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Development of a New Test Method for Alpha Plane Differential Protection Characteristic Using IEC61850 Standard Based Numerical Relays

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Abstract

This paper focuses on three-terminal Alpha Plane differential protection to develop a complete test method using the OMICRON test universe software essentially defining security, dependability, and sensitivity of the Alpha Plane characteristic. It analyses the three-terminal alpha plane characteristic and the existing primitive test method and develops an improved test method using the IEC 61850 standard. The primitive method is time-consuming and results in unnecessarily prolonged outages. The primitive test method is discussed and improved by implementing the IEC 61850 standard. First, the standard IED Capability Description (ICD) file is modified by developing new logical nodes using AcSELerator Architect and XML Maker software. Then the developed logical nodes, Three-Terminal differential protection Alpha Plane characteristic with its additional infeed/outfeed check logic, and the developed test method are tested simultaneously using Test Universe software. A laboratory test bench is built using three SEL311L relays, two CMC 356 Omicron injection devices, PC, MOXA Ethernet switch, CMIRIG-B time synchronizing unit, SEL 2407 satellite synchronized clock, and a DC power supply. The developed test method vindicates the benefits of IEC 61850 standard over hard-wired systems. Prolonged outage times due to test set preparation using hard wires are drastically reduced.

Keywords: Alpha Plane, Differential Protection, IEC 61850 Standard, Intelligent Electronic Devices (IED), IED Capability Description (ICD), Configured IED Description (CID), Generic Object-Oriented Substation. Event (GOOSE) Message, Logical Node (LN)

I. INTRODUCTION

Any power system is prone to 'faults', (also called short-circuits), which occur mostly as a result of insulation failure and sometimes due to external causes. When a fault occurs, the normal functioning of the system gets disturbed. If a fault is not properly detected and removed, widespread damage or a power system blackout may take place [1]. The high current resulting from a fault can stress the electrical conductors and connected equipment thermally and electro-dynamically. Arcs at the fault point can cause dangerous or even fatal burn injuries to operating and maintenance workers in the vicinity. Faults involving one phase and ground give rise to high 'touch' and 'step' voltages posing the danger of electrocution to personnel working nearby. It is, therefore, necessary to detect and clear any fault quickly.

Transmission lines are a vital part of the electrical distribution system, as they provide the path to transfer power between generation and load. Transmission lines operate at voltage levels from 69kV to 765kV and are ideally tightly interconnected for reliable operation. Factors like de-regulated market environment, economics, etc. have pushed utilities to operate transmission lines close to their operating limits. There is an economic pressure to build lower cost and simpler to use systems. The most efficient way to decrease costs is to decrease the number of primary apparatus. A solution often used is to build multi-terminal lines [2].

Any fault, if not detected and isolated quickly will cascade into a system-wide disturbance causing widespread outages for a tightly interconnected system operating close to its limits. Transmission lines protection systems are designed to identify the location of faults and isolate only the faulted section. The key challenge to the transmission line protection lies in reliably detecting and isolating faults compromising the security of the system.

The current differential criterion is used with success to protect various elements in power systems, i.e. power transformers, generators, busbars, and transmission lines. The basic operating principle of this criterion is to compare currents flowing into the object with the currents flowing out of the object at the other end [3].

Countermeasures of measuring differential current became more sophisticated with advancements in the field of differential protection and progressed from adding an intentional time delay, percentage restraint, harmonic restraint, and blocking to sophisticated external fault detection algorithms and adaptive restraining techniques [4]. The alpha plane differential relaying system provides sensitive protection for transmission lines, security, and dependability for external faults. The relaying system is tolerant of unequal

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communication channel delays [5].

Other form of multi-terminal transmission line protection based on impedance/distance protection is presented by [6] Multi-terminal transmission line protection based on current differential method is one of the oldest methods of protection and continues to be used or dominates other forms of protection as it is considered superior with respect to selectivity, sensitivity, stability and speed of operation as compared with other forms of protection. Apart from percentage current differential protection method. In [7] present a novel transient differential protection based on distributed parameter and [8] present a methodology for adaptive control of the restraining region in a current differential plane based on equivalent –model. These methods inherit a common disadvantage of Voltage Transformer fuse failures. Traditional percentage current differential protection as one form of differential protection is mostly used in one form or the other. In [9] presents one form of protection based on sampled values implementing percentage differential protection. In [10] describe other method of current differential protection scheme for Teed transmission lines using superimposed components, also implementing percentage differential protection.

Interestingly, [11] present Alpha Plane differential characteristic on two terminal application in comparison with percentage current differential characteristic and outline the advantages of Alpha Plane differential characteristic over percentage current differential characteristic. In [12] it also present Alpha Plane differential protection for multi-terminal transmission line and outline general design directions for a next generation line current differential protection scheme. The alpha plane method has been a tool available to protective engineers to study line current differential characteristics and faults, but now is been deployed as algorithm within relays for protection purpose. Apart to multi-terminal application, alpha plane has been implemented for 3-terminal application with different algorithm. The research is aimed at investigating, evaluating and analysing methods and algorithms of existing IEDs implementing alpha plane characteristic. The aim is to develop a complete test method for three terminal differential alpha plane characteristic using OMICRON test universe software essentially defining security, dependability and sensitivity of alpha plane characteristic

Test procedures have been developed for testing alpha plane characteristics on two-terminal differential applications only. 3 terminal differential applications needed to be developed, thus testing between two terminals at a time i.e. terminals A-B; B-C and A-C have been the test method for 3 terminal applications. This posed a need for research on the Intelligent Electronic Devices (IED) algorithm and or test methods which is mainly the subject of this paper or considered in this paper.

The content of this paper is presented as follows: The development of a new logical node with restraint elements is described in part 2. Configuration of the IEDs and OMICRON devices is presented in part 3. The Three-Terminal Alpha Plane characteristic is discussed in part 4. Part 5 presents the development of a new test method for testing the Three-terminal Alpha Plane characteristic using the newly developed logical node. Case studies in developing the test method and obtained results are presented in part 6. Discussion of the obtained results and benefits are presented in part 7 and part 8 presents the conclusion.

II. DEVELOPMENT OF NEW LOGICAL NODE WITH RESTRAINT ELEMENTS

The instability of voltage in the power systems has become a concern. The primitive test method required that all differential elements be hardwired from the relay to the OMICRON device at each substation as shown in Figure 1. Differential elements include 5 operating elements and 5 restraint elements. Before wiring, the elements had to be programmed or mapped to 10 relay outputs which created a big room for human error either in programming or wiring. The entire process is time-consuming, resulting in prolonged outages.

