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A Cumulative Sum-Based Fault Detection Technique for the Series-Compensated Line During Power Swing

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Abstract - *There is a noticeable difference in fault detection technique of series compensated transmission line during usual operating condition and power swing condition due to certain reasons like frequency modulation, sub-harmonic oscillations, transients etc. Particularly during power swing condition the frequency of power change is modulated and it is twice of frequency of voltage variation and current variation. So, cycle to cycle or sample to sample comparison is not reliable here. Other methods like Voltage Change, Current Change or Impedance change methods are also not applicable during power swing condition. Transients and sub-synchronous resonance activity in series-compensated line appear due to inclusion of capacitor in transmission line. So, fault detection during power swing condition in case of series-compensated line is extreme difficult. In this paper a method is developed to detect fault of series-compensated transmission line during power swing condition. Here it proposes a negative-sequence current based technique for detecting presence of fault during the power swing condition in a series-compensated line. The proposed approach is a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence current based approach and is tested for an SMIB system. Various types of faults like Symmetrical, asymmetrical, and high resistance occurring during the power swing are simulated through EMTDC/PSCAD to test algorithm.*

Keywords- *Distance protection, fault detection, power swing, series compensation, negative-sequence current*

I. INTRODUCTION

Recent regulatory developments, increased electricity demand, and restrictions on building new transmission lines result in enhanced transmission-line loading and necessitate optimized operation of transmission networks. To fulfill such requirements, the inclusion of a series capacitor in long transmission lines is increasing day by day. However, a series capacitor in a line introduces protection problems [1]–[5].

Power system at steady operation maintains a balance between the generation and load. System disturbances, such as line switching following the fault, generator disconnection, and switching ON/OFF large loads cause oscillations in rotor angles among generators and can result in severe power-flow swings. As a consequence, the apparent impedance seen by a distance relay may fall within its operating zone. This may be misinterpreted as a fault and the relay would trip the line unnecessarily. To ensure stability, the power-swing blocking (PSB) function is integrated with the distance relay to block it during the power swing [6]. However, if a fault occurs during the power swing, the relay must detect the fault and operate quickly. The detection of faults in a series-compensated line during power swings is more challenging due to the generation of different frequency components in the fault signals which depend on the fault location, fault type, the level of compensation, and functioning of MOV [9]. This causes the apparent impedance seen by the relay to oscillate which imposes difficulty to distinguish faults from the power swing. This paper proposes a technique for detecting faults in a series-compensated line during the power swing.

Techniques available to detect the fault during the power swing in uncompensated lines find limitations in the presence of series compensation due to the nonlinear functioning of the series capacitor combination. Though power swing is a balanced phenomenon, a small value of negative-sequence component of current is observed as the conventional phasor estimation technique does not consider the signal modulation. During unbalanced faults, the negative-sequence components become significant and due to transients in current signals in the initial period, a negative sequence component is noticed even for three-phase faults. To discriminate the faults during swing in a series-compensated line, a cumulative sum (CUSUM) of change in the magnitude of the negative-sequence-current-based approach is proposed in this paper. The CUSUM test is being employed widely as a technique for detecting abrupt changes in various fields [11]. The performance of the algorithm is tested for an SMIB system and simulated with EMTDC/PSCAD and found to be accurate and fast.

II. FAULT DETECTION CHALLENGES DURING THE POWER SWING IN SERIES-COMPENSATED LINES

Series compensation imposes protection problems and are related to the level of compensation, location, and the operation of its overvoltage protection devices like MOV and air gap. The use of series capacitors in transmission lines results in various special phenomena, such as voltage/current inversion, subharmonic oscillations, and transients caused by the MOV operation during the fault period [1]–[5].

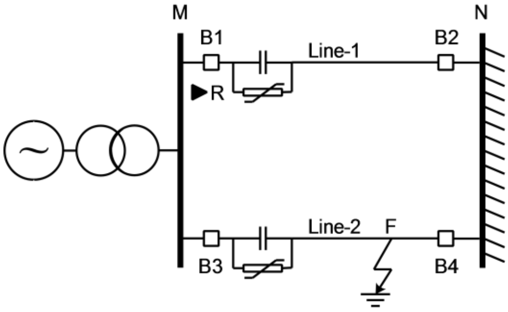

Figure 1. Single-line diagram of the 400-kv power system.

The detection of the fault during the power swing in an MOV protected series-compensated line is difficult. The pattern of the fault current during such a period depends on the operation of the MOV. This imposes difficulty for the existing phasor estimation techniques to distinguish faults from the power swing. During the power swing when faults occur in a series-compensated line at the far end of a line or at a power angle close to 180^o or with high fault resistance, the magnitude of the fault current produced may be less than or at par with the swing current. Such a low fault current may prevent the capacitor bypassing. The presence of the series capacitor in the fault circuit results in subsynchronous oscillations which will cause variation in the estimated impedance. This also creates difficulty to distinguish faults from the power swing.

