of little practical consequence. However, its effect on test results can be minimized by starting the test at the highest current point.

TESTS

Various tests are made on current transformers: by the manufacturer, to insure that the transformers meet the specifications set up for them; and by the user, to insure that the devices continue to meet the specifications during their lifetime. A very brief outline of the various test methods that may be employed is described in the following sections.

ACCURACY

Ammeter Method—This is the simplest method for determining ratio. With ammeters of suitable rating in the primary and secondary, the ratio is the ratio of the two currents indicated.

The range of usefulness of this method is naturally limited by the rating of the highest current ammeter available. However, it can, of course, be extended by adding a calibrated current transformer in the primary circuit.

Shunt Method—The shunt method of checking the accuracy of current transformers consists basically of (1) bucking the millivolt drop of a shunt, placed in the primary circuit of the transformer, against the drop of a shunt placed in the secondary, and (2) adjusting the drop on one of these shunts until a null indication is obtained on a suitable detector. Both shunts must have the same nominal voltage drop, usually in the order of two to four hundred millivolts. The shunt which is connected in the primary circuit should have a fixed voltage drop; the secondary shunt should have a sliding contact which will permit the drop to be adjusted over a suitable range.

To obtain the null indication mentioned before, a mutual inductor is also needed. This is used to introduce a quadrature voltage into the circuit through the detector. The amount of this voltage required for a null indication is a measure of the phase-angle error of the transformer under test.

In use, the magnitude of the voltage drop from the secondary shunt is adjusted by means of the sliding contact; the amount of the quadrature voltage needed for balance is controlled by the position of the coils on the mutual inductor. Both are adjusted until a null balance is obtained on the detector. The ratio error is determined then from the position of the slider on the secondary shunt, and the phase angle is indicated by the position of the scale on the mutual inductor.

Transformer-shunt Method—This method of checking the accuracy is the same as the shunt method except that a standard transformer with known characteristics is introduced into the primary circuit of the transformer under test, and the primary shunt is replaced by one which is put in the secondary of the standard transformer. By this means it is necessary to maintain only one current rating of primary shunt whereas a "standard" transformer for each current rating to be tested would be required. However, such transformers are usually more stable and easier to maintain than shunts, particularly those required for high primary currents.

Comparison Method—The comparison method of checking accuracy of current transformers consists basically of comparing the transformer under test with a "standard" transformer of a suitable rating. The secondary currents of both transformers are bucked against each other and the difference may be read on an instrument. To obtain a suitable reading, however, this difference in current is placed on a sensitive wattmeter, with the potential of the instrument excited in phase with the secondary current of the standard transformer. This test, as described, will check only the ratio error, and not the phase-angle error of the transformer.

Exciting Current Method—Another simple test that can be made by the user is the exciting-current test (primary open). This method requires an initial test, before the transformer is installed, which can be compared with checks made at a future date. This test, of course, will not provide calibration curves, but it will detect failures.

Overcurrent Ratio and Phase Angle—A combination transformer-comparison two-wattmeter method is used. The "standard" is a high-ratio, high-current, high-accuracy transformer whose secondary current is compared with the secondary current of the "test" transformer. Auxiliary transformers are inserted in the "standard" and/or "test" transformer secondary circuits to balance the nominal ratios. The difference current is measured on two indicating wattmeters. One potential circuit is excited in phase with the test current, the other circuit is 90 degrees out of phase; by this means, a measure of both ratio and phase angle is given.

POLARITY

Polarity is checked automatically in practically all ratio and phase-angle test methods. Polarity may also be determined by any one of the methods described below.

D-c Test

Connect a d-c permanent-magnet ammeter of five-ampere capacity or less, depending on the transformer ratio, across the transformer secondary; the marked secondary terminal to be connected to the "plus" terminal of the ammeter. Then, connect two dry cells in series; connect the "negative" terminal of the battery to the unmarked primary terminal of the transformer. Make an instantaneous contact with the marked primary terminal of the transformer and the positive terminal of the battery. A deflection or "kick" will be obtained on the ammeter. If the initial kick (the one resulting from "making," not "breaking," the circuit) is in the positive direction, that is, up-scale, the transformer leads are marked correctly. If the initial kick is negative or down-scale (below zero), the marking of the transformer is not correct.