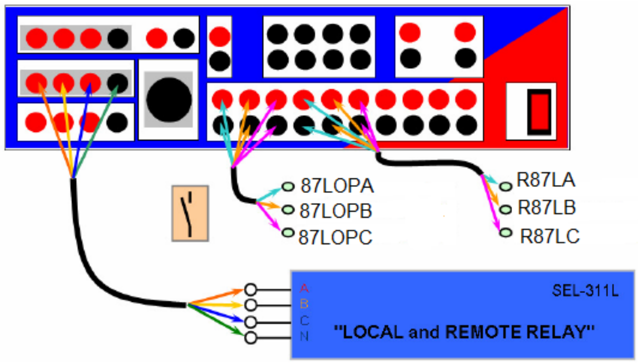

Figure 1. Hardwiring of differential elements

To avoid the shortcomings of the primitive test method, a new method is proposed in this paper using IEC61850 standard which allowed differential elements to be published by the relay in a form of Generic Object Orientated Substation Event (GOOSE) message and subscribed by the OMICRON devise as opposed to hard wiring. However, the standard IED Capability Description (ICD) file for SEL311L relay only has operated elements logical node and does not have restraint elements logical node which explains the need for a new logical node to be developed.

SEL has its standard Logical Devices in AcSELerator Architect palette as shown in Figure 2. The IED Palette provides a source of IED files to add to a project, to export and import ICD files. To configure GOOSE messages through the use of Architect software, an engineer copies and pastes graphical objects representing IEDs from the IED Palette into a project and then accesses the properties of the selected IED for either outgoing or incoming GOOSE messages[6 -13].

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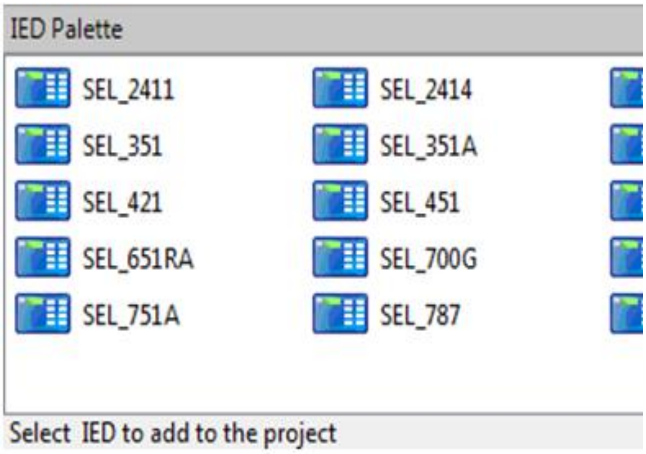

Figure 2. SEL standard Logical devices in AcSElerator software

SEL-311L Standard Logical Device does not have PDIF Differential Logical Node with Restraint elements as shown on Figure 3, only the operate Elements are available. These operate elements are PRO.D87LPDIF1.Op.phsA, PRO.D87LPDIF1.Op.phsB, PRO.D87LPDIF1.Op.phsC, PRO.D87LPDIF1.Op.neut, PRO.D87LPDIF1.Op.neg.

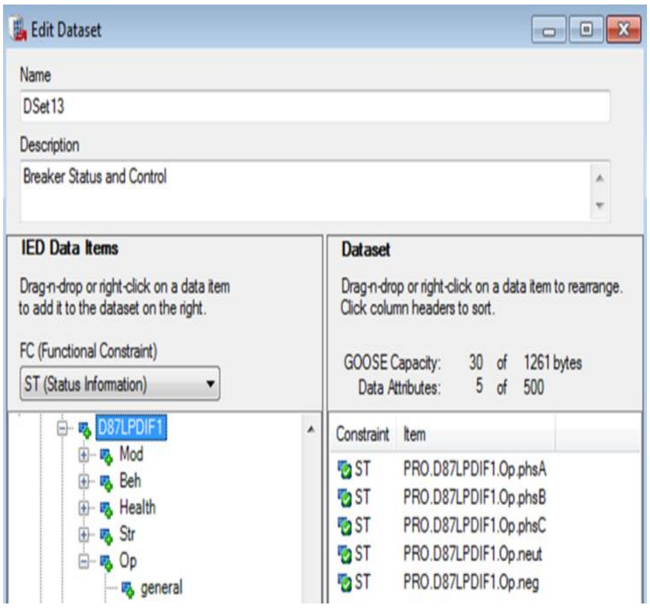

Figure 3. PDIF Logical Node with Operate Elements Only

The flow chart in Figures 4 shows steps followed to create a logical node with restraint elements.

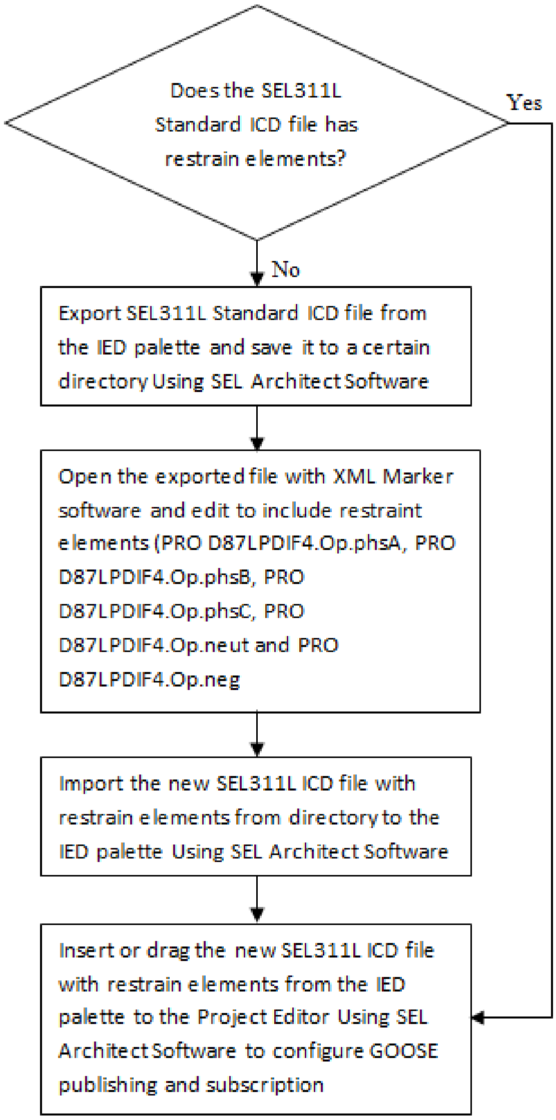

Figure 4. The flow chart followed to create a logical node with restraint elements

To model, an SEL 311L IED PDIF Logical Node with restraint elements, first the standard SEL 311L ICD file is exported from the palette using AcSELerator Architect software and renamed as ‘SEL-311L with restraint elements - R411 and Higher’ in this case.

