

IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes

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Abstract: The characteristics and classification of current transformers (cts) used for protective relaying are described. This guide also describes the conditions that cause the ct output to be distorted and the effects on relaying systems of this distortion. The selection and application of cts for the more common protection schemes are also addressed.

Keywords: current transformers, protective relaying

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Introduction

(This introduction is not part of IEEE Std C37.110-1996, IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes).

This guide was prepared by the Guide for the Application of Current Transformers for Relaying Working Group of the Relay Inputs Sources Subcommittee of the IEEE Power System Relaying Committee. The guide is intended to assist relay engineers in understanding the operation of current transformers and their selection and application to specific relay protection schemes.

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IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes

1. Overview

1.1 Scope

This standard describes the characteristics and classification of current transformers (cts) used for protective relaying. It also describes the conditions that cause the ct output to be distorted and the effects on relaying systems of this distortion. The selection and application of cts for the more common protection schemes are also addressed.

1.2 Purpose

The purpose of this document is to present a comprehensive treatment of the theory and application of cts to assist the relay application engineer in the correct selection and application of cts for protective relaying purposes.

2. References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEC 44-6 (1992), Instrument transformers—Part 6: Requirements for protective current transformers for transient performance.¹

IEC 185 (1987), Current transformers.

IEEE Std C37.103-1990, IEEE Guide for Differential and Polarizing Relay Circuit Testing (ANSI).²

¹IEC publications are available from IEC Sales Department, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse. IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std C57.13-1993, IEEE Standard Requirements for Instrument Transformers (ANSI).

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).

3. Definitions

The following definitions are taken from IEEE Std 100-1992 except as noted. The symbol ^(a) indicates that at the time the standard was approved there was no corresponding definition in IEEE Std 100-1992. Symbol ^(b) indicates the definition was taken from British Standard B.S.3938, Specification for Current Transformers.

3.1 accuracy: The extent to which the current in the secondary circuit reproduces the current in the primary circuit in the proportion stated by the marked ratio, and represents the phase relationship of the primary current.

3.2 accuracy classes for relaying (instrument transformer): Limits in terms of percent ratio error that have been established.

3.3 accuracy ratings for relaying: The relay accuracy class is described by a letter denoting whether the accuracy can be obtained by calculation or must be obtained by test, followed by the minimum secondary terminal voltage that the transformer will produce at 20 times rated secondary current with one of the standard burdens without exceeding the relay accuracy class limit. (This is usually taken as 10%.)

3.4 burden (of a relay): Load impedance imposed by a relay on an input circuit, expressed in ohms and phase angle at specified conditions.

3.5 burden on an instrument transformer: That property of the circuit connected to the secondary winding that determines the active and reactive power at the secondary terminals. The burden is expressed either as total ohms impedance, together with the effective resistance and reactance components, or as the total voltamperes and power factor of the secondary devices and leads at the specified values of frequency and current.

3.6 bushing type current transformer: A current transformer that has an annular core with a secondary winding insulated from and permanently assembled on the core but has no primary winding or insulation for a primary winding. This type of ct is for use with a fully insulated conductor as a primary winding. A bushing type ct is usually used in equipment where the primary conductor is a component part of other apparatus.

3.7 continuous thermal current rating factor (RF): The specified factor by which the rated primary current of a ct can be multiplied to obtain the maximum primary current that can be carried continuously without exceeding the limiting temperature rise from 30 °C ambient air temperature. When current transformers are incorporated internally as parts of larger transformers or power circuit breakers, they shall meet allowable average winding and hot-spot temperatures under the specific conditions and requirements of the larger apparatus.

3.8 current transformer (ct): An instrument transformer that is intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled. In window-type cts, the primary winding is provided by the line conductor and is not an integral part of the transformer.

3.9 instrument transformer: A transformer that is intended to reproduce in its secondary circuit, in a definite and known proportion, the current or voltage of its primary circuit with the phase relations substantially preserved.

3.10 knee-point voltage (Class C transformers): The point on the excitation curve where the tangent is at 45° to the abscissa. The excitation curve shall be plotted on log-log paper with square decades. This definition is for nongapped cts. When the ct has a gapped core, the knee-point voltage is the point where the tangent to the curve makes an angle of 30° with the abscissa.^a

3.11 knee-point voltage: That sinusoidal voltage of rated frequency applied to the secondary terminals of the transformer, all other windings being open circuited, which, when increased by 10% causes the exciting current to increase by 50%.^b

3.12 marked ratio: The ratio of the rated primary value to the rated secondary value as stated on the nameplate.

