SELECTION OF CURRENT TRANSFORMERS & WIRE SIZING IN SUBSTATIONS

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ABSTRACT

More and more sub-stations are retrofitted with numerical relays, meters and monitoring devices. Most often, the older relay gets replaced with a newer relay with the rest of the installation such as Current Transformer (CT) and lead remaining undisturbed. Utilities have standardized on their older current transformers and want to maintain the same current transformer specifications throughout their system even in their newer installation. An extension of the above approach is that even the cable leads and panel wiring sizes are over-specified resulting in totally unjustified cost of installations as well as difficulty in terminating such wires in the modern panels and equipment.

On the other end of the spectrum, in rare cases, the existing CT sizes and lead sizes of electromechanical relays may not be adequate for the latest protective relays which might demand a different current transformer performance. A careful evaluation of current transformer size and their leads is recommended, either to save an appreciable cost of installation or to avoid costly protection mis-operation or non-operation.

This paper systematically lists and analyses such requirements for various modern protective relays. This work is expected to be a good reference source for the new generation utility protection engineers in selecting the CTs and wire sizes and understanding impact of various connections in determining the reliability of components in the installation.

1. INTRODUCTION

The foremost interface device between the power system and the protective relaying is the ubiquitous current transformer. The standard current transformer secondary winding is rated at 5A as per ANSI standards. Other rated currents such as 1A exist elsewhere. The main purpose of a current transformer is to translate the primary current in a high voltage power system to a signal level that can be handled by delicate electromechanical or electronic devices. The secondary connected devices could be indicating or energy integrating instruments, protective relays, transducers etc. Since the applications are so varied, it is natural that the CT be properly specified, depending on the exact application to which it is applied. To this extent, it is necessary to understand some of the fundamental ways the CTs behave. This paper makes an attempt to present the basics to understand the behavior and application of the CTs. The bibliography at the end of the paper provides more detailed analysis and application data.

2. CHARACTERISTICS OF CT

The current transformer primary is connected in series with the device in which the current is to be measured. Since Current Transformer is fundamentally a transformer, it translates the current from the **P**rimary to the **S**econdary side, inversely proportional to the turns so as to maintain the relationship,

$$\mathbf{I_P = n\, I_S}$$

where, **n** is the turns ratio of turns between the secondary and primary winding. Mostly, the primary of a CT is a straight-through bar, meaning the number of turns on the primary is just 1. Hence **n** is often the number of turns of the secondary.

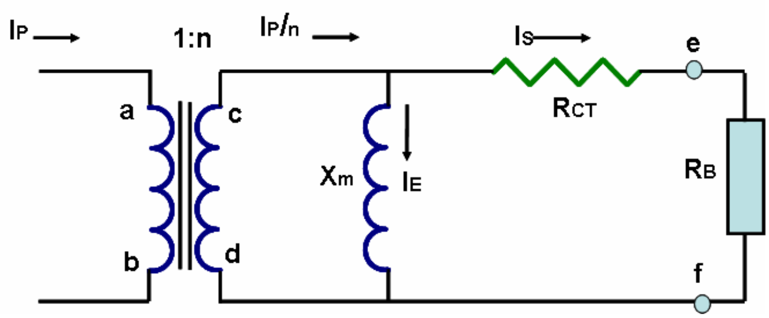


Figure 1a. Simplified equivalent circuit of a current transformer

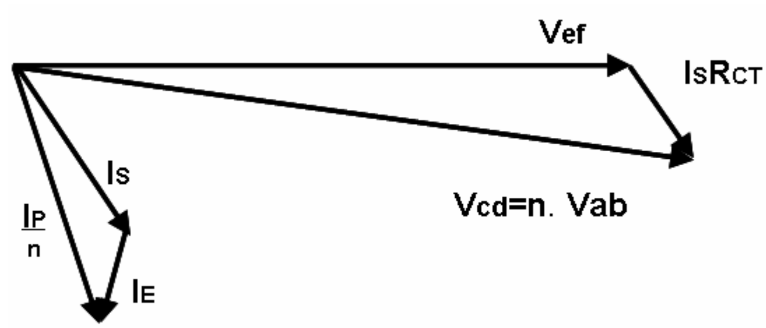


Figure 1b. Phasor diagram of a Current Transformer

The relationship above is assuming an ideal current transformer without any losses and negligible magnetizing current. In actual practice, the CTs draw a current to keep the iron core excited and drop a voltage proportional to the current transformed because of the inherent resistance of its windings. An equivalent circuit of a CT is represented by Figure 1a, where **Xm** represents the magnetizing current reactance and **R_{CT}** represents the internal winding resistance.

The current transformer is expected to deliver about 5A or lower under healthy load conditions. The current goes to a high value if a fault occurs. As per ANSI, the CT ratio shall be chosen so that the maximum symmetrical fault current on the CT secondary is limited to 100A. Since it is very difficult to meet the high accuracy requirement for billing purposes near rated current as well as maintain an acceptable linearity for protection at current levels of 100A, it is usual to separate the functions to two different sets of CT cores.

2.1 Specifying Metering core Current Transformer

The main concern here is that the CT core is sized to adequately meet the burden requirements. The burden includes the connected metering burden as well as the lead burden. The metering class CT is specified with accuracy rating for each standard burden for which it is rated. An example provided in IEEE C57.13 is 0.3 B-0.1 and B-0.2, 0.6 B-0.5. The number after the letter B indicates the standard burden in Ohms at a power factor of 0.9. The number 0.3 or 0.6 indicate accuracy class.

Protection class CT is mostly accurate enough to drive a set of indication instruments (but may not be good enough for revenue class summation energy metering). One disadvantage of using protection class CT for indication is that the CT is capable of being driving up to 100A and beyond, which the delicate metering equipment may not be able to withstand thermally. In such cases the norm is to provide an interposing auxiliary transformer, star/star connected. The auxiliary transformer is arranged to saturate for currents beyond a few 10s of amperes. While specifying metering or auxiliary current transformers, the design burden needs to be closely matched to the actual connected burden. Connecting too low a burden compared to the design burden of the current transformer will allow higher currents through the metering equipment before saturation comes into play.

Often a scheme is required to sum up the currents from two more incomers, to arrive at the net current or power flow into the switchgear. A special auxiliary transformer with multiple primary 5A windings is common. The secondary winding rating is chosen based on the net current expected with two or more of the incomers in service (Figure 2).