The SEL 311L ICD file is then edited using XML Marker software. In XML Marker language, SEL Configuration Language (SCL) is the root element, IED is the child element and AccessPoint, Server, Ldevice, LN, DOI, and DAI are the subchild elements as shown in Figures 5 and 6. The SEL standard structure consisting of a root, child, and subchild elements was maintained.

```
<root>
  <child>
    <subchild>.....</subchild>
  </child>
</root>
```

Figure 5. XML Marker language

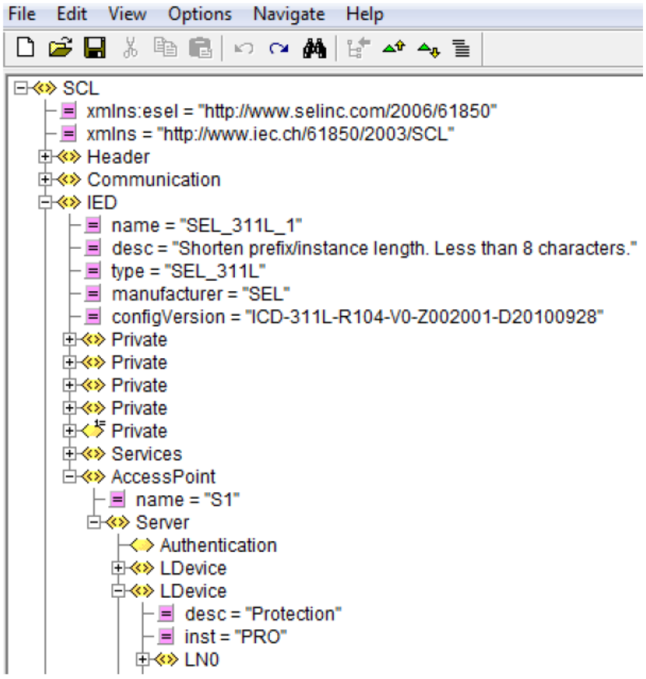

Figure 6. SEL standard structure consisting of Root, Child and subchild elements

Using XML Marker software, the Logical Node Type, Class Instance and Prefix were defined as well as the mandatory and optional Logical Node information as shown from Figure 7 to Figure 13 in line with IEC61850-7-4 guidelines. This part of IEC 61850 specifies the information model of devices and functions related to substation applications. In particular, it specifies the compatible logical node names and data names for communication between the Intelligent Electronic Devices (IEDs). This includes the relationship between Logical Nodes and Data [7-14].

```
<LN lnType="PDIF1" lnClass="PDIF" inst="4" prefix="R87L">
```

Figure 7. Logical Node Type, Class Instance and Prefix description

```
<DOI name="Mod">
  <DAI esel:datasrc="db:E3_001?5:1" name="stVal"/>
  <DAI esel:datasrc="db:E3_001" name="q"/>
  <DAI esel:datasrc="imm" name="ctlModel">
    <Val>0</Val>
  </DAI>
</DOI>
```

Figure 8. Mode: consisting of Status Value, Quality, and Control Model data attributes.

```
<DOI name="Health">
  <DAI esel:datasrc="db:E3_001?3:1" name="stVal"/>
  <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 9. Health: consisting of Status Value and Quality data attributes.

```
<DOI name="Beh">
  <DAI esel:datasrc="db:E3_001?5:1" name="stVal"/>
  <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 10. Behavior: consisting of Status Value and Quality data attributes.

```
<DOI name="NamPlt">
  <DAI esel:datasrc="imm" name="vendor">
    <Val>SEL</Val>
  </DAI>
  <DAI esel:datasrc="dbi:FID" name="swRev"/>
  <DAI esel:datasrc="imm" name="configRev">
    <Val>0</Val>
  </DAI>
  <DAI esel:datasrc="imm" name="d">
    <Val>Protection</Val>
  </DAI>
</DOI>
```

Figure 11. Nameplate: consisting of Vendor swRev and configRev and description data attributes.

```
<DOI name="Str">
  <DAI esel:datasrc="db:E3_008" name="general"/>
  <DAI esel:datasrc="imm" name="dirGeneral">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:R87LA" name="phsA"/>
  <DAI esel:datasrc="imm" name="dirPhsA">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:R87LB" name="phsB"/>
  <DAI esel:datasrc="imm" name="dirPhsB">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:R87LC" name="phsC"/>
  <DAI esel:datasrc="imm" name="dirPhsC">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:R87LG" name="neut"/>
  <DAI esel:datasrc="imm" name="dirNeut">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:87L2" name="neg"/>
  <DAI esel:datasrc="imm" name="dirNeg">
    <Val>1</Val>
  </DAI>
  <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 12. Start: consisting of restraint elements General, Directional General, Phase A, Directional Phase A, Phase B, Directional Phase B, Phase C, Directional Phase C, Neutral, Directional Neutral, Negative Sequence, Directional Negative, and Quality data attributes.