In order to demonstrate the fault detection issues during power swing in a series-compensated line, a test system [12] shown in Figure. 1 is considered. Both Line-1 and Line-2 are 40% compensated and the capacitors are placed at the relay end and the protection scheme of each series capacitor including an MOV as shown. The system details are provided in Appendix. The power angle here refers to the angle between the voltages at buses M and N. The distance relay R for breaker B1 is considered for the study. A three-phase fault is created at the middle of Line-2 at 0.6 s and cleared at 0.7 s by opening breakers B3 and B4. This causes a power swing condition in Line-1 and is observed by the relay R. During this condition, phase-a current and voltage waveforms are shown in Figure. 2(a) and (b), respectively. From the figure, it is clearly observed that during swing current and voltage waveforms are modulated with the swing frequency. As a result, the traditional fault detection techniques, such as the sample-to-sample or cycle-to-cycle comparison of current (or voltage) signals [14] cannot be reliable during the power swing.

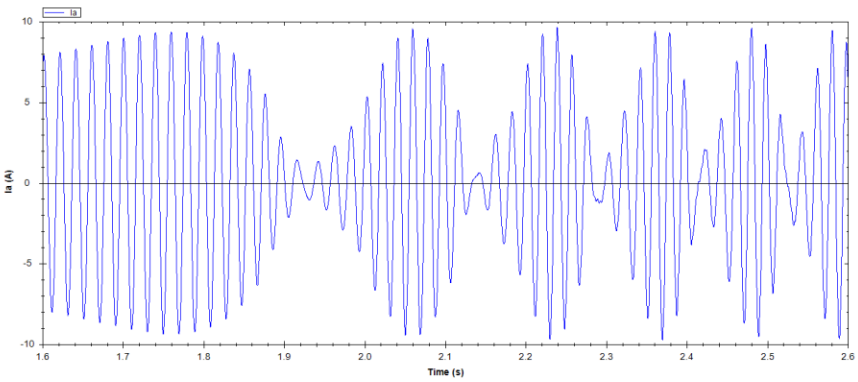

Figure 2(a). Current waveforms of phase-a at the relay bus during the power swing.

To study the variation in the current waveforms for faults during the power swing, a three-phase fault is created at 2.47 s for two different fault locations (64 and 240 km) from the relay bus in line-1 following the removal of line-2. The corresponding current waveforms are shown in Figure. 3(a) and (b), respectively.

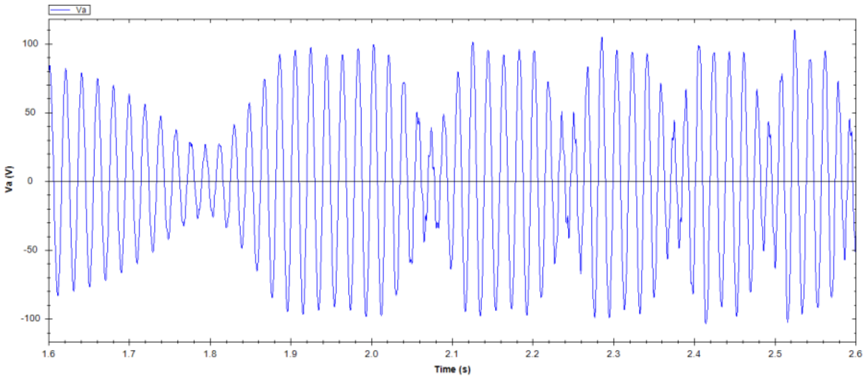

Figure 2(b). Voltage waveforms of phase-a at the relay bus during the power swing.

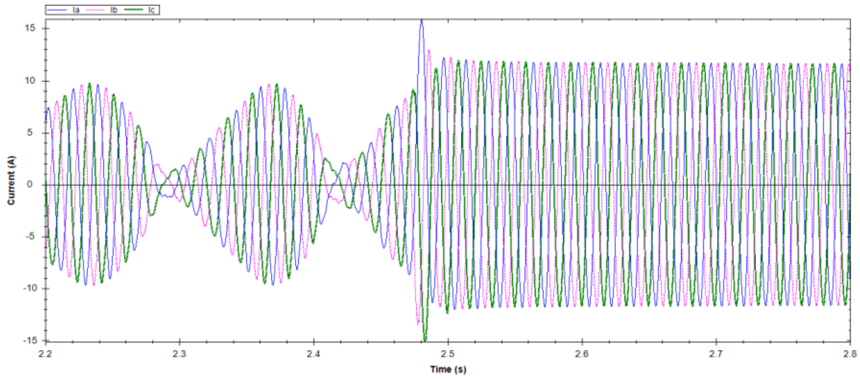

Figure 3(a). Current waveforms at the relay bus for a three-phase fault during the power swing at 2.47 s at locations of 64 km.

