

Rating CTs for Low Impedance Bus and Machine Differential Applications

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Revised edition released October 2003

Previously presented at the
55th Annual Georgia Tech Protective Relaying Conference, May 2001,
54th Annual Conference for Protective Relay Engineers, April 2001,
V Simposio Iberoamericano Sobre Proteccion de Sistemas Electricos de
Potencia, November 2000,
and Southern African Power System Protection Conference, November 2000

Previous revised edition released April 2002

Originally presented at the
27th Annual Western Protective Relay Conference, October 2000

RATING CTS FOR LOW IMPEDANCE BUS AND MACHINE DIFFERENTIAL APPLICATIONS

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INTRODUCTION

Differential relays provide speed and sensitivity for clearing internal faults in critical bus and generator applications. These relays are fast enough to operate during the offset portion of fault currents where high current magnitudes together with high X/R ratios conspire to produce CT saturation and false differential current. Such high fault current applications require full rated current transformers (CTs) to prevent saturation and for security rely on the percentage differential slope characteristic to override incidental false differential. The total scheme must restrain from operating for the most severe external fault and yet have the sensitivity to operate on the minimum fault. In existing schemes, the application engineer must live with legacy CT ratings. Even in new installations, the engineer must contend with switchgear space limitations or with CTs with ratings dictated by company standards rather than by specific application. The application engineer must determine the percentage slope setting in relation to the degree of saturation that provides the required security. This paper explores the relation between the percentage slope characteristic and the degree of saturation produced by a range of CT ratings encountered in utility and industrial applications. The paper will show the plots of the trajectories of operating current versus the restraint characteristic for field applications, and establish settings versus fault currents and CT ratings.

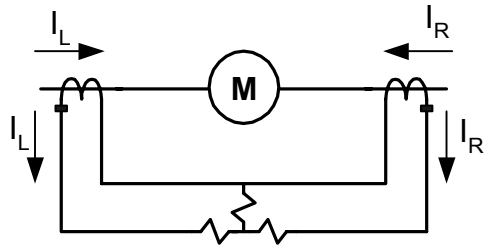


Figure 1 Differential Protection

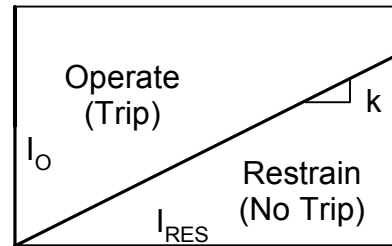


Figure 2 Percentage Characteristic

PERCENTAGE SLOPE CHARACTERISTICS

Figure 1 shows the single-line diagram of a machine differential relay where the currents I_L and I_R are shown in the polarity of an internal fault. As shown in Figure 2, in a percentage differential relay the magnitude of the sum of the currents entering the zone must exceed a predetermined percentage of a restraint quantity. The restraint quantity may have one of several definitions. Two common characteristics are given in Equations (1) and (2) below:

$$|I_L + I_R| = k|I_L - I_R| \quad (1)$$

$$|I_L + I_R| = k(|I_L| + |I_R|) \quad (2)$$

The left hand side in each equation is the operate signal equal to the magnitude of the sum of the currents. The right hand side in each equation is the restraint signal that is multiplied by the slope k . The restraint signal in Equation (1) is the magnitude of the difference of the currents. In Equation (2), the restraint signal is the sum of the magnitudes of the currents. Both characteristics produce the relay characteristic shown in Figure 2. Some relays use the average magnitude of the currents as the restraint. In this case, the slope k in Equation (2) is half the slope setting of the relay.

There is no other purpose for the percentage differential characteristic than to override false differential current caused by CT ratio error. Furthermore, since the CT ratio errors are less than 10 percent in the linear range, the only purpose for the percentage slope characteristic is to override ratio error from saturation caused by the dc offset. What is the nature of the errors caused by saturation and how significant are they?

