Abstract—There is continuous variation in amplitude, phase, and frequency of voltage and current signals during power swing in a power system. Such variation makes the memorized pre-fault data less accurate to be used as non-fault component while computing superimposed quantity for protection decisions during power swing. In this paper, the voltage and current signal characteristics during power swing are analyzed and a technique is proposed to obtain correct non-fault components for superimposed quantity computation. The accuracy of the method in estimating the non-fault components is observed for different power swing conditions simulated in a 39-bus New England system and field data. The relay performance improvement as observed is also provided while applying the method to directional relaying, fault type classification, and fault location applications for faults during power swing. Comparative assessment reveals the superiority of the proposed method in improving the accuracy of the superimposed components computed during power swing.

Index Terms—Power system faults, numerical relaying, superimposed component, power swing.

I. INTRODUCTION

A. Motivation and Incitement

Power swing is a rotor angle oscillation phenomena caused by the unbalance in generated and consumed power following disturbances like loss of generation, bulk load switching and line tripping [1], [2]. Such an oscillation results in continuous and significant variation in amplitude, phase, and frequency of voltage and current signals. The variation affects the performance of different protection schemes like distance relaying, directional relaying etc. [3]–[6]. Such degraded relay performance may result in maloperation at times and also may lead to cascading outages, as reported in [7], [8]. Severity and frequency of occurrence of power swing are in an increasing trend with the gradual reduction in power system inertia [9], [10]. Such a situation asks for improvement in the performance of network protection schemes to ensure reliable protection decisions during power swing.

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B. Literature Review

Modulation in voltage and current waveforms during power swing affects the performance of different network protection schemes for faults, occurred in such a situation [3], [11]. Zone-3 of distance relay backing up the adjacent power line covers a large operating region in impedance plane and is more vulnerable during power swing. Different methods are now being used to block the unintentional distance relay operation during power swing [12], [13]. Proper unblocking techniques are also used to ensure its correct operation for fault during swing. Unstable power swing may even lead to zone-1 malfunction at times. Supervisory methods are available in blocking its operation for such a situation [14], [15]. Fault type classification is a prerequisite to different relaying applications like distance relay and autoreclosing. Performance of sequence current based fault classification approaches is also found to be affected during power swing [16], [17]. Directional relay generally uses pre-fault voltage data for close-in fault situations. Large variation in voltage signal during power swing may lead such relays to malfunction at times [18]. Communication assisted protection schemes employing remote end signal (like current differential and synchrophasor based approaches) are immune to power swing but have issues associated with latency and communication failure [19], [20]. Superimposed component based approaches are being employed for different protection applications in both time and phasor domain, to reduce the impact of load variations and change in system conditions [21]–[24]. These methods compute superimposed components by using memorized pre-fault data as the non-fault component during fault for decision. Modulation of voltage and current waveforms during power swing changes their periodicity [25]. This results in erroneous computation of superimposed components, which may affect the performance of associated protection methods for fault during power swing [26]. So there is a scope to derive improved accuracy in computing the pure-fault component of voltage and current during power swing which is expected to enhance relay performance. Thereby a reliable protection scheme can be obtained.

C. Contribution

In this work, the performance of superimposed component based protection schemes is analyzed for fault during power swing and a method is proposed to compute superimposed components accurately improving their performance. The main contributions of this work are summarized below:
1) Least square (LS) based technique is applied to demodulate the voltage and current signals during power swing using memorized pre-fault data and all the frequency components in the swing signals are extrapolated to obtain correct non-fault data in the fault period.

2) Superimposed components are computed by subtracting the extrapolated data (summation of all frequency components) from the measurements obtained during fault.

3) Each frequency component in the superimposed data is extracted by applying the LS based technique.

4) Protection decisions are derived in both phasor and time domain applications by applying any single frequency superimposed component therein, with proper frequency based adjustment in system impedances.

The performance of the proposition in acquiring non-fault component is tested for different power swing conditions simulated in 39-bus New England system using PSCAD/EMTDC platform and field data obtained from Indian Power Grid. The compatibility of the proposed method is verified using OPAL-RT real-time simulation. The advantage of the proposed method while applying to different protection principles is demonstrated for fault during power swing. Comparative assessment reveals the superiority of the proposed method in superimposed component computation during power swing.

II. PROBLEM STATEMENT

This section demonstrates the limitation of the conventional approach in obtaining accurate superimposed component during power swing and evaluates its impact on the performance of relevant protection schemes.