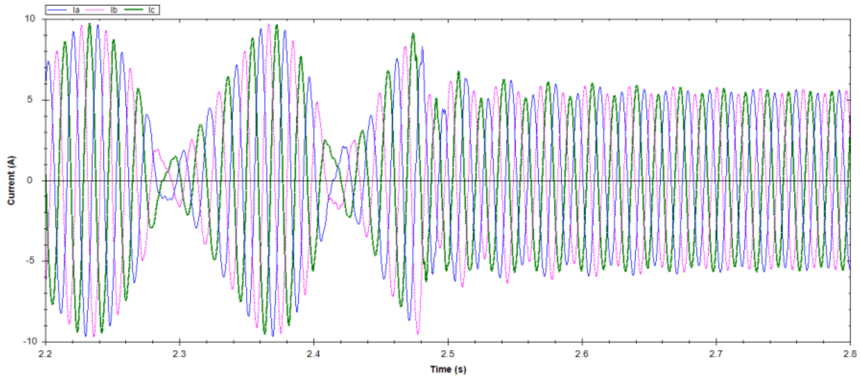

Figure 3(b). Current waveforms at the relay bus for a three-phase fault during the power swing at 2.47 s at locations of 240 km.

It is clearly observed from Figure. 3(a) that in the case of the fault being close to the relay, the current level as seen from the plot is higher than the swing current which causes the MOV to operate. As a result, in most portions of the fault, the series capacitor is bypassed and no oscillation is observed in the fault current. However, in case of a fault at the far end [Figure. 3(b)], the level of fault current is lower than the swing current which does not enable MOV conduction and results in subsynchronous oscillation in the current waveforms. These issues result in more complexity to identify the fault.

III. PROPOSED FAULT DETECTION TECHNIQUE

The power swing is a balanced phenomenon [7], but a small percentage of negative-sequence components of current ($\bar{I}_2$) is found due to signal modulation and the related phasor computation technique. For unbalanced faults during the power swing, a significant amount of negative-sequence current is observed. In case of a three-phase fault during the power swing, negative-sequence current is observed at the initial period of the fault due to transients in the current signals and in the subsequent period due to the presence of modulated frequency components by the power swing. To observe the variation of $|\bar{I}_2|$ during swing and fault, an ag-fault with a fault resistance of 0.1 Ω and a three-phase fault are created at 2.8 s during the power swing at a distance of 64 km from relay R toward bus N of Figure. 1, and the corresponding results are provided in Figures. 4 and 5, respectively. In case of the ag-fault, phase-a current only exceeds the swing current as a result MOV of only phase-a operates. For the three-phase fault, MOVs of all three phases conduct. Figure. 4(c) and 5(c) clearly show the low value of $|\bar{I}_2|$ that is present during the power swing. From figure. 4(c), it is evident that during the ag-fault, $|\bar{I}_2|$ becomes significant and oscillates due to modulating frequency components in the fault signals. From figure. 5(c), it is observed that during the three-phase fault, $|\bar{I}_2|$ varies rapidly at the inception of the fault due to the initial transient and following that, it has a low value due to signal modulation by the swing.

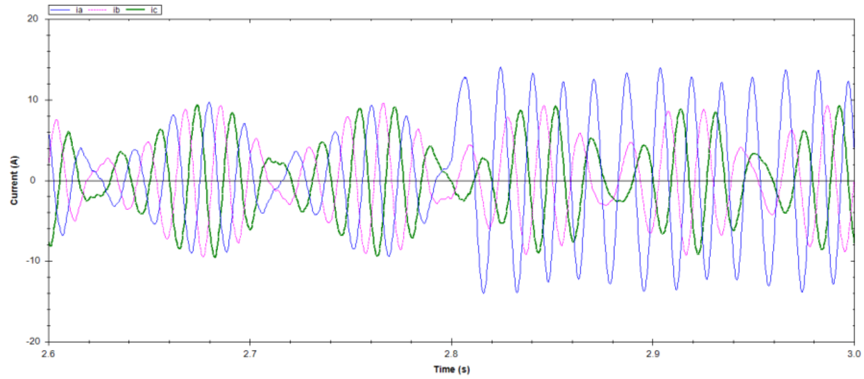

Figure 4(a). Three-phase current waveforms for an ag-fault during the power swing at 2.8 s.

