Line Differential Protection with an Enhanced Characteristic

Demetrios A. Tziouvaras, Hector Altuve, Gabriel Benmouyal, Jeff Roberts
Schweitzer Engineering Laboratories, Inc.

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Demetrios A. Tziouvaras*, Hector Altuve, Gabriel Benmouyal, Jeff Roberts
Schweitzer Engineering Laboratories, Inc.
2350 NE Hopkins Court, Pullman, WA 99163 USA
Tel: 707-447-8686, Fax: 707-447-3088, E-mail: demetz@selinc.com

ABSTRACT: This paper describes a new digital line differential relaying system with an enhanced characteristic. In the paper, we first present the concept of the complex current-ratio plane for the analysis of current-only pilot unit-type relay characteristics. Next, we briefly discuss different unit-type protection relaying systems including their advantages and disadvantages. We then propose a new line differential relay characteristic in the current-ratio plane, describe the relay design, and finally present and discuss the relay performance using digital simulation of the algorithms. The new relaying system design, presented in this paper, provides sensitive protection for transmission line and cable faults, and high security and stability for external faults. The relay system is tolerant of the unequal communications channel delays that are typical of modern networked digital communications channels. Unequal communications channel delays can be detrimental to the stability of unit-type relaying systems that require precise channel delay compensation. The new relaying system also accommodates outfeed currents caused by high-resistance internal line faults in two-terminal applications, or by strong back-ties between two-line terminals in three-terminal transmission line applications. The operating time of this new differential relaying system is less than one cycle, and it is applicable for the protection of HV and EHV lines, including series-compensated lines.

Keywords: Current differential, digital relay, differential protection, transmission line protection, cable protection.

I. Introduction

Modern power systems operate close to their security limits and require high-speed fault clearing to preserve transient stability, reduce fault damage, minimize outage duration, and improve power quality. To provide high speed clearing times for faults occurring at any point on a transmission line, there must be some form of communications channel available between the transmission line terminals. This communications or pilot channel is used for the exchange of information between the protective relaying systems, called pilot relaying systems, to determine whether the fault is internal or external to the protected transmission line.

Pilot relaying systems provide high-speed simultaneous fault clearing for 100 percent of the protected transmission line from all line terminals. Pilot relaying systems are either directional comparison type or unit-type protection systems. Directional comparison systems compare the direction of fault current flow at the two line terminals, and declare internal faults if there is no disagreement in flow direction between the line terminals. Unit-type current-only protection systems measure the fault currents at the transmission line terminals, compare them via the pilot channel, using either phase comparison, charge comparison, or current differential principles, and determine whether the fault is within the protected zone.

The most widely used pilot relaying system is directional comparison. An IEEE survey published in 1988 [1] showed that about 80 percent of the most important lines, in 116 utilities in the USA, have directional comparison protection. The main reasons for this wide acceptance are the low communications channel requirements and the inherent redundancy and backup protection of directional comparison systems. However, directional comparison systems require system voltages in addition to line currents. Voltage inputs can introduce problems in a directional comparison system because of loss of voltage for close-in faults or blown fuses, ferroresonance problems in instrument voltage transformers, and transient response problems associated with capacitive-coupled voltage transformers [2].

Unit-type systems such as phase comparison, charge comparison, and current differential systems only require line currents to determine whether the fault is within the protected zone. Unit-type protection systems are suitable for the protection of complex transmission network configurations because they exhibit good performance during evolving, intercircuit, and cross-country faults [5]. In addition, unit-type protection systems are immune to power swings, mutual coupling, and series impedance unbalances. Unit-type systems offer a good application solution for the protection of cables, as well as for series-compensated, three-terminal, and short transmission lines.

The amount of tolerance a unit-type protection system has for current transformer (CT) saturation, current outfeed, and channel delay asymmetry depends largely on the operating characteristic. These tolerances often limit the unit protection scheme performance. In addition, unit-type protection systems require a reliable high-bandwidth communications channel.

These limitations are rapidly disappearing with new developments, such as the introduction of an enhanced line differential characteristic that we present in this paper, and with the use of modern digital fiber-optic channels that meet the communications requirements of unit-type pilot protection systems [3]-[4]. Also, today's digital technology permits the inclusion of many additional protection functions in a relay unit, which makes it possible to combine a directional comparison and a current-only pilot system in the same relay. This diversity of operation principles in the same unit can enhance the overall performance without a significant increase in cost.

II. Current Ratio Plane

Because relay input signals are complex quantities, the most comprehensive way to represent the relay characteristics is to use a complex plane defined by the ratio of the relay input signals [6]-[7]. The relay characteristics, for relay functions that use current and voltage signals, can be represented using the impedance, or an admittance complex plane. On the other hand, relay characteristics for relay functions that use multiple current or voltage inputs can be represented using the complex current ratio or the complex voltage ratio plane, respectively.

