THE CT BEHAVIOR AND ITS COMPATIBILITY WITH RELAY PROTECTION

Ionuț Ciprian BORĂSCU[1]

A current transformer associated with protective and control equipment must however perform acceptably, often in conjunction with others, over the whole range of currents which may flow in it. These currents are dependent on the network in which the protective equipment is used and on factors such as the fault conditions encountered and the instants at which they occur.

In this article I showed the real and transient behavior of a CT, as well the influence of CT saturation to the performance of the overcurrent relays and distance relays. The personal contribution of the author consists also a calculation of compatibility CT-protection.

Keywords: current transformer, DC component, relay

1. Introduction

Correct operation of most protective relays is dependent on the relays being supplied with sufficient information from the high voltage system [3].

The error of a conventional current transformer is dependent on, whether the core is saturated or not. When the core is saturated the magnetizing current is large compared to the secondary current and the error is high. The degree of saturation depends on the magnitude of fault current, primary time constant, secondary time constant of the current transformer and the magnitude of the DC component that can cause large errors in the estimation of the fundamental frequency signal.

It has been reported that relays act differently during CT saturations and their response may not meet the published time-current characteristics. These problems can cause severe loss of production to various plants or damage to critical electrical equipment [13].

The simplest means by which the effects of saturation can be demonstrated is through the use of Fig.1. This represents the waveform of current that would be delivered to a relay while experiencing saturation at time T_S and on each subsequent half-cycle [8]. No effect of DC offset in the primary current is considered in this figure. After T_S and until the next zero crossing, zero current is

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[1] PhD student, Faculty of Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania

assumed to delivered by the current transformer to the relay. This is referred to as "symmetrical saturation". The process repeats each half-cycle.
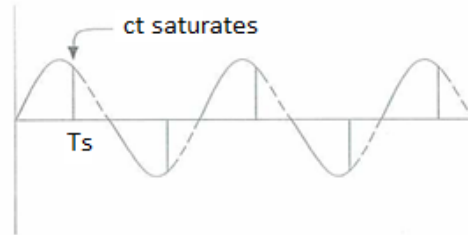

Fig. 1. Effects of saturation

The CT has to be designed so that saturation will not delay the response of the relay longer than what is required to guarantee the necessary fault clearing time in the application.

The quality of the CT is related to the relative permeability μ_r of the magnetic circuit. μ_r which is approximately 1,000 for iron, becomes very small (several units) when B rises above the magnetic saturation induction B_{sat}. The magnetizing current or magnetic field H is related to induction as in the curve in Fig. 2, where μ_0 represents the magnetic vacuum permeability, n_2 number of turns on the secondary side of a CT, I_m the magnetizing current and L the length of the toroidal[11].

The protection class CTs are designed to work in the linear range, with minimal errors and minimal waveform distortion, only up to 20 times the rated nominal current with the burden as defined by the relay class (saturation voltage) of the CT per IEEE Std. C57.13.
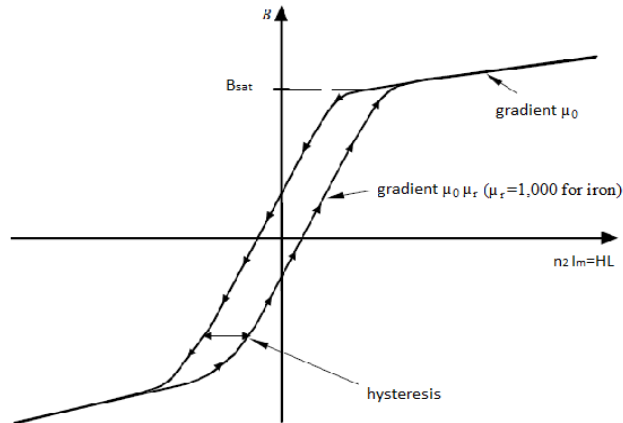

Fig. 2 Magnetizing current curve in relation to magnetic induction B

2. CT behavior

2.1. Real CT behavior

Real CTs have copper losses, core losses, leakage flux, and require a certain current to magnetize the core. As a result, the secondary current of a CT is not perfectly proportional to the primary current. For most operating conditions, CTs reproduce the primary currents well. However, under certain conditions, the CT core saturates and the CT fails to correctly reproduce the primary current [5].