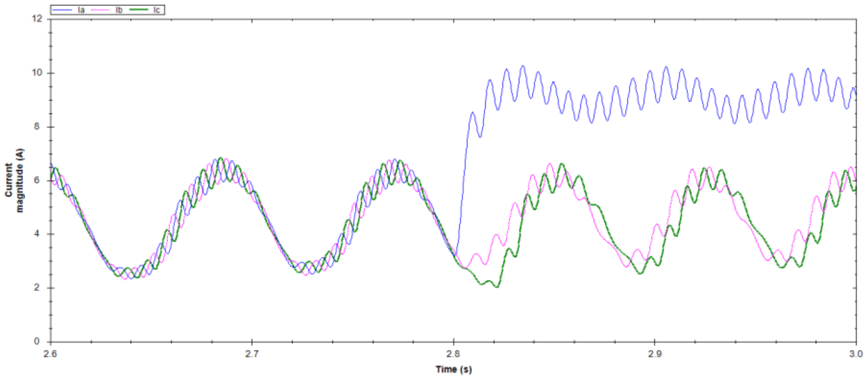

Figure 4(b). Current magnitude for an ag-fault during the power swing at 2.8 s.

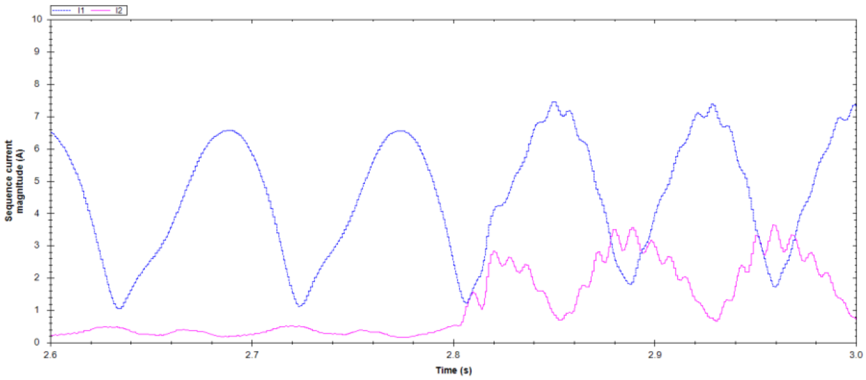

Figure 4(c). Negative-and positive-sequence current magnitude for an ag-fault during the power swing at 2.8 s.

It is evident from the previous discussion that negative-sequence current is available in the computation process during the swing. But with a small amount of $\bar{I}_2$ remaining during the swing condition, a change in the magnitude of the negative-sequence current $\left(\Delta|\bar{I}_2|\right)$ based technique suits the purpose. With a suitable threshold, the cumulative sum of the $\Delta\left|\bar{I}_2\right|$-based technique is selected in this paper for the fault detection during swing. CUSUM is a versatile technique used for abrupt change detection in various fields [11]. It is to be noted that the CUSUM-based approach is applied for transmission-line fault detection using sampled values of the current signal [14] and has limitations due to uneven variation in sample-to-sample magnitude difference of current during power swing. In this paper, CUSUM is applied to obtain a good index for fault detection during the power swing where a change in negative-sequence current is being used as the input signal. The computation steps for the method are provided

$$\bar{I}_2 = \frac{\left(\bar{I}_a + \alpha^2 \bar{I}_b + \alpha \bar{I}_c\right)}{3} \quad (1)$$

Where $\bar{I}_2$ is the sequence-sequence current; $\alpha = e^{j2\pi/3}$ and $\bar{I}_a$, $\bar{I}_b$ and $\bar{I}_c$ are the phase currents.

A derived signal s_k is obtained as

$$s_k = \Delta\left|\bar{I}_2\right| = \Delta\left|\bar{I}_{2_k}\right| - \Delta\left|\bar{I}_{2_{k-1}}\right| \quad (2)$$

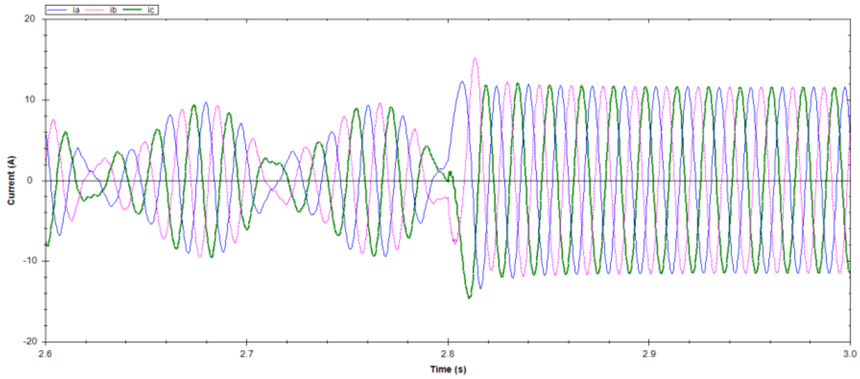

Figure 5(a). Three-phase current waveforms for a three-phase fault during the power swing at 2.8 s.