Current ratio plane:

Distance and directional element characteristics are often depicted on either the complex admittance or impedance plane. Warrington in [6]-[7] introduced a complex plane called the alpha plane (α-plane) that depicts the complex ratio $\vec{I}_R / \vec{I}_L$ of the remote $\vec{I}_R$ to the local $\vec{I}_L$ currents. In addition, he introduced the term beta-plane (β-plane) for the $\vec{I}_L / \vec{I}_R$ plane. Both planes are equivalent in terms of the information they provide, so we will only discuss and use the α-plane in this paper.

We define a complex variable given by the ratio of the remote, $\vec{I}_R$, to the local, $\vec{I}_L$, currents:

$$\frac{\vec{I}_R}{\vec{I}_L} = a + jb = \vec{r} = re^{j\theta} \qquad (1)$$

where:

$$a = \frac{\left|\vec{I}_R\right|}{\left|\vec{I}_L\right|}\cos\theta = r\cos\theta$$

$$r = \sqrt{a^2 + b^2}$$

$$\theta = \arctan\frac{b}{a}$$

Equation (1) is the basis for the Cartesian, or polar coordinates, versions of the current ratio plane. The α-plane depicts the complex ratio of $\vec{I}_R / \vec{I}_L$ as shown in Figure 1.

Representing Power System Conditions on the α-Plane:

The α-plane is useful for visualizing various power system load and fault conditions and sources of instrumentation error. For example, consider load current flowing from Terminal L to Terminal R in Figure 2.

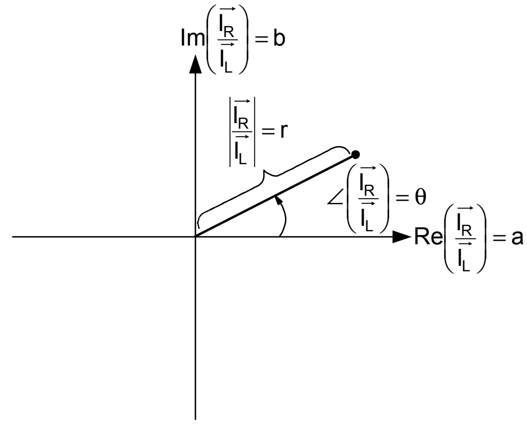


Fig. 1. α-Plane represents the complex ratio of $\vec{I}_R / \vec{I}_L$

Neglecting line-charging current, for through-load conditions the magnitude of $\vec{I}_{AL}$ and $\vec{I}_{AR}$ are equal, and their phases are 180 degrees out of phase. Therefore:

$$\vec{I}_{AR} / \vec{I}_{AL} = 1\angle 180° = -1$$

Load current plots one unit to the left of the α-plane origin, at a = -1, regardless of the size or angle of the load current. Under ideal conditions, the current ratio for external faults is the same as the current ratio for load conditions.

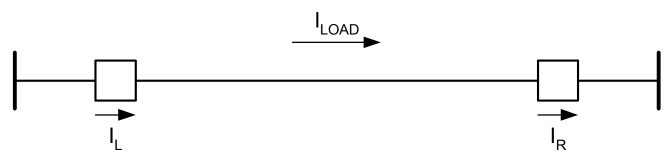


Fig. 2. Terminal currents for through-load condition

Figure 3 shows α-plane region areas, along the real axis of the α-plane for ideal fault and load conditions. Internal faults with infeed from both line terminals have a > 0 and internal faults with outfeed at one terminal have a < 0.

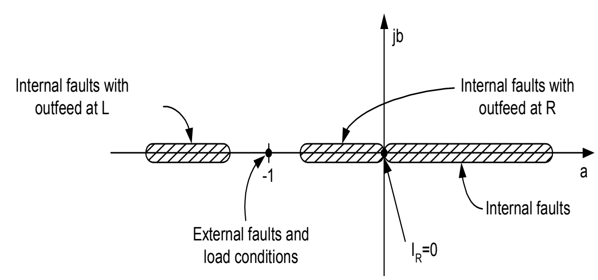


Fig. 3. α-Plane regions for ideal fault and load conditions

For internal faults, the angles of the phase currents $\vec{I}_L$ and $\vec{I}_R$ depend on the angles of the corresponding source voltages and on the angles of the impedances from the corresponding source to the fault point. In general, the currents at both line ends are not exactly in phase for an internal fault. Figure 4 shows the modification of the fault regions allowing ±30 degrees for system power angle and impedance angle difference. Note that the point corresponding to load and external faults is not affected.

