Secured Zone 3 Protection During Stressed Condition

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***Abstract*—Maloperation of the zone 3 element of distance relays during stressed system conditions, such as power swing, load encroachment, or voltage stressed condition is one of the main reasons for large disturbances in power systems. The improved protection technique for zone 3 can help to prevent such maloperation and, thus, more reliable power systems can be envisaged. This paper proposes an algorithm that utilizes two new criteria: 1) the maximum value of the transient monitoring function obtained from three-phase currents and 2) the phase angle of the positive-sequence impedance to support zone 3 of the distance relay. The technique is tested for various power system events, such as the three-phase fault during the power swing, load encroachment, voltage stressed conditions, and current-transformer saturation during the three-phase fault using data simulated through EMTDC/PSCAD in the IEEE 39-bus New England system. The simulation results show that the zone 3 protection scheme using the proposed technique can correctly discriminate the three-phase fault from stressed system conditions.**

***Index Terms*—Distance protection, load encroachment, power swing, voltage stressed condition, zone 3.**

I. Introduction

ZONE 3 of a stepped-distance relay scheme is used to provide remote backup protection to adjacent sections of transmission lines in a power system. The large reach of the zone 3 element increases the risk of maloperation under stressed system conditions. Investigations on different blackouts show that zone 3 maloperation is one of the important contributing reasons for cascade tripping in power systems worldwide [1]. The presence of negative- and/or zero-sequence current components during an unbalanced fault makes it easy to discriminate from stressed system conditions. However, since three-phase fault and stressed system conditions are balanced phenomena, the zone 3 element of a distance relay finds difficulty to distinguish them. To solve this problem, many schemes have been proposed in recent years [2]–[12].

Power swing is a phenomenon that causes variations in power flow between two areas of a power system and is observed followed by faults, line switching, generator disconnection, switching on/off large loads, or other system disturbances. During power swings, the load impedance may enter into the distance relay's operating characteristics which can cause undesired tripping of transmission lines. Several techniques are available to discriminate the three-phase fault from power swings. The rate of change of apparent impedance, the rate of change of swing center voltage, and the blinder and R-dot schemes are conventional swing detection techniques and their relative merits and demerits are well documented in [2]. The superimposed component of current is used to differentiate the three-phase fault from the power swing [3]. A symmetrical fault detector is proposed based on the relative presence of decaying dc in the current waveforms during the power swing [4]. Using fundamental frequency components of instantaneous three-phase active power, a symmetrical fault detection technique during the power swing is proposed in [5]. Performances of the aforementioned techniques are not tested during other stressed system conditions, such as load encroachment and voltage-stressed conditions.

The encroachment of load impedance into the zone 3 element is another reason for distance relay maloperation [6]. The careful setting of the zone 3 element can help avoid load encroachment under normal operating conditions. However, it is difficult to prevent load encroachment under extreme conditions since it is not included in the regular setting process, and it is very difficult to decide the setting of a distance relay under contingency conditions if normal apparent load impedance is very close to the protective zone. In [7], an adaptive load encroachment prevention scheme based on steady-state security analysis and an adaptive anti-encroachment zone is proposed. A technique based on the value of fault resistance, calculated from synchrophasor data, is proposed to distinguish the three-phase fault from load encroachment [8]. The reliability of both proposed techniques mainly depends on the communication channel.

During the voltage-stressed condition, with reduced voltage magnitude, the positive-sequence impedance seen by the distance relay becomes small and the trajectory may enter into zone 3 characteristic. This situation can cause the relay to trip the line unnecessarily. In [9], an adaptive algorithm based on the rate of change of voltage is used as a criterion to prevent zone 3 maloperation due to voltage instability. In addition, an additional feature, called the voltage stability index, is used in [10] to distinguish the three-phase fault from voltage instability. However, the threshold settings of both features for a system are still a challenge. In [11], to distinguish the three-phase fault from load encroachment and voltage instability for the zone 3 protection scheme, a combination of steady-state and transient components of current using a state diagram is proposed. The real-time power-flow estimation approach is proposed in [12] to distinguish the three-phase fault from load encroachment. However, the estimation of the value of power flow of the line is not always guaranteed to be correct due to the loop flow. In [13], apparent impedance computed from the synchronized voltage and current phasors is used to assist zone 3 protection for discriminating a fault from stressed system conditions. Performance of

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the method depends mainly on the strategic location of phasor measurement units and on the communication medium.

In this paper, enhanced zone 3 protection for the distance relay is proposed where the three-phase fault is distinguished from the stressed condition by utilizing only the local information, that is, the voltage and current signal. There is no need for synchrophasor data and the communication medium, such as [13]. The method uses two new criteria, namely, the maximum value of the transient monitoring function obtained from three-phase currents and the phase angle of the positive-sequence impedance to accomplish the task. The technique using the two criteria is tested for various cases for the IEEE 39-bus New-England system simulated with EMTDC/PSCAD. The results show that zone 3 of a distance relay using the proposed method is more secure during stressed system conditions, and the method detects the three-phase fault correctly.

