# Percentage Restrained Differential, Percentage of What?

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# Percentage Restrained Differential, Percentage of What?

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*Abstract*—**Percentage restrained differential protection is one of the oldest forms of adaptive protection algorithms. The slope characteristic provides high sensitivity when low levels of current are flowing in the zone of protection but has less sensitivity when high levels of current are flowing and false differential current due to current transformer (CT) saturation is more likely.**

**The percentage restraint characteristic operates on the ratio of operate-to-restraint current in the zone of protection. The operate quantity is universally defined as the magnitude of the differential current in the zone of protection. However, several different methods have been developed to quantify the restraint quantity, which is a measure of the through current in the zone of protection. The definition of the restraint magnitude will have an impact on the effective sensitivity and security of a given percentage slope characteristic.**

**This paper examines several common methods for defining restraint and slope characteristics and provides guidance on selection of the correct slope setting. Examples are used to examine a multirestraint transformer differential application with steady-state, proportional, and transient sources of mismatch in the zone of protection.**

## I. Introduction

Most fault detection elements used in power system protection fall into one of four general categories:

- Overcurrent
- Directional overcurrent
- Underimpedance (distance)
- Differential

These elements are ranked in the previous list in order of selectivity—lowest to highest. Selectivity is defined as the ability of an element to determine whether a fault is internal or external to its protected zone. An element with high selectivity can trip with no intentional time delay because it knows that the fault is in its zone of protection. Differential protection works on Kirchoff's current law that states that the currents flowing into a node of the power system must sum to zero, as shown in Fig. 1. The differential zone is defined by the location of current transformers (CTs) on the primary circuits around a power system bus or apparatus. If the currents sum to zero, all is well. If they do not, there is a fault. Therefore, differential protection is theoretically perfectly selective. It will respond to all internal faults and ignore all external (through) faults and load flow.

For this reason, differential protection is often applied to high-value apparatus such as transformers, large motors, and generators. It can precisely determine if the fault is within the protected apparatus and trip with no intentional time delay. Fast tripping can limit damage and mean the difference between repairing the apparatus and scrapping it.

Another attribute of differential protection is that it has generally higher sensitivity relative to the other three types of fault detection elements because it responds to the difference current in the zone of protection. It does not need reduced sensitivity to accommodate load flow, natural system unbalances, or out-of-zone faults. This is especially important when the protected apparatus is a power transformer. Detecting partial winding faults within a power transformer requires high sensitivity [1].

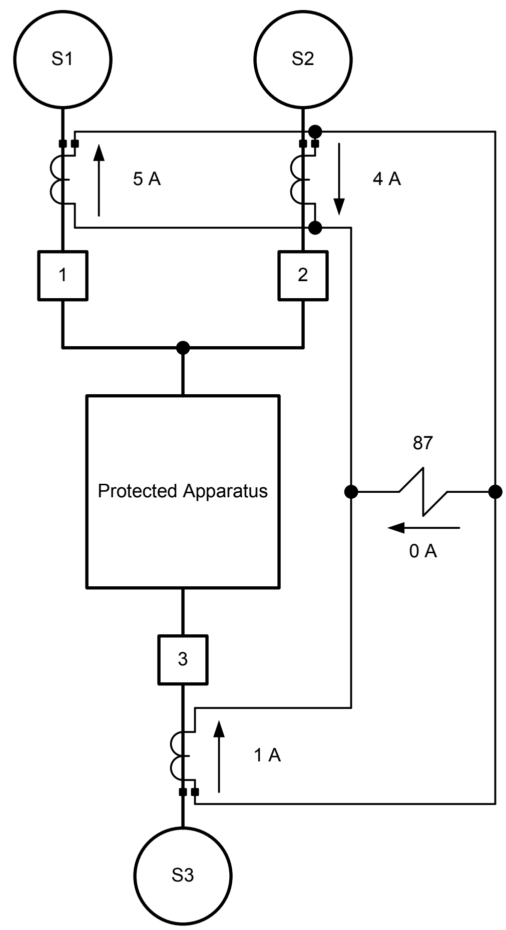


Fig. 1. Differential zone operates on the sum of currents entering the zone

The main application concern with differential protection is to make it secure from operating on false differential current. False differential current is differential current that does not exist in the primary circuits. The main source of false differential current is CT saturation.

The dc offset in the primary current can cause the flux in the iron core of the CT to build up in one direction until it reaches the maximum flux density that the core can hold.

Once the core becomes saturated, the primary of the CT is no longer magnetically coupled to the secondary, and the secondary current rapidly falls to zero. When the dc transient dissipates, the CT eventually recovers. Reference [2] provides a detailed discussion of the nature of CT saturation and how to analyze a given CT application to determine the likelihood of saturation occurring.

Differential protection falls into one of the following three categories:

- Differentially connected overcurrent
- Impedance stabilized differential
- Percentage restrained differential

Each differs in how it deals with false differential current. Differentially connected overcurrent relays respond to the current in the differential leg of the CT circuit. To be secure from false differential current, it is necessary to either increase the pickup (reduce sensitivity) of the overcurrent element above any anticipated false differential current or to add a time delay to ride through transient CT saturation. Impedance stabilized differential relays place intentional impedance in the differential leg of the CT circuit to create a current divider that forces most of the false differential current to flow away from the relay. Percentage restrained differential relays measure the individual branch currents and quantify the through current in the zone of protection. The percentage restraint characteristic requires that the differential current be greater than a percentage of the through (restraint) current.

The focus of this paper is percentage restrained differential protection as applied to a power transformer. Percentage restrained differential protection is one of the oldest forms of adaptive protection algorithms. The slope characteristic can provide high sensitivity when low levels of current are flowing in the zone of protection but has less sensitivity when high levels of current are flowing. This improves security because CTs are more prone to saturation when they have to reproduce high levels of current in the primary circuits.

The percentage restraint characteristic operates on the ratio of operate-to-restraint current in the zone of protection. Fig. 2 shows a typical single-slope characteristic. The operate quantity ($I_{OP}$) is universally defined as the magnitude of the differential current in the zone of protection. However, many different methods have been developed to quantify the restraint quantity ($I_{RST}$). The definition of the restraint magnitude has an impact on the effective sensitivity and security of a given slope setting.

In this paper, we first review sources of differential current in a transformer application; we then examine several percentage restraint characteristics and common methods of defining the restraint quantity. By doing so, we can better understand how to set the slope characteristic to achieve an acceptable balance between security and sensitivity. Equations are provided for slope ratios versus differential current for each method of defining restraint. Minimum and maximum slope setting ranges for each method of defining restraint are illustrated for an example application.

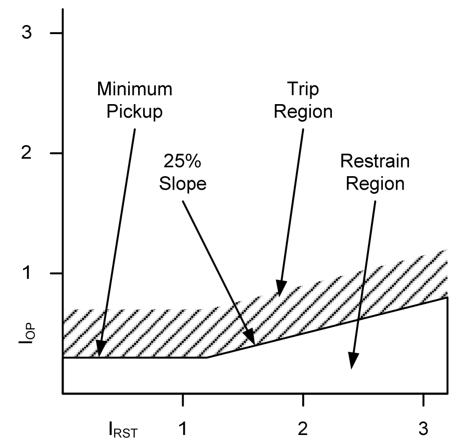


Fig. 2. 25 percent slope percentage restraint characteristic

## II. Sources of Differential Current in an Unfaulted Zone With a Power Transformer

Unlike a bus or motor/generator application, a transformer differential zone has normal and expected differential current when everything is operating normally. It is not possible to completely balance the currents at the boundaries of the zone to eliminate these natural differential currents. The percentage restraint characteristic tolerates these normal differential currents, in addition to false differential current, and that is why transformers are typically protected by this type of differential relay.