```
<DOI name="Op">
  <DAI esel:datasrc="db:E3_008" name="general"/>
  <DAI esel:datasrc="db:R87LA" name="phsA"/>
  <DAI esel:datasrc="db:R87LB" name="phsB"/>
  <DAI esel:datasrc="db:R87LC" name="phsC"/>
  <DAI esel:datasrc="db:R87LG" name="neut"/>
  <DAI esel:datasrc="db:R87L2" name="neg"/>
  <DAI esel:datasrc="db:E3_001" name="q"/>
</DOI>
```

Figure 13. Operate: consisting of restraint elements General, Phase A, Phase B, Phase C, Neutral, Negative Sequence, and Quality data attributes.

The new model of the SEL 311L relay ICD file has now been developed. This model is then imported as a new SEL 311L relay ICD file into the AcSELerator Architect palette as a new SEL311L with restraint elements as its name implies as shown in Figure 14. The CID file is then configured using AcSELerator Architect software to develop the CID file with a newly developed logical node for restraint elements.

The CID file is then tested in conjunction with the 3 terminal alpha plane characteristic as discussed in part 6 of this paper.

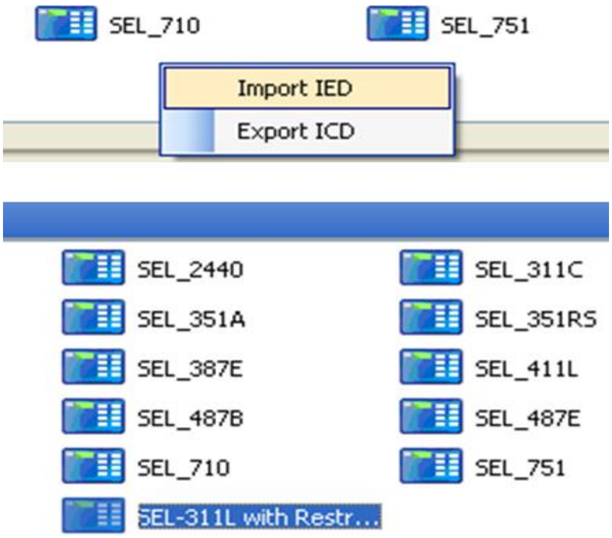

Figure 14. New SEL 311L IED into AcSELerator Architect palette

Figure 15 shows the newly developed restrain elements in PDIF logical node.

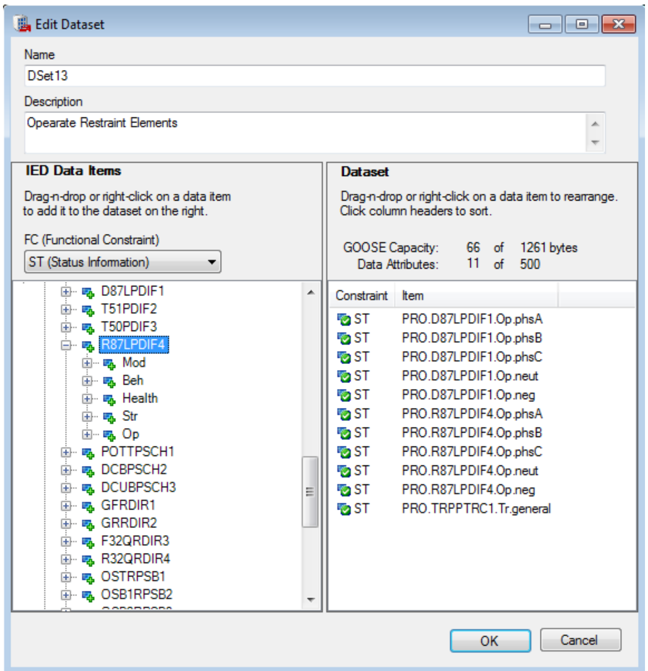

Figure 15. Newly developed logical node with restraint elements

Part 3 describes the configuration of IEDs and Omicron devices for GOOSE publishing using a newly developed logical node.

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III. CONFIGURATION OF THE IEDS AND OMICRON DEVICES

Once the CID file is developed, it is necessary to test it to prove its functionality. First, the CID file is exported from AcSELerator Architect software and saved in a general folder. This file is then imported to OMICRON Test Universe software to configure the CMC test equipment or test set. The same file is also uploaded or sent to the respective SEL 311L relays. This is done to ensure that the test set can subscribe to messages published by the relays. The test set injects fault currents into the relays and subscribes to messages published by the relays. One test set is used to inject two relays and the second test set is used to inject the third relay. The two test sets are then synchronized to inject fault currents simultaneously. The testing of the logical node is presented in part 6.

The mapping of operating and restraint elements GOOSE messages from the CID file to the test set binary inputs is performed via the GOOSE Configuration module [8-15]. The operation and restraint signals are subscribed and used for testing the protection function. Figure 16 shows the example of a relay publishing the Red phase differential protection operated element (PRO.PDIF87L1.Op.phsA) GOOSE message and the test set subscribing to this message, mapping it to the binary input 1.

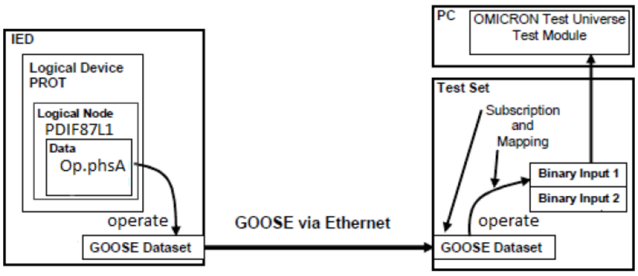

Figure 16. Publishing and subscription of the operating element

Figure 17 shows the example of a relay publishing the Red phase differential protection restraint element (PRO.R87LPDIF4.Op.phsA) GOOSE message and the test set subscribing to this message, mapping it to the binary input 2.

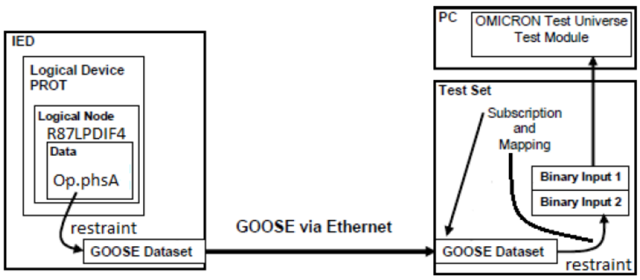

Figure 17. Publishing and subscription of the restraint element

Figure 18 shows the test bench setup with two test sets synchronized via IRIGB, connected to an Ethernet switch and protection relays which are also interconnected with fiber optic cables for differential protection communication purposes. One PC is used to control both test sets and communicates with all three relays.

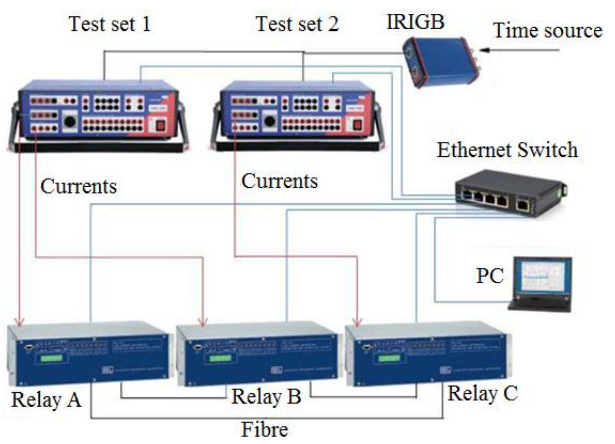

Figure 18. Test-bench setup

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IV. THREE-TERMINAL ALPHA PLANE CHARACTERISTIC

The SEL-311L Relay contains five-line current differential elements: one for each phase, one for the negative-sequence, and ground current. The phase elements provide high-speed protection for high current faults. Negative-sequence and ground elements provide sensitive protection for unbalanced faults without compromising security [9-16-11-18]. Zero-sequence and negative-sequence currents are completely independent of the load current and angle, the pure fault current, and, consequently, the fault resistance [12-19]. Figure 19 shows the SEL-311L Relay Line Current Differential Elements.

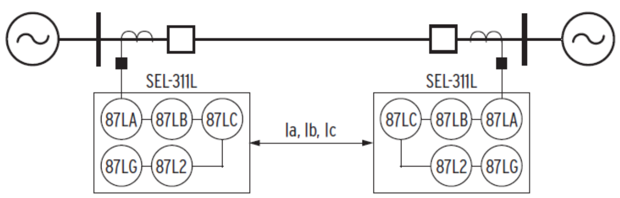

Figure 19. SEL-311L relay line current differential elements

The SEL-311L Relay exchanges time-synchronized Ia, Ib, and Ic samples between two or three line terminals. Each relay calculates negative sequence (3I2) and zero sequences (3I0) for all line terminals. Current differential elements 87LA, 87LB, 87LC, 87L2, and 87LG in each relay compare Ia, Ib, Ic, 3I2, and 3I0 (IG) from each line terminal. All relays perform identical line current differential calculations in a peer-to-peer architecture to avoid transfer trip delays. Figure 20 shows the alpha plane, which represents the phasor or complex ratio of remote (IR) to local (IL) complex currents [9-16]. There is a separate alpha plane for every current (phase, negative-sequence, and zero-sequence).

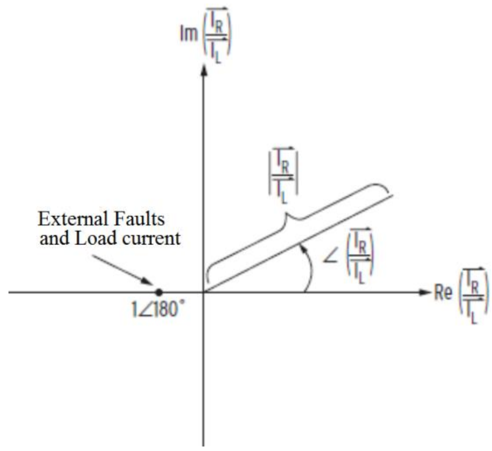

Figure 20. Alpha plane represents a complex ratio of remote-to-local complex currents

Arbitrarily assign current flowing into the protected line to have zero angles, and the current flowing out of the protected line to have angle 180 degrees. Five Amps of load current flowing from the local to the remote relay produces an A-phase current of 5∠0° at the local relay, and 5∠180° at the remote relay. The ratio of remote to local current is:

$$\frac{I_{AR}}{I_{AL}} = \frac{5\angle 180^\circ}{5\angle 180^\circ} = 1\angle 180^\circ$$

$$\frac{I_{BR}}{I_{BL}} = \frac{5\angle 60^\circ}{5\angle -120^\circ} = 1\angle 180^\circ$$

$$\frac{I_{CR}}{I_{CL}} = \frac{5\angle -60^\circ}{5\angle 120^\circ} = 1\angle 180^\circ$$

On the phase alpha plane, 1∠180° plots one unit to the left of the origin, as shown in Figure 20. The other two phases also reside at 1∠180° on their respective alpha planes. All through-load current plots at 1∠180° regardless of magnitude and regardless of the angle concerning the system voltages [5]. Likewise, an external fault has equal and opposite current at the two-line ends and so external faults also plot at 1∠180°. The SEL-311L Line Current Differential Relay surrounds point 1∠180° on the alpha plane with a restraint region, as shown in Figure 21. The relay trips when the alpha plane ratio travels outside the restraint region, and the differential current is above a settable threshold. The relay restrains when the alpha plane ratio remains inside the restraint region, or when there is insufficient differential current.