3.13 multi-ratio ct: A ct from which more than one ratio can be obtained by the use of taps on the secondary winding.

3.14 multiple-secondary current transformer: A ct that has two or more secondary coils each on a separate magnetic circuit with all magnetic circuits excited by the same primary winding.

3.15 polarity: The designation of the relative instantaneous directions of the currents entering the primary terminals and leaving the secondary terminals during most of each half cycle. Primary and secondary terminals are said to have the same polarity when, at a given instant during most of each half cycle, the current enters the identified, similarly marked primary lead and leaves the identified, similarly marked secondary terminal in the same direction, as though the two terminals formed a continuous circuit.

3.16 rated primary current: Current selected for the basis of performance specification.

3.17 rated secondary current: The rated primary current divided by the marked ratio.

3.18 remanence: The magnetic flux density that remains in a magnetic circuit after the removal of an applied magnetomotive force.

NOTE — This should not be confused with *residual flux density*. If the magnetic circuit has an air gap, the remanence will be less than the residual flux density. *See:* residual flux density.

3.19 residual flux density: The magnetic flux density at which the magnetizing force (H) is zero when the material is in a symmetrically, cyclically, magnetized condition. *See:* remanence.

3.20 saturation factor (K_s): The ratio of the saturation voltage of a current transformer to the excitation voltage. Saturation factor is an index of how close to saturation a current transformer is in a given application.^a

3.21 saturation voltage (V_x): The symmetrical voltage across the secondary winding of the current transformer for which the peak induction just exceeds the saturation flux density. It is found graphically by locating the intersection of the straight portions of the excitation curve on log-log axes. This is not the same as the knee-point voltage which is the point on the curve where the tangent to the curve makes an angle of 45° to the abscissa.^a

3.22 time-to-saturation: The time during which the secondary current is a faithful replica of the primary current.^a

NOTE — The core does not saturate suddenly. Beyond the saturation flux level, the exciting current increases more rapidly than the secondary current, causing distortion in the secondary waveform.

3.23 transactor: A magnetic device with a gapped core having an input winding that is energized with an alternating current and having an output voltage that is a function of the input current. The term transactor is a contraction of the terms *transformer and reactor*.^a

3.24 turns ratio of a current transformer: The ratio of the secondary winding turns to the primary winding turns.

3.25 window-type current transformer: A ct that has a secondary winding insulated from and permanently assembled on the core, but has no primary winding as an integral part of the structure. Complete insulation is provided for a primary winding in the window through which one turn of the line conductor can be passed to provide the primary winding.

3.26 wound-type current transformer: A ct that has a primary winding consisting of one or more turns mechanically encircling the core or cores. The primary and secondary windings are insulated from each other and from the core(s) and are assembled as an integral structure.

4. Current transformer characteristics and classification

Faults on power systems cause transients in the system currents, which modify the steady state behavior of cts. Both steady state and transient conditions, therefore, must be considered when examining the characteristics of cts.

4.1 Current transformer equivalent circuit and phasor diagrams

4.1.1 Current transformer equivalent circuit

Figure 1 shows a simplified equivalent circuit of a ct and its connected burden. The primary leakage impedance and the reactive part of the secondary leads do not substantially affect calculations and are, therefore, neglected.

4.1.2 Phasor diagram of a current transformer with burden

To construct the phasor diagram for a ct, the procedure is as follows:

- Start with the secondary load current I_S
- Draw the secondary volt drops: $I_S \times R_S$ and $I_S \times X_L$
- Add V_B to the resultant voltage in order to obtain the internal secondary exciting voltage V_S
- When V_S has been obtained, draw the flux phasor lagging V_S by 90°
The exciting current, I_E , is composed of the magnetizing current, I_M , which is needed to generate the flux in the ct core, and the loss current, I_{LOSS} , which is mainly due to the hysteresis and eddy current losses
- Draw the magnetizing current, I_M , in quadrature with the voltage and the resistive loss current, I_{LOSS} , in phase with the secondary exciting voltage

