

***DIMENSIONING OF CURRENT
TRANSFORMERS FOR PROTECTION
APPLICATION***

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1. TRANSIENTS ON CURRENT TRANSFORMERS - FUNDAMENTALS

More than the steady state under load conditions of the CT's, the main concern is about the fault conditions when the protections installed in their secondaries must respond correctly to the short-circuit transient, specially during the first cycles. Because of this, it is necessary to define how much a CT must be oversized in order to avoid the saturation due to the asymmetrical component of the fault current (the dc offset or exponential component).

The initial value of this dc offset depending on the voltage incidence angle (the voltage value when the fault occurs), and the line parameters may be between 0 and $\sqrt{2}I_{sc}$, being I_{sc} the rms value of the short-circuit symmetrical current.

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

$$i_{(t)} = I * \sin(\pi t + \pi - \pi) - I * \sin(\pi - \pi) * e^{-\frac{t}{T_1}} \quad (1)$$

Where:

- I = Peak value of current
- $\omega = 2 * \pi * f$
- $\alpha =$ angle on voltage wave at which fault occurs
- $\theta = \arctan(\omega * X/R)$
- $T_1 = X/R$ (of power system)

Assuming that the secondary load is essentially resistive, the necessary flux in the CT to avoid saturation is defined by the following expression:

$$\varphi_T = \varphi_A \left[\frac{\pi T_1 T_2}{T_1 - T_2} e^{-\frac{t_s}{T_1}} - e^{-\frac{t_s}{T_2}} \right] - \sin \pi t \quad (2)$$

Where:

- $T_1 =$ Line time constant or primary time constant = L/R
- $T_2 =$ CT time constant or secondary time constant
- $\varphi_A =$ 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 $T_2 \gg T_1$ (the case of TPY and TPX class CT's – with and without air gaps),

Equation (2) turns to:

$$\varphi_T = \varphi_A \left[\pi T_1 \left(1 - e^{-\frac{t_s}{T_1}} \right) \right] - \sin \pi t \quad (3)$$

As the load and wiring are mainly resistive, we can consider $\sin \alpha t = -1$; and then equation (3) is reduced to:

$$\varphi_T = \varphi_A \left[\pi T_1 \left(1 - e^{-\frac{t_s}{T_1}} \right) + 1 \right]$$

Finally because T_s (relay response time + Circuit Breaker operating time) is normally much higher than T_1 , the expression can be reduced as follows:

$$\varphi_T = \varphi_A (\omega T_1 + 1) \tag{4}$$

During faults the CT's will be forced to develop a flux necessary to feed fault current to the secondary with two components: the exponential (dc offset asymmetrical component) and the ac component (symmetrical component). The resultant voltage must be higher than that necessary to feed the load connected in the secondary side of CT's without distortions caused by saturation. Hence, the necessary oversize factor K_s is defined by:

$$\varphi_{\text{transient}} = \varphi_{\text{dc}} + \varphi_{\text{ac}} = * K_s \varphi_{\text{ac}}$$

where the overdimensioning or transient factor is:

$$K_s = \pi T_1 \left(1 - e^{-\frac{t_s}{T_1}} \right) \left| -\sin \pi t \right. \tag{5}$$

2. RESULTANT VOLTAGES ON CT SECONDARIES DURING FAULTS

In general, testing and experience have shown that the performance of many relays will not be adversely affected by moderate degrees of CT saturation. However, since it is not economically feasible to test and determine the performance of all types of 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. In general different standards as IEC 185, BS3938 or ANSI/IEEE C5713 fix this voltage by the general expression:

$$V_s = k_0 k_s k_R I_2 R_2 \quad (6)$$

where:

V_s = Saturation voltage as defined by the intersection point of the extensions of the straight line portions (the unsaturated and the saturated regions) of the excitation curve

I_2 = Symmetrical fault current in secondary Amperes

R_2 = Total secondary resistance burden including CT secondary, wiring loop resistance, lead resistance and load resistance.

$$k_s = \text{Saturation or transient factor} = \frac{\pi T_1 T_2}{T_1 - T_2} \left| e^{-\frac{t_s}{T_1}} - e^{-\frac{t_s}{T_2}} \right| + 1 \quad (\text{as per Eq. 2})$$

where

T_2 = Secondary time constant

T_1 = Time constant of the dc component of fault component. It is proportional to the X/R ratio of the system.