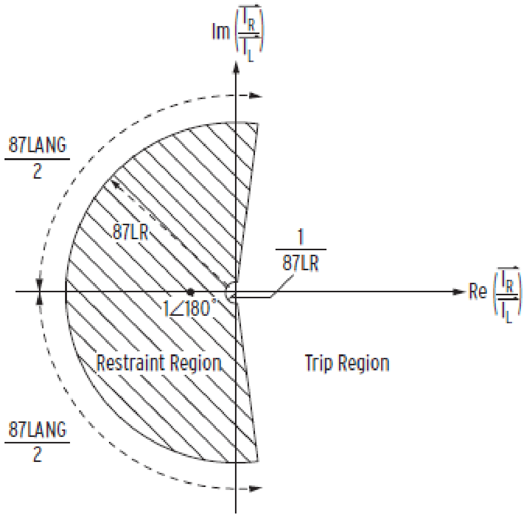

Figure 21. SEL-311L relay restraint region surrounds external faults

According to the literature, the SEL-311L relay applies the alpha plane concept of two-terminal application to three-terminal lines by combining (vectorially adding) currents from two of the terminals to produce the remote current. The remaining (uncombined) current becomes the local current when calculating the alpha plane ratio of the remote to the local currents. In other words, the SEL-311L Relay converts the three-terminal line to an electrically equivalent two-terminal line and then applies two-terminal protection algorithms. All of the considerations described in the two-terminal discussion apply to three-terminal protection also.

For internal faults with no outfeed and for external faults with no CT saturation, there is no wrong way to choose which two currents to combine into the remote current because all three possibilities result in the correct trip/restrain decision. The SEL-311L Relay processes all 87L elements using all three possible combinations of remote current. Table 1 shows the three possibilities.

Table 1. Three possible combinations of remote and local currents at relay R.

Combinations / Currents	1	2	3
I_{Remote}	$I_B + I_C$	$I_A + I_C$	$I_A + I_B$
I_{Local}	I_A	I_B	I_C

During the research, it was also found that if at least one or more terminals see the fault as internal, additional check logic is used to ensure that the fault is within the protective zone. This logic exists in the relays but is not in the relay manual which also formed the basis of this research as it was found that the relays do not operate as described in the manual. Figure 22 shows the additional trip/restraint check logic. Once the logic has established that one of the permutations has detected the fault as internal it then determines which of the three currents is the largest and which current is the second largest (middle value). It then checks the angle between these two currents. If the angle difference between the largest and second-largest (middle) current is greater than 90 degrees, the fault is external and the element is blocked from operating. If the angle is less than 90 degrees, the fault is internal and the 87L element is allowed to trip.

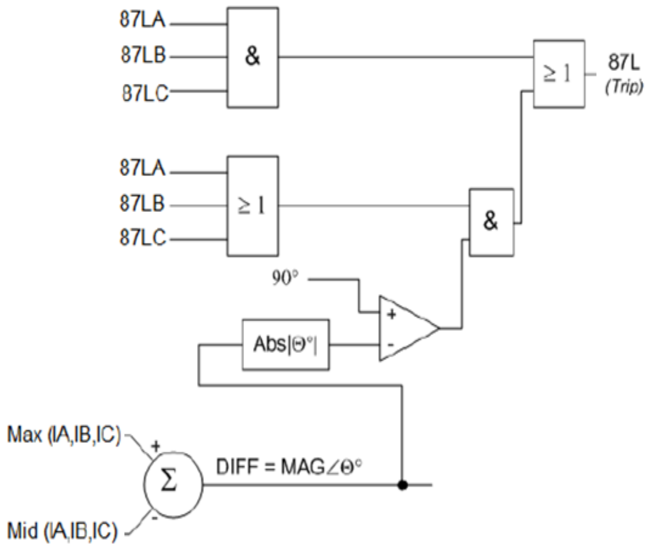

Figure 22. Additional trip/restraint check logic

V. DEVELOPMENT OF A METHOD FOR TESTING 3 TERMINAL ALPHA PLANE CHARACTERISTIC USING NEWLY DEVELOPED LOGICAL NODE

The SEL-311L Relay contains five-line current differential elements: Once the additional logic was found, the test method for 3 terminal alpha plane differential protection was developed. The aim of the test is 3 fold:

- To prove the functionality of the 3 terminal alpha plane characteristic with the additional logic
- To prove the functionality of the newly developed logical node
- Development of a new test method

All the tests are carried out simultaneously. 8 case studies represented by 8 test point as shown in Figure 23 and an additional 2 case studies represented by the additional check logic are described below.

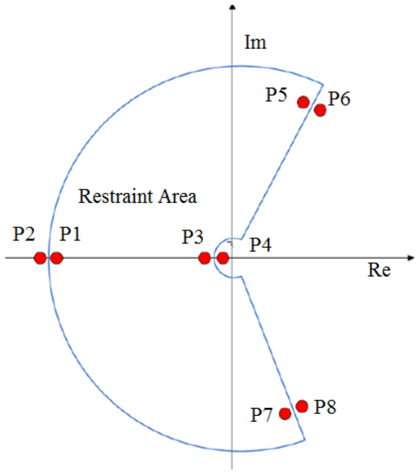

Figure 23. Alpha plane test points

Test points with even numbers are placed in the trip region, whereas test points with odd numbers are placed in the restraint region. From the test module's view of the OMICRON Test Universe software, the binary inputs are configured in the hardware configuration and applied for the testing. The mapping of the Binary input signals is verified using the 'State Sequencer' test module in line with Alpha Plane Operate and Restraint regions as discussed below.

For testing three-terminal 311L, two criteria were established in line with the Alpha Plane algorithm.

V.1. Internal fault without out-feed

If each of the permutations sees the fault as internal i.e. in each case the I_R/I_L ratio goes outside the blocking zone and enters the operating zone then the element trips without any further checks

V.2. Internal fault with out-feed

If at least one terminal sees the fault as internal, the additional check logic in Figure 22 is followed. With alpha (α) set to 6∠195°, a set of eight test points are established, the eight test points are:

- P1: α= 5.5∠180°
- P2: α = 6.5∠180°
- P3: α = 0.3∠180°
- P4: α = 0.05∠180°
- P5: α = 5.5∠87.5°
- P6: α = 5.5 ∠77.5°
- P7: α = 5.5 ∠-87.5°
- P8: α = 5.5∠ -77.5°

To achieve these alpha values, a set of currents to be injected on all three relays were calculated as follows;

$$\alpha A = \frac{I_B+I_C}{I_A} \quad (1)$$

$$\alpha B = \frac{I_A+I_C}{I_B} \quad (2)$$

$$\alpha C = \frac{I_A+I_B}{I_C} \quad (3)$$

For Relay A Point 1:

$$\frac{I_B+I_C}{I_A} = 5.5\angle 180° \quad (4)$$

$$\frac{I_A+I_C}{I_B} = 5.5\angle 180° \quad (5)$$

$$\frac{I_A+I_B}{I_C} = 0.31\angle 180° \quad (6)$$

From Equation (1) **Error! Digit expected.** (7)

From Equation (2)**Error! Digit expected.** (8)

From Equation (3) **Error! Digit expected.** (9)

Substituting Equation (7) and (8) into Equation (9) gives:

$$I_C = \left(\frac{I_B+I_C}{5.5\angle 180°} + \frac{I_A+I_C}{5.5\angle 180°}\right) \div 0.31\angle 180° \quad (10)$$

$I_A = 1.705I_C - 2I_C - I_B$
$I_A = -I_B - 0.295I_C$ (11)

Equation (7) = Equation (11) = I_A

$$\frac{I_B + I_C}{5.5\angle 180°} = -I_B - 0.295I_C$$

$I_B - 5.5I_B = 1.623I_C - I_C$
$I_B = -0.138I_C$ (12)
Substituting Equation (12) into Equation (11) gives:

$I_A = -(-0.138I_C) - 0.295I_C$
$I_A = 0.138I_C - 0.295I_C$
$I_A = -0.157\ I_C$
If $I_A = 1\angle 180°$ A
$\therefore I_c = 6.4\angle 0°$A
& $I_B = 0.88\angle\mathbf{180}°$A $\cong I_A$

For Relay A point 2 assuming αA = 6.5∠180° and αB = αC = 0.2∠0° (reciprocal of αA)

$$\alpha A = \frac{I_B + I_C}{I_A}$$

$$\alpha B = \frac{I_A + I_C}{I_B}$$

$$\alpha C = \frac{I_A + I_B}{I_C}$$

From Equation (1) – (3) and the assumed values of αA, αB, αC the following can be derived:

$$\frac{I_B+I_C}{I_A} = 6.5\angle 180° \quad (13)$$

$$\frac{I_A+I_C}{I_B} = 0.2\angle 0° \quad (14)$$

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$$\frac{I_A+I_B}{I_C} = 0.2\angle 0° \qquad (15)$$

From Equation (1) **Error! Digit expected.**
(16)

From Equation (2)**Error! Digit expected.**
(17)

From Equation (3) **Error! Digit expected.**
(18)

Substituting Equation (16) and (17) to Equation (18) gives:

$$I_C = \left(\frac{I_B + I_C}{6.5\angle 0°} + \frac{I_A + I_C}{0.2\angle 0°}\right) \div 0.2\angle 0°$$

$I_A = 0.04\ I_C - I_C\ 0.031\ I_B\ 0.031\ I_C$