$$I_M + I_{LOSS} = I_E$$

$$I_{ST} = I_S + I_E$$

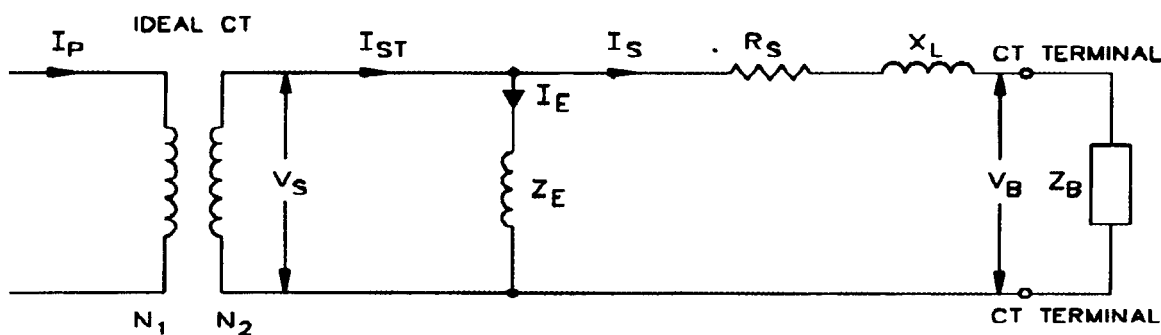
The primary current is then

$$I_P = \left(\frac{N_2}{N_1} \right) (I_S + I_E)$$

where

N_2/N_1 the turns ratio

Figures 2 and 3 show the phasor diagrams for a resistive burden (power factor of 1.0) and a standard burden (power factor of 0.5).



- V_S is the secondary exciting voltage
- V_B is the ct terminal voltage across external burden
- I_P is the primary current
- Z_E is the exciting impedance
- I_{ST} is the total secondary current
- R_S is the secondary resistance
- I_S is the secondary load current
- X_L is the leakage reactance (negligible in Class C cts)
- I_E is the exciting current
- $N_2:N_1$ is the ct turns ratio
- Z_B is the burden impedance (includes secondary devices and leads)

Figure 1—Equivalent circuit of a current transformer

4.2 Current transformer secondary excitation characteristics

When the voltage developed across the ct burden is low, the exciting current is low. The waveform of the secondary current will contain no appreciable distortion. As the voltage across the ct secondary winding increases because either the current or the burden is increased, the flux in the ct core will also increase. Eventually the ct will operate in the region where there is a disproportionate increase in exciting current. The ct core is entering the magnetically saturated region; operation beyond this point will result in an increasing ratio error and a distorted secondary current waveform.

