Enhanced Alpha Plane Line Protection

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Abstract— The ratio of currents at both ends of the transmission line is utilized in alpha plane differential principle to detect an internal fault. Such a scheme uses either phase current or sequence currents. As the ratio computed using phase current and sequence currents has their own demerits, both are combined to enhance the security and sensitivity of the protection scheme. However, such a scheme which uses both phase and sequence current demands large communication channel requirement and has limited performance during high resistance fault during single pole tripping and Metal oxide Varistor (MOV) operation in series compensated line. In this work, phase current based adaptive alpha plane differential protection scheme is proposed which uses change in current and phase angle between voltage and current at both ends of the line. The proposed method is tested for Western-System-Coordinating-Council 9-bus system and results show it works for all circumstances and it is also valid for series compensated line.

Index Terms— Current transformer; capacitor coupled voltage transformer; Digital Relay; Global positioning system; Series compensation;

I. INTRODUCTION

Differential relaying which uses both end data has limited performance for long transmission line due to the latency and charging current. In the advent of microwave and direct fiber-optic communications [1]-[2], data availability from other end is feasible. This has opened new doors of differential protection even for long transmission lines. Such both end data based schemes have inherent immunity to power swing, mutual coupling and series impedance unbalances and improves security of the system [3]. However the performance is compromised during CT saturation and loses its sensitivity to high resistance fault and seeks external supervision using additional features which can prevent such maloperations. This is possible in digital relaying which can adapt the decision in accordance with system condition.

Directional comparison based scheme which requires voltage and current data from both sides of the line is widely adopted in power system [4]. However the performance of such scheme is compromised during voltage signal distortion for close-in faults or blown fuses, ferro-resonance problems in voltage transformers and transients in capacitor coupling voltage transformer (CCVT) [5]. A technique which uses both ends current provides a solution to such issues. Among the current based techniques phase comparison, charge comparison, and current differential schemes are well known [6]. However, such techniques are sensitive to intercircuit, cross country fault and has setting limitations during current transformer saturation. The threshold setting is difficult which varies with system condition [7].

Now-a-days with the help of Global Positioning System current phasors are obtained and applied for differential relay. This provides immunity to channel delays and asymmetry [8]-[10]. Synchronized phasors are also utilized to eliminate the errors caused by charging current for high voltage transmission line [11]. In [12], an adaptive restraining quantity is derived using the synchronized currents to improve the stability and sensitivity. Power from both ends of the line is also applied to detect the internal fault [13]. However such schemes have limited performance when GPS signal is interrupted and this is not under the control of the protection engineer.

In [14]-[15], alpha plane, a geometric representation in the complex plane is proposed which computes the ratio of the phase or sequence currents at both ends of transmission line to detect internal fault. It has important advantages such as: significant tolerance to CT saturation and synchronization errors. Phase current based Alpha plane scheme maloperates during high resistance fault and weak source condition. The sequence current based schemes are sensitive to high resistance faults but they are limited to single pole operations and line impedance dissimilarity during the MOV operation in series compensated lined. In [16], negative, zero and phase currents are applied to improve the sensitivity and stability of alpha plane relaying. A modified alpha plane characteristic is proposed to improve the sensitivity [17]. During single pole tripping new sequence element logic is adopted to improve the sensitivity of the relay in alpha plane [18].

In this work, phase current based technique is developed which has improved performance for high resistance fault and series impedance unbalances. In the proposed method, the phase angle between the voltage and current and magnitude of change in current from both the ends are utilized to compute modified current ratio which has better performance for high resistance fault, current transformer saturation, single pole tripping. The proposed method is tested for WSCC 9-bus...
system with and without series compensated line. Simulation results show the accuracy of the proposed method.

II. ALPHA PLANE CHARACTERISTIC FOR LINE PROTECTION

The two bus system as in Fig 1 is considered to describe the current differential scheme. For any operating condition both end current phasors are taken and ratio is computed as,

$$\frac{i_s}{i_R} = k e^{j\alpha}$$

where k is the magnitude and $\alpha$ is the phase angle difference between currents at R and S sides as in Fig. 1. The alpha plane characteristic is provided in Fig. 2.