For discussion, we can classify the sources of differential current into three categories:

- Differential current that is not proportional to the current flow through the zone (steady state).
- Differential current that is proportional to current flow through the zone (proportional).
- Differential current that is transient in nature (transient).

### *A. Sources of Steady-State Differential Current*

Steady-state differential current is not proportional to through current. The main source of steady-state differential current is the magnetizing branch of the transformer equivalent circuit. Under normal operating conditions, this current is typically in the order of 1 to 4 percent of the transformer rating. This source of differential current plots on the percentage restraint characteristic as shown in Fig. 3.

The impedance of the magnetizing branch is nonlinear, and under abnormal operating conditions such as energization (inrush) or overexcitation, the differential current that flows contains high levels of harmonics. This differential current is not false differential because it is actually flowing in the primary circuits. However, we do not want the differential protection to operate for these conditions. For this reason, harmonic restraint or harmonic blocking functions are added to most relays intended for transformer applications. Further discussion of this topic is outside the scope of this paper. Reference [3] should be consulted for further information.

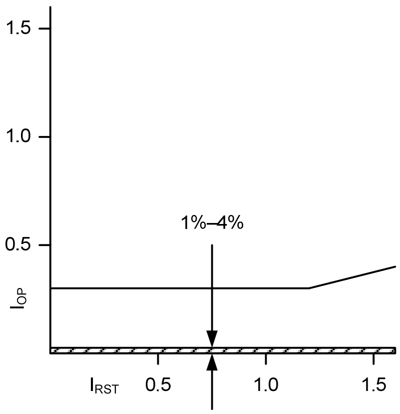


Fig. 3. Steady-state differential current on a percentage restraint characteristic

Another source of steady-state mismatch is unmonitored load in the zone of protection. A typical unmonitored load is a station service transformer connected to the secondary or tertiary winding of the protected transformer. Of course, this source of differential current is not steady state at all. But, for purposes of this discussion because it is not proportional to the through current of the transformer, we will consider it as such.

Typically, we can use the full rating of the station service transformer as a conservative estimate of the differential current attributed to this source. Of course, when the secondary of the station service transformer is short-circuited, the differential current will be much higher than the rating of the transformer. However, the size of the station service transformer is usually relatively small so that its impedance will typically limit the differential current to a level below the minimum pickup of the percentage restraint characteristic. It is recommended to evaluate the minimum pickup setting of the percentage restraint characteristic versus the short-circuit current on the secondary of the station service transformer.

### *B. Sources of Proportional Differential Current*

Proportional differential current is a function of through current in the zone of protection. The amount of differential current that must be tolerated is relatively proportional to the flow of current through the zone of protection. For this reason, the percentage restraint characteristic is well suited to deal with this source of differential current. Sources of proportional differential current include:

- Tap compensation mismatch.
- Tap changers on the protected transformer.
- Relay measuring error.
- Steady-state CT ratio (CTR) error.

The following sections examine each of these in turn.

#### *1) Tap Compensation Mismatch*

A power transformer typically has a different voltage rating on each winding for the purpose of stepping the system voltage up or down to interconnect power systems of differing voltage ratings. It is desirable to choose CTRs to offset the ratio of the power transformer such that the current in the secondary of the CTs is the same on each side of the transformer. In the example shown in Fig. 4, the primary ratio is 138 kV/69 kV = 2. The ratio of the CTs is selected to exactly offset the primary ratio, 120 T/240 T = $2^{-1}$. Please note that considerations for phase shift and zero-sequence compensation are ignored in the examples as outside the scope of this paper. See [1] for detailed discussion of those issues.

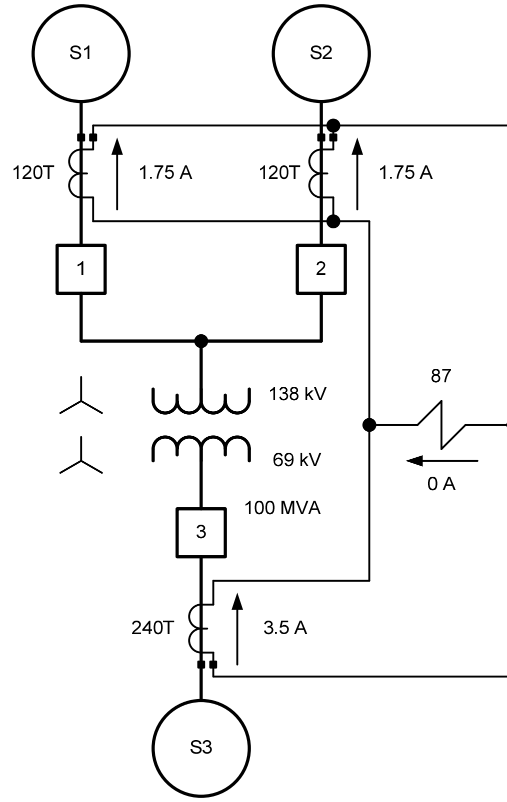


Fig. 4. Compensation for primary turns ratio

However, in most applications, it is not possible to achieve perfect compensation for the primary ratio by choosing CTRs. In the Fig. 4 example, the lines connecting S1 and S2 to the substation are rated 1200 A. A CTR of 600:5 = 120 T would limit these lines to only 600 A. So, instead, we choose a ratio of 1200:5 = 240 T. The CT secondary currents from Breakers 1 and 2 are now half of what they need to be to offset the current in Breaker 3.

A percentage restrained differential relay usually has ratio matching taps that can scale the currents and compensate for this mismatch. Electromechanical (EM) relays typically have a limited number of taps, so it is not possible to totally eliminate the mismatch. Applying a popular EM transformer differential relay [4] [5] to this example, we choose TAP1 and TAP2 = 4.2 for the 138 kV CTs and TAP3 = 8.7 for the 69 kV CTs. This provides a good mismatch of only 3.6 percent but a poor minimum pickup of 75 percent per (1) and (2).

$$\text{Mismatch \%} = \frac{\frac{I1}{TAP1} - \frac{I3}{TAP3}}{\min\left(\frac{I1}{TAP1}, \frac{I3}{TAP3}\right)} \bullet 100 \tag{1}$$

$$\text{Minimum pu \%} = 0.3 \bullet \max\left(\frac{TAP1}{I1}, \frac{TAP3}{I3}\right) \bullet 100 \tag{2}$$

where:

I1 and I3 are the secondary currents in a pair of CTs at 100 percent transformer rating.

Alternatively, we could choose TAP1 and TAP2 = 2.9 and TAP3 = 5.0, which would provide a poorer mismatch of 16 percent and a better minimum pickup of 50 percent. Trying different combinations of CTRs could also yield better results. The tap compensation mismatch is not a false differential current. It needs to be added to the percentage restraint characteristic.

Microprocessor-based differential relays have virtually eliminated tap compensation mismatch because they typically allow selection of tap compensation factors with 1/100th of an ampere increments.

*2) Tap Changers*

Transformer windings are often tapped to provide the ability to adjust their ratios to accommodate local conditions. Often, they include a no-load tap changer (NLTC) that allows the ratios to be adjusted up or down by 2.5 or 5 percent. If the setting engineer knows what tap the transformer will be placed on, the engineer can include the actual transformer ratio in the determination of tap compensation factors. But if operators or system planners can change the NLTC setting without the setting engineer's knowledge, it is a good idea to set the relay based upon the nominal tap and allow for the maximum tap difference from nominal in the percentage slope setting.

