Dimensioning of Current Transformers for Protection Applications

GE Publication No.: GER-3973B

Transients on Current Transformers

INTRODUCTION

When system protection installed on CT secondaries must correctly respond to short circuit transients, especially during the first few cycles, fault conditions (even more than steady state under load conditions) must be taken into account when using current transformers. As such, it is necessary to define how much a CT must be oversized to avoid saturation due to the asymmetrical component of the fault current (the DC offset or exponential component).

The initial value of this DC offset is dependent on the voltage incidence angle (the voltage value when the fault occurs). The line parameters may be between 0 and $\sqrt{2}I_{sc}$, where I_{sc} represents the RMS value of the short-circuit symmetrical current.

Considering this maximum value, the transient short-circuit current is defined by the following equation:

$$i(t) = I\sin(\omega t + \alpha - \theta) + I\sin(\alpha - \theta) \cdot e^{-t/T_1} \quad \text{(EQ 1)}$$

where: I = peak value of the current = $\dfrac{E_p}{\sqrt{R^2 + \omega^2 L^2}}$

E_p = peak system E.M.F.
R = system resistance
L = system inductance
$\omega = 2\pi f$
α = angle on the voltage wave at which fault occurs
$\theta = \arctan(\omega X / R)$
$T_1 = X / R$ of the power system

Assuming that the secondary load is essentially resistive, the necessary flux in the CT to avoid saturation is defined as follows:

$$\varphi_T = \varphi_A\left(\frac{\omega T_1 T_2}{T_1 - T_2}e^{-\frac{t_s}{T_1}} - e^{-\frac{t_s}{T_1}} - \sin\omega t\right) \qquad \text{(EQ 2)}$$

where: T_1 = line time constant or primary time constant = L/R
T_2 = CT time constant or secondary time constant
φ_A = peak value of symmetrical AC flux
t_s = any given time during which maximum transient flux will remain without CT saturation, or the time after which saturation is permitted.

For $T_2 >> T_1$ (the case of TPY and TPX class CTs – with and without air gaps), Equation 2 is reduced to:

$$\varphi_T = \varphi_A\left(\omega T_1 - e^{-\frac{t_s}{T_1}} - \sin\omega t\right) \qquad \text{(EQ 3)}$$

As the load and wiring are mainly resistive, we can consider $\sin\omega t = -1$; as such, Equation 3 is reduced to:

$$\varphi_T = \varphi_A\left(\omega T_1 - e^{-\frac{t_s}{T_1}} + 1\right) \qquad \text{(EQ 4)}$$

Finally, since t_s (relay response time + circuit breaker operating time) is normally much greater than T_1, the above expression can be reduced to:

$$\varphi_T = \varphi_A(\omega T_1 + 1) \qquad \text{(EQ 5)}$$

During faults, the CTs are forced to develop a flux sufficient to feed fault current to the secondary with two components: the exponential component (DC offset asymmetrical component) and the AC component (symmetrical component). The resultant voltage must be greater than that necessary to feed the load connected in the secondary side of CTs without distortions caused by saturation. Hence, the necessary oversize factor K_s is defined by:

$$\varphi_{\text{transient}} = \varphi_{\text{DC}} + \varphi_{\text{AC}} = K_s\varphi_A \qquad \text{(EQ 6)}$$

where the overdimensioning or transient factor is:

$$K_s = \omega T_1 - e^{-\frac{t_s}{T_1}} - \sin\omega t \qquad \text{(EQ 7)}$$

Voltage on CT Secondaries During Faults

DESCRIPTION

Testing and experience have shown that the performance of many relays can be adversely affected by moderate degrees of CT saturation. However, since it is not economically feasible to test and determine the performance of all relays with different degrees of saturation, it is common practice to specify CT requirements for various protective schemes. The requirement generally specified is that the CTs should not saturate before the relays operate for some specified fault location.

