Not All Differentials are the Same: How Different Percent Differential Relay Algorithm Methods Can Impact Relay Settings and Performance

Matt Proctor (GE Digital Energy)

Abstract — This paper explores different commonly used methods of performing percent differential protection. Despite a common fundamental concept, differential relays can behave very differently. Relays have different methods of calculating restraint current and different ancillary methods of producing restraint to improve security. To properly apply and test these relays, engineers and technicians must go beyond the basic concept of summing currents entering and exiting the zone of protection. This paper gives suggestions for developing protective relay settings giving consideration to these nuances.

Index Terms —Differential Protection, Percent Slope Differential, Restraint Current, Operate Current

I. Introduction

In its simplest form, a differential relay is simply an instantaneous overcurrent relay that is operating based on the physical summation of two CT's that are wired together with opposite polarity.

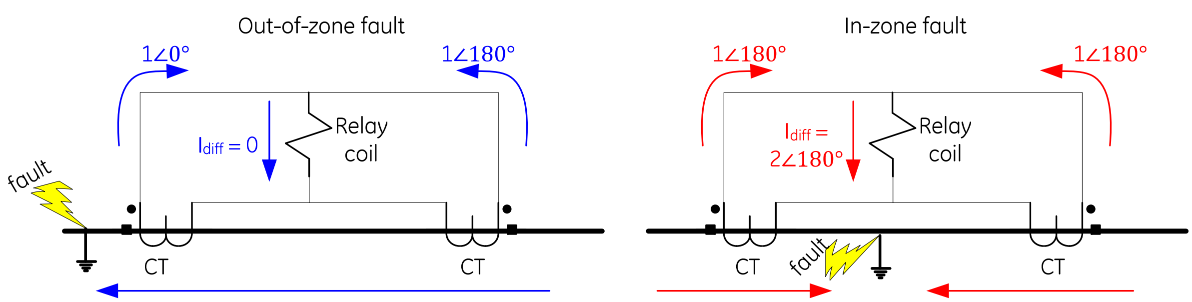

Figure 1: Basic Unrestrained Differential

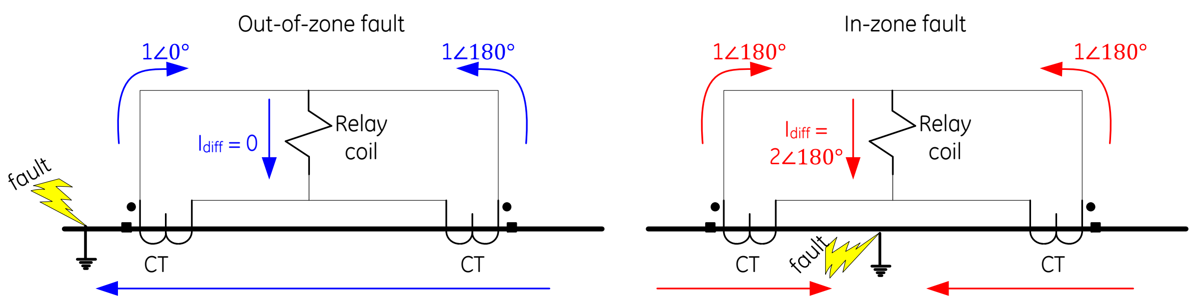

Figure 1 shows a basic unrestrained differential. On the left, a fault out of the zone of protection, defined as the energized equipment between the two CT's, results in a phasor sum of 0 differential current. On the right, a fault within the protected zone results in a non-zero differential current.

This example demonstrates how differential relays meets specific protection challenges, "The 5 S's":

- **Selectivity** – The relay will not detect faults external to the protected zone.

- **Speed** – Because they do not detect out-of-zone faults at all, they can be set relatively quickly to meet the protection challenge of speed. Unlike other protection methods like time-overcurrent, no coordination time delay is required.
- **Sensitivity** – Because the relay operates off a measured quantity that is normally zero until an internal fault occurs, the pickup can be set relatively sensitive. There is no ambiguity between what is fault current and what is load current.
- **Security** – Assuming ideal performance of CT's and ideal relay performance, the differential system is inherently secure. The topic of the remaining sections of this paper is centralized around the challenges that arise because these ideal conditions do not exist.
- **Simplicity** – Although a basic differential scheme is intuitive, different techniques can be applied to enhance security, and unfortunately, this enhancement comes at the cost of simplicity, as will become evident later in this paper.

