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Determining alpha plane characteristics of line current differential protection in two-terminal high voltage transmission with different current transformer ratio

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Abstract

Transmisson lines are a crucial part of the power system, as it provides the path to transfer generated power to the load. The main challenge to its protection lies in reliably and isolating faults to secure the system. Commonly, in two terminal transmission line, the Current Transformer Ratio (CTR) are equal. Hence, it is a challenging situation if the system have different CTR. This study, is to determine Alpha Plane characteristics method of Line Current Differential protection to solve high voltage transmission protection with different CTR condition. The Alpha plane is a method using the complex plane to plot the ratio of remote and the local current. The internal fault is simulated using secondary current injection to test the protection scheme of two Line Current Differential relays (87L). The result show that the Alpha Plane characteristic method are able to perform as Line Current Differential protection with different CTR, with average trip time around 48.6ms.

Keywords: Line current differential, alpha plane, current transformer ratio, transmission protection

1. Introduction

Transmisson lines have a major role in power system to deliver generated electric energy from power plant to distribution units to provide the power to the customers. Therefore, if any fault occur not detected and not isolated shortly, it will cause widespread outages. Hence, reliable and fast protection schemes for transmission lines are needed.

Nowadays Line Current Differential relay is one of the main protection principle used for transmission line. It is considered more selective, sensitive and have a better speed of operation compared to Distance relay schemes [1]. The philosophy of Line Current Differential is comparing the current flowing in and out at the same line of transmission. In most application this principle of protection is independent from weak terminals, series compensation, power swings, current inversion and any other issues related to transmission lines protection [2].

At present percentage differential relays and alpha plane characteristic are the most measuring principle used for Line Current Differential protection. Several study about these two principles have been published [3-8]. The challenge when applying Line Current Differential protection is the CTR in both end terminal of protected transmission line are different. In this paper the determining alpha plane characteristic of Line Current Differential protection in two terminal high-voltage transmission with different CTR are describe.

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2. Methodology

2.1. Theory of operation

In this study we used two units SEL-311L-6 Line Current Differential relay from Schweitzer Engineering Laboratories. From the relay manual [9], SEL-311L relay contains five Line Current Differential elements; one for each phase (87LA, 87LB, 87LC), one each for negative-sequence (87L2) and ground current (87LG). For high current faults, the element for each phase provides high-speed protection. The others elements are used for unbalanced faults.

In the Fig. 1 shows the relay exchanges sampling of Ia, Ib, and Ic in synchronized time. Both SEL-311L calculate negative sequence current (3I2) and zero sequence current (3I0). All relays execute identical the calculation of Line Current Differential in a peer-to-peer scheme to prevent transfer trip delay.

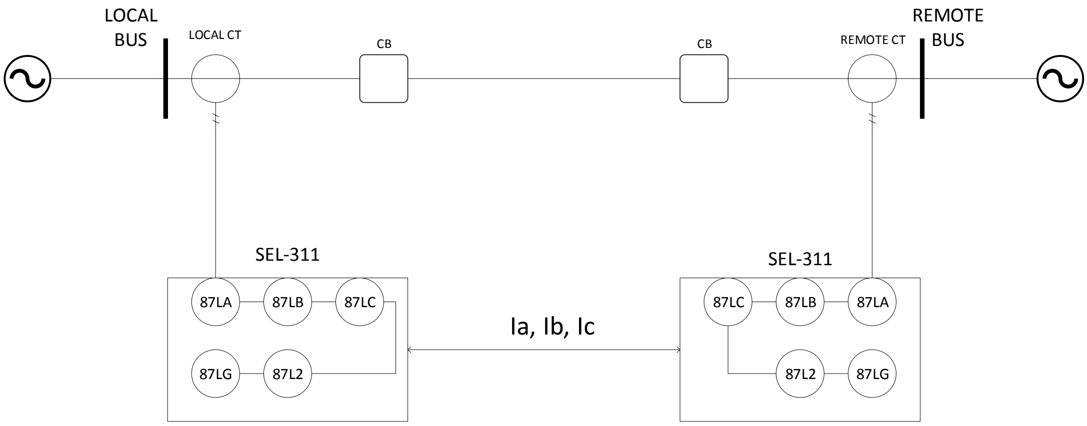


Fig. 1. SEL-311L Line Current Differential elements

Fig. 2 illustrates alpha plane graph, which indicate complex ratio of remote currents (IR) to local currents (IL). All differential element in SEL-311L relay are calculated from the vector ratio of remote to local currents for each phase and also negative and zero sequence currents. The alpha plane is a phasor plot of ratio I_R/I_L.