On-load tap changers (LTCs), however, can introduce typically ±10 percent mismatch in the current magnitude through the transformer. This source of mismatch changes dynamically in service, based on the tap-changer position, and can only be accommodated by the percentage restraint characteristic—unless the relay has the ability to read the tap-changer position and dynamically change its tap compensation factors in service. Differential current caused by tap-changer position is not a false differential current.

*3) Relay Measuring Error*

All relays have accuracy limitations that can introduce a false differential current measurement. The accuracy is often specified as ±5 percent or $\pm 0.02 \cdot I_{NOM}$, whichever is largest. The second term is used to provide a floor to the accuracy at low levels of current where the signal-to-noise ratio is low. For example, at 1 A through current in a 5 A relay, 5 percent error would be only 50 mA. But the minimum accuracy limit of $0.02 \cdot 5\ A_{NOM}$ = 100 mA would be the accuracy specification in force. The minimum pickup portion of the percentage restraint characteristic prevents operation at low levels of current where the absolute accuracy is reduced.

*4) Steady-State CTR Error*

CTs create both steady-state and transient errors, which can result in false differential current. CTs are, as their name implies, transformers. So the transformer equivalent circuit shown in Fig. 5 can be used to understand the nature of CT error. $Z_P$ and $Z_S$ are the series combination of the leakage reactance of each winding and the winding resistance. In a C-class relay-accuracy CT, the leakage reactance is negligible, so the only impedance is the CT winding resistance. Also, most relay-accuracy class CTs only have a single turn primary, so $Z_P$ is also negligible.

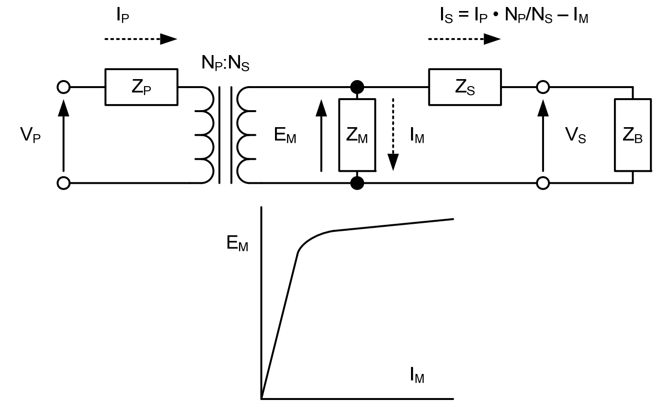


Fig. 5. CT equivalent circuit

$Z_M$ is the magnetizing branch impedance of the CT. This impedance is nonlinear, as shown in the graph of $E_M$ versus $I_M$ in Fig. 5, and generally taken to be a function of the voltage, $E_M$, across it under steady-state conditions. $E_M$ is given by $I_S \cdot (R_S + Z_B)$. $R_S$ is the secondary winding resistance, and $Z_B$ is the external burden. Reference [6] specifies that a relay-accuracy CT must be 3 percent accurate at rated current and 10 percent accurate at 20 times rated current when $Z_B$ is the standard burden. It is important to note that the rated current specified in [6] is a symmetrical sinusoidal waveform.

Examination of Fig. 5 shows that the error in $I_S$ is defined by $I_M$. From this, we can conclude that $Z_M$ will only shunt 3 percent or less of the current away from the external secondary circuit under normal load flow conditions as long as the external burden is less than the standard burden. In fact, the burden of the external CT circuit is often designed to be much smaller than the standard burden to reduce the likelihood of transient CT saturation during fault conditions. In that case, the error current will likely be much less than 3 percent for current flow at low multiples of the nominal rating of the CTs.

Another observation that can be made is that CT errors are always subtractive, and errors in the CTs with current entering the zone tend to cancel errors in the CTs with current exiting the zone.

*C. Sources of Transient Differential Current*

CT saturation is the primary source of transient differential current. A CT becomes saturated when the volts per turn required to drive ratio current through the secondary burden requires greater flux than can be concentrated in the magnetic core linking the primary and secondary windings of the CT. Once the flux density is exceeded, the core becomes saturated. Symmetrical saturation can occur when the magnitude of the primary current flow requires that $I_S \cdot (R_S + Z_B)$ exceed the volts-per-turn capability of the CT.

Symmetrical CT saturation occurs when testing the accuracy class rating of a CT. A primary current of 20 times rating is passed through the CT with the standard burden connected across the secondary terminals of the CT. The CT has adequate iron when the current in the magnetizing branch shunts less than 10 percent (10 A in the case of a 5 A rated

CT) from the secondary current. As can be seen in Fig. 6, the 10 A of error current is not sinusoidal.

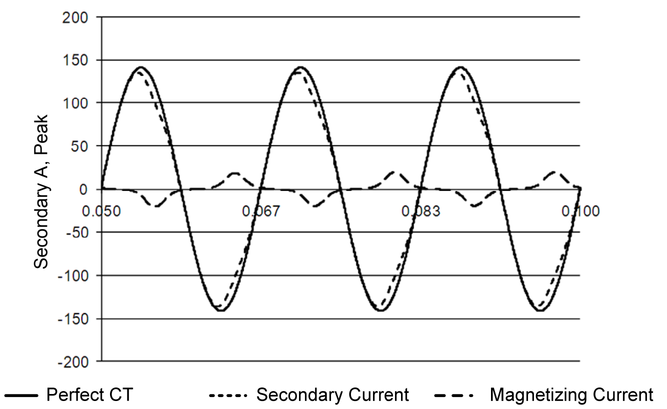


Fig. 6. Symmetrical CT saturation at 20 times nominal with standard burden

High current with a dc offset, as often occurs during a fault, causes asymmetrical saturation. An asymmetrical current causes the flux 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. 7 shows how the flux accumulates in a saturated CT. The flux density is a function of the integration of the volt-time area [7]. Notice that where the change in flux is zero, the induced secondary current is also zero.

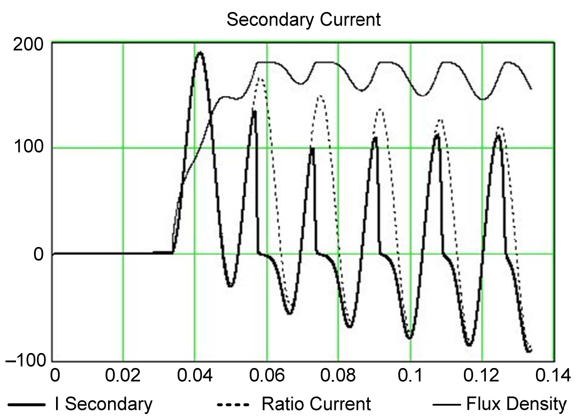


Fig. 7. Secondary current and flux density for CT with asymmetrical saturation

Asymmetrical CT saturation is experienced in real-world cases. Transient differential current cannot be characterized by steady-state analysis. Determination of transient differential current requires time domain simulation. From the previous discussion, it can be concluded that we cannot simply add 10 percent to the slope setting per the relay-accuracy class specification of 10 percent error at 20 times nominal to allow for transient CT saturation during external fault conditions.

