

End-to-End Testing of the Alpha Plane Characteristic of the New Line Differential Relays Using Satellite Synchronization Signals

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Abstract - The paper describes the impact of advancements in automatic testing of the new line differential microprocessor based protective relays. First, a review of line differential relays concepts is provided. The applications, advantages and limitations of these relays are described. Among these a particular emphasis on the relays with a built-in Alpha Plane Characteristic is given. Then the challenges associated with field testing of these types of relays are explained. Also the paper describes different approaches to test Line Differential Protective Relaying Systems. The paper further describes the concept of End-to-End testing and why this is the only reliable way of testing these relays. The article presents the hardware and software requirements and describes how the test will be performed at each of the substations where the relays under test are actually located. The paper also presents an innovative method of plotting in real time the trip characteristic of a line differential relay. Finally, the test results are explained and conclusions are drawn.

Index Terms - alpha plane characteristic, differential relay, End-to-End testing.

I. LINE DIFFERENTIAL RELAYS-PAST AND PRESENT

For the last decades power systems have been loaded more and more while adding new transmission lines to reduce congestions did not keep up with the increased demand. Consequently the systems operate close to the stability limit which calls for higher speed fault clearing in the transmission lines. As the technology advances communication-assisted tripping technology became widely accepted in the industry. This type of system, also called pilot relaying systems has the advantage of clearing the fault securely for the entire length of the line. The pilot schemes rely on one of the following two principles: directional comparison or unit-type systems. The direction of the fault current flow is the criteria employed by the directional comparison systems while a real time comparison of the currents of the transmission line(s) terminals is used in the second case. Also the unit type systems use one of the three techniques to compare the currents of the terminals: phase comparison, charge comparison or current differential principle. Historically the directional comparison schemes have been widely accepted because of their low communications channel requirement and low backup protection needs [1]. The shortcoming of the

method is that system voltages are needed to calculate the power flow. Voltage collapse in case of close-in faults and ferroresonance due to capacitive voltage transformers can drive these types of differential relays to miss-operate. The unit-type relays need the currents only and thus the above problems are avoided. Each of the 3 unit-types systems has its advantages and limitations as described below [1].

Phase comparison systems compare the phase relationship of the currents at line terminals. A segregated phase comparison algorithm is implemented in modern numerical relays and provides faulted phase(s) identification along with a better response to complex faults. The shortcoming of these systems is that they may fail to detect high impedance ground faults under outflow condition. Some relays use an offset-keying phase comparison. The relays have a better response provided the outfeed is low. These systems can also be insensitive under weak infeed conditions.

Charge comparison schemes rely on a numeric integration of samples of the currents over a half cycle. The zero crossing detection is essential for this technique. The Ampere-seconds area is stored along with polarity and timing of the event information. The information is sent to the remote terminal every half cycle. The charge comparison system provides a higher tolerance to channel asymmetry and outfeed condition than traditional phase comparison or classic current differential relays. As a disadvantage of the method the zero crossing detection is the most important one since a reliable zero crossing detection will introduce a half a cycle delay. Also an external fault which drives a CT into saturation can significantly affect the detection of the zero crossing and thus cause relay to miss-operate.

Current differential relays consider both the phase and magnitude of the currents in a single comparison. The method of operation is based on the percentage differential principle that is the current at the ends will provide the restraining and the operating quantities. The bigger the slope the higher the operating threshold current will be. One of the limitations of these relays is the requirement for shielded metallic pilot wire. Modern systems allow nowadays the analog information to be sent via fiber optic or microwave communication channels. Another limitation of these relays is that the user has to carefully select a slope to compensate for CT saturation and channel-delay asymmetry.¹

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A. Alpha Plane Characteristic – A revived concept

About a half century ago A.R. van C. Warington mentioned for the first time about an innovative method to be considered when protecting transmission lines [2], [3]. Basically he suggested a characteristic similar to an admittance complex plane instead of using a classic percentage differential. Since the currents can be represented as complex quantities, they can be represented in a complex ($a + jb$) plane where the vector to be displayed is the complex **ratio** of the remote to the local current. He named the plane – Alpha Plane. This concept has not been further implemented in practice because the technology of real time processing of the analog quantities and transmit them from one terminal to another was not available at that time. But the concept has significant advantages over other methods employed in current differential protection systems. The concept has been introduced in the industry recently and proved to be a reliable alternative to classical methods.