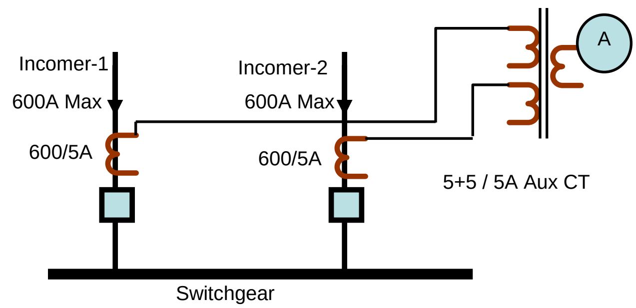


Figure 2. Summation Auxiliary Current Transformer

2.2 Specifying Protection Class Current Transformers

In order to specify or check the ratings of a current transformer, a thorough understanding of the application is required. With respect to ANSI CTs, some of the major details that one would look for in the CT are:

CT Ratio, frequency etc.

Polarity

Class, Saturation Voltage, Knee point voltage

Excitation characteristics

Voltage rating, current rating, thermal ratings etc. to suit primary power system

2.2.1 CT Ratio

The ratio is expressed in terms of rated primary and secondary currents. Excluding special applications, the primary rating has to be more than the maximum current that the primary of the current transformer is expected to carry. When the CT is located in the outgoing feeder circuit, the maximum primary current is the same as the maximum feeder current. The next thing to check is the maximum symmetrical fault current. Choose the primary rating so that with the maximum fault current, the CT secondary current is less than 100A. In short the primary rating shall be above the load current as well above $1/20^{th}$ of the fault current in such applications. With respect to 100A maximum secondary fault current, exceptions occur often in case of HV transformer CT applications where the load currents are quite low compared to the maximum fault current. A thorough application check with respect to the CT performance and the withstand capability and linearity of the connected devices need to be thoroughly checked.

In 'ring main' or 'breaker-and-a-half' schemes the primary current rating is decided by the current flowing across the bus and accordingly the CT primary rating is chosen. As we will see further, choosing a higher CT ratio increases the available knee point voltage to the relay, but the secondary current gets reduced greatly. The latter could be an issue where load matched currents is expected such as transformer differential protections.

Rarely CTs are provided with primary taps and require special attention with respect to selecting the ratios. Since a couple of cores are stacked inside a CT, changing the primary tap would result in changing the ratios of all the cores. Necessary adjustments may have to be done on the CT secondary taps of the other cores to maintain their ratios.

2.2.2 Polarity

Polarity is not of direct concern for non-directional Phase OC relays. However, where ground relaying is concerned the polarities are to be properly observed before residual connections are formed.

As regards directional protection applications, their operation depends on the phase angle of the measured current with reference (polarizing) signal. It is mandatory to observe the polarity of the current transformer secondary in such installations.

2.2.3 Class, Knee point voltage, excitation characteristics

The major error of a CT can be attributed to the magnetizing current drawn. Hence, the excitation characteristics define the performance of the CT best. With both primary and secondary open, a voltage is applied across the secondary and the current drawn is measured and plotted on a log-log graph.

In this graph, the knee point voltage is defined as the point on the excitation curve where the tangent is at 45 degree to the abscissa. The log-log graph paper shall be with square decades. (The definition here is applicable for non-gapped CT core, which exist in most of the installations in the U.S. More details and definitions are available in IEEE standard for air-gapped cores.)

The knee point voltage represents the point beyond which the CT becomes non-linear. Further voltage increases will make the CT draw larger currents. Beyond a certain level, the primary and secondary windings physically exist next to each other, but the magnetic coupling becomes insignificant. The current in the CT secondary is no longer influenced by the primary current.

2.2.3.1 AC Saturation:

The TOC curve of the earlier electromechanical relays was achieved by allowing partial saturation of the internal magnetic circuits. Currents much higher than the higher limits of the TOC relays, which cause 'partial' saturation of the CTs should not affect the applications. However, if an application involves severe CT saturation, the relay may not function. Where the CT ratio is very low, CT secondary currents could exceed 20 times rated current causing severe saturation. The net outputs of such CTs may become so low (Figure 3) that operation of most of the protections become impossible.

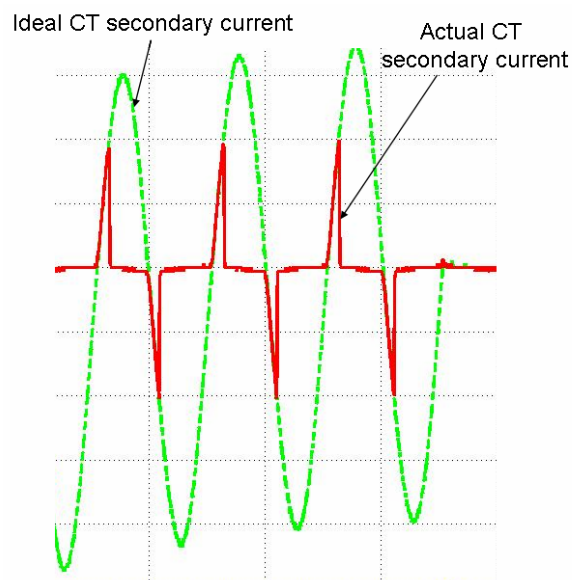


Figure 3. CT secondary waveform when severe AC saturation occurs

To avoid saturation, the CT shall develop adequate voltage such that

$$\mathbf{V_X > I_f\,(R_{CT}+R_L+R_B)} \qquad \text{- - - - - -} \qquad \mathbf{(1)}$$

where,

$\mathbf{I_f}$ = Fault current on CT secondary (Amps)

$\mathbf{R_{CT}}$ = CT Secondary resistance (Ohms)

$\mathbf{R_L}$ = CT Secondary total lead resistance (Ohms)

and $\mathbf{R_B}$ =CT secondary connected burden (Ohms)

The lead resistance $\mathbf{R_L}$ is the total secondary loop lead resistance. In case of single phase to ground faults, the current from the CT secondary flows through the phase connection and returns through the neutral wire. Hence twice the 'one-way' lead resistance shall be considered. In case of multi-phase faults, the phase currents cancel out with negligible current in the common neutral return lead. Hence the lead resistance for such faults will be just that of the 'one-way' lead. Special cases arise with delta connected CTs. In all such cases a very careful evaluation of how the CT under question drives currents through the leads would be necessary.

2.2.3.2 Transient Saturation:

Transients, especially the decaying DC waveform in the primary current, cause the CT to go into saturation and produce distorted current waveform. Once the transients vanish the steady state performance of the CT gets restored.

To further understand the phenomenon of saturation of CT during DC transients, one has to understand how and why the DC transients occur in the power system and its effects on the CT.

Considering a fault in a Transmission line, the moment a fault occurs, one would expect the currents to follow the relationship **I** = **V/Z.** This equation, however, represents a simplified steady state Phasor relationship. Assuming a pure inductive circuit, if the fault occurs at maximum point of wave, the current which was earlier zero, would rise from that value, and hence no transients are to be expected.

However, fault may occur when the voltage waveform goes through near zero. The steady state waveform indicates that the current should be at the maximum value when the fault occurs. This is impossible since the inductance in the transmission system does not allow an instantaneous change from current zero level prior to fault to a high value just after the incidence of the fault.