Fig.3 depicts the equivalent circuit of a CT, referred to the transformer secondary side. The CT primary current Ip is dictated by the power system because the CT primary winding is connected in series with the protected element. The current source Ip/n represents the power system in Fig.3. CT leakage impedances are R'p +jX'p for the primary windings (referred to secondary) and Rs + jXs for the secondary winding. As a result of the current source, the primary leakage impedance has no practical effect on the CT behavior and can be disregarded [5]. The nonlinear excitation impedance Z_E represents CT magnetization.

The excitation current I_E flowing through the excitation impedance has two components. One component is the magnetizing current (flowing through the inductive component of Z_E), which is needed to generate the flux in the CT core. The other component of I_E is the loss current (flowing through the resistive component of ZE), which mainly results from the core hysteresis and eddy losses.

The secondary excitation voltage E_S is the voltage induced in the secondary winding. Impedance Z_B represents the total load connected to the CT secondary windings. This impedance is referred to as the CT burden. The CT secondary terminal voltage appears across the CT burden [5].

When the secondary voltage Vs is low, the excitation current I_E is low and the CT behaves almost linearly, with no saturation in the magnetic core. As Vs increases because of the current or the burden impedance increasing, the excitation current increases and the magnetic flux in the core also increases. At a given flux magnitude, the core saturates, the excitation current increases disproportionately and the secondary current is no longer an accurate replica of the primary current [5].
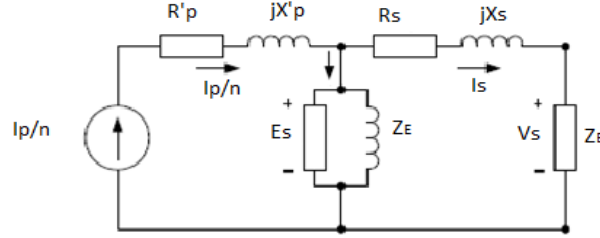
Fig.3. Equivalent circuit of a CT

Based on Fig. 3, the phasor values of the secondary current and the CT terminal voltage are,

$$I_S = \frac{I_p}{n} - I_E$$

$$V_S = I_S \cdot Z_B = E_S - I_S(R_S + j \cdot X_S)$$

(1)

Fault clearance reduces the primary current to zero, but some magnetic flux remains trapped in the CT core. Remanence is the magnetic flux that remains in the magnetic circuit after the removal of the primary current. Remanence is approximately equal to the residual flux density in a nongapped-core CT. An advantage of gapped-core CTs is that their remanence is lower than the residual flux [5].

2.2. Transient behavior

During faults, the currents have a substantial decaying DC component which depends on the time constant of the primary system and the point on the voltage waveform when the fault occurred.

Three factors contribute to the Vk (knee point voltage) dimensioning of the CT.

They are:

-*Short circuit factor (K_{SSC}):* This factor accounts for the symmetrical fault current magnitude under the worst case of the fault. This is given by the ratio of the maximum secondary symmetrical short circuit current to the secondary nominal current [7]. It is given by:

$$Kssc = \frac{Issc\,\text{max}}{I_N}$$

(2)

Where: $Issc\,\text{max}$ -is the maximum secondary symmetrical short circuit current;

I_N – CT secondary nominal current;

-*Remanent flux factor (K_{REM}):* CT cores with air gap can retain remanent flux for a very long time. Thus, if the increases in flux during fault is in the same direction of the remanent flux, then the CT core can reach a saturation value faster it would have if the remanent flux was zero. Thus, K_{REM} accounts for dimensioning the CT to take care of remanent flux [7]. The amount of remanent flux would depend on the type of CT (high, medium or low remanence and point on the current waveform when the last fault current was interrupted. The remanent flux factor is given by:

$$K_{REM} = \frac{1}{1 - \dfrac{\psi_R}{\psi_S}} \tag{3}$$

where

ψ_S saturation flux;