To meet this criterion, the required transient performance for a current transformer can be specified by calculating the minimum required saturation voltage. Generally, different standards as IEC 185, BS3938, or ANSI/IEEE C5713 fix this voltage through the general expression:

$$V_s = K_0 K_s K_R I_2 R_2 \qquad \text{(EQ 8)}$$

where:
- V_s = saturation voltage defined by the intersection of the extensions of straight line portions (unsaturated and saturated regions) of the excitation curve
- I_2 = symmetrical fault current in secondary amps.
- R_2 = total secondary resistance burden including CT secondary, wiring loop resistance, lead resistance, and load resistance.
- K_0 = the effect of the offset present during the fault (see details below)
- K_R = remanent flux factor (see details below)
- K_s = saturation or transient factor (see details below)

The offset present during the fault (K_0) is a function of the time when the fault occurs, being maximum at zero voltage (0° or 180°). Incidence angles of the faulted voltage near 90° generally produce a lower offset effect. Therefore, this factor applies in those cases where offset exceeds 0.5 p.u.

The remanent flux can remain in the core due to the following:

- The excitation current leads the load current by 90° and thereby under normal control open commands, the load current is cut near or at zero crosses, but the excitation current in the CT has significant value.
- DC tests performed on the CTs.
- The effect of the DC component on offset fault currents (exponential component) which is interrupted when tripping the circuit breaker.

The saturation or transient factor K_s is expanded as follows (as per Equation 2):

$$K_s = \frac{\omega T_1 T_2}{T_1 - T_2} e^{-\frac{t_s}{T_1}} - e^{-\frac{t_s}{T_1}} - \sin \omega t \qquad \text{(EQ 9)}$$

where:
- T_2 = secondary time constant
- T_1 = time constant of the DC component of the fault component; this is proportional to the X / R ratio of the system
- ω = system angular frequency
- t_s = time to saturation; this is equal to or greater than the relay operating time

Equation 2 is valid for CTs with air-gapped cores because of their low magnetizing impedance and then with low secondary time constant T_2. The air-gaps used in CTs tends to drastically reduce the effect of the remanent flux left in the core as a result of its lower magnetizing impedance and much lower secondary time constant. The effect of the remanent flux is also to reduce the time to saturation. This factor may vary from 1.4 to 2.6 times the rated flux in the core.

For a closed-core CTs (normal CTs), if the secondary time constant T_2 is too high ($L_{magnetizing} \approx \infty$ before saturation), Equation 7 does not include it. As such, a conservative value for time to saturation will result.

Time to Maximum Flux – Time to Saturation

DESCRIPTION

After the appearance of the short circuit, the flux β_0 and the corresponding magnetizing current I_0 will reach a maximum at a time defined by:

$$t_{\varphi(\max)} = \frac{T_1 T_2}{T_1 - T_2} \cdot \ln\frac{T_1}{T_2} \qquad \text{(EQ 10)}$$

The time to saturation is given by the following expression:

$$t_s = \frac{-X/R}{2\pi f} \cdot \ln\left(1 - \frac{K_s - 1}{X/R}\right) \qquad \text{(EQ 11)}$$

where: $K_s = V_{saturation} / I_{fault} R_2$
$V_{saturation}$ = saturation voltage as defined by Equation 8
I_{fault} = secondary fault current
R_2 = total loop resistance
X / R= reactance to resistance ratio of any given circuit, generator, etc. See the following tables and curves.

The rate of decay of the DC component is proportional to the ratio of reactance to resistance of the complete circuit from the generator (source) to the short circuit.

If the ratio of reactance to resistance is infinite (i.e. zero resistance), the DC component never decays. On the other hand, if the ratio is zero (all resistance, no reactance), it decays immediately. For any ratio of reactance to resistance in between these limits, the DC component takes a definite time to decrease to zero.

In generators, the ratio of subtransient reactance to resistance may be as high as 70:1; as such, it may take several cycles for the DC component to disappear. In circuits remotely located from generators, the ratio of reactance to resistance is lower, and the DC component decays more rapidly. The higher the resistance in proportion to the reactance, the more I^2R loss from the DC component, and the energy of the direct current is dissipated faster.