Solving the differential equation of the fundamentals of the inductive circuit, it can be proven that the inductance would draw a combination of steady state DC current as well as an alternating current waveform, with apparently no instantaneous change in the current value prior to and after the incidence of the fault (Figure 4).

In practical applications the DC current is not sustained but decays with a time constant equal to the system time constant L/R where L is the inductance in Henry and R is the resistance in Ohms of the primary power system.

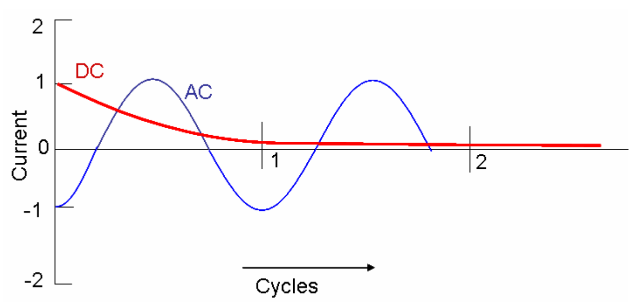


Figure 4. Components of currents in an inductive circuit with maximum DC transients

Transient behavior of CT:

Reverting back to the subject of current transformers, it is definitely burdened with the task of translating not only the steady state AC current waveform but also the DC transient. While current transformers are designed to work with transferring alternating current, the situation here warrants translating DC current from the primary to the secondary side. CTs use magnetic field to couple the electrical signal from primary to the secondary side using dynamic 'changes' rather than absolute magnitude. The voltage induced in the secondary is thus proportional to the 'rate of change' of the magnetic flux. Assuming CT secondary burden to be purely resistive, the voltage across the CT is directly proportional to the current.

Considering

i = CT secondary current (instantaneous)

v = CT secondary voltage (instantaneous)

Φ = Flux in the magnetic core

$$i \;\; \alpha \;\; v \;\; \alpha \;\; (d\,\Phi/d\,t)$$

where $d\,\Phi/d\,t$ represents the rate of change of flux with respect to time

Rewriting the last part of the above,

$$i\;\alpha\;\;(d\,\Phi/d\,t)$$

Integrating both sides,

$$\int i\;\alpha\;\;\Phi \qquad - \quad - \quad - \quad - \quad - \quad - (2)$$

In other words, the flux necessary to drive a current is proportional to the area under the envelope of the current wave shape.

Figure 5a indicates the variation of flux when AC current waveform is involved. Figure 5b indicates the excursion of flux when translation of DC offset transient waveform is involved. In the first case, the flux excursion involves increasing as well as decreasing flux. Thus the saturation flux limits are not reached. However, in the latter case, integration of the unidirectional DC waveform involves excursion of the flux only in the increasing direction. The longer the DC transient, the larger will be the excursion of the flux level, resulting in exceeding the saturation limits of the iron core, causing total distortion of the output waveform.

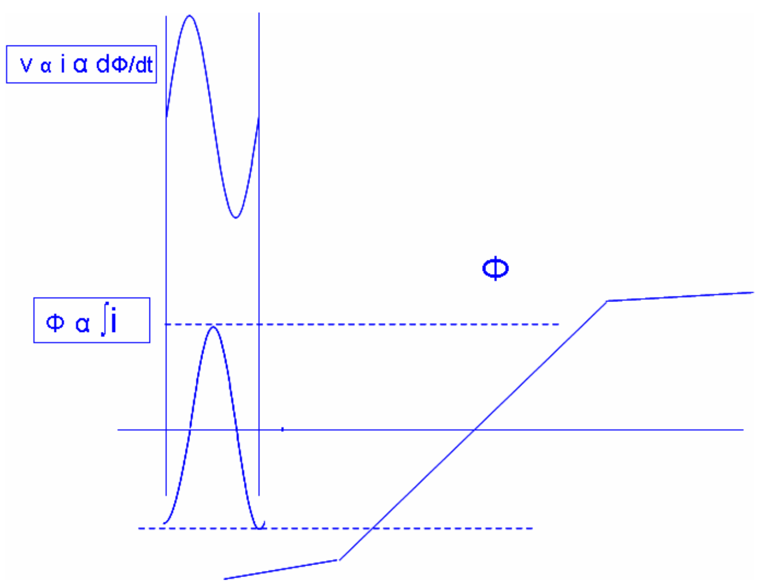


Figure 5a. Excursion of flux waveform Φ is well within the saturation limits with AC current waveforms

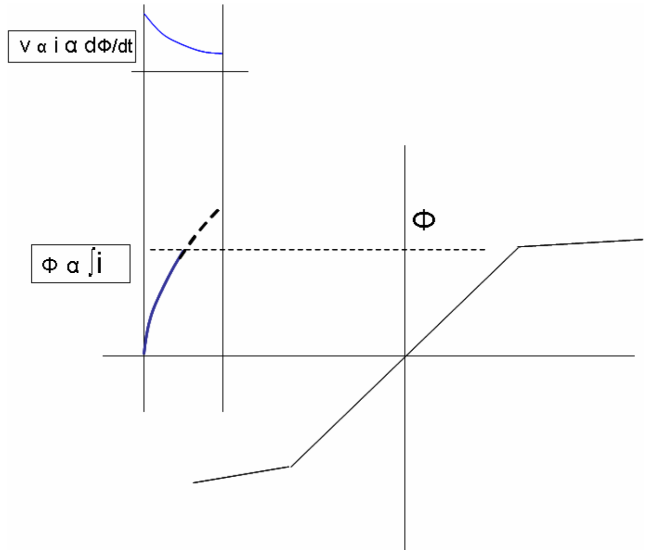


Figure 5b. Excursion of flux waveform Φ shoots past the saturation limits quickly with DC transients

Figure 6 indicates the actual CT secondary current waveform when CT saturates because of the requirement to translate primary DC current transients.

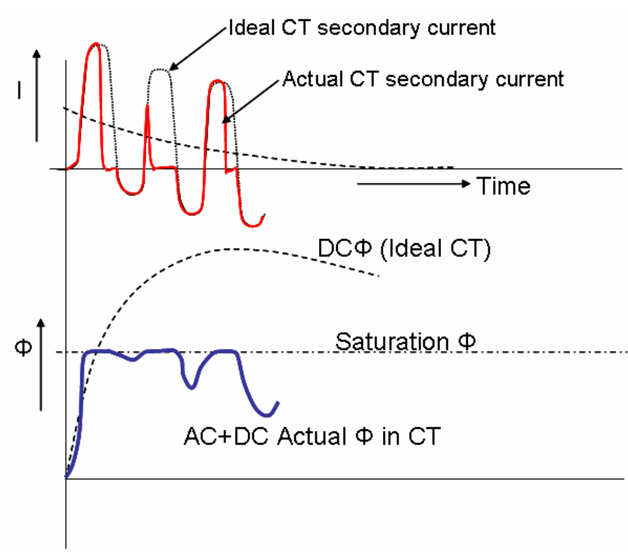


Figure 6. Saturation due to DC transient distorts the AC waveform output as well

It is clear that to produce the DC offset along with an AC waveform without distortion, the requirement of the steel core flux in the CT is not just twice the flux required for the AC waveform but much larger, big enough to sustain the growth of flux as long as the DC transient persists.