II. Proposed Scheme

The three-phase fault and stressed condition are balanced phenomena, and zone 3 protection finds it difficult to distinguish them. Negative- and zero-sequence components present in the signals during the unbalanced fault are good indicators of this purpose. To support the zone 3 decision process by differentiating the three-phase fault from other conditions, the proposed method employs two new criteria: 1) the maximum value of the transient monitoring function obtained from three-phase currents and 2) the phase angle of positive-sequence impedance. The first criterion filters transient events, and the second one identifies the three-phase fault from there.

A. Criterion-1 Using the Transient Monitoring Function

The least square method is one of the important techniques to estimate the fundamental component in a digital relaying scheme. A reconstructed signal from the estimated fundamental component matches the actual signal during normal conditions. In case of a three-phase fault, a significant difference exists between the actual and the reconstructed samples of current. The presence of decaying dc component in the fault current is the main reason for this difference [4], [14]. Signal modulation during the power swing also contributes to some nonfundamental component, but the difference will not be significant.

For discrimination of the three-phase fault from other conditions, the absolute sum of the differences between the actual and the reconstructed samples of the current signal over a cycle is computed, which is defined as the transient monitoring function. This function is used in [14] to validate the correctness of a phasor estimation process whereas, in this paper, the function is applied to support zone 3 protection directly. The detail computation steps for the function using the least-square approach are provided as follows.

The fault current signal is modeled including the decaying dc component where the sample value at an instant can be expressed as

$$i_k = \mathrm{I_m}\sin(k\omega_0 T_s + \varphi) + \mathrm{k_0} e^{\frac{-kT_s}{\tau}} \tag{1}$$

where "l_m" is the peak of the fundamental component, "ω_0" is the fundamental frequency, "T_s" is the sampling interval, "φ" is the phase angle of the fundamental frequency component, "k_0" is the magnitude of the dc component at $t = 0$, and "τ" is the time constant of the decaying dc component.

To estimate the fundamental component, (1) can be formulated as below by varying k from 1 to N. N is the number of samples per cycle

$$[\mathrm{A}][x] = [\mathrm{B}] \tag{2}$$

where

$$[A] = \begin{bmatrix} \sin(\omega_0 T_s) & \cos(\omega_0 T_s) & 1 & -T_s & T_s^2 \\ \sin(\omega_0 2T_s) & \cos(\omega_0 2T_s) & 1 & -2T_s & (2T_s)^2 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \sin(\omega_0 \mathrm{N}T_s) & \cos(\omega_0 \mathrm{N}T_s) & 1 & -\mathrm{N}T_s & (\mathrm{N}T_s)^2 \end{bmatrix}.$$

The state vector

$$[X] = \left[I_m\cos\varphi \quad I_m\sin\varphi \quad k_0 \ \frac{k_0}{\tau} \quad \frac{k_0}{2\tau^2} \right]^{\mathrm{T}}$$

and the measurement vector

$$[B] = [i(t_0 + T_s)\ i(t_0 + 2T_s) \cdot \cdot\ i(t_0 + NT_s)]^T.$$

With the least square approach, the unknown vector can be estimated by using

$$[X] = \left([\mathrm{A^T A}]^{-1}\mathrm{A^T}\right)[B]. \tag{3}$$

The current signal can be reconstructed using the least square estimates for the fundamental components [15]. Let the vector $[\hat{B}]$ represent the reconstructed samples from the estimate $[X]$ and can be expressed as

$$[\hat{B}] = [\mathrm{A}][X] = [\mathrm{A}]\left\{\left([\mathrm{A^T A}]^{-1}\mathrm{A^T}\right)[B]\right\}. \tag{4}$$

The difference between the reconstructed sample from the estimate $([\hat{B}])$ and the actual sample of the current signal $([B])$ can be computed as

$$[D] = [\hat{B}] - [B] = \left[[\mathrm{A}]\left([\mathrm{A^T A}]^{-1}\mathrm{A^T}\right) - I\right][B] \tag{5}$$

where $[D] = [d_1, d_2, d_3 \ldots d_k]$. Defining the transient monitoring function as a sum of the absolute values of d_k over one cycle, that is

$$\mathrm{TMF} = \sum_{k=1}^{N} |d_k|. \tag{6}$$

At the inception of a three-phase fault, a significant decaying dc component is observed at least in one of the three phases of current signals [4]. To have a purposeful index, the largest value of TMF is obtained out of the three phases as

$$g = \max(\mathrm{TMF}_a,\ \mathrm{TMF}_b,\ \mathrm{TMF}_c) \tag{7}$$

where a, b, and c refer to different phases. The proposed method ensures a three-phase fault if

$$g > \mathrm{gth} \tag{8}$$

where gth in criterion-1 is the threshold selected for a system, and its selection is detailed in Section V. The index g provides information on maximum nonfundamental components present in the current signals at the inception of a three-phase fault which helps in the identification. However, the value of g may be higher for nonfault transients, such as the sudden increase of large load or line outage. To distinguish such events from the three-phase fault, an angle-based criterion is added to the proposed scheme.