Figure 3 and Figure 4 illustrate the severity of the CT saturation error. Figure 3 compares the saturated secondary current with the true ratio sine wave current for a C200 2000:5 CT for a 10,667 A fault. When processed by a microprocessor relay, the digital filter removes the dc component and all harmonics, leaving only the fundamental of the waveform as shown in Figure 4. In the saturated waveform, the later part of the half cycle of ratio current is missing since it flows into the magnetizing impedance and not to the burden. As a result, the fundamental extracted from the saturated waveform is reduced in magnitude and shifts leading in phase with respect to the ratio current as shown in Figure 4. These are the signals processed by the relay, the worst case being when the left hand set of CTs saturates and the right hand set does not.

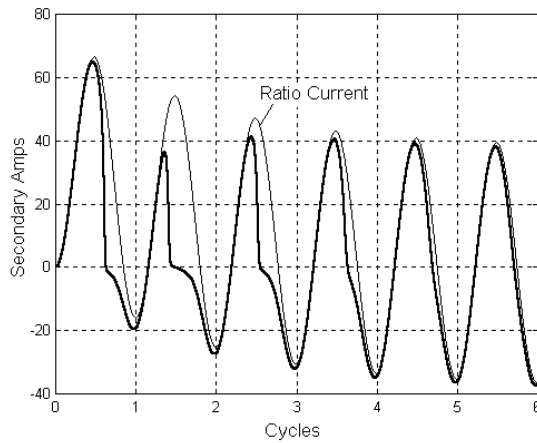


Figure 3 Saturation Caused By DC Offset.
C200 2000:5 CT, 2.0 Ω Burden. Fault Current
10667 Amp. X/R =14

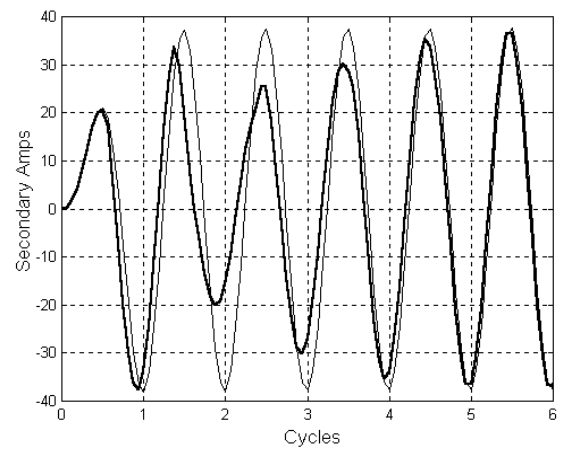


Figure 4 Fundamental Waveforms Extracted
By Digital Filter

ALPHA PLANE DIFFERENTIAL CHARACTERISTIC

The percentage differential characteristic can be visualized by expressing Equations (1) and (2) in terms of the ratio [1]:

$$(I_R / I_L) = a + jb \quad (3)$$

Equation (1) written in terms of the ratio becomes:

$$\left| 1 + \frac{I_R}{I_L} \right| = k \cdot \left| 1 - \frac{I_R}{I_L} \right| \quad (4)$$

Substituting the complex number (a+jb) for the ratio and expanding gives the equation:

$$a^2 + 2 \frac{1+k^2}{1-k^2} a + 1 + b^2 = 0 \quad (5)$$

By completing the square, Equation (5) can be recognized as a circle with radius and center at:

$$\text{Radius} = \frac{2k}{1-k^2} \quad (6)$$

$$\text{Center} = -\frac{1+k^2}{1-k^2} + j \cdot 0 \quad (7)$$

Consequently, the percentage slope characteristic is a circle enclosing the stability (no trip) region in the complex plane called the alpha plane. Similarly, Equation (2) written in terms of the ratio of currents becomes:

$$\left| 1 + \frac{I_R}{I_L} \right| = k \cdot \left| 1 + \frac{I_R}{I_L} \right| \quad (8)$$

Substituting the complex number (a+jb) for the ratio and expanding gives the equation of a characteristic resembling a cardioid that circumscribes the circle characteristic:

$$r^2 + \frac{2}{1-k^2} (\cos(\theta) - k^2) \cdot r + 1 = 0 \quad (9)$$

where $r^2 = a^2 + b^2$ and $a = r \cdot \cos(\theta)$. Figure 5 and Figure 6 show the plots in the alpha plane.