A. Challenges in superimposed component computation during power swing

Available relays calculate superimposed components by subtracting few cycles (one or more) memorized data from the present measurements (voltage and current) with the time reference computed based on the steady state frequency. Voltage and current signals during power swing are modulated by low frequency components [25]. This affects the periodicity of the signals and results in a significant difference between the present and corresponding memorized data. This is demonstrated for a swing situation created in 39-bus New England system of Fig. 1 [27], [28]. A three-phase fault created in line 26-29 is cleared by opening the circuit breakers (CBs) at both ends of the line. As a result, a power swing is observed in the system.

Fig. 2 shows the phase-A current in line 26-28 seen by the relay at bus 28 during the swing. Samples obtained from a 1-cycle data window (with a sampling rate of 1.2 kHz) are compared with the corresponding memorized data (2-cycles earlier in this case) [24], [29]. A difference is observed between the present and memorized samples clearly, as well as the phasors estimated using both the data sets (shown in Fig. 2). With such a difference between present and memorized data, a significant superimposed component is obtained for a signal even without any fault in the system.

Such variation in signal results in erroneous computation of superimposed components for faults during power swing, when the memorized pre-fault data is used as the non-fault component during fault (a common practice employed in the available relays). In addition, such a conventional approach may even compute significant non-zero superimposed components for the healthy phases, which have an inevitable contribution in the calculation of sequence components. This is evident from the results shown in Fig. 3 for a phase-A-to-ground (AG) fault in line 26-28 of the system in Fig. 1, created at 6.3s during the ongoing swing situation.

B. Performance of superimposed component based protection scheme during power swing

With such erroneous computation of superimposed components for fault during power swing, performance of many available protection schemes may be affected. Such a case is demonstrated below with the performance of a superimposed positive sequence component based directional relay at bus 28 for the fault case mentioned above. Phase angle difference between positive sequence superimposed voltage and current...
components is used for identification of fault direction, as in (1) [30], [31]. $\Delta V_1$ and $\Delta I_1$ represent the positive sequence superimposed voltage and current components respectively. Such a technique is immune to the pre-fault loading conditions and also applicable to all fault types.

$$\Phi = \angle \Delta V_1 - \angle \Delta I_1 = \begin{cases} < 0; & \text{for forward fault} \\ > 0; & \text{for reverse fault} \end{cases}$$ (1)

Result in Fig. 4 shows that the directional relay at bus 28 identifies the forward AG fault in line 26-28 as a reverse fault. This shows the limited performance of the relay for a fault during power swing. Similar issues for relays can also be observed while performing other important functionalities (like fault type classification, fault distance calculation etc.) using superimposed component based approaches.

![Fig. 4. Malfunction of directional relay during power swing showing (a) voltage, (b) current, (c) superimposed component angles and (d) relative angle.](image)

Thus to improve the performance of such available protection schemes, there is a need of an alternative technique to calculate superimposed components correctly for faults during power swing.

### III. PROPOSED METHOD

For a two bus equivalent power system during power swing, the voltage and current signals from both end sources contain two different frequency components [25], [32]. Thus the signals obtained by the relay can be modeled as,

$$v(t) = V_m \sin(2\pi f_m t + \alpha_m) + V_n \sin(2\pi f_n t + \alpha_n)$$

$$i(t) = I_m \sin(2\pi f_m t + \beta_m) + I_n \sin(2\pi f_n t + \beta_n)$$

where $V_m$ and $V_n$ are the amplitudes of the voltage signal having frequencies $f_m$ and $f_n$, and the initial phase angles $\alpha_m$ and $\alpha_n$ respectively. Similarly, $I_m$, $I_n$, $\beta_m$ and $\beta_n$ represent the corresponding parameters of the current signal.

$$\begin{bmatrix} i(t_0) \\ i(t_0 - 1/f_s) \\ \vdots \\ i(t_0 - (N-1)/f_s) \end{bmatrix} = \begin{bmatrix} -\sin(0) & \cos(0) \\ -\sin(2\pi \frac{f_m}{f_s}) & \cos(2\pi \frac{f_m}{f_s}) \\ \vdots & \vdots \\ -\sin(2\pi (N-1) \frac{f_m}{f_s}) & \cos(2\pi (N-1) \frac{f_m}{f_s}) \end{bmatrix} \begin{bmatrix} I_m \cos\beta_m \\ I_m \sin\beta_m \\ I_n \cos\beta_n \\ I_n \sin\beta_n \end{bmatrix}$$

The above equation can be rewritten as,

$$[M_i] = [A] [X_i].$$ (7)

With the superposition principle for a multi-source power network, both end sources contribute separately during fault with different frequencies. Therefore, in order to obtain the superimposed quantities correctly in such a situation, the individual contribution of each frequency component is required to be computed. The proposed method is presented here in two subsections. The first part illustrates the extraction of different frequency components in the swing signal before fault, which are extrapolated in the second part to estimate correct non-fault components, required for superimposed quantity computation.

