Performance of power swing blocking methods in UPFC-compensated line

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Power Swing Detection in UPFC-Compensated Line by Phase Angle of Current

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***Abstract*—Power Swing Blocker (PSB) is a complementary part of distance relay protection that detects power swing, in order to prevent unintended operation of a distance relay. Unified Power Flow Controller (UPFC) is used in power system to control both active and reactive powers and its operation during power swing influences the performance of PSB. In this paper, two traditional methods for detecting power swing are analyzed in UPFC-compensated condition to show how UPFC influences the performance of these methods. The indices proposed for the above methods are examined in compensated condition. The results show that these indices may no longer work in systems with UPFC. Additionally, this paper proposes a new method for detecting power swing based on the phase angle of current at relay point and compares it with two other methods. The new method distinguishes power swing from a fault through the trend of the phase angle of current. Finally, intensive studies are performed and simulations demonstrate the merits of the proposed method.**

***Index Terms*—Distance relay, Power Swing, PSB, UPFC.**

I. INTRODUCTION

GENERALLY it is necessary to test the impact of Flexible AC Transmission Systems (FACTS) on distance relays in different conditions (steady state, fault, transient and power swing). Since FACTS devices lead to variations of line current and bus voltage, they influence the performance of relays under different conditions [1-3].

Unified Power Flow Controller (UPFC) is a FACTS device used to control the power flow of a transmission line and to improve system stability [4]. However, the use of FACTS devices may lead to distance relays being over-reaching or under-reaching during a fault [5]. Many publications are devoted to evaluate the performance of distance relays in lines compensated by FACTS. In [6], the impact of UPFC on distance relay is discussed, and an adaptive scheme using the neural network is proposed. Reference [7] presents a study of the performance of distance relay when Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) are used and it is shown that these compensation devices cause mal-operation of the distance relay by influencing the estimation of impedance. In [8], the impacts of different modes of Thyristor Controlled Series Compensation (TCSC) on distance relay are analyzed, whereas the effect of Static Synchronous Series Compensator (SSSC) on the tripping characteristics of distance relays is examined in [9]. Despite extensive research on the impact of FACTS devices on the performance of distance relays during a fault, limited work exist on their impact during a power swing. For example, three methods for power swing detection, impedance decrease, swing center voltage (SCV) and power derivative are studied in [10] for fixed capacitor compensated lines. However, this reference does not analyze the impact of fixed capacitor mathematically; it only gets results by simulation. Moreover, fixed capacitor is a simple compensator device and it is necessary to analyze the above methods for more sophisticated FACTS devices. A method based on negative sequence component is proposed in [11] to discriminate the power swing from a fault in a fixed capacitor compensated line. However, this method is only applicable in compensated lines, with the index value in uncompensated lines being negligible; therefore, the reliability of this method in uncompensated condition is low. In [12], impact of UPFC on swing characteristics (variations of radius and center point) is studied, and it is shown that parameters of transmission line (ABCD) would change in the presence of UPFC. Based on the definitions of these parameters and the steady-state model of UPFC, new parameters (A'B'C'D') are extracted. The reference also examines the impact of UPFC on the rate of change of impedance by simulating a compensated power system during unstable power swing. The results showed that the time recorded by CPSB is reduced significantly because of the UPFC. These results motivated the authors to research how UPFC affect different PSB methods. The aim of this paper is to analyze the impact of UPFC on different power swing blocking methods using both analytical and simulation methodologies. The main contributions of this paper are as follows:

- Comprehensive investigation of two common PSB methods (Method 1, Method 2) in UPFC-compensated line. Each method is mathematically analyzed in UPFC-compensated condition and it is demonstrated that how each perform in this condition.
- A new index is proposed (Proposed method) based on the phase angle of current for discriminating power swing from fault. It is shown that this proposed method is valid in both uncompensated and UPFC-compensated lines.

The paper is organized as follows: Section II examines the performance of two PSB methods in UPFC-compensated lines, and analytically shows UPFC interferences in the formulation of these methods. A novel index based on the use of the

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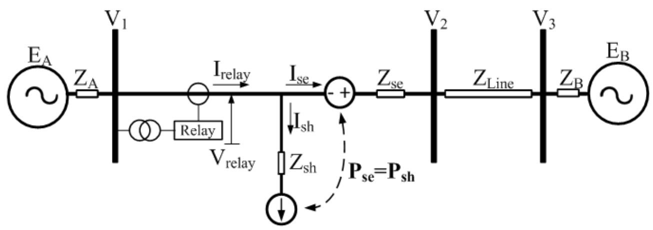


Fig. 1. Two-machine equivalent system with UPFC-compensated line.

phase angle of current for discriminating fault from power swing is presented in Section III. Finally, Section IV presents simulation results to verify the analytical achievements.

II. Impact of UPFC on two different power swing blocking methods

This section performs mathematical analysis of different methods for PSB and their index is reformulated in UPFC-compensated condition. In order to examine the UPFC operation in a wide range of variations, it is assumed that UPFC compensates all changes during power swing.

