CT Application Guide for the 489 Generator Management Relay

GE Publication No. GET-8402

Introduction

A protection scheme operates reliably only if all scheme elements are properly coordinated. The two most critical elements of any scheme are the protective relay and its signal sources. Many maloperations are the result of the relay not receiving proper signal from the current or voltage transformers. This problem is most frequently encountered with differential protection where the relay is responding to signals from two current transformers at different locations, which often come from different manufacturers.

Relay Characteristics and Settings

The relay's operating characteristics have a large influence on how the CT should be selected for a given application. Some of these are design related, such as the burden, speed, and frequency response. Others are the function of the environment in which the relay is operating: the physical distances of the relays from the CT, the system time constant, and the protection philosophy. These factors are discussed in some detail in the following sections.

BURDEN AND OTHER OPERATING CHARACTERISTICS

Full descriptions of the relay characteristics are found in the 489 manual; only the characteristics that affect the operation of the differential elements are shown here.

- Relay type: 489 Generator Management Relay
- Input impedance (mΩ): 33 + j0 mΩ
- Burden at I = 1 A: 0.033 VA
- Burden at I = 30 A: 24 VA
- 5 A unit input impedance (mΩ): 25 + j0 mΩ
- Minimum operating time at $I < 2\ I_{pu}$: 33 ms
- Detection principle: Fundamental

LEAD RESISTANCE

If the relay is a great distance from the CT that supplies the currents, heavy gauge CT cables must be used to ensure good performance. The diagram below can be used to select wire size if the lengths of the leads are known. Note that the loop length, not the physical distance between the relay and CT, is the important factor.

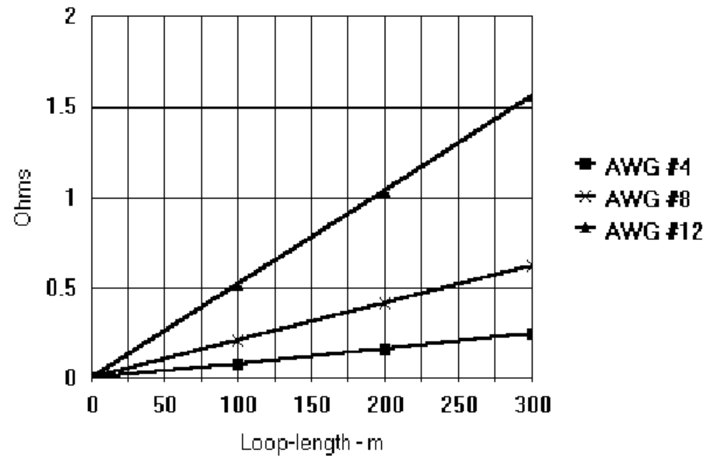


FIGURE 1. Lead resistance vs. conductor length

A handy formula for resistance versus AWG (American Wire Gauge) number is:

$$\text{Ohms / 1000 ft} = e^{0.232 \cdot \text{AWG} - 2.32} \qquad \textbf{(EQ 1)}$$

Many designers consider 1 Ω as an upper limit for lead resistance for 5 A CT circuits. If this yields a wire size too difficult to handle, then running one or more smaller gauge leads in parallel is a good alternative.

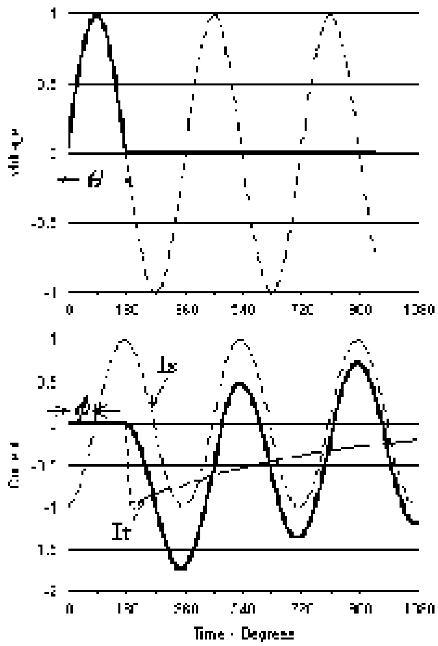
For CT leads, AWG #12 wire is considered to be the minimum acceptable wire size regardless of the distance between the CT and relay.

FAULT LEVELS AND SYSTEM TIME CONSTANT

For differential relay applications the most important fault parameters are:

- The range of internal fault levels the relay should detect
- The maximum external fault level
- The system impedance angle (ϕ) or one of its derivatives: X / R ratio or system time constants (T_S)

The first two requirements are obvious and well understood, but the significance of system impedance angle (ϕ), which controls the duration of the DC transients, may not be immediately apparent. The fault incidence angle (θ) controls the initial magnitude of the DC transients. Figure 2 illustrates a typical DC transient waveform and the mathematical expressions associated with it.