#### A. Extraction of the two frequency components of swing signal

For a swing signal as in (2), (3) can be obtained using approximately one-and-a-half cycle sample values of the signal [25]. With the current signal as reference,

$$\cos \left(2\pi \frac{f_m}{f_s}\right) + \cos \left(2\pi \frac{f_n}{f_s}\right) = \frac{\sum_{k=1}^{N} |p_k q_1 - p_k q_3|}{\sum_{k=1}^{N} |p_k q_1 - p_k q_3|}$$

$$\cos \left(2\pi \frac{f_m}{f_s}\right) \cdot \cos \left(2\pi \frac{f_n}{f_s}\right) = \frac{\sum_{k=1}^{N} |p_k q_2 - p_k q_3|}{\sum_{k=1}^{N} |p_k q_2 - p_k q_3|}$$ (3)

where $f_s$ is the sampling frequency, $N$ is the number of samples per cycle and

$$p_1 = i_{k-2}, \quad p_2 = (i_{k-3} + i_{k-1})/2$$

$$q_1 = i_{k-1}, \quad q_2 = (i_{k-3} + i_{k-1})/2$$

$$q_3 = i_{k-1} + i_{k-2}$$

$i_k$ represents the $k^{th}$ sample of the current signal, $l = \frac{N}{4}$ is a suitable choice [25]. From (3), the frequencies of the current signal can be computed as in (4).

$$f_m = \frac{\cos^{-1} \left(D_1 + \sqrt{D_1^2 - 4D_2} \right)}{2\pi} \cdot f_s$$

$$f_n = \frac{\cos^{-1} \left(D_1 - \sqrt{D_1^2 - 4D_2} \right)}{2\pi} \cdot f_s$$

where $D_1 = \sum_{k=1}^{N} |p_k q_1 - p_k q_3|$ and $D_2 = \sum_{k=1}^{N} |p_k q_2 - p_k q_3|$. $\sum_{k=1}^{N} |p_k q_1 - p_k q_3|$ is the known matrix $[X_i]$ can be estimated using Least-square technique as in (8). In this way, the current amplitudes ($I_m$ and $I_n$) can be obtained.
I_n) and phase angles (β_m and β_n) at t_0 can be determined.

\[ [X_i] = [A]^+ [M_i] \]  

(8)

where \([A]^+ = \left([A]^T [A] \right)^{-1} [A]^T\).

In a similar way, V_m, V_n, α_m and α_n associated with the voltage signals in (2) can also be estimated.

**B. Computation of superimposed components for faults during power swing**

A protection scheme using superimposed component, calculated by subtracting one or two cycles earlier memorized pre-fault data from present measurement, should take a decision within a cycle following fault inception [33]. Non-fault sample corresponding to each frequency component of the swing current signal in (2) can be predicted using (9), with the frequency, amplitude, and phase information estimated using (4) and (6). Consider t_0 in (6) as the fault inception instant.

\[ i_{tf_k} = I_m \sin(2\pi f_m k T + \beta_m) \]

(9)

where \(i_{tf_k}\) is the k\(^{th}\) sample of the current signal following fault inception and \(\Delta T\) is the time interval between two consecutive samples. Superscripts represent the frequency of corresponding signal. With k value of 1 to N, each of the signals in (9) can be extrapolated for 1-cycle following fault inception. Thus the non-fault component for the period can be obtained as,

\[ i_{nf_k} = i_{tf_k}^{(f_m)} + i_{tf_k}^{(f_n)} \]  

(10)

By subtracting the non-fault component obtained using (10) from the present measurement, the correct superimposed current can be calculated. This is also comprised of two frequency components and can be expressed as,

\[ \Delta i(t) = \Delta I_m \sin(2\pi f_m k \Delta T + \gamma_m) \]

\[ + \Delta I_n \sin(2\pi f_n k \Delta T + \gamma_n) + I_{0f} e^{-\frac{t-t_0}{\tau}} \]  

where \(\Delta I_m\) and \(\Delta I_n\) are the amplitudes of the superimposed current signal having frequencies \(f_m\) and \(f_n\), and \(\gamma_m\) and \(\gamma_n\) are the phase angles at fault inception instant. \(I_{0f} e^{-\frac{t-t_0}{\tau}}\) is the decaying-DC component observed following fault inception.