A. Method based on center of impedance trajectory (Method 1)

The main idea of this method is presented in [13] and it consists in using circular locus of impedance trajectory together with its center position to detect power swing. It is shown in [13] that the center of impedance trajectory seen by a distance relay will never come to Zone 1 (first zone of distance relay) during power swing, but it will come to that zone during a fault.

1) Performance of Method 1 in compensated line: The index presented in [13] was not considered for UPFC-compensated lines, but as a result of UPFC operation, the impedance trajectory in a compensated line is different from an uncompensated one. According to the topology of the compensated line (shown in Fig.1), the active power at Bus 1 associated with compensated condition can be written as:

$$P_1^{COM} = P_2^{COM} + P_{se} + P_{Loss} - P_{sh} \tag{1}$$

where, P_2^{COM} is the active power at Bus 2 in compensated condition, P_{se} is the injected series active power by the series branch of UPFC, P_{sh} is the drawn shunt active power by the shunt branch of UPFC, P_{loss} is active power loss in the converters. Moreover, the reactive power at Bus 1 associated with compensated condition can be written as:

$$Q_1^{COM} = Q_2^{COM} + Q_{se} + Q_{Loss} \tag{2}$$

where, Q_2^{COM} is the reactive power at Bus 2 in compensated condition, Q_{se} is the injected series reactive power by series branch and Q_{sh} is the produced shunt reactive power by shunt branch to maintain amplitude of V_1 at its reference value (this parameter is considered zero ($Q_{sh} = 0$), because this paper focuses on the power control property of UPFC). Based on (1) and (2), the active and reactive powers at Bus 1 are:

$$P_1^{COM} = P_2^{ref} \quad , \quad Q_1^{COM} = Q_2^{ref} + Q_{se} \tag{3}$$

where, P_2^{ref} and Q_2^{ref} are the reference values of active and reactive powers for UPFC, respectively, and $P_{sh} = P_{se}+P_{loss}$. As the energy storing capacity of DC capacitor is small, the active power drawn by the shunt converter should be equal to the active power generated by the series converter. Furthermore, the shunt converter should support active power loss in converters. Hence, according to Fig. 1 and (3), the impedance seen during power swing is:

$$Z_{relay}^{COM} = \frac{|V_1|^2}{P_1^{COM} - jQ_1^{COM}} = \frac{|V_1|^2}{P_2^{ref} - j(Q_2^{ref} + Q_{se})} \tag{4}$$

where, $V_1 = |V_1|\angle\delta_1$ is voltage at Bus1. In order to understand the center of impedance trajectory in this condition, the denominator of (4) is analysed first. Since P_2^{ref} and Q_2^{ref} are constant values and Q_{se} is a time-varying quantity during power swing, the denominator is a vertical line in the complex plane R,X that crosses the horizontal axis at $R = P_2^{ref}$. As this vertical line is in the denominator of (4), its reciprocal should be examined.

The reciprocal of any complex point $(R+jX)$ on vertical line is considered new complex point $(RR + jXX)$ given by the following relation:

$$RR = \frac{R}{R^2+X^2} \quad , \quad XX = \frac{-X}{R^2+X^2} \tag{5}$$

Therefore, based on (5), the reciprocal of every point in denominator (4) is:

$$RR = \frac{P_2^{ref}}{\left(P_2^{ref}\right)^2 + \left(Q_1^{ref} + Q_{se}\right)^2} \tag{6}$$
$$XX = \frac{-(Q_1^{ref} + Q_{se})}{\left(P_2^{ref}\right)^2 + \left(Q_1^{ref} + Q_{se}\right)^2}$$

By summing the square of XX and RR, (7) is obtained:

$$RR^2 + XX^2 = \frac{1}{\left(p_2^{ref}\right)^2 + X^2} \tag{7}$$

By adding $\frac{1}{4(p_2^{ref})^2}$ to both sides of (7) and after some simplification procedures, the connection between RR and XX can be formulated as:

$$\left(RR - \frac{1}{2.P_2^{ref}}\right)^2 + (XX-0)^2 = \left(\frac{1}{2.P_2^{ref}}\right)^2 \tag{8}$$

Equation (8) represents a circle with center $C_1 = (\frac{1}{2.P_2^{ref}}, 0)$ and radius $r_1 = \frac{1}{2.P_2^{ref}}$. Based on (4) and (8), the impedance trajectory during power swing in a compensated line is a circle with the center (C^{COM}) and radius (r^{COM}) as:

$$C^{COM} = \frac{k_1^2}{2.P_2^{ref}} + j0 \quad , \quad r^{COM} = \frac{k_1^2}{2.P_2^{ref}} \tag{9}$$

where, $k_1 = |V_1|/|V_3|$ and $V_3 = |V_3|\angle 0$ is voltage at Bus3. From (9), it can be concluded that UPFC changes the center of impedance trajectory during the power swing. Although the center of impedance trajectory during power swing in uncompensated condition has to be in limited region (out of Zone 1), there is no limitation for the center position in compensated condition and so the center can be anywhere in the complex plain based on the power system (associated with k_1) and UPFC states (associated with P_2^{ref}). Accordingly, the presented method in [13] for detecting power swing is not applicable in the UPFC-compensated transmission lines.