B. Criterion-2 Using the Phase Angle of the Positive-Sequence Impedance

In a transmission system, during steady state, the line current lags voltage by 45° for the theoretical maximum loading condition (power angle = 90° across the line) and this corresponds to the positive-sequence impedance angle ϕ_z to be within 45° [16] at the relay. Note that in case of load change or parallel line outage, it is also limited to 45°. This is because both events result in change from one loading pattern to another as observed by the relay. For a three-phase fault in a line, ϕ_z lies between 65° and 85° [16]. Thus, ϕ_z can be suitably used to discriminate the three-phase fault from load change or a similar event. Thus, for conformity of a three-phase fault, ϕ_z should satisfy

$$\phi_z > \Phi\text{th} \tag{9}$$

where Φth in criterion-2 is the threshold, and its selection is provided in Section V.

C. Flow Diagram for the Method

The flow diagram for the proposed method is shown in Fig. 1. First, the positive-sequence impedance at the relay location is computed using three-phase voltages and currents. If the calculated impedance falls within zone 3 of the relay under study, then additional criteria are applied to verify whether a three-phase fault is the reason for it or it is due to stressed system conditions. Criterion-1 is checked by using (8), which identifies the transient event. In such a case, criterion-2 in (9) is applied which confirms a three-phase fault.

III. Simulation Results

The proposed enhanced zone 3 protection is tested in the IEEE 39-bus New England system as shown in Fig. 2. Using EMTDC/PSCAD, simulations are carried out for various power system events, such as the three-phase fault during power swing, load encroachment, and voltage-stressed conditions to test the performance of the proposed scheme. The performance of the proposed scheme is also tested for a three-phase fault producing CT saturation. The nonlinear model of the CT is considered for performance evaluation. The least-square technique is applied to estimate the fundamental component of current. The data sampling rate is maintained at 1 kHz. The MATLAB R2008a software tool has been used for computation purposes. The reach of zone 3 (phase-to-phase) is set such that it is able to protect full length of an adjacent line. In this paper, the thresholds gth and Φth are set at 8.0 p.u. and 50°, respectively, for correctly discriminating the three-phase fault from other stressed power system operating conditions (refer to Section V).

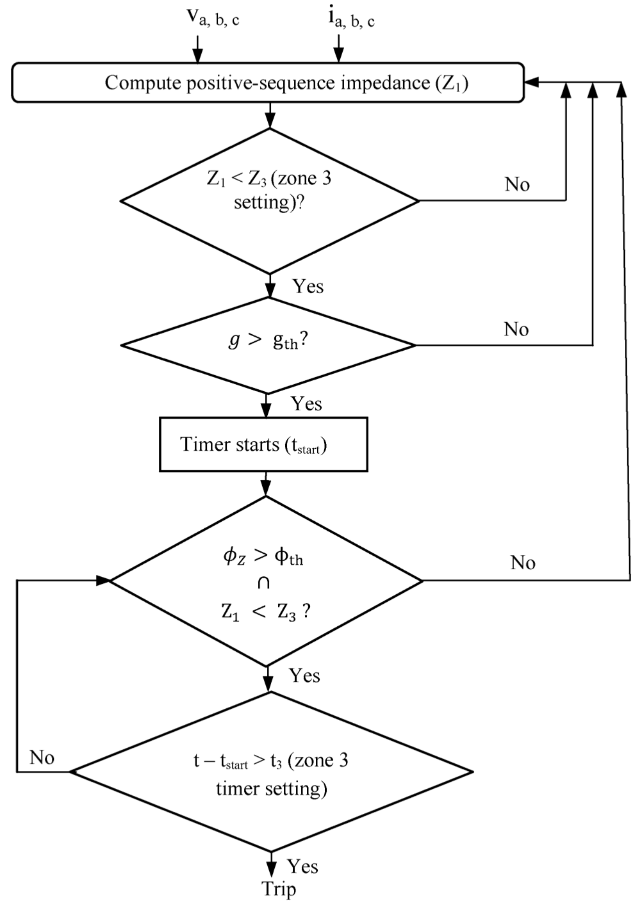

Fig. 1. Flow diagram for discriminating the three-phase fault from the stressed condition.