In a similar way, the superimposed voltage is expressed as,

\[ \Delta v(t) = \Delta V_m \sin(2\pi f_m k \Delta T + \theta_m) + \Delta V_n \sin(2\pi f_n k \Delta T + \theta_n) \]  

(12)

The equivalent reactance of the network varies with changes in system frequency. Thus the performances of the protection schemes, which decide based on system impedance information, may be affected during power swing. As an example, a superimposed component based directional relay calculates the phase angle of equivalent source impedance for its decision. Therefore the frequency components of the superimposed signals, in (11) and (12), are to be demodulated using least-square technique, similar to (6) and required to be adjusted to fundamental frequency component properly before applying to the protection applications. The decaying-DC component in (11) can be eliminated in least-square estimation by modeling it using Taylor series expansion [34].

**C. Proposed approach**

The proposed method is to be initiated when the power swing condition is detected in a power system [1], [25]. During no power swing condition, \(f_m\) and \(f_n\) are almost equal, and the value of \(\sum_{k=1}^{N} |p_2 q_1 - p_1 q_2|_k\) becomes close to zero for a long period of time. Therefore, the proposed method based on double-frequency signals cannot be applied. The non-swing condition can be detected by setting a threshold (ζ) to \(\sum_{k=1}^{N} |p_2 q_1 - p_1 q_2|_k\). A suitable value of ζ is considered as 40% of the full-load current [25]. The steps followed in the proposed approach to enhance the performance of superimposed component based protection scheme during power swing are provided below, which are also shown in Fig. 5 for only current signal. Similar steps are followed for voltage signals.

Step 1: Extract the multiple frequency information of a swing signal using (4), with approximately one-and-a-half cycle samples during pre-fault.

Step 2: Demodulate the swing signal by computing the amplitudes and phases of both frequency components using least-square technique, as in (6).

Step 3: Extrapolate each frequency component for 1-cycle following fault inception using (9).

Step 4: Calculate the non-fault component using (10), with the sample values extrapolated for each frequency component in Step 3.

Step 5: Compute the superimposed component by subtracting the non-fault samples (obtained in Step 4) from the present measurement.

Step 6: Demodulate the frequency components of the superimposed signals in (11) and (12) using least-square based technique and apply in the protection schemes, as required.

**D. Computational requirement**

One-cycle summation of both the equations in (3) are obtained using the moving window. The frequency estimation
using (4) requires six real multiplications, two real divisions, nine real summations, and the calculation of the solution to one quadratic equation. Each phasor computation using least square technique in (6), with a window length of N samples requires \(4N\) real multiplications and \(4(N-1)+2\) real summations. In order to reduce the computational burden, the pseudoinverse in (8) for the required frequency combination is calculated offline and stored in memory [35]. The computational burden can be further minimized by keeping the sampling rate low. In terms of memory, the method needs to store approximately one-and-a-half-cycle sample values. This requires additional memory of approximately 9 MB (\(4 \times 7 \times 4 \times 2 \times 200 \times 200\) B) to store the elements of the first four rows of the pseudoinverse matrix in (8). Up to fifth harmonic, and decaying dc are considered. The higher order harmonics are removed from the signals using the anti-aliasing filter. The computational burden and memory requirement is found to be compatible with the present technology being used for relay applications.

IV. RESULTS

Performance of the proposed extrapolation technique for estimating the non-fault component during power swing is tested for different power swing situations created in 39-bus New England system using PSCAD simulation platform. The performance of the proposed method is also tested with field data obtained from the Indian Power Grid. The advantage of the proposed method in improving relay performance is demonstrated by applying it to three protection applications. The swing situations are created as mentioned in Section-II.

A. Verifying proposed extrapolation approach during swing

1) With variation in swing frequency: The proposed method demodulates the swing signal during pre-fault and then extrapolates the individual frequency component to obtain correct non-fault quantity for the situation. The performance of such an approach is tested for different swing signals created in the 39-bus system of Fig. 1. The non-fault swing signals are compared with the extrapolated signals to verify the tracing capability of the technique. Starting time for extrapolation (\(t_0\)) is varied to test the performance of the approach in acquiring non-fault signals for different fault inception angles. Results in Fig. 6 demonstrate the performance of relay at bus 28 in extrapolating phase-A current signals in line 26-28 during power swing, with swing frequencies (\(f_{sw}\)) of 1 Hz, 4 Hz, 7 Hz, and 10 Hz respectively. Corresponding power angles (\(\delta\)) set for all the four cases are \(20^\circ, 60^\circ, 120^\circ\) and \(170^\circ\). Results show that the extrapolated signals follow the actual measurements for all the cases. This demonstrates the accurate performance of the proposed method in estimating correct non-fault component during power swing. The adaptivity with high swing frequency advocates the applicability of the proposed approach even for a low inertia system.