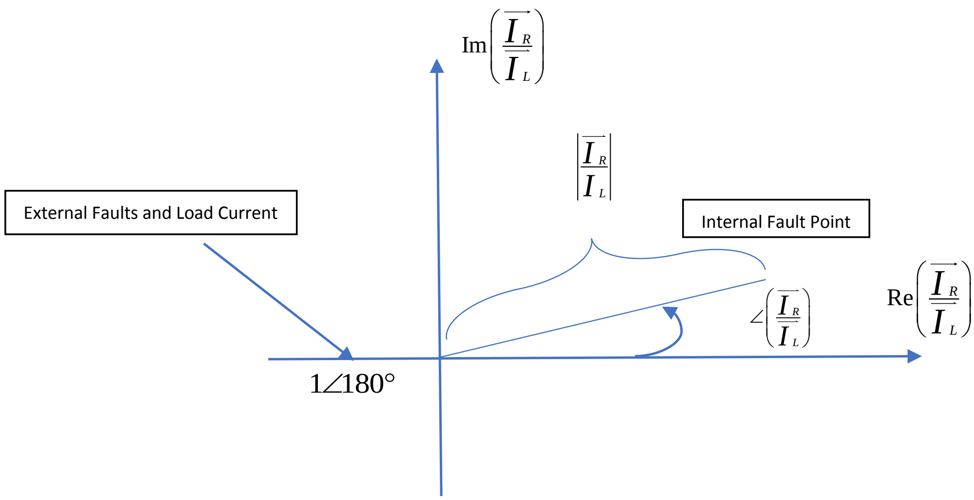


Fig. 2. Alpha plane represents complex ratio of remote to local currents

Assume the current flowing into the protected line have angle 0 degree and the current flowing out of the line have angle 180 degrees (opposite direction). 5 Amperes of load current flowing from local to remote relay makes an A-phase current of $5\angle 0°$ at local relay and $5\angle 180°$ at remote relay. The ratio of remote current to local current is as follows:

$$k = \frac{\vec{I}_R}{\vec{I}_L} \tag{1}$$

where:

k = Ratio of remote current to local current

$\vec{I}_R$ = Remote current

$\vec{I}_L$ = Local current

- For phase A

$$\frac{\vec{I}_{AR}}{\vec{I}_{AL}} = \frac{5\angle 180°}{5\angle 0°} = 1\angle 180° \tag{2}$$

- For phase B

$$\frac{\vec{I}_{BR}}{\vec{I}_{BL}} = \frac{5\angle 60°}{5\angle -120°} = 1\angle 180° \tag{3}$$

- For phase C

$$\frac{\vec{I}_{CR}}{\vec{I}_{CL}} = \frac{5\angle -60°}{5\angle 120°} = 1\angle 180° \tag{4}$$

Equation (2), (3) and (4) show the magnitudes and angles of each phase alpha plane are equal. All through-current plots at $1\angle 180°$. Similarly external fault has equal and opposite current at both of end of lines. Hence, An external fault conditions (Fig. 3) also plot at $1\angle 180°$ if no Current Transformer (CT) saturation or current alignment errors and no line charging current)[2].

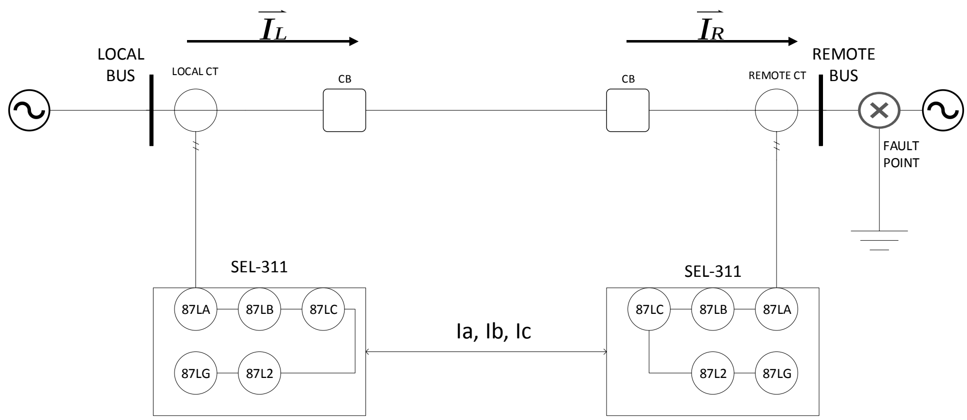


Fig. 3. External fault

As shown in Fig. 4, the point $1\angle 180°$ is inside restraint region on the alpha plane. The condition of no trip occurs whenever the ratio of remote to local current is inside restraint region or the different current is insufficient. On the opposite the relay trips when the alpha plane ratio is in trip region, and the different current is above set point.