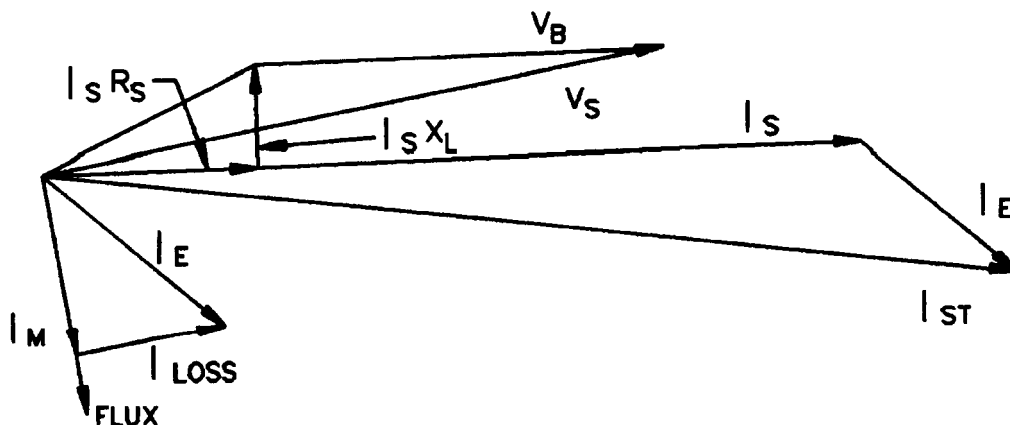


Figure 2—Phasor diagram of a current transformer with a resistive burden

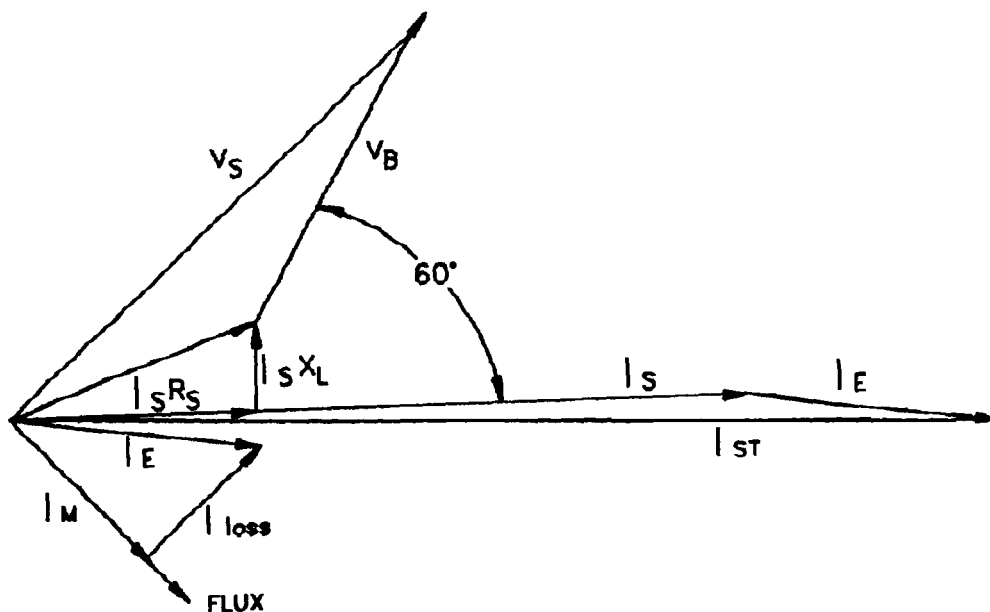


Figure 3—Phasor diagram of a current transformer with a standard burden (0.5 power factor)

CT operation is illustrated by using excitation curves. These curves show the relationship of secondary exciting voltage (V_E) to the excitation current (I_E). A typical set of excitation curves for a C class ct is shown in figure 4. The curves are plotted on log-log coordination paper and are developed from test data. The primary winding shall be open circuited for this test. Curve tolerances are stated in figure 4. More specific information concerning construction of excitation curves is found in 6.10 and 8.3 of IEEE Std C57.13-1993.

4.3 Knee-point voltage

The knee-point voltage of a ct with a nongapped core is defined as the point of maximum permeability on the excitation curve, plotted on log-log axes with square decades, where the tangent to the curve makes a 45° angle with

the abscissa. This is shown in figure 4 and gives a knee-point for the 1200/5 A winding of about 240 V. When the ct has a gapped core, the definition of the knee-point voltage is the point where the tangent to the curve makes an angle of 30° with the abscissa.

4.4 Current transformer accuracy

The ANSI ct accuracy class is determined by a letter designation and a secondary terminal voltage rating. These effectively describe the steady-state performance. (See IEEE Std C57.13-1993, 6.4.1.)³ The secondary terminal voltage rating is the ct secondary voltage that the ct will deliver when it is connected to a standard secondary burden, at 20 times rated secondary current, without exceeding a 10% ratio error. Furthermore, the ratio correction shall be limited to 10% at any current from 1 to 20 times rated secondary current at the standard burden or any lower standard burden. The voltage rating given applies to the full winding ratio only. If a tap is utilized on a multi-ratio ct, the voltage capability is directly proportional to the ratio between the tap value being used and the full winding capability, provided the windings are fully distributed around the core. This is usually the case with cts made after 1978, but not necessarily with cts made before that date.

For example, ct accuracy class C100 means that the ratio error will not exceed 10% at any current from 1 to 20 times rated secondary current with a standard 1.0 Ω burden (1.0 Ω times 20 times rated secondary current equals 100 V). Almost all of the cts used for protective relay applications are covered by the C or K classification. This includes bushing cts with uniformly distributed windings and other cts with minimal core leakage flux.

NOTE — IEEE standard C values and standard burdens are listed in annex B.

The letter designation codes are as follows:

- C indicates that the leakage flux is negligible and the excitation characteristic can be used directly to determine performance. The ct ratio error can thus be calculated. It is assumed that the burden and excitation currents are in phase and that the secondary winding is distributed uniformly. (See 8.1.10 of IEEE Std C57.13-1993 for further detail.)
- K is the same as the C rating, but the knee-point voltage must be at least 70% of the secondary terminal voltage rating.
- T indicates that ratio error must be determined by test. The T class ct has an appreciable core flux leakage effect and contributes to appreciable ratio error.
- H, L are old ANSI classifications. There were two accuracy classes recognized—2.5% and 10%. Cts were specified in the following manner—10 L 200, 2.5 H 400, etc. The first number indicated the accuracy class and the last number indicated the secondary voltage class. L cts were rated at the specified burden and at 20 times normal current. H cts were rated at any combination of burden from 5 times to 20 times the normal current. These ratings are applicable only to old cts mostly manufactured before 1954.