### *D. Steady-State and Proportional Differential Current Examples*

We use simple analysis to determine the amount of slope required to accommodate steady-state and proportional sources of differential current. The following example is based on the application shown in Fig. 4 with TAP equal to 3.5 on all restraint inputs. Fig. 8 illustrates the example using the following parameters:

- Excitation current = 4 percent
- CT accuracy = 3 percent
- NLTC = 5 percent
- LTC = 10 percent
- Tap mismatch = 0 percent
- Relay accuracy = 5 percent or 0.1 A (0.0286 • TAP)

If we simply add up the various percentages, we get 27 percent. We recognize that the differential current from excitation is not proportional but include it as a proportional error as a conservative approach. The graph in Fig. 8 shows that a 27 percent setting, along with a minimum pickup of 0.2 times TAP, should be adequate if transient differential current is not considered.

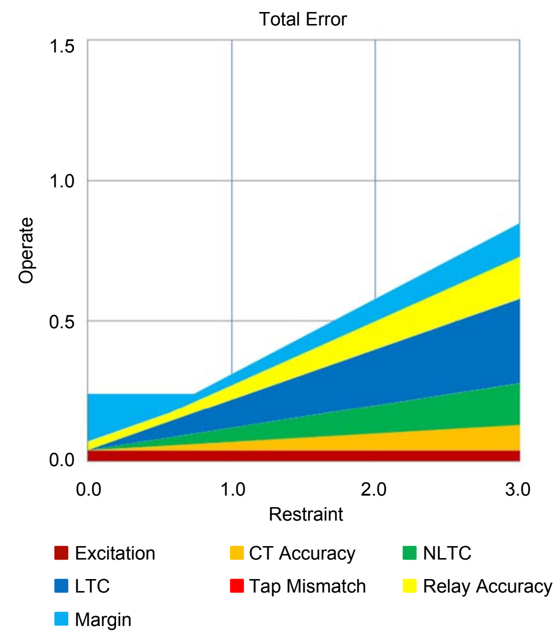


Fig. 8. Steady-state and proportional mismatch error, Example 1

Note that the point of minimum margin is where the minimum pickup line intersects with the slope line. Increasing the minimum pickup to 0.3 times TAP would improve this margin. But assuming that all errors will be maximum and additive is already a conservative approach, so additional margin is probably not warranted.

For a second example, we set our tap compensation factors based upon the in-service NLTC position. We also determine that the CT burden is much smaller than the standard burden so that we can assume only 1 percent for CT error. Fig. 9 illustrates this example using the following parameters:

- Excitation current = 4 percent
- CT accuracy = 1 percent
- NLTC = 0 percent
- LTC = 10 percent
- Tap mismatch = 0 percent
- Relay accuracy = 5 percent or 0.1 A (0.0286 • TAP)

This gives us a total of 20 percent. Fig. 9 shows that we have a positive margin.

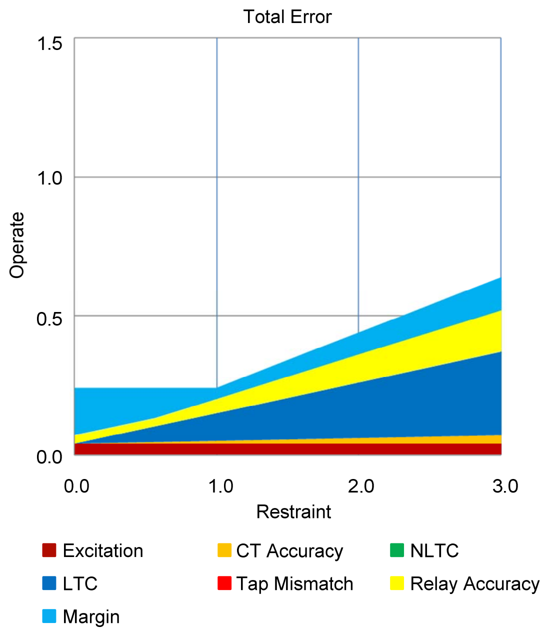


Fig. 9. Steady-state and proportional mismatch error, Example 2

The previous graphs are a simplification but useful in visualizing the nature of the various errors that have been described. These graphs are valid for a differential element using MAXIMUM restraint with all errors additive. Section IV describes MAXIMUM restraint.

## III. Percentage Restraint Characteristics

As stated in Section I, percentage restrained differential relays measure the individual branch currents and quantify the through current in the zone of protection. The percentage restraint characteristic operates on the ratio of:

- Operate current. This is the differential current, which is the phasor or instantaneous sum of the currents flowing into the zone of protection.
- Restraint current. This 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, as discussed in Section IV.

The ratio of operate current to restraint current that will determine if the relay restrains or trips can be a simple ratio check (with a minimum pickup cutting off the ratio check at low levels). This is a single-slope characteristic. Fig. 2 is an example of such a characteristic. In many cases though, the percentage restraint characteristic can be a complex shape. Fig. 10 shows three such characteristics: a single-slope characteristic set at 25 percent, a dual-slope characteristic set at 25 percent transitioning to 50 percent at three times TAP, and a variable percentage characteristic from a popular EM relay [8].

The requirement that the operate current exceed a percentage of the restraint current allows the relay to tolerate sources of steady-state and proportional mismatch in the zone of protection. It also allows the relay to tolerate transient differential current caused by CT saturation.

Fig. 10 shows that the variable percentage and dual-slope characteristics require a higher percentage of differential current to operate at higher levels of through current. This desirable attribute allows higher sensitivity at low current levels and progressively higher security at higher current levels when CT saturation is more likely. We can set Slope 1 of a dual-slope relay considering only the steady-state and proportional sources of differential current and use the second (higher) slope to accommodate transient differential current from CT saturation. The slope setting of a single-slope relay must be set to accommodate all sources of differential current, which reduces the sensitivity at low current levels.

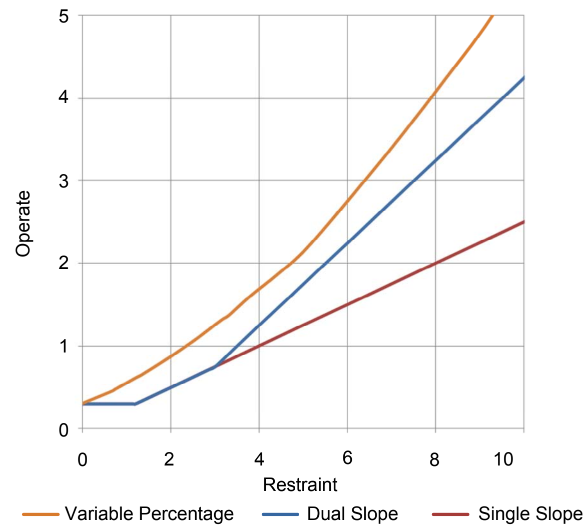


Fig. 10. Example percentage restraint characteristics

Fig. 11 shows another form of percentage restraint characteristic, called an adaptive-slope characteristic. The relay has logic to determine when an external through fault occurs. When the relay detects an external fault, it switches to the second (higher) slope until the fault is cleared [9]. The idea is that, if an external fault occurs, there is the possibility of false differential current appearing if a CT goes into asymmetrical saturation. The higher slope allows the relay to better tolerate the CT saturation. But, if the fault evolves to an internal fault, the differential element is not blocked and can still trip—although with less sensitivity. Slope 1 of an adaptive-slope relay can be set considering only the steady-state and proportional sources of differential current, and the second (higher) slope can be set to accommodate transient differential current. Comparing the dual-slope characteristic in Fig. 10 to the adaptive-slope characteristic in Fig. 11 shows that the adaptive-slope relay, when operating on Slope 2, has a greater restraining area than the dual-slope relay.