$I_A = 0.031\ I_B - 0.929\ I_C$ (19)

Equation (16) = Equation (19) = I_A

$$\frac{I_B + I_C}{6.5\angle 180°} = 0.031 I_B - 0.929 I_C$$

$I_B + 0.202\ I_B = 5.039\ I_C$

$I_B = 4.192\ I_C$ (20)

Substituting Equation (20) to Equation (19) gives

$I_A = 0.031 \times 4.192\ I_C – 0.929\ I_C$

$I_A = 0.13\ I_C – 0.929\ I_C$

$I_A = -0.799\ I_C$

If $I_C = 1\angle 180°$ A

$\therefore I_B = 4.192\angle 180°$ A

& $I_A = 0.799\angle 0°$ A

Table 2 shows the number of currents that are injected simultaneously on each relay for relay A equivalent alpha value.

Table 2: Simultaneous injected analog values of currents for relay A for point 1 to point 8

Relay A			
Alpha α	Relay A current (A)	Relay B current (A)	Relay C current (A)
P1: α= 5.5∠180°	1∠180°	1∠180°	6.4∠0°
P2: α= 6.5∠180°	0.799∠0°	4.192∠180°	1∠180°
P3: α= 0.3∠180°	6.5∠0°	1∠180°	1∠180°
P4: α= 0.05∠180°	4.192∠180°	0.799∠0°	1∠180°
P5: α= 5.5∠87.5°	1∠180°	1∠180°	5.548∠-82°
P6: α= 5.5∠77.5°	1∠180°	5.66∠-112°	0.948∠-9.9°
P7: α= 5.5∠-87.5°	1∠180°	5.547∠82°	1∠180°
P8: α= 5.5∠-77.5°	1∠180°	5.66∠112°	0.948∠9.9°

Table 3 shows the number of currents that are injected simultaneously on each relay for relay B equivalent alpha value.

Table 3: Simultaneous injected analog values of currents for relay B for point 1 to point 8

Relay B			
Alpha α	Relay A current (A)	Relay B current (A)	Relay C current (A)
P1: α= 5.5∠180°	1∠180°	1∠180°	6.4∠0°
P2: α= 6.5∠180°	4.192∠180°	0.799∠0°	1∠180°
P3: α= 0.3∠180°	1∠180°	6.5∠0°	1∠180°
P4: α= 0.05∠180°	0.799∠0°	4.192∠180°	1∠180°
P5: α= 5.5∠87.5°	1∠180°	1∠180°	5.548∠-82°
P6: α= 5.5∠77.5°	5.66∠-112°	1∠180°	0.948∠-9.9°
P7: α= 5.5∠-87.5°	5.547∠82°	1∠180°	1∠180°
P8: α= 5.5∠-77.5°	5.66∠112°	1∠180°	0.948∠9.9°

Table 4 shows the number of currents that are injected simultaneously on each relay for relay C equivalent alpha value.

Table 4: Simultaneous injected analog values of currents for relay C for point 1 to point 8

Relay C			
Alpha α	Relay A current (A)	Relay B current (A)	Relay C current (A)
P1: α= 5.5∠180°	6.4∠0°	1∠180°	1∠180°
P2: α= 6.5∠180°	1∠180°	4.192∠180°	0.799∠0°
P3: α= 0.3∠180°	1∠180°	1∠180°	6.5∠0°
P4: α= 0.05∠180°	1∠180°	0.799∠0°	4.192∠180°
P5: α= 5.5∠87.5°	5.548∠-82°	1∠180°	1∠180°
P6: α= 5.5∠77.5°	0.948∠-9.9°	5.66∠-112°	1∠180°
P7: α= 5.5∠-87.5°	1∠180°	5.547∠82°	1∠180°
P8: α= 5.5∠-77.5°	0.948∠9.9°	5.66∠112°	1∠180°

VI. CASE STUDIES AND RESULTS

Using values from Table 2, the results from Figure 24 and Figure 25 using the method discussed in section 5 show that Relay A and B point 1 were tested simultaneously as shown with notification 1 in Figure 24. The currents 1∠180°A on red phase with balanced angles and equal magnitudes for all phases was injected on relay A and B as shown with notification 2 on Figure 24, and 32∠0°A (= 6.4 x I nominal) on red phase with balanced angles and equal magnitudes for all phases was injected on relay C as shown with notification 2 on Figure 25 since relay C secondary current rating was 5A.

This external fault was simulated for 1 second as shown with notification 3 in Figure 24 and Figure 25. Restraint elements R87LA, R87LB, and R87LC (notification 4 on Figure 24) picked-up almost instantaneously (just above 17ms) as shown with notification 5 in Figure 24. This is the indication that the newly developed logical nodes are functioning and the relays restrain as required for this test case.

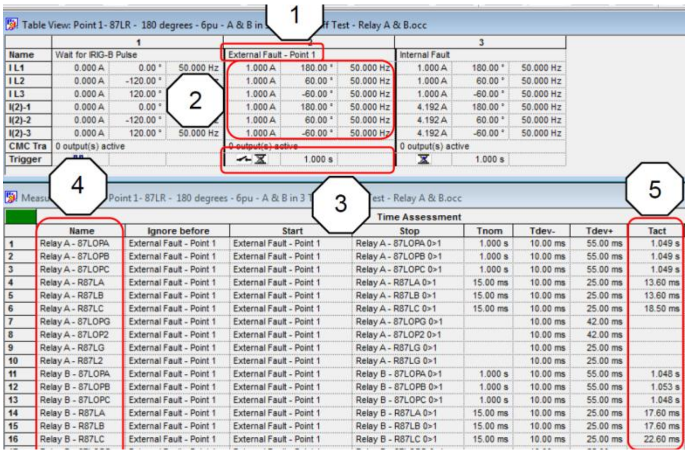

Figure 24. Injected analog values and test results for relay A and B for point 1

Elements 87LOPA, 87LOPB, and 87LOPC (notification 4 on Figure 24) operated and picked-up 1 second later. When the internal fault was simulated after 1 second external fault as shown with notification 5 in Figure 24 above. This is the indication that the alpha plane differential protection characteristic operates as required for this test case.

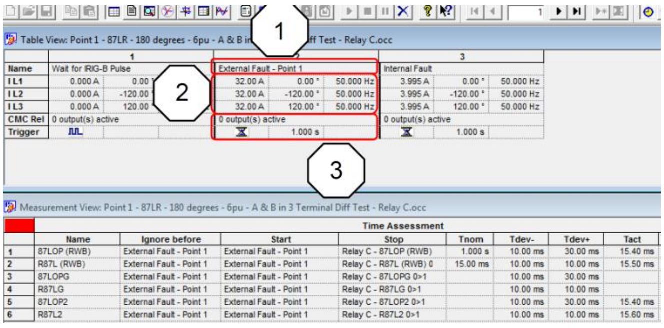

Figure 25. Injected analog values and test results for relay C

VI.1. The results for primary currents and alpha values for all three relays

The measured primary currents by all three relays which correspond to the injected secondary currents as well as corresponding calculated alpha values. Each relay displays its local current and remote currents received through communication channels X and Y. Relay A (SEL-311L A) measured its local currents and received measured currents from Relay B(SEL-311L B) and Realy C (SEL-311L C) via communication channel X and Y respectively.

VI.2. Relay A (SEL-311L A) results

Observed from Relay A and shown with notification 1 in Figure 26 it can be seen that the measured currents are displayed in primary values corresponding to the injected secondary currents. The results shows that Relay A Red Phase current = 597.984∠-0.1°A, White Phase current = 597.793∠-120.1°A and Blue Phase current = 597.4∠120.1A°. The results for Relay B are as follows Red Phase current = 597.75∠0.6°A, White Phase current = 596.473∠-120.6°A and Blue Phase current = 598.456∠119.2°A. Lastly the results for Relay C are Red Phase current = 3824.561∠179.7°A, White Phase current = 3819.937∠59.8°A and Blue Phase current = 3814.48∠-60°A. Relay A then calculated its alpha values as shown with notification 2 in Figure 26. The results shows that Relay A Red Phase Alpha α = 5.39∠179.6°, White Phase Alpha α = 5.39∠179.8° and Blue Phase Alpha α = 5.38∠179.7° respectively.

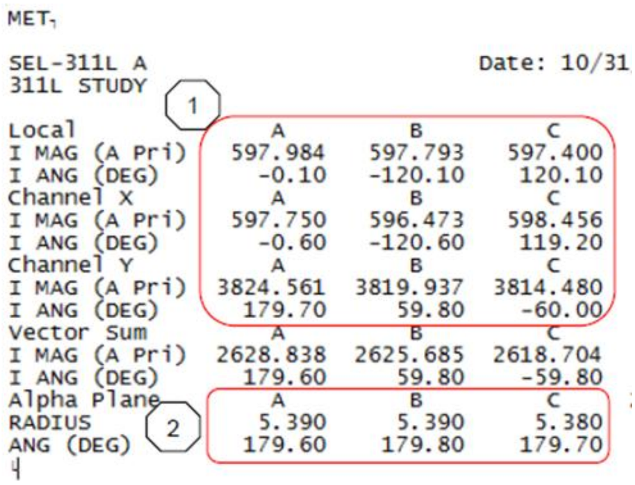

Figure 26. Primary currents and alpha values for Relay A (311L A)

VI.3. Relay B (SEL-311L A) results

Relay B measured its local current and received measured currents by relay A and C via communication channels Y and X respectively the notification 3 on Figure 27.

Observed from relay B and shown with notification 3 on Figure 26 it can be seen that relay A Red Phase current = 598.555∠-0.2°A, White Phase current = 599.147∠-120.1°A and Blue Phase current = 597.584∠120.1°A. While relay B Red Phase current = 598.914∠-0.1°A, White Phase current = 596.901∠-120°A and Blue Phase current = 597.581∠119.9°A. Lastly relay C Red Phase current = 3818.339∠179.4°A, White Phase current = 3825.214∠59.5°A and Blue Phase current = 3832.049∠-60.4°. Relay B then calculated its alpha values as shown with notification 4 in Figure 26. Relay B Red Phase Alpha α = 5.37∠179.4°, White Phase Alpha α = 5.4∠179.4° and Blue Phase Alpha α = 5.4∠179.4° as shown with notification 4 on Figure 27

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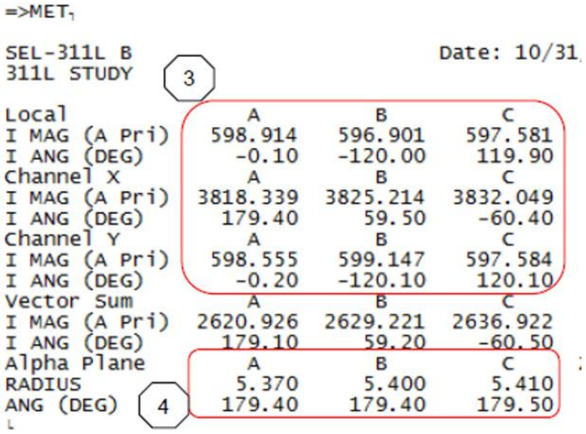


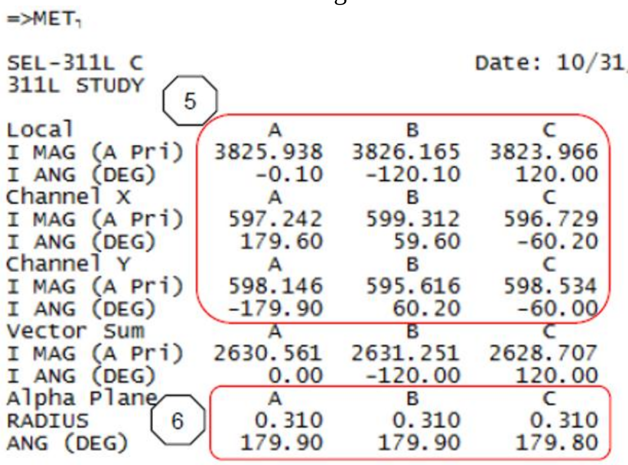
```
=>MET
SEL-311L B                                  Date: 10/31
311L STUDY        3