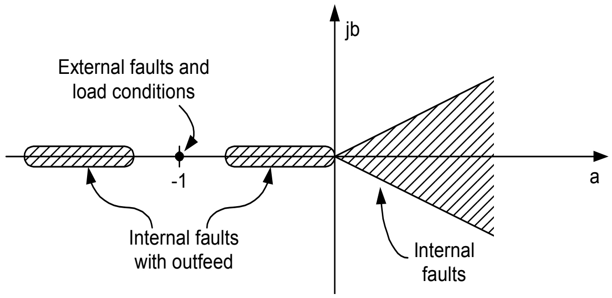


Fig. 4. Effect of system power angle and system impedance nonhomogeneity on the α-plane

The communications channel delay also produces an apparent phase shift between the local current and the received remote current. The relay must compensate for the channel delay to prevent the apparent phase shift from either corrupting the current ratio calculation or producing excessive difference current. A common technique to compensate for the channel delay, known as the ping-pong technique, involves measuring the roundtrip channel delay. The relay calculates the one-way channel delay as half the roundtrip delay. This calculation is accurate if the delays in transmit and receive directions are equal. In some channels the transmit path has a different propagation delay from the receive path. This asymmetrical communications delay can exist, for example, on SONET systems. The level of asymmetry depends mostly on the architecture of the telecommunications system. The communications path delay differences are typically less than 2 ms. Delays of 3-5 ms are rare.

Delay asymmetry produces an error in the channel-delay compensation. The effect of the error is to rotate the current ratio around the origin on the α-plane. A 1 ms error rotates the current ratio 21.6 degrees when the system frequency is 60 Hz. The steady-state magnitude of the ratio is unchanged. Figure 5 shows this effect. Note that channel asymmetry expands the ideal fault and load regions of Figure 5.

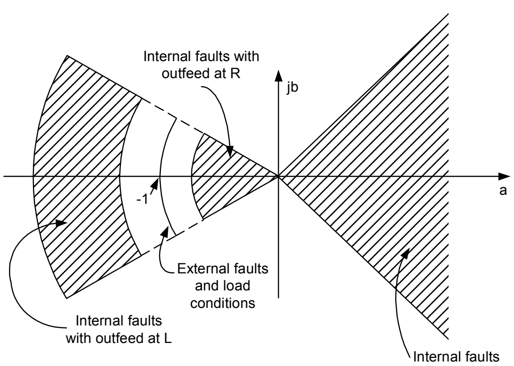


Fig. 5. Effect of channel delay compensation errors and system impedance nonhomogeneity on the α-plane

When a CT saturates, the fundamental component of the secondary waveform decreases in magnitude, and advances in angle. If the local CT saturates, and the CT at the remote end of the protected line does not saturate, the α-plane ratio magnitude increases, and the phase angle of the ratio advances, creating an error with significant magnitude and angle components. We discuss CT saturation and its effect on the trajectory of $\vec{I}_R / \vec{I}_L$ later in this paper.

Representing Protective Relaying Operating Principles on the α-Plane:

A current-only relay must restrain for load current. Therefore it must contain a restraint region on the alpha plane that includes the point $1\angle 180°$. The relay must trip for internal faults, so the restraint region on the α-plane must exclude the crosshatched areas shown in Figure 5. It is possible to derive the α-plane operation/restraint characteristic of current-only relays from the published operation/restraint quantities. Such operation/restraint characteristic derivations are shown in [8]. This reference describes the resulting dynamic restraint regions as circles or cardioids with centers and diameters that vary as a function of the relay setting parameters and load current. In this paper we restrict our discussion to a single line differential principle, and how its operating and restraining regions plot on the α-plane.

Current-Differential Relay System Characteristic:

Percentage-differential elements compare an operating current (also called the differential current) with a restraint current. The operating current, I_{OP}, is the magnitude of the phasor sum of the currents entering the protected element.

$$I_{OP} = \left| \vec{I}_L + \vec{I}_R \right| \tag{2}$$

I_{OP} is proportional to the fault current for internal faults and approaches zero for any other operating (ideal) conditions. The most common alternatives for obtaining the restraint current, I_{RT}, are the following:

$$I_{RT} = k\left| \vec{I}_L - \vec{I}_R \right| \tag{3}$$

$$I_{RT} = k\left(\left|\vec{I}_L\right| + \left|\vec{I}_R\right| \right) \tag{4}$$

$$I_{RT} = \text{Max}\left(\left|\vec{I}_L\right|, \left|\vec{I}_R\right| \right) \tag{5}$$

$$I_{RT} = \sqrt{\left|\vec{I}_L\right| \cdot \left|\vec{I}_R\right| \cos\theta} \tag{6}$$

where k, is a constant coefficient usually taken as 1 or 0.5, and θ is the angle between $\vec{I}_L$ and $\vec{I}_R$. Equations (3-4) are applicable to differential relays with two or more restraint elements. For example, for a two-terminal line we may use the following quantities:

$$I_{OP} = \left| \vec{I}_X + \vec{I}_Y \right| \tag{7}$$

$$I_{RT} = k\left(\left|\vec{I}_X\right| + \left|\vec{I}_Y\right| \right) \tag{8}$$

where $\vec{I}_X$, and $\vec{I}_Y$ are the currents at the two line terminals.

