Secure Application of Transformer Differential Relays for Bus Protection

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Abstract—**The greatest challenge of bus differential protection is dealing with false differential current due to current transformer (CT) saturation. Percentage-restrained differential relays are often applied for bus differential protection applications. The percentage restraint principle provides security by requiring that the differential current exceed some percentage of the current flowing through the zone. There are few application guidelines for choosing a secure slope setting when applying this type of relay for bus protection. This paper reviews basic concepts of differential relays and CTs and then describes a study that was performed to determine secure settings for a relay in a specific bus protection application. Results of the study and recommendations are included. Additional simulations were run to develop a general application guideline for selecting a secure dual-slope setting.**

I. INTRODUCTION

In applying a percentage-restrained differential relay to a bus protection application, we must select a slope setting that will be secure (not false trip) for faults outside of the zone of differential. The primary difficulty is preventing a trip caused by false differential current due to current transformer (CT) saturation. The percentage restraint principle provides security by requiring that the differential current exceed some percentage of a measure of the current flowing through the zone before the relay may operate. Thus, for situations where the through current is high, the differential current must also be high to cause a trip.

There are few application guidelines for choosing a secure slope setting when applying this type of relay for bus protection. Reference [1] provides an empirical formula for selecting a secure slope setting based upon fault current levels, system X/R ratio, and CT secondary burden. This guideline was used to evaluate an existing percentage-restrained bus differential relay installation prior to the addition of cogeneration to the system. The result raised concern that the differential relay installed may be marginal in this application and that further study was required. This paper describes the study that was conducted to examine the application in more detail. This specific application study led to a follow-up effort to run a more generalized series of simulations to develop a general application guideline for selecting a secure dual-slope setting where a single-slope characteristic is not adequate. Before describing the study, we will review the principles of differential relaying and the causes of its most difficult challenge—CT saturation.

II. REVIEW OF BASIC PRINCIPLES

Before we discuss the application study, we need to understand how differential relays work and what the application considerations are in using them for bus differential protection. We also need to understand how CTs work and what causes CT saturation. After we have reviewed these two basic topics, we will review some application considerations of using percentage-restrained differential relays on bus applications.

A. Differential Protection Basics

Let us first discuss differential relays in general and then specifically percentage-restrained differential relays.

1) Differential Relays

Any relay that has information on the sum of all currents entering and exiting the zone of protection and operates on the difference in these currents falls under the category of "differential" relaying. There are three general categories of differential relays used in bus applications:

- Differentially connected overcurrent (instantaneous or inverse time)
- Percentage-restrained differential
- High-impedance differential

In deciding what type of protection system to apply for a specific application, protection engineers consider cost, complexity, reliability, and performance. The performance attributes they evaluate are selectivity, sensitivity, and speed.

Differential protection is often applied on bus protection for its high selectivity. All current into and out of a zone of protection is measured. The zone of protection is precisely determined by the location of the current transformers that define the differential zone. With high selectivity, a differential relay does not need to have any intentional time delay to coordinate with relays in adjacent zones. Thus, differential protection can provide relatively high speed. As mentioned above, there are a number of different types of differential relays. Each has different levels of performance with regard to ultimate speed, selectivity, and sensitivity.

The other great attribute of differential relays is high sensitivity. The relay operates on the difference current instead of the through current in the system. Thus, it can have much greater sensitivity than an overcurrent or distance relay that must be set above the load flow through the protected zone. However, for a bus protection application, high sensitivity is generally not particularly critical. A bus fault typically has

relatively high fault current levels. The exception to this is on a high-impedance grounded system where the single line to ground (SLG) fault current levels may be very low.

2) Percentage-Restrained Differential Relays

The percentage-restrained characteristic operates on the ratio of:

- Operate current—also called the differential current. It is the phasor sum of the currents flowing into the zone of protection. Under normal conditions, the currents should sum to zero.
- Restraint current—for purposes of keeping the relay secure from operation on an external fault, it is helpful to think of this as the through current. That is, the restraint current is some measure of the current flowing through the zone of protection. This provides the desirable feature of restraining the relay when high levels of current are flowing through the zone. When high currents are present, it is more likely that a CT can saturate and cause false differential current. There are several common ways of quantifying the restraint (through) current, which will be described in a moment.

The ratio of operate to restraint current is referred to as the slope, which is often expressed in percent. When the operate current divided by the restraint current exceeds the slope, the relay operates. The requirement that the operate current exceed a percentage of the restraint current allows the relay to tolerate low levels of mismatch in the current measurement at each boundary of the zone of protection. This same characteristic also enables the relay to tolerate false differential current caused by CT saturation. Most percentage-restrained differential relays also include the ability to compensate for steady-state current measurement differences to make the mismatch as small as possible.

The percentage of operate to restraint is dependent upon the principle by which the restraint current is quantified. There are three common methods for determining the restraint current:

- Summation—relays using summation restraint have the polarities of each current input arranged such that they tend to be additive for external faults and subtractive for internal faults. Considering a simple two-restraint circuit with equal sources on each circuit, an external fault will have restraint that is two times the current measured by each input of the relay. For an internal fault, the two currents will cancel, resulting in restraint that is zero times the current measured by the relay.
- Average—relays using average restraint measure the magnitudes of the current in each current input and take the average. That is, the sum of the magnitude of the individual currents divided by the number of input circuits (or sometimes divided by two). Considering a simple two-restraint circuit with equal sources on each circuit, an external fault will have restraint that is half the sum of the currents measured by each input of the

relay. For an internal fault, the restraint will also be half the sum of the currents measured by the relay.

- Maximum—relays using maximum restraint measure the magnitudes of the current in each input and take the largest of these as the restraint quantity. Considering a simple two-restraint circuit with equal sources on each circuit, an external fault will have restraint that is one times the current measured by each input of the relay. For an internal fault, the restraint will also be one times the maximum current measured by the relay.

In this application, the relay under study operates on the "average" restraint principle. The restraint is the sum of the magnitude of the currents into and out of the zone of protection divided by two.

This ability to tolerate mismatch in the current measurement makes this type of relay desirable for applications where there is a power transformer in the zone with a turns ratio that cannot be perfectly matched by available CT ratios. In a bus differential application, mismatch is not as common, but the relay's ability to compensate for differing CT ratios makes it desirable where this is an issue.

Percentage-restraint characteristics can be classified as two types:

- Straight percentage
- Variable percentage

The solid line in Fig. 1 shows a straight percentage-restraint characteristic set at 50%. For this type of relay, the slope has to be set to accommodate both mismatch current and CT saturation. The minimum pickup line provides a cutoff of the characteristic at low levels where accuracy errors would result in poor ratio measurements.

A variable percentage restraint characteristic typically requires a lower percentage of differential current at low restraint current levels for more sensitivity to low-level faults and a higher percentage of differential current at high restraint current levels where CT saturation can become a problem. This is especially desirable for transformer protection where low-level faults are more common.