ψ_R remanent flux;

-*Asymmetry transient factor (K_{TF}):* The transient over dimensioning factor is given by the ratio of the secondary linked flux in the CT due to the total fault current to the flux linked due to the ac component of the fault current. This is given by

$$K_{TF} = \frac{\omega Tp Ts}{Tp - Ts} \cos\theta (e^{\frac{-t}{Tp}} - e^{\frac{-t}{Ts}}) + \sin\theta e^{\frac{-t}{Ts}} - \sin(\omega t + \theta) \tag{4}$$

Where:

ω - is the angular frequency ($2\pi f$);
Tp-is the primary system constant;
Ts-CT secondary time constant {$Lm/(RCT+RB)$};
θ-difference between point on wave angle and fault current phase angle (switching angle);
t-time since fault.

It is known that the maximum DC offset in the fault current occurs when $\theta=0^0$, thus the transient dimensioning factor becomes:

$$K_{TF} = \frac{\omega Tp Ts}{Tp - Ts} (e^{\frac{-t}{Tp}} - e^{\frac{-t}{Ts}}) - Sin(\omega t). \tag{5}$$

Equation (5) has two components, an exponential and a sinusoidal. The value of K_{TF} used in dimensioning the CT, thus depends on the minimum duration

for which CT is required to operate unsaturated. This duration is termed as time to saturation of the CT [7].

Now, the maximum knee point voltage requirement of the CT can be written as

$$V_{K\max} \geq K_{TF} K_{SSC} K_{REM} I_N (R_B + R_{CT}) \tag{6}$$

2.3. Direct current saturation

CT performance is affected significantly by the DC component of the AC current. When a current change occurs in the primary AC system, one or more of the three-phase currents will have some DC offset, although none may be maximum and one could not have much impact. This DC results from the necessity to satisfy two conflicting requirements that may occur: (1) in a high inductive network of power systems, the current wave must be near maximum when the voltage wave is at or near zero and (2) the actual current at the time of change is that determined by the prior network conditions.

Fig. 4 shows the current immediately following the fault inception for two cases: fully offset and with no offset [1]. In the fully offset case, the fault is assumed to occur at the instant that produces the maximum DC component. In the second case, the fault occurs at a time that produces no DC offset.

The DC component can disappear only by decaying according to the L/R time constant of the power system. This decaying acts more or less like a low-frequency alternating current in passing through the CT. It can saturate the iron such that the secondary reproduction of the primary current can be severely limited and distorted. After saturation occurs, the decay of the DC component results in the CT recovering, so that during each subsequent cycle, the secondary current more nearly approaches the primary. As the DC disappears, the secondary is again a reproduction of the primary. This assumes no AC saturation. It is possible, but rarely occurs that the secondary current may be practically zero for a few cycles in very severe cases.
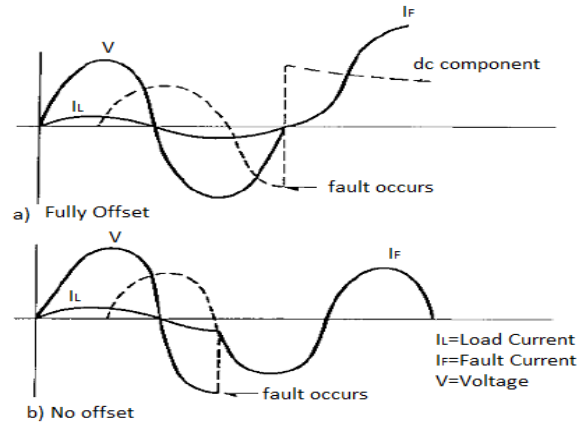
Fig. 4 Current immediately after fault inception.