It can be shown that the CT shall have enough capacity to develop the following voltage not to saturate at all for a combination of AC and DC transient.

$$V_X > I_f\,(1+X/R)\,(R_{CT}+R_L+R_B) \qquad - \quad - \quad - \quad - \quad - \quad - \qquad (3)$$

where,

I_f = Fault current on CT secondary (Amps)

X = System primary reactance (Ohms)

R = System primary resistance (Ohms)

R_{CT} = CT Secondary resistance (Ohms)

R_L = CT Secondary total lead resistance (Ohms)

and **R_B** =CT secondary connected burden (Ohms)

Note that there is an additional factor (1+X/R) on the right side of the equation compared to the equation applied for AC saturation, Equation (1).

The ANSI specifies CTs for protection performance by a letter (See IEEE Std C57.13- 1993). The classification codes are **C**, **K** and **T**. The classification **C** and **K** are widely used for protection. They indicate that the winding is uniformly wound around the core with negligible leakage flux. The **C** class CT is furnished with excitation characteristics which can be used to "**C**alculate" the CT performance. The standard ratings are C100, C200, C400, C800 corresponding to 100, 200, 400 and 800 volts respectively at 100A CT secondary. This would mean the design burdens are 1, 2, 4 and 8 Ohms respectively. Other burdens such as 0.1, 0.2 and 0.5 with corresponding voltages 10, 20, 50 are also specified but are not often used for HV and EHV applications. ANSI specifies the power factor of the burden at 0.5.

A steady state current error of 10% is allowed at 100A secondary, which translates into 10A excitation current. It is easy to look up the CT excitation characteristics corresponding to 10A excitation current and find out the induced voltage inside the CT. Subtracting the internal drop of **R_{CT}** through 100A fault current from the voltage should be above 100, 200, 400 or 800V to classify the CT as either C100, C200, 400 or 800. In figure 7a, corresponding to maximum tap ratio of 600/5A, the voltage developed corresponding to 10A excitation current is 150V. The **R_{CT}** for this ratio is 0.296 Ohms. So the voltage developed across the external burden is 150-100x 0.296 which is about 120V. The CT is designated as C100 which is the next lower rating below 120V. The knee point voltage for the above tap is about 70V. Note that when a lower tap is adopted the voltage available for the relay application comes down proportionately.

The **K** classification is the same as **C** rating but the knee-point voltage must be at least 70% of the secondary terminal voltage rating. The letter **T** indicates the ratio error must be determined by '**T**est'. There are other classification types **H** and **L,** which are older specifications and are no longer in use.

An ANSI C800 CTs will have a saturation voltage of about,

$$Vx = 100(R_{CT} + 8)$$

Here 100 represents the recommended maximum CT secondary current of the CT during fault conditions (= 20 times nominal current of 5A), 8 is the burden expected to be connected to C800 class CT.

Comparing against the earlier equation (3), to avoid saturation,

$$100(R_{CT} + 8) > I_f\,(1+X/R)\,(R_{CT}+R_L+R_B) \quad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad (4)$$

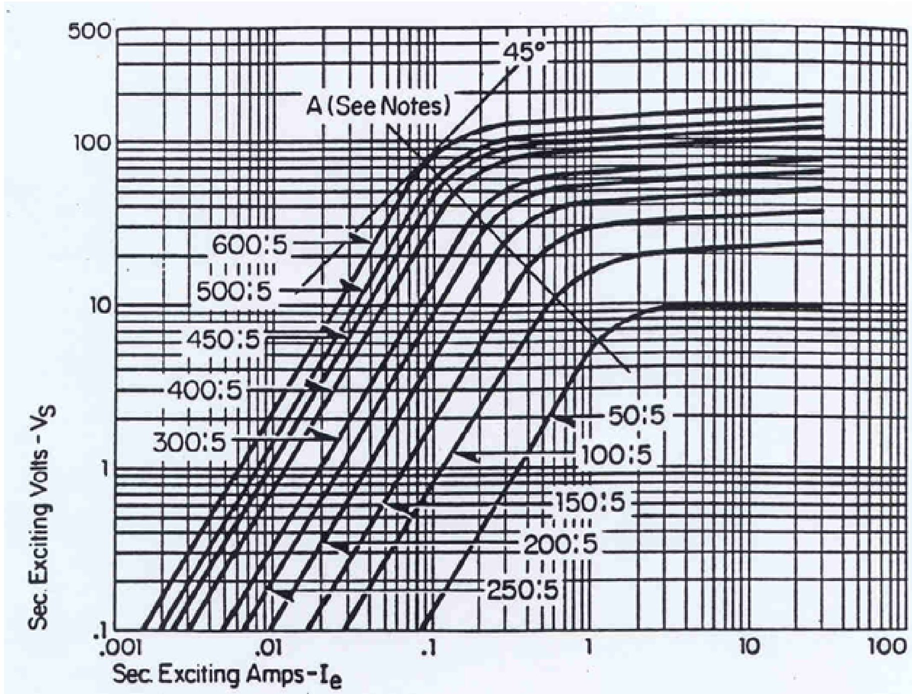
Define $Ni = 100/If$

$$Nr = \{R_{CT} + 8(\text{design burden for C800})\} \,/\, (R_{CT}+R_L+R_B)$$

Substituting in (4) above,

$$(1+X/R) < Ni\ Nr \qquad - \quad - \quad - \quad - \quad - \quad - \quad - \qquad (5)$$

In other words, in order not to have CT saturation, the factor **(1+X/R)** can be accounted for partly by reducing actual secondary current during fault to less than 100A. Sometimes an attempt is made to increase the CT ratio to achieve the above. The factor **Nr** can be manipulated often reducing the secondary connected burden so. The latter is achieved by reducing the connected relay burden (almost zero with the latest numerical relays), reducing the lead resistance (by either reducing the distance between the relay to the CT, multiple parallel runs of CT leads, thicker wire size etc.). Note that increasing the CT ratio increases **Ni** factor but also increases **Nr** factor because of increased CT secondary resistance. The effects may cancel out if the connected lead burden resistances are low compared to the CT secondary resistance. In a few occasions when higher CT ratios are not possible in the main CTs, auxiliary CTs close to the CT location to step down the current flowing through the lead and hence effectively reducing the net lead resistance, as seen by the CTs, have been successfully applied.