The dotted line in Fig. 1 shows a dual-slope characteristic that provides this variable percentage restraint characteristic. It starts out as a straight percentage restraint up to a point of inflection where it goes to a higher slope. The second slope crosses the y-axis in the negative region. Thus, as the restraint current increases, the percentage of differential current required to cause a trip increases. This example has the first slope set at 30% and the second slope set at 60%.
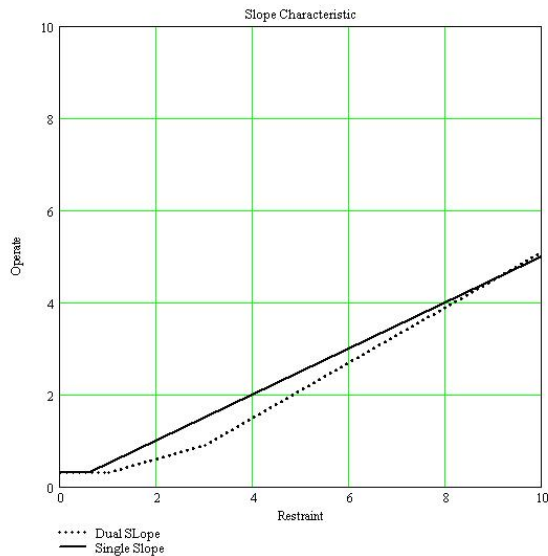
Fig. 1. Single- and Dual-Slope Differential Characteristics

The magnetic core material has a characteristic that is described by the familiar B-H curve. The "S" shaped characteristic in Fig. 2, a reproduction of Fig. 9 in Reference [2], is an example of a typical B-H curve. The x-axis is H, which is the magnetic field intensity. This is measured in Oersteds in cgs units or in Ampere-Turns/Meter (A/m) in SI units. The y-axis is B, which is the magnetic flux density. This is measured in Gauss in cgs units or Tesla in SI units. The magnetic flux density, B, has a nonlinear relationship to the magnetic field intensity, H. Examination of Fig. 2 reveals that as the magnetic field intensity, H, increases, it reaches a point where the magnetic flux density, B, levels off because nearly all of the magnetic domains in the core material have become aligned with the magnetic field. Where B levels off is known as B_{max}. This is where the magnetic core material is said to be saturated. The B-H curve can be converted to a similar-looking magnetic flux, Φ, versus excitation current, I_E, curve. The Y-axis, Φ, is given by B times A (the area of the magnetic material). The X-axis, I_E, is proportional to H.

For a relay using average restraint, a single-slope characteristic set at or below 100% is acceptable for most bus applications where sensitivity to low-level faults is not a concern. CT saturation is generally the only concern. Table 1 shows the operating condition for internal and external faults, with and without CT saturation.

TABLE 1
DIFFERENTIAL CASES

	Internal Fault	External Fault
Without CT Saturation	200% Slope Line	Along the Restraint Axis
With CT Saturation	200% Slope Line	Above the Restraint Axis

For an internal fault without CT saturation, the operating point will fall near the 200% ratio line. For an external fault without CT saturation, the operate current should be zero, and the operating point will fall near the horizontal restraint axis of the characteristic.

For an internal fault with CT saturation, the operating point will still fall near the 200% ratio line of the characteristic. For an external fault with CT saturation, the operate current will not be zero, and the operating point will fall above the restraint axis of the characteristic. If the operate current due to CT saturation exceeds the slope characteristic, the relay will misoperate.

B. Current Transformer Basics

The following is a brief description of the causes of CT saturation. Reference [2] provides a thorough treatment of the subject and is recommended reading for those wanting to learn more.

A transformer consists of at least two windings on an iron core. Under normal operation, changing current flowing in the windings creates changing magnetic flux. The iron core couples the magnetic flux equally to the windings such that the ampere-turns (proportional to the magnetic flux) balance. The volts per turn also balance between the two windings.
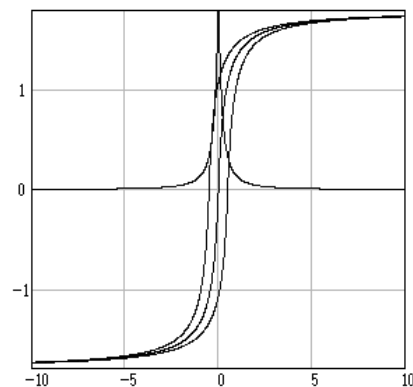

Fig. 2. B-H Loop and the Slope of the Mean Curve

When the core becomes saturated, the magnetic flux, Φ, ceases to change with the current flowing in the primary winding of the transformer. The secondary current drops rapidly to zero until the next primary current zero crossing when the primary current flow adds flux of opposite polarity to the core. Once the flux starts changing again, transformer action (induction) resumes. The heavy solid line in Fig. 3 shows an example of the secondary current in a saturated CT. During this time, the current is no longer a turns-ratio multiple of the primary current. Another way of looking at this situation is to say that the primary current is going to excite the magnetic material instead of being transformed to the secondary of the transformer. Note that in the Φ-I_E curve described above, when Φ stops changing, I_E increases rapidly. Notice that the CT comes out of saturation when the dc transient in the current dissipates.

During the half cycle that the current is positive, the magnetic flux in the iron core accumulates in the positive direction and during the half cycle that the current is negative, the flux accumulates in the negative direction. Reference [2] develops the relationship between the burden voltage (secondary current times the burden ohms) and the level of flux in the core. The instantaneous flux density level can be determined by integrat-

ing the area under the secondary voltage curve. The following summarizes the relationships: the higher the current or the higher the burden, the higher the flux density. The higher the instantaneous flux density, the more likely it is that the core will become saturated.

With this background established, we can see that the primary cause of CT saturation is the dc transient associated with a rapid change in current such as might occur when the power system experiences a fault. With an asymmetrical current, the flux will tend to accumulate in one direction because the negative current excursions are smaller than the positive current excursions (or vice versa). The thin line in Fig. 3 shows how the flux accumulates in a saturated CT. Notice that where the change in flux is zero, the induced secondary current is also zero.
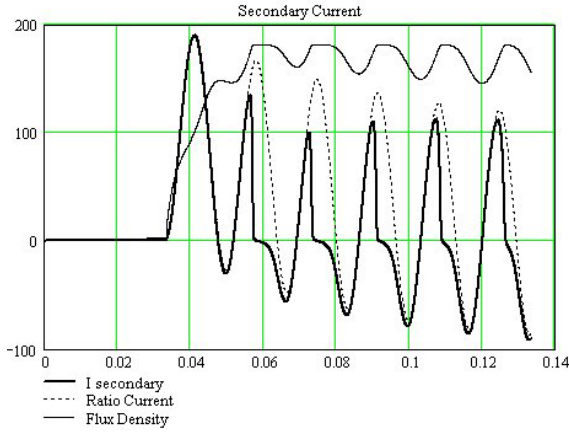

Fig. 3. CT Current and Flux Density for Saturated CT

1) Checking Current Transformer Suitability

Reference [3] includes a formula for determining if a CT has the possibility of going into saturation. This equation applies to ANSI Relay Class CTs.

$$20 \geq V_S = \left(\frac{X}{R}+1\right) \bullet I_f \bullet Z_b \tag{1}$$

Where:

I_f is the maximum fault current in per unit of CT rating.

Z_b is the CT secondary circuit burden in per unit of standard burden.

X/R is the X/R ratio of the primary fault current.

V_S is the per-unit saturation voltage.