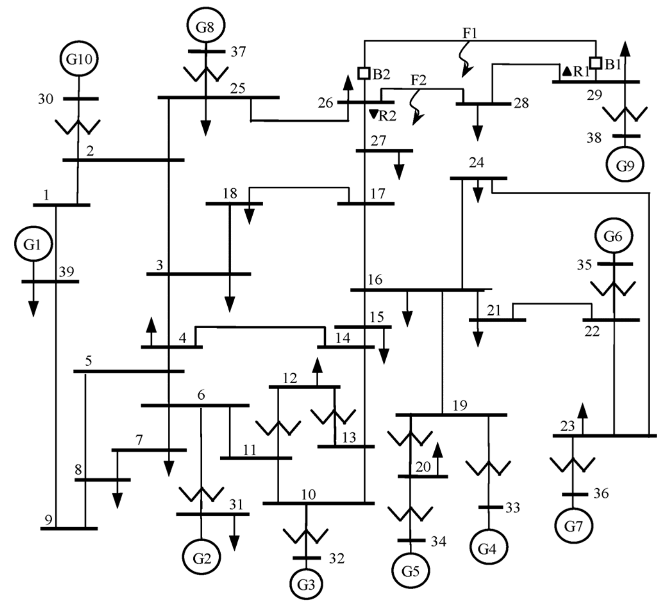

Fig. 2. Single-line diagram of the IEEE 39-bus New England system.

A. Performance for the Three-Phase Fault During the Stable Power Swing

Operation of transmission-line protection systems during the stable power swing may not be directly responsible for system

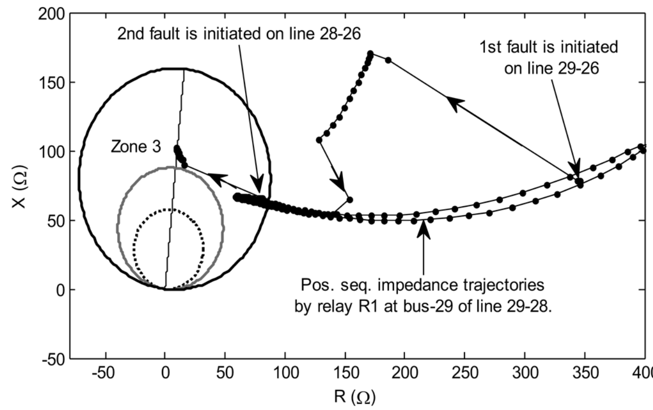

Fig. 3. Trajectory of the positive-sequence impedance seen at relay R1 for the three-phase fault during the power swing (time interval between adjacent points is 0.02 s).

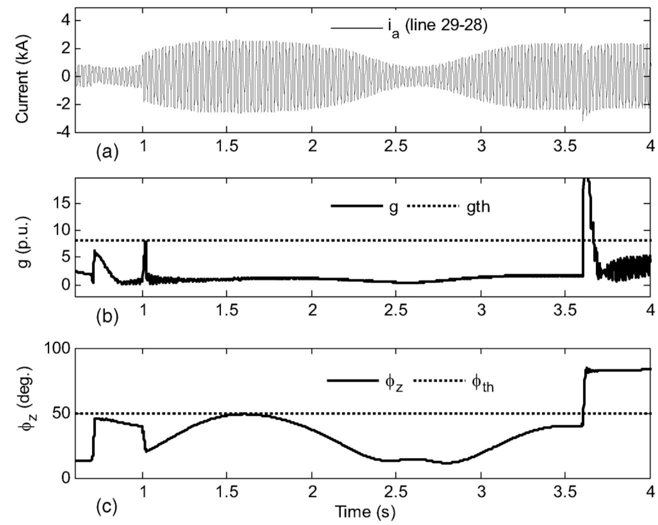

Fig. 4. Different quantities at relay R1 for the three-phase fault during the power swing: (a) phase-a current, (b) magnitude of g, and (c) the value of ϕ_z.

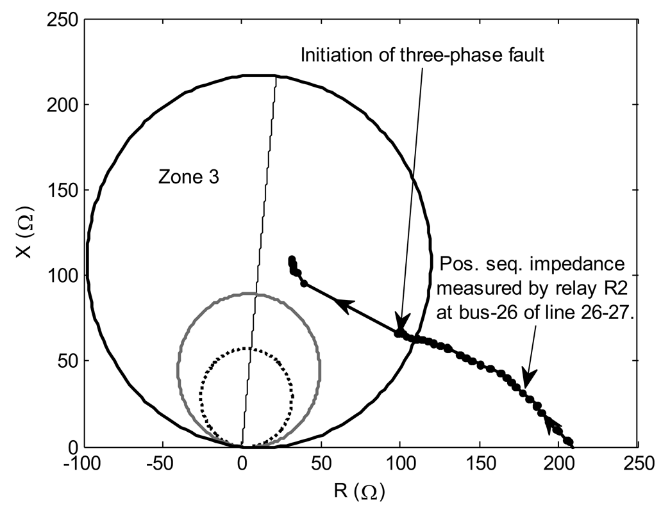

Fig. 5. Positive-sequence impedance trajectory at relay R1 for the three-phase fault during load encroachment (the time interval between adjacent points is 0.02 s).