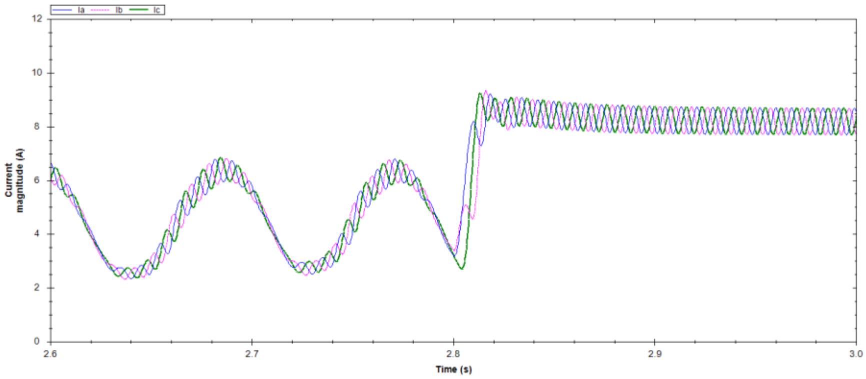

Figure 5(b). Current magnitude for a three-phase fault during the power swing at 2.8 s.

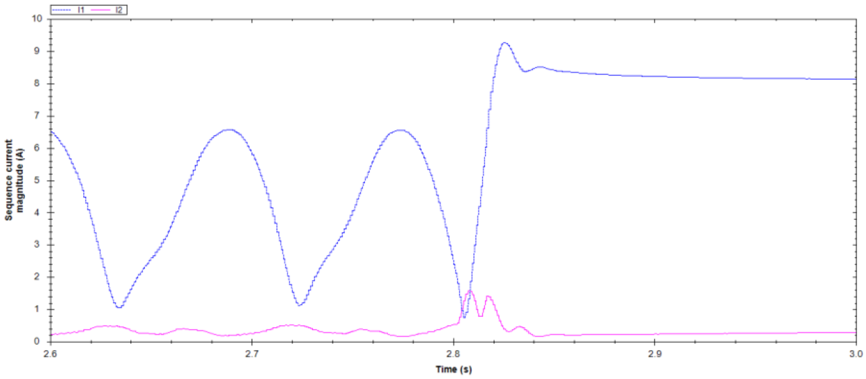

Figure 5(c). Negative-and positive-sequence current magnitude for a three-phase fault during the power swing at 2.8 s.

For $s_k > \varepsilon$, the proposed CUSUM test is expressed as

$$g_k = \max\left(g_{k-1} + s_k - \varepsilon, 0\right) \quad (3)$$

Where the index g_k represents the test statistics and s_k is the drift parameter in it. A fault is registered if

$$g_k > h \quad (4)$$

Where h is a constant and should be ideally zero. In (3), ε provides the low-pass filtering effect and influences the performance of the detector. When $s_k > \varepsilon$, the value increases by a factor of the difference between s_k and ε. With further current samples available, the CUSUM process provides an easy way to decide on the fault situation by applying (4). After each fault detection index g, is reset to zero. For only the swing situation, g_k will be zero as $\Delta\left|\bar{I}_2\right| < \varepsilon$. For the technique that is based on the negative-sequence component for the single-pole tripping condition, the method will also not be affected.

The selection of ε and h is important for determining the performance of the algorithm. It is already demonstrated that though the power swing is a balanced phenomenon, a small amount of negative-sequence component of current is observed in the phasor extraction process which increases slowly with an increase of swing cycle slip frequency. In the proposed CUSUM-based fault detection technique, the value of ε is set to make $s_k = 0$ during swing (both stable and unstable) which finally helps to maintain the fault detector index $g = 0$. In this paper, the setting of ε is set at 0.04. The value of h is set such that the algorithm can maintain the balance between dependability versus security and speed versus accuracy requirements of the relaying scheme. In this paper, the value of h is set at 0.05, considering all extreme fault situations during the power swing, for example, high resistance faults occurring at the far end of the line. The proposed method is based on the CUSUM approach and, therefore, a distinctly much higher index value g is obtained during the fault.

IV. RESULTS

The algorithm for fault detection is tested for different conditions including balanced and unbalanced faults, high resistance faults, and close-in faults during the power swing. Using EMTDC/PSCAD with distributed parameter line model data was generated. The inputs to the relay are fed from the secondary of a current transformer with a turns ratio of 1000:5. The nonlinear CT model is considered in the simulations. Sequence components were estimated considering phase-a as reference. The convention used in this paper is such that the output of the algorithm should be '1' for fault and '0' for the no-fault situation.