Generators, motors, and circuits all have a certain DC time constant that refers to the rate of decay of the DC component. The DC time constant is the time, in seconds, required by the DC component to drop to approximately 37% of its original value at the instant of short circuit. It is expressed as the ratio of inductance in Henrys (V × s / A) to resistance in Ohms. This is merely a guide to illustrate how quickly the DC component decays.

TYPICAL X/R RATIOS

Typical values of X / R ratios of distribution and transmission lines, depending on their rated voltages and geometrical configuration, are shown in the following table.

TABLE 1. X/R Ratios for Distribution and Transmission Lines

Sequence	69 kV (avg.)	115 kV (avg.)	138 kV (avg.)	230 kV (avg.)	380 kV (line type)	500 kV (line type)
X_1 / R_1	2.30	3.40	3.98	7.36	9.8 (horiz.) 9.6 (delta)	24.3 (horiz) 18.5 (vertical)
X_0 / R_0	1.95	3.05	4.23	4.08	3.2 (horiz.) 3.3 (delta)	3.5 (horiz.) 5.0 (vertical)

The table below shows the X / R ratios for selected power system elements as a function of their rated power.

TABLE 2. X/R Ratios for Other Power System Elements

Large Generators	Power Transformers	Reactors	Utilities
40 to 120 typically 80	see curve	40 to 120 typically 80	15 to 30 (near generating plant)

Power transformer X / R ratios for 0.03 to 3.0 MVA and 3 to 200 MVA rated transformers are indicated in the curves below:

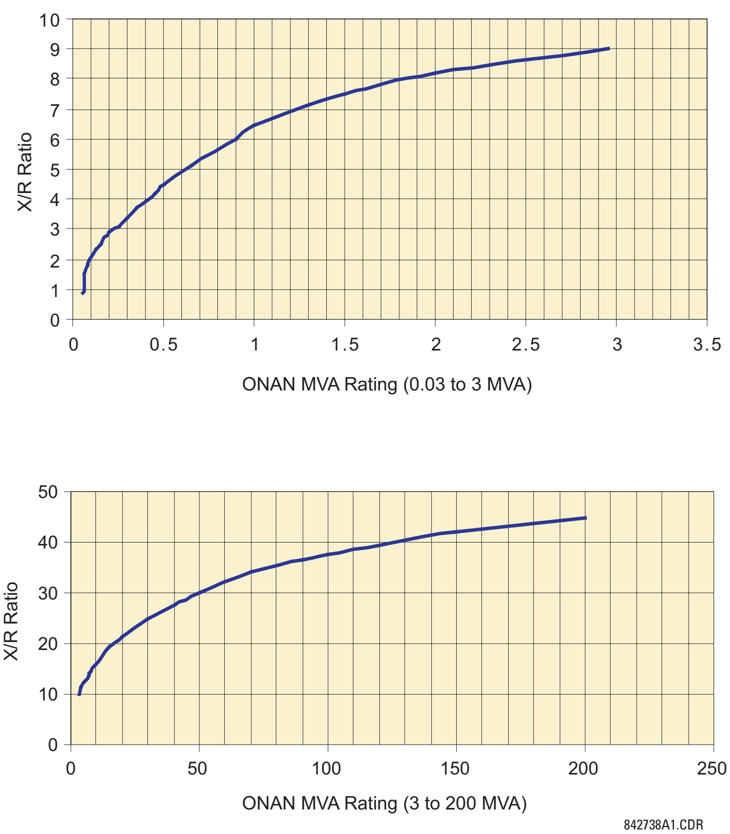

FIGURE 1. Power Transformer X/R Ratios

Tripping Time of Protection Devices

DESCRIPTION

Instantaneous overcurrent (ANSI device 50) and distance (ANSI device 21) protection normally operate in a 15 to 30 ms range. As such, dimensioning factors must recognize that relay tripping times should be lower than time to saturation t_s. To guarantee the correct operation of protection devices, Equation 2 must be applied with parameter t representing the instantaneous overcurrent operating time of the relay. The following table shows typical tripping times for different GE relays and the necessary overdimensioning factor K_s, using a class TPX CT with a secondary time constant T_2 = 3 seconds.