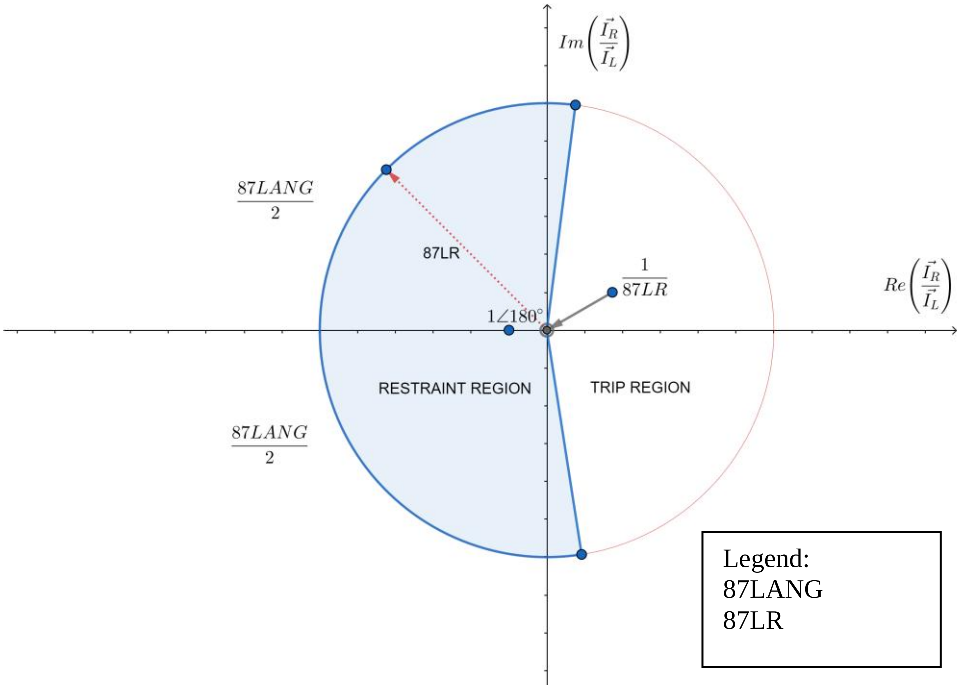


Fig. 4. SEL-311L operation region

The alpha plane restraint region is built by two setting, as shown in Fig. 4. The angular area of restraint region is determined by setting 87LANG and its outer radius is determined by setting 87LR. The inner radius is inversely proporsional with 87LR. Each of three types of Line Current Differential elements (phase, negative-sequence, and zero-sequence) advance qualify trips with a differential pickup setting. Setting 87LPP qualifies trips generated by phase elements (87LA, 87LB, 87LC). Whenever A-phase current ratio is outside the restraint region, and the A-phase difference current surpasses setting 87LPP, at this condition element 87LA declares, indicating an internal fault (Fig. 5). Differential pickup settings 87LGP and 87L2P give comparative supervision for the ground current differential component 87LG and the negative-sequence current differential component 87L2, separately. For simple explanation, the alpha plane area operation desctibed on Table 1.

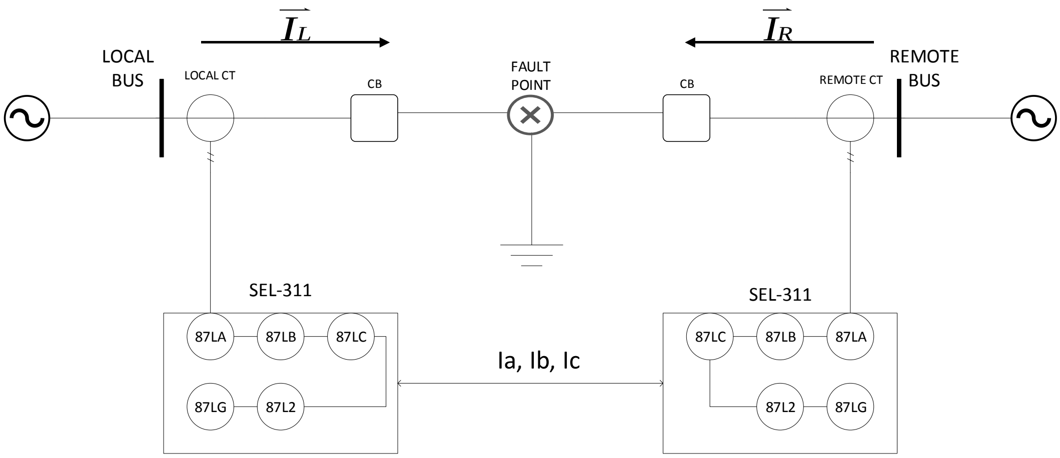


Fig. 5. Internal fault

Table 1. Alpha plane area of operation

Region	k	
	Magnitude	Phase Angle
Restraint	$87LR \geq k \geq \frac{1}{87LR}$	Inside 87LANG Area
Trip	$k < \frac{1}{87LR} or\ k > 87LR$	Outside 87LANG Area

2.2. Alpha plane 87L two-terminal application with different CT ratios

SEL-311L which are used for this study have two communication channel, labeled as Channel X and Channel Y. For two-terminal application, only one communication channel is utilized (Channel X) that consists of a Tx and an Rx port. Each relay processes the secondary current of CT as local current, and the current received from other relay over Channel X (Rx port) is defined as remote current. Fig. 6 shows actual condition of this study where the relay at the left bus processed local current of 3.46 secondary A and remote current (Channel X) of 6.92 secondary A and the relay of right bus processes local current of 6.92 secondary A and remote current of 3.46 secondary A.