Roberts et al. [4] introduced the concept of Alpha Plane Characteristic implemented in microprocessor based relay for line current differential relay. For a better understanding of the concept Fig. 1 and Fig.2 are provided. In Fig.1 a pre-fault and a fault condition are shown. During pre-fault the current flows naturally from one source to another (we assume a current

flow from the left to right). Neglecting the line charging currents the ratio of the remote to local current will be:

$$\frac{\vec{I}_R}{\vec{I}_L} = 1 \angle 180^\circ \quad (1)$$

where \vec{I}_R, \vec{I}_L are the remote and the local current respectively. In the complex plane (see Fig.2) this pre-fault stage lies on the negative axis at unit magnitude. Under fault condition both sources will provide current towards the fault (See Fig.1- bottom part). Ideally, if the sources are strong enough and the fault does not have significant impedance the ratio between remote to local currents will be:

$$\frac{\vec{I}_R}{\vec{I}_L} = 1 \angle 0^\circ \quad (2)$$

The locus of an “ideal” fault on the complex plane will be on the positive axis at unit magnitude (see Fig.2). Practically the locus of the current ratio during a fault and normal conditions varies significantly so a restraint characteristic to surround the ideal non-fault point is requested. The relay has to provide a highly secured restrained characteristic which has to be insensitive to external faults or outfeed conditions but sensitive to high impedance faults at the same time.

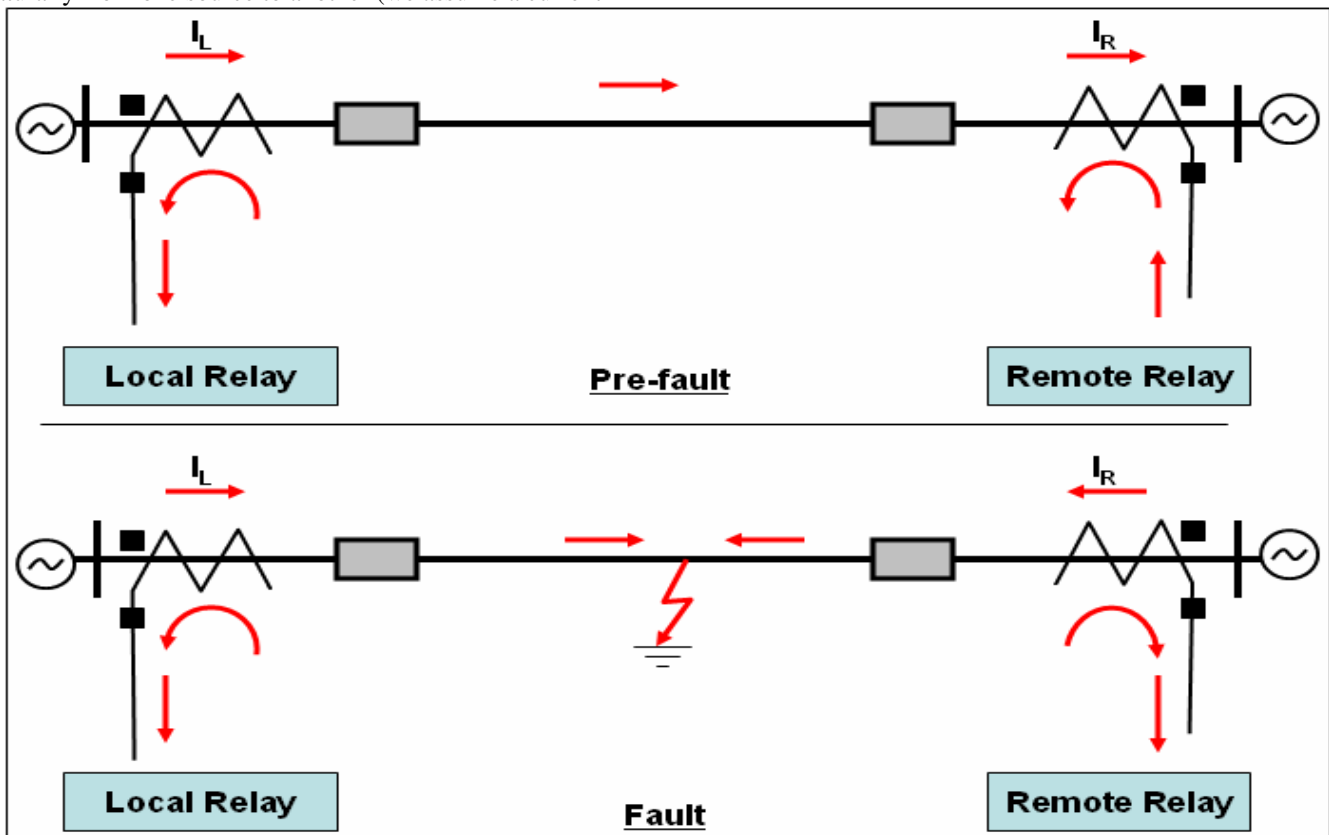


Fig.1 The flow of the current during pre-fault and fault respectively (see Fig.5 also)

Below are explained some of the factors impacting the shape of the characteristic. Also a brief comparison between the new Alpha Plane Characteristic and the conventional Percentage Restraint Characteristic is provided. The most important factors to be considered for designing the characteristic are the following: the channel time delay, power system impedance non-homogeneity, current transformers saturation, weak infeed, load and outflow condition (high impedance faults) [1], [6].