We may define the operation condition of a percentage-differential relay as:

$$I_{OP} \geq K I_{RT} \tag{9}$$

where K is a constant coefficient representing the slope of the relay characteristic. To provide the relay with a minimum pick-up current, K_0, we add the condition:

$$I_{OP} \geq K_0 \tag{10}$$

Another possible definition of the differential relay operation condition is:

$$I_{OP} \geq KI_{RT} + K_0 \tag{11}$$

Figure 6 shows the percentage differential relay operating characteristic resulting from the equality conditions of both Equations (9) and (10).

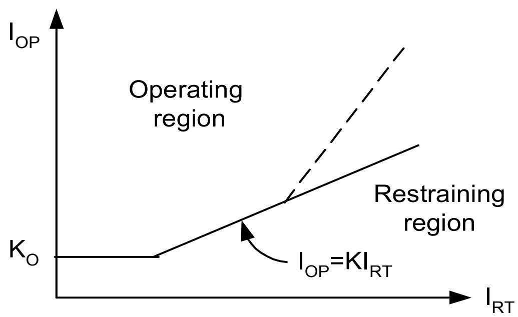


Fig. 6. Traditional percentage differential characteristic

The differential current is rarely exactly zero for external faults. The most common causes of false differential current in transmission line differential relays are the following:

- Line charging current
- Current transformer saturation
- Channel time-delay compensation errors
- Tapped load

Let us obtain the current ratio plane characteristic of a differential relay having (9) as the operating equation, a restraint quantity given by (3), and k = 1 for simplicity.

Substituting (2) and (3) into (9):

$$\left|\vec{I}_L + \vec{I}_R\right| \geq K\left|\vec{I}_L - \vec{I}_R\right| \tag{12}$$

$$\left|1 + \frac{\vec{I}_R}{\vec{I}_L}\right| \geq K\left|1 - \frac{\vec{I}_R}{\vec{I}_L}\right| \tag{13}$$

Substituting (1) in (13):

$$\left|1 + a + jb\right| \geq K\left|1 - a - jb\right|$$

Expanding the previous equation we get:

$$a^2 + b^2 + 2\frac{1+K^2}{1-K^2}a + 1 \geq 0 \tag{14}$$

The equality condition in (14) represents the relay threshold operation condition and describes the relay operation characteristic. It is the equation of a circle, with a radius, R_c, given by:

$$R_c = \frac{2K}{1-K^2} \tag{15}$$

The location of the circle center in the complex plane is:

$$a_c + jb_c = -\frac{1+K^2}{1-K^2} + j0 \tag{16}$$

Figure 7 shows a family of relay operation characteristics for different values of the slope, K. The operating region is the area out of the circle (see equation (14), and the restraint region is inside the circle. Note that the –1 + j0 point, corresponding to an ideal through-current condition, is inside the relay restraint region.

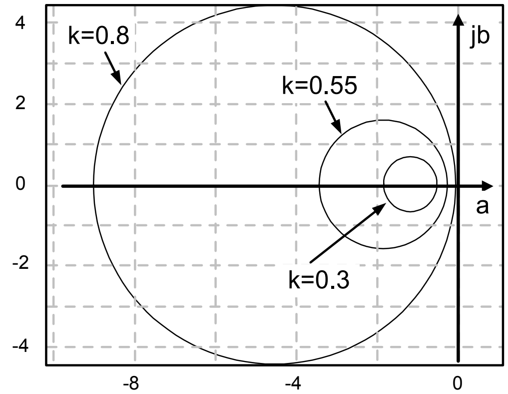


Fig. 7. α-Plane operating characteristic of a differential relay described by equations (3) and (9).

Phase comparison, charge-comparison, and other current differential characteristics can be plotted similarly on the α-plane. There are cases where a closed form solution of the characteristic is not available. However, you can use other methods to define the α-plane characteristic representation of almost all unit-type relay characteristics.

III. Unit-Type Protection Systems

Phase comparison, charge comparison, and current differential systems only require line currents to determine whether the fault is within the protected zone. Phase comparison systems compare the phase relationship of the currents at all line terminals. Early systems used a composite sequence network to form a single-phase voltage signal for phase comparison. Modern digital communications channels permit implementation of segregated phase comparison systems that provide faulted phase identification and enhance the protection response to complex faults. Traditional phase comparison systems may fail to detect higher impedance internal faults with outfeed. Offset keying is an enhancement to phase comparison that adds magnitude information to the phase comparison principle in order to accommodate small levels of outfeed [9]. However, offset-keying phase comparison systems could exhibit sensitivity limitations for faults with low fault current contributions at all line terminals (i.e. high-impedance faults).

Charge comparison is an alternate form of line current differential protection intended to reduce the communications channel bandwidth requirements [10]. Charge comparison performs a numeric integration of the samples of the phase and residual currents over half a cycle. The sample integration process takes place between current zero-crossings. The system stores the resulting ampere-seconds area in memory (converted into an rms current equivalent), along with polarity and start/finish time-tag information. Storage occurs only if the magnitude exceeds a certain threshold, and the half-cycle pulse width is equal to or greater than 6 ms. Every half-cycle the local system also sends information to the remote terminal. The charge comparison system provides higher tolerance to channel asymmetry and outfeed than traditional phase comparison or current differential systems. However, the required zero-crossing detection introduces a half-cycle latency that penalizes speed and introduces additional time delay for internal faults with full dc-offset. External faults with CT saturation that affect zero crossings may jeopardize system security.