Note: The extrapolation performed for several cycles is to demonstrate the accuracy of the proposed technique in non-fault swing situations, whereas it is required to be performed only for a cycle following fault inception to apply in protection applications.

2) In the presence of measurement noise: One-cycle summation of numerators and denominators associated with \(D_1\) and \(D_2\) in (3) weakens the effect of noise in frequency estimation. In order to test the performance of the proposed extrapolation technique in the presence of noise, a test current signal is generated as in (2) with \(I_m = 200\); \(f_m = 58.5\) Hz; \(f_n = 61.5\) Hz; \(f_n = 7\) Hz; \(\beta_m = \frac{\pi}{4}\) and \(\beta_n = -\frac{\pi}{4}\).

The signal is contaminated with uniform distribution noise with zero mean and a standard deviation of 0.5%. Results shown in Fig. 7(a) demonstrate that the proposed method can correctly estimate the frequencies during power swing even in the presence of noise. Extrapolated signal in Fig. 7(b) also follows the actual signal.

3) In the presence of harmonics: In order to test the performance of the proposed extrapolation technique in the presence of harmonics, all the lower order harmonics (\(\leq 5^{th}\) order) are added in the same test signal considered in section IV.A.(2), as per IEEE Std. 519-1992. All the higher order harmonics are filtered out using anti-aliasing filter. Results shown in Fig. 8(a) demonstrate that the estimated frequencies are very close to the actual frequencies and the extrapolated signal in Fig. 8(b) closely follows the actual signal for the first 2 cycles after \(I_0\). The small deviation can also be eliminated with improved filtering technique.

4) With varying swing frequency: The swing frequency may not remain constant with time. It changes very slowly in a power system. In order to verify the performance of the proposed method in such a situation, a test signal is generated as in (13).

\[
i(t) = I_m \sin(2\pi(f - \Delta f)t + \beta_m) + I_n \sin(2\pi(f + \Delta f)t + \beta_n) \quad (13)
\]
where $I_{n0} = 1.5 \, kA$, $I_n = 1 \, kA$, $f = 60 \, Hz$, $\beta_{m} = \frac{\pi}{6}$ and $\beta_n = -\frac{\pi}{3}$. $\Delta f$ has an initial value of 0.5 Hz and changes at a rate of 1.5 Hz/s and 2.5 Hz/s for two cases respectively. The signal is sampled with a rate of 1.2 kHz. Results shown in Fig. 9 demonstrate that the extrapolated signals closely follow the actual signal even for such situations. The extrapolation is performed at 0.64s for both the cases.

5) For a three machine equivalent system: A multi-machine system may consist of more than two coherent areas, where frequency of each area may deviate from nominal frequency. In order to verify the performance of the proposed method for such a situation, a test current signal is generated as in (14), considering a three machine equivalent system.

$$i(t) = I_1 \sin(2\pi f_1 t + \beta_1) + I_2 \sin(2\pi f_2 t + \beta_2) + I_3 \sin(2\pi f_3 t + \beta_3)$$

(14)

where, $I_1 = 2 \, kA$, $I_2 = 1.5 \, kA$, $I_3 = 1 \, kA$, $f_1 = 58 \, Hz$, $f_2 = 61 \, Hz$, $f_3 = 59 \, Hz$, $\beta_1 = \frac{\pi}{6}$, $\beta_2 = -\frac{\pi}{3}$ and $\beta_3 = \frac{\pi}{4}$. Results in Fig. 10(a) shows that the estimated frequencies are not constant for three machine equivalent system, but not changes rapidly with time. Fig. 10(b) demonstrates that the extrapolated signal generated by the proposed method follows the actual signal correctly even for such a situation. This justifies the signal model considered in (2) to be proper for this work.

6) With field data during power swing: In order to validate the accuracy of the proposed method with field data, the method is applied to a sampled current data of a power swing condition collected from the Indian Power Grid (50 Hz system). Result is shown in Fig. 11. The extrapolated signal generated by the proposed method is observed to overlap with the actual measurement signal. This validates the accuracy of the proposed method while applied to field data.

B. Performance of the proposed method for fault type classification during power swing

Fault type classification is an integral part of relay decision process for transmission networks required for different applications such as in single pole tripping, distance relaying, etc. For fault type classification, phase angle comparison of the superimposed sequence currents is a common technique, as shown in Fig. 12 [36], [37].