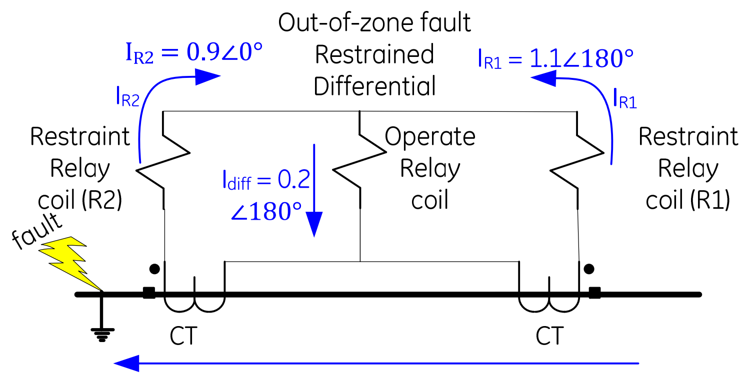

Figure 2: Restrained Differential

Figure 2 shows a basic percent differential. Notice that in this example, CT's do not perform ideally, so there is operate current despite the fact that the fault is not within the zone. With electromechanical relays, restraint coils are used to produce a force that partially counteracts the force produced by the current in the operate coil. The circuit is tuned so that tripping only occurs once the current through the operate coil reaches a certain percentage of the restraint current. With two identical restraint coils, equivalent restraint current is given by: $(I_{R1} + I_{R2})/2$, the average of the vector sum. A minimum pickup overcurrent function is added to the operate coil to prevent tripping on low levels of differential current that are not indicative of a fault. The overall slope characteristic is shown in Figure 3.

It can be clearly seen in Figure 3 that the differential current required to trip the relay continuously increases as restraint current increases. This yields the benefit of additional security when currents are high and CT's are more prone to inaccuracy due to saturation of the core.

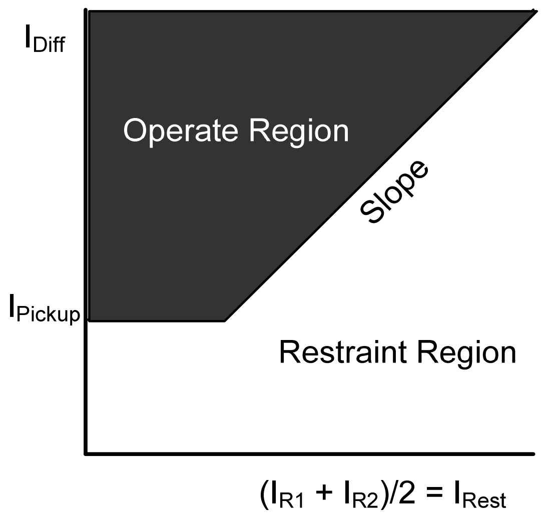

Figure 3: Operate vs. Restraint Percent Differential Characteristic

These characteristics are considered fundamental to a percent differential relay: restraint and differential currents, a percentage slope and a pickup setting. Whether the protected device is a bus, transformer, generator, or motor, the percent differential relay will have some variation of these characteristics. It is these variations that may cause two fundamentally similar relays, that operate by measuring identical current from the same CT's, to perform very differently. We will explore these variations.

II. Variations in Restraint Calculation and Slope

The overall restraint current shown in the example electromechanical system in the previous section was shown to be an average of the current in the two restraint coils. This characteristic was due to its physical design. With the advent of digital relays, the calculation of overall restraint was unencumbered by physical constraints, and thus relay manufacturers began to enhance the protection systems by using different calculation methods and dynamic slope characteristics to strike a desired balance between sensitivity and security.

A. Restraint Current Variations

i. Average

$I_{Rest} = 1/n(I_{Rest1} + I_{Rest2} + \ldots I_{Restn})$; where n is the number of current sources in the differential calculation.

This method most closely mimics traditional electromechanical designs.

ii. Scaled

$I_{Rest} = 1/k(I_{Rest1} + I_{Rest2} + \ldots I_{Restn})$; where n is the number of current sources in the differential calculation, and k is a scaling factor. A typical value is 2. This method is very similar to average but offers slightly more security. If the applied scaling factor is 1, the restraint current is simply a sum of all restraint currents in the system. The pure sum method is a very secure method, relative to alternate methods. The consequence is that a relay may over-restrain and fail to trip for an internal fault.

iii. MAXIMUM

$I_{Rest} = MAX(|I_{Rest1}|, |I_{Rest2}|, \ldots |I_{Restn}|)$; where n is the number of current sources in the differential calculation. This method achieves greater sensitivity than the summation method but better security than the average method.

iv. EXTRA BIASED RESTRAINT

To meet the seemingly mutually exclusive goals of simultaneously enhancing sensitivity and security, relay developers have gone well beyond a simple, current-magnitude-based restraint system. This will be explored in more detail in the Advanced Techniques section.