blackouts. However, unintended line tripping during the stable power swing may exacerbate the power swing to the extent that a stable swing becomes unstable. An unstable swing can cause loss of synchronism between groups of generators or between neighboring utility systems. To avoid maloperation during stable power swings, the power-swing blocking (PSB) function is integrated with a distance relay. However, if a fault occurs during the swing, the relay must detect the fault and operate quickly. Power swing and the three-phase fault are balanced phenomena. Conventional PSB schemes, such as dZ/dt and blinder methods, find difficulty in distinguishing them [2]. Therefore, the correct discrimination of the three-phase fault from the power swing is an important issue. With this paper focusing on secured zone 3 protection, three-phase faults are simulated within zone 3 reaching the relay during the power swing. The result for a test case is provided as follows.

A three-phase fault is created at the middle of line 29-26 (point F1 of Fig. 2) at 0.7 s, and the fault is cleared at 1.0 s by opening breaker B1 and B2. The intentional delay in fault clearance time introduces the power-swing condition for relay R1 at bus-29 protecting lines 29-28. The positive-sequence impedance seen at relay R1 is plotted in an R-X plane during the power swing and is shown in Fig. 3. From the figure, it is observed that the positive-sequence impedance enters the zone 3 characteristic of relay R1 during the swing and lies more than the operating time of zone 3 protection. This may lead relay maloperation.

To test the performance of the proposed scheme for faults during the power swing, a three-phase fault (with a fault resistance of 1 Ω) is created at 3.6 s in the zone 3 region of relay R1 (at the middle of line 28-26) during the swing. Corresponding results are provided in Fig. 4. From the figure, it is observed that during the power swing, the index [Fig. 4(b)] remains well below confirming the situation as a nonfault event. However, g and ϕ_z surpass their respective threshold values within 10 ms after the initiation of a three-phase fault which confirms the occurrence of a fault. From the results, it can be concluded that the proposed scheme is immune to the power swing and it has the capability to correctly discriminate a three-phase fault from the power swing.

B. Performance During Load Encroachment

The change in transmission network structure or shifting the power flow from one line to another under steady-state operating conditions may cause the positive-sequence impedance to enter the zone 3 characteristic of a distance relay. This phenomenon is referred to as load encroachment [7]. The undesired line trip may occur in such a situation. Load encroachment and three-phase fault both are balanced phenomena. Zone 3 of the conventional distance relay finds difficulty in distinguishing them. Thus, correct discrimination of the three-phase fault from load encroachment is important.

To create the load encroachment condition for zone 3 of relay R2 at bus-26, the load at bus-27 is increased gradually to twice its steady-state value in 30 steps during 2 to 4.6 s such that the NERC "extreme" emergency loading condition is maintained. This event causes a positive-sequence impedance trajectory entering the zone 3 characteristic of relay R2 and

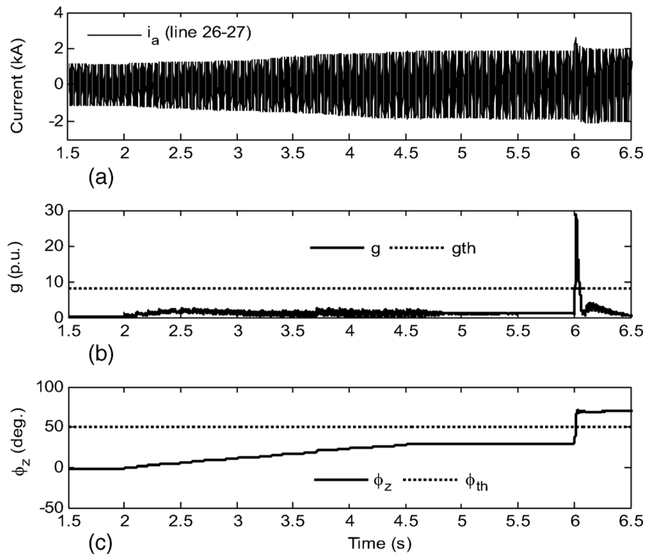

Fig. 6. Different quantities at relay R2 for a three-phase fault during load encroachment: (a) phase-a current, (b) magnitude of g, and (c) the value of ϕ_z.

stays beyond its operating time as is evident from Fig. 5. This situation could be misinterpreted as three-phase fault by zone 3 of the conventional distance relay. However, the proposed technique determines this event as a no-fault situation as g and ϕ_z are below their respective threshold values as evident from Fig. 6(b) and (c).

To test the performance of the proposed algorithm for discriminating the three-phase fault from load encroachment, a three-phase fault is created at 6.0 s in the zone 3 region of relay R2, that is, on line 27-17. Observations of Fig. 6(b) and (c) show that g and ϕ_z, calculated at relay R2, cross their respective threshold in 10 ms after the initiation of the fault even if the change in current magnitude [Fig. 6(a)] is not significant. This confirms that the proposed method has the capacity to discriminate the three-phase fault from load encroachment.