![Fig. 1. Two source equivalent system.](image)

![Fig. 2. Differential characteristic in current ratio plane.](image)

During normal operating condition the locus of current ratio remains within the boundary which is the restraining region as in Fig. 2. During any disturbance the locus moves out of the restraining region the scheme declares it as an internal fault. The characteristic is set considering two parameters: the radius R of the greater arc (5<R<10) and the angle alpha($\alpha$) (160° < $\alpha$ < 210°)[15]. In this case to incorporate the communication delay and errors due to CT saturation and channel asymmetry. The main challenge is prevent the maloperation of the scheme during high resistance fault.

During higher loading condition when high resistance fault occurs the phase angle between voltage and line current is modulated and it is different from the line impedance angle. The deviation in phase angle from impedance angle indicates fault resistance is high and this is utilized to modify the computation in (1) during such events.

$$f(\alpha) = \frac{i_s}{i_R} e^{-j K_1(\theta_1+\theta_2)}$$

Where $\theta_1$ and $\theta_2$ are the phase angle deviation from transmission line impedance angle at both ends of the transmission line. This can be computed with known values X and R for transmission line and phase angle between the voltage and current at S and R buses. $K_1$ will be set as 1 or 0 depending on the rule given below.

$$K_1 = \begin{cases} 0 & \text{if } \theta_{min} < \theta_{th} \text{ or } (\Delta I) < \varepsilon \\ 1 & \text{if } \theta_{min} > \theta_{th} \text{ and } (\Delta I) > \varepsilon \end{cases}$$

$\theta_{min}$ and $\Delta I$ are the two criteria chosen to discriminate external, internal high resistance fault and normal operating condition. $\theta_{th}$ and $\varepsilon$ are the thresholds selected for $\theta_{min}$ and $\Delta I$ respectively.

The change in phase angle $\theta_1$ and $\theta_2$ at both ends of the line is considered to discriminate high resistance fault condition to normal operating condition. As the change in phase angle for both internal and external high resistance fault is similar, the deviation of voltage and current phase angle from line impedance does not conclude internal and external high resistance fault. For any external fault or load increment, the magnitude of change in current at both ends of the line is equal. To differentiate the internal and external high resistance fault another criteria difference in magnitude of change in current at both ends of the line is selected. The difference in magnitude of change in current at both ends is expressed as,

$$\Delta I = abs(\Delta I_s) - abs(\Delta I_R)$$

However during CT saturation, the current difference will be high but the phase angle change $\theta_1$ and $\theta_2$ may not be
significant at both ends. For this reason minimum of both ends phase angle deviation is considered to discriminate high resistance fault from CT saturation and $\varnothing_{\text{min}}$ is expressed as,

$$\varnothing_{\text{min}} = \min(\varnothing_1, \varnothing_2) \quad (5)$$

Similarly during external high resistance fault change in phase angle are significant but $\Delta I$ is negligible. Both the features are combined to detect the internal high resistance fault and relation (1) is modified whenever it is required. The

Next section describes the threshold selection criteria for the features.

A. Threshold selection criteria for $\Delta I$

Phase angle deviation indicates a high resistance fault but it cannot confirm internal or external fault. During normal operating condition and external fault current entering to the line is equal to leaving current. Current magnitude can be selected as parameter which can external or internal fault. Shunt capacitance may cause in variation in current magnitude at both the ends. For this reason magnitude of change in current is considered, where effect of shunt capacitance is nullified. There may be difference in current $\Delta I$ during normal loading condition due to CT error. This is considered in threshold setting to discriminate high resistance internal fault to load change condition. Considering the 2% error for C class CT at both the ends [19] and to provide a secured to load change condition. The prefault power is flowing from bus 7 to 8. To test the proposed method a line-to-ground fault with $R_f = 200 \, \Omega$ is simulated in EMTDC/PSCAD for various system conditions such as internal and external high resistance line-to-ground and double-line-ground fault, CT saturation, load increment and among them few cases are provided in this section. The method is also tested for series compensated line. Current phasors are obtained by using one cycle Discrete Fourier Transform (DFT). Data sampling rate is maintained at 1.2 kHz.

$$I_{\text{AR}} = I_{\text{pre}} + I_{\text{IL}} + I_{\text{2L}} + I_{\text{0L}} \quad (7)$$

Similarly, the voltage at the bus relay can be computed as,

$$V_{\text{AR}} = 3R_f I_f + (2I_{\text{IL}} + I_{\text{pre}})(Z_{\text{IL}}) + I_{\text{0L}}(Z_{\text{0L}}) \quad (8)$$

The phase angle between $V_{\text{AR}}$ and $I_{\text{AR}}$ can be computed for different operating conditions. The source impedances are varied and the impact on phase angle is observed. The variations in voltage and current angle depend on line length and line parameters.