CAUTION: A d-c test such as this may produce a magnetic bias on the core so, to prevent any error as a result of the test, the core should be "demagnetized." (See section entitled "Magnetic Bias," page 47.)

A-c Tests

Substitution Method—If a transformer of known polarity is available, the substitution method may be used. See Fig. 54. Connect, first, the transformer of known polarity in the circuit; then, replace it with the transformer of unknown polarity in the circuit. If the wattmeter deflects in the same direction in both cases, the polarities of the two transformers are alike.

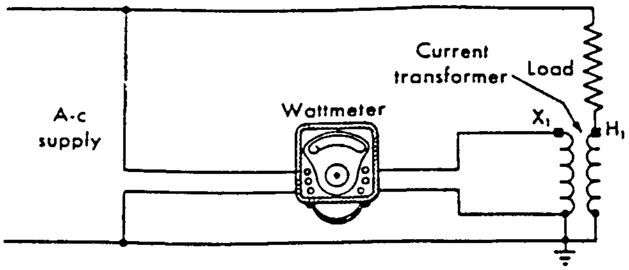


Fig. 54. Connection diagram of a current transformer and the associated equipment used to determine the polarity of the transformer by the substitution method

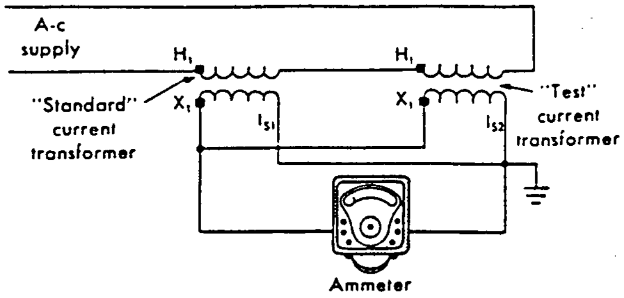


Fig. 55. Connection diagram of current transformers and the associated equipment used to determine the polarity of one of the transformers by the differential method

Differential Method—Another way is to excite both primaries simultaneously and make a differential measurement in the secondary circuits by using an ammeter. The connections are shown in Fig. 55. The ammeter should read $I_{S1} + I_{S2}$ (arithmetical sum) when the polarities are as shown.

INSULATION

Both high-potential tests at 60 Hz and impulse tests are used to check the insulation of current transformers. The test values for these tests and a description of the requirements and test methods may be found in USASI Standard C57.13.

The test values listed in Table IV are for factory dielectric tests which are designed to check the insulation and workmanship of individual transformers. All dielectric tests impose a severe stress on the insulation, and if applied frequently at a high value, may shorten the life of the insulation considerably. For this reason the USASI recommended practice for making periodic dielectric tests in the field is to limit the test values to 65 percent of the factory test voltages listed in USASI Standard C57.13. Customers' incoming acceptance tests for instrument transformers can be made at 75 percent of USASI values.

High-voltage direct-current (kenetron) testing is often employed on cables and other gear. If the circuit to be tested contains current transformers, the d-c voltage should not exceed the RMS voltage value listed in USASI Standard C57.13. This procedure is in accordance with USASI recommended practice.

SELECTION INFORMATION

To select the proper transformer for each application, considerable information concerning the conditions under which the transformer is to be used must be made available to the person selecting the transformer. This is particularly true in those cases where special transformers for unusual applications are required. Often a General Electric engineer, familiar with instrument transformers, can suggest relatively slight changes in the conditions of application that will make possible the use of a standard transformer for special requirements provided he is given complete information. For these reasons, it is suggested that complete information accompany every request for selection of instrument transformers for a particular application.

To provide a reference of the type of information needed, the following chart gives check lists for potential and current transformers.