Current Ratio	Turn Ratio	Sec. Res. 1
50:5	10:1	.061
100:5	20:1	.082
150:5	30:1	.104
200:5	40:1	.125
250:5	50:1	.146
300:5	60:1	.168
400:5	80:1	.211
450:5	90:1	.230
500:5	100:1	.242
600:5	120:1	.296

Notes:

1) Above The Line, The Voltage for a Given Exciting Current Will Not be Less Than 95% of The Curve Value.

2) Below The Line, The Exciting Current for a Given Voltage Will Not Exceed The Curve Value by More Than 25%.

Figure 7a. Typical ANSI CT secondary exciting characteristics

(Chapter 5, Protective Relaying Theory and Applications, book edited by Walt Elmore, ABB Inc., published by Marcel Dekker Inc)

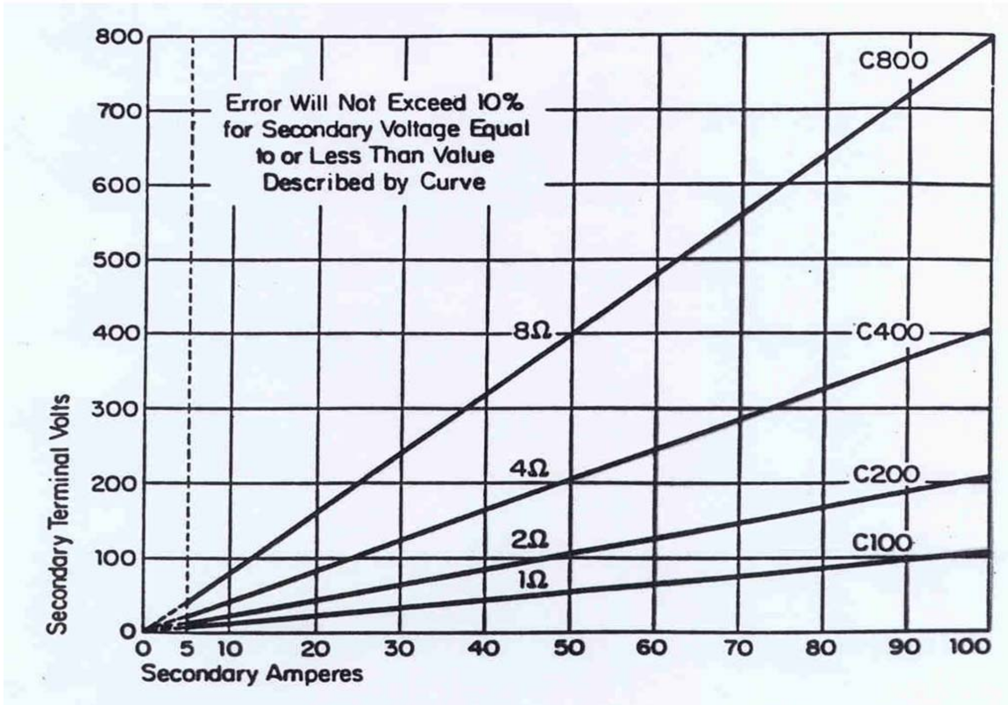


Figure 7b. ANSI CT secondary terminal voltage with rated burdens of 1, 2, 4 and 8Ohms for C100, C200, C400 and C800 CTs

(Chapter 5, Protective Relaying Theory and Application, book edited by Walt Elmore, ABB Inc., published by Marcel Dekker Inc)

Example:

What can be the maximum lead resistance for the application of a distance relay with the following data?

Primary fault current	=10kA (from system study)
System X/R	=15 (from system study)
CT ratio	= 1000/5A
CT rating	=C400 (CT existing)
Design burden	= 4 Ohms (as per standards for C400 CT)
CT resistance	= 0.25 Ohms (Data from manufacturer)
Relay burden	= Negligible (numerical relay)

Calculations:

Secondary fault current

= 10000/ (1000/5)

=50A

Ni = 100/50 =2

Nr = $(R_{CT} +4) / (R_{CT}+R_L+R_B)$

= $(0.25+4) / (0.25+ R_L)$

= $4.25/ (0.25+ R_L)$

Substituting in the inequality (5),

$(1+X/R) < Ni\ Nr$

$(1+15) \quad < 2 \times 4.25 / (0.25+ R_L)$

Solving for R_L,

$R_L \quad < 0.28$ Ohms

In other words the lead resistance shall be kept ***less*** than 0.28 Ohms.

HV systems are designed with high X/R to reduce the losses to the minimum. X/R ratios can be as high as 30 for EHV systems. Apparently where X/R ratios are high, they have to be accounted for by a combination of higher C rating, lower fault current, and lower CT secondary loop resistance.

Residual flux:

An additional dimension to the above issue is the residual magnetizing field (remanence) left over in the CT core on clearance of a fault. When a fault with a heavy DC transient occurs, the flux density may go to a very high level. Once the fault is cleared, due to magnetic retention of the excited material, a certain amount of magnetism is retained. This has been found to be as high as 90% in some of the magnetic material.

In other words, in order to design a CT which will always reproduce the currents accurately, it may be necessary to increase the CT size by a term $\mathbf{(1+X/R)/(1-\psi)}$ where $\boldsymbol{\psi}$ represents the per unit of maximum flux remaining in the CT core after removal of the primary fault current.

For example if the residual flux is 25%, $\psi = 0.25$. So the resultant CT sizing requirement goes up by a factor $\mathbf{1/(1-\psi)} = 1/(1-0.25) = 1.33$. In other words the requirement goes up by 33%. In case the CT retains 90% residual flux, it can be seen that the requirement of the CT size goes up by a factor of 900%.

Caution: The continuity or polarity of a current transformer is tested before putting it into service. DC test current injected into the CT will cause a unidirectional flux build up, sufficient to cause adequate residual magnetic flux that may interfere with relay operation. It is very difficult to get rid of the residual flux once established. Special de-magnetizing procedure is adopted to reduce the remaining flux.

During faults, if the remanence flux direction is opposite to that of the transient DC current, the CT will produce correct secondary waveform. On the contrary, if the remanence flux and the DC transient occur in the same direction, a more distorted waveform than usual occurs.

Various methods are used to reduce the effects of remanence (Std. IEEE C37.110):

a. Using different grades of steel for the core

b. Gapped core

c. Biased core CTs.

Of the three, the second method is widely practiced and is discussed further.

Introduction of air gap will surely increase the magnetizing current, but will reduce remanence. It has been observed that the increase in the magnetizing current is often very small. The cost of such CTs are higher since they call for special construction and tolerance limits of the gap over the lifetime of the CT.