In the figure, A, B, C, and G represent three phases and ground respectively and subscripts 0, 1, and 2 are for sequence components. $\delta^+_i$ and $\delta^-_i$ are the angle of negative sequence superimposed current relative to the positive and zero sequence superimposed currents respectively. Inaccuracy in obtaining correct superimposed components during power swing may result in misidentification of fault type with such an approach. This is demonstrated for a phase-to-phase fault (AB type), created in line 26-28 at a distance of 0.4 pu from bus 28 with a fault resistance ($R_f$) of 2 $\Omega$ during a power swing situation. The current signals for the situation is shown in Fig. 13 (a). Presence of multiple frequency components modulates the amplitude and phase angles of the fundamental signal and the conventional approach of using 2-cycle memorized data as the non-fault component computes.
the superimposed phase currents incorrectly. The performance of fault type classifier with such improper superimposed component is demonstrated in Fig. 14. Result shows that the fault classifier using conventional approach identifies the fault as BG type using $\delta^+_f$ comparator of Fig. 12 instead of AB. On the other hand, the proposed method extracts a single frequency component accurately by demodulating the swing current signal and computes the correct superimposed component of the corresponding frequency. The swing frequency observed at bus 28 is 3 Hz. The current signal with a single frequency component (57 Hz) extracted from the actual measured signal is shown in Fig. 13 (b). Result in Fig. 14 demonstrates that the fault classifier identifies the fault type correctly using proposed approach.

With homogeneity of the conventional transmission network, the phase angle of the superimposed current component measured by the relay is the same as that of currents in the faulted path. This is valid for each single frequency component in a power network. Thus the performance of the current angle based classifier applying the proposed approach remains unaffected by $R_P$. Performances of fault classifier applying both conventional and proposed approaches are provided in Table I for variation in $R_P$. Results show that $\delta_f^+$ and $\delta_f^-$ calculated by the proposed method are within the correct classification zones as mentioned in column II of Table I, whereas the conventional approach fails to identify the fault types correctly for some cases. For the case of BCG fault with $R_P = 100 \, \Omega$ (Second row of Table I), the conventional approach calculates $\delta_f^+ = 71.88^\circ$, which lie outside the classifier zone setting of BCG fault ($180^\circ \pm 15^\circ$). On the other hand, the relay using proposed method calculates $\delta_f^+ = -173.56^\circ$ and $\delta_f^- = -9.23^\circ$ and identifies the fault type correctly. This clearly demonstrates the superiority of the proposed approach in enhancing the performance of the current angle based fault classifier during power swing.

### Table I

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>Classifier Zone Setting (Fig. 12)</th>
<th>$R_P$ ((\Omega))</th>
<th>Current ((\text{kA}))</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>AG</td>
<td>$\delta_f^+; 0 \pm 15$</td>
<td>5</td>
<td>-99.87</td>
<td>0.88</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>$\delta_f^-; 0 \pm 30$</td>
<td>100</td>
<td>-101.51</td>
<td>1.34</td>
<td>0.00</td>
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<td>BCG</td>
<td>$\delta_f^+; 180 \pm 15$</td>
<td>5</td>
<td>74.24</td>
<td>-12.68</td>
<td>177.52</td>
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<tr>
<td></td>
<td>$\delta_f^-; 0 \pm 30$</td>
<td>100</td>
<td>71.88</td>
<td>-10.28</td>
<td>-173.36</td>
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<tr>
<td>CA</td>
<td>$\delta_f^+; -60 \pm 15$</td>
<td>1</td>
<td>-162.54</td>
<td>-</td>
<td>-60.00</td>
</tr>
</tbody>
</table>

(Angles in degree)

C. Performance of the proposed method for fault direction identification during power swing

Superimposed component based directional relaying is accomplished in both time and phasor domain applications. Performance of such relaying schemes is tested in this section for faults during power swing.

1) Performance of phasor based superimposed component direction relaying during power swing: A directional relay uses phase angle difference between positive sequence superimposed voltage and current phasors, as in (1) for acquiring decision [30], [31]. Incorrect computation of superimposed components during power swing may result in malfunction of such relays at times. One such malfunction scenario is demonstrated in Section-II.B. In this section, the performance of the proposed method is demonstrated while preventing such malfunctioning of directional relays.

The proposed method demodulates the superimposed voltage and current signals and extracts the frequency components. Ratio of superimposed voltage and current of any single frequency provides the negative of equivalent source impedance ($Z_e = R_e + jX_e$) corresponding to the relay. This impedance angle is used by the relay for acquiring decision. As the reactance ($X_e$) is dependent on system frequency, it should be adjusted, as in (15), for the correct decision.

$$\Phi = \tan^{-1}\left(\frac{\text{Im} \left(\frac{\Delta V(f_m)}{\Delta f(f_m)}\right)}{\text{Re} \left(\frac{\Delta V(f_m)}{\Delta f(f_m)}\right)}\right)$$

(15)

Result in Fig. 15 (a) shows the performance of directional relay at bus 28 using proposed and convention approaches for a forward three-phase fault created in line 26-28. The result demonstrates that the relay using the proposed approach performs correctly for the situation, where the conventional approach identifies the fault in the reverse direction. Fig. 15 (b) and (c) show the positions of superimposed voltage and current components computed by the relay after 1-cycle following fault inception by applying conventional and proposed approaches respectively.