Current differential protection combines phase and magnitude current information in a single comparison. The percentage-differential principle, originally developed for the protection of transformers and generators, was extended to the protection of short transmission lines in the 1930s. Early current differential protection systems required a pilot wire channel to exchange analog information between the line terminals. Composite phase or sequence networks, a weighted combination of phase or sequence currents, form voltage signals that contain magnitude and phase information on the currents at the line terminals. Percentage differential relays at each end respond to the currents derived from the comparison of these voltages through the pilot wire. There are a number of limitations in the application of pilot wire relaying systems that stem from special protection requirements for the metallic pilot wire. The availability of fiber-optic and digital microwave communications channels permits modern current differential systems to exchange raw sampled currents (not digitally filtered) or phasor current information using a 64 kps digital channel.

A basic limitation of percentage differential relay systems is that the user must select a slope, or slopes, appropriate to the expected CT saturation and maximum channel asymmetry. This slope setting defines a relay characteristic with a given tolerance to channel-delay asymmetry and CT saturation. Often the tolerance to those sources of error is a complex function of load and fault current.

IV. New Enhanced Current Differential Characteristic

The key factors to consider, in defining the required shape of a line differential relay characteristic in the current ratio plane, are: channel time-delay compensation errors, power system impedance nonhomogeneity, CT saturation, and low frequency oscillations in series-compensated lines. We could virtually eliminate the effect of line charging current and the system power angle using negative- or zero-sequence currents. The channel time-delay compensation errors create a rotation of the ideal fault and load regions in the current ratio plane (see Figure 5). The angle of that rotation equals the error in angle θ created by channel asymmetry. The system impedance nonhomogeneity also produces a rotation of the ideal internal fault region in the current ratio plane (see Figure 4). In a worst-case scenario this angle error adds to that produced by channel asymmetry compensation error.

Figure 8 shows the new differential element characteristic for transmission line protection. The relay restraining region in the current-ratio plane is the area between two circle arcs and two straight lines and includes the $a = -1$ point. Two amplitude and one phase comparison element are needed to create this characteristic. Amplitude comparison provides the circular parts of the characteristic with independent settings R and 1/R (circles radii). Phase comparison provides the linear parts of the characteristic and defines the angular settings α.

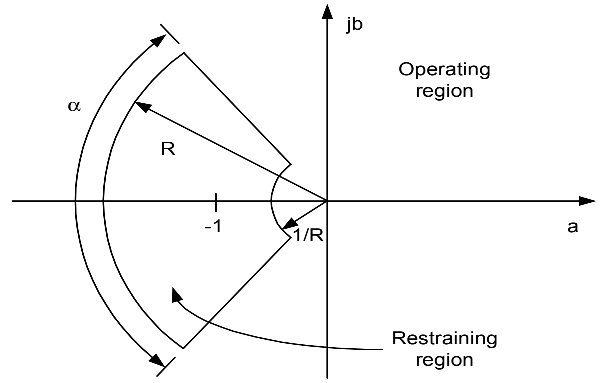


Fig. 8. Characteristic of the new differential element in the current-ratio plane

Note that the characteristic is designed to match perfectly with the different fault and load regions depicted in Figure 5 and yet accommodate CT saturation as well as low-frequency oscillations present in series-compensated lines. The characteristic is symmetrical with respect to the a-axis, and the radii of both circle arcs are reciprocal.

Figure 9 shows a comparison between the new characteristic and that of a popular percentage differential element. When both relays are set for the same level of tolerance to outfeed, as in Figure 9a, the traditional differential relay has very low tolerance to channel asymmetry. If we increase the slope of the percentage differential relay to accommodate a high level of channel asymmetry, as in Figure 9b, the relay loses sensitivity to internal faults with outfeed.

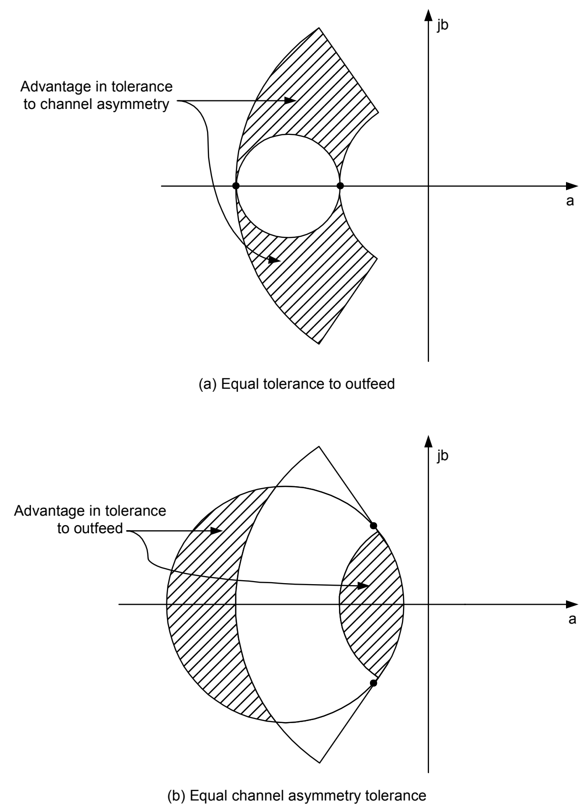


Fig. 9. Advantages of the new characteristic over the percentage differential characteristic

The angle α of the new line differential system is adjustable and can be increased beyond the 180-degree setting to allow for maximum channel asymmetry.