C. Performance During the Voltage-Stressed Condition

During the voltage-stressed condition, the voltage at various buses in the system reduces rapidly [13]. Due to the reduction of voltage levels at different buses, the load impedances at different buses may enter the zone 3 characteristic of some relays, causing them to maloperate. To test the performance of the proposed scheme during the voltage-stressed condition, reactive loads at buses 27, 18, and 16 (Fig. 2) increase from time 2.0 to 4.0 s at the 1.0-s interval, respectively. During this situation, positive-sequence voltage and current magnitudes adjacent to the load buses are plotted in Fig. 7. From the figure [Fig. 7(a)], it is observed that the reactive load increase at buses 27, 18, and 16 causes a significant reduction in bus voltage magnitudes. From Fig. 7(b) it is seen that there is a significant increase in load current on line 267–27. Positive-sequence impedances are computed at buses 26, 27, and 29, and it is found that the impedance locus at bus-26 of relay R2 of line 26–27 enters its zone 3 characteristics and stays permanently inside it (Fig. 8). In this situation, the relay may maloperate. The performance of

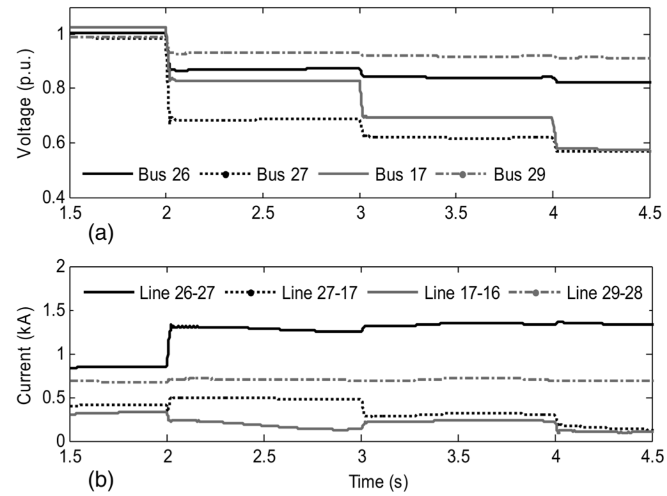

Fig. 7. Voltage and current magnitudes during the voltage-stressed condition: (a) positive-sequence bus voltage magnitudes and (b) positive-sequence line current magnitudes.

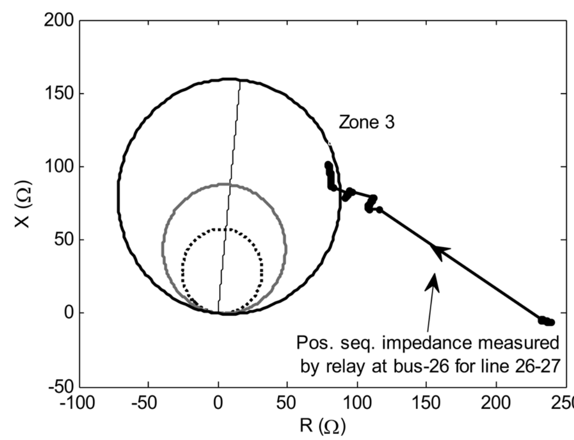

Fig. 8. Positive-sequence impedance trajectory at relay R2 (bus-26) during the voltage-stressed condition. (The time interval between adjacent points is 0.02 s.)

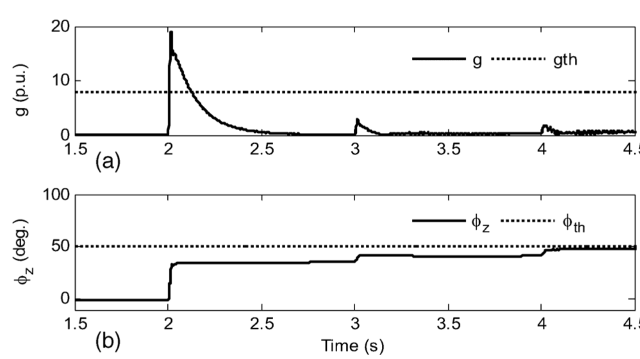

Fig. 9. Different quantities at relay R2 (bus-26) during the voltage-stressed condition. (a) Magnitude of g and (b) the value of ϕ_z.

the proposed scheme is shown in Fig. 9. From the figure, it is observed that at the instant of increasing the first load, the apparent impedance locus lies beyond the zone 3 characteristic. In this situation, the proposed scheme will not activate. A further increase of reactive loads in subsequent buses causes the apparent impedance to enter the zone 3 characteristic. However, in this such situation with the proposed scheme, both indices g and ϕ_z