The goal is to provide a fixed ratio restrained characteristic which provides enough coverage for most of the faults and applications. Once accomplished, this would be a “zero settings” relay – a concept with a significant impact in relay world since it will be a simple solution to growing complexity of the Power Systems.

The load is produced when the sources behind the line to be protected are at different angles. During a fault this angle difference can be up to 10° in either direction so a total of 20° (10° clockwise and 10° counterclockwise) has to be eliminated from the restrained characteristic [6].

Since Power Systems have a degree of non-homogeneity also, this introduces a phase shift between the sources due to the different source angles during a fault. The area the restraint characteristic has to be shifted clockwise and counterclockwise is another 10° each direction. [6].

The new numerical Line Differential Relays are connected via fiber optic cables. This allows the protective system to process the fault quantities fast and send the permissive/blocking signals to the other end more reliable.

A direct single or multimode fiber optic cable is the simplest and most reliable way to assure communication between relay terminals. An IEEE C37.94 compliant multimode fiber-optic interface can be used also [8]. A complex Synchronous Optical Systems (SONET) assures the communication between multi-terminal lines and substations but may introduce delays. Even unequal forces on the fiber optic cable can introduce delays [5]. This channel delay asymmetry has to be taken into consideration and adjust the restraint characteristic accordingly. Basically any delay in transmitting the currents from one terminal to another has the effect of rotating the complex ratio of the remote to local currents about the origin. Since one cycle has 360° and corresponds to 16.66ms at 60Hz it means that every millisecond of delay will introduce a 21.6° phase shift in the complex plane. About 2 milliseconds is a maximum delay time expected in SONET systems during an internal fault so

an additional 22° in each direction has to be considered when building the restrained characteristic. [6]. It has been reported delays of 3ms or bigger but these are very rare and will require additional consideration respective to what type of characteristic or method to be used [5].

Another factor to be considered is the CT saturation. When the CT saturates the fundamental component of the fault current decreases in magnitude and advances in angle. This has the effect of rotating the ratio of the currents in the complex plane up to 40° [1].

If we add up all the angles explained above we obtain 82° the new characteristic has to be sensitive to (with reference to origin, quadrant 1 and 4). Consequently the new restraint angle coverage has to be $360^\circ - 2 \times 82^\circ = 196^\circ$ in quadrants 2 and 3 mostly. Fig. 2 shows the maximum angular restraint region accordingly.

The maximum and minimum ratios are determined by load and type of fault. A weak remote source will determine a very low ratio of the currents for the local terminal and a large ratio at the remote one. A similar effect will be obtained in case of a broken conductor, open breaker pole or highly saturated CT. The characteristic negotiates a maximum ratio of 6 and excludes a ratio of 1/6 close to the origin to accommodate these situations (see Fig.2 also) [6]. Some relays allow the radius to be changed if the application requires a larger or smaller restraint coverage.

It has been demonstrated that a conventional Percentage Differential Characteristic can be plotted in a complex Alpha Plane as a circle with the center in the negative axis [1]. Fig.2 shows three overlaid percentage characteristics for different pickup and slope levels (a, b, c). The higher the likelihood a CT will saturate the higher the slope should be. The higher the slope the less sensitive the relay to high impedance faults is. If we reduce the slope the circle lowers the diameter (from circle (a) or (b) to (c) in Fig.2). This means the differential element may become less secure to CT saturation and channel asymmetry [1], [7]. The new Alpha Plane Characteristic offers a good balance between security and sensitivity for most of the fault cases including CT saturation at one end, weak in-feed, outflow and high impedance faults. Since the implementation of this new concept in the market steadily increases a new testing approach has to be considered.