B. Method based on the maximum rate of change of active and reactive powers (Method 2)

The main idea of this method is presented in [14]. In this method, the rate of change of power is utilized to detect power swing. During power swing, the maximum value between the rate of change of both active and reactive powers is higher than a threshold value, decreasing to a value lower than the threshold value during a fault.

1) Performance of Method 2 in compensated line: The index presented in [14] was not considered for UPFC-compensated lines. According to Fig.1, apparent power at distance relay point is:

$$S_1^{COM} = P_1^{COM} + jQ_1^{COM} = V_1\ (I_{se} + I_{sh})^* \qquad (10)$$

where, I_{sh} is the shunt current drawn by shunt branch of UPFC and I_{se} is the series current in series branch of UPFC, which can be formulated as:

$$I_{se} = \frac{V_2 - V_3}{jX_{Line}} = \frac{V_2 + V_{se} - V_3}{jX_{Line}} \qquad (11)$$

where, X_{line} is the reactance of transmission line. By separating active and reactive powers of (11), the active and reactive powers at the relay point in compensated condition are (12) and (13) respectively.

$$P_1^{UN} = \frac{|V_1|.|V_3|}{X_{Line}} sin\delta_1 - \frac{|V_1|.|V_{se}|}{X_{Line}} sin(\delta_1 - \rho') + |V_1|.|I_{sh}|cos(\delta_1 - \theta_{sh}) \qquad (12)$$

$$Q_1^{UN} = \frac{|V_1|}{X_{Line}}(|V_1| - |V_3|cos\delta_1) + \frac{|V_1|.|V_{se}|}{X_{Line}} cos(\delta_1 - \rho') + |V_1|.|I_{sh}|sin(\delta_1 - \theta_{sh}) \qquad (13)$$

where, ρ' is the phase angle of series voltage and θ_{sh} is the phase angle of shunt current. According to (12) and (13), active and reactive powers in compensated condition include three parts: the first parts for both the active and reactive powers) are similar to those in the uncompensated condition, but the second and third parts result from the operations of series and shunt branches of UPFC. Although it is possible to conclude that this index value during power swing in uncompensated condition is inside a limited range $(0.7 - 1)$; this conclusion cannot be drawn in compensated condition because of the second and third items in (12) and (13). Therefore, the method presented in [14] for detecting power swing is not applicable in UPFC-compensated transmission lines.

C. Proposed PSB based on phase angle of current

A new method for PSB is proposed in this paper, which is based on the phase angle of current and can be used in both uncompensated and compensated conditions. In order to present the proposed method, it is necessary to understand the variation of the currents angle.

1) Angle of current at relay point: The proposed method considers the trend of the angle of current at the relay as an event detection index. Therefore, in this section, the behavior of this parameter is examined for power swing and fault conditions in uncompensated lines.

$Power\ swing:$
PSB should detect power swing condition and send blocking command (BLOCK=1) for distance relay to prevent unintended operation. Suppose that the uncompensated system is in power swing condition, and the current at relay point is given by (14).

$$I_1 = \frac{|V_1|\angle\delta_1(t) - |V_3|\angle 0}{Z_{Line}} = \frac{|V|}{Z_{Line}}(1\angle\delta_1(t) - 1) = \frac{|V|}{Z_{Line}}(cos\delta_1(t) - 1 + jsin\delta_1(t)) \qquad (14)$$

where, $|V_1| = |V_3| = |V|$. Based on (14), the angle of current during power swing is:

$$\angle I_1 = Arctan(\frac{sin\delta_1(t)}{cos\delta_1(t) - 1}) - \angle Z_{line} = \frac{\pi}{2} + \frac{\delta_1(t)}{2} - \angle Z_{line} \qquad (15)$$

where, $\angle Z_{line} = Arctan(X_{line}/R_{line})$, which is constant during the power swing. Equation (15) is obtained based on $sinx/(1 - cosx) = cot(x/2)$ and $Arctancotx = (\pi/2) - Arccotcotx = (\pi/2) - x$. It is worthy to note that power swing is actually the modulation of both amplitude and phase of the signal, so considering variable parameter for $k_1 = |V_1|/|V_3|$ is more reasonable hypothesis. However, according to the proposed method, k_1 being constant or variable does not affect on variation of phase angle of current. Hence, in order to provide straightforward formulation for phase angle of current during power swing (equation (14) and (15)), k_1 is considered constant value. In addition, this hypothesis is examined in simulation result section where the performance of proposed method is investigated in real power system (IEEE 39-Bus power system) which k_1 is not constant. The simulation results shows that the proposed method operates accurately even in varying k_1 condition.