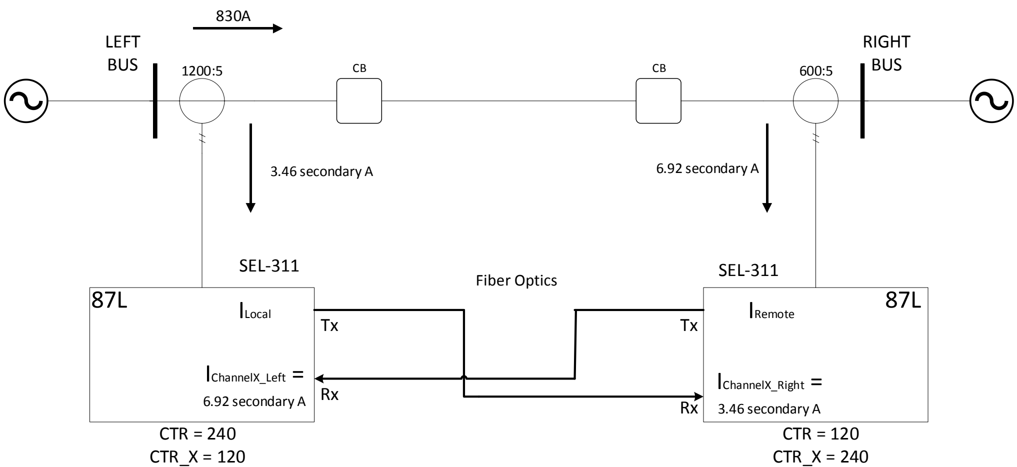


Fig. 6. Two-terminal alpha plane 87L application with different CT ratios

Fig. 7 is a simplified diagram of differential element figures[9], as we can see how the differential element processing works in SEL-311L relay. By reason of two CTRs of each end-terminal is different, the secondary current of local and remote side shall be referenced to the maximum CTR (CTRmax). First, the primary currents shall be obtained by multiplying local current with CTR, and the Channel X current is multiplied by CTR_X. And last, each of primary currents is divided by CTRmax to obtain the local and remote secondary currents refered to CTRmax. The sum of these currents is the difference current.

SEL-311L relay compares the difference level between absolute value of difference current in secondary Amperes with current 87L*m*P settings (where *m*=P for phase, 2 for negative-sequence, and G for zero-sequence). The result gives the relay a value to decide whether to confirm or disconfirm the differential operate 87LOP*k* elements (Where *k* = A for A-phase, B for B-phase, C for C-phase, 2 for negative sequence, or G for zero-sequence differential).

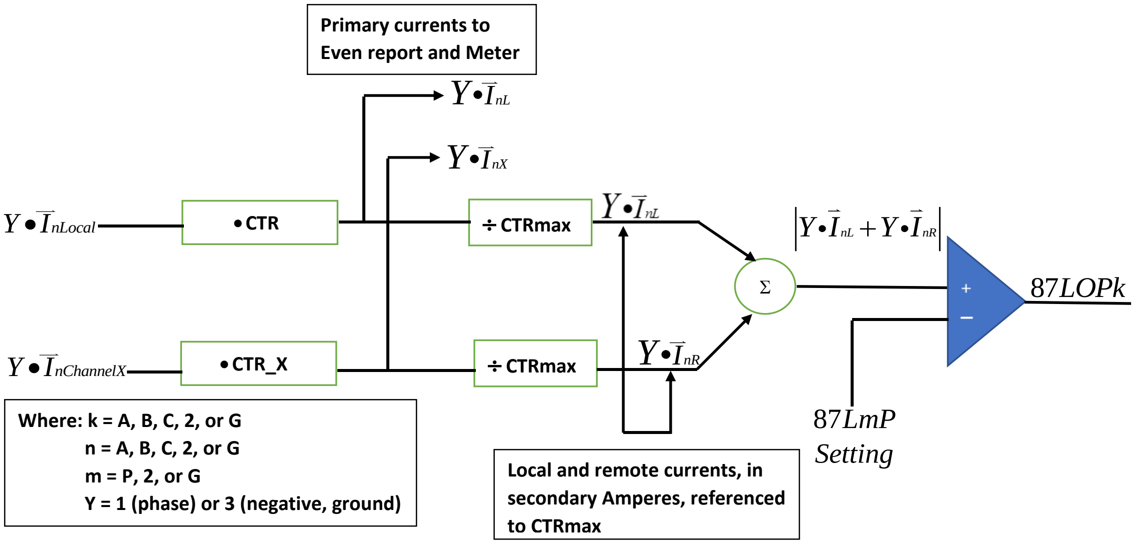


Fig. 7. Phase, negative-sequence, and ground differential element processing for Channel X