ω = System angular frequency

t_s = Time to saturation. This is equal or greater than the relay operating time.

K_0 = Represents the effect of the offset present during the fault. This offset is a function of the time when the fault occurs, being maximum at zero voltage (0° or 180°). Experience states that the incidence angle of the faulted voltage is near 90° that produce a lower offset effect. Therefore this factor will apply in those cases where offset exceeds 0.5 p.u

K_R = Remanent flux factor. 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 CT's
- The effect of the dc component on offset fault currents (exponential component) which is interrupted when tripping the circuit breaker.

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 reduce drastically the effect of the remanent flux left in the core due to its lower magnetizing impedance and therefore 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 CT's), the secondary time constant T_2 is too high ($L_{\text{magnetizing}} \approx \infty$ before saturation), equation (5) does no include it, and then a conservative value for time to saturation will result.

3. TIME TO MAXIMUM FLUX – TIME TO SATURATION

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

$$t_{\pi \max} = \frac{T_1 * T_2}{T_1 - T_2} \left| \ln \frac{T_1}{T_2} \right| \quad (7)$$

Finally the time to saturation is given by the following expression:

$$t_s = - \frac{X/R}{2\pi f} \ln \left| 1 - \frac{K_s - 1}{X/R} \right| \quad (8)$$

Where:

$$K_s = V_{\text{Saturation}} / (I_{\text{fault}} * R_2)$$

$V_{\text{Saturation}}$ = Saturation voltage as defined in page 5

I_{fault} = Secondary fault current

R_2 = Total loop resistance as defined in page 5

X/R = Reactance to resistance ratio of any given circuit, generator, etc. See Tables 1 or 2 and specific curves herein enclosed.

The decrement or rate of decay of the d-c 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 d-c 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 d-c component takes a definite time to decrease to zero.

In generators the ratio of subtransient reactance to resistance may be as much as 70:1; so it takes several cycles for the d-c component to disappear. In circuits remote from generators, the ratio of reactance to resistance is lower, and the d-c component decays more rapidly. The higher the resistance in proportion to the reactance, the more I^2R loss from the d-c component, and the energy of the direct current is dissipated sooner.

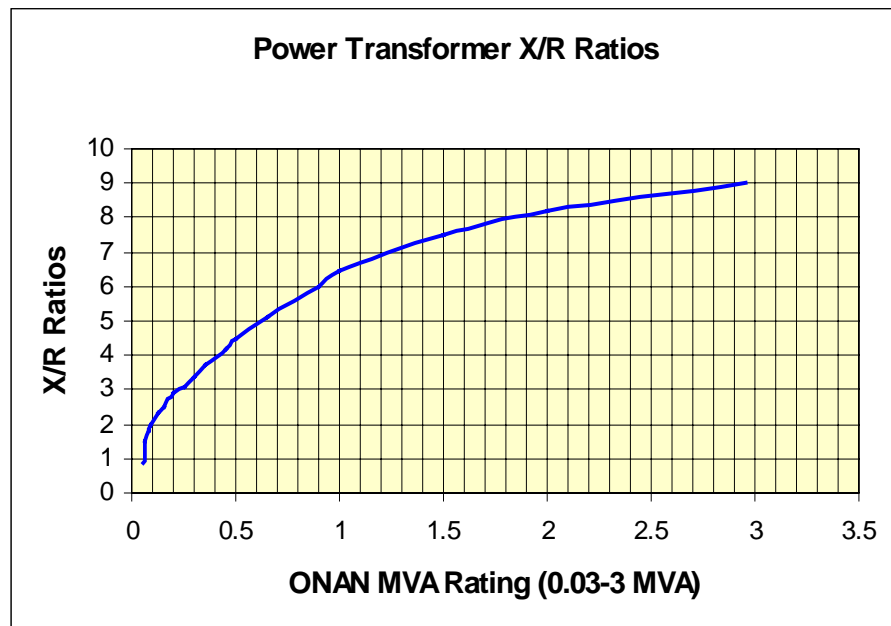
Often said that generators, motors, or circuits have a certain d-c time constant. This refers again to the rate of decay of the d-c component. **The d-c time constant is the time, in seconds, required by the d-c component to reduce to about 37% of its original value at the instant of short circuit. It is the ratio of the inductance in Henrys [V·s/A] to the resistance in Ohms of the machine or circuit.** This is merely a guide to show how fast the d-c component decays.