According to (15), variation of the angle of the current ($\angle I_1$) during power swing is as (16), which shows that it relates directly to the variation of δ_1. If $\Delta\delta_1$ is positive, $\Delta(\angle I_1)$ would be positive and vice versa.

$$\Delta(\angle I_1) \propto \Delta\delta_1 \tag{16}$$

When a power swing occurs in a transmission line, the impedance trajectory moves towards the relay zones due to the positive trend of phase angle of current ($\Delta\delta_1 > 0$). Therefore, we can conclude that the variation of the angle of current is positive during power swing when the impedance trajectory goes towards the relay zones; the trend of currents angle is negative ($\Delta\delta_1 < 0$) during the time interval the impedance trajectory goes backward, but this time interval is not considered by the proposed detection process.

$Fault\ Condition$:
PSB should detect fault and provide unblocking command ($BLOCK = 0$). Assuming that the power system is in steady state condition and a fault happens at $t = t_f$, the currents at the relay before (I_1^S) and after (I_1^F) fault are:

$$I_1^S = \frac{|V_1|\angle\delta_1(t) - V_3}{Z_{line}} \tag{17}$$
$$I_1^F = \frac{|V_1|\angle\delta_1(t) - V_F}{m\ Z_{line}}$$

where, V_F is the voltage of fault point, and $mZLine$ is impedance from the relay point to fault point ($0 < m < 1$). According to (17), the angles of current before and after fault are (18) and (19) respectively.

$$\angle I_1^S = Arctan(\frac{|V_1|sin\delta_1(t)}{|V_1|cos\delta_1(t) - |V_3|}) - \angle Z_{line} \tag{18}$$

$$\angle I_1^F = Arctan(\frac{|V_1|sin\delta_1(t)}{|V_1|cos\delta_1(t) - |V_F|}) - \angle(mZ_{line}) \tag{19}$$

where, $\angle Z_{line} = \angle(mZ_{line})$ because the transmission line is considered homogeneous. In order to analyze the trend of angle of current at fault initiation, it is necessary to analyze (18) and (19) separately. In (18), $|V_1|cos\delta_1 < |V_3|$, and the argument of $Arctan$ is a negative value and so, its $Arctan$ is an angle bigger than 90^0. However, in (19), $|V_1|cos\delta_1 > |V_F|$, and the argument of $Arctan$ is a positive value and so, its $Arctan$ is an angle inferior to 90^0. Therefore, $\angle I_1^F - \angle I_1^S$ is negative and (20) is valid:

$$\Delta(\angle I_1) = \Delta(\angle I_1^F - \angle I_1^S) \tag{20}$$

According to (20), it can be concluded that when a fault occurs, there is a downfall in the angle of current, which demonstrates the negative trend. In order to make the analysis easier, it is assumed that the angle of V_1 is not affected by the fault significantly. Moreover, in a real power system, there is transient period, which is solved by cumulative summation operator.

2) Proposed algorithm for detecting power swing and fault: When a power swing occurs on a power system, the impedance trajectory moves toward the distance protection zones. Based on this, it is necessary to program a detector ($Flag_1$) able to detect the presence of impedance trajectory inside the farthest protection zone (for example Zone 3; third zone of distance relay). This detector helps to prevent false operation caused by other transients (e.g. load changing) far from the distance relay zones. This detector can be programmed as:

$$D(n\Delta t) = |Z_{relay}(n\Delta t) - Z_{center}| \tag{21}$$
$$if \quad D(n\Delta t) < r_3 \rightarrow Flag_1(n\Delta t) = 1$$

where, Z_{relay} is the impedance seen by the distance relay, $n\Delta t$ is the current sample time, Z_{center} is the center of Zone 3, D is the difference between the impedance and the center of Zone 3, r_3 is radius of zone3 and $Flag_1$ is the output of the first detector, which is 1 when the impedance measured by the distance relay is inside Zone 3. Moreover, another detector ($Flag_2$) is necessary to detect that the impedance trajectory is entering to Zone 3 or leaving it. This detection can be obtained by comparing two consecutive samples of D. It is worthy to mention that $Flag_2$ is activated when $Flag_1$ is up. This detector can be programmed (22).

$$if \quad (Flag_1(n\Delta) = 1\ \&\ D(n\Delta t) < D((n-1)\Delta t)) \tag{22}$$
$$\rightarrow \ Flag_2(n\Delta t) = 1$$

$Flag_2$ is the output of second detector, which is 1 when the direction of impedance trajectory is toward the inside of Zone 3. These two detectors are used for power swing detection.
Based on the index proposed in this paper, power swing and fault can be detected by monitoring the variation of the phase angle of the relay current. This parameter is obtained by subtracting the angles of current (θ_1) for the current sample time ($n\Delta t$) and the previous sample time ($(n-1)\Delta t$), and use of cumulative summation (CS) over one fundamental cycle. Cumulative summation is used to increase the method's reliability by removing instantaneous changes.