TABLE 3. Tripping Times for Selected Relays

Relay	Instantaneous operating time	Primary time constant T_1 (after which saturation is permitted)	Overdimensioning factor K_s
MIC / MRC	25 ms	40 ms	6.81
		60 ms	7.39
		70 ms	7.57
		80 ms	7.72
DLP	20 ms	70 ms	6.45
ALPS	10 ms	70 ms	3.92
DGP	25 ms	70 ms	7.57
489	45 ms	70 ms	11.34
SMOR	25 ms	70 ms	7.57
DTP	45 ms	70 ms	11.34

Resultant Fault Voltages and CT Dimensioning

DESCRIPTION

With results shown in the table above and neglecting the K_0 and K_R parameters in Equation 8, the following example illustrates how to determine the resultant “precision limit” and the necessary overdimensioning of the CT core (rated power dimensioning) to avoid saturation previous to the tripping time of relays under consideration.

If the phase-to-phase short circuit current is assumed to be the same order of magnitude as the phase-to-ground short circuit current, then a single equation should be used. If not, then the K_s factor must be verified for both situations: the positive sequence component during three-phase faults as well as the zero sequence component for phase-to-ground faults. In the present case, Equation 8 will be used for all calculations.

EXAMPLE

Given a system with the following parameters:

K_s = 6.18, V_{rated} = 1.38 kV at 50 Hz, R_{relay} = 0.04 Ω,
$P_{short\text{-}circuit}$ = 0.597 GVA (assumed), CT ratio = 600:1, CT class = 5P20,
CT secondary winding resistance = 1.5 Ω (assumed),
L_{wiring} = 2 × 10 m (6 mm^2 cross-section cable, assumed), and R_{wiring} = 0.059 Ω.

K_0 and K_R are not considered.

The saturation voltage is given by:

$$\begin{aligned} V_s &= \frac{P_{\text{short-circuit}} / \sqrt{3} V_{\text{rated}}}{\text{CT ratio}} K_s (R_{\text{CT}} + R_{\text{wiring}} + R_{\text{relay}}) \\ &= \frac{0.597 \text{ GVA} / (\sqrt{3} \cdot 13.8 \text{ kV})}{600} \cdot 6.18 \cdot (1.5\ \Omega + 0.059\ \Omega + 0.04\ \Omega) \\ &= 411 \text{ V} \end{aligned} \quad \text{(EQ 12)}$$

The equivalent power is therefore:

$$P_{\text{equivalent}} = \frac{411 \text{ V} / 20}{1 \text{ A}} - 1.5\ \Omega \times (1)^2 = 19 \text{ VA} \quad \text{(EQ 13)}$$

Terms and Definitions

RATED PRIMARY SHORT CIRCUIT CURRENT

The rated primary short circuit current is the RMS value of the primary symmetrical short-circuit current on which the rated accuracy performance of the current transformer is based.

INSTANTANEOUS ERROR CURRENT

The instantaneous error current (I_e) is the difference between instantaneous values of the primary current and the product of the turns ratio times the instantaneous values of the secondary current. When both alternating current and direct current components are present, I_e must be computed as the sum of both constituent components:

$$\begin{aligned} I_e &= I_{e(\text{AC})} + I_{e(\text{DC})} \\ &= (nI_{\text{secondaryAC}} - I_{\text{primaryAC}}) + (nI_{\text{secondaryDC}} - I_{\text{primaryDC}}) \end{aligned} \quad \text{(EQ 14)}$$

PEAK INSTANTANEOUS ERROR

The peak instantaneous error (ξ_i) is the maximum instantaneous error current for the specified duty cycle, expressed as a percentage of the peak instantaneous value of the rated primary short-circuit current

PEAK INSTANTANEOUS AC COMPONENT ERROR

The peak instantaneous AC component error is the maximum instantaneous error of the alternating current component expressed as a percentage of the peak instantaneous value of the rated primary short-circuit current.

$$\xi_{\text{AC}} = \frac{100 I_{e(\text{AC})}}{\sqrt{2} I_{\text{primary short-circuit}}} \% \quad \text{(EQ 15)}$$

CT ACCURACY CLASS / CLASS INDEX

The accuracy class is defined by the 'class index' (see below) followed by the letter 'P'.