The variation in phase angle depends on prefault loading condition and both end source impedance. To observe the effect of source impedance variation on phase angle between voltage and current, the source impedance at one end is varied from 0.2 pu. to 2 pu [21]. The variation of $\varnothing_1$ is observed and the maximum value is found as 0.362 radian.

Similarly the maximum deviation of phase angle is observed for $h$ and $\delta$. Magnitude ratio is varied from 0.9-1.1 pu. and $\delta$ is varied form 0–35°. The maximum deviation of phase angle at R bus for $h$ and $\delta$ variations is observed as 0.362 and 0.4178 radian respectively. From all these observations the threshold $\varnothing_{\text{th}}$ is selected as 0.436 radian.

C. Flow diagram of the Proposed Method

The flow diagram of the proposed method is shown in Fig 4. The input to the scheme is voltage and current phasor data from both ends of the line. In first step both ends current ratio is calculated using (1). Whenever locus is inside the restraining area the scheme computes the change in current $\Delta I$. When the change in current is more than the predefined threshold $\varepsilon$, the minimum of $\varnothing_1$ and $\varnothing_2$ is calculated. The minimum value is compared with $\varnothing_{\text{th}}$ and if it is more than the threshold, $K_1$ is set as 1 and current ratio is calculated using (2). During fault even though phasor computation is affected by decaying DC, it does not affect the decision process as the difference in line impedance angle and angle between voltage and current is more. The scheme performs well during power swing as $\Delta I$ is low during these conditions.

IV. SIMULATION RESULTS

The 230 kV, 60 Hz WSCC 9-bus system as shown in Fig 5 [20] systems are used to test the effectiveness of the proposed method. The line connected between 4 and 5 busses are selected. The system is simulated in EMTDC/PSCAD for various system conditions such as internal and external high resistance line-to-ground and double-line-ground fault, CT saturation, load increment and among them few cases are provided in this section. The method is also tested for series compensated line. Current phasors are obtained by using one cycle Discrete Fourier Transform (DFT). Data sampling rate is maintained at 1.2 kHz.

A. Case-1: Test for Internal High Resistance fault

The prefault power is flowing from bus 7 to 8. To test the proposed method a line-to-ground fault with $R_f = 200 \, \Omega$ is simulated at 5 km from the bus 7 on the line connecting
between the buses 7 and 8. The voltage and current phasors are obtained and $\Delta I$ is calculated and plotted in Fig. 6 (a). The increased value of $\Delta I$ form the preset threshold triggers the proposed scheme and phase deviations are calculated and minimum of both the phase angle are plotted in the Fig. 6 (c). As the $\Phi_{\text{min}}$ is more than the $\Phi_{\text{th}}$ $K_1$ is set as 1 and the current ratio is calculated using (2). Current ratio calculated by both the conventional and proposed method is plotted in Fig. 7. From the figure it is observed that the conventional current ratio remains inside the restraining region and at the same time the current ratio using the proposed method shift to operating region. This reveals correct operation of alpha plane characteristic using the current equation by proposed method.

**B. Case II. Test for External High Resistance Fault**

The proposed method is tested for external line-to-ground fault with $R_F = 200 \, \Omega$ is simulated at 5 km from the bus 8 on the line connecting between the buses 8 and 9. The voltage and current phasors are obtained and $\Delta I$ is calculated and plotted in Fig. 8 (a). The increased value of $\Delta I$ from the preset threshold triggers the proposed scheme and phase deviations are calculated and minimum of both the phase angle are plotted in the Fig. 6 (b). As the $\Phi_{\text{min}}$ is more than the $\Phi_{\text{th}}$ $K_1$ is set as 0 and the current ratio is calculated using (1). Current ratio calculated by both the conventional and proposed method is plotted in Fig. 9 which reveals both methods provide correct result.