$$S(n\Delta t) = \theta_1(n\Delta t) - \theta_1((n-1)\Delta t) \tag{23}$$
$$CS(n\Delta t) = \sum_{n=r-N}^{n=r} S(n\Delta t)$$

where, N is sample number in one cycle and r is the last sample inserted in the data window. Therefore, if $CS > h_p$, it means that the variation trend of the phase angle of the current is positive, and it is negative if $CS < h_p$ (h_p is the threshold value, which is ideally zero; however, it is considered a small positive value to improve the reliability of the proposed method. The exact value of this parameter is mentioned in the Simulation Results section and it is defined based on different simulation cases during power swing). Therefore, power swing is detected according to (24).

$$Flag_1 = 1\ \&\ Flag_2 = 1\ \&\ CS > h_p \tag{24}$$

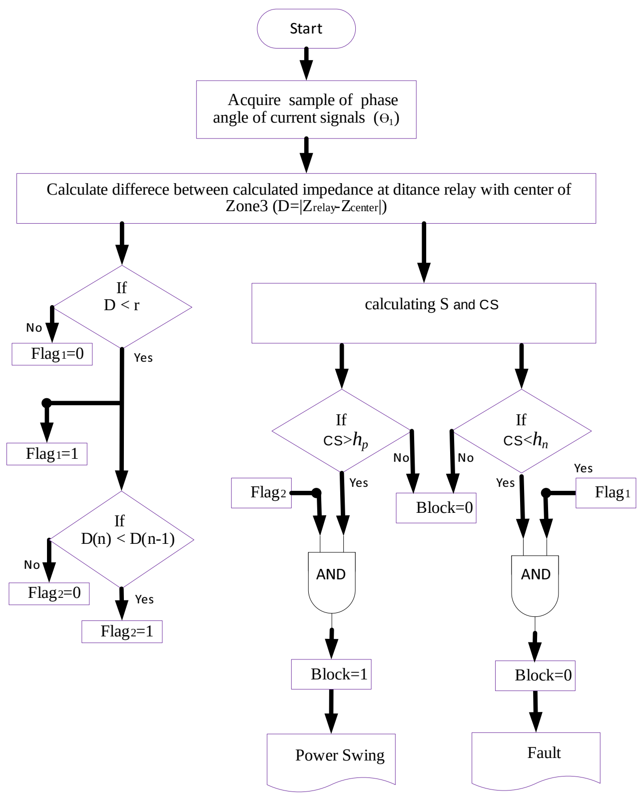


Fig. 2. Flowchart of the proposed method.

If the impedance trajectory is inside Zone 3 ($Flag_1 = 1$), the direction of the impedance movement is towards the inside Zone 3 ($Flag_2 = 1$), and if the trend of the phase angle of current is positive ($CS > h_p$), then a power swing is present and the proposed method issues blocking command ($Block = 1$). Moreover, the blocking command is kept at 1 until the impedance trajectory is inside Zone 3 ($Flag_1 = 1$). The proposed method should also detect fault and unblock distance relay. Based on the explanation given in the previous section, when a fault happens the phase angle of current decreases. This decrease causes a negative trend of the phase angle of the current at the fault inception. Therefore, any fault can be detected when:

$$Flag_1 = 1 \ \& \ CS > h_n \tag{25}$$

It means than if the impedance trajectory is inside Zone 3 ($Flag_1 = 1$) and the trend of the phase angle of the current is negative ($CS < h_n$), a fault has occurred and the proposed method removes the blocking command of the distance relay. h_n is the threshold value, which is ideally zero , but a small negative value is considered, in order to improve the reliability of the proposed method. The flowchart of this method is shown in Fig. 2.

III. Simulation Results

Two simulations test scenarios are prepared: the first uses a single machine to infinite bus (SMIB), whereas the second is based on the IEEE 39-Bus power system. Both detailed time model and simple phasor model of UPFC are used, with the latter being used to illustrate the theoretical concept more clearly and the former in the validation of the results. Generally, six different modes of UPFC-compensated system are considered in the simulation sections:

- Uncom: UPFC is out of service.
- Mode 1: UPFC is in service, and its reference values (active and reactive powers) are equal to the uncompensated case.
- Mode 2: Reference active power is increased, but not the reactive one.
- Mode 3: Reference active power is decreased, but not the reactive one.
- Mode 4: Reference reactive power is increased, but not the active one.
- Mode 5: Reference reactive power is decreased, but not the active one.

A. Simulation results in SMIB (phasor model of UPFC)

The compensated two-machine equivalent system (Fig. 1) is considered in this section. The phasor models of the power system and UPFC (programmed sing MFILE-MATLAB) are used, in order to reduce the time required for simulation. The phasor model of UPFC is programmed by a time-varying controlled series voltage source, which provides desired active and reactive powers at Bus 2. Therefore, the amplitude and the phase of series voltage are (26) and (27), respectively.