The class index represents the accuracy limit defined by composite error (ξ_c) with the steady state symmetrical primary current. This number indicates the upper limit of the composite error at the maximum accuracy current feeding the accuracy load. The standard class indexes are 5 and 10.

There is no limit for remnant flux.

LIMIT FACTOR

The limit factor represents the ratio between the limit accuracy current and the rated primary current. For protection applications this factor normally is 10 or 20.

CT CLASSES

The various CT classes are indicated as follows:

- **Class P**: These are "protection" current transformers designed specifically to feed protection relays. The accuracy limit is defined by composite error ξ_{AC} with steady state symmetrical primary current. There is no limit for remanent flux.
- **Class TPS**: These are low-leakage flux current transformers. Their performance is defined by the secondary excitation characteristics and turns ratio error limits. There is no limit for remanent flux.
- **Class TPX**: The accuracy limit for class TPX CTs is defined by the peak instantaneous error (ξ_i) during the specified transient duty cycle. There is no limit for remanent flux.
- **Class TPY**: The accuracy limit for class TPY CTs is defined by the peak instantaneous error (ξ_i) during the specified transient duty cycle. The remanent flux does not exceed 10% of the saturation flux.
- **Class TPZ**: The accuracy limit is defined by the peak instantaneous alternating current component error (ξ_{AC}) during single energization with maximum DC offset at specified secondary loop time constant. There are no requirements for DC component error limit. Remanent flux is practically null.

PRIMARY AND SECONDARY TIME CONSTANTS

The primary time constant T_1 represents the time constant of the DC component of the primary current on which CT performance is based.

The secondary time constant T_2 represents the time constant of the secondary loop of the CT obtained from the sum of the magnetizing and leakage inductance (L_s) and the secondary loop resistance (R_s). Normally, this value is higher than T_1 in TPS class current transformers (about 10 seconds). The value of T_2 depends on the specific requirements but normally oscillates between 0.3 and 1 second for TPY class CTs. For TPZ class CTs, T_2 is generally much more lower (approximately 0.07 seconds).

TIME TO MAXIMUM FLUX

The time to maximum flux ($t_{\varphi(\max)}$ – see Equation 10) is the elapsed time during a prescribed energization period at which the transient flux in a CT core achieves maximum value, assuming that core saturation does not occur.

SECONDARY WINDING AND LOOP RESISTANCE

The secondary winding resistance R_{CT} represents secondary winding DC resistance in ohms, corrected to 75°C (unless otherwise specified) and inclusive of all external burden.

The secondary loop or burden resistance (R_B) is the total resistance of the secondary circuit, unless otherwise specified, and inclusive of all external burden.

FLUX PARAMETERS

A low leakage flux current transformer is a CT for which a knowledge of the secondary excitation characteristic and secondary winding resistance is sufficient for an assessment of its transient performance. This is true for any combination of burden and duty cycle at rated or lower value of primary symmetrical short-circuit current, up to the theoretical limit of the current transformer determined from the secondary excitation characteristic.

The saturation flux (Ψ_S) is the peak value of the flux that exists in a core during a transition from a non-saturated to a fully saturated condition. This corresponds to the point on the B-H characteristic of the core at which a 10% increase in B causes H to be increased by 50%.

The remanent flux (Ψ_R) is the value of flux that remains in the core three minutes after the interruption of an exciting current of sufficient magnitude as to induce the saturation flux (Ψ_S).