B. SLOPE VARIATIONS

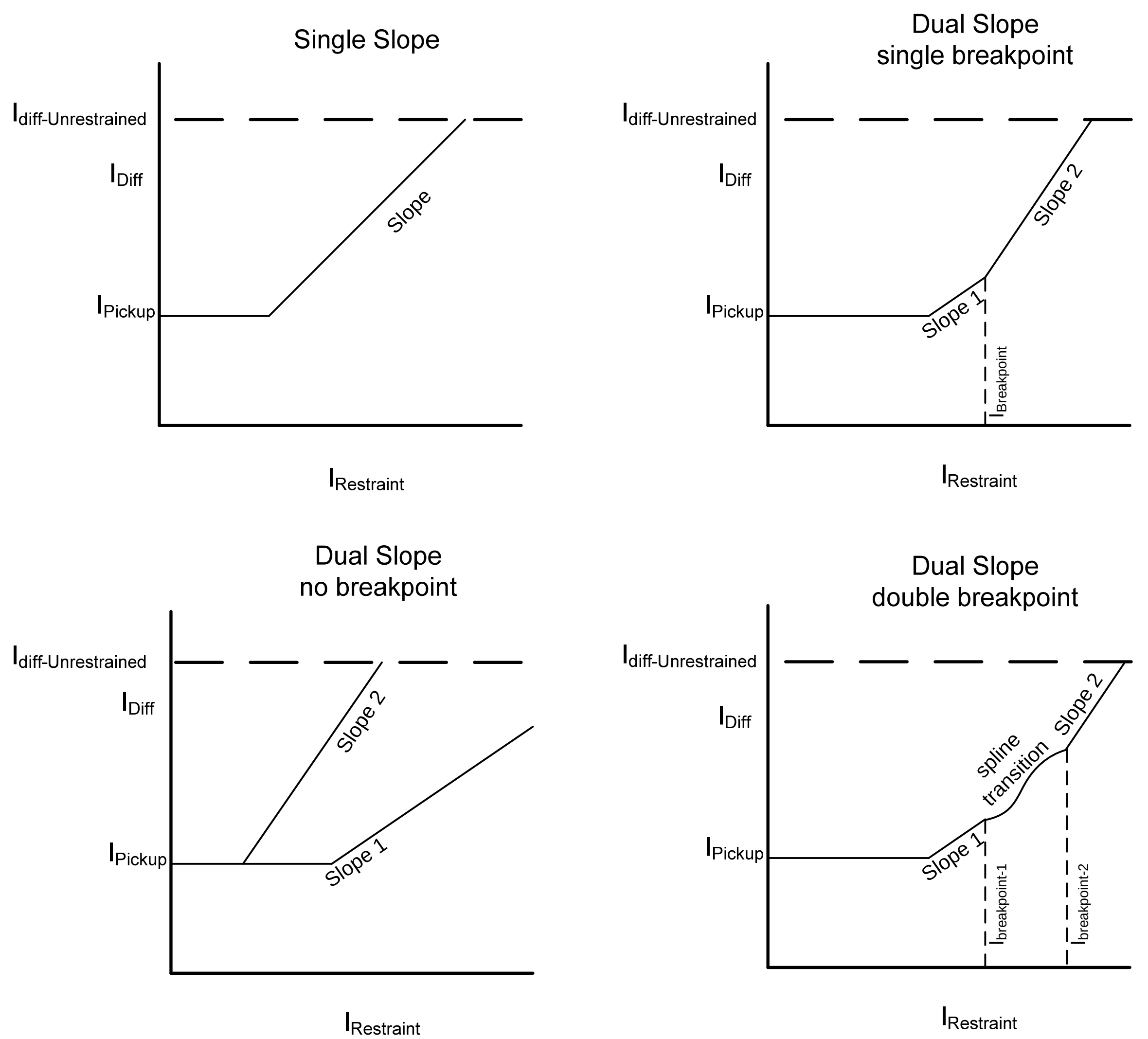

Figure 4: Four Different Implementations of Percent Slope Differential

Figure 4 shows four different implementations of percent slope differential:

Single Slope – The simplest implementation with the fewest setpoints, this concept is likely to be the least sensitive of those listed.

Dual Slope (single breakpoint) – The addition of a second slope makes the scheme more sensitive under lower current levels. This allows the relay to trip for lower-level faults within the zone but still remain secure against false trips due to CT inaccuracy. Slope 1 provides security for steady-state CT inaccuracy this is typical of systems with a high X/R ratio or CT's with high levels of remanence. Slope 2 provides security for CT inaccuracy that occurs for external faults that produce high fault currents and CT saturation.

Dual Slope (no breakpoint) – Slopes 1 and 2 provide a blend of sensitivity and security by operating concurrently across the spectrum of restraint current values. To prevent Slope 1 from overtripping, it must be dynamically enabled or disabled based on some criteria other than a simple restraint current magnitude.

Dual Slope (transitional spline) – Again, Slopes 1 and 2 provide both sensitivity and security depending on the restraint current value. The spline prevents the unlikely but mathematically possible event in which fault current persists at the exact region where Slopes 1 and 2 intersect, potentially causing an indeterminate state in the relay.

It should be noted that most if not all modern digital percent differential relays have an Unrestrained differential function that effectively has a 0% slope. This function is generally faster than the percent differential function by 0.5 to 1 cycle because it requires less processing time to calculate restraint. This function should be set higher than any differential current that could possibly occur due to CT error. The benefit of using this function, marginally faster tripping speeds, should be carefully weighed against the risk of eliminating all restraint functions.

C. Impact on Settings and Performance

To understand the impact of these nuances of restraint current and slope variations, consider this hypothetical but plausible scenario in Figure 5:

Both Relay A and Relay B are nearly identical relays, applied with the same CT's, with identical settings. A fault occurs external to the zone, and CT3 saturates heavily.