The calculation of local and remote currents for differential element processing of SEL-311L relay is as follows[10]:

$$Y\bullet \vec{I}_{nL} = \frac{Y\bullet \vec{I}_{nLocal}\bullet CTR}{CTR\max} \tag{5}$$

$$Y\bullet \vec{I}_{nR} = \frac{Y\bullet \vec{I}_{nChannelX}\bullet CTR\_X}{CTR\max} \tag{6}$$

Where:

$\vec{I}_{nL}$ = Local *n* current in secondary amperes, referenced to the maximum CTR.

$\vec{I}_{nLocal}$ = *n* current injected at local relay.

CTR = Current Transformer Ratio for the local relay.

$\vec{I}_{nR}$ = remote *n* current in secondary amperes, referenced to the maximum CTR.

$\vec{I}_{nChannelX}$ = *n* current injected at the remote relay.

CTR_X = Current Transformer Ratio for the remote relay.

CTRmax = maximum CTR (i.e., the larger of CTR or CTR_X).

Y = 1 for phase differential or 3 for negative-sequence and ground differential.

n = a, b, or c (phase), 2 (negative-sequence), or 0 (zero-sequence).

The minimum sensitivity settings of SEL-311L differential element need to be determined based on the expected primary current sensitivity divided by CTRmax and shall be applied for both relay. Equation used to determine the minimum difference current that will cause the operate elements is as follows:

$$\left| Y\bullet \vec{I}_{nL-primary} + Y\bullet \vec{I}_{nR-primary} \right| > 87LmP\bullet CTR\max \tag{7}$$

Where:

$\vec{I}_{nL-primary} = \vec{I}_{nLocal}\bullet CTR$ = Local *n* current in primary amperes.

$\vec{I}_{nR-primary} = \vec{I}_{nChannelX} \bullet CTR\_X$ = Remote n current in primary amperes.

$\left| Y \bullet \vec{I}_{nL-primary} + Y \bullet \vec{I}_{nR-primary} \right|$ = Difference current in primary amperes.

CTRmax = maximum CTR (i.e., the larger of either CTR or CTR_X).
Y = 1 for phase differential or 3 for negative-sequence and ground differential.
m = P for phase, 2 for negative-sequence, or G for zero-sequence differential.
87L*m*P = difference level current setting (in secondary amperes, referenced to CTRmax).

As shown in Fig. 6, if 87LPP (phase) is equal 1 secondary ampere and CTRmax is equal to 240, the phase differential element declares for internal fault that produce a phase different current of higher than 1 • 240 = 240 primary A. Or in details, the magnitude of the sum of local and remote phase currents must be higher than 240 primary A, or 1 seocndary A (referenced to CTRmax), for 87LOP*k* to confirm.

3. Test and Result

3.1. Test setup

Table II show equipment details for testing purpose. For complete test setup described in Fig.8.

Table 2. Test equipment

Description	Manufacture	Type	Unit	Quantity
Line Current Differential protection and automation system.	SEL	SEL-311L-6	Unit	2
Universal relay test set and commissioning tool.	Omicron	CMC-356	Unit	1
Multimode fiber optic duplex ST-ST connector.	Belden	Non-armored	meter	10

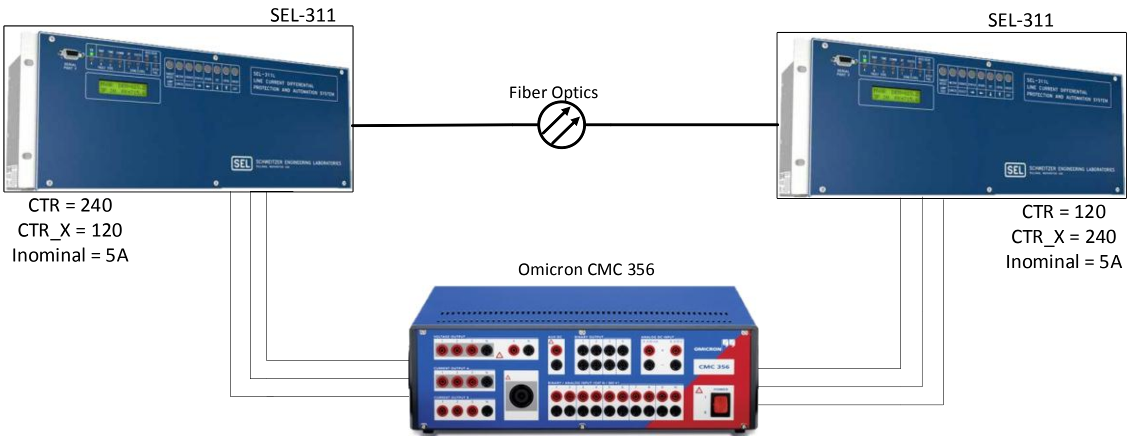


Fig. 8. Test setup for determining alpha plane Line Current Differential protection