The angle $\phi$ calculated by the directional relay at bus 28 using (1) and (15), applying conventional and proposed
approaches is provided in Table II demonstrating the performance for different fault types created in line 26-28 and line 28-29 with change in fault resistance and swing frequency. Results show that the proposed method calculates $\phi$ as negative for forward faults and positive for reverse faults and identifies the fault direction correctly for all the cases. On the other hand, the conventional approach fails to identify the fault direction correctly for some cases. The shaded boxes in the Table II show the maloperation cases using the conventional approach. Thus the superiority of the proposed method is confirmed in enhancing the performance of directional relay in phasor domain.

Fig. 15. (a) Performance of superimposed component based phasor-domain directional relaying with superimposed voltage and current phasors computed using (b) conventional and (c) proposed approach.

The relation in (16) can be rewritten as,

$$\Delta v_a = - |Z_s| \cdot \Delta i_{az}$$

(17)

where $\Delta i_{az} = \left( \frac{R_s}{|Z_s|} \cdot \Delta i_a + \frac{L_s}{|Z_s|} \cdot \frac{d\Delta i_a}{dt} \right)$ represents the replica current waveform of phase-A. Thus the sample wise multiplication of $\Delta v_a$ and $\Delta i_{az}$, denoted by $S_{OP}$ becomes negative for forward fault. In a similar way, $S_{OP}$ becomes positive for reverse fault. Thus by comparing the polarities of $\Delta v_a$ and $\Delta i_{az}$ waveform direction information of the fault can be acquired.

Presence of multiple frequency components during power swing modulates the voltage and current signals and thereby changes the relative polarity of $\Delta v_a$ and $\Delta i_{az}$. Thus the performance of such directional relaying may be affected. Such a case is demonstrated below for an AG fault created in line 26-28 at a distance of 0.4 pu with $R_F = 5 \Omega$ during a power swing situation. Fig. 16 (a) and (b) show the phase-A voltage and current waveforms for the situation, whereas the single frequency components extracted from those signals are shown in Fig. 16 (c) and (d).

Fig. 16. (a) Phase-A voltage and (b) phase-A current measured by the relay. (c) single frequency component of measured voltage signal and (d) single frequency component of measured current signal

Results in Fig. 17 (a) and (c) demonstrate the performance of time-domain superimposed component based directional relaying. $S_{OP}$ with positive value, as shown in Fig. 17 (c) indicates that the relay malfunctions in such a situation. On the other hand, $\Delta v_a$ and $\Delta i_{az}$ computed from the single frequency signals of Fig. 16 (c) and (d) are shown in Fig. 17 (b). Result in Fig. 17 (d) demonstrates that the relay employing proposed approach calculates $S_{OP}$ as negative. Thus the fault direction is identified correctly. This confirms the effectiveness of the proposed approach compared to conventional technique even for time domain based protection applications.

D. Performance of the proposed method for calculating fault location during power swing

Accurate fault location is required to expedite repair and restoration of lines and avoid lengthy and expensive patrols. Takagi method is one of the well-known approaches used for the purpose [38]. With this approach, the per-unit fault distance for an AG fault is determined using (18) [38].

$$x = \frac{Im (V_a \cdot \Delta I_f)}{Im (Z_{1L} \cdot (I_a + K_0J_0) \cdot \Delta I_f)}$$

(18)
Where $V_a$ and $(I_a + K_0 I_0)$ are the operating voltage and current for the relay, $Z_{1L}$ is the positive sequence impedance of the protected line. $K_0$ represents the zero sequence compensation factor. Expanding the complex variables used in (18), the relation can be rewritten as in (19).

$$x = \frac{|V_a| \sin (\theta_v - \alpha)}{|Z_{1L}| (I_a + K_0 I_0) \sin (\theta_{1L} + \theta_t - \alpha)}$$

(19)

Where $\theta_v$, $\theta_t$, $\theta_{1L}$ and $\alpha$ are the angles associated with $V_a$, $(I_a + K_0 I_0)$, $Z_{1L}$ and $\Delta I_1$ respectively. The incorrect computation of $\Delta I_1$ during power swing results in $\alpha$ to be erroneous and thereby affecting the calculation of fault distance using (19). In addition, frequency modulation during power swing changes $Z_{1L}$ and $K_0$ by influencing the line reactance. The incorrect phasor computation in the presence of multi-frequency signals during power swing may also amplify the fault location error. The proposed method overcomes such sources of errors by correct computation of superimposed components using single frequency data extracted from the swing signal, and frequency based adjustment in the line impedances.