This equation states:

- If the per-unit saturation voltage is greater than or equal to 20, the CT can saturate.
- If the per-unit saturation voltage is less than 20, it will not saturate.

For these statements to be true, there must be zero flux remnance in the core. For any particular in-service CT, this will never be the case. Let us examine the equation in more detail so that we can better understand its practical application.

- The equation assumes the worst-case scenario of a completely offset waveform. The actual offset of the

current for a particular fault is a function of the fault incidence angle and the system X/R ratio. A fault incidence angle that results in less dc offset will result in less likelihood of saturation.

- The *X/R* ratio of the system determines the time constant for the decay of the dc transient. The longer the time constant, the longer the current excursions are more positive than negative (or vice versa), resulting in a greater accumulation of flux.
- The standard burden for a particular CT class does not include internal CT winding resistance. The calculation of Z_b can be refined to include the internal resistance of the CT secondary.
- If the whole winding of the CT is not used, the standard burden is multiplied by the tapped ratio divided by the full ratio.
- $I_f \bullet Z_b$ represents the per-unit voltage around the CT circuit secondary loop. It is important to understand how the current flows in the CT secondary loop based upon the fault type (SLG, 3Ph, etc.). In some cases, a three-phase fault may be the worst case. In others, an SLG fault may be the worst case.
- Reference [1] indicates that you can accommodate remnance by derating the CT, effectively reducing the cross-sectional area of the iron. This method will correctly determine if the CT will saturate during the first half cycle of fault current, but is too conservative to be used in a model that calculates CT performance over time.

2) Calculating V_S

Z_b in Equation (1) is the CT burden in per unit, which is given in Equation (2). The base of the per-unit calculation is the standard burden for the CT class.

$$Z_b = \frac{Z_{BURDEN}}{Z_{ADJ\_STD}} \tag{2}$$

Since Reference [3] was published, refinements have been developed to better address how the CT internal resistance should be treated in the burden impedance calculation. The ANSI C class rating is based upon the voltage that the relay can develop at its terminals with 20 times nominal current through the standard burden connected to those terminals. The voltage drop across the internal resistance of the CT at 20 times nominal current should be added to the ANSI C class rating used in the calculation. The internal CT resistance is added to the external burden and compared to the adjusted standard burden. Equations (3) and (4) describe how to calculate the two terms used in Equation (2). The application study section of this paper shows a numerical example of how this calculation is made.
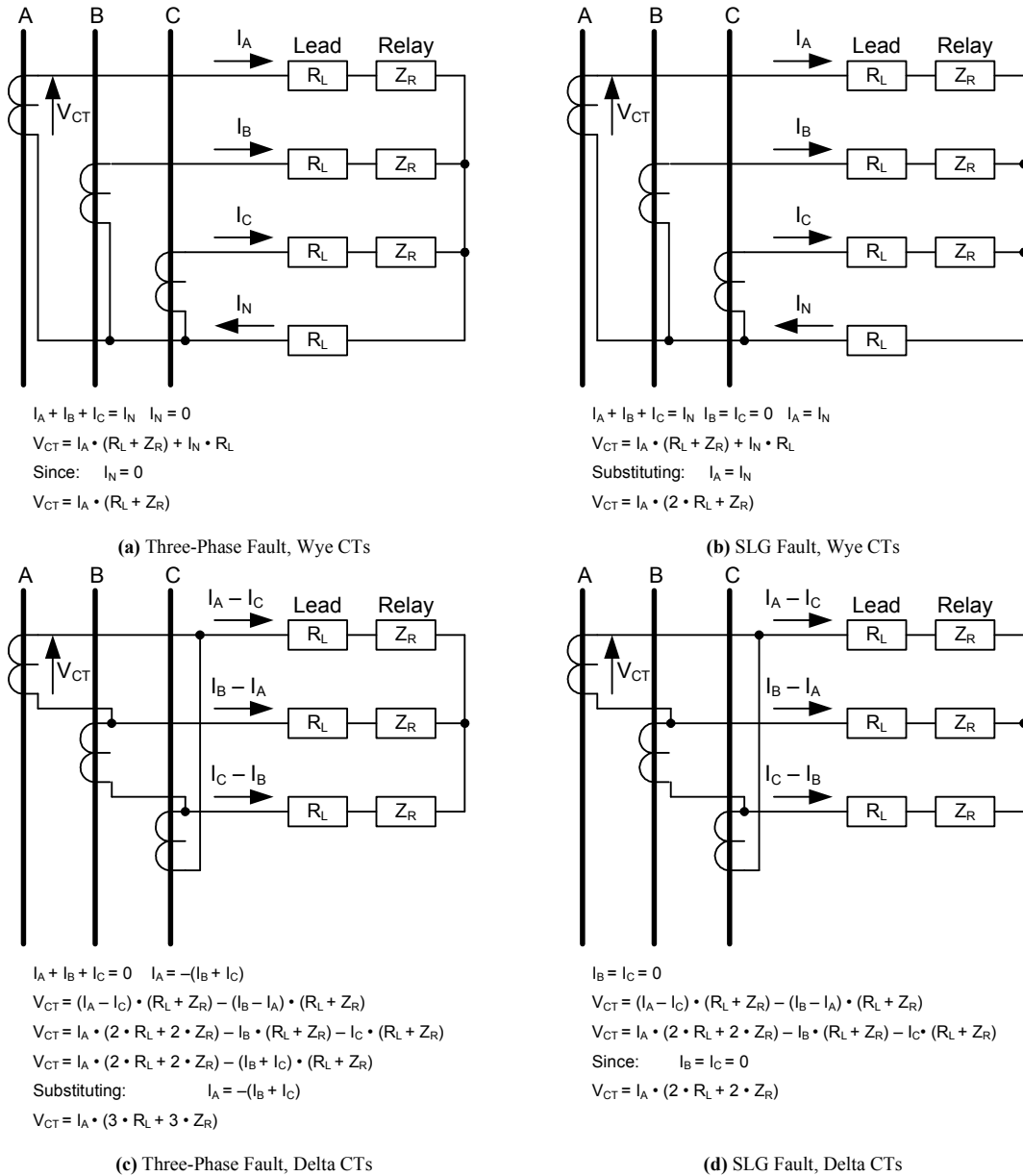
Figure 4(a) — Three-Phase Fault, Wye CTs

Labels: A B C, I_A, Lead R_L, Relay Z_R, V_{CT}, I_B, R_L, Z_R, I_C, R_L, Z_R, I_N, R_L

$I_A + I_B + I_C = I_N \quad I_N = 0$

$V_{CT} = I_A \cdot (R_L + Z_R) + I_N \cdot R_L$

Since: $\quad I_N = 0$

$V_{CT} = I_A \cdot (R_L + Z_R)$

(a) Three-Phase Fault, Wye CTs

Figure 4(b) — SLG Fault, Wye CTs

Labels: A B C, I_A, Lead R_L, Relay Z_R, V_{CT}, I_B, R_L, Z_R, I_C, R_L, Z_R, I_N, R_L