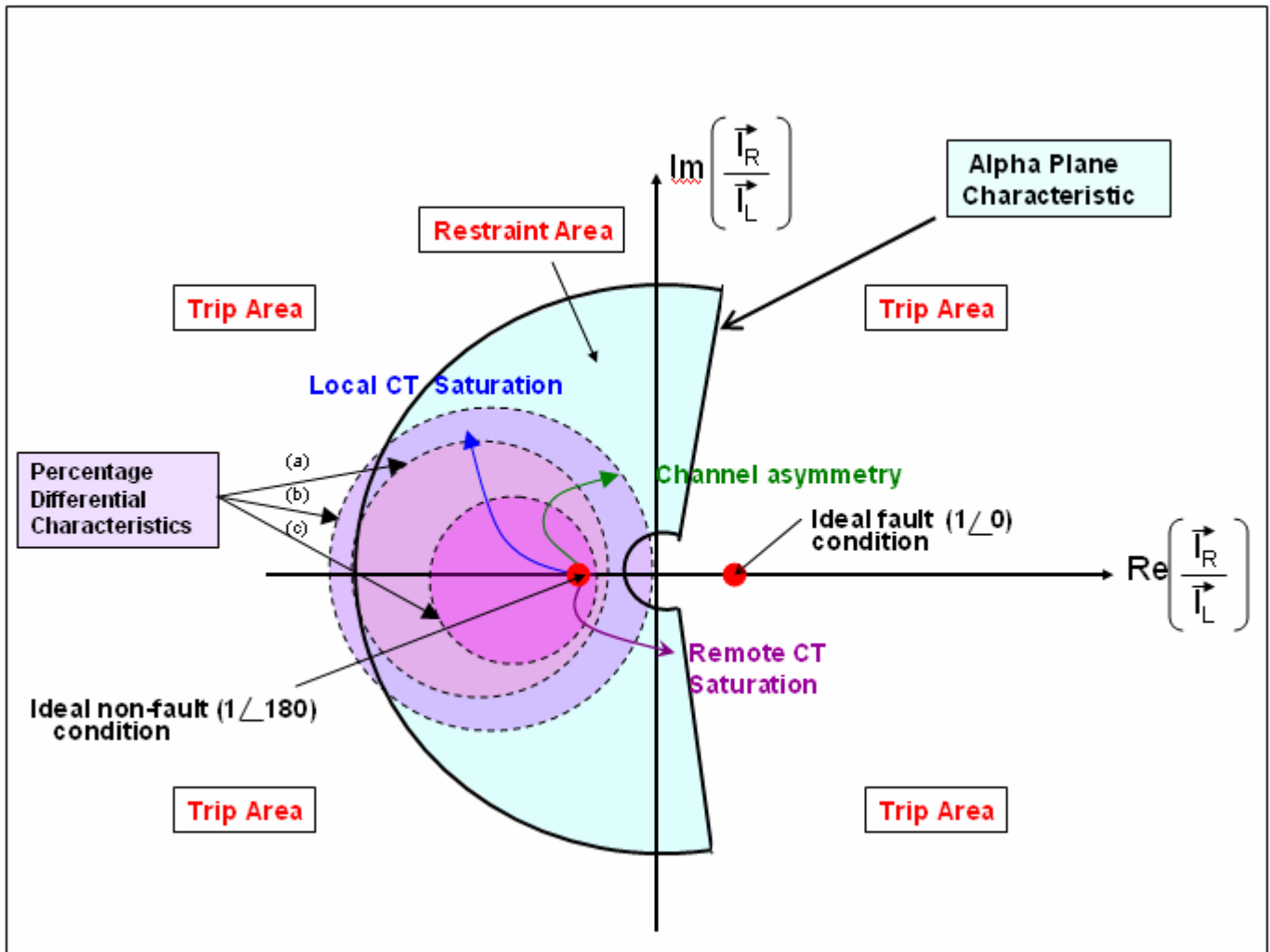


Fig.2 Alpha Plane Characteristic versus Percentage Differential Characteristic

B. End-To-End Testing of the Line Differential Relays

The most important challenge in testing line differential relays is to provide the test quantities at all the line terminal relays at the same time. A line differential relay acquires the currents from its own terminal only and, based on the method employed, the remote current is provided via various communication channels. A simple and quick test can be detecting the individual pickup level for each of the relay by increasing gradually the current(s) at one end. Since no current is provided from the other terminal the local relay will trip as soon as the threshold is reached. This method is not suitable to determine the operating or restraining characteristic. In order to determine the characteristic all the terminal currents have to be provided synchronously and each of the relays has to send the quantities to the remote ends real time.