A lot of the installations in the U.S. have non-gapped iron core with high remanence. It might appear that the CTs are likely to saturate whenever fault occurs. However, this is not true for the following reasons:

1. Most of the faults are ground faults which tend to have lesser DC offset and associated saturation issues. The ground faults tend to have more resistance (lower X/R ratio). Ground faults rarely occur with maximum DC offset due to the fact that the onset of a fault is less probable near zero crossing of the voltage waveform. (Note however that in case of faults involving multi-phases, one or the other phase will always have DC offset because of phase angle differences between the phases involved.)

2. The inequality considered earlier assumes no saturation. Modern high-speed relays operate quite fast, often taking an internal trip decision quite earlier than the onset of saturation even after considering remanence.

It is possible to calculate the time to saturate for any CT given the set of saturation voltage, remanence level, details of connected burden etc. Once the time to saturation is known a quick check against the time of operation of the protective relay would indicate whether the application would function properly with respect to the CT characteristics. Special care is needed when high speed autoreclose is concerned since the remanance magnetism and the CT secondary transient effects are the maximum when a reclose is attempted with a permanent fault on the line. Figure 8 provides a graphical representation of time to saturation of a CT. Detailed mathermatical terms to calculate 'time-to-saturate' are available in IEEE C37.110.

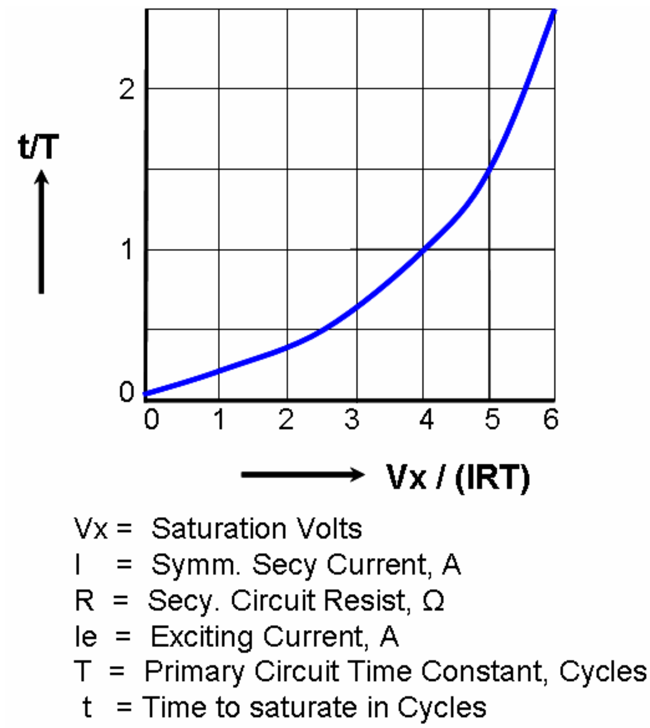


Figure 8. Time to saturate as a function of the saturation voltage and secondary circuit resistance

IEC standards have special classifications for CTs with gaps and specify their performance and remanence limits (IEC-60044-6)

3. CT REQUIREMENTS FOR VARIOUS PROTECTION APPLICATIONS

Once the CT specifications are known, it is necessary to match against the requirements of the protections. The following highlight some of the most often used protections and how CTs are matched for proper performance.

3.1 Time OC protection
TOC protection demands currents up to about 20 to 30 times the set current. The transient saturation is not of concern since the protection operating times are much after the CT comes out of saturation. AC saturation is of concern and CT saturation voltage has to be checked against the voltage generated during maximum fault conditions at which grading with other protections are provided.

3.2 High Set
The operating times of High-set Phase or Ground OC elements are of the order of about a cycle. To ensure high speed of operation, it is essential to check both AC saturation as well as transient saturation of the CT. Where CT saturation cannot be avoided, it is necessary that the highest operates before the CT starts saturating on transients.

3.3 Distance Protection

The lines usually carry higher primary amperes. The ratios are high resulting typically in currents much lower than 100A. Saturation during transient is of major concern. Saturation is accepted after the operation of the Zone-1 operation. Delayed elements of Zone-2 and Zone-3 are given necessary logic circuits to ride through the saturation time of the current transformers before recovery occurs after the DC transients decay or some minor errors in their operating times are tolerated.

3.4 Differential protection

Biased differential protection applications have operating characteristics with pickup increasing with higher through fault currents. This is defined by a slope of the bias characteristics. The higher the slope, the larger is the tolerance of the relay to errors and CT saturation. Some differential protections have multiple slope characteristics. Higher slopes are provided for higher through fault currents to account for possible CT saturation. The disadvantage of higher slope is that the relay might need higher currents for severe in-zone faults. This is overcome in modern numerical relays using special saturation detectors or special through fault detectors. When there is no saturation or when no through fault is detected, a low slope is retained, resulting in very sensitive differential protection. With severe saturation or with through fault detection, the slope gets automatically increased resulting in good stability. Relay designs exist which decide whether the fault is internal or external within a few milliseconds, well before any CT saturation occurs and need very minimum CT voltage. Relay manufacturers can provide reduced requirements of CT with such special logics.

A special case of differential protection is High Impedance scheme, used for Bus bars, generator windings and Y connected or auto transformer windings. CTs of identical ratios with very low leakage reactance and magnetizing currents, exclusively for this use is recommended. Lower magnetizing current is recommended to have as good a sensitivity of protection as possible. The CT knee point voltage rather than the saturation voltage is of concern here. In this scheme CTs on all the incoming and outgoing circuits are paralleled together, the junction point is formed in the switchyard. The idea is to limit the lead resistance ***between the CTs*** to the minimum. A high impedance voltage operated relay is connected across the junction point. The lead resistance from the junction point to the relay is not critical, and in fact, as will see further actually helps in stability of the relay for external faults.

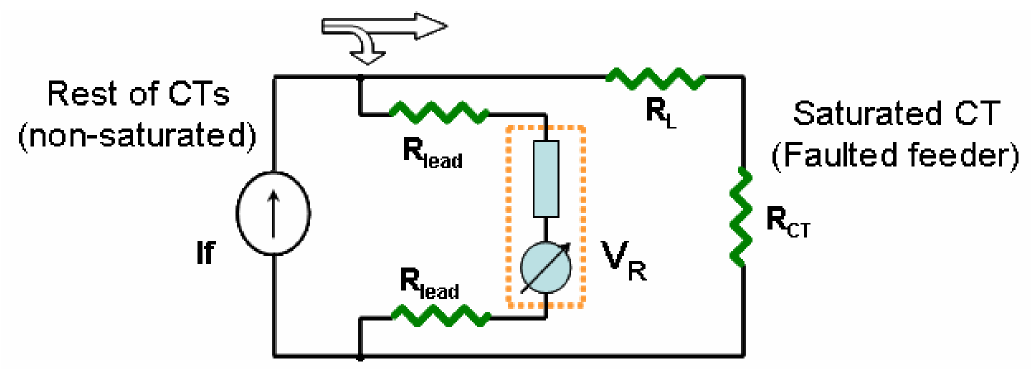


Figure 9. Equivalent circuit of High Impedance Differential Scheme with one of the CTs fully saturated

The relay is set such that,

setting VR $>K \times If \times (R_L + R_{CT})$ (Volts)

If = Secondary Fault current (Amps)

R_L = CT secondary lead resistance (Ohms)

R_{CT} = CT secondary resistance (Ohms)

K = Margin Factor (=1 for full saturation)

Saturation factor

SF $= Vk / If\,(R_L + R_{CT})$

Vk = CT Knee point voltage

Refer to manufacturer guidelines for relationship of SF with respect to K.