Local              A          B          C
I MAG (A Pri)   598.914    596.901    597.581
I ANG (DEG)      -0.10    -120.00     119.90
Channel X          A          B          C
I MAG (A Pri)  3818.339   3825.214   3832.049
I ANG (DEG)     179.40      59.50     -60.40
Channel Y          A          B          C
I MAG (A Pri)   598.555    599.147    597.584
I ANG (DEG)      -0.20    -120.10     120.10
Vector Sum         A          B          C
I MAG (A Pri)  2620.926   2629.221   2636.922
I ANG (DEG)     179.10      59.20     -60.50
Alpha Plane        A          B          C
RADIUS            5.370      5.400      5.410
ANG (DEG)    4  179.40     179.40     179.50
```

Figure 27. Primary currents and alpha values for Relay B (311L B)

VI.4. Relay C (SEL-311L A) results

Relay C measured its local current and received measured currents by relay A and B via communication channel X and Y respectively (notification 5 on Figure 28). Observed from relay C and shown with notification 5 on Figure 28 it can be seen that: Relay A Red Phase current = 597.242∠179.6°A, White Phase current = 599.312∠59.6°A and Blue Phase current = 596.729∠-60.2°A. Relay B Red Phase current = 598.146∠-179.9°A, White Phase current = 595.616∠60.2°A and Blue Phase current = 598.534∠-60°A. Relay C Red Phase current = 3825.938∠-0.1°A, White Phase current = 3826.165∠-120.1°A and Blue Phase current = 3823.966∠120°A. Relay C then calculated its alpha values as shown with notification 6 in Figure 26. Relay C Red Phase Alpha α = 0.31∠179.9°A, White Phase Alpha α = 0.31∠179.9°A and Blue Phase Alpha α = 0.31∠179.9°A as shown with notification 6 on Figure 28.