In order to test the algorithm at critical conditions, all faults are created at a fault inception time of 2.54 s which corresponds to $\delta = 175^{\circ}$. As mentioned in Section II, faults occurring far away from the series capacitor produce current magnitude less than the swing current when MOV does not operate. At this condition, the presence of series capacitor in the circuit during the fault period results in subsynchronous oscillations which complicate the fault detection process. In order to test the proposed technique for far-end faults, all faults are created at 240 km from the capacitor toward bus N which corresponds to 75% of the line length.

A. Line-to-ground fault in the series-compensated line

The algorithm is tested for a line-to-ground fault of ag-type with a fault resistance of 0.1 Ω initiated at 2.54 s at a distance of 240 km from the relay location, and the results are shown in Figure. 6.

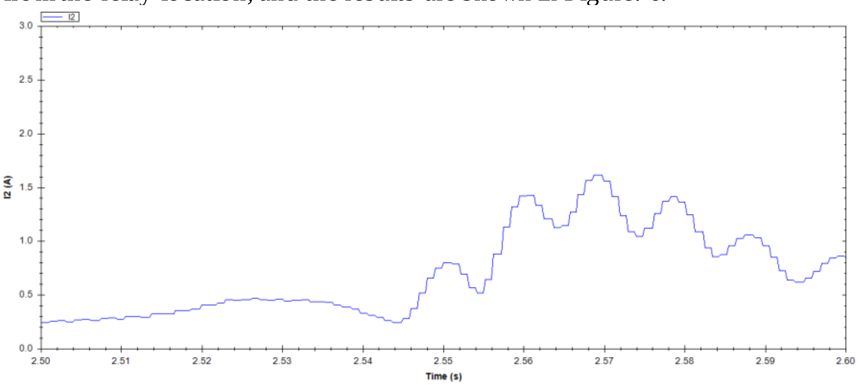

Figure 6(a). Negative-sequence current magnitude during the line-to-ground fault.

With the fault being unbalanced, the observed during the fault is significant and oscillating in nature due to signal modulation. The index g , which decides the output of the algorithm, is zero before the inception of the fault. The output "1" clearly shows that the fault is detected after 6 ms of fault initiation.

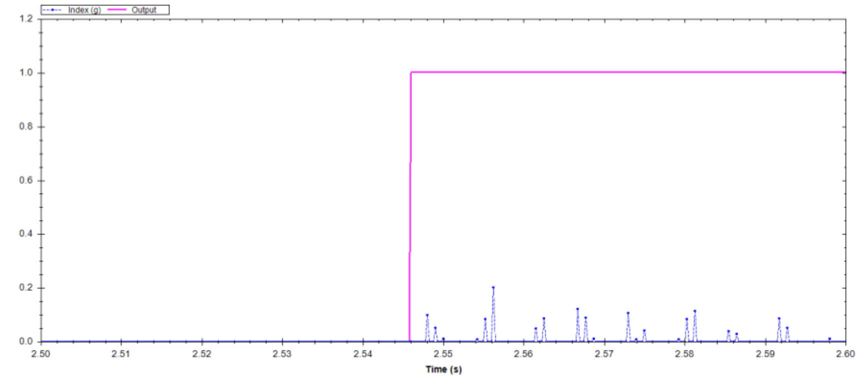

Figure 6(b). Performance during the line-to-ground fault.

B. Line-to-ground fault with high fault resistance

The detection of high-resistance ground faults during the power swing with a large value of prefault current (i.e., near δ = 180°) is a difficult issue as the change in current is not significant. To test the technique, a line-to-ground fault of an ag-type with fault resistance 100 Ω is initiated at 2.54 s during the power swing at a distance of 240 km from the relay location, and the results are shown in Figure. 7. It is clearly observed that the presence of high fault path resistance reduces $\left|\bar{I}_2\right|$ compared to case-A during the fault, but the pattern of current is unaltered. The index g grows but with a little less of a rate than case-A. Since the proposed method is a CUSUM-based approach, the output "1" shows correct fault detection after 11 ms of fault initiation.

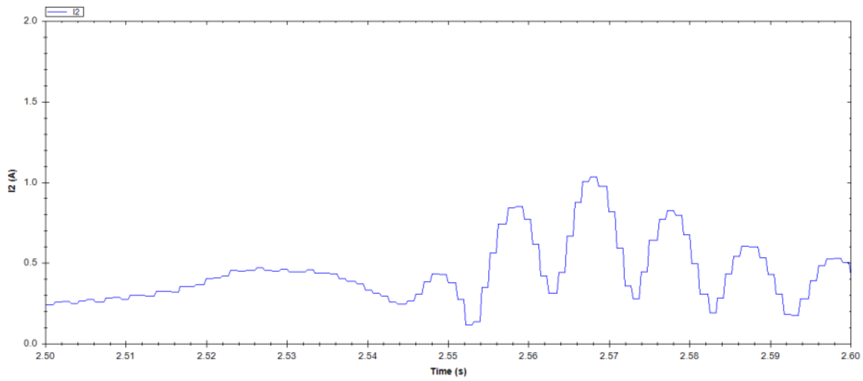

Figure 7(a). Negative-sequence current magnitude during the line-to-ground fault with fault resistance 100 Ω .