Next we review the performance of the new relay characteristic using Electromagnetics Transients Program (EMTP) and Matlab™ simulations. We first look at a CT saturation case for an out-of-section fault (see Figure 10) to illustrate how the new α-plane element maximizes sensitivity while optimizing security. To illustrate a worst-case scenario, we purposefully mismatch the CT voltage accuracy classes at the two line ends. For the fault shown in Figure 10, we assume that only the CTs associated with the relay at Terminal R saturate. This situation can also be caused by remanent flux in the CT core from an earlier internal fault. Figure 10 shows the raw sampled currents presented to the relay element and the resulting current magnitude at both line ends. The digital filter for this example is a one-cycle cosine filter. If the CTs connected to Relay R had not saturated, the current magnitude calculated by Relays R and L would differ only by the line charging current and communications channel errors. However, because CTs associated with Relay R do saturate, the differential scheme is presented with a significant amount of difference current. The plot shown in Figure 11 shows the results of the two different, yet secure, line differential protection schemes for the external fault described above. The numbered dots connected by a solid line represent the calculated α-plane results progressing in time.

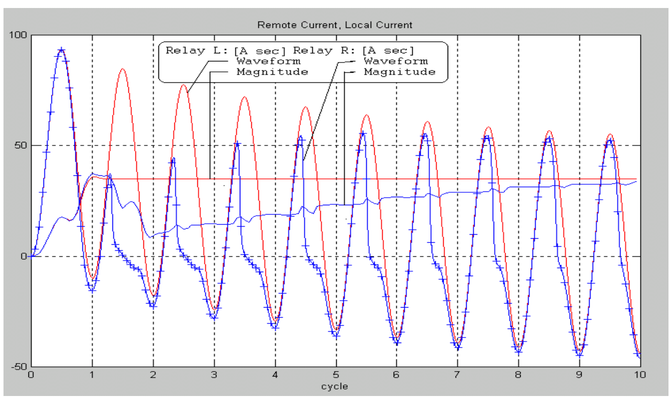


Fig. 10. Raw phase and filtered currents for an external fault

To obtain this figure, we calculated the fundamental phasor values of currents $\vec{I}_L$ and $\vec{I}_R$, using the output signals of the 16 samples-per-cycle cosine filters. We then determined the phasor $\vec{I}_R / \vec{I}_L$ ratio and plotted the result on the complex plane.

To achieve the same security as the new relay element for the case shown in Figure 10, the user should select a slope setting in the percentage differential relay such that the relay characteristic encloses the cluster of all points where the difference current is above the relay minimum pickup value. Notice in Figure 11 that the α-plane restraint region of the enhanced element characteristic covers less area, along the negative real axis, than the percentage differential element, yet both methods achieve the same security for CT saturation. Therefore, the new phase differential element characteristic provides higher ground fault sensitivity during heavy load flow periods, because its restrain region does not include the area mentioned above.

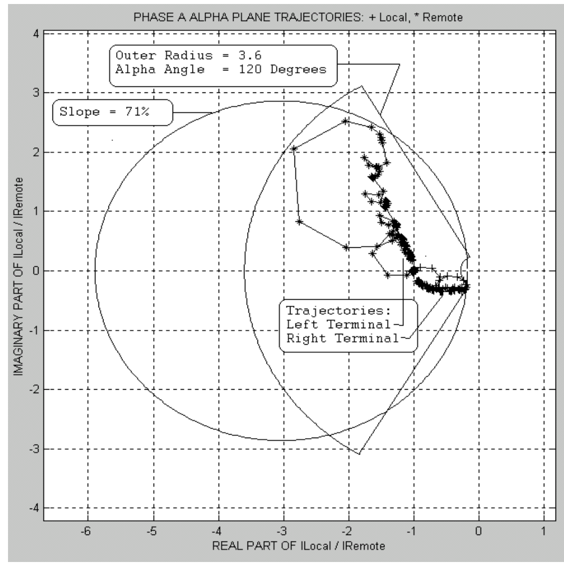
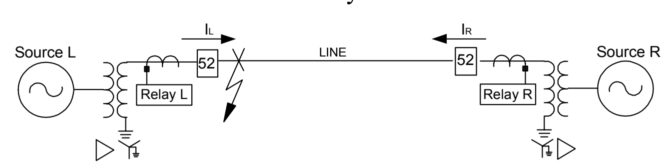