During external fault, the CT on the faulted feeder may saturate during DC transients. However since the equivalent circuit of the concerned CT gets reduced to that of just the CT secondary resistance, currents from the other healthy CT get pushed into the saturated CT (rather than the relay path because of relatively higher impedance) so the relay remains stable. The relay pickup voltage is set just above the voltage created across the saturated CT circuit to make it operate. During internal fault, there is a period during each cycle of the power system when all CTs do not saturate and push currents through the high impedance relay to make it operate just about in a cycle. The CT knee point voltage must be high enough to do that. Figure 9 indicates the CT requirements of a high impedance scheme.

4. WIRING SIZING AND OTHER INSTALLATION REQUIREMENTS

Most of the field (cable) wiring sizes are done with 10 AWG for CT. The resistance of #10 lead is easy to remember since it is 1 Ohm (almost) per 1000 feet. The resistance of the other AWG wire numbers can be quickly determined since they follow a logarithmic scale with base 10. In other words the resistance gets doubled with every #3 increase in wire size. In other words #13 has a resistance of about 2 ohm per 1000ft. Similarly a wire of #7 AWG will have a resistance of about 0.5Ohm per 1000ft.

The protection application engineer would often end up with the total resistance allowed for a particular application based on the CT; either existing CT when refurbishing of existing substations are involved or based on the standards the utility is following in procuring the CT. Since the lead resistance is directly proportional to the length a reduction of distance could be attempted. Solutions include providing the relay close to the CT. In case of outdoor sub-stations, a separate relay room close to the relay location could be attempted. The next, often the last, option is to increase the area of the lead to reduce the lead resistance. A reduced #AWG wire gauge or multiple runs of the CT wires is the solution.

General ways to work around the application requirement, to keep thinner CT leads are:

1. Increase the CT tap to a higher value if possible, which results in proportionately higher saturation voltage and lower secondary fault current, giving advantage on either side of the equation. (1A CT secondary is the standard in Europe and other countries.). The resulting increase $\mathbf{R_{CT}}$ could be a disadvantage in some applications.
2. Reduce the distance between relay and CT. In outdoor stations, relays can be located adjacent to the CTs in marshalling box or in small bay buildings depending on ambient conditions.
3. Reduce the connected burdens: If electromechanical relays are in use, reduce the burdens by changing to static or numerical relays.
4. Modern high speed protective relays operated in less than a few cycles, so the CT *may be* allowed to saturate beyond the relay operating time.
5. Work out alternative arrangements of routing of CT leads.

The case study that follows is a typical example of how a reconsideration of the CT routing and formation of junction point could improve the operation of the protection rather than going for extremely larger CT wire sizes.

Other than CT wire sizes, there are other considerations such as polarity etc. Mistakes could happen in installations wherein metering and protection CT cores may get connected to the wrong burdens. In critical installations necessary pre-commissioning checks are done to ensure the correct CT secondary winding with right polarity is applied to appropriate burden. This is done by a combination of polarity checks, primary injection tests, magnetizing characteristics verifications etc. to ensure correct ratio, right type of cores and appropriate CT cores get connected to the right burdens.

5. APPLICATION STUDIES

5.1 Current Transformers in a "breaker-and-a-half" system

In 'breaker-and-a-half' or 'ring-bus' schemes, the line protection is fed by paralleling the current transformers from the breakers serving the feeder. The following describes an incident of a line feeder fed from a breaker-and-a-half bus (Figure 10a). The generation or in-feed from the remote end of the feeder was known to be negligible. However, during a reverse bus bar fault, a few pulses of current were observed which made the distance relay to misoperate (Figure 10b).

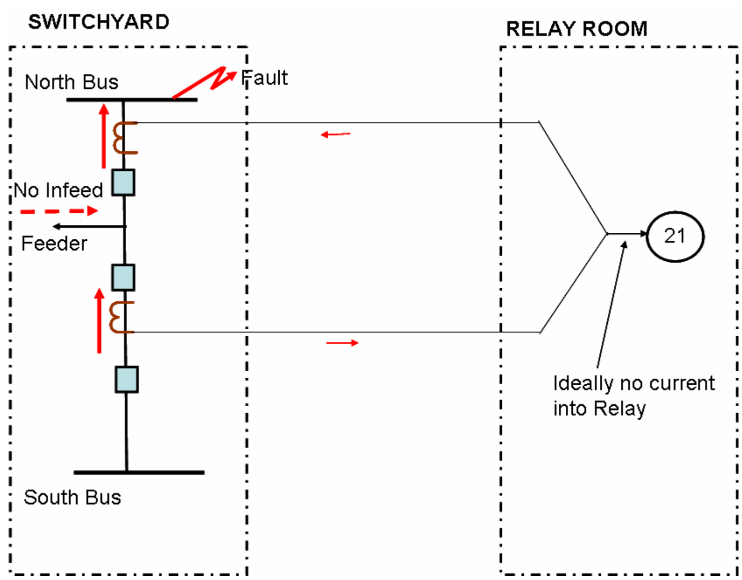


Figure 10a. Application of a distance relay in a 'breaker-and-a-half' system

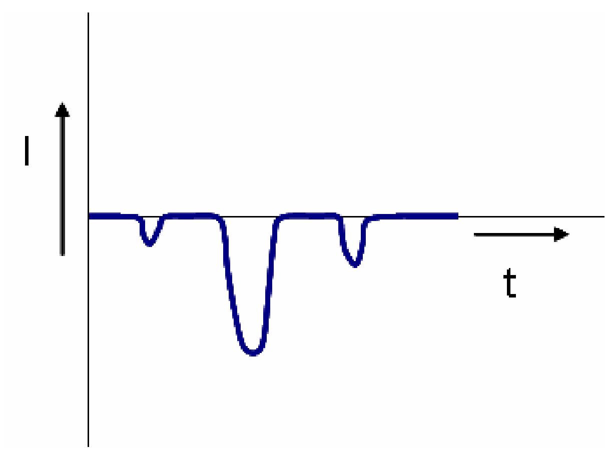


Figure 10b. CT secondary waveform as seen by distance relay in Figure 10a

Since the current transformers that are paralleled should have ideally cancelled out through fault currents, it is obvious that one of the CTs did not behave properly. Apparently, one CT got into saturation, making the other CT spill the currents into the summated path as well as into the saturated CT (Figure 10c).