$I_A + I_B + I_C = I_N \quad I_B = I_C = 0 \quad I_A = I_N$

$V_{CT} = I_A \cdot (R_L + Z_R) + I_N \cdot R_L$

Substituting: $\quad I_A = I_N$

$V_{CT} = I_A \cdot (2 \cdot R_L + Z_R)$

(b) SLG Fault, Wye CTs

Figure 4(c) — Three-Phase Fault, Delta CTs

Labels: A B C, $I_A - I_C$, Lead R_L, Relay Z_R, V_{CT}, $I_B - I_A$, R_L, Z_R, $I_C - I_B$, R_L, Z_R

$I_A + I_B + I_C = 0 \quad I_A = -(I_B + I_C)$

$V_{CT} = (I_A - I_C) \cdot (R_L + Z_R) - (I_B - I_A) \cdot (R_L + Z_R)$

$V_{CT} = I_A \cdot (2 \cdot R_L + 2 \cdot Z_R) - I_B \cdot (R_L + Z_R) - I_C \cdot (R_L + Z_R)$

$V_{CT} = I_A \cdot (2 \cdot R_L + 2 \cdot Z_R) - (I_B + I_C) \cdot (R_L + Z_R)$

Substituting: $\quad I_A = -(I_B + I_C)$

$V_{CT} = I_A \cdot (3 \cdot R_L + 3 \cdot Z_R)$

(c) Three-Phase Fault, Delta CTs

Figure 4(d) — SLG Fault, Delta CTs

Labels: A B C, $I_A - I_C$, Lead R_L, Relay Z_R, V_{CT}, $I_B - I_A$, R_L, Z_R, $I_C - I_B$, R_L, Z_R

$I_B = I_C = 0$

$V_{CT} = (I_A - I_C) \cdot (R_L + Z_R) - (I_B - I_A) \cdot (R_L + Z_R)$

$V_{CT} = I_A \cdot (2 \cdot R_L + 2 \cdot Z_R) - I_B \cdot (R_L + Z_R) - I_C \cdot (R_L + Z_R)$

Since: $\quad I_B = I_C = 0$

$V_{CT} = I_A \cdot (2 \cdot R_L + 2 \cdot Z_R)$

(d) SLG Fault, Delta CTs

Fig. 4. Burden Loops for Fault Types and CT Connections

$$Z_{ADJ\_STD} = \frac{V_{ANSI} + 20 \cdot I_{SEC} \cdot R_{CT}}{20 \cdot I_{SEC}} = \frac{V_{ANSI}}{20 \cdot I_{SEC}} + R_{CT} \quad (3)$$

$$Z_{BURDEN} = R_{CT} + C_L \cdot R_{LEAD} + C_R Z_{RELAY} \quad (4)$$

Where:

Z_{ADJ_STD} is the adjusted standard burden for the ANSI rating.

V_{ANSI} is the CT C rating—800 V for a C800 CT.

I_{SEC} is the secondary current rating of the CT.

R_{CT} is the internal resistance of the CT secondary winding.

C_L is the lead burden multiplying factor for the fault type (Table 2).

C_R is the relay burden multiplying factor for the fault type (Table 2).

R_{LEAD} is the one-way lead resistance.

Z_{RELAY} is the relay burden impedance.

The fault type determines how the external burden is calculated and provides guidance on how to calculate Z_{BURDEN}. In a solidly grounded system, an SLG fault is the worst-case scenario because the lead burden must be multiplied by two. For the SLG fault, wye CT's case, the burden of any ground relays in the neutral path should be included in Z_{BURDEN} as well.

TABLE 2
FAULT TYPE BURDEN MULTIPLIER

Fault Type	Figure	Multiplier "C_L"	Multiplier "C_R"
Three-Phase, Wye CTs	4(a)	1	1
SLG, Wye CTs	4(b)	2	1
Three-Phase, Delta CTs	4(c)	3	3
SLG, Delta CTs	4(d)	2	2

I_f, the per-unit fault current, can be calculated using Equation (5). The base of the per-unit calculation, I_{PRI}, is the primary current rating of the CT. For a differential application, we are concerned that we do not saturate during an external (through) fault. We use the value of fault current, I_{FAULT}, which is the maximum fault current seen by the CT during an external fault. The fault current corresponds to the fault type used in calculating Z_b.

$$I_f = \frac{I_{FAULT}}{I_{PRI}} \qquad (5)$$

Where:

I_{FAULT} is the maximum external fault current in primary amperes for the particular fault.

I_{PRI} is the primary current rating of the CT.

If you are calculating V_S for a transformer differential application, you should consider the phase shift across the transformer for an unbalanced through fault when figuring the worst-case fault current and CT circuit loop impedance burden.

3) Remnant Flux Considerations

As stated earlier, Equation (1) is valid for the case of a CT with zero flux in the core. This will never be the case in a real application. Each time the CT reproduces an asymmetrical waveform, the net change in flux will differ. And, this net change in flux can be additive or subtractive from the remnant flux in the core prior to the fault. The net change depends upon the fault incident angle, the magnitude of the fault, and the speed with which the current is interrupted. The result is that the magnitude of remnant flux is completely random.

C. Sharing Restraint Inputs

One limitation of a percentage-restrained differential relay for bus applications is that the number of circuits on the bus is quite often greater than the number of restraint inputs available on the relay. For this reason, it is sometimes necessary to parallel multiple CT circuits on a single restraint input. This practice can reduce the security of the protection system.

To illustrate the problem, let us examine a common situation as illustrated in Fig. 5(a). A two restraint input relay is applied to protect this bus. We wish to make the differential relay secure for external faults. If there is saturation in one of the paralleled CTs, false differential current will appear as operate current but will be divided by two in the restraint current calculation. The result is that the false differential current will appear on the relay characteristic on the 200% slope line, making it less secure.

Let us consider the problem of remnant flux in this situation. For an external fault at location F2, the dc transient in CT 1 and CT 2 will have the same polarity (into the zone of protection). As a result, the remnant flux after this fault will be the same polarity in both CT 1 and CT 2. Now, for a subsequent external fault at location F1, there will be significant current from the strong system through the zone of protection. For this case, the dc transient will be of opposite polarity in

CT 1 and CT 2. The result is that the remnant flux will be additive for one CT, causing it to go into saturation, whereas the remnant flux in the other CT will be subtractive, helping to prevent it from going into saturation. If one CT saturates and the other does not, this will cause a false differential current to flow into the relay.

To mitigate this problem, it is advisable to put each of the CT circuits on the strong source circuits on its own restraint input as shown in Fig. 5(b). For many bus protection applications, there are too many circuits for this to be practical. In this case, the protection engineer should consider using a high-impedance differential relay where there is practically no limit on the number of circuits that define the zone of the differential.

(a) Paralleling CTs

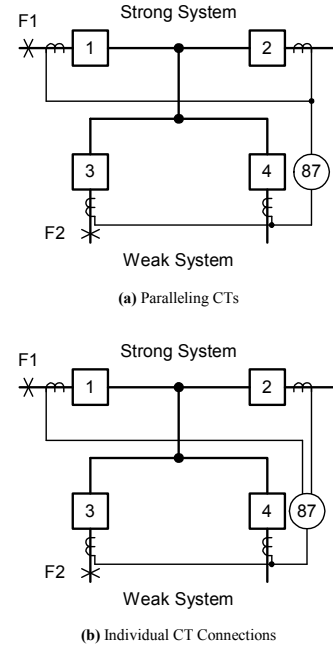**(b)** Individual CT Connections

Fig. 5.   Sharing Restraint Inputs

III. APPLICATION STUDY

A. Background

The study that is the subject of this paper was for an existing substation at an oil refinery. The original system configuration included two feeders connected to the local utility via a pair of 60 MVA transformers. Fig. 6 shows a simplified single line of the facility. Substation 2A, the site under study, has a single tie breaker, two supply breakers, and multiple machine and transformer loads on each bus. The need for review of the existing percentage-restrained differential bus protections arose with the arrival of a 125 MVA generator. The generator is connected to the site with two breakers, one on each bus. The site is physically located an equal distance from the two utility transformers and new generation power island.