Modern relays are connected between each other by fiber optic system so the processing of the pre-fault and fault quantities and transmitting the trip or block decisions to the remote ends are performed extremely fast. In the recent years the advancements in the new microprocessor

based relay test sets allowed to test the line differential relays in such a way that simulates the real life processes in the Power Systems. The concept of testing the relays is so called End-To-End and became rapidly implemented as a standard technique in the industry. Basically the method requires two three phase test sets equipped with a Global Positioning System (GPS) receiver and an antenna. Fig.3 depicts the standard setup (antenna and the receiver not shown). A Global Positioning System (GPS) consists of a number of satellites orbiting at high altitude (approx. 11000 miles) and ground stations which monitor and control the system [9]. The system consists of 21 active satellites and 3 in-orbit spares each of which orbit the earth twice per day. The design of the system is such that at least four satellites are in view at all times from all places on the earth, thus providing continuous, world-wide, three dimensional navigation capabilities. The satellites transmit encoded signals at either 1575.42 or 1227.6 MHz.

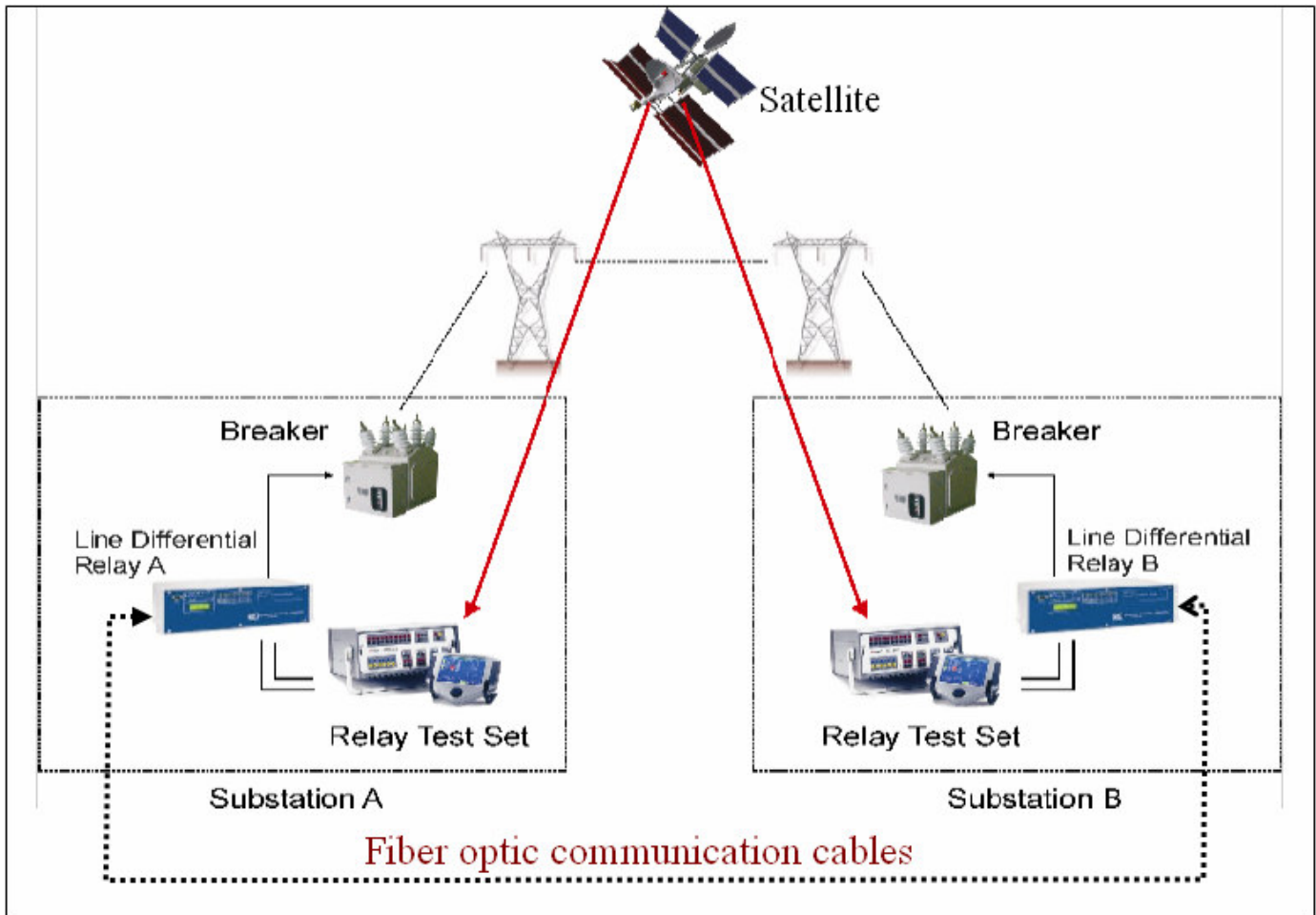


Fig.3 End-To-End Testing of the Line Differential Relays

For End-To-End testing it is recommended that a minimum of 3 satellites must be tracked simultaneously. However a precise time (the only important parameter for this application) can be derived by tracking one satellite only. The GPS receivers are highly accurate with a drift in the nanoseconds range. The satellites send “corrective” signals to GPS receivers which allow the internal clock to be aligned to the high accuracy Cesium atomic clock of the satellites. The programming of the system is simple since the tracking is performed automatically when the unit is powered up initially. Basically the user has to set the coincidence time (compared to the Universal Time Clock-UTC) he wants to start the test. The same coincidence time has to be set at both terminals. The time is usually displayed with a resolution within microseconds. Once the time is reached a transistor-transistor logic (TTL) pulse is provided by the receiver. The signal will trigger the process of End-To-End which can be performed in 3 ways as further explained. The first method, a widely used one, is to upload into the test set converted comtrade files (so called cfg files). These files have a fixed number of samples and simulate a pre-fault and fault sequence. The original cfg files can be produced by ATP/EMTP fault simulation software or extracted directly from a relay based on previous operation