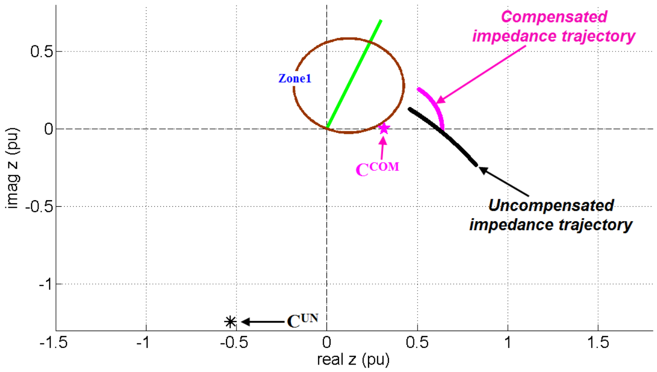
$$|V_{se}(t)| = [(|V_2|cos\delta_2 - |V_1(t)|cos\delta_1(t))^2 + (|V_2|sin\delta_2 - |V_1(t)|sin\delta_1(t))^2]^{(1/2)} \tag{26}$$

$$\rho'(t) = tan^{-1}(\frac{|V_2|sin\delta_2 - |V_1(t)|sin\delta_1(t)}{|V_2|cos\delta_2 - |V_1(t)|cos\delta_1(t)}) \tag{27}$$

The shunt branch of UPFC is programmed by time-varying controlled current source. Shunt current consists of two parts: reactive power compensation part (I^2_{sh}) to keep the amplitude of bus voltage ($|V_1|$) at its reference and series active power compensation part (I^1_{sh}), which provides the active power demanded by series branch. The phasor data of the power system are $V_3 = 1\angle 0$, $V_1 = 1\angle\delta_1$, $Z_A = 0.1\angle 90^0$, $Z_B = 0.1\angle 90^0$, and $Z_{Line} = 0.1 + j0.9$. Amplitude values are in per unit, with $V_{base} = 500kV$ and $S_{base} = 100MVA$. The fundamental frequency is $60Hz$ and UPFC is located at the left end of the transmission line. In order to produce the power swing, the displacement angle of V_1 is considered as:

$$\delta_1(t) = \delta_1^0 + k \ sin(2 \ \pi \ f_{slip} \ t) \tag{28}$$

where, k is the scaling factor, δ_1^0 is the initial value of δ_1, and f_{slip} is swing frequency. Performances of three mentioned methods are analyzed next.



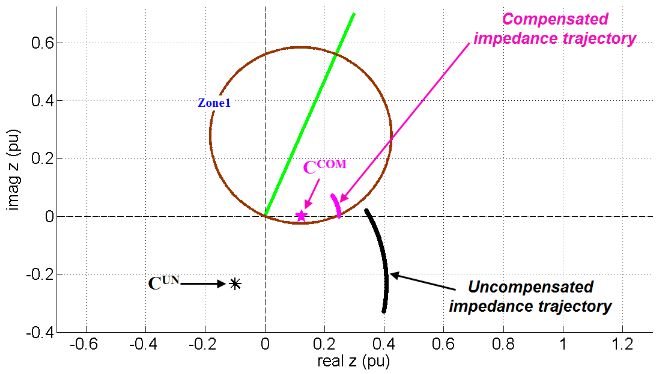


Fig. 3. Impedance trajectory and its center during power swing for uncompensated and compensated conditions; (a) the conditions in which the index is not contradicted, (b) the conditions in which the index is contradicted.

TABLE I
SIMULATION RESULT OF METHOD 1

Cases	Uncompensated		Compensated	
$K_1 = 0.95$, $P_{ref} = 1.00$	-2.780-j6.460	×	0.449+j0	×
$K_1 = 0.80$, $P_{ref} = 1.00$	-0.533-j1.244	×	0.318+j0	×
$K_1 = 0.50$, $P_{ref} = 1.00$	-0.100-j0.240	×	0.07+j0	$\surd$
$K_1 = 0.40$, $P_{ref} = 1.00$	-0.057-j0.133	×	0.06+j0	$\surd$
$K_1 = 0.70$, $P_{ref} = 0.98$	-0.288-j0.673	×	0.250+j0	×
$K_1 = 0.70$, $P_{ref} = 1.00$	-0.288-j0.673	×	0.244+j0	×
$K_1 = 0.70$, $P_{ref} = 1.03$	-0.288-j0.673	×	0.06+j0	$\surd$
$K_1 = 0.70$, $P_{ref} = 1.06$	-0.288-j0.673	×	0.05+j0	$\surd$

1) Performance of Method 1: This section analyzes the impact of UPFC on the performance of Method 1, which is based on monitoring the center of circular impedance trajectory. Here, the center of impedance trajectory during the power swing is always outside Zone 1. In order to examine this index, a compensated two-machine equivalent system (Fig. 1) is simulated. The UPFC is set to maintain active and reactive powers at Bus2 equal to their reference values ($P_{ref} = 0.8118p.u$ and $Q_{ref} = 0.2352p.u$, respectively). Power swing occurs on the power system at $t = 1s$, which is simulated based on (28) where $k = 1$, $f_{slip} = 0.5Hz$ and $\delta_1^0 = 45^0$. First, two cases are simulated to show that the proposed index in [13] is not always true if an UPFC is installed in the transmission line. The first case simulates the power system with $k_1 = |V_1|/|V_3| = 0.8$, and the second case simulates the power system with $k_1 = 0.5$. The simulation results of these cases are shown in Fig. 3.