The addition of the generation not only increases the available fault levels, but also, as was determined later, more than doubles the X/R ratio. Loss of power to either bus at this location in the oil refinery has both extreme environmental and commercial impact. The concern is that with the added genera-

tion, the slope restraint may not be sufficient to resist false operation for out-of-zone faults.
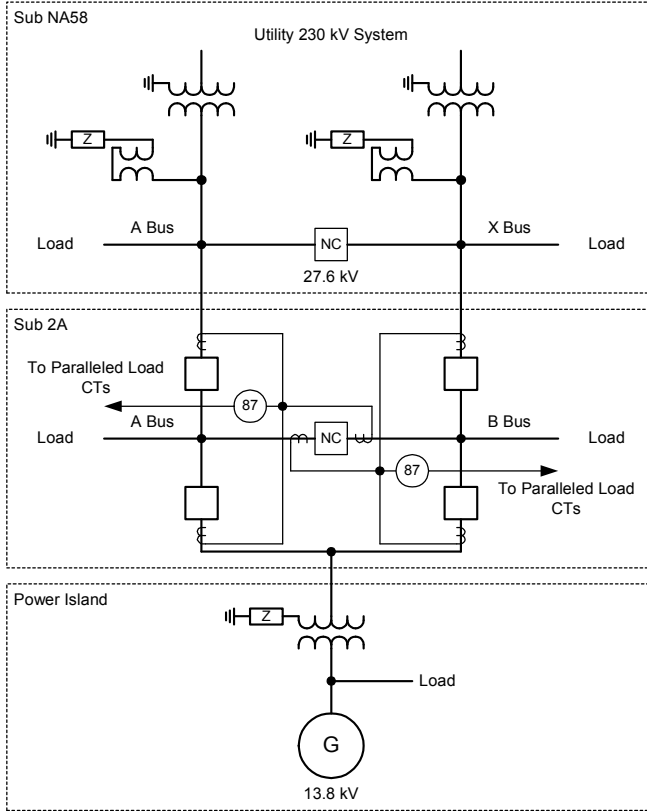

Fig. 6.   Simplified System Single-Line Diagram

The settings criteria provided by Reference [1] were used to determine whether the existing percentage-restrained differential could be set with an acceptable slope setting. The following initial calculations were made:

TABLE 3
APPLICATION PARAMETERS

I_F = 29,000 (SLG)	X/R = 13	R_L = 0.3 (one way)	*Z_R = 0.0
CTR = 2000/5	V_{ANSI} = 800	R_{CT} = 0.9	

* For microprocessor-based relays, 0.0 ohms burden is a safe assumption. Actual burden for this relay is around 0.01 ohms.

Using Equations (5), (2), and (1) with the application data in Table 3:

$$I_f = \frac{29,000}{2000} = 14.5$$

$$Z_b = \frac{(2 \bullet 0.3 + 0.9)}{\left(\dfrac{800}{(20 \bullet 5)} + 0.9\right)} = 0.169$$

$$V_S = (1 + 13) \bullet 14.5 \bullet 0.169 = 34.3$$

The resulting V_S = 34.3 is greater than 20, which indicates that the CT can saturate in this application.

Reference [1] provides an empirical formula for determining the secure single-slope setting for applying a percentage-restrained differential relay. This equation is valid for V_S less than 150.

$$k = 0.842(V_S) - 0.00242(V_S)^2 \qquad (6)$$

Where:

k is the slope factor.*

V_S is the per-unit saturation voltage.

*   For a relay that quantifies restraint as magnitude of currents divided by two, the k factor given by this equation would be multiplied by two.

Applying Equation (6) produced a slope setting of 52%. To ensure that the relay would be secure in the field, the CT was derated to account for remnance. If one assumes a remnance of 55%, the recommended slope setting provided by Equation (6) is above 100%. This raised the question, "What is an acceptable guideline for assuming remnance?"

Note that the above calculations were made with the assumption that the system was solidly grounded. Examination of Fig. 6 shows that this assumption was not correct. The impact of this incorrect assumption on the results of the application study will be discussed later under the heading of *Follow-Up Case Studies*.

Another problem with the application can also be discerned from examination of Fig. 6. The relay was originally installed as a two-restraint relay installation. All of the source breaker currents are summed for the first restraint input and all of the load breaker currents are summed for the second restraint input. As described earlier, for a percentage-restrained differential relay to be secure from CT saturation, it must be able to measure the current flowing through the zone. As originally wired, false differential current caused by saturation of any of the source breaker CTs would not have been restrained, and the relay would trip regardless of the slope setting. As part of the upgrade to the system, we planned to connect each of the source breakers to its own restraint input and connect the sum of the load breaker currents to the fourth restraint input on the relay.

B. Application Study

Because of the criticality of the application, a study was commissioned to further explore the application. The study had the following objectives:

- Explore the effect of different levels of remnance.
- Explore the effect of variations in the fault current levels.
- Explore the effect of variations in the X/R ratio.
- Determine a secure single-slope or dual-slope setting for the application based upon these considerations.
- An additional area for study was to determine if the 2nd harmonic blocking logic could be used to improve our security for an external fault yet not reduce dependability for an internal fault with saturation.

1) Mathcad Simulation

To explore these various considerations, a Mathcad simulation was developed. The Mathcad simulation included the following features:

- A CT model that could calculate the saturated waveform of the CT for a fully offset waveform.
- A model of the numerical relay's filtering algorithms.
- A model of the numerical relay's differential, and harmonic blocking algorithms.
- Calculation of the operate points of the relay at each sample point during the fault, plotted on the percentage-restrained differential characteristic.
- Calculation of the slope setting required to cover the worst case operate point for an external fault. Both single-slope and dual-slope settings were determined. If the desired single-slope setting is greater than the maximum of 100%, we use the dual-slope characteristic instead of the single-slope characteristic.
- The ability to freeze the settings so that various parameters could be adjusted to determine their effect on the security of the settings.
- Calculation of the worst case 2nd harmonic ratio for an internal fault with saturation and setting the blocking ratio to that value times 1.5.

The CT model is a Mathcad implementation of the MATLAB simulation described in Reference [4]. The model was enhanced to include a starting remnant flux level.

2) Case Studies

To get an understanding of the effects of remnance on the setting, we ran the simulation at 0% to 90% remnance in 10% steps. For the dual-slope setting, an arbitrary setting of 30% was chosen for Slope 1. The setting IRS1 is the point where the Slope 2 starts. This point was calculated as the point at which the CT would just go into saturation. That is, we solved Equation (1) for the current where the Saturation Voltage, V_S, = 20 and converted that current to multiples of tap. To get the new current that corresponded with V_S = 20 for each case, the ANSI class of the CT was derated by the amount of remnance. The results for this specific application with these specific details are shown in Table 4.