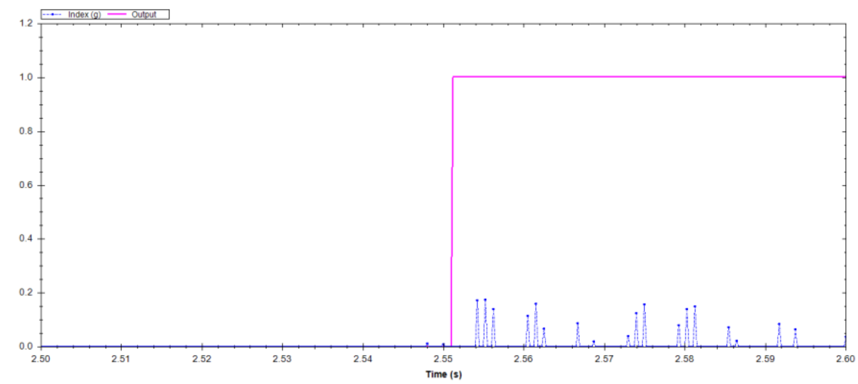

Figure 7(b). Performance during the line-to-ground fault with fault resistance 100 Ω .

C. Three-phase fault in the series-compensated line

The power swing and three-phase faults are balanced in nature. It is difficult to distinguish three-phase faults during the power swing. A three-phase fault created at 2.54 s (δ = 175^o) during the power swing at a distance of 240 km from the relay location in line-1 is used to test the algorithm. The index g and the output are shown in Figure. 8. For such fault situations, the magnitude of fault current is less than that of the swing current and it is oscillatory in nature which causes difficulty in distinguishing three-phase faults from the power swing. In the initial period of a three-phase fault due to the transient in the current signals, $\left|\bar{I}_2\right|$ computed will not be zero. The index as the cumulative sum of $\Delta\left|\bar{I}_2\right|$, remains high following the transient also. As observed from the plot, the index g computed is high after the inception of the fault and is zero before it. The output "1" in the plot clearly shows that the fault can be detected after 4 ms of fault inception.

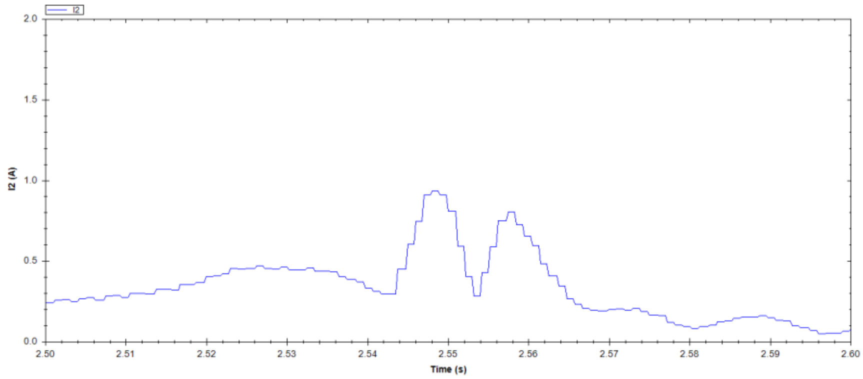

Figure 8(a). Negative-sequence current magnitude during the three-phase fault.

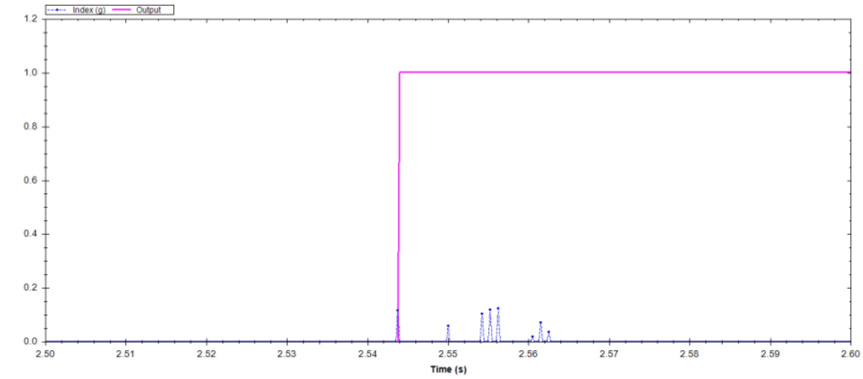

Figure 8(b). Performance during the three-phase fault.