A fault location case is demonstrated for an AG fault created in line 26-28 at a distance of 40 km from bus 28 with $R_F = 10 \Omega$ during a power swing situation. Fig. 18 shows the differences observed in $|V_a|$, $(I_a + K_0 I_0)$, $\theta_v$, $\theta_t$ and $\alpha$, as computed by the relay at bus 28 with conventional and proposed approaches. It is observed that $Z_{1L}$ and $K_0$ computed using fundamental frequency (60 Hz) are 28.74 ± 0.06Ω and 1.94 ± 0.06 respectively. On the other hand, those parameters are computed as 27.79 ± 0.06Ω and 1.94 ± 5.06Ω, when the frequency reference is changed to 58 Hz (one of the frequencies extracted from the swing signal). Fig. 19 shows the performance of the relay in calculating the fault distance using conventional and proposed approaches. Result shows that the fault distance calculated using the conventional approach is 81.17 km (after 1-cycle following fault inception), whereas the proposed method calculates the distance as 40.07 km which is close to the actual fault distance of 40 km. The possibility of any inherent error in computing fault location using Takagi method due to system non-homogeneity is eliminated here by modifying the system impedances suitably. Performance of Takagi method for faults at different locations and fault resistances are provided in Table III using both conventional and proposed approaches. This demonstrates the superiority of the proposed method in improving the performance of such an approach in determining the fault location.

![Fig. 17. Phase-A voltage and replica current waveform obtained from (a) measured signals and (b) single frequency component extraction. Performance of superimposed component based time-domain directional relaying using (c) conventional and (d) proposed approaches.](image)

![Fig. 18. Differences observed in (a) $V_a$, (b) $(I_a + K_0 I_0)$ and (c) $\alpha$ with conventional and proposed approaches.](image)

![Fig. 19. Performance of proposed method in acquiring correct fault distance.](image)

### TABLE III

<table>
<thead>
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<th>$x_{act}$ (pu)</th>
<th>$x_{calc}$ (pu)</th>
<th>$R_F$</th>
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<td>0.900 0.902 0.907 0.922 0.943</td>
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### V. REAL-TIME VALIDATION

The proposed method is validated using OP4510 (OPAL-RT) real-time simulator. Fig. 20 shows the real-time simulation experimental setup used for this work. Parameters associated with real-time simulator are provided in Table IV. The 39-bus New England system (of Fig. 1), the proposed superimposed component computation algorithm and the relaying algorithm are modeled in MATLAB integrated with OPAL-RT, which are compiled with RT-LAB to run as an effective platform for developing and testing real-time operation of the proposed method. The fault location technique, available in [38], is tested for an AG fault created in line 26-28 at a distance of 0.9 pu from the relay location at bus 28 with $R_F = 10 \Omega$. Using conventional approach the error is found to be 19.22%, whereas it is only 0.28% when the superimposed component is computed using proposed approach and applied to the fault location algorithm. This demonstrates that the compatibility of the proposed method for real-time application.
VI. CONCLUSION

Power swing results in modulation in amplitude, phase, and frequency of voltage and current signals. This creates issues in obtaining accurate non-fault component for fault during power swing and resulting in superimposed components be erroneous. The protection schemes employing such incorrect superimposed component may be affected in deriving correct decisions. This work proposes a method to compute superimposed components correctly for fault during power swing and gives a scope to enhance the performance of associated protection schemes for such a situation. The method extrapolates the pre-fault signal to acquire the correct non-fault component during fault for computing superimposed quantity correctly for the situation. The proposed method demodulates the swing signal and the associated protection decision can be obtained by using any single frequency component as extracted from the superimposed signal. The method is adaptive to variation in swing frequency. The accuracy of non-fault component estimation method is tested for different swing conditions with variation in swing frequency and its rate, power angle variation, and in the presence of measurement noise and harmonics. The performance is also evaluated using power swing field data and the compatibility of the proposed method is checked with real-time simulator. The improved performance of different protection schemes are observed for faults during power swing with changes in fault type, fault location, fault resistance, swing frequency, and fault inception angle. The proposed method is applied for both time and phasor domain protection applications. Comparative assessment reveals the superiority of the proposed method.

REFERENCES


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