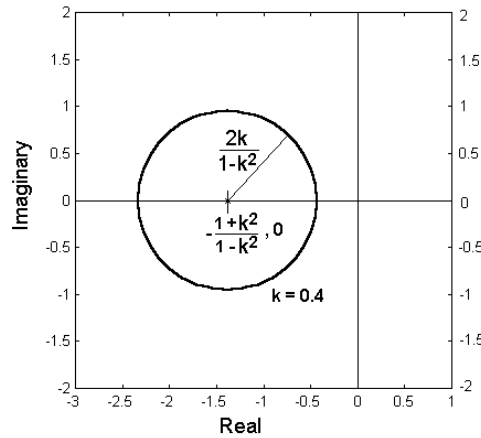


Figure 5 Circle Characteristic

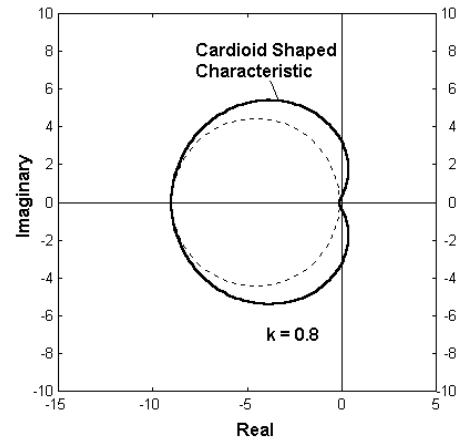


Figure 6 Characteristic Resembling a Cardioid

DETERMINING THE SLOPE FOR A GIVEN DEGREE OF SATURATION

The alpha plane characteristic provides a convenient way of determining the slope setting in relation to a given degree of CT saturation. The method is to plot the ratio of currents (I_R/I_L) in the alpha plane for an external fault and then choose slope k such that all the points are enclosed by the circle or cardioid shaped characteristic. The current samples are obtained from a Matlab simulation program GUI_2CTS.m [2] that calculates current samples at 57.87 microsecond intervals for 6-cycles. The program interface shown in Figure 7 lists the CT data.