The fault current is a sum of two current components: a steady-state component (Is) and a transient component (It). Expressed in mathematical terms, the current is:

$$I = I_s + I_t$$

$$I_s = \sin(\omega t - \phi) \text{ and } I_t = \sin(\theta - \phi)e^{-t / T_s}$$

where:

$T_s = L / R$
$L = X / \omega$
$\omega = 2\pi f$
X = system reactance
R = system resistance
f = system frequency

FIGURE 2. Offset waveform

The transient term is at maximum when the difference between θ and ϕ is at 90 or 270°. In the example above, ϕ = 84° and θ = 174° to yield maximum negative offset fault. As seen above, the maximum transient develops when the fault occurs at the time the system voltage is near zero. This is why fully offset faults are very rare. Faults tend to occur when the insulation is stressed to its maximum level at the voltage peaks. At that point the transients magnitude is small. The decay rate in the illustration is 24 ms (518°). The transient component is affecting the waveform for about 3 times the value of T_S.

PROTECTION PHILOSOPHY

The most important protection performance parameters – speed, dependability and stability – are interrelated. A more sensitive and faster protection system is more likely to operate when unnecessary. This concept should be kept in mind when selecting protection settings. Setting a relay to be overly fast and sensitive makes it susceptible to false trips.

System conditions dictate what is more important, fast clearance of a fault or security from unnecessary operations. In situations where some important process is affected by a false trip, it may be desirable to set relays to be less sensitive or slower.

Current Transformer Characteristics

In protection and control applications, current transformers (CTs) are used for metering and relaying. In some cases the CT designed for relaying are also used for metering, but metering CTs are not suitable for protective relaying. Metering CTs are designed to operate at or below the rated current (1 or 5 A secondary) while relaying CTs are required to operate with currents well above the rated value. Only relaying performance and requirements are considered in this paper.

The basic principles associated with CTs can be explained with the help of a simplified equivalent circuit as shown below:

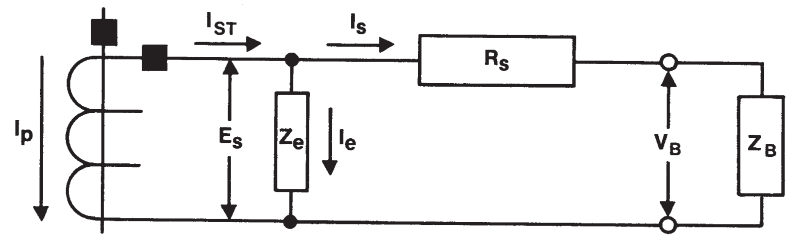


FIGURE 3. Equivalent circuit for current transformers

In this model, the conventional CT symbol is assumed to be an ideal CT where the relationship between the primary (I_p) and secondary current (I_{ST}) is a function of the turns ratio only. The impedance across the secondary terminals is called excitation or magnetizing impedance (Z_e). This is a nonlinear impedance and its magnitude depends on the voltage across it. The relationship between the secondary excitation voltage (E_S) and the excitation current (I_e) is defined by the CT excitation curve, the most important CT characteristic. There is a maximum value of E_S the CT can support as defined by the following expression:

$$E_s = 4.44 f \times A \times N \times B_{max} \quad \textbf{(EQ 2)}$$

where f is the system frequency, A is the cross sectional area of the core in square inches, N is the number of secondary turns, and B_{max} is the maximum flux density of the core in lines per square inch.

The other elements of the model are the secondary winding resistance (R_S) and the burden impedance (Z_b), which includes the input impedance of the relay and associated lead resistance.

This model can be used to assess the steady state performance of a CT.

OPERATION UNDER STEADY-STATE CONDITIONS

Under steady-state conditions, a CT operates its linear or saturated mode depending on the level of core excitation. The excitation curve determines the threshold between the two operating regions. A typical simplified CT excitation curve is shown below:

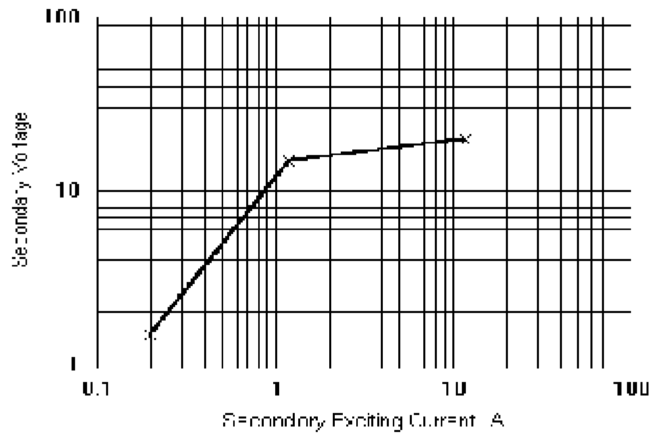


FIGURE 4. Simplified CT excitation curve

This graph was obtained by fitting two straight lines to the excitation curve of a 50-5 A GE Power Management CT (#138-500). Excitation curves must be plotted in log-log scales to obtain straight line graphs since the voltage/current function is in the following form:

$$V_e = K \times I_e^x \qquad \textbf{(EQ 3)}$$

where V_e represents the excitation voltage, I_e the excitation current, and x the slope of the curve. We have $x > 1.0$ in the linear region and $x < 1.0$ in the saturated region. The characteristics of the steel used and the core design determines the exponent x. As seen above, only three points are required to define the curve: the saturation point (V_{sat}, I_{sat}), a point well below the saturation point (V_{e1}, I_{e1}), and a point well above the saturation point (V_{e2}, I_{e2}).

The saturation point is at a voltage 10 to 20% greater than the true knee-point of the curve. The knee-point is defined differently in ANSI standards and the IEC standards, and neither is as easily definable as the saturation voltage. This value was used in Reference 4 for all the CT performance analysis, and will be used here also.

For a given core, the excitation curve can be scaled to any number of turns, so only one excitation curve is needed in a multi-ratio CT or CT supplied on the same core with different turn ratios. It is convenient to define the excitation curves in units of Ampere-Turns (At) and Volts per Turn (V/t); this way CT of different makes and turns ratio can be easily compared. The following table compares the excitation curves of four different CT. The first two are industrial 15 kV class GE Power Management CTs; CTs 3 and 4 are multi-ratio high voltage bushing CT, number 4 with a gapped core.

TABLE 1. TYPICAL EXCITATION CURVE DATA

CT / Curve Data	1	2	3	4
V_{sat} (V/Turn)	1.5	0.73	1.5	3.8
I_{sat} (AmpereTurn)	12	9.2	10	240
I_{e1} (AT at $V_{a1} = V_{sat} / 10$)	1.5	1.6	2.4	24
V_{e2} (V/T at $I_{e2} = 10 I_{sat}$)	2	0.86	1.65	4.2
R_s (mΩ/Turn)	3.3	2	2.5	3.4
x_1 (slope in the linear range)	1.28	1.32	1.61	1.1
x_2 (saturated area slope)	0.13	0.08	0.04	0.1
Core design	Solid	Solid	Solid	Gapped

It is important to remember that manufacturer CT excitation curves are based on calculation and are intended to specify minimum guaranteed performance. Industry standards do not require the curves to be an accurate representation of true measurable values. The ANSI/IEEE requirement is that in the linear part the excitation current should not exceed the calculated value by more than 25%; in the saturated region the voltage should not be less than 95% of the indicated value. There is no limit placed on how better a CT can be from the guaranteed performance. It is important to remember this when using CT of different design for differential relaying applications. In this case good matching of the performance is important, so it may be necessary to actually measure the CT excitation curve.

Test procedures for the measurement of the knee-point are described in the Appendix. This measurement, very simple in principle, can present considerable problems because of the high power requirements in the saturated region.

THE LIMITS FOR LINEAR OPERATION

The linear operating range in terms of current is a function of the burden. If the CT is used only to supply current for a solid-state relay than Z_b can be assumed to be resistive and controlled by the lead resistance. For example, assume that the previously described 50-5 A CT is used with an SR489 relay, then the total secondary burden is:

$$\begin{aligned} Z_s &= R_s + R_{lead} + R_{relay} \\ &= 0.033\ \Omega + 0.500\ \Omega + 0.033\ \Omega = 0.566\ \Omega \end{aligned} \quad \textbf{(EQ 4)}$$

The saturation voltage from the CT excitation curve is 15 V, therefore the maximum current delivered by this CT to this burden without distortion is:

$$I_{rs} = \frac{V_{sat}}{Z_s} = \frac{15\ \text{V}}{0.566\ \Omega} = 26.5\ \text{A} \quad \textbf{(EQ 5)}$$

This is the most important reference current for all CT performance calculations. It is used as a base or reference level for all other current level considerations. Up to this secondary current level the excitation current is negligible, therefore the primary and secondary currents are in phase and their ratio is determined by the turn ratio (N). The limit of linear operation in terms of primary current is therefore:

$$I_{rp} = N \times I_{rs} = 10 \times 26.5\text{ A} = 265\text{ A} \qquad \textbf{(EQ 6)}$$

All relay settings should be below this critical reference level to ensure that the relay will operate correctly. This requirement could be used as one of the limitations on the relay burden.