```
=>MET
SEL-311L C                                  Date: 10/31
311L STUDY        5

Local              A          B          C
I MAG (A Pri)  3825.938   3826.165   3823.966
I ANG (DEG)      -0.10    -120.10     120.00
Channel X          A          B          C
I MAG (A Pri)   597.242    599.312    596.729
I ANG (DEG)     179.60      59.60     -60.20
Channel Y          A          B          C
I MAG (A Pri)   598.146    595.616    598.534
I ANG (DEG)    -179.90      60.20     -60.00
Vector Sum         A          B          C
I MAG (A Pri)  2630.561   2631.251   2628.707
I ANG (DEG)       0.00    -120.00     120.00
Alpha Plane        A          B          C
RADIUS       6    0.310      0.310      0.310
ANG (DEG)       179.90     179.90     179.80
```

Figure 28. Primary currents and alpha values for Relay C (311L C)

VII. DISCUSSION OF OBTAINED RESULTS

Ten case studies were conducted and analyzed similarly to Case study 1. The analysis shows that in all case studies the newly developed logical node, the alpha plane characteristic, and additional check logic are functioning as required. The case studies define the new method of testing 3 terminal alpha plane differential protection using standard-based numerical relays. The new method has significant advantages over the primitive method. As opposed to the primitive method, the new method offers the following advantages: No hardwiring is required which eliminates a room for human error and save time. Relays are tested simultaneously, this shortens the outage period and the relays are tested in a more realistic environment in which they would be exposed in a real network unlike testing 2 relays at a time method.

VIII. CONCLUSION

This paper described the principle of alpha plane differential protection characteristics. This principle is presented in its simplest form in a two-terminal differential protection application which is the ratio of remote to local current. According to the literature, the SEL-311L relay applies the alpha plane concept of two-terminal application to three-terminal lines by combining (vectorially adding) currents from two of the terminals to produce the remote current. It was also found that there is an additional check logic that the SEL-311L relay applies in case of infeed and outfeed. This additional check logic is discussed in part 4 of this paper. This logic is not in the relay manual but exists in the relays, which also formed the basis of this research.

Based on the additional logic, the test method for 3 terminal alpha plane differential protection was developed and this method is defined by different case studies as presented in part 6. The three-terminal alpha plane differential protection characteristic and the additional check logic are tested in conjunction with the newly developed logical node. The results of the case studies are discussed analyzed. In summary, the newly developed logical node, three-terminal alpha plane characteristic, and additional check logic and the developed test method are all proved to be functioning as required. The benefits and advantages of the new test method are discussed in part 7 of this paper.

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