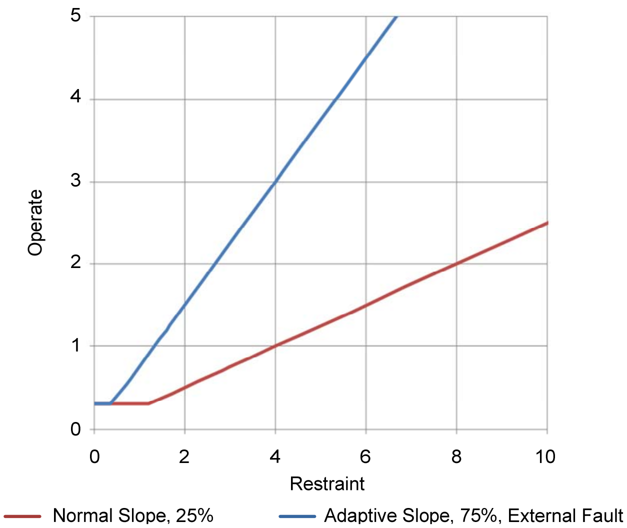


Fig. 11. Example adaptive percentage restraint characteristic

## IV. Restraint Quantities

The effective sensitivity and security of a given percentage restraint characteristic are dependent upon the principle by which the restraint current is quantified. The two most common principles are given by (3) and (4).

$$I_{RST} = k\left(\left|I_{W1}\right| + \left|I_{W2}\right| + \ldots \left|I_{Wn}\right|\right) \tag{3}$$

$$I_{RST} = MAX\left(\left|I_{W1}\right|, \left|I_{W2}\right|, \ldots \left|I_{Wn}\right|\right) \tag{4}$$

where:

$I_{RST}$ = restraint current in restraint characteristic

$I_{Wn}$ = individual branch currents

k = scaling factor

MAX = function to find the maximum value

Equation (3) is commonly referred to as AVERAGE restraint. For a two-restraint input zone, the average of the branch currents is measured when *k* is equal to 0.5. For multiple restraint applications, it is desirable to think in terms of measuring the average of the total current entering the zone and the total current exiting the zone. When *k* is equal to 0.5, (3) still yields the average current through the zone. Scaling factor *k* can be other values as well.

Equation (4) is commonly referred to as MAXIMUM restraint. It uses the maximum branch current measured to determine the through current in the zone of protection. If we consider Fig. 4, the through current in the zone flows from S1 and S2 towards S3. The differential input of a multirestraint relay on the CB3 CT measures the sum of the currents; this current is the maximum of the three, so it is a good measure of through current. The same would be true for an external fault on the S3 line. If the external fault is on the S2 line, typically there would be fault current contribution from both S1 and S3. The differential input on the CB2 CT would measure the sum of the currents and be the maximum in this case.

When differential current is present, either from the natural sources of differential current previously described or from an internal fault, the through current is less obvious. To illustrate the concepts, we will examine five common relay characteristics versus a reference relay characteristic. Three EM relays are included to help understand the basis from which the digital techniques were developed.

To directly compare the characteristics, it is necessary to convert them to a common definition of operate and restraint so that their characteristics can be plotted on the same operate-versus-restraint graph. All of the relays can be set at 25 percent slope with a minimum pickup of 0.3 times TAP, except the variable percentage relays that have no defined slope percentage. So, for comparison purposes, each relay characteristic is compared to the reference relays [10] [11]. The reference relays use (3) with *k* equal to 0.5 and a tripping characteristic set at 0.3 times the TAP minimum pickup and 25 percent slope.

### *A. Two Widely Used EM and Static Relays With Single Slope and AVERAGE Restraint*

These relays detail their operating characteristic in a graph of through current versus percentage slope. The manuals define through current as "the sum of the incoming or sum of the outgoing current—whichever is smallest" [4] [5]. This definition implies that the current entering the zone minus the current that stays in the zone (the differential current) is the through current. It also states a minimum pickup at zero restraint. For both of these statements to be true, the relay would have to subtract the differential current from the branch circuit currents to determine the restraint quantity. Examination of the relay circuitry indicates that this is not the case. The relay actually uses (3) with a *k* factor of 0.4444 ($2.25^{-1}$) instead of 0.5 ($2^{-1}$). Fig. 12 shows the characteristic relative to the reference characteristic. The 25 percent slope on this relay equates to only 22.2 percent slope on the reference characteristic.

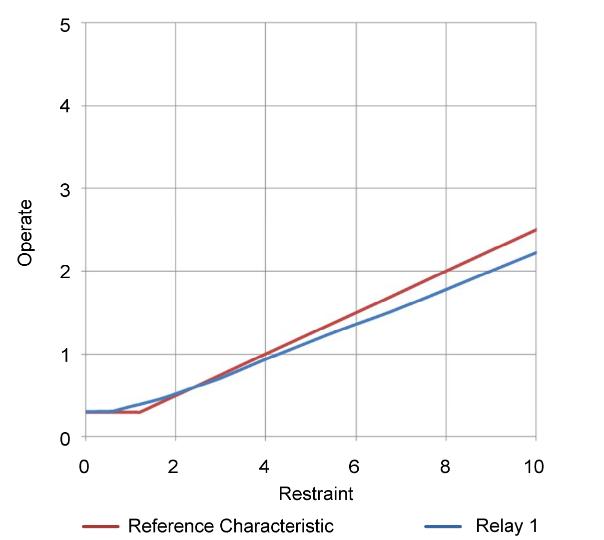


Fig. 12. Example relay with 25 percent slope, AVERAGE restraint, *k* = 0.444

### *B. Widely Used EM Relay With Variable Slope and MAXIMUM Restraint*

This relay with variable slope and MAXIMUM restraint provides its operating characteristic in a log-log graph [8]. It uses (4) to quantify restraint. Fig. 13 shows the characteristic relative to the reference characteristic.

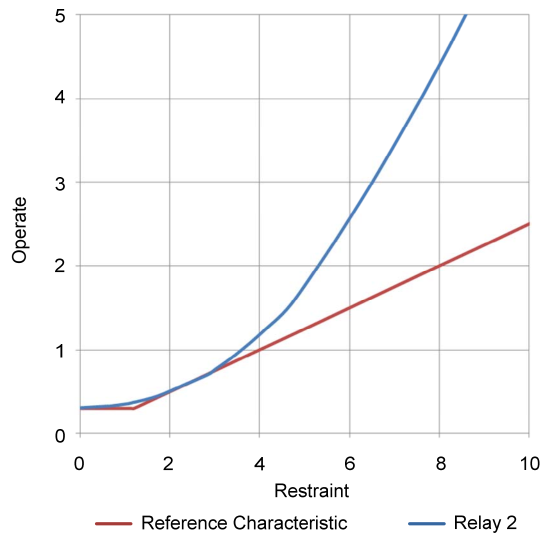


Fig. 13. Example relay with variable slope and MAXIMUM restraint

### C. *Widely Used EM Relay With Variable Slope and AVERAGE Restraint*

This relay with variable slope and AVERAGE restraint is similar to Relay 2 except that it has more restraint inputs, and because of that, it uses AVERAGE restraint per (3). Because it has a variable-slope characteristic, $k$ is equal to 1 and the operate points are taken off of the characteristic graph [8]. Fig. 14 shows the characteristic relative to the reference characteristic.