Relay A calculates its restraint current using a scaling factor:

Relay A $I_{Rest} = 1/2(I_{R1} + I_{R2} + I_{R3})$

Relay B calculates its restraint current using the maximum of all restraints:

Relay B $I_{Rest} = MAX(|I_{R1}|, |I_{R2}|, |I_{R3}|)$

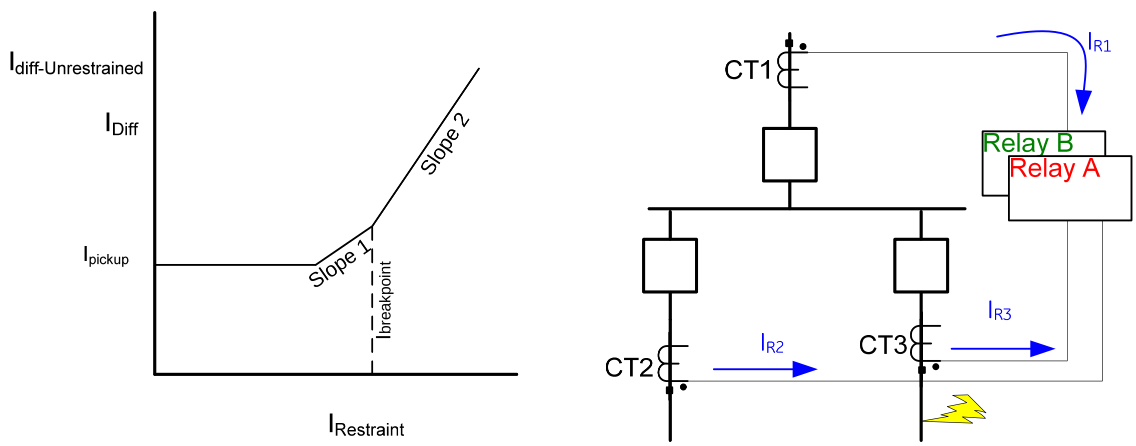

Figure 5: External Fault

Scenario:	Relay A & Relay B are redundant relays using the same CT's. Fault occurs outside of the zone, and CT3 saturates heavily.	
I_{R1} = 20 A∠180°		
I_{R2} = 20 A∠180°		
I_{R3} = 23 A∠0°		
	Relay A	Relay B
I_{pickup}	1 Amp	1 Amp
$I_{breakpoint}$	10 Amps	10 Amps
Slope 1	30%	30%
Slope 2	70%	70%
I_{RTotal} =	23 Amps	31.5 Amps
I_{Diff} =	17 Amps	17 Amps
I_{Diff} / I_{RTotal} ==	74%	54%
Result =	TRIP	No Operate

III. ADVANCED TECHNIQUES

Microprocessors capable of advanced digital signal processing have enabled relay developers to succeed in meeting the challenge to make percent differential relaying both more sensitive and more secure without sacrificing one benefit for the other. Although the specifics of how relay manufacturers accomplish these goals are well beyond the scope of this paper, the tools used can be generalized as follows: restraint current manipulation, and internal/external fault discernment.

A. RESTRAINT CURRENT MANIPULATION

It is well known that CT's produce harmonics when they saturate. These high frequency signals can be captured using a digital bandpass filter, quantified and added to the calculated restraint current in order to increase restraint when it is needed.

Harmonic restraint is not a new concept. Electromechanical relays were once tuned to 2nd harmonic frequencies with electric filters[2]. Producing additional harmonic restraint using the harmonics created by magnetizing inrush is useful because magnetizing inrush appears as a fault to a differential relay. 2nd harmonic restraint helps a relay restrain during that time, but it may also hinder a relay from operating when that 2nd harmonic is due to CT saturation. When a CT saturates due to an internal fault, it is not desirable to add restraint. The advanced algorithms must be capable of distinguishing an internal fault from an external fault and from an energization in the case of transformer differential.

One technique introduced by Moscoso et al [1], called transient bias, temporarily increases the system restraint (actually increases the pickup threshold value) immediately after there is a sudden increase in restraint current. This creates a pulse-increase in restraint that immediately begins to decay exponentially. A delayed restraint function uses the maximum calculated restraint over the past 1 cycle to ensure that the threshold remains high as the saturated CT's DC offset decays.

Figure 6 basically explains that the differential tripping threshold becomes a moving target as restraint current suddenly increases due to an external fault. The Transient Bias and Delayed Bias work together to produce an operate current threshold/restraint that is greater than the differential current caused by CT saturation. Note that the success of this algorithm depends upon: 1) The physical phenomenon that CT's do not instantaneously saturate. For a brief period of time that the CT core builds flux, restraint current increases, and 2) the CT's saturation conditions must improve with time. There is a finite limit to the severity of saturation with this method, so CT's cannot be haphazardly chosen.