TABLE 4
RELAY SETTINGS FOR 0% TO 90% REMNANCE, 100% FAULT CURRENT

Remnance Case	Single Slope	Dual Slope			2nd Harmonic Blocking
		Slope 1	IRS1	Slope 2	
0%	61%	30%	8.5	132%	15%
10%	65%	30%	7.6	119%	15%
20%	74%	30%	6.8	135%	18%
30%	86%	30%	5.9	151%	15%
40%	96%	30%	5.1	161%	15%
50%	99%	30%	4.2	147%	15%
60%	99%	30%	3.4	133%	17%
70%	NA	30%	2.5	130%	30%
80%	NA	30%	1.7	120%	14%
90%	NA	30%	1	121%	36%

The results correlated well with the setting guideline provided in Reference [1]. That setting guideline recommended a setting of 100% at 55% remnance for this application. The recommended single-slope setting reached 100% at 50% to 60% remnance. Above this level of remnance, a secure single-slope characteristic is not possible.

Fig. 7 and Fig. 8 show an example of the current and differential characteristic plots for 0% remnance, and Fig. 9 and Fig. 10 show an example of the plots for 50% remnance. Note that, in the differential characteristic plots, the operate axis is two times the scale of the restraint axis.

The series of simulations, 0% remnance to 90% remnance, were then rerun using 120% fault current level. The purpose of these simulations was to determine the effect of increased fault duty on the setting. Based upon this series of tests, the calculated setting for 120% fault duty and 50% remnance was Slope 1 = 30%, IRS1 = 4.2, Slope 2 = 154%, and 2nd harmonic block = 32%.

The simulations were repeated using the original parameters with the settings locked at the 120% fault duty and 50% remnance settings of Slope 1 = 30%, IRS1 = 4.2, and Slope 2 = 154%. Each case was examined to see if any points plotted above the operate line. A numerical relay typically has a security count for its restrained differential element. Thus, if any case resulted in more than a few points above the operate line, the settings would require adjustment to provide adequate margin. This was not the case. The worst case was two points over the line for the 90% remnance case. For the cases at 120% fault level, the worst was two points over the line as well.
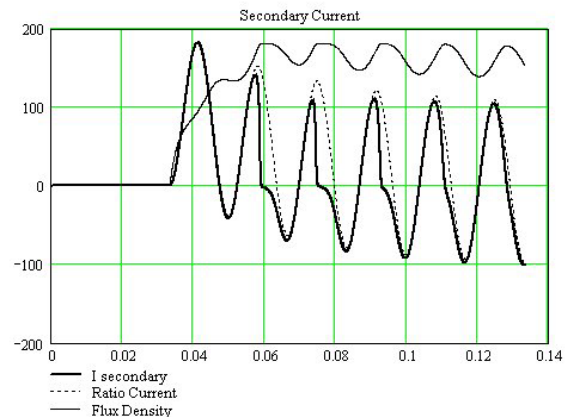

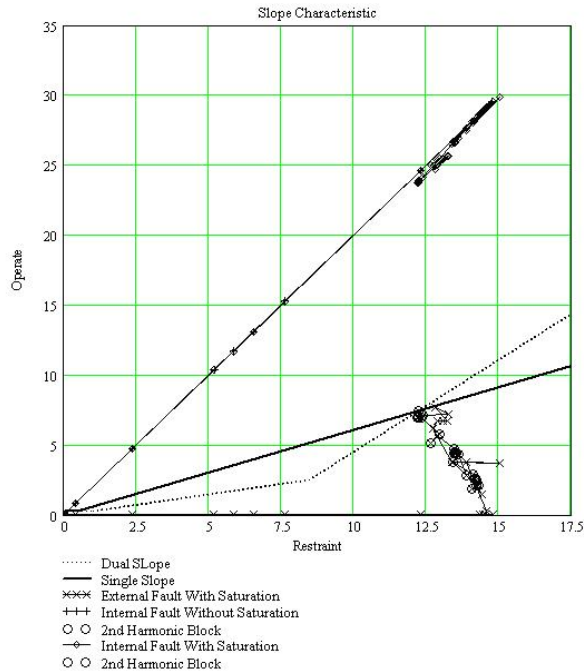Fig. 7. CT Current and Flux Density for 0% Remnance Case

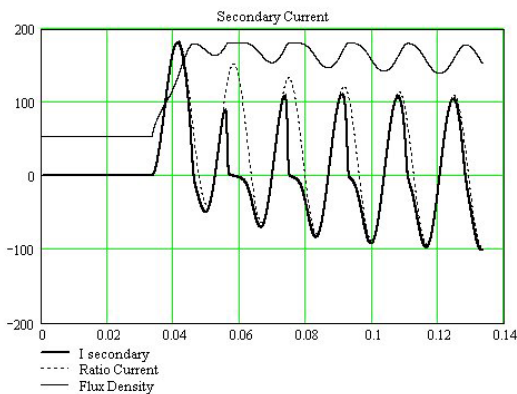Fig. 8.   Differential Characteristic for 0% Remnance Case

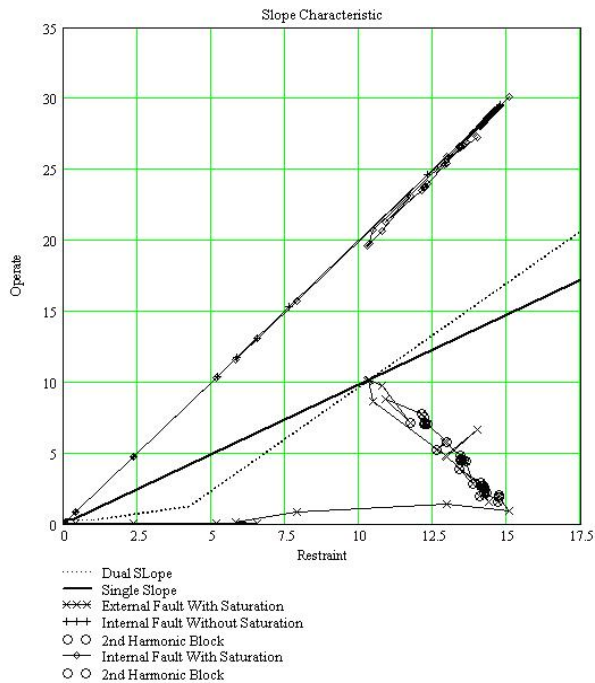Fig. 9.   CT Current and Flux Density for 50% Remnance Case

Fig. 10.   Differential Characteristic for 50% Remnance Case

3) 2nd Harmonic Blocking for Bus Differential Applications

Because CT saturation results in fairly large amounts of 2nd harmonics, we wanted to see if the 2nd harmonic blocking feature in the relay would enhance security. However, we did not want the relay to be blocked for an internal fault with saturation. So we could determine a setting that would not block the restrained differential element during an internal fault, the Mathcad simulation calculated the ratio of 2nd harmonic to fundamental of the differential current at each sample for an internal fault with saturation. We then set the harmonic blocking element at 1.5 times the highest value. The right-most column in Table 4 shows the resulting harmonic blocking ratio setting for each case.