For example, if the highest current setting (I_{max}) on the above mentioned 489 relay is 60 A (6 A secondary) than the burden limit becomes:

$$Z_b < \frac{V_{sat}}{I_{max}} - R_s = \frac{15\text{ V}}{6\text{ A}} - 0.033\ \Omega = 2.5\ \Omega \qquad \textbf{(EQ 7)}$$

OPERATION IN THE SATURATED REGION

Once the current exceeds the reference level (I_{rs}, calculated in the previous section), the excitation current becomes significant, the waveform becomes distorted and there will be a significant error between the nominal and actual secondary current. Figure 5 illustrates the relationship between primary and secondary currents. The primary current is assumed to be a steady state sinusoidal current and the burden resistive. The previously defined limit of linear operation is used as a base current for the scales. Therefore, 1 pu equals 26.5 A for the previous example. The method of derivation for this curve is described in the References. Figure 6 illustrates the waveform of the secondary current when the primary is 1, 2, and 15 pu.

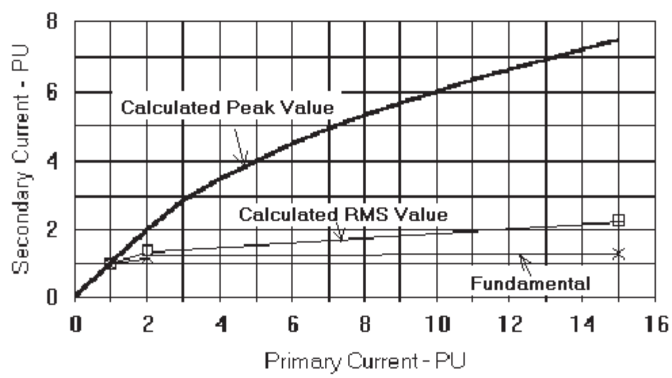


FIGURE 5. Overloaded CT output

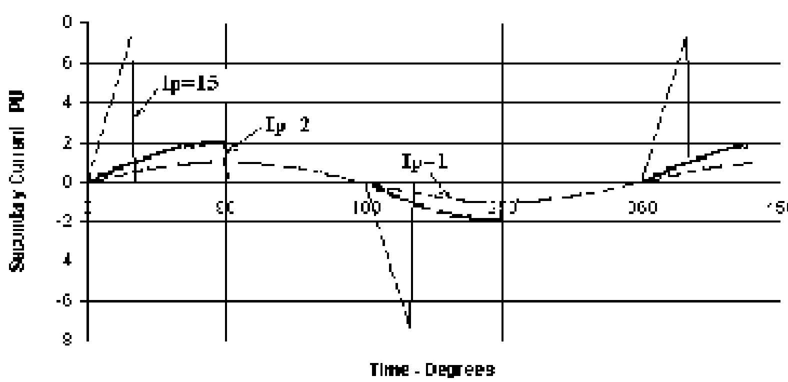


FIGURE 6. Overloaded CT waveforms

It is important to note that in terms of the 60 Hz component, the CT output is practically flat once the overload factor exceeds 2. Therefore the 489, which responds only to the fundamental, will not see currents higher than about twice the limit of linear operation. Other relays which respond to RMS or average or peak may be able to recognize the higher current, but it is not safe to assume operation without an actual test or simulation.

OPERATION WITH DC TRANSIENT

To understand CT response to DC transients, it is necessary to consider flux levels in the core. The mathematical treatment of this question is adequately described in the references; for now it is sufficient to say that the core flux is a function of the integral of the voltage developed across the windings. So if the fault has a DC component it is not symmetrical along the zero line the area under a volt/time curve will not average to zero and the flux requirement will increase.

Figure 7 illustrates how the flux is building up in a CT when the primary current is fully offset and the system time constant is 50 ms (X / R = 19). The dotted lines shows the flux and the secondary current if the CT has the capacity to carry the increased flux requirement. As can be seen in this case the primary waveform is reproduced without distortion.

The solid line shows what happens when the CT saturates when the flux level reaches the flux level corresponding to 5 times the level required under steady state. In this case the secondary current will be distorted. When the flux is not changing no secondary voltage is induced and therefore with a resistive burden the secondary current will be zero.