³Information on references can be found in clause 2.

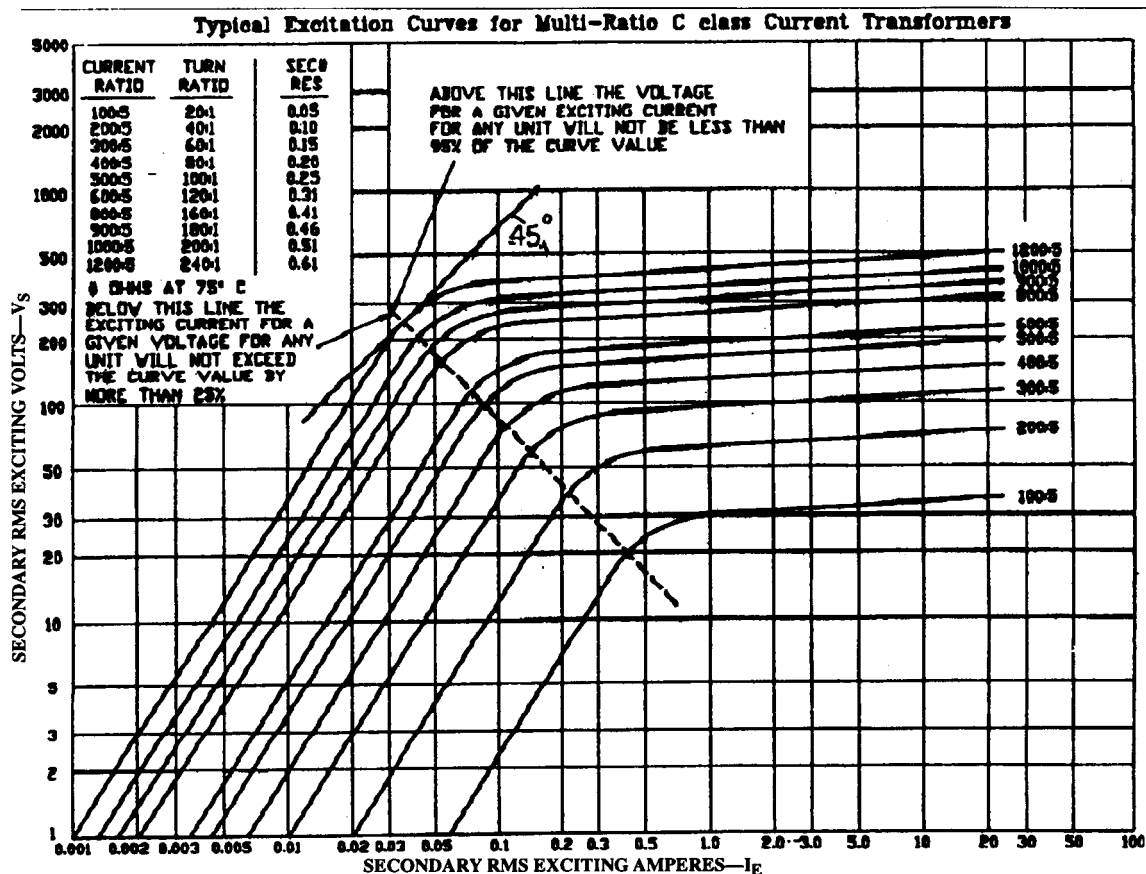


Figure 4—Typical excitation curves for a multi-ratio C class current transformer

4.4.1 Determination of the C or K classification using the excitation curve

Figure 1 shows the ct secondary winding, the secondary winding resistance, R_S , and a connected burden, $Z_B \cdot I_E$ is the excitation current, and I_S is the secondary load current through the burden.