3.2. Case study

The system studied consists of 115kV, 60Hz ring bus system network for two-terminal configuration with details as below:

- Conductor: 715.5 kmilc, ACSR, "Redwing", single circuit
- Transmission length: 1.5558 miles
- Maximum line load current: 830A

- CTR left bus: 1200/5 = 240/1
- CTR right bus: 600/5 = 120/1
- Transmission line main protection: 87L (Line Current Differential relay)
- Protection relay: SEL-311L-6
- Nominal relay current (I_{Nom}): 5A

3.3. Test scenario

As shown in Fig. 8, the left and right SEL-311L relays are connected with fiber optics and single-phase or three-phase current is injected into each relay using Omicron CMC 356. Left relay considered as the local relay because it is used as reference when observing 87LOP*k* elements, and the right relay is considered as remote relay. In this study both relay parameter settings shown in Table III.

Table 3. Relay settings

Setting	Setting function	Local relay	Remote relay
E87L	Number of 87L terminal	2	2
87LPP	Minimum differential current enable level setting (phase)	1	1
87L2P	$3I_2$ negative-sequence 87L	OFF	OFF
87LGP	Ground 87L zero-sequence	0.5	0.5
CTR	Local phase CT ratio	240	120
CTR_X	CTR at remote terminal connected to ChannelX	120	240
87LR	Outer Radius. This setting controls the outside radius of restraint region.	6.00	6.00
87LANG	Angle. This setting controls the angular extend of restraint region	195	195

For remote relay, the current injected is constantly at 5A∠0° on A-phase, and for local relay the current injected variously to observe 87LOP*k* element. As shown in table 3, 87LPP is setup to value of 1. The minimum A-phase current is as below:

$$Y \bullet \vec{I}_{nLocal} > \frac{(\pm 87LPP \bullet CTR\max) - Y \bullet \vec{I}_{nChannelX} \bullet CTR\_X}{CTR} \tag{8}$$

$$I_{aLocal} > \frac{(1 \bullet 240) - 5 \bullet 120}{240} = -1.5A \tag{9}$$

$$I_{aLocal} > -1.5A \tag{10}$$

Based on Table III, the 87L2P is set OFF and there is no need to calculate the minimum A-phase current (injected into the local relay) that confirm 87LOP2. For 87LOPG the equation is as follows:

$$Y \bullet \vec{I}_{0Local} > \frac{(\pm 87LGP \bullet CTR\max) - Y \bullet \vec{I}_{0ChannelX} \bullet CTR\_X}{CTR} \tag{11}$$

Since $I_b = I_c = 0$ and $3I_0 = I_a$:

$$I_{aLocal} > \frac{(\pm 0.5 \bullet 240) - 5 \bullet 120}{240} = -2A \tag{12}$$

$$I_{aLocal} > -2A \tag{13}$$

In this test, the value of $\vec{I}_{aL}$ already referenced to CTRmax, where CTR is bigger than CTR_X. For the $\vec{I}_{aR}$ referenced to CTRmax is as follows:

$$\vec{I}_{aR} = \frac{\vec{I}_{aChannelX} \bullet CTR\_X}{CTR\max} \tag{14}$$

$$\vec{I}_{aR} = \frac{5\angle 0° \bullet 120}{240} = 2.5\angle 0° A \tag{15}$$

The alpha plane area of operation in Table 1 and the operation of differential element described in Fig. 7 and equation (7) are the principles used in this study to determine the alpha plane Line Current Differential in two-terminal application for different CTR. R87LA is A-phase restraint region detection output. In word bit R87LA have a logic value '1' if k is inside alpha plane and '0' if outside alpha plane. Finally, 87L for A-phase is the output of AND logic gate with input of 87LOPA and the output of NOT gate with R87LA input (Fig. 9).