Fig. 11. The α-plane element provides the same level of security for external faults while permitting higher sensitivity than the percentage differential element for internal faults

Once a CT saturates during an out-of-section fault, it does not immediately recover from this saturation when the external fault is cleared. Hence, if one terminal CT saturates for an out-of-section fault while the other terminal CTs do not saturate, and the line is carrying load current, the differential relay can measure an operate current until the saturated CT recovers. Given sufficient operate current, a differential relay may operate shortly after the external fault is cleared. To address this possible maloperation condition, the line differential relay must include security logic to block element operation for a short time after the relay detects an out-of-section fault. Otherwise, the user must desensitize the relay to avoid a maloperation, if the relay is not equipped with this logic.

Let us next review how much ground fault resistance the traditional percentage and the new α-plane differential elements can sense on the example system shown in Figure 12. To illustrate a worst-case example, we include load flow of 4.9 A secondary from left to right. The A-phase ground fault location shown in Figure 12 is on the line-side of the breaker associated with Relay L.



	Source L	Line	Source R
Positive-Sequence:	1Ω ∠90°	5.0Ω ∠84.3°	1Ω ∠90°
Zero-Sequence:	1Ω ∠90°	15.0Ω ∠84.3°	1Ω ∠90°

Fig. 12. System single-line diagram for sensitivity study.

Table 1 presents the maximum settings allowed for each type of protective element to detect just the internal fault for the fault resistance values listed. All of the protective elements sense low-impedance faults very well while being very secure. To detect the internal fault as fault resistance increases, we must decrease the slope of the traditional percentage differential element.

Table 1

Sensitivity Comparisons of Differential Elements			
R_F	New α-Plane Phase and Negative-Seq. Elements		Percentage Diff. Phase Element
[Ω sec.]	I_{AR}/I_{AL}	I_{2R}/I_{2L}	Max. Slope [%]
0	0.13∠-32°	0.17∠5°	100
2	0.06∠-139°	"	90
5	0.21∠-178°	"	65
10	0.39∠-178°	"	44
15	0.50∠178°	"	33
20	0.58∠178°	"	27
35	0.74∠178°	"	14
125	0.90∠178°	"	5

In a practical application, we should limit the inner and outer α-plane radii to 0.25 and 4 respectively to allow for some degree of CT saturation. Thus, the sensitivity of the new enhanced phase current α-plane element is limited to $5 < R_F < 10\ \Omega$. Notice, however, that the new negative-sequence α-plane element operates to trip until 125 Ω secondary (where the element becomes blocked by a supervisory ratio of $|I2|/|I1| >$ design constant). For the traditional phase percentage differential element, we must decrease the slope setting to sense the higher impedance ground faults. This decreasing slope makes the element less secure to CT saturation and communications channel asymmetry.

The new relaying system described in this paper has five line differential elements; three phase segregated elements, one negative sequence element, and one zero sequence element. In addition, the relaying system has a sensitive and secure phase selection algorithm that provides accurate fault type selection that is essential for single-phase tripping applications. The new relaying system accommodates with outfeed currents that sometimes are caused by high-resistance internal line faults, or by strong back-ties between two line terminals in three-terminal transmission line applications. The operating time of the relaying system is less than one cycle, and it is applicable for the protection of EHV lines, including series-compensated lines. In addition to the current differential elements, the relay system includes a plethora of other protection elements such as distance, directional and nondirectional phase and ground elements, over- and underfrequency elements, synchronism check and reclosing elements, pilot protection relaying scheme logic, and an advanced control equation logic capability. All of these features provide users with a tremendous flexibility for the design of a complete, dependable, and secure protection system.

V. Conclusions

1. Current-only differential schemes must balance security challenges from CT saturation and channel asymmetry with sensitivity: the more secure the scheme, the less fault coverage.
2. Percentage differential relays using a slope setting cannot achieve the same sensitivity and security as the new α-plane relay element when we consider the cumulative errors of CT saturation and channel asymmetry.
3. The slope setting of a traditional percentage differential element defines its restrain region security, dependability, and sensitivity. It is difficult to increase one without decreasing another.
4. The new α-plane element is very tolerant of CT saturation while maintaining a maximum degree of fault resistance coverage.
5. Restricting phase differential elements to detecting three-phase faults, while using a negative-sequence differential element to detect all other fault types, maximizes sensitivity while maintaining security.
6. The α-plane analysis helps to visualize how various power system and protection system phenomena affect unit-type protective relay element security, dependability, and sensitivity.

VI. References

[1] "Line Protection Design Trends in the USA and Canada", IEEE Power System Relaying Committee Report, IEEE Transactions on Power Delivery, Vol. 3, No 4, October 1988, pp. 1530–1535.

[2] Tziouvaras D.A., Roberts J., D.A., Benmouyal G, and Hou D., "The Effect of Conventional Instrument Transformer Transients on Numerical Relay Elements", 28th Annual Western Protective Relay Conference, Spokane, Washington, USA, October 2001.