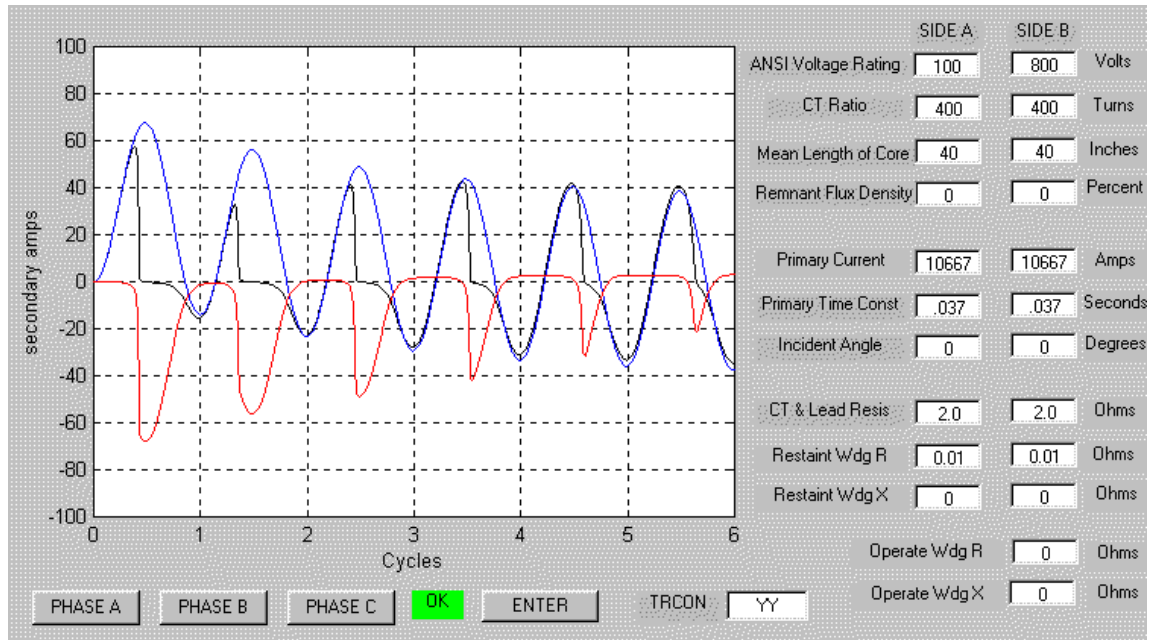


Figure 7 Matlab Program Graphic Interface

The 1815 samples of each of the two currents are re-sampled by the 16-sample per cycle cosine filter to obtain the fundamental phasor values. The ratios of the samples are then calculated. The samples are plotted and appear as a cluster of points in the left complex plane for an external fault. A slope k is then selected so that the plot of the characteristic encloses all of the samples.

The degree of saturation depends on the saturation voltage V_s across the burden impedance given in the following equation [3]:

$$V_s = \left(1 + \frac{X}{R}\right) \cdot I_f Z_b \quad (10)$$

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

Z_b is the burden in per unit of the standard burden

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

Our procedure will be to start with the left and right set of CTs rated at C800 and apply the maximum fault current that just produces the threshold of saturation for a predetermined X/R ratio. The value of V_s equals 20 in this case [3]. This value of fault current will be retained in all subsequent cases. The saturation voltage V_s will then be doubled from the previous case by lowering the ANSI voltage class of one set of CTs by one standard rating. In this way the

saturation voltage will take on the values 20, 40, 80, and 160. Each simulation will produce 101 phasor samples that plot as a cluster of points in the alpha plane. In each case the value of k will be selected such that the circle characteristics will enclose all the points. The values of k will then be plotted as a function of the saturation voltage V_s . Each simulation was run for a 2000:5 CT with a lead and relay burden of 1 ohm total and a winding resistance of 1.0 ohm. The fault current in each case is an offset 10667 amps where the X/R ratio is 14. The cases are plotted in Figure 8 thru Figure 11 below. The darker points in each plot are the ratios (IR/IL). The lighter points are the reciprocal ratios (IL/IR). Note that the k in each plot is in percent. Plots using the cardioid shaped characteristic are shown in Figure 12 and Figure 13.