Set $I_E/I_S = 0.1$ to define a 10% error (I_E and I_S are assumed to be in phase). For the 1200:5 ct in figure 4,

$$I_S = 100 \text{ A (20 times rated secondary current)}$$

$$I_E = 10 \text{ A}$$

The secondary exciting voltage, V_S for the full-ratio winding, corresponding to $I_E = 10 \text{ A}$, is obtained from the excitation curve. Figure 4 shows that with $I_E = 10 \text{ A}$, V_S is 500 V. Although the standard burdens involve power factor, a quick arithmetic (worse case) calculation of the secondary terminal voltage, V_B , may determine the classification since the standard voltage values for 5 A secondaries are 10 V, 20 V, 50 V, 100 V, 200 V, 400 V, or 800 V (see annex B).

From figure 1: $V_B = V_S - (I_S \times R_S)$ (X_L is negligible)

$$V_S = 500 \text{ V}$$

$$R_S = 0.61 \, \Omega \text{ (from figure 4)}$$

$$I_S \times R_S = 100 \times 0.61 = 61 \text{ V}$$

$$V_B = 500 - 61$$

$$V_B = 439 \text{ V}$$

By selecting the next lowest classification voltage, this ct is determined as having a C400 classification.

If the arithmetic calculation of V_B is marginal with respect to a standard classification voltage, a more exact check should be done with a standard burden, Z_B , at 0.5 pF. For the ct shown in figure 4 at a standard 4 Ω burden:

$$\begin{aligned} V_S &= I_S \times (R_S + Z_B) \quad (\text{refer to figure 1}) \\ &= 100 \times (0.61 + 2.0 + j3.464) \\ &= 261 + j346.4 \\ &= 434 \text{ V } \angle 53^\circ \end{aligned}$$

Referring to figure 4 for $V_S = 434 \text{ V}$, I_E is approximately 2.0 A. The error, I_E/I_S , is about 2% so the ct has a classification of C400 because at this secondary terminal voltage ($V_B = I_S \times Z_B = 400 \text{ V}$), the error is < 10%.

4.4.2 Examples of using the accuracy classification to assess steady-state current transformer performance

Example 1:

A 1200/5, C400 ct with excitation curves, shown on figure 4, is connected to a 2.0 Ω burden. Based on the accuracy classification, what is the maximum symmetrical fault current that may be applied to this ct without exceeding a 10% ratio error?

Answer:

Based on the criteria that the ct can deliver 20 times rated secondary current without exceeding a 10% ratio error, the maximum fault current will be 24 000 A. However, with a 2.0 Ω burden, this will result in a voltage below the knee-point of the ct and, as a practical matter, it will be within 10% accuracy at higher currents. This can only be accurately determined from excitation or ratio correction curves and not from the accuracy classification. For example, a ct with characteristics shown on figure 4 will produce between 180–240 A without exceeding the 10% ratio error, depending on the power factor of the 2.0 Ω burden.

Example 2:

A 1200/5, C400 ct is connected on the 1000/5 tap. What is the maximum secondary burden that can be used and still maintain rated accuracy at 20 times rated symmetrical secondary current?

Answer:

Since the secondary voltage capability is directly proportional to the connected tap, the ct will support a voltage of $1000/1200 \times 400 \text{ V}$ or 333 V. Twenty times rated secondary current is 100 A. Therefore, the maximum burden is $333 \text{ V}/100 \text{ A}$ or 3.33 Ω .

4.4.3 Determination of percent error and ANSI voltage classification for "T" class cts using overcurrent ratio curves

For "T" class cts, the secondary leakage reactance is not negligible. For this reason, IEEE Std C57.13-1993 requires manufacturers to provide overcurrent ratio curves for these cts on rectangular coordinate paper plotted in terms of

primary versus secondary current from 1 to 22 times rated primary current for all standard burdens up to the burden that causes a ratio correction of 50%. Figure 5 is a typical overcurrent ratio curve for a "T" class ct.

The percent error of a T class ct can easily be computed from an overcurrent ratio curve for any standard burden and a known primary current using the following relationship:

$$\% \text{ error} = \left[\left(\frac{\text{Multiples of rated primary current}}{\text{Multiples of rated secondary current}} \right) - 1 \right] \times 100$$

Example 1: From figure 5, find the percent error of a T class ct with a 4 Ω standard burden carrying 17 times rated primary A. When "times rated primary current" equals 17, then "times rated secondary current" equals 13 at the intersection of 17 with the 4 Ω curve.

$$\therefore \% \text{ error} = \left(\frac{17}{13} - 1 \right) \times 100\% = 30.77\%$$

The ANSI voltage accuracy rating can also be determined from a T class overcurrent ratio curve. By trial and error, find the ratio of "times rated primary current" to 20 times rated secondary current starting with the lower standard burden and incrementing to the next higher burden until the percent error calculated exceeds 10%. The burden with the percent error no greater than 10% is the one with which to classify the ANSI accuracy voltage rating.