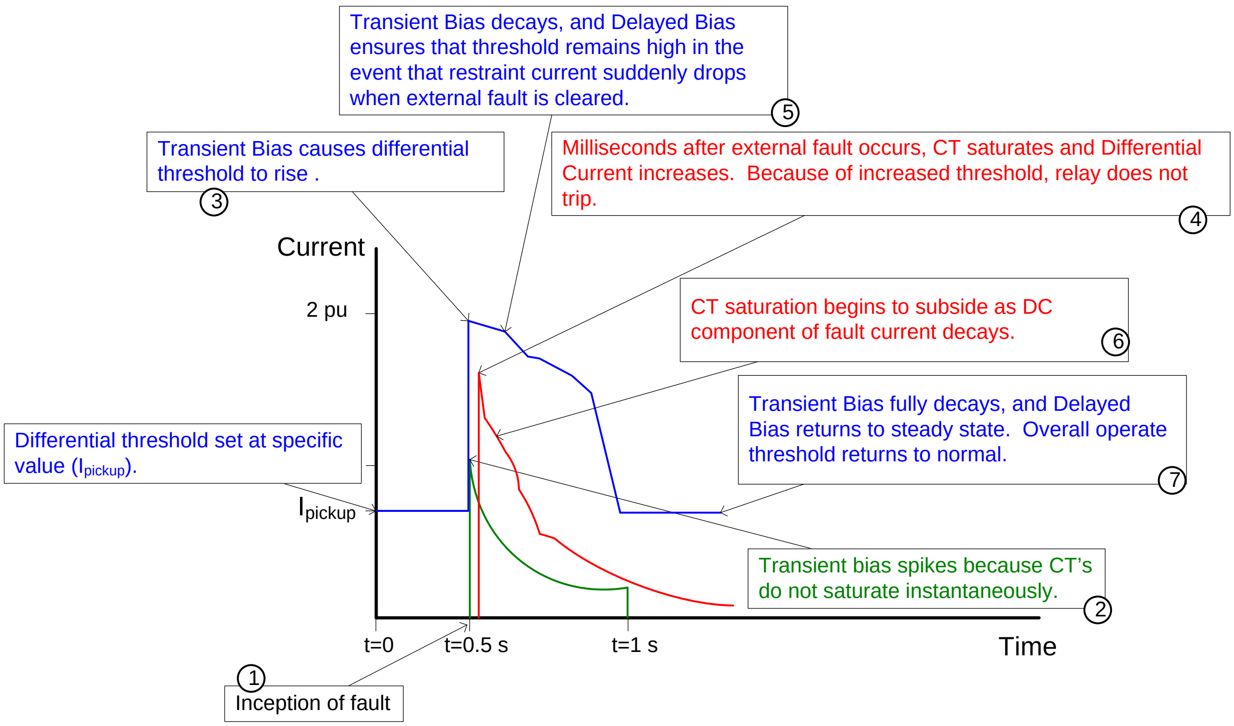

Figure 6: Rough sketch of the timing sequence of the Transient Bias Method of [1] – External Fault

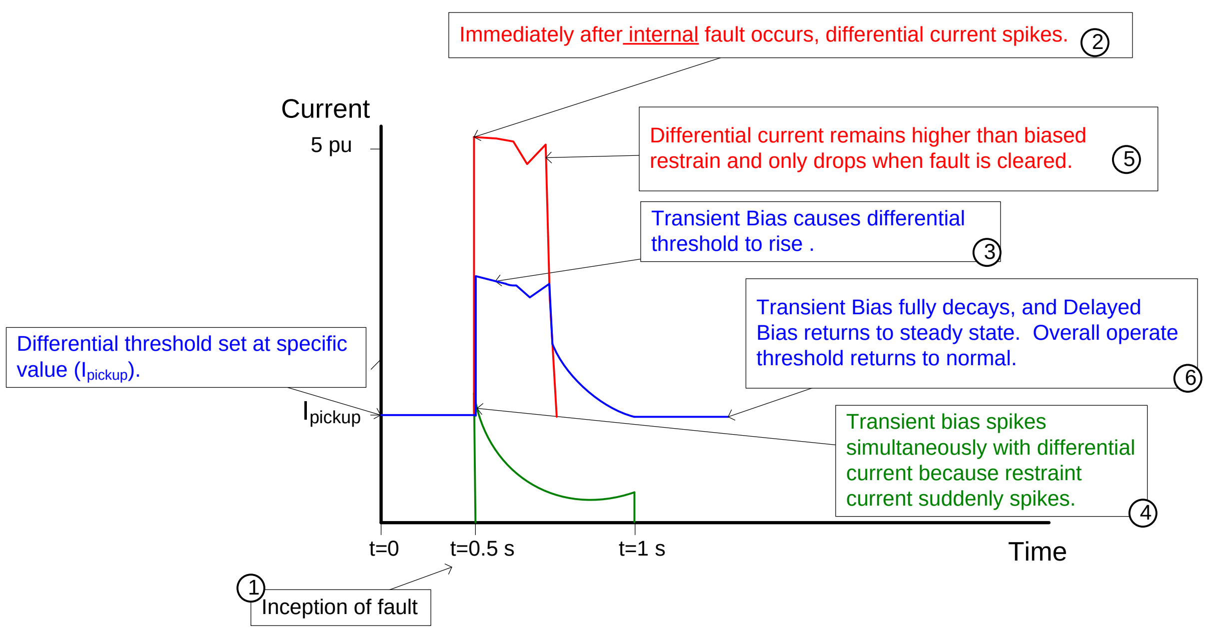

Figure 7: Rough sketch of the timing sequence of the Transient Bias Method of [1] – Internal Fault

B. INTERNAL/EXTERNAL FAULT DISCENRNMENT

In another method proposed by Kasztenny and Kulidjian [3], additional differential security is obtained by specifically determining whether the fault is internal or external to the zone using the relative direction of restraint currents rather than manipulation of the restraint quantities.