3. The influence of CT saturation to the performance of the relay

3.1. Distance relays

In general, the reach of distance relays will be affected by CT saturation. This is true whether the relay design is an electromechanical design utilizing rms current measurement, or a microprocessor design referencing peak instantaneous or rms current levels or various combinations of waveform values for measurement [9]. During CT saturation, a portion of the current is missing, so that principally ($Z=U/I$) an impedance which is too large, is measured. This implies that the zone reach is reduced. This is acceptable for close-in faults because the distance to the zone limit is large. However, close-in high magnitude faults in the reverse direction may result in false tripping by directional relays.

For faults close to the zone limit, an under-reach is however not permitted, as the protection in this case would only trip in the second zone, with a time delay [4]. The distance element needs to wait for the DC offset to die out and the CT to recover. However, saturation must occur before the element has a chance to pick up. The situation can be made worse if the reach is reduced because of high source impedance ratio (SIR); however, getting CT saturation with a high SIR is unlikely.

3.2. Overcurrent relays

Instantaneous overcurrent (ANSI device 50) normally operate in a 15 rms range. As such, dimensioning factors must recognize that relay tripping times should be lower than time to saturation.

In digital instantaneous overcurrent relays the derived operating current signal is compared against a user set threshold. Extra security may be implemented by requiring several consecutive checks to confirm the trip ("security counters") [13]. This impacts when and for what current the relay would operate. Another aspect is the rate at which the operating conditions are checked. They may be executed with each new sample, every other sample, once a cycle, etc. This again impacts if and when a given function operates if the current is not steady.

Transient saturation may delay the operation while severe steady state CT saturation may prevent pick-up at all [12].

Failure to trip or a slow trip would cause miss-coordination of the protection system or primary equipment damage. It is clear that severely saturated CT presents a fault current waveform that has very sharp peaks with a short duration of few milliseconds only. Traditional RMS based IOC algorithms will fail to sense these very high fault currents. A simple approach is to keep the RMS based comparator and augment with parallel technique that will identify the high current level with severe CT saturation.

4. CT dimensioning example

In this section I did a calculation of compatibility CT- relay protection 7SA6.

Table 1

General system data

Nominal voltage of the system	110	kV
Nominal frequency(f)	50	Hz
Power system time constant(Tp)	50	ms
Max. short-circuit current at bus station at 1 second (Imax)	27.4	kA
Max. short-circuit current for CT dimensioning	31.5	kA

Table 2

Main Data of CT

CT type	10P20	
Transformation ratio	600/1	A/A
Internal resistance (R_{CT})	9.3	Ω
Nominal burden	60	VA
Nominal accuracy limiting factor(Knalf)	20	
Power factor	0.8	
CT primary current(Inp)	600	A
CT secondary current(Ins)	1	A

Table 3

Relay Data

Manufacture	Siemens
Relay Type	7SA6
Nominal Current	1 A
Relay burden(Sn)	0.05 VA

Table 4

Cable burden

Length(Lc)	120	m
Cross section(s)	4	mm^2
Specific resistivity at 20^0C(ρ_{Cu})	$1.67 \cdot 10^{-8}$	Ωm
Relay burden	0.05	VA
Additional resistance(R_A)	0.01	Ω

Table 5

Factors and primary DC time constant Tp [ms][10]

Factor	Primary DC time constant Tp [ms]			
	≤30	≤50	≤100	≤200
Ktda	1	2	4	4
Ktdb	4	5	5	5

CT requirements:

$$K_{oalf} > \frac{Ktda \cdot I_{\max}}{In_{TC}}$$

$$K_{oalf} > \frac{Ktdb \cdot Ik \lim}{In_{TC}} \tag{7}$$

Calculation of total CT connected burden:

The performance of current transformer depends on the connected burden at the secondary terminals. The total burden includes the relay burden and additional burdens, the burden of cables and, if used, the burden of connected matching transformer.