![Flow diagram for proposed algorithm](image)

**Fig. 5. WSCC 9-bus system for testing $\alpha$-plane relay at bus 7 for line 7-8.**

![Indices for internal line-to-ground fault with $R_F = 200 \, \Omega$. (a) $\Delta I$ increment (pu.), (b) $\Phi_{\text{min}}$ (rad), (c) $\Phi_{\text{th}}$ (rad), (d) Index $K_1$.](image)

**Fig. 6. Indices for internal line-to-ground fault with $R_F = 200 \, \Omega$. (a) $\Delta I$ increment (pu.), (b) $\Phi_{\text{min}}$ (rad), (c) $\Phi_{\text{th}}$ (rad), (d) Index $K_1$.**

![Alpha plane characteristic for internal line-to-ground fault with $R_F = 200 \, \Omega$.](image)

**Fig. 7. Alpha plane characteristic for internal line-to-ground fault with $R_F = 200 \, \Omega$.**
C. Test for Load change

As change in current at both ends of the line is considered as input to the proposed scheme, the accuracy of the method is tested for load change. The load connected to bus-8 is increased by 50 MW at 2.4 s. The current ratio computed using (1) is plotted in Fig. 11 and it settles inside the restraining region. During this period $\Delta I$ for the line 7-8 is plotted in Fig. 10. It is observed $\Delta I < \varepsilon$ which computation of $\Phi_{\text{min}}$ is not required. This implies as per (3) $K_1=0$. The current ratio computed using (2) is also plotted in Fig. 11 and both ration computed by conventional and proposed scheme remains in the restraining region. Thus, the method works accurately for load change also. During unbalance loading also the method performs correctly as the phase currents are taken as inputs. Negative and zero sequence component based method has limitations for unbalance loading condition.

D. Test for Series compensated line

MOV protected series compensated line introduces challenges to existing protection schemes. The MOV operation depends on fault resistance, type of fault, prefault current and distance up to the fault point. Operation of MOV introduces asymmetry in the phase impedances [18] and computation of the sequence components becomes erroneous. This makes proposed phase based approach advantageous than the conventional method.

![Fig. 8](image8.png)

Fig. 8     Indices for external line-to-ground fault with $R_f = 200\ \Omega$. (a) $\Delta I$ increment (pu.). (b) $\Phi_{\text{min}}$ (rad). (c) Index $K_1$.

![Fig. 9](image9.png)

Fig. 9. Alpha plane characteristic for external line-to-ground fault with $R_f = 200\ \Omega$.

![Fig. 10](image10.png)

Fig. 10. Result for load case $\Delta I$ (pu.).

![Fig. 11](image11.png)

Fig. 11. Alpha plane characteristic for load increment.

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![Fig. 12](image12.png)

Fig. 12. Result for high resistance fault in series compensated line (a) $\Delta I$ (b) Phase angle deviation at both ends. (c) $\Phi_{\text{min}}$ (d) Index $K_1$.

The accuracy of the proposed method is tested with different compensation level and location of the line. Among them one case is presented with a 40% series compensation
is considered in line 7-8, at bus 7 of Fig. 4. The rating of MOV is selected as in [12]. A line-to-ground fault with $R_F = 200 \, \Omega$, at 5 km from the bus 8 on the line 7-8 is created at 0.99s. As observed form Fig. 13, the current ratio computed by conventional method remains in restraining region. $\Delta I$ is computed with phase angle change at both ends of line. From Fig. 12, the computed index shows $K_1 = 1$ during the fault and the current ratio computed using (2) is plotted in the Fig. 13 which settles outside the restraining region. This confirms the proposed scheme identifies it as an internal fault which is correct.

![Fig. 13. Alpha plane characteristic for internal high resistance fault in series compensated line.](image)

V. CONCLUSIONS

Phase current based alpha plane relay has limited performance during high resistance fault. In this work computed ratio is modified using change in current and the phase angle between the voltage and current at both ends of the line. The proposed scheme is tested for numerous cases with and without series compensated line. The results show the sensitivity of the conventional scheme has improved and performs correctly for high resistance fault in a series compensated line. The proposed method tested for 9 bus system results show the methods works accurately.

REFERENCES