This implementation applies an adaptive directional check prior to allowing the differential element to operate.

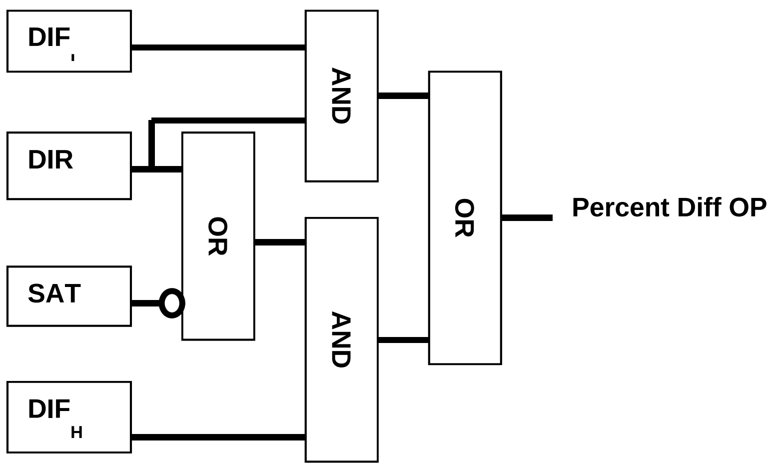

Figure 8: Logic Diagram of Adaptive Percent Differential

Figure 8 shows an adaptive percent differential implementation where a directional check must be satisfied (DIR), and the differential current must exceed the Slope 1 characteristics of the percent differential function (DIF_L) prior to a trip in the Slope 1 region. This prevents false trips due to CT saturation due to high DC offset rather than high currents. In the Slope 2 region (DIF_H), a trip will be issued if differential current exceeds the Slope 2 percentage of restraint and the directional check is satisfied or if no CT saturation is detected.

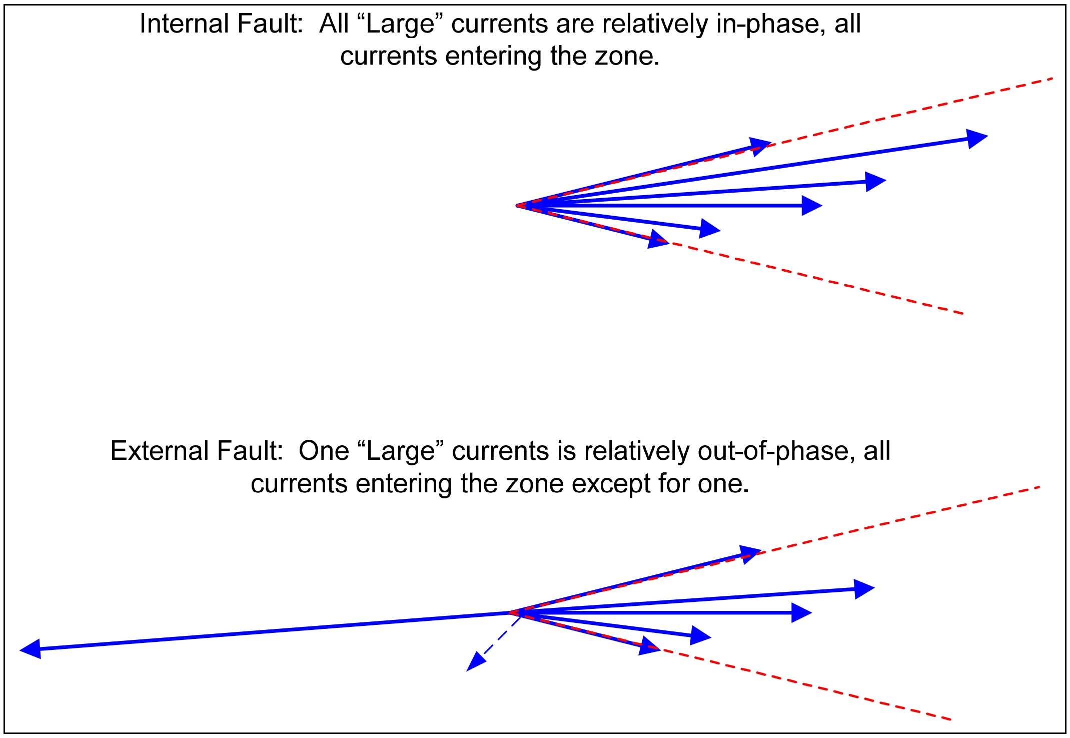

Figure 9: Directional Check

Figure 9 shows that each restraint current into the relay is checked for direction against each of the other restraint currents. If there is one restraint current that is relatively out-of-phase with the others, this is indicative of an external fault. The “DIR” logic block in Figure 8 would be FALSE.