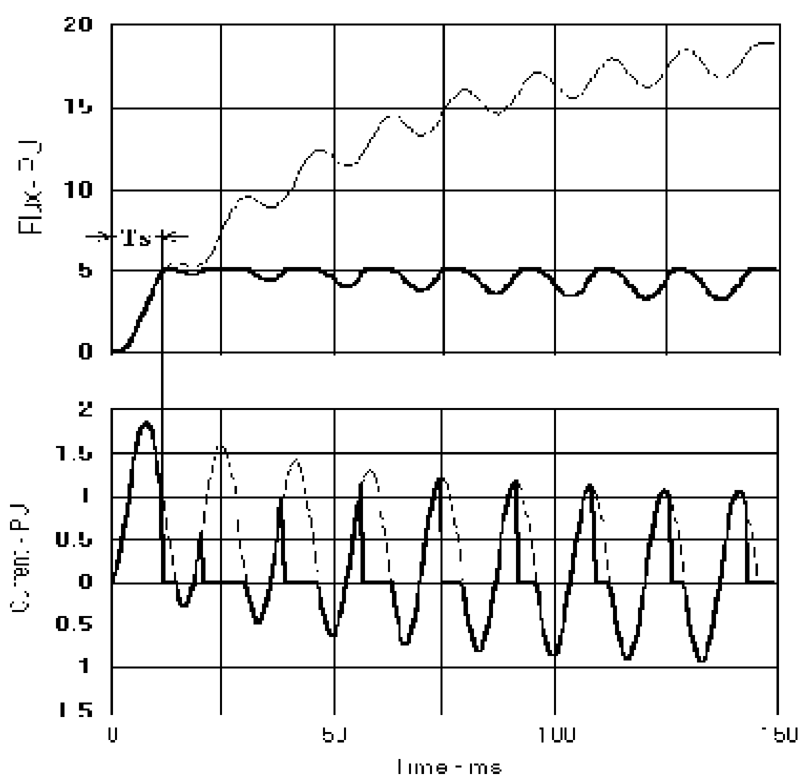


FIGURE 7. Operation with DC transient

It is clear from above that large core over sizing is required to prevent transient distortion. The term Saturation Factor (K_S) is used by the industry to indicate the amount of over sizing available to accommodate DC transients.

$$K_s = \frac{V_{sat}}{V_e} = \frac{V_{sat}}{I_s \times (R_s + Z_b)} \qquad \textbf{(EQ 8)}$$

For distortion free operation K_S should meet the following requirement:

$$K_s \geq \left(1 + \frac{X}{R}\right) \qquad \textbf{(EQ 9)}$$

If this condition is not met, then at some point in time saturation will start. The time duration before saturation begins is called the Time-to-Saturate (T_S):

$$T_s = \frac{-(X/R)}{2\pi f} \times \ln\left(1 - \frac{K_s - 1}{X/R}\right) \qquad \textbf{(EQ 10)}$$

For a system frequency of 60 Hz, substituting X / R = 19 and K_S = 5 in Equation 10 yields T_S = 11 ms. This is in agreement with the value that can be observed in Figure 7. Note that the calculation assumes that the core flux starts to build up from zero. However, this hardly ever occurs in practice.

As can be seen from Figure 7, the flux level in a core does not come down to zero as the dc component dies out. The steady-state flux variations will not reduce the flux to zero, therefore if another fault occurs, the flux excursion will start at the residual flux (B_r) from the last fault.

Figure 8 illustrates how the residual flux effects T_S. The error currents are plotted as a function of time (the error current is the missing portion of the distorted current waveform plotted in Figure 7). The dotted error curve shows that saturation occurs in 7 ms if a 60% residual magnetism is in the direction of flux created by the transient, and in 26 ms (solid line) if the residual is in opposite polarity. The calculated T_S = 11 ms should therefore be considered as a nominal value, unless the CTs are demagnetized after each offset fault or the CT is of the Low Remanence Type.

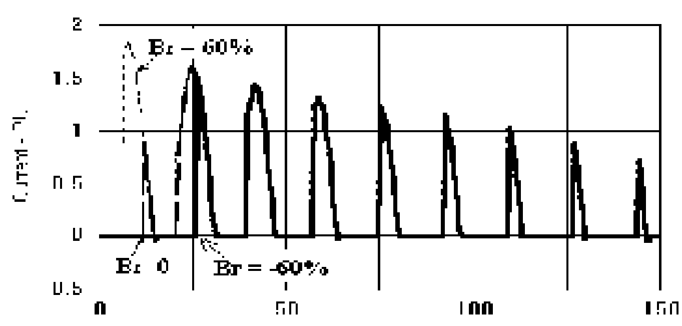


FIGURE 8. Effect of residual magnetism on the transient error current

CONTROL OF RESIDUAL MAGNETISM

Residual magnetism, or remanence, has a large impact on transient performance. The cause of the problem is that all magnetic materials display some degree of hysteresis. The manifestation of this is that as flux in the core is not reduced to zero when the excitation stops, a portion of the flux remains in the core as residual magnetism. This can be seen from the core's hysteresis curves. The diagram below shows the hysteresis curve of a GE Power Management CT.