Example 2: From figure 5, find the ANSI accuracy voltage rating of this 5 A rated T class ct.

Assume 2 Ω standard burden

When $I_S = 20 \times$ rated secondary current, then

$I_P = 22 \times$ rated primary current

$$\% \text{ error} = \left(\frac{22}{20} - 1 \right) \times 100\% = 10\%$$

Voltage rating = $20 \times 5 \times 2 = 200$ V

Therefore, the ct can also be classified as a T200 where the 10% error is implied.

All higher burdens will exceed 10% error. Therefore, the ANSI classification is not applicable in this case for the 4 Ω and 8 Ω burdens.

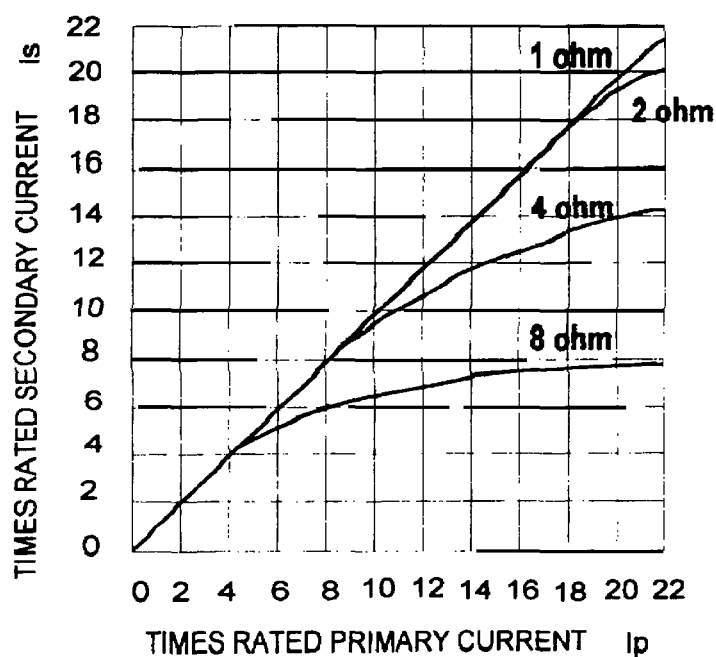


Figure 5—Overcurrent ratio curve

4.5 Dynamic characteristics

4.5.1 Flux change with asymmetrical primary current

The dc component of an asymmetrical current greatly increases the flux in the ct. When the dc offset is at a maximum, the ct flux can potentially increase to $1 + X/R$ times the flux resulting from the sinusoidal, or non-offset component, where X and R are the primary system reactance and resistance to the point of the fault [B11]⁴.

The difference between the non-offset and offset flux is illustrated in figures 6 and 7. In figure 6, there is remanent flux but no offset in the primary current. The ct core does not go into the saturated region of operation so the secondary current is undistorted. Figure 7 shows the resulting flux and secondary current when the primary current is fully offset. The increase in flux is not instantaneous, indicating that saturation does not occur instantaneously but takes time. This time is called the *time-to-saturation*.

⁴The numbers in brackets preceded by the letter B correspond to those of the bibliography in annex D.