In the simulation graphs, any point that is circled would be blocked by the 2nd harmonic blocking logic. As expected, during saturation, the currents contain significant levels of 2nd harmonic. When the setting was set at 32% (1.5 times the worst calculated ratio for an internal fault for the 120% fault level, 50% remnance case), we discovered that, while the 2nd harmonic blocking element did block some points for an external fault, it did not make a material difference in the results. Thus, the 2nd harmonic blocking logic can be either turned off or set to 32%.

C. Follow-Up Case Studies

After completing the study and recommendations, we became aware of two fundamental assumptions that were wrong. The system turned out to be an impedance-grounded system. Thus, the worst-case situation was a three-phase fault instead of an SLG fault. As per Table 2, the calculation for Z_b includes only one times the lead resistance, which should improve the security of the system. However, a new updated fault study placed the system X/R ratio at 29 instead of 13. This, of course, has a significant negative impact on the security of the protection system.

The case studies were repeated with the parameters shown in Table 5.

TABLE 5
FINAL APPLICATION PARAMETERS

I_F = 29,000 (3Ph)	X/R = 29	R_L = 0.3 (one way)	Z_R = 0.0
CTR = 2000/5	V_{ANSI} = 800	R_{CT} = 0.9	

Fig. 11 shows an example of the current and differential characteristic plots for 50% remnance with an X/R ratio of 29. As expected, the CT takes a great deal longer to recover from saturation due to the long time constant of the dc transient. The calculated slope setting for this case was: Slope 1 = 30%, IRS1 = 2.5, and Slope 2 = 172%. A secure single-slope characteristic is not possible. This case shows a dramatic example of how a dual-slope (variable percentage) characteristic can be set to accommodate false differential current due to severe CT saturation. However, the margin between an internal fault and an external fault is very small.
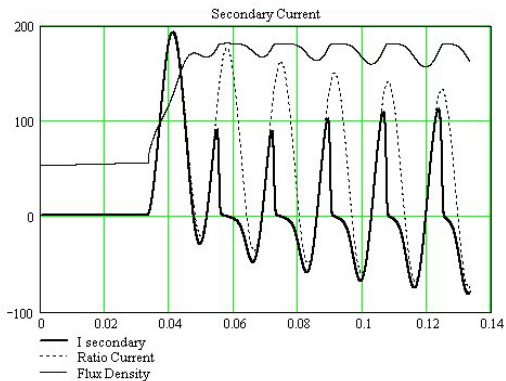
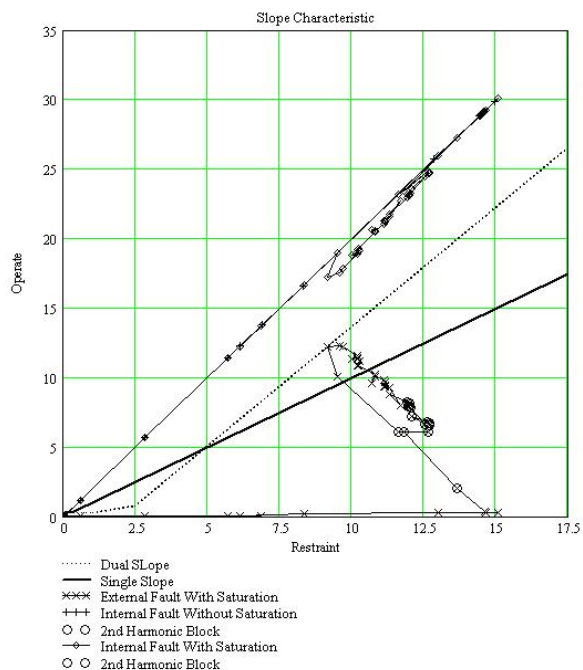Fig. 11. Plot of CT Current and Flux Density for 50% Remnance Case, X/R = 29

Fig. 12. Differential Characteristic for 50% Remnance Case, X/R = 29

D. Final Recommendations

Based upon these final simulations, we decided that the optimal solution would be to upgrade the relay from a percentage-restrained type to a high-impedance type. A high-impedance bus differential relay provides security from CT saturation by presenting a high-impedance path to the flow of differential current. If the differential current is false differential caused by CT saturation, the current will be forced down the low-impedance path of the saturated CT. If the differential current is caused by a true internal fault, the relay responds to the voltage across the high impedance and operates very quickly. The high-impedance type relay is also extremely sensitive. A very small amount of differential current through the high impedance of the relay results in an easily detectable voltage to respond to. For an impedance-grounded system such as this, the percentage-restrained type will not provide enough sensitivity to detect an SLG fault. The high-impedance type of relay is very secure in the presence of CT saturation, highly sensitive, and is very fast.

IV. DEVELOPMENT OF A GENERAL GUIDELINE

One thing that stood out in the application study was that the IRS1 point, where the relay transitions from Slope 1 to Slope 2, seemed to have a more significant effect on accommodation of CT saturation than the slope setting. We had chosen to set the IRS1 point by solving for the current level in multiples of tap at which the CT, derated by 50%, would just go into saturation. This is a function of the X/R ratio and the amount of burden in the CT circuit. It was hypothesized that we could choose a fixed minimum pickup, Slope 1, and Slope 2 setting, and adjust the IRS1 point based upon the application-specific data to obtain a setting that would be secure, even in the presence of significant levels of remnant flux.

Equation 1 can be broken down into two main terms that result in saturation—the (X/R + 1) term and the $I_f \cdot Z_b$ term. For a given application, the CT can reach a given saturation voltage level, V_S, due to either high X/R ratio or high burden/fault current. For example, if we have a V_S = 40 case with high X/R ratio and low $I_f \cdot Z_b$, the CT will take several cycles to go into saturation, but it will stay in saturation for a long time. If we have a V_S = 40 case with low X/R ratio and high $I_f \cdot Z_b$, the CT will quickly go into saturation but come out quickly as well. These two cases may present different challenges to the differential relay.

A. Simulation Series

To explore the effects of different situations and more fully develop the proposed application guideline settings, a series of simulations were run. The cases had the following bounds:

- X/R ratio   3 to 30
- $I_f \cdot Z_b$ 1, 2, 3, 4 per unit
- I_f <30 per unit
- Z_b 0.10, 0.25, 0.50 per unit
- Remnance   0%, 20%, 40%, 60%, 80%

The method for developing the test cases to be examined was:

Step 1: Set Z_b to one of the three values.
Step 2: Set $I_f \cdot Z_b$ to one of the four values.
Step 3: Solve for primary current level for the given Z_b and $I_f \cdot Z_b$.
Step 4: Solve Equation 1 for X/R ratio using cases for: V_S = 10, 20, 40, 60, 80, 100, 120.
Step 5: Throw out the cases where X/R and I_f are out of bounds.

This method was intended to cover a wide range of cases with high burden, high fault current, or high X/R ratios. The simulations were then run for each of the remnant flux cases to ensure that the guideline provided a setting that was secure, regardless of the level of remnant flux in the CT. Table 6, Table 7, and Table 8 list the test cases that were run.