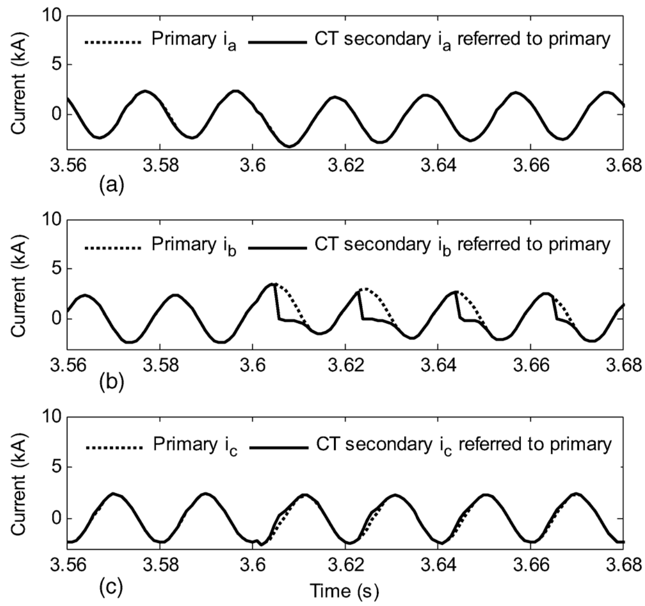

Fig. 10. Comparison of the primary phase currents with the CT secondary phase currents referred to the primary side for a three-phase fault during the power swing.

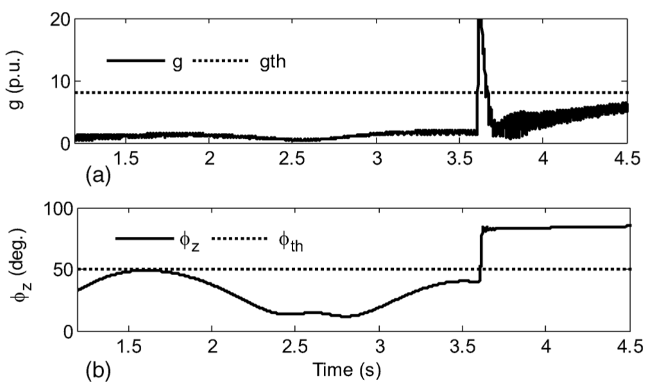

Fig. 11. Performance of a three-phase fault during the power swing with CT saturation.

lie below their respective threshold, indicating such a situation to be a nonfault event. Thus, during the voltage-stressed condition, if the apparent impedance enters the zone 3 characteristic of any relay, the proposed scheme will treat such situation as a nonfault event.

D. Performance of the Three-Phase Fault with CT Saturation

Depending on the severity of the fault and burden setting of the CT, CT saturation may occur at the inception of a three-phase fault. To test the performance of proposed scheme during CT saturation, a three-phase fault is created in the zone 3 region of relay R1 at bus-29 of line 29-28 (Fig. 2) at 3.6 s during the power swing. The burden of phase-b CT at bus-29 is set such that its secondary current is referred to the primary-side mismatches with the actual primary current, which is observed in Fig. 10(b). This shows that the phase-b CT gets saturated. The performance of the proposed scheme for CT saturation for a three-phase fault during the power swing is shown in Fig. 11.

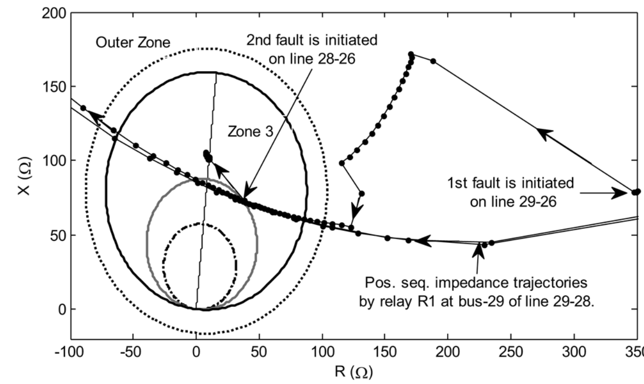

Fig. 12. Positive-sequence impedance trajectory during the out-of-step condition. (The time interval between adjacent dots in the trajectory is 0.02 s.)

From the figure, it is observed that despite CT saturation, the proposed scheme is able to distinguish the three-phase fault from the power swing as the indices g and ϕ_z exceed their respective thresholds. Thus, CT saturation does not affect the performance of the proposed scheme.

IV. Comparative Assessment

Among the conventional methods, the rate of change of apparent impedance (dZ/dt) is widely used to distinguish the fault from the power swing. Such a scheme blocks the relay elements prone to operate during the stable and unstable swing. To block during the stable power swing is called PSB and to block during the unstable power swing is called out-of-step blocking (OSB). Out-of-step tripping (OST) functions are available with modern distance relays at preselected network locations for discriminating stable swings from unstable swings. In the case of an unstable swing, the OST trips the relay. During an unstable power swing, as the impedance locus enters the distance relay characteristics, the very fast method based on dZ/dt has limitations during OSB.