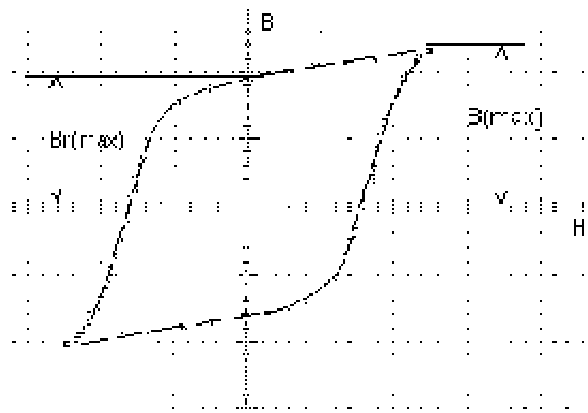


FIGURE 9. Typical CT hysteresis curve

The maximum residual flux density B_r (max) is usually expressed in terms of percentage of the saturation flux density B (max) and called the Remanence Factor (K_r).

From the measurement result shown above the Remanence Factor of this particular GE Power Management CT is 80% (900 / 11.3). This is a typical value of current transformers with wound toroid core. This means that under the worst case condition only 20% of nominal flux range is available to produce an output at the start of a fault. This introduces a large degree of uncertainty of the performance of high speed relaying.

To eliminate the risk of slower than expected operation or false tripping, manufacturers developed the so-called Low Remanence CT. The hysteresis curve of these CT are elongated such that the value of B_r (max) is kept below 10%. This is achieved by placing a small air-gap in the core; hence they are also referred to as Gapped Core CT.

Gapped Core CT are more expensive and they have higher magnetizing current in their linear operating range (lower accuracy) hence they are only used where the system X / R ratio is high and fast, stable relay operation is critical for system security. In applications where the CT transient factor is low (less than 4) remanence is of lesser importance. In this case T_s is short and the effects of remanence are less significant.

The applications of Low Remanence CTs are also complicated by the fact that the ANSI/IEEE standards do not have a classification for them, so purchasing them can involve complicated negotiations with the manufacturer.

CURRENT TRANSFORMER STANDARDS

Current transformer standards are designed to simplify CT purchasing by eliminating the need to provide a complicated description of the requirements by simply selecting from a range of available classes and rating. There are two major standard organizations that issue CT standards for relaying:

- ANSI/IEEE: the dominant standard for North American manufacturers
- IEC: the dominant European standard

ANSI/IEEE C57.13 recognizes three classes of CT for relaying purposes, but only the low leakage type "C" is used in large numbers by the industry. The class was named “C” because its excitation curves can be prepared by *calculation*. The standard details many physical and electrical characteristics of this CT type, but it is vague in terms of characteristics discussed in this report. The "C" classification only guaranties that the CT can deliver, with less than 10% accuracy at 20 times rated current, into one of 7 standard burden values: 0.1, 0.2, 0.5, 1, 2, 4, and 8 ohms. The first three are metering burdens with 0.9 Power Factor, the others are relaying burdens with a Power Factor of 0.5. The code for this accuracy classification is the letter C followed by the voltage across the burden at the specified burden. For example if a 5 A CT is purchased for 0.2 Ω burden, then the accuracy classification would be C20 (100 A develops 20 V across 0.2 Ω). The standard also specifies that the manufacturer must supply typical excitation curves and give the secondary winding resistance.

The weakness of this classification is that the tolerances for the excitation curves are very wide, and the remanence factor is not part of the specification. Therefore, matching CTs manufactured to the same standard by different manufacturers is difficult. An attempt was made to tighten the tolerances by introducing the "K" classification, which places a limit on the knee-point voltage with respect to secondary terminal voltage rating, but not many manufacturers offer such CTs as standard product.

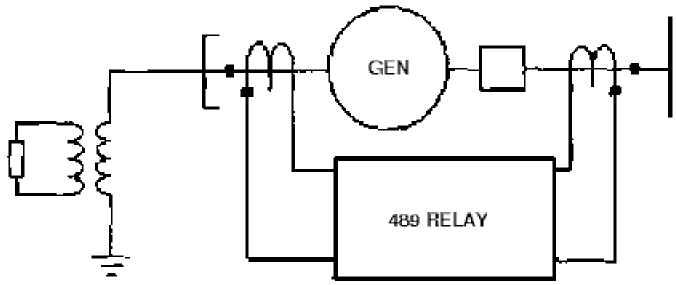
The IEC 60044-6 standard has five classes for relaying CTs and a much wider range of options for specifying accuracy requirements. The important difference between the ANSI and IEC standards is that IEC has two classes of CTs where the residual magnetism is limited. The TPY transformers have a limit of 10% on remanence, while in the TPZ class transformers the remanent flux is practically negligible.