TABLE 6
SIMULATION CASES FOR $Z_b = 0.10$ PER UNIT

$I_f \bullet Z_b$	I_{Fault}	X/R	V_S
1	19,778 A	9	10
1	19,778 A	19	20
2	39,556 A	4	10
2	39,556 A	9	20
2	39,556 A	19	40
2	39,556 A	29	60
3	59,333 A	5.67	20
3	59,333 A	12.33	40
3	59,333 A	19	60
3	59,333 A	25.67	80
3	59,333 A	32.33	100

TABLE 7
SIMULATION CASES FOR $Z_b = 0.25$ PER UNIT

$I_f \bullet Z_b$	I_{Fault}	X/R	V_S
1	8,000 A	9	10
1	8,000 A	19	20
2	16,000 A	4	10
2	16,000 A	9	20
2	16,000 A	19	40
2	16,000 A	29	60
3	24,000 A	5.67	10
3	24,000 A	12.33	20
3	24,000 A	19	40
3	24,000 A	25.67	60
3	24,000 A	32.33	80
4	32,000 A	4	20
4	32,000 A	9	40
4	32,000 A	14	60
4	32,000 A	19	80
4	32,000 A	24	100
4	32,000 A	29	120

TABLE 8
SIMULATION CASES FOR $Z_b = 0.50$ PER UNIT

$I_f \bullet Z_b$	I_{Fault}	X/R	V_S
1	4,000 A	9	10
1	4,000 A	19	20
2	8,000 A	4	10
2	8,000 A	9	20
2	8,000 A	19	40
2	8,000 A	29	60
3	12,000 A	5.67	20
3	12,000 A	12.33	40
3	12,000 A	19	60
3	12,000 A	25.67	80
4	16,000 A	4	20
4	16,000 A	9	40
4	16,000 A	14	60
4	16,000 A	19	80
4	16,000 A	24	100
4	16,000 A	29	120

B. Application Guideline

Each of the simulations was run for remnant flux levels up to 80% using the following setting guideline.

- TAP   1 per unit (5 for a 5 A relay)
- Min. PU   0.5 per unit
- Slope 1   80%
- Slope 2   160%
- IRS1   Per Equation 7

Equation 7 is derived from Equation 1 to solve for the current, in per unit of tap, where the CT, derated by 50%, will just go into saturation. If Equation 7 resulted in an *IRS1* setting of less than one, one was used.

$$IRS1 = \frac{V_S \bullet I_{SEC}}{Z_b \bullet \left(\dfrac{X}{R} + 1 \right) \bullet TAP} \qquad (7)$$

Where:

V_S is 10 (the saturation voltage derated by 50%).

I_{SEC} is the secondary current rating of the CT.

TAP is the relay tap value setting.

Z_b is the CT secondary circuit burden in per unit of standard burden. (Equation 2)

X/R is the *X/R* ratio of the primary fault current.

Each case was checked for the number of consecutive points over the tripping characteristic on the operate versus restraint plot. Due to the fact that the relay includes several security counts, a few points over the trip characteristic is acceptable. The results of the tests indicate that the above setting guideline remained secure within the constraints listed above. If your application parameters fall outside of the listed constraints, it is recommended that the application be simulated and studied in detail, or a different type of differential relay be used.

It should be understood that this setting guideline is suitable only for solidly grounded systems. This guideline will not result in enough sensitivity for medium- and high-impedance grounded systems. For these systems, where phase faults are an order of magnitude greater than ground faults, a low-impedance, percentage-restrained differential relay generally cannot be set with adequate sensitivity for ground faults and remain secure for phase faults. For impedance-grounded applications, a high-impedance type bus differential relay or a low-impedance bus differential relay that can recognize CT saturation and go into high-security mode is recommended.

V. SUMMARY

Percentage-restrained differential relays can be used for bus protection applications because they are highly selective. A percentage-restrained differential relay relies upon its slope characteristic to be secure for external faults with false differential current caused by CT saturation. A variable percentage, dual-slope characteristic can provide both high sensitivity for low-level faults and high security for high-level faults with CT saturation.

For a differential relay that uses "average" restraint, an internal fault with or without CT saturation will fall on the 200% slope line. For most bus applications, a single-slope relay set at 100% should provide adequate security. For applications where CT saturation is a problem, the dual-slope characteristic can provide the needed accommodation for false differential current.

The susceptibility of a particular installation to CT saturation can be evaluated based upon the CT accuracy class, the CT secondary burden, the fault current level, and the system X/R ratio. The fault current level and burden calculation have to consider the fault type to determine which is the worst-case scenario when applying this equation. The saturation voltage equation is true for a CT core with zero remnant flux. In service, there is always going to be some flux remnance in the CT core. This problem is completely random and cannot be easily predicted. The remnant flux can be either helpful or harmful depending upon the polarity of the dc transient in the fault current versus the polarity of the remnant flux. The equation can be adjusted to accommodate some degree of remnance.

A secure single slope can be calculated based upon an empirical formula obtained from a previous study of CT saturation phenomena for bus protection applications. However, better security can be obtained by taking advantage of the dual-slope characteristic of a variable percentage differential relay.

A Mathcad CT simulation with the numerical relay filtering and protective algorithms was developed to explore the effects of remnance and other factors in determining a secure slope setting for the application. This tool was used to calculate a setting for this application that would be secure for levels of remnance up to 90% and fault current levels up to 120%.

The 2nd harmonic blocking logic was also evaluated to see if it could help with making the relay secure under conditions of CT saturation. It was determined that this element had little effect and could be turned off.

When the X/R ratio is increased significantly, it has an adverse effect on the security of the application. In cases where there is high X/R ratio or where the CTs are inadequate in accuracy class for the burden and fault levels that they are to be subjected to, a high-impedance type bus differential relay can be applied to improve both security and performance of the bus protection system.

This study provided additional insight into the behavior of a percentage-restrained differential relay in the presence of CT saturation. It shows that the variable percentage, dual-slope characteristic can provide accommodation for significant levels of CT saturation. The analysis techniques that were developed for this study were then used to run enough additional simulations to develop a general guideline that can be used for selecting secure dual-slope settings for this type of relay in applications where a single-slope characteristic is not adequate.

VI. REFERENCES

[1] S. E. Zocholl, "Rating CTs for Low Impedance Bus and Machine Differential Applications," 27th Annual Western Protective Relay Conference, Spokane, WA, October 23–26, 2000, page 6.

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VII. BIOGRAPHIES

Michael J. Thompson received his B.S., Magna Cum Laude from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. He has broad experience in the field of power system operations and protection. Upon graduating, he served nearly 15 years at Central Illinois Public Service (now AMEREN), where he worked in distribution and substation field engineering before taking over responsibility for system protection engineering. Prior to joining Schweitzer Engineering Laboratories in 2001, he was involved in the development of a number of numerical protective relays. He is a senior member of the IEEE and has authored and presented several papers on power system protection topics.

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Amy Sinclair received her BSc in Electrical Engineering from Queen's University, Kingston, (1989). She joined Ontario Hydro in 1989, working for ten years as protection and control engineer in areas of design, operations, and project management. In 2000, she joined ELECSAR Engineering as a project manager. Her field of interest is protective relaying and substation design. She has been registered as a professional engineer of Ontario since 2001.

VIII. PREVIOUS PUBLICATIONS

Presented at 2005 Texas A&M Conference for Protective Relay Engineers.