CASE PLOTS

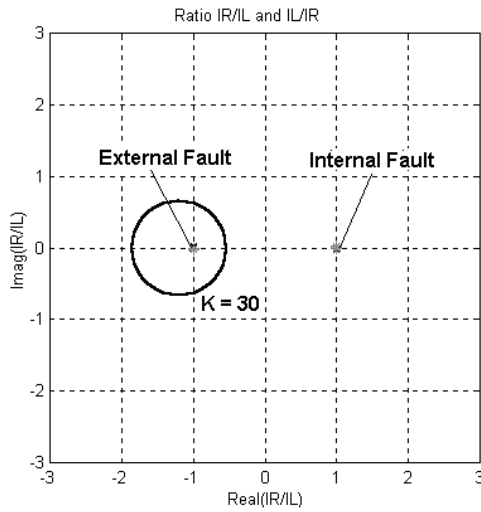


Figure 8 $V_s = 20$ Fault Current 10667 A

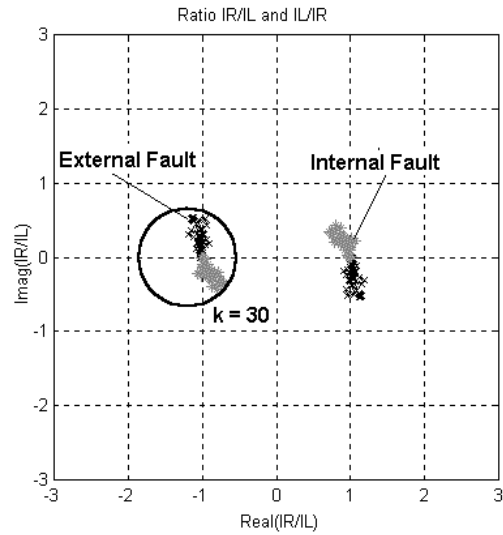


Figure 9 $V_s = 40$ Fault Current 10667 A

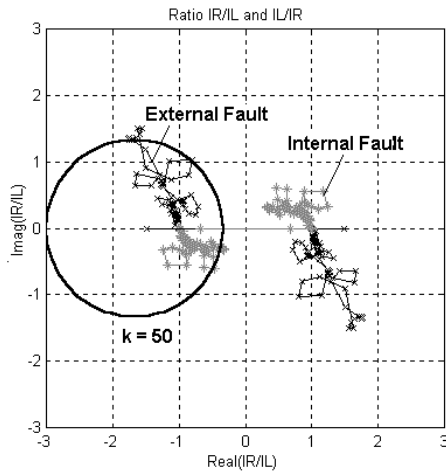


Figure 10 $V_s = 80$ Fault Current 10667 A

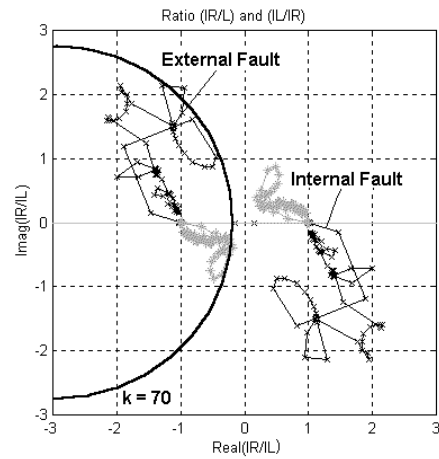


Figure 11 $V_s = 160$ Fault Current 10667 A

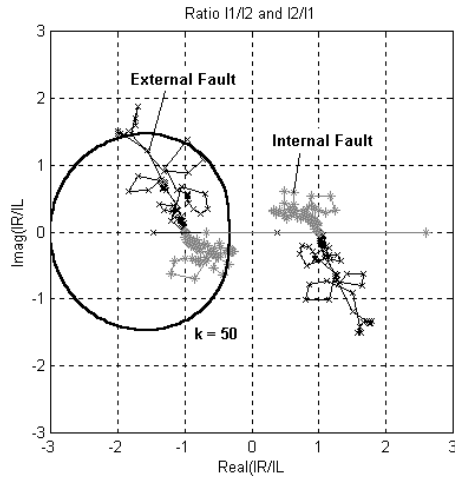


Figure 12 $V_s = 80$ Fault Current 10667 A with Cardioid Shaped Characteristic

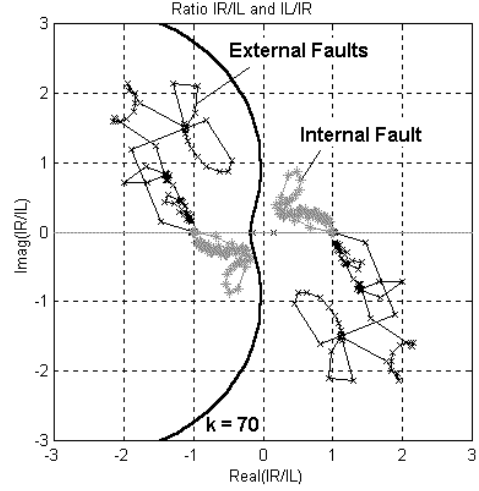


Figure 13 $V_s = 160$ Fault Current 10667 A with Cardioid Shaped Characteristic

SATURATION VOLTAGE

The relation between the slope setting and the degree of saturation is given by plotting the slope k as a function of the saturation voltage. The curve with its empirical equation shown in Figure 14 determines the slope setting for a given degree of saturation. This equation is valid for $V_s < 150$.