CT Requirements for Differential Protection

The 489 has two current inputs. The relay operates when the following trip condition is met:

$$I_1 - I_2 \geq k \times \frac{|I_1| + |I_2|}{2} \qquad \textbf{(EQ 11)}$$

This shows that protection will require higher differences between the inputs for operation as the absolute value of the input current increases. The 489 Generator Protection Relay is designed for this type application. Its connection is illustrated below:



The following are typical settings used for differential protections:

- Pickup: 20% of the rated current of the protected unit
- Slope 1: 10%
- Slope 2: 20%
- Delay: 0 cycles

The pickup setting should be chosen to operate for the minimum expected internal fault. Note that for high impedance grounded generators a ground fault near generator neutral results in very low currents (1 to 10 A primary). The differential element is not expected to operate for these faults.

The basic CT requirements are common for all differential relays and are listed below:

- The primary current rating should be between 120 to 150% of the continuous current rating of the protected apparatus
- All CTs should be of the same ratio, except in transformer protection where the ratio should compensate for the ratio of the protected transformer
- All CTs should have similar transient performance

This last requirement is critical – more important than the actual accuracy classification. To obtain identical transient performance, the characteristics and the burden of each CT circuit should be the same. Unfortunately it is difficult to satisfy this requirement in some installations. The distance between the CTs and relay may be different from the neutral and the bus side, or the CTs are different because they are from a different manufacturer. In this situation some discrepancy between the circuits is inevitable. The circuit with the smaller transient factor saturates sooner; consequently, during external faults with substantial DC components, the relay will see a different current and trip.

This raises the question: how much discrepancy can be safely tolerated before the risk of false trips becomes unacceptably high? To answer this question, it is necessary to develop a measure of the discrepancy. It is recommended that the difference between the time-to-saturations (*dT*) be used for this purpose. Equation 10 shows how to calculate the time-to-saturation. With this equation it is easy to set up a spreadsheet program for the calculation of *dT*s. With the help of such a program, it is easy test the effects of all the critical parameters involved. The table below demonstrates the results of using of such a spreadsheet program:

TABLE 2. SAMPLE CT MISMATCH COMPUTATIONS

Neutral CT circuit							Terminal CT circuit				
f	X / R	I_f	V_{sat}	R_b	K_s	T_s	V_{sat}	R_b	K_s	T_s	dT
60 Hz	100	30 A	340 V	8.43 Ω	1.34	0.9151 ms	200 V	1.43 Ω	4.66	9.90 ms	8.98 ms
60 Hz	100	20 A	340 V	8.43 Ω	2.02	2.7104 ms	200 V	1.43 Ω	6.99	16.39 ms	13.68 ms
60 Hz	100	10 A	340 V	8.43 Ω	4.03	8.1704 ms	200 V	1.43 Ω	13.99	36.90 ms	28.73 ms
Balancing by reducing the neutral side burden											
60 Hz	100	20 A	340 V	2.73 Ω	6.23	14.241 ms	200 V	1.43 Ω	6.99	16.39 ms	2.15 ms
60 Hz	100	10 A	340 V	2.73 Ω	12.45	32.269 ms	200 V	1.43 Ω	13.99	36.90 ms	4.63 ms
Balancing by increasing the terminal side burden											
60 Hz	100	20 A	340 V	8.43 Ω	2.02	2.7104 ms	200 V	3.43 Ω	2.92	5.13 ms	2.42 ms
60 Hz	100	10 A	340 V	8.43 Ω	4.03	8.1704 ms	200 V	3.43 Ω	5.83	13.13 ms	4.96 ms

The first three rows in the table represents the conditions reported by one customer. It shows how the through fault current magnitude affects the dTs. As can be seen, at lower current levels the discrepancy is more severe. This shows that when checking for maximum difference the critical current level is the lowest current, which can produce errors sufficiently large to cause false trips.

The second set of calculations (rows 4 and 5) show the improvement achieved by reducing the burden from the unreasonable high value of 8.43 Ω to 2.73 Ω. This is considered the maximum acceptable value for this installation. For perfect balance, the required value is 2.4 Ω. The lower burden is also beneficial in case of internal fault by ensuring faster operation.

The third set of calculations (rows 6 and 7) shows that similar balance is obtained by increasing the burden of the terminal CT by inserting a 2 Ω resistor. This method is probably easier to implement but undesirable for several reasons. The circuit's time-to-saturation becomes very short with high fault currents, so the relay may not operate as fast as expected on internal faults. Also the resistor in the current circuit reduces the reliability of the scheme. A failure of this resistor can cause serious damage.

Appendix

A1 CURRENT TRANSFORMER TESTS

Before any test on a CT, first the CT should be demagnetized. ANSI C57.13.1 Standard lists several methods. All involves driving the CT into saturation one way or another and than slowly reducing the magnetizing force to zero.

EXCITATION CURVE

Excitation curves are usually measured by connecting a voltage source to the secondary winding while the primary is open-circuited. The applied voltage is gradually increased until the excitation current reaches the accuracy class rated value (10 A for 5 A CT). The voltage waveform during the test should remain sinusoidal, while the current becomes increasingly distorted. This is only possible if the voltage source is capable to supply the very high peak power is required to measure the saturated part of the excitation curve.