of the differential protective devices system. A second approach is to upload the box with predefined sequence of states that is Pre-Fault and Fault. Upon operation, the relay test sets will display the trip time and information about correct or incorrect operation of the overall system. Both of the above methods test the system on a point to point basis. Hereinafter an innovative method of actually plotting the Alpha Plane Characteristic of the new Line Differential Relays is presented.

C. Real time testing of the Alpha Plane Characteristic using Satellite Synchronization Signals

As explained above the most important challenge in testing these types of relays is to synchronize the test quantities at both ends. To test the characteristic we basically need to provide the currents in such a way that the ratio between the remote and local ones will be changed continuously and “crosses” the characteristic from restraint into the operating region. This will be performed by holding the remote current at a constant value and ramp down the local

current magnitude at specified calculated angles until the relay trips. Note that injection of the test quantities (currents only in this case) is started synchronously with the help of GPS system as explained above. Once the quantities are applied, a nominal frequency (50 or 60HZ) signals will assure that the quantities will stay in sync during the test. To be noted that these relays have multiple differential elements – three phase elements (87LA, 87LB and 87LC), a negative-sequence element (87L2) and a zero-sequence element (87L0). The threshold is set very low for both negative and zero sequence elements (0.1 per unit nominal) and higher for phase element (1.2 per unit nominal) [8]. This will ensure a high sensitive fault detection for high impedance faults while being stable to CT saturation. When testing, the current level at remote end has to be chosen accordingly for the relay to pick up properly.

Especially when performing the test simulating a three phase fault, the magnitude of the three phase current has to be greater than 6A (for 5A relays). The test we select to describe the new method of plotting the Alpha Plane Characteristic is a Phase (A)-to-Ground Fault. The current at the remote end is held constant at **6A**. If the relay characteristic border radius is set at **6** it means that **1A** is required for the local relay to trip. The local relay receives and processes real time the magnitude (and phase angle also) from the remote terminal and compares them with the similar quantities injected by the test set. The currents at both terminals along with a real time value of the ratio between them can be displayed during the test along with the trajectory (of the ratio) during the process. A snapshot during performing an actual test is shown in Fig.4.