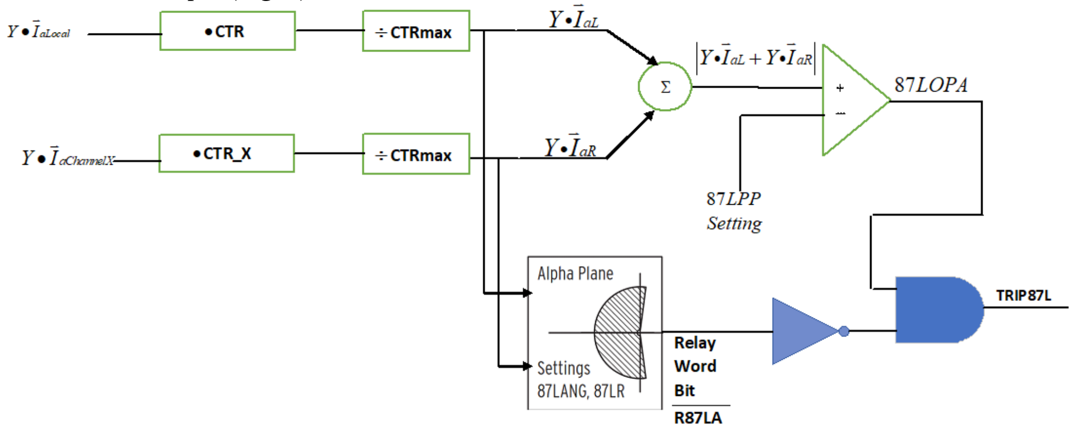


Fig. 9. Differential element 87L processing for A-phase Channel X

To fullfill this study the local relay was injected with ten various different current I_{aL} to determine whether the alpha plane Line Current Differential is correct or incorrect. To obtain the value of k, the current injected to local relay is divided by the current injected to remote relay. The value and position of k in alpha plane graph shown in Fig. 10.

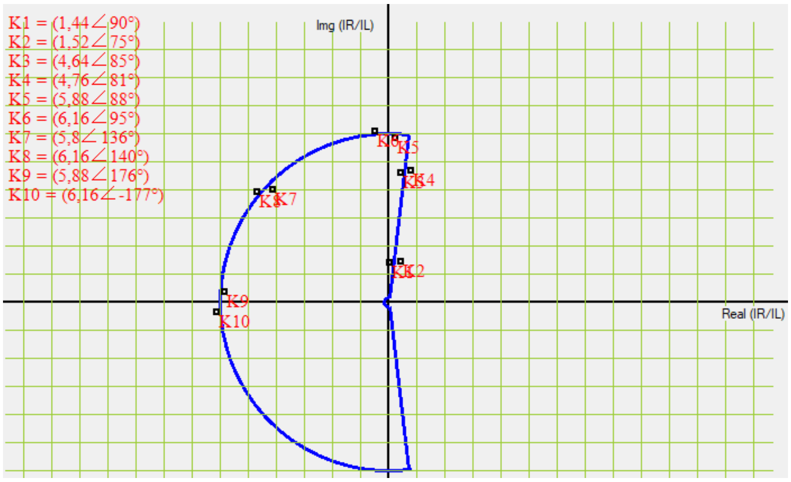
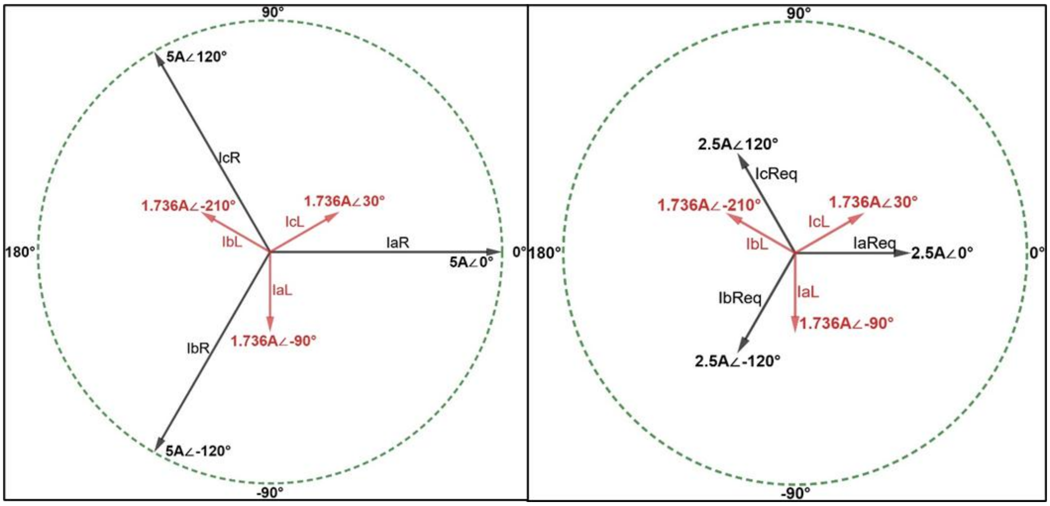


Fig. 10. k position in alpha plane graph

To calculate I_{aL} + I_{aR} both of I_{aL} and I_{aR} must be converted to rectangular. The result of calculation shown in Table 4. In this this table, the value of I_{aR} already referenced to CTRmax as shown in Fig. 11(b).



(a) (b)

Fig. 11. Secondary current of remote and local relay for A, B and C-phase: (a) Injected current to remote and local relays (b) Secondary current remote and local relays referenced to CTRmax.