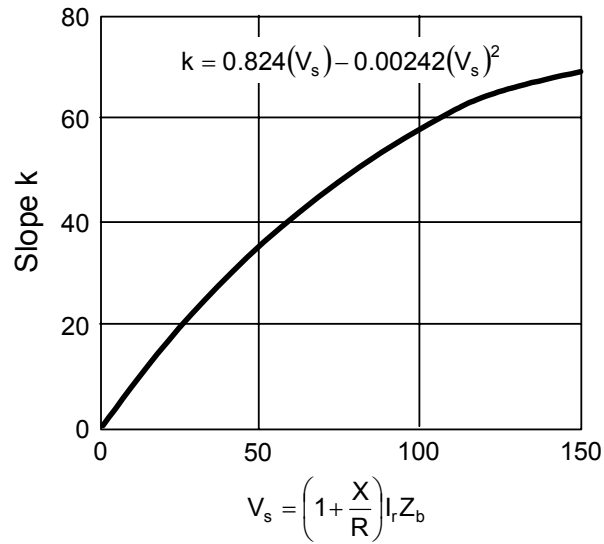


Figure 14 Slope k Versus CT Saturation Voltage

BUS AND MACHINE DIFFERENTIAL APPLICATIONS

In machine differential applications [4] there is no reason for the terminal-side CTs and the neutral-side CTs to have a different ANSI voltage rating. In fact, it is impractical to size CTs to avoid transient saturation in a generator differential because of high current magnitude and high

X/R ratios encountered. Consequently, the rule is to select the largest practical rating and match the terminal- and neutral-side CTs so that in the presence of saturation both sets of CTs produce the identical waveform and the ratio (I_R/I_L) remains at -1 during an external fault.

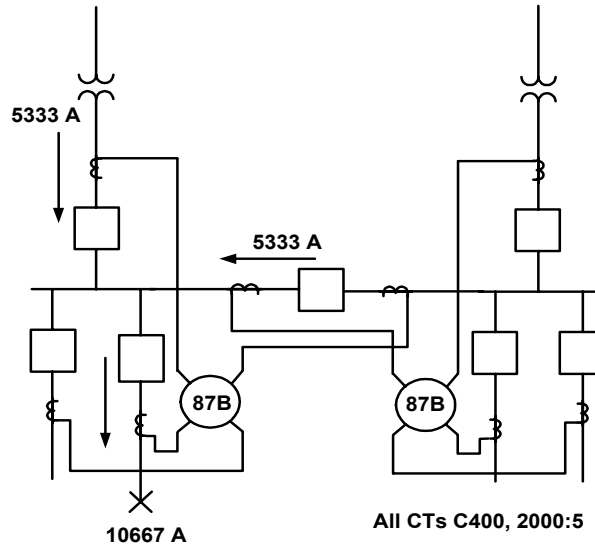


Figure 15 Multi-Restraint Bus Differential

Unlike the machine differential application, identical CTs in a multi-restraint bus differential scheme do not guarantee the same waveform in all CTs. For example, the bus differential scheme in Figure 15 shows the maximum external fault on a feeder. The CT on the faulted feeder carries the total fault current of 10667 A. For an X/R ratio of 14, V_s is 40 and the fault current produces saturation. However, the CTs of the transformer and the tie carry only half the total current. Consequently, they act as one equivalent C800 CT with a saturation voltage V_s of 20 that produces undistorted secondary current. These are the exact conditions of the case shown in Figure 9 and the k of 30 is obtained by using V_s equal to 40 in the equation developed from the plot in Figure 14. The alpha plane plot and a plot of the operate versus the restraint current for the case are shown in Figure 16 and Figure 17.