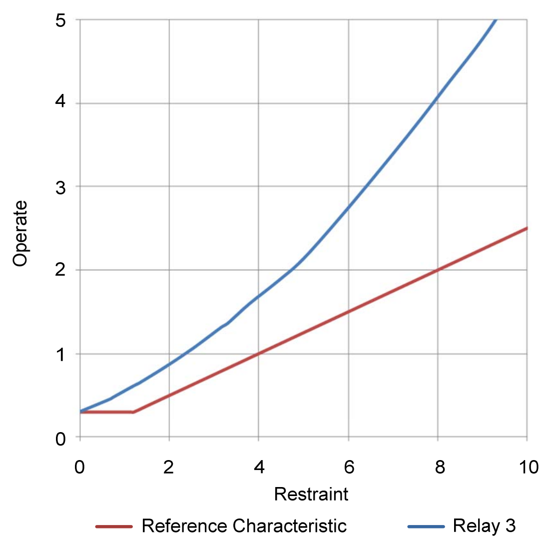


Fig. 14. Example relay with variable slope and AVERAGE restraint

### D. *Numerical Relay With AVERAGE/k = 1 Restraint*

These numerical relays [9] [12] are similar to the reference relays except that $k$ is equal to 1 in (3). Fig. 15 shows the relay characteristic set to 25 percent relative to the reference characteristic. The 25 percent slope on this relay equates to 50 percent slope on the reference characteristic.

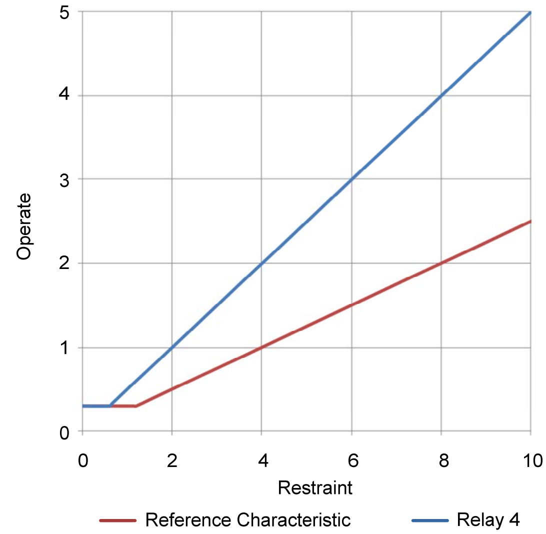


Fig. 15. Example relay with 25 percent slope, AVERAGE restraint, and $k = 1.0$

### E. *Numerical Relay With MAXIMUM Restraint*

The numerical relay in this example has a setting for the user to select AVERAGE or MAXIMUM restraint [13]. MAXIMUM restraint is shown here for illustration. Because the maximum current will always be higher than the average current when differential current is present, MAXIMUM restraint provides a higher restraint ratio. Fig. 16 shows the characteristic relative to the reference characteristic. The 25 percent slope on this relay equates to 28.57 percent slope on the reference characteristic.

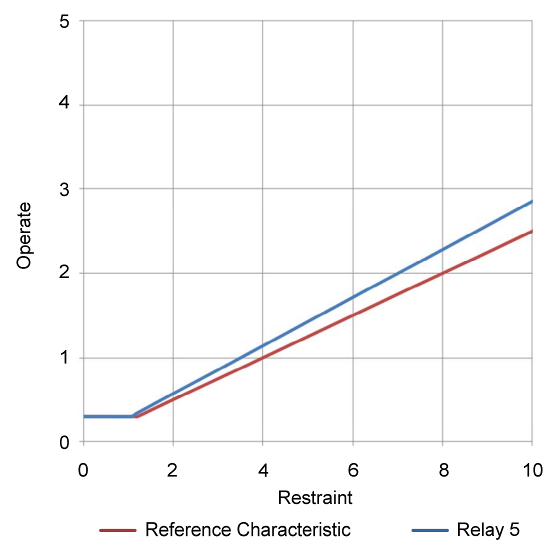


Fig. 16. Example relay with 25 percent slope and MAXIMUM restraint

## V. Setting the Slope Characteristic

The purpose of the percentage restraint characteristic is to allow the relay to differentiate between differential current from an internal fault versus differential current during normal or external fault conditions. The engineer must select slope characteristic settings that balance security and dependability.

To do this, it is helpful to determine what slope ratio is characteristic of normal conditions (slope must be above that for security) and what slope ratio is characteristic of an internal fault (the slope must be below that for dependability). This bounds the upper and lower limits of the slope ratio that can be selected. The engineer then chooses a setting with margin to each of these limits, also considering sensitivity requirements.

### *A. Minimum Slope Ratio Limit*

Section II describes the various normal sources of differential current that the differential element must tolerate. Considering only steady-state and proportional differential current, we can determine the minimum limit of the allowable slope ratio using (5) and (6).

$$SLP1_{MIN}\% = \left( \frac{Err\%}{(200 - Err\%) \cdot k} \right) \cdot 100 \tag{5}$$

$$SLP1_{MIN}\% = Err\% \tag{6}$$

where:

$SLP1_{MIN}$ = slope ratio that will just accommodate Err with no margin

Err = amount of error expected in normal operation

k = AVERAGE restraint scaling factor from (3)

Equation (5) applies to relays using AVERAGE restraint. Equation (6) applies to relays using MAXIMUM restraint. Equation (5) is derived by assuming that the error is subtractive and reduces either the current entering the zone or exiting the zone. This gives the highest slope ratio. When we assume that the error adds to the current at the boundary of the zone, it creates additional restraint and therefore a lower slope ratio.

Table I shows the minimum slope setting obtained from (5) and (6) for the example application described in Section II, Subsection D and shown in Fig. 8.

TABLE I
MINIMUM SLOPE SETTING FOR 27 PERCENT ERROR EXAMPLE

| Restraint Method | Minimum | Maximum |
|---|---|---|
| AVERAGE, k = 0.50 | 32% | 200% |
| AVERAGE, k = 0.44 | 36% | 225% |
| AVERAGE, k = 1.00 | 16% | 100% |
| MAXIMUM | 27% | 100% |

### *B. Maximum Slope Ratio Limit*

For the following discussion, we make the simplifying assumption that the source impedance angles are the same. This allows us to assume that, for an internal fault, the fault current contributions in each restraint input to the relay are in phase and can be summed by simple addition. This assumption is acceptable when the variation in source impedance angles is not great. We also assumed that there is no outfeed.

For an AVERAGE restraint differential element, the slope ratio for an internal fault is $k^{-1}$. For a MAXIMUM restraint differential element, determining the slope ratio for an internal fault is much more complex. It falls in a range of 100 to 300 percent for a three-restraint application and is dependent upon the distribution of contributions from each source. The upper boundary condition occurs when all sources contribute exactly the same magnitude of fault current. Equation (4) yields $I_{RST} = 1/3 \cdot I_{OP}$, giving a slope ratio of 300 percent. The lower boundary condition occurs when only one source contributes fault current, as would be the case for a radial-sourced transformer or when energizing the zone into a fault. Equation (4) yields $I_{RST} = I_{OP}$, giving a slope ratio of 100 percent. For dependability, the MAXIMUM restraint relay cannot be set above 100 percent. These values are summarized in Table I.

### *C. Slope Ratio for External Fault With CT Saturation*

Table I tells us the range of slope settings that we can consider for each relay. However, transient differential current from CT saturation has not yet been considered. In a dual-slope or adaptive-slope relay, the minimum value given by (5) and (6) with a small margin could be used for Slope 1. False differential current from CT saturation would be covered by the Slope 2 characteristic. A single-slope relay would have to be set with higher than these minimum values.