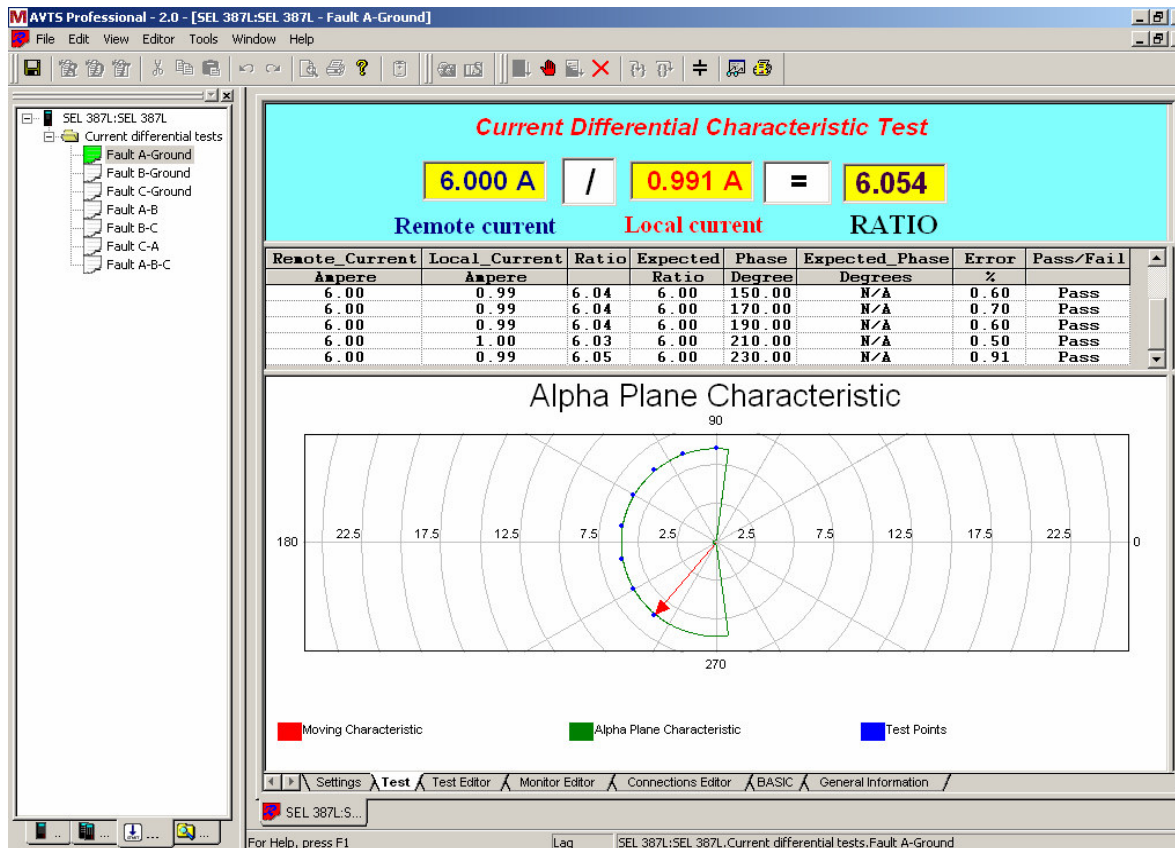


Fig.4 Snapshot during an actual test of the Alpha Plane Characteristic.

Fig. 5 shows a capture of a fault recorded in a line differential relay. As shown in Fig.1 also the currents at the local and the remote terminal are out-of-phase when no fault is present and in-phase during a fault. The total current is zero during pre-fault and increases significantly during a fault. The trip bit (87L) picks up immediately and provides a reliable sub-cycle tripping. Once the outer radius is tested point by point then the magnitude of both current is adjusted accordingly for testing the linear portions of the characteristic. For this test (we are still in sync condition!) the test sets holds the currents constant and the local test set starts ramping down the phase (for testing the line in quadrant 1) or ramping up the phase (for testing the line in quadrant 2). Finally the

inner radius is tested in a similar manner as the outer radius. Since this radius is much smaller a much larger current has to be provided by the test set at the local terminal and a smaller one at the remote end. A snapshot of the test results is shown in Fig.6. For each of the test point the magnitude of the remote and local currents along with the calculated ratio are displayed. Also the expected ratio and the accuracy are shown. For the linear portions of the characteristic the phase angle between the currents is the parameter to be monitored. Finally a “Pass/Fail” decision is provided and the test is completed. The procedure is performed automatically and the test results are obtained in practically no time.