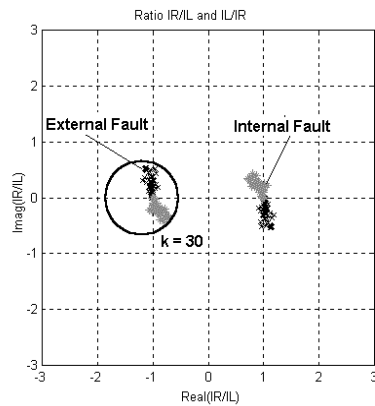


Figure 16 $V_s = 40$, $k = 30$

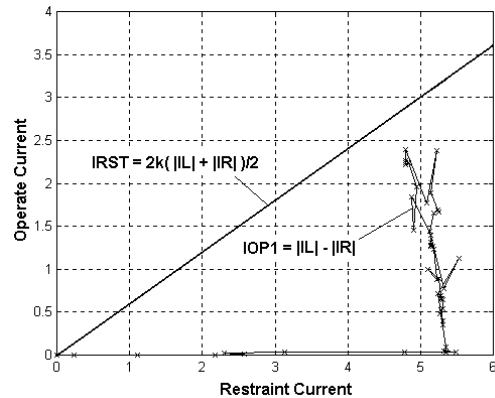


Figure 17 Operate Signal Versus Restraint

THE EFFECT OF REMANENT FLUX ON THE SLOPE SETTING

A high offset fault current is usually interrupted in a few cycles. Consequently, the duration of the fault current can be much shorter than the time constant of the primary circuit. The interruption leaves a remanent flux in the core that is not affected by normal load current and that can only be removed by demagnetization. A survey of 141 current transformers on a 230 kV system is reported in Annex C of reference [4]. In this survey, the remanent flux ranged from 20 to 80 percent of the flux at the threshold of saturation.

The ANSI voltage rating of a CT is the voltage caused by 20 times the rated 5-ampere secondary current flowing in the standard burden. Furthermore, the volt-time area of the rated voltage represents the flux at the threshold of saturation [3]. Consequently, the remanent flux in percent of the flux at the threshold of saturation reduces the voltage rating of the CT by that percentage. For example, a C400 CT with 40 percent remanent flux has been effectively reduced to a C240 rating.

The effect of remanent flux can be included in the calculation of the saturation voltage V_s by modifying the standard burden as follows:

$$Z_{std} = \frac{V_{ANSI}}{100} \left(1 - \frac{\% \text{Remanence}}{100} \right) \quad (11)$$

The calculation of k for the case shown in Figure 16 and Figure 17 for a C400 CT with 40 percent remanent flux is as follows:

Maximum Fault current	$I_F = 10667 \text{ amps}$
X/R ratio of primary circuit	$X/R = 14$
CT primary current rating	$CT_{rating} = 2000$
CT burden in ohms	$Z_{burden} = 2.0 \text{ ohms}$
Percent remanent flux	$\%Rem = 40$
Standard Burden	$Z_{std} = \frac{V_{ANSI}}{100} \left(1 - \frac{\% \text{Rem}}{100} \right) = \frac{400}{100} \left(1 - \frac{40}{100} \right) = 2.4$
Saturation voltage	$V_s = \left(1 + \frac{X}{R} \right) \frac{I_F}{CT_{rating}} \frac{Z_{burden}}{Z_{std}} = (1 + 14) \frac{10667}{2000} \frac{2.0}{2.4} = 67$
Slope setting	$k = 0.824V_s - 0.00242V_s^2 = 44$

The calculation shows that the 40 percent remanent flux increases the saturation voltage from 40 to 67 and the secure slope from 30 to 44. The alpha plane plot and the plot of the operate versus the restraint current for the case are shown in Figure 18 and Figure 19.