SELECTION CHART

	POTENTIAL TRANSFORMERS	CURRENT TRANSFORMERS
VOLTAGE RATING		
1. Voltage of primary circuit	X	X
2. Type of circuit (3-wire, 3-phase, etc.)	X	X
3. How transformer is connected in circuit	X	X
4. Ratio	X	—
5. Special insulation requirements*	X	X
CURRENT RATING		
1. Ratio	—	X
2. Secondary current rating	—	X
FREQUENCY OF PRIMARY CIRCUIT	X	X
SERVICE		
1. Indoor or outdoor	X	X
2. Special service conditions*	X	X
BURDEN DATA		
1. Volt-amperes and power factor, or resistance and reactance of burden	X	X
2. Limiting conditions for possible future change in burden requirements	X	X
ACCURACY		
1. Desired accuracy at specified burden	X	X
2. Desired accuracy at highest burden anticipated for future requirements	X	X
LIMITING DIMENSIONS AND WEIGHT	X	X
UNDERVOLTAGE AND OVERVOLTAGE REQUIREMENTS	X	—
OVERCURRENT REQUIREMENTS		
1. Desired overcurrent accuracy†	—	X
2. Desired mechanical rating†	—	X
3. Desired thermal rating†	—	X
4. Position of return conductor with respect to transformer	—	X
FUSES		
1. Any special conditions pertaining thereto	X	—
SPECIAL CONDITIONS	X	X

---

* Standard conditions defined in USASI Standard C57.13.

† As defined in USASI Standard C57.13.

BIBLIOGRAPHY

How to Fuse Potential Transformer Primary Circuits
C. L. Schuck, *General Electric Review*, July, 1941, pp. 385–389

Criteria for Neutral Stability of Wye-Grounded-Primary Broken-Delta Secondary Transformer Circuits
H. S. Shott and H. A. Peterson, *AIEE Transactions*, Vol. 60, 1941, pp. 997–1002

Instrument Transformers
B. Hague, London, Sir Isaac Pitman and Sons, Ltd., 1936

A Simple Method for the Determination of Bushing-Current-Transformer Characteristics
S. D. Moreton, *AIEE Transactions*, Vol. 62, 1943, pp. 581–585

New Developments in Potential Transformer Design
G. Camilli, *AIEE Transactions*, Vol. 62, 1943, pp. 483–487

Sensitive Ground Protection for Radial Distribution Feeders
L. F. Hunt and J. H. Vivian, *AIEE Transactions*, Vol. 59, 1940, pp. 84–90

Functional Analysis of Measurements
I. F. Kinnard, *AIEE Transactions*, Vol. 60, 1946, pp. 987–992

Some Recent Developments in Impulse Voltage Testing
C. M. Foust and N. Rohats, *AIEE Transactions*, Vol. 59, 1940, pp. 257–265

Current Transformers and Relays for High Speed Differential Protection, With Particular Reference to Offset Transient Currents
E. C. Wentz and W. K. Sonnemann, *AIEE Transactions*, Vol. 59, 1940, pp. 481–488

Analysis of Bushing-Current-Transformer Performance
J. P. Gebelein and J. A. Elzi, *AIEE Transactions*, Vol. 59, 1940, pp. 541–546

A Proposed Method for the Determination of Current Transformer Errors
G. Camilli and R. L. Ten Broeck, *AIEE Transactions*, Vol. 59, 1940, pp. 547–550

Overcurrent Performance of Bushing Type Current Transformers
C. A. Woods, Jr., and S. A. Bottonari, *AIEE Transactions*, Vol. 59, 1940, pp. 554–560

Computation of Accuracy of Current Transformers
A. T. Sinks, *AIEE Transactions*, Vol. 59, 1940, pp. 663–668

Essentials of Transformer Practice
E. G. Reed, New York, D. Van Nostrand Company, Inc., 1927

Characteristics of Current Transformers During Faults, Part II
F. S. Rothe and C. Concordia, *AIEE Transactions*, Vol. 66, 1947, pp. 731–734

Dielectric Phenomena in High Voltage Engineering; 3rd ed.
F. W. Peek, Jr., New York, McGraw-Hill Book Company, Inc., 1929

Relative Accuracy of Three-phase Metering Combination
C. T. Weller, *AIEE Transactions*, Vol. 60, 1941, pp. 925–929

New Current Transformer for Bus Differential Protection .
L. F. Kennedy and A. T. Sinks, *AIEE Transactions*, Vol. 60, 1941, PP. 1180–1187

How to Use Certificate Test Values to Determine Complete Potential Transformer Accuracy Characteristics
F. R. D'Entremont, *Transmission and Distribution*, Dec., 1951

NOTE: Additional reference material is listed in the bibliography of USASI Standard, C57.13.

GENERAL ELECTRIC COMPANY
METER AND INSTRUMENT BUSINESS DEPT.
SOMERSWORTH, N. H. 03878

GENERAL ELECTRIC

11–76 (2M)