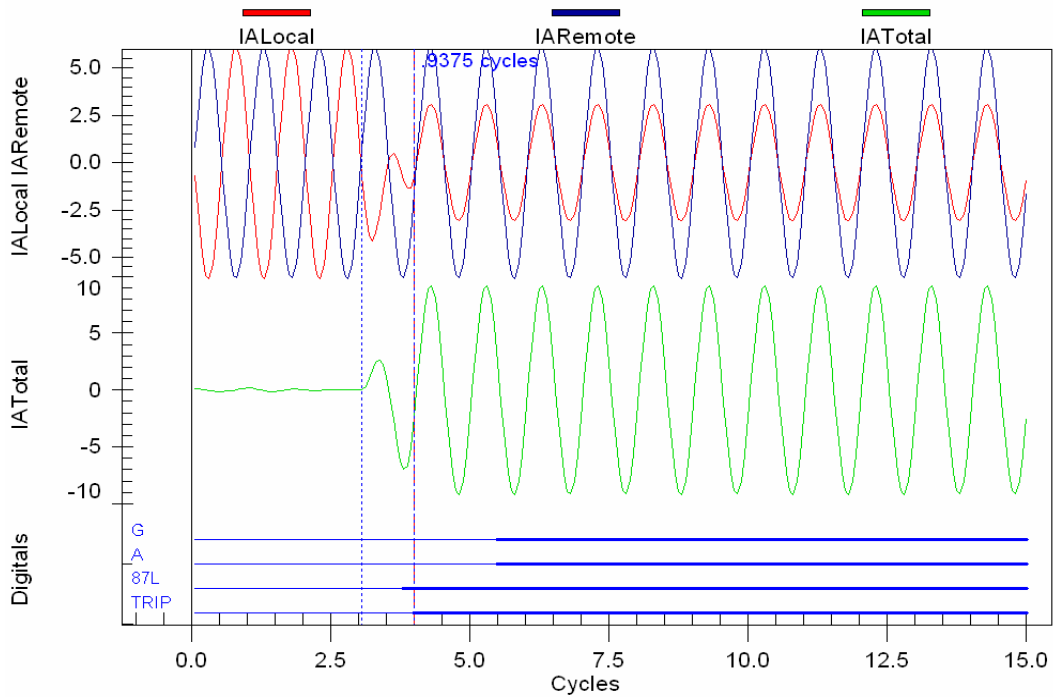


Fig.5 Fault Record captured from a numerical relay with an embedded Alpha Plane Tripping Characteristic

AVTS Professional - 2.0 - [SEL 387L:SEL 387L - Fault A-Ground]

File Edit View Editor Tools Window Help

SEL 387L:SEL 387L

- Current differential tests
 - Fault A-Ground
 - Fault B-Ground
 - Fault C-Ground
 - Fault A-B
 - Fault B-C
 - Fault C-A
 - Fault A-B-C

Current Differential Characteristic Test

2.000 A / 12.050 A = 0.166

Remote current Local current RATIO

Remote_Current	Local_Current	Ratio	Expected	Phase	Expected_Phase	Error	Pass/Fail
Ampere	Ampere	Ratio	Ratio	Degree	Degrees	%	
6.00	1.00	6.03	6.00	90.00	N/A	0.50	Pass
6.00	0.99	6.04	6.00	110.00	N/A	0.60	Pass
6.00	0.99	6.04	6.00	130.00	N/A	0.60	Pass
6.00	0.99	6.04	6.00	150.00	N/A	0.60	Pass
6.00	0.99	6.04	6.00	170.00	N/A	0.70	Pass
6.00	0.99	6.04	6.00	190.00	N/A	0.60	Pass
6.00	1.00	6.03	6.00	210.00	N/A	0.50	Pass
6.00	0.99	6.05	6.00	230.00	N/A	0.91	Pass
6.00	0.99	6.05	6.00	250.00	N/A	0.81	Pass
6.00	0.99	6.04	6.00	270.00	N/A	0.60	Pass
6.00	1.20	N/A	N/A	83.90	82.50	1.70	Pass
6.00	3.00	N/A	N/A	82.90	82.50	0.48	Pass
6.00	1.20	N/A	5.98	277.20	277.50	-0.11	Pass
6.00	3.00	N/A	6.00	276.60	277.50	-0.32	Pass
2.00	12.05	0.166	0.166	180.00	N/A	-0.18	Pass

Alpha Plane Characteristic

Alpha Plane Characteristic Test Points

Settings Test Test Editor Monitor Editor Connections Editor BASIC General Information

SEL 387L:S... For Help, press F1 Lag SEL 387L:SEL 387L.Current differential tests.Fault A-Ground

Fig.6 Sample of results generated when testing the Alpha Plane Characteristic.

C. Conclusions

As the technology advances new algorithms are implemented in the new microprocessor based relays. One of them is the new Alpha Plane Characteristic implemented in the new Line Differential Relays. The paper presented initially the types of the line differential protective systems and methods employed over the years. Then the Alpha Plane Characteristic concept and its implementation in the numerical Line Differential Relay have been described. All the factors impacting the shape of the restraint characteristic have been outlined. A comparison between performances of this type of relays and the classic Percentage Differential ones has been presented also. Then the paper introduced the concept of End-To-End testing. The preparations for actually performing this type of test are shown. An innovative method of automatic testing of the overall Line Differential Protective scheme has been further described. The method allows plotting real time the actual Alpha Plane Characteristic and generates the test results automatically.

II. ACKNOWLEDGEMENT

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IV. BIOGRAPHY



Cristian Paduraru is a graduate of Polytechnic Institute of Iasi, Romania with a Master Degree in Power Engineering. He joined MEGGER (former AVO International) in 2001 as a Senior Application Engineer in Technical Support Group and he is in charge with developing custom applications for numerical protective relays using AVTS (Advanced Visual Test Software). He is also in charge with testing and deploying auto test modules, which allow the customer to evaluate and diagnose the operation of microprocessor based protective relays. Prior position he held was System Engineer with General Electric Automation Services in Dallas, Texas (from 2000 to 2001) where he designed Generator Protection Panels for large combined cycle power plants. He also worked for Romanian Electricity Authority as a System Protection Engineer (1993-2000). He is a registered Professional Engineer in the state of Texas and a member of Power Engineering Society of IEEE and IEE.