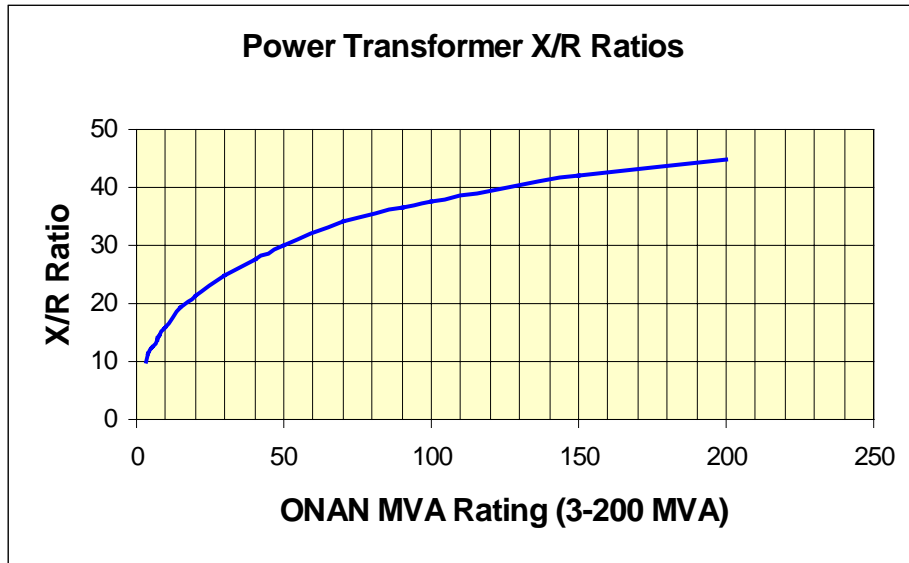
Typical values of X/R ratios of distribution and transmission lines depending on their rated voltages and geometrical configuration are shown in Table 1.

TABLE 1						
Sequence	X/R Ratios for Distribution and Transmission Lines					
	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	9.80 (Hor.)	24.3 (Hor.)
					9.6 (Delta)	18.5 (Vert.l)
X_0/R_0	1.95	3.05	4.23	4.08	3.2 (Hor.)	3.5 (Hor.)
					3.3 (Delta)	5.0 (Vert.)

Table 2 shows X/R ratios for generators, transformers, etc. as a function of their rated power.

TABLE 2			
X/R Ratios for Other Power System Elements			
Large Generators	Power Transformers	Reactors	Utilities
40-120 Typical 80	See Curve	40-120 Typical 80	15-30 (near generating plant)





4. TRIPPING TIMES OF PROTECTION DEVICES

Instantaneous units of overcurrent (50) and distance protections normally operates in 15 to 30 ms, and therefore dimensioning factors must consider that the relay tripping times should be lower than time to saturation t_s . Therefore to guarantee the correct operation of protection devices the equation (2) must be applied choosing as parameter t the instantaneous operating times of the different relays. Table 3 shows typical tripping times for different GE relays and the necessary overdimensioning factor K_s using CT class TPX with a secondary time constant $T_2 = 3$ seconds.

TABLE 3			
Relay	Instantaneous Operating Time (s)	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	70ms	6.45
ALPS	10 ms	70ms	3.92
DGP	25 ms	70ms	7.57
SR489	45 ms	70ms	11.34
SMOR	25ms	70ms	7.57
DTP	45ms	70ms	11.34

5. RESULTANT FAULT VOLTAGES AND CT DIMENSIONING

With results shown in TABLE 3 and neglecting factors K_0 and K_R for equation (6), the next lines describe the way to find 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 assumes that the phase-to-phase short-circuit current is of the same order of magnitude than the phase-to-ground short-circuit current, then a single equation should be used. If not 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 will use equation (6) for all:

Example

Being:

$$K_s = 6.18$$

$$V_{\text{rated}} = 13.8 \text{ kV}, 50 \text{ Hz}$$

$$\text{Relay Resistance: } 0.04\Omega$$

$$P_{\text{shortcircuit}} = 0.597 \text{ GVA (assumed)}$$

$$\text{CT Ratio: } 600/1$$

$$\text{CT Class: } 5P20$$

$$\text{CT Secondary Winding Resistance: } 1.5\Omega \text{ (assumed)}$$

$$L_{\text{wiring}}: 2 * 10\text{m (6 mm}^2 \text{ cross section cable) (assumed)}$$

$$R_{\text{wiring}} = 0.059\Omega$$

$$K_0 \text{ not considered}$$

$$K_R \text{ not considered}$$

$$V_s = k_0 k_s k_R I_2 R_2$$

$$V_s = \frac{P_{\text{sc}}}{\sqrt{3} V_{\text{rated}} \text{CT}_{\text{ratio}}} K_s (R_{\text{CT}} + R_{\text{W}} + R_{\text{R}}) = 24976/600 (1.5\Omega + 0.059\Omega + 0.04\Omega) = 411 \text{ V}$$

$$\text{Equivalent Power: } \frac{\left(\frac{411}{1\text{A}} \right)^2}{1.5\Omega} * (1)^2 = 19 \text{ VA}$$

6. TERMS AND DEFINITIONS

6.1 Rated Primary Short-circuit Current ($I_{Primarysc}$)

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

6.2 Instantaneous Error Current (I_e)

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:

$$I_e = I_{e\ ac} + I_{e\ dc} = (n * I_{Secondary\ ac} - I_{Primary\ ac}) + (n * I_{Secondary\ dc} - I_{Primary\ dc})$$

6.3 Peak Instantaneous Error (ξ_i)

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

6.4 Peak Instantaneous Alternating Current Component Error (ξ_{ac})

Maximum instantaneous error of the alternating current component expressed as a percentage of the peak instantaneous value of the rated primary short-circuit current.

$$\xi_{ac} = 100 * I_{e\ ac} / (\sqrt{2} * I_{Primary\ Short-circuit}) \quad (\%)$$

6.5 Accuracy Class

Defined by the "Class Index" followed by the letter P

6.6 Class Index

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.

No limit for remnant flux.

6.7 Limit Factor

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

6.8 Class P Current Transformer

Indicates “Protection” current transformers destined to feed protection relays. Accuracy limit is defined by composite error ξ_{ac} with steady state symmetrical primary current. There is no limit for remanent flux.

6.9 Class TPS Current Transformer

Low leakage flux current transformer for which performance is defined by the secondary excitation characteristics and turns ratio error limits. There is no limit for remanent flux.

6.10 Class TPX Current transformer

Accuracy limit defined by peak instantaneous error (ξ_i) during specified transient duty cycle. There is no limit for remanent flux.

6.11 Class TPY Current Transformer

Accuracy limit defined by peak instantaneous error (ξ_i) during specified transient duty cycle. Remanent flux does not exceed 10% of the saturation flux.

6.12 Class TPZ Current Transformer

Accuracy limit defined by peak instantaneous alternating current component error (ξ_{ac}) during single energization with maximum dc. offset at specified secondary loop time constant. No requirements for dc. component error limit. Remanent flux to be practically null.

6.13 Primary Time Constant (T_1)

That specified value of the time constant of the dc. component of the primary current on which the performance of the current transformer is based.

6.14 Secondary Loop Time Constant (T_2)

Value of the time constant of the secondary loop of the current transformer obtained from the sum of the magnetizing and the leakage inductance (L_s) and the secondary loop resistance (R_s).

Normally this value is higher as compared with T_1 in TPS class current transformers (about 10s).

T_2 will depend on the precision requirements but normally oscillates between 0.3 and 1 seconds for TPY class current transformers.

Finally T_2 is much more lower in TPZ class current transformers (about 0.07 seconds).

6.15 Time to Maximum Flux ($t_{\phi_{max}}$)

Elapsed time during a prescribed energization period at which the transient flux in a current transformer core achieves maximum value, it being assumed that saturation of the core does not occur.

6.16 Secondary Winding Resistance (R_{CT})

Secondary winding dc. resistance in Ohms, corrected to 75° C, unless otherwise specified, and inclusive of all external burden connected.

6.17 Secondary Loop or Burden Resistance (R_B)

Total resistance of the secondary circuit, unless otherwise specified, and inclusive of all external burden connected.

6.18 Low Leakage Flux Current Transformer

Current transformer 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.

6.19 Saturation Flux (Ψ_S)

That peak value of the flux which would exist in a core in the transition from the non-saturated to the fully saturated condition. This regards 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%.

6.20 Remanent Flux (Ψ_R)

That value of flux which would remain in the core three minutes after the interruption of an exciting current of sufficient magnitude as to induce the saturation flux (Ψ_S).