Fig. 3(a) shows the impedance trajectories of the first case ($k_1 = 0.8$) for both the uncompensated and compensated conditions and the respective centers. According to this figure, the centers of both compensated and uncompensated conditions are outside Zone 1. Therefore, the proposed index operates properly in this case. However, the second case ($k_1 = 0.5$) indicates that the proposed index is not valid for UPFC-compensated lines (Fig. 3(b)). Although the center of impedance trajectory in uncompensated condition is outside Zone 1, the center of compensated trajectory enters Zone 1. Eight others cases (different K_1 and P_{ref}) are also examined and their results are tabulated in Table I. The center of each case is tabulated, and $\surd$ means that the center is inside Zone 1, whereas × means that the center is outside Zone 1 (radius of Zone 1 is $0.8 \times |Z_{Line}|$). According to this table, the centers of impedance trajectories for all 8 cases in uncompensated condition are outsides Zone 1. However, in compensated condition, the centers of trajectories come to Zone 1 in 4 of the 8 cases. Therefore, it can be concluded that presence of an UPFC invalidates the use of this method for detecting power swing.

2) Performance of Method 2: This section, analyzes the impact of UPFC on the performance of Method 2, which is based on the maximum rate of change of active and reactive powers. In uncompensated condition, the index value during power swing is larger than 0.7, but it decreases to zero during a fault. Therefore, by considering a threshold value between 0.7 and zero, power swing is discriminated from fault. However, based on the explanations previously presented, UPFC operation decreases the value of the proposed index to lower than 0.7 making this index impracticable for UPFC-compensated lines. The compensated two-machine equivalent system (Fig. 1) is simulated in different conditions to examine the index values in different conditions (the resistance part of line impedance is ignored to make the analysis easier).
The analyses is divided into two cases that consist in having the UPFC out of service, uncompensated, (Case1) and in service (Case2). Power swing occurs on the power system at $t = 1s$. The simulations is based on (28) where $k = 1$, $f_{slip} = 0.5Hz$ and $\delta_1^0 = 45^0$. The index values obtained in these cases are shown in Fig. 4. The figure shows that the index value during the steady state ($0 < t < 1s$) is zero for both uncompensated and compensated conditions. However, when the power swing starts at $t = 1s$, the index value increases and oscillates ($1 < t < 2s$). According to Fig. 4, the lowest value of the index in the uncompensated case is $0.7p.u$; however, it decreases to $0.27p.u$ in compensated condition. This decrease is a result of compensating the variations of active power by UPFC. Moreover, in order to widen the simulation cases, different swing frequencies, scale factors and initial values of δ_1 in (28) are investigated. Minimum values of the index in different cases during power swing are tabulated in Table II. As shown, the minimum value in uncompensated condition is always equal to $0.7p.u$. However, the UPFC reduces this minimum value to lower than 0.7. Since the threshold value of this method should be considered lower than the minimum index during power swing, it can be concluded that the presence of UPFC invalidates this method

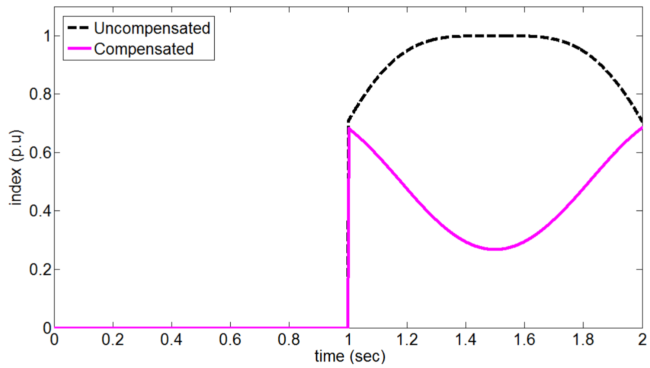


Fig. 4. Index of Method 2 for uncompensated and compensated conditions.