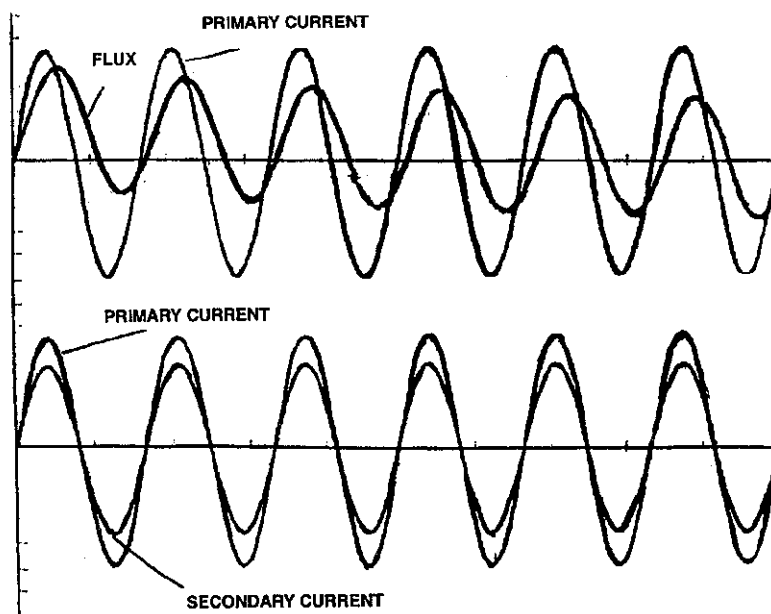


Figure 6—Relationship between primary current and flux and between primary current and secondary current for a nonsaturated current transformer

4.5.2 Saturation factor and time-to-saturate

If practical, the effects of saturation can be avoided by sizing the ct to have a knee-point voltage above that required for the maximum expected fault current and ct secondary burden, with suitable allowance for possible dc component and remanence. The knee-point voltage may be 50% to 75% of the standard accuracy class voltage rating of the ct (e.g., C 400). Saturation can be avoided by observing the following:

- a) To avoid ac saturation, the ct shall be capable of a secondary saturation voltage, V_X :

$$V_X > I_S \times Z_S$$

where

I_S is the primary current divided by the turns ratio, and Z_S is the total secondary burden ($R_S + X_L + Z_B$).

- b) To avoid saturation with a dc component in the primary wave and with a pure resistive burden, the required saturation voltage is

$$V_X > I_S \times Z_S \left(1 + \frac{X}{R} \right)$$

where

X and R are the primary system reactance and resistance up to the point of fault [B11].

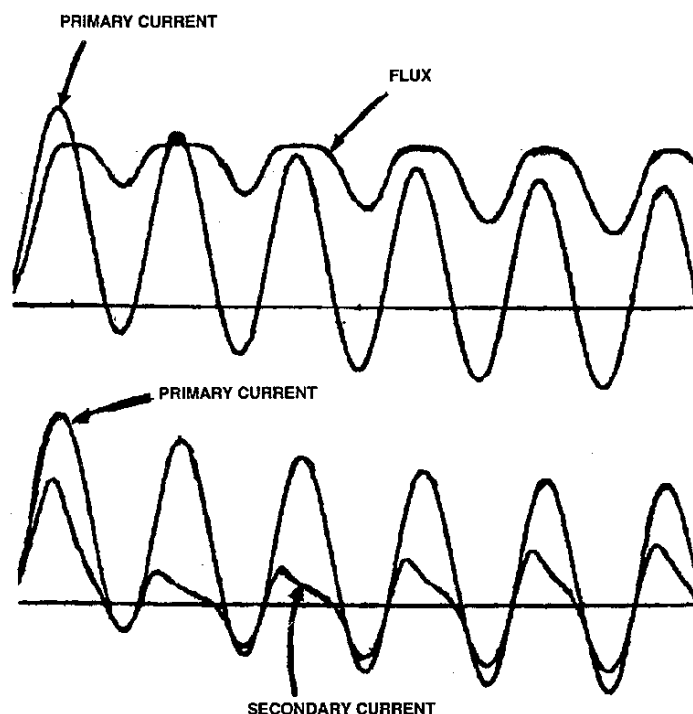


Figure 7—Relationship between primary current and flux and between primary current and secondary current for a saturated current transformer

If the ct burden is also inductive, the required saturation voltage to avoid saturation caused by primary dc is

$$V_X > I_S \times Z_S \left(1 + \frac{X}{R} \times \frac{R_S + R_B}{Z_S} \right)$$

To also account for possible premagnetization (in the worst direction)

$$V_X > \frac{I_S \times Z_S \left(1 + \frac{X}{R} \times \frac{R_S + R_B}{Z_S} \right)}{1 - \text{per unit remanence}}$$

These requirements generally result in impractically large cts and hence compensating steps must be taken to minimize saturation effects on the relay protection plan. Some high speed instantaneous relays can operate before saturation has time to occur.

4.5.2.1 Saturation voltage

The saturation voltage (V_X) is that symmetrical voltage across the secondary winding of the ct for which the peak induction just exceeds the saturation flux density.

4.5.2.2 Saturation factor

The ratio of the saturation voltage to the excitation voltage is defined as The Saturation Factor K_S and is an index of how close to saturation a ct is in a given application. It is used to calculate the time-to-saturate under transient conditions.