For comparative assessment of the proposed scheme with the dZ/dt method, a three-phase fault is created at 2.0 s at the middle of line 29-26 (Fig. 2), and the fault is cleared at 2.35 s by opening breakers B1 and B2. The removal of line 29–26 leads to an unstable power swing condition for relay R1 of line 29–28. The impedance trajectory during the swing is plotted in the R-X plane and is shown in Fig. 12. From the figure, it is observed that in the second swing cycle, the trajectory of apparent impedance takes around 80 ms to cross the path between the outer zone and zone 3 characteristic which is slow, and the PSB scheme based on dZ/dt will block the relay from operation. However, in the subsequent swing cycle, the trajectories of the positive-sequence impedance move faster and take less time for crossing the path between the outer zone and zone 3 characteristic. The OSB scheme based on dZ/dt may treat such a fast swing as a three-phase fault and can trip lines unnecessarily.

To test the performance of the proposed scheme for a three-phase fault during an unstable power swing, a three-phase fault is created at the middle of line 28-26 (falls under zone 3 region of relay R1 at bus-29) at 3.75 s. The result for the fault case

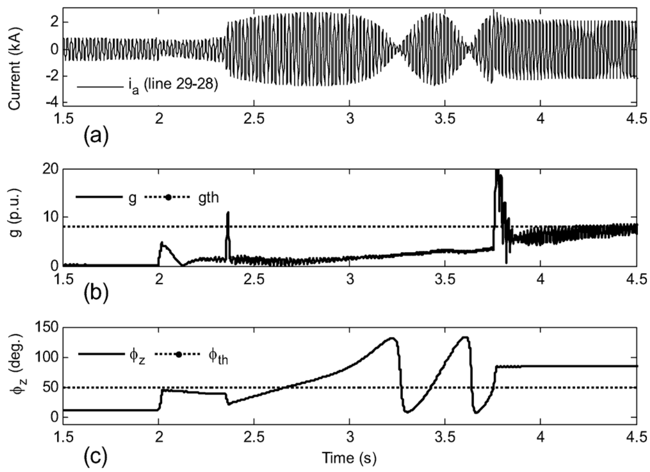

Fig. 13. Different quantities at relay R1 during the out-of-step condition: (a) phase-a current, (b) magnitude of g, and (c) the value of ϕ_z.

is provided in Fig. 13. From Fig. 13(a), it is clear that slip frequency increases in subsequent swing cycles. From Fig. 13(b), it is observed that even during an unstable swing, g remains well below its threshold, confirming the situation as a nonfault event. Though the value of ϕ_z [Fig. 13(c)] exceeds its threshold for a few swing cycles, the g criterion ensures stable and unstable power swing conditions as a nonfault event. As soon as the three-phase fault is initiated, the indices g and ϕ_z exceed their respective threshold within 10 ms. Thus, the proposed scheme can distinguish the three-phase fault even from an unstable power swing.

V. Threshold Selection

In this paper, the magnitude of the transient monitoring function (g) and the phase angle of the positive-sequence impedance (ϕ_z) are utilized along with zone 3 of the distance relay to achieve enhanced performance during the stressed power system condition. To maintain a balance between the security and dependability of the relay decision during the stressed system condition, the selection of thresholds for the indices are important.

The index g is observed only during the transient period of an event, for example, at the inception of a three-phase fault, and its magnitude mainly depends on the severity of the event and switching instant. However, during the power swing, a small value of g is observed due to signal modulation which depends on the swing cycle frequency. The value of g increases with swing frequency. In this paper, it is set at 8.0 p.u., considering a maximum swing frequency of 5 Hz for the system [2], [20]. This setting helps the algorithm to correctly distinguish the three-phase fault from both stable and unstable power swings.

For most transmission systems, typically ranging from $-40°$ to $+40°$ during normal conditions and, in the case of a three-phase fault, it lies within 65° to 85° [16]. However, ϕ_z may be affected for the three-phase fault occurring at the remote end of the adjacent line with significant infeed from the other lines or a heavy load present on an adjacent bus. Considering all of the issues and simulation results for the three-phase faults with significant fault resistance [21], ϕth is set as 50°.

VI. Conclusion

Zone 3 of a distance relay has limitations to distinguish a three-phase fault from a stressed power system condition. Zone 3 maloperation during such situations is the main reason for many cascade trippings worldwide. This paper has proposed a technique which uses the transient function derived from three-phase currents and the positive-sequence impedance phase angle to enhance zone 3 protection during the stressed condition. The technique using the combined criteria is tested for various power system events, and the results clearly show that a distance relay, supported by such a technique, can correctly discriminate the three-phase fault from other stressed conditions. A comparative assessment of the proposed scheme with a conventional method also demonstrates its strength.

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