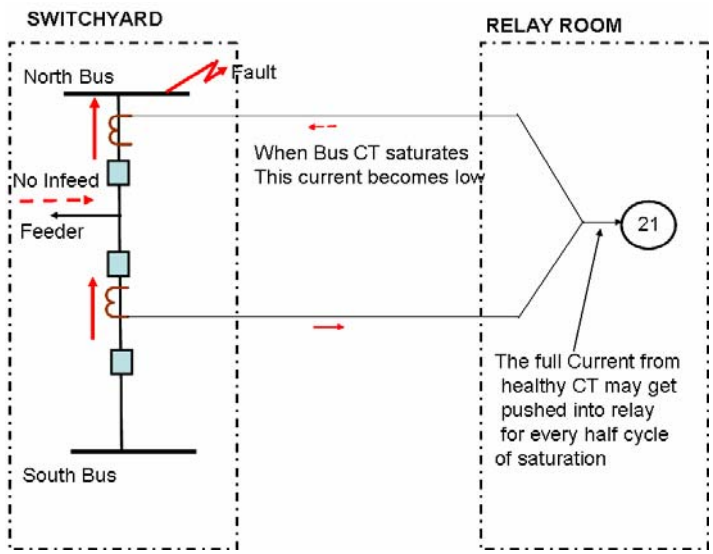


Figure 10c. Flow of CT secondary currents in Figure 10a, when bus side CT saturates

Further study of the system as a whole, including the wiring of the CTs revealed that paralleling of the CTs in the yard would have somewhat mitigated the problem (Figure 10d). This of course always comes with a price. With modern numerical relays with more input information required from each CT (breaker fail protection, breaker monitoring, fault recording etc.), paralleling of CTs in the yard may not always be a viable solution. Other suggestions for implementation included reducing the lead resistance (increasing the CT lead size), biased line differential protection with individual bias for each CT input etc. Special algorithms also have been provided in some relays to detect saturation of CTs and provide corrective solutions.

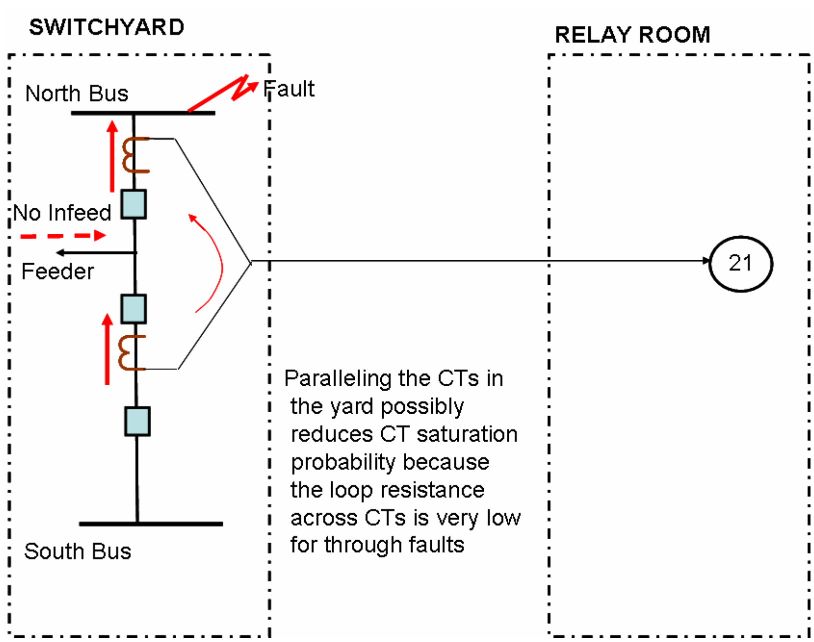


Figure 10d. Suggested CT connection to reduce probability of CT saturation

5.2 Current Transformers saturation with transformer In-Rush current

In another installation, a short feeder ending with a transformer was protected by a differential relay. On charging the line for the first time, the line tripped on differential protection. Further studies revealed that there was a heavy transformer inrush, with a good amount of effective DC primary current, effectively saturating the Current Transformer after a few cycles. This large DC offset coupled with higher lead resistance caused CT saturation, eventually causing misoperation of the protection. Suggested remedies included reducing the CT lead resistances, special 2nd harmonic blocking circuits, interlocking the tripping with a current level.

6. IEC STANDARDS ON CT

It is often required to correlate performance of CTs with respect to IEC specifications. There are various classifications such as Class **P**, **TPS**, **TPX**, **TPY** and **TPY** in IEC

In Class **P** Current transformers, accuracy limit is defined by composite error with steady state symmetrical primary current. This specification is most useful when applying simple time delayed protection. There is no limit specified for residual flux.

Class **TPS** represents low leakage flux current transformer with performance limits specified by excitation characteristics and turns ratio error limits. The IEC specifications of TPS are similar to Class C but not identical. One needs to pay keen attention as to the details of what is specified in terms of peak or rms values or slope of the characteristics as defined in those standards.

Class **TPX** accuracy is defined by peak instantaneous error during specified transient conditions. No limit is specified for remanent flux, indicative of non-gapped CT core.

Class **TPY** has a small air-gap, hence its residual flux is very small, limited to 10%.

Class **TPZ** has an air-gap, not necessarily suitable for all high speed applications. The large air-gap provides a very short secondary time constant with very short DC collapse time, making the CT ideally suitable for breaker failure applications.

7. OPTIC AND OTHER CURRENT TRANSFORMERS

Latest developments offer state of the art technologies in translating the primary current directly into signals compatible with the electronics of protection, control, metering devices with very minimum chances of CT saturation and other issues. IEC61850-9 addresses electronic current and voltage transformers (ECT and EVT) with digital output via merging units for communication with measuring instruments and protective devices. While these would simplify the application of such current transformers for newer installations, it is expected that the large installed base of existing CT technology would require application knowledge of protection technology as it exists today for a long time to come.

8. CONCLUSIONS

In order to properly apply protection and other devices in the sub-stations, a thorough understanding of the application is necessary. Application of CTs and cable and wire sizes based on previous existing practices may take care of most of the applications but do not necessarily guarantee correct application of the devices in all situations. Too big CTs and wire sizes for an application where it is not warranted would mean wasted resources. Standardized CTs, cable and wire size do not always guarantee correct application. A check of the application in detail, especially for critical installations is highly recommended.

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10. BIOGRAPHICAL SKETCH

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