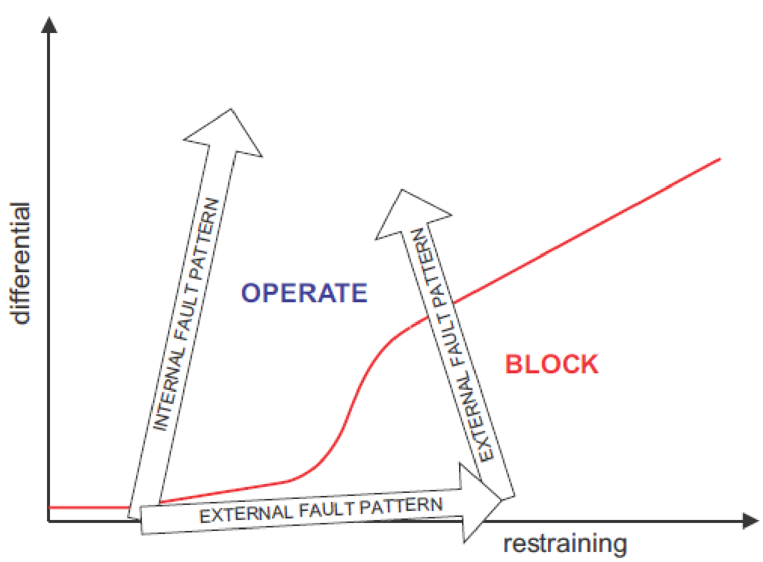

Figure 10: CT Saturation Detection

Figure 10 shows how the trajectory of restraint current is used to declare CT saturation. Like the method described in Section A, Restraint Current Manipulation, this CT saturation detection relies on the principle that CT's cannot saturate instantaneously. When a CT saturates, the restraint current spikes. If this spike lasts long enough for the relay's digital sampling algortithm to detect it, the relay can recognize that operate current (saturation) occurred immediately following a spike in restraint.

Per the logic in Figure 8, a positively detected CT saturation will require the directional check to be met prior to allowing a trip in Slope 2.

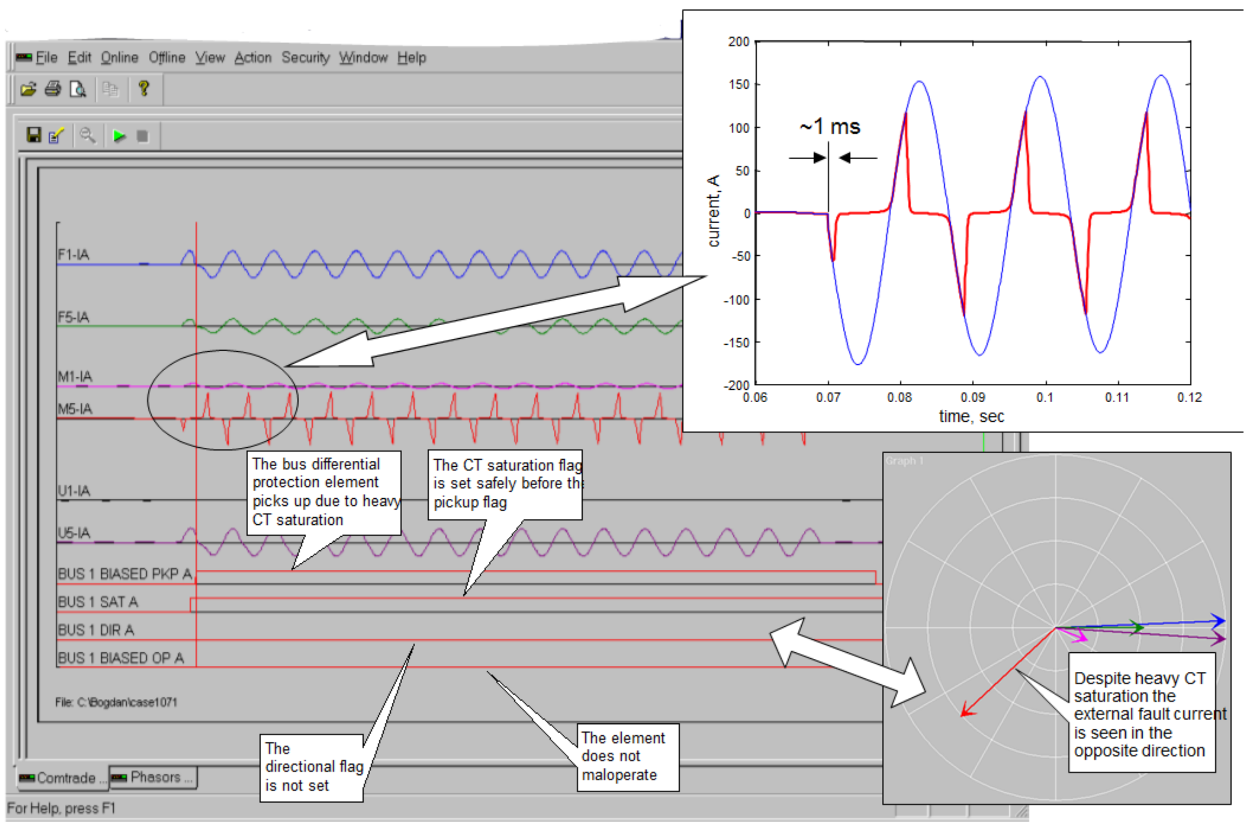

Figure 11: Example of an External Fault with CT Saturation and Directional Algorithm Applied.