$$Rc = \frac{\rho_{Cu}}{s} \cdot Lc \tag{8}$$

$$Rc = 1.002[\Omega]$$

$$S_{relay} = 2 \cdot Sn$$

$$S_{relay} = 0.1[VA] \tag{9}$$

The total effective burden is given by the sum of all connected burdens:

$$R_t = R_C + R_{CT} + R_A + \frac{S_{relay}}{I_{ns}^2} = 10.41[\Omega] \qquad (10)$$

Check of CT requirements:

The CT behavior acc. to IEC-P will be described by the operating accuracy limiting factor Koalf. It depends on the nominal accuracy limiting factor Knalf, the nominal burden Pn, the internal CT burden Pct and the total effective connected burden Ptotal.

$$R_b = Sn \cdot \cos\phi$$

$$X_b = Sn \cdot \sqrt{1 - \cos\phi^2}$$

$$K_{0alf} = K_{alf} \cdot \frac{\sqrt{(R_{CT} + R_b)^2 + X_b^2}}{R_t} \qquad (11)$$

$$K_{0alf} = 129.98$$

Max. symmetrical short-circuit current Ik, for faults at zone 1 limit:

For CT dimensioning, the short-circuit current and system time constant a set zone 1 limit of 1% has to be taken into consideration. With a max. symmetrical short-circuit current of 27.42 kA, the equivalent source can be calculated:

$$Z_q = \frac{1.1 \cdot Un}{\sqrt{3} \cdot I_{sc}} \qquad (12)$$

$$Z_q = 2.54[\Omega]$$

Taking into account the system time-constant of 50 ms the resistive and reactive part of the source impedance can be calculated:

$$R_q = \frac{Z_q}{\sqrt{1 + (2 \cdot \pi \cdot f \cdot \frac{T_p}{1000})^2}} \qquad (13)$$

$$R_q = 0.16[\Omega]$$

$$X_q = \frac{Z_q \cdot (2 \cdot \pi \cdot f \cdot \frac{T_p}{1000})}{\sqrt{1 + (2 \cdot \pi \cdot f \cdot \frac{T_p}{1000})^2}} \qquad (14)$$

$$X_q = 2.54[\Omega]$$

With the ohmic and reactive per line length values R' and X' the set zone 1 limit Klim, and the line length, the short-circuit current at zone 1 limit Ik_{lim} and the corresponding time-constant:

$$R_L = L \cdot R'_L = 2.90 [\Omega]$$

$$X_L = L \cdot X'_L = 7.98 [\Omega]$$

$$K_{lim} = 0.30$$

$$Ik_{lim} = 1.1 \cdot \frac{\dfrac{Un}{\sqrt{3}}}{\sqrt{(R_q + K_{lim} \cdot R_L)^2 + (X_q + K_{lim} \cdot X_L)^2}} \tag{15}$$

$$Ik_{lim} = 7.21 [kA]$$

$$T_{p1} = (\frac{1000}{2 \cdot \pi \cdot f}) \cdot \frac{(X_q + K_{lim} \cdot X_L)}{(R_q + K_{lim} \cdot R_L)}$$

$$T_{p1} = 11.28 [ms]$$

Conditions check

$$\frac{Ktda \cdot I_{max} \cdot 1000}{In_{TC}} = 91.4 \qquad\qquad K_{0alf} = 129.98 \tag{16}$$

$$\frac{Ktdb \cdot Ik\,lim \cdot 1000}{In_{TC}} = 48.06 \qquad\qquad K_{0alf} = 129.98 \tag{17}$$

Both requirements are met and the CT corresponds with relay 7SA6.

5. Conclusions

Calculation of compatibility CT-relay protection that I made in this paper represents a solid technical background for checking and indication of the current transformer who will power numerical protection 7SA6 from Siemens. This information would be vital in analyzing the performance of different protection relay algorithms and study the performance during CT saturation.

Since the safe operation of the relay protection is mandatory, each manufacturer provides guidelines and dimensioning factors for simplifying the CT selection calculations. The adequacy of these guidelines has been confirmed by the manufacturer often through rigorous testing of the particular relay in different conditions of the system.

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