For example, a 200-5 A CT with ANSI accuracy class of C20 is expected to draw 10 A rms during this test at 40 V. At this level, the current is heavily distorted and its peak to rms ratio (crest factor) will be in the order of 2.5. This means the test source should be capable of supplying a peak power of:

$$\text{Power} = 1.4 \times 40\ \text{V} \times 2.5 \times 10\ \text{A} = 1400\ \text{VA} \qquad \textbf{(EQ 12)}$$

An alternative to this method is to use a current source. In this case the current is applied to a test winding which gives a convenient range of currents for the tests. For example, to measure the excitation curve of a small CT, rated 1 to 0.001 A, it is better to apply the current to the primary winding and measure the voltage at the secondary. This way both the currents and voltages are in a convenient range. The results should be plotted in diagram with logarithmic scale of equal cycle length on the horizontal and vertical scales. The measured current should be scaled to the secondary winding by dividing the measured value with the turn ratio.

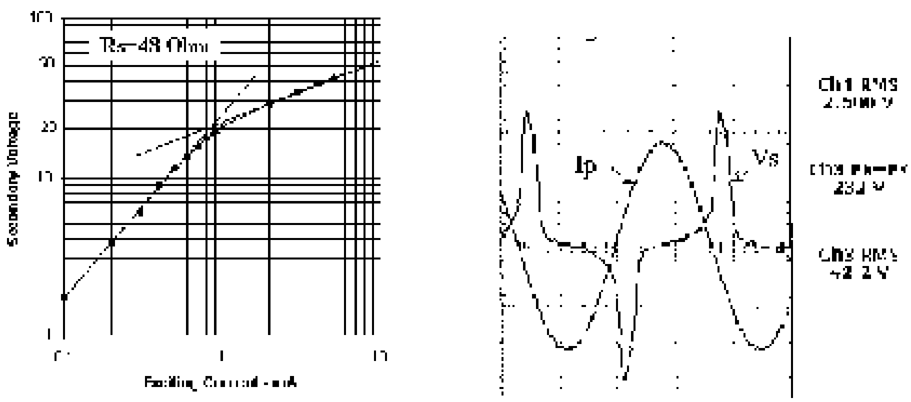


FIGURE 10. Excitation curve test result and waveforms

The measurement points should define two straight lines as shown above. The intersection of these lines defines the Saturation Voltage, one of the key CT parameters, which 20 V in this particular case. The other key CT item, the secondary winding resistance, should also be shown with the excitation curve. The secondary resistance is measured with a DC source.

REMANENCE FACTOR

There are several methods to measure the remanence factor of a current transformer (IEC Standard 60044 defines two: an AC and a DC method) The AC method is the easiest, but again the power requirement could be a problem. The CT must be driven to full saturation during the test and this as may require a test source capable of delivering several kVA. The test can be conducted at lower frequencies at much lower power level since the flux is directly proportional to the applied frequency. The method illustrated in Figure 11 was used to obtain the hysteresis curve shown in Figure 9. The operational amplifier with the capacitor in the feedback loop act like an integrator.

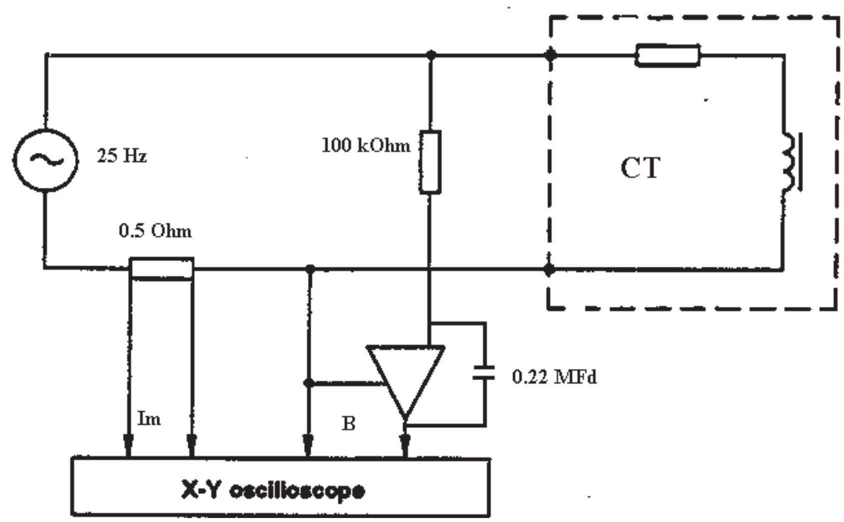


FIGURE 11. **Remanence factor test arrangement**

References

STANDARDS AND GUIDES

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