Next, we examine the effect of CT saturation on the differential elements using the different restraint calculations. Fault currents are calculated for three external faults for the three-restraint application shown in Fig. 17. Methods can be used to gain a better idea of how much saturation can be expected in a given application, but transient simulation is the only way to accurately assess this [2]. For the purposes of this example, we assume that the CT with maximum current saturates and only provides 50 percent ratio current. The TAPS are 1.75 for R1 and R2 and 3.5 for R3. Table II summarizes the results.

TABLE II
EXTERNAL FAULTS WITH FAULTED CIRCUIT CT SATURATING 50 PERCENT

| Restraint Method | $I_{RST}$ F1 | Ratio F1 | $I_{RST}$ F2 | Ratio F2 | $I_{RST}$ F3 | Ratio F3 |
|---|---|---|---|---|---|---|
| AVERAGE, k = 0.50 | 29.88 • TAP | 66.7% | 42.34 • TAP | 66.7% | 6.67 • TAP | 66.7% |
| AVERAGE, k = 0.44 | 26.56 • TAP | 75.0% | 37.63 • TAP | 75.0% | 5.93 • TAP | 75.0% |
| AVERAGE, k = 1.00 | 59.77 • TAP | 33.3% | 84.67 • TAP | 33.3% | 13.34 • TAP | 33.3% |
| MAXIMUM | 33.20 • TAP | 60.0% | 49.81 • TAP | 56.7% | 5.34 • TAP | 83.3% |

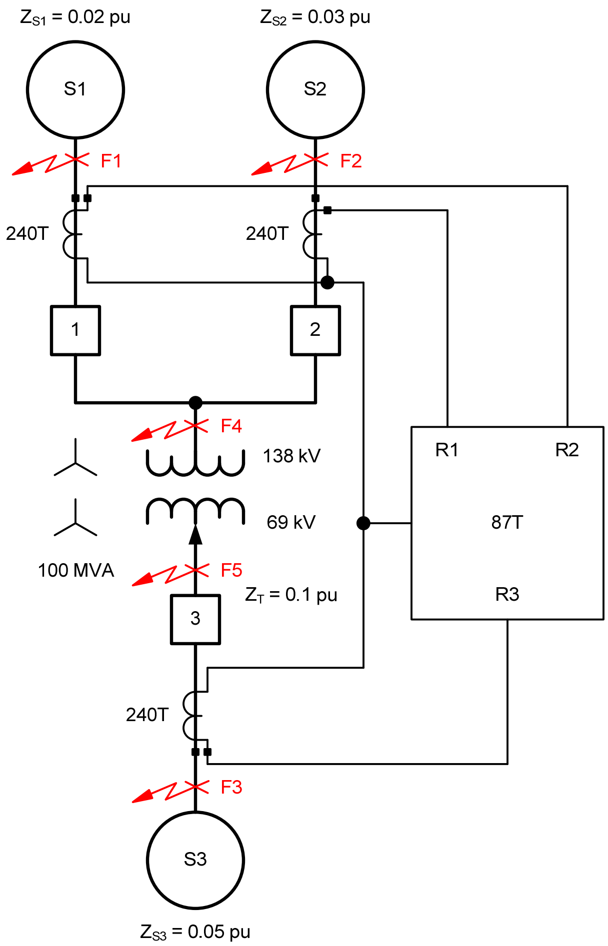


Fig. 17. Example through fault with 50 percent CT saturation

All of the AVERAGE restraint elements provide the same slope ratio, regardless of the level of through-fault current. This is because all of the branch currents contribute to restraint. In contrast, the MAXIMUM restraint element has widely different slope ratios, depending upon the distribution of fault contributions. This principle of restraint ignores information from all but one input to the zone.

Table III shows the results for the internal faults. Comparing the difference between an internal fault and an external fault with 50 percent CT saturation, we would need to set the AVERAGE/k = 0.50 with a slope higher than 66.7 percent and lower than 200.0 percent. For the AVERAGE/k = 1.0 element, the range is 33.3 to 100.0 percent. The AVERAGE elements provide a wide difference between distinguishing an internal fault from an external fault with 50 percent CT saturation.

TABLE III
INTERNAL FAULTS

| Restraint Method | $I_{RST}$ F4 | Ratio F4 | $I_{RST}$ F5 | Ratio F5 |
|---|---|---|---|---|
| AVERAGE, k = 0.50 | 44.83 • TAP | 200.0% | 14.41 • TAP | 200.0% |
| AVERAGE, k = 0.44 | 39.84 • TAP | 225.0% | 12.81 • TAP | 225.0% |
| AVERAGE, k = 1.00 | 89.65 • TAP | 100.0% | 28.28 • TAP | 100.0% |
| MAXIMUM | 49.81 • TAP | 180.0% | 19.92 • TAP | 144.6% |

Examining Table II and Table III for the MAXIMUM restraint element, we find the acceptable range is higher than 83.3 percent and lower than 100 percent, which is a very small difference, and the 83.3 percent case was specific to the distribution of contributions in the example. If we are unlucky enough to have equal contributions from S1 and S2 to the fault at F3, S1 and S2 each contribute 0.5 per-unit current, while S3 sees 0.5 per-unit current because of the 50 percent error—making the lower limit 100 percent while the upper limit is still 100 percent. There is no acceptable secure and dependable slope characteristic for this case.

Fig. 18 shows the fault cases for the AVERAGE/k = 1 differential element. The single-slope element is set at 35 percent slope. The dual-slope element is set at Slope 1 equal to 17.5 percent, transition point equal to 6, and Slope 2 equal to 50 percent. These slope settings accommodate all external faults with up to 50 percent error. Finding the second slope that will cover the external fault cases with the desired amount of error requires simple arithmetic.

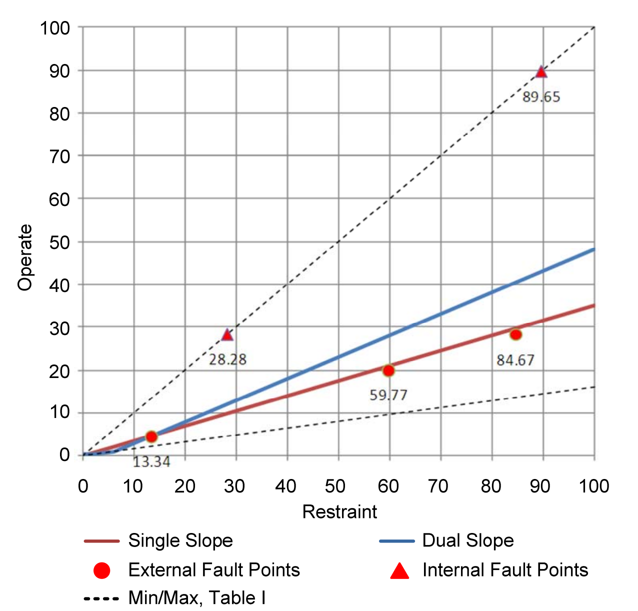


Fig. 18. Table II and Table III fault cases for AVERAGE/k = 1.0

Fig. 19 shows the same plot enlarged to show the F3 point. The external fault at F3 is limited by the transformer impedance and is almost an order of magnitude smaller than the faults at F1 and F2. If we assume that this fault is much less likely to have severe CT saturation, we could lower the Slope 2 setting to 35 percent. This setting provides enough slope to accommodate 50 percent error for the faults at F1 and F2—but not at F3. This example illustrates the advantage of the adaptive-slope differential element. Single Slope 1, set at 17.5 percent, would be in service for all internal faults, and single Slope 2, set at 35 percent, would be in service for all external faults.