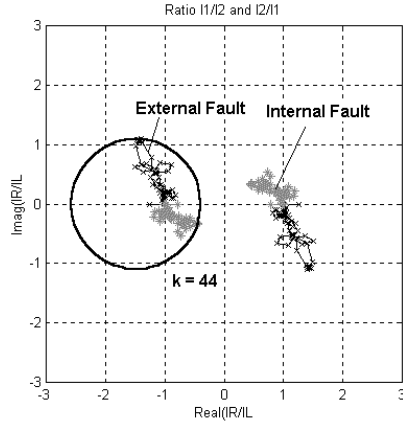


Figure 18 $V_s = 67$, $k = 44$, 40 Percent Remanence

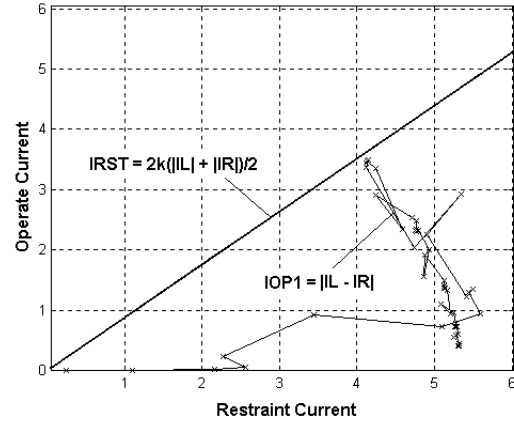


Figure 19 Operate Signal Versus Restraint with 40 Percent Remanence

CONCLUSIONS

1. The percentage slope characteristic defined by Equation (1) is a circle when plotted in the complex alpha plane. The characteristic as defined in Equation (2) is a characteristic that resembles a cardioid that circumscribes the circle. The stability (no trip) region is the area enclosed within the circle or cardioid-shaped characteristic.
2. The ratio of the differential currents (IR/IL) that occur during an external fault forms a collection of points in the alpha plane that should reside within the circle characteristic.
3. The radius and center of the circle characteristic are determined by setting the slope k . Consequently, the alpha plane characteristic provides a convenient way of determining the slope setting in relation to a given degree of CT saturation.
4. It is impractical to size CTs to avoid transient saturation in a generator differential because of the high current magnitude and high X/R ratios encountered. Select terminal- and neutral-side CTs of identical rating and manufacture type.
5. The security of bus differential applications relies on the percentage slope setting. A bus scheme with more than one source contributing to an external fault can be analyzed as a two-CT equivalent with k determined by the CT saturation voltage V_s in the relation:

$$k = 0.824 \cdot V_s - 0.00242 \cdot (V_s)^2 \quad (11)$$

6. The remanent flux expressed as a percent of the flux at the threshold of saturation reduces the CT voltage rating by that percent. Consequently, the effect of remanent flux can be incorporated into the calculation of the saturation voltage V_s . The remanent flux causes a significant increase in V_s and in the secure slope setting.

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- [4] IEEE Std C37.110-1996, IEEE Guide for the Application of Current Transformer Used for Relaying Purposes (ANSI), Clause 7.2.2.6, pages 34; Annex C, page 55.

ACKNOWLEDGEMENT

The author wishes to thank Dr. Hector Altuve for introducing us to the classical attributes of the alpha plane [1] and for his derivation of the alpha plane characteristics of percentage differential relays.

BIOGRAPHY

Stanley (Stan) Zocholl has a B.S. and M.S. in Electrical Engineering from Drexel University. He is an IEEE Life Fellow and a member of the Power Engineering Society and the Industrial Application Society. He is also a member of the Power System Relaying Committee and past chair of the Relay Input Sources Subcommittee. He joined Schweitzer Engineering Laboratories in 1991 in the position of Distinguished Engineer. He was with ABB Power T&D Company Allentown (formerly ITE, Gould, BBC) since 1947 where he held various engineering positions including Director of Protection Technology.

His biography appears in Who's Who in America. He holds over a dozen patents associated with power system protection using solid state and microprocessor technology and is the author of numerous IEEE and Protective Relay Conference papers. He received the Best Paper Award of the 1988 Petroleum and Chemical Industry Conference and the Power System Relaying Committee's Distinguished Service Award in 1991.