Table 4. I_{aL} + I_{aR} referenced to CTRmax

I_{aL} (Secondary A)	I_{aR} (Secondary A) referenced to CTRmax	I_{aL} (Secondary A) in rectangular		I_{aR} (Secondary A) in rectangular, referenced to CTRmax		I_{aL} + I_{aR} (Secondary A)	
		Real	Imaginary	Real	Imaginary	Real	Imaginary
1.736∠-90°	2.5∠0°	0	-1.736j	2.5	0j	2.5	-1.736j
1.630∠-75°	2.5∠0°	0.422	-1.574j	2.5	0j	2.922	-1.574j
0.536∠-85°	2.5∠0°	0.047	-0.534j	2.5	0j	2.547	-0.534j
0.523∠-81°	2.5∠0°	0.082	-0.517j	2.5	0j	2.582	-0.517j
0.425∠-88°	2.5∠0°	0.015	-0.425j	2.5	0j	2.515	-0.425j
0.404∠-95°	2.5∠0°	-0.035	-0.402j	2.5	0j	2.465	-0.402j
0.429∠-136°	2.5∠0°	-0.309	-0.298j	2.5	0j	2.191	-0.298j
0.404∠-140°	2.5∠0°	-0.309	-0.26j	2.5	0j	2.191	-0.26j
0.424∠-176°	2.5∠0°	-0.423	-0.03j	2.5	0j	2.077	-0.03j
0.405∠177°	2.5∠0°	-0.404	0.021j	2.5	0j	2.096	0.021j

In the Fig. 7, the 87LOPA is the output of comparator as $|I_{aL} + I_{aR}|$ and 87LPP are the input. $|I_{aL} + I_{aR}|$ is the positive input of comparator, otherwise 87LPP is the negative input. Hence, the comparator will produce an output (87LOPA=1) if the positive input is bigger than negative input (equation 16).

$$87LOPA = \begin{cases} 1, if \left|\vec{I}_{aL} + \vec{I}_{aR}\right| > 87LPP \\ 0, if \left|\vec{I}_{aL} + \vec{I}_{aR}\right| < 87LPP \end{cases} \tag{16}$$

The result of 87LOPA is shown in Table 5.

Table 5. 87LOPA result

$\lvert I_{aL} + I_{aR} \rvert$	87LPP setting	87LOPA
3.04	1	1
3.32	1	1
2.60	1	1
2.63	1	1
2.55	1	1
2.50	1	1
2.21	1	1
2.21	1	1
2.08	1	1
2.10	1	1

On Fig. 9, TRIP87L will correct if R87LA have value of logic ‘0’ and 87LOPA have a value of logic ‘1’. To confirm the test result, we compare the word bit of TRIP87L with word bit of R87LA and 87LOPA. Table 6 shows the comparison between TRIP87L word bit and the test result.

3.4. Test Result

Table 6. TRIP87L compares to test result.

k	R87LA	87LOPA	TRIP87L	Test result	Trip time (ms)
1.44∠90°	1	1	0	No Trip	Not applicable
1.52∠75	0	1	1	Trip	46.6
4.64∠85°	1	1	0	No Trip	Not applicabel
4.76∠81°	0	1	1	Trip	47.8
5.88∠88°	1	1	0	No Trip	Not applicable
6.16∠95°	0	1	1	Trip	49.7
5.8∠136°	1	1	0	No Trip	Not applicable
6.16∠140°	0	1	1	Trip	49.7
5.88∠176°	1	1	0	No Trip	Not applicable
6.16∠-177°	0	1	1	Trip	52.3

4. Conclusion

This study describes the determining, implementation and performance evaluation of alpha plane line protection in two-terminal application with different Current Transformer Ratio. Both of secondary current relay must be referenced to CTRmax. Two unit of SEL-311L-6 relays are used for the test. Two relays are directly connected with fiber optic for communication of protection. The secondary current of both relay are injected using Omicron CMC 356 (secondary current injection) test set. The simulations and results had made possible in determining the alpha plane characteristic of Line Current Differential protection. The performance Alpha plane characteristic of Line Current Differential protection is capable to protect high voltage transmission line in two-terminal application with different CTR with average trip time around 48.6ms.

For future study, the backup protection of the relay such as distance protection, overcurrent protection should be considered as a full function of this relay. The uncertainty of the real disturbance should be calculate for the next.

Conflict of Interest

The authors declare no conflict of interest

Author Contributions

Aldo Bona Hasudungan designed and set up the experiment, Agus Indarto, Aldo Bona Hasudungan and Chairul Hudaya collected data from experiment, Aldo Bona Hasudungan, Agus Indarto, Chairul Hudaya and Iwa Garniwa worked for modelling, analysis and documenting the work, Aldo Bona Hasudungan, Iwa Garniwa and Chairul Hudaya reviewed the the result of all experiments. All authors had approved the final version.

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