[3] "A Current Differential Relay System Using Fiber Optics Communications", S. C. Sun and R. E. Ray, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, No 2, February 1983, pp. 410–419.

[4] "A Survey of Optical Channels for Protective Relaying: Practices and Experience", IEEE Power System Relaying Committee Report, IEEE Transactions on Power Delivery, Vol. 10, No 2, April 1995, pp. 647–658.

[5] CIGRE Application Guide on Protection of Complex Transmission Network Configurations, CIGRE SC34-WG04, May 1991.

[6] A.R. van C. Warrington, Protective Relays: Their Theory and Practice, Volume 1, London, Chapman and Hall, 1962.

[7] A.R. van C. Warrington, Protective Relays: Their Theory and Practice, Volume 2, London, Chapman and Hall, 1969.

[8] Roberts J., Tziouvaras D.A., Benmouyal G, and Altuve H., "The Effect of Multiprinciple Line Protection on Dependability and Security", 54th Annual Conference for Protective Relay Engineers, Texas A&M University, College Station, Texas, USA, April 2001.

[9] Calero F. and Elmore W., "Current Differential and Phase Comparison Relaying Schemes", 19th Annual Western Protective Relay Conference, Spokane, Washington, USA, October 1992.

[10] "Charge Comparison Protection of Transmission Lines – Relaying Concepts", L.J. Ernst, W.L. Hinman, D.H. Quam, and J.S. Thorp, IEEE Transactions on Power Delivery, Vol. 7, No 4, October 1992, pp. 1834-1852.

VII. Biographies

Demetrios A. Tziouvaras received his BSEE degree in 1980 from the University of New Mexico, and his MSEE in 1986 from Santa Clara University. He worked for Pacific Gas and Electric Co. for 18 years in the System Protection Group. He served as a Principle Engineer responsible for the selection of relaying systems, system protection design standards, and application of new technologies in substation automation. In 1988, he joined Schweitzer Engineering Laboratories in the position of Research Engineer where he is currently involved in the development of numerical relays. His main interests are protection of power systems, power system transients, and digital relaying. He is the author or co-author of numerous papers in the area of power system protection. He holds one patent and has several patents pending. He is an IEEE senior member, a member of the Power System Relaying Committee, and a member of CIGRE. He is also the convenor of CIGRE SC34-WG15 on “Distance Protection Functions for Modern Applications.”

Héctor J. Altuve received his BSEE degree in 1969 from the Central University of Las Villas, Santa Clara, Cuba, and his Ph.D. in 1981 from Kiev Polytechnic Institute, Kiev, Ukraine. His main research interests are in power system protection and control. From 1969 until 1993, Dr. Altuve served on the faculty of the Electrical Engineering School, at the Central University of Las Villas. Author of more than 80 technical papers, Dr. Altuve served as professor, Graduate Doctoral Program, Mechanical and Electrical Engineering School, at the Autonomous University of Nuevo León, Monterrey, Mexico, from 1993 to 2000 and continues to instruct there on a part-time basis. In 1999-2000, he was the Schweitzer Visiting Professor at Washington State University’s Department of Electrical Engineering. In 2001, he joined SEL as a senior research engineer based in Monterrey, Mexico. In November 2001, Dr. Altuve became the General Director of SEL S.A. de C.V., the SEL subsidiary in Mexico. He is also an IEEE senior member.

Gabriel Benmouyal, P.E. received his B.A.Sc. in Electrical Engineering and his M.A.Sc. in Control Engineering from Ecole Polytechnique, Université de Montréal, Canada in 1968 and 1970, respectively. In 1969, he joined Hydro-Québec as an Instrumentation And Control Specialist. He worked on different projects in the field of substation control systems and dispatching centers. In 1978, he joined IREQ, where his main field of activity was the application of microprocessors and digital techniques to substation and generating-station control and protection systems. In 1997, he joined Schweitzer Engineering Laboratories in the position of Research Engineer. He is a registered professional engineer in the Province of Québec, is an IEEE member, and has served on the Power System Relaying Committee since May 1989. He is the author or co-author of several papers in the field of signal processing and power networks protection. He holds one patent and has several patents pending.

Jeff Roberts is a Research Fellow at Schweitzer Engineering Laboratories in Pullman, WA. Prior to joining SEL he worked for Pacific Gas and Electric as a Relay Protection Engineer. He received his BSEE from Washington State University in 1985. Mr. Roberts holds 19 patents and has several other patent applications pending; he has written many papers in the areas of distance element design, sensitivity of distance and directional elements, directional element design, and analysis of event report data. He has delivered papers at the Western Protective Relay Conference, Texas A&M University, Georgia Tech, Monterrey Symposium on Electric Systems Protection, and the South African Conference on Power System Protection. He is a Senior Member of the IEEE and was recognized by the Spokane chapter of the IEEE as Engineer of the Year for 2001.

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