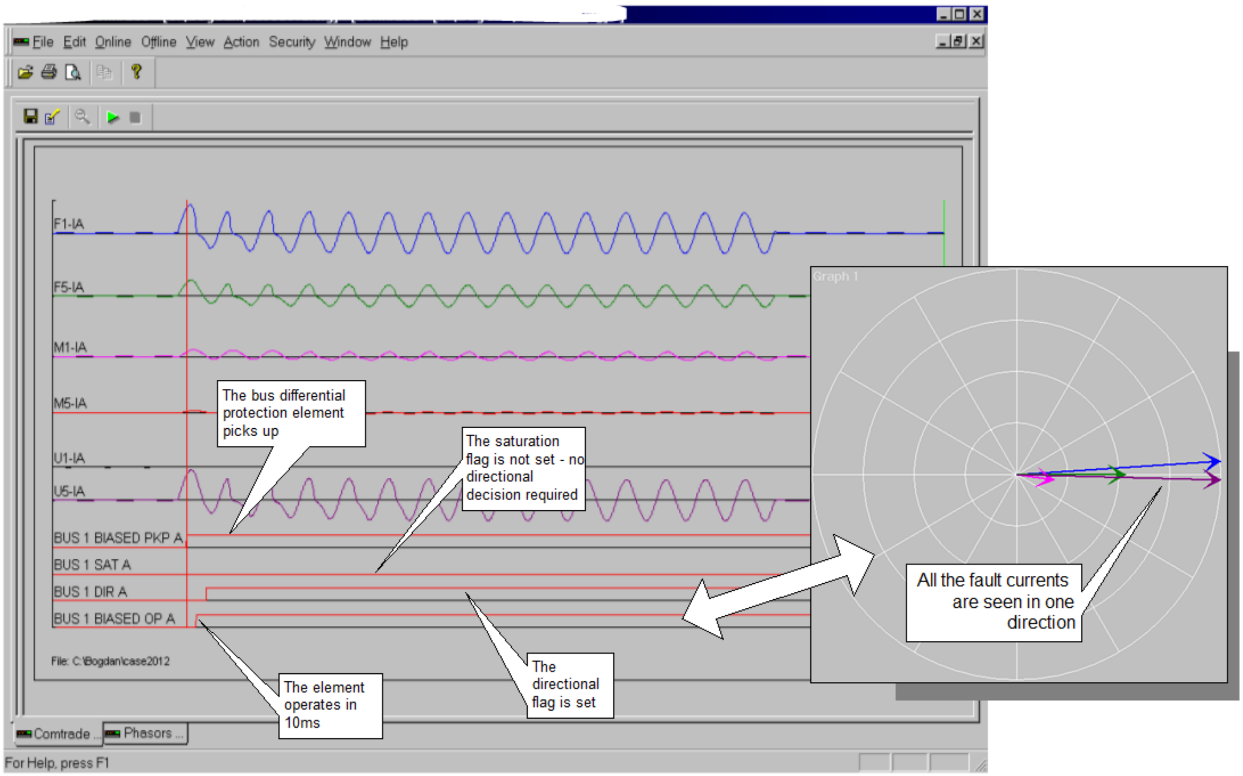

Figure 12: Example of an Internal Fault with CT Saturation and Directional Algorithm Applied.

After seeing how the relay algorithm will block trip for external faults, it becomes evident that analyzing a relay trip or developing a test plan is not possible when only considering the traditional differential/restraint percentage.

IV. Conclusions

Despite being built around a similar fundamental concept, modern percent differential relays can behave quite differently, even when set seemingly identically and subjected to the same operating conditions. An in-depth look at the algorithms behind the functions may be necessary for proper settings configuration, testing and troubleshooting of trips and failures to trip.

V. REFERENCES

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[2] GEK-45307K - Transformer Differential Relays with Percentage and Harmonic Restraint Types STD15C and STD16C, GE Protection & Control, Malvern, PA, pp. 12-13.

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VI. BIOGRAPHY

Matt Proctor is currently a Technical Application Engineer at GE Multilin and has been with GE Multilin for over 6 years. Matt earned Bachelor of Science in electrical engineering from Louisiana State University in Baton Rouge, LA in 2001 and an MBA from LSU in 2005. He has been working in the electrical power field in various capacities since 1997. He specializes in power system studies and protection and control relay applications.