D. Performance during the close-in fault

Three-phase close-in faults apparently bypass the capacitor due to the MOV operation. This may lead to voltage collapse at the relay bus. Due to the subsidence transients in the coupling capacitor voltage transformer (CCVT), the fault detectors based on voltage phasors, for example, the rate of change of impedance or the rate of change of swing-center voltage will be affected.

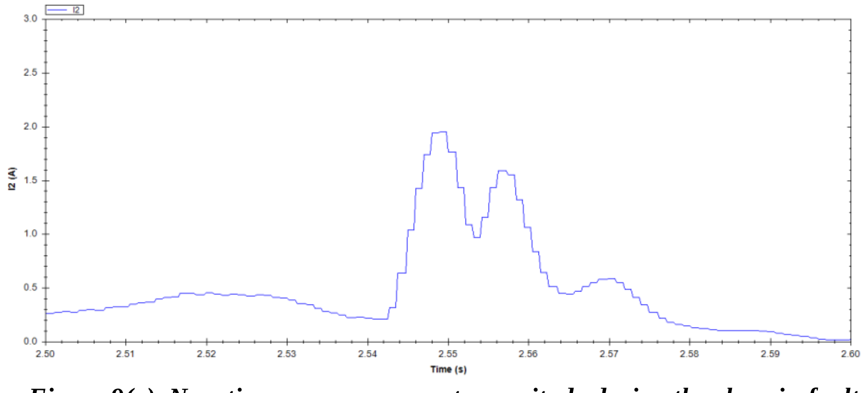

Figure 9(a). Negative-sequence current magnitude during the close-in fault.

In the proposed technique as the current signal is used to detect fault during the power swing, such a close-in fault is not an issue. To test the algorithm, a three-phase fault is created at 2.54 s (δ = 175°) at a distance of 1 km behind the series capacitor, and the results are provided in Figure. 9. The observation on $|\bar{I}_2|$ in the present fault case is similar to that of case-C. The observation on index g clearly shows that during the power swing, its value is zero and it grows quickly to a high value after the inception of the fault. The output of "1" is consistent, and fault detection is possible within 2 ms.

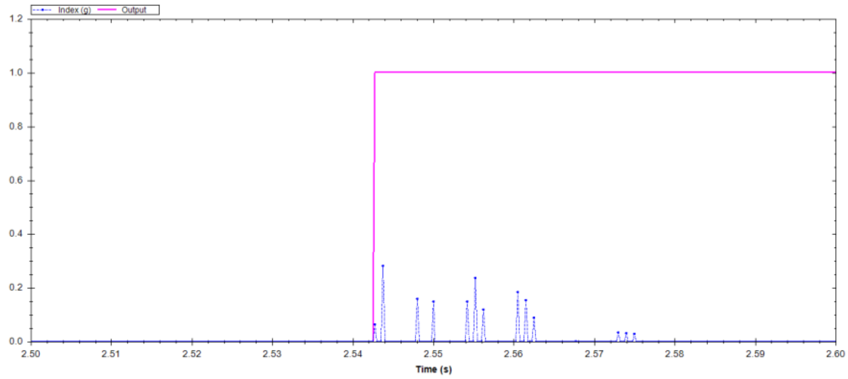

Figure 9(b). Performance during the close-in fault.

V. CONCLUSION

A novel fault detection technique for the series-compensated line during the power swing is presented in this paper. It uses a cumulative sum of change in the magnitude of negative-sequence current to detect faults. The performance of the proposed algorithm is applied for balanced and unbalanced faults for different series-compensated systems. Conditions, like high-resistance fault and close-in fault are considered to test the algorithm. The proposed method, as a current based technique, is not affected by issues like close-in fault. This method is precise and fast in detecting faults during the power swing in a series compensated line.

APPENDIX

System data for SMIB:

Generator:

600 MVA, 22 kV, 50 Hz, inertia constant = 4.4 MW/MVA, $X_d = 1.81$ p.u., $X_d^{'} = 0.3$ p.u., $X_d^{''} = 0.23$ p.u.,
$T_{do}^{'} = 8$ s, $T_{do}^{''} = 0.03$ s, $X_q = 1.76$ p.u., $X_q^{''} = 0.25$ p.u., $T_{qo}^{''} = 0.03$ s, $R_a = 0.003$ p.u., $X_p = 0.15$ p.u.

Transformer:

600 MVA, 22/400 kV, 50 Hz, Δ/Y, X = 0.163 p.u., X_{core}=0.33 p.u., R_{core}=0.0 p.u., P_{copper} = 0.00177 p.u.

Transmission lines:

Length = 320 km.
Positive - sequence impedance = 0.12 + j 0.88 Ω/km.
Zero - sequence impedance = 0.309 + j 1.297 Ω/km.
Positive - sequence capacitive reactance = 487.723×10^3 Ω.km.
Zero - sequence capacitive reactance = 419.34×10^3 Ω.km.

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