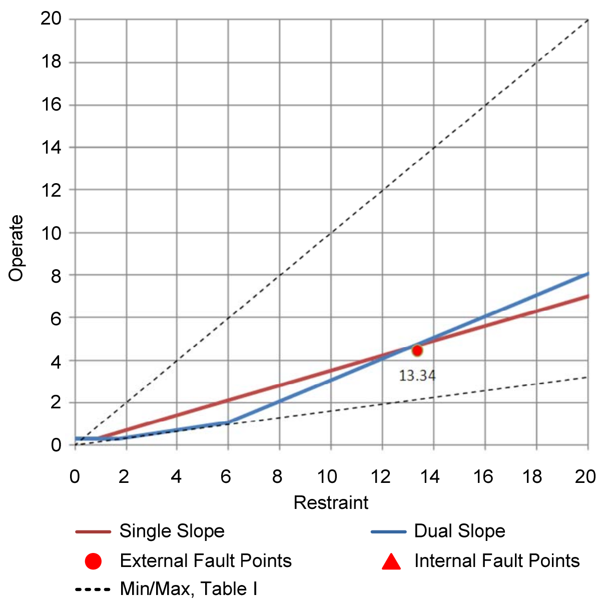


Fig. 19. Fig. 18 with reduced axis

To find the equivalent settings for this example for an AVERAGE/k = 0.5 relay, we multiply the slope settings by 2 and the point of transition for the dual-slope relay by 0.5.

### *D. Additional Observations on the Example Application*

The two 138 kV terminals have to have a CTR of 1200:5 to not limit the 1200 A lines and bring the maximum through-fault current, 23.1 kA at F2, to less than 100 A secondary.

With a high CTR relative to the transformer rating, the minimum pickup cannot be set as sensitively as we might like. As the relay minimum pickup is in per unit of tap, it is a good idea to convert it to actual primary and secondary amperes to gain a better understanding of the actual setting. The minimum sensitivity limit of a numerical relay is typically 500 mA. If we try to select 0.20 per unit, the actual secondary current that the relay will measure at that level is only 0.20 • 1.75 = 350 mA using the minimum TAP value. So we are forced to set it at 0.29 • 1.75 = 508 mA. The 0.2 to 0.3 per unit of transformer rating is an acceptable level of sensitivity. But, if the CTR on the 138 kV terminals has to be 2000:5, the minimum sensitivity could only be set to 0.48 per unit of transformer rating.

Other considerations are that the through-fault current for the two 138 kV terminals is not limited by the transformer impedance and current can be a very high multiple of TAP. In the example application, the current is nearly 50 times TAP. The Slope 2 setting needs to be set similarly to that for a bus application instead of a sensitive transformer application.

To obtain better sensitivity for the transformer and security for the bus, a better solution uses two relays—a bus differential relay that wraps the transformer lead bus up to the transformer bushings and a transformer differential relay that wraps only the transformer. Then, there is no need to compromise the sensitivity and security for the two very different conditions on the bus and the transformer. The cost of a second relay for this zone is minimal compared to the cost of the transformer that is being protected.

## VI. Protection for Partial Winding Faults

All of the analysis up to this point has focused on bolted faults with no outfeed. Outfeed happens when we have a low-grade fault that does not depress the voltage enough to prevent load flow from flowing out of the zone and adding restraint. Transformer differential applications need high sensitivity because a turn-to-turn fault inside the tank can cause high current in the shorted turns and a great deal of localized damage. But the current in the faulted loop is transformed by the autotransformer effect such that it can be quite small at the terminals of the zone. If 5 percent of the winding is shorted, fault current is reduced by a factor of 20 at the terminals of the transformer. A partial winding fault also typically does not depress the voltage enough to prevent outfeed. High sensitivity (low minimum pickup and low Slope 1) can help detect a partial winding fault and trip the transformer to limit damage. If the fault is not detected, it will eventually grow to the point where more turns are involved and the fault can be detected. The degree of coverage for partial winding faults is a function of the load flow through the zone of protection.

A negative-sequence differential element can provide additional sensitivity for partial winding faults [1] [9] [14]. Under normal balanced conditions, the negative-sequence load flow through the transformer zone is near zero. When a partial winding fault occurs, it generates negative-sequence differential current with little or no restraint, which makes this element very sensitive. The negative-sequence through current behaves similarly to any other current flow in that the steady-state and proportional differential currents for the phase currents will also exist in the negative-sequence current. The minimum slope setting limit will be calculated similarly to the way it is calculated for the phase elements.

The negative-sequence differential element uses MAXIMUM restraint per (4), so for the example illustrated in Table I, the minimum slope ratio is 27 percent. This element does not have a dual slope or adaptive slope to accommodate CT saturation at higher levels. Instead, the logic that detects an external fault, instead of switching to a higher slope, simply blocks the element. For this application, a good setting for the negative-sequence differential element might be 27 percent per (6) plus 3 percent margin equals 30 percent.

## VII. Conclusions

Unlike simple differential zones that only have to deal with CT saturation during external faults, differential relays for transformer applications must be able to accommodate steady-state and proportional sources of differential current in the zone of protection under normal conditions. The minimum slope setting to accommodate these sources of differential current can be calculated based upon equations provided in this paper. The required percentage slope is dependent upon how the restraint value is calculated.

The slope characteristic settings must also accommodate transient differential current from CT saturation. Determining transient CT performance and false differential current with any precision requires transient simulation. But it is possible to evaluate the probability of CT saturation for a given application and select an amount of error that the engineer wants to accommodate to base the setting on. A 50 percent error was used in the examples in this paper.

The percentage restraint characteristic that determines if the operate-versus-restraint ratio is in the restraining region or the tripping region also affects the settings. Slope characteristics can be single-slope, dual-slope, variable-slope, or adaptive-slope. Characteristics that provide a low slope ratio at low through current and high slope ratio at high through current provide better balance between sensitivity and security than a fixed single-slope characteristic.

Relays that use the MAXIMUM restraint principle are less able to distinguish between internal and external faults with CT saturation because they effectively ignore current contributions from all but one terminal of the zone. For this reason, one of the EM relays that was examined uses MAXIMUM restraint for two- and three-input versions and switches to AVERAGE restraint in the four-input version [8].

All differential elements that use AVERAGE restraint have the same level of sensitivity and security when the $k$ factor used in scaling the restraint signal is considered to determine the slope setting.

Low minimum pickup and low slope ratios are helpful to detect partial winding faults in transformers in order to trip before the fault grows and causes more extensive damage. But settings have to be balanced with security for CT saturation on external faults. Even with settings as low as security considerations allow, the ultimate sensitivity to partial winding faults can be reduced by the slope characteristic under high load-flow conditions. The negative-sequence differential element provides much higher sensitivity because normal load flow has very little negative-sequence current to restrain the element.

Understanding the way that the restraint value is measured and taking that into consideration when calculating settings for the percentage restraint characteristic will result in a good balance between sensitivity and security.

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## IX. Biography


**Michael J. Thompson** received his BS, 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, Inc. (SEL) in 2001, he was involved in the development of several numerical protective relays while working at Basler Electric. He is presently a principal engineer in the engineering services division at SEL, a senior member of the IEEE, a main committee member of the IEEE PES Power System Relaying Committee, and a registered professional engineer. Michael was a contributor to the reference book, *Modern Solutions for the Protection, Control, and Monitoring of Electric Power Systems*, has published numerous technical papers, and has a number of patents associated with power system protection and control.



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