TABLE II
SIMULATION RESULT OF METHOD 2

UPFC	k=0.77 f=0.5 $\delta = 45$	k=1 f=0.5 $\delta = 45$	k=1 f=0.5 $\delta = 50$	k=1 f=0.5 $\delta = 40$	k=1 f=1 $\delta = 45$	k=1 f=2 $\delta = 45$
Uncom	0.7	0.7	0.7	0.7	0.7	0.7
Mode1	0.41	0.27	0.22	0.34	0.41	0.41
Mode2	0.46	0.34	0.36	0.39	0.46	0.46
Mode3	0.33	0.22	0.15	0.31	0.33	0.33
Mode4	0.35	0.24	0.18	0.31	0.35	0.35
Mode5	0.44	0.32	0.32	0.37	0.44	0.44

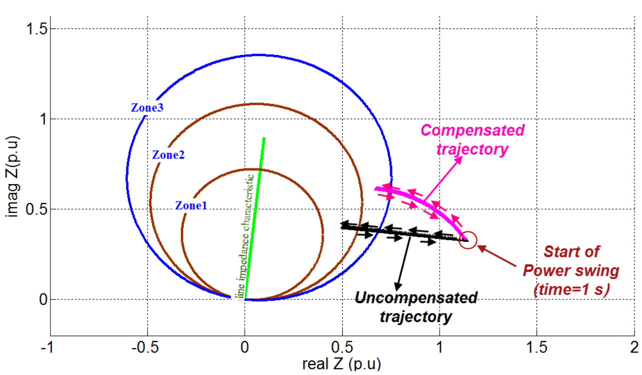


Fig. 5. Impedance trajectories during power swing.

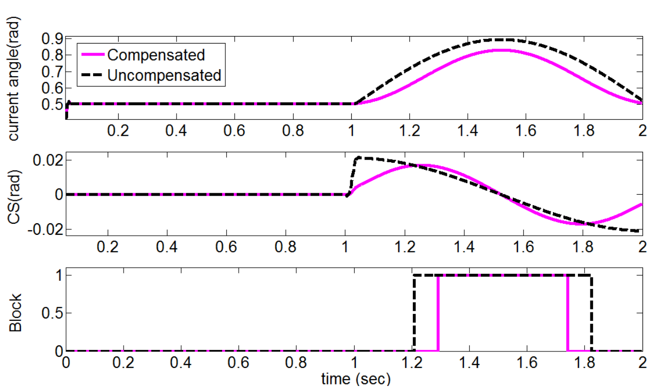


Fig. 6. Performance of the proposed PSB during power swing.

in compensated line.

3) Performance of the proposed method: To investigate the merit of the proposed algorithm the compensated power system shown in Fig. 1 is used.

TABLE III
CS(P.U) VALUES DURING POWER SWING IN DIFFERENT CASES

UPFC	k=1.2	k=1	$f_{slip} = 3Hz$	$f_{slip} = 7Hz$
Uncom	+0.0230	+0.0180	+0.0361	+0.0744
Mode 1	+0.0239	+0.0165	+0.0335	+0.0674
Mode 2	+0.0218	+0.0152	+0.0304	+0.0605
Mode 3	+0.0251	+0.0172	+0.0349	+0.0706
Mode 4	+0.0252	+0.0178	+0.0359	+0.0720
Mode 5	+0.0223	+0.0152	+0.0306	+0.0615

$Power\ swing\ condition$: A power swing occurs in the two-machine equivalent system (Fig. 1) at $t = 1s$ based on (28); where, $k = 1$, $f_{slip} = 0.5Hz$ and $\delta_1^0 = 45^0$. UPFC is set to keep active and reactive powers at Bus2 equal to their reference values. Fig. 5 shows the impedance trajectories for compensated and uncompensated conditions during power swing, whereas Fig. 6 shows the performance of the proposed method.

According to Fig. 5, the impedance movements of both conditions start at the same complex value $Z_{relay} = 1.14 + j0.33p.u.$ in plane R,X at $t = 1s$. The reason behind this is that the reference values of active and reactive powers of UPFC are set initially equal to uncompensated condition. As a result of the UPFC operation, the impedance trajectory in compensated conditions is different from uncompensated conditions. This leads to different entrance times of the impedance trajectories into Zone 3 for uncompensated and compensated conditions. Uncompensated trajectory enters Zone 3 at $t = 1.21s$ and compensated trajectory enters Zone 3 at $t = 1.29s$. When the impedance trajectories come inside Zone 3, the first detector sets $Flag_1$ to 1 and triggers the second detector to detect if the impedance trajectory is entering or leaving Zone 3. The output of the second detector is set to 1 ($Flag_2 = 1$) if the impedance trajectory is entering Zone 3. According to Fig. 6, $CS = +0.018$ at $t = 1.21s$ for uncompensated condition and $CS = +0.0165$ at $t = 1.29s$ for compensated condition. It is worthy to note that, according to Fig. 6, CS becomes negative at some points; however, the negative part does not correspond to the impedance trajectory entering Zone 3, so these points are not considered in the detection process. Therefore, since both values of CS for compensated and uncompensated conditions are positive (bigger than $h_p = 0.005$) when the impedance trajectories enter Zone 3, the proposed method detects this event as power swing and sets $Block = 1$. Moreover, it keeps $Block = 1$ until the impedance trajectories are inside Zone 3.

Additionally, in order to widen the simulation, power swings with different swing frequencies and scale factors in (28) are examined. CS values of all the examined cases are tabulated in Table III. According to this table, in all conditions, the CS values are positive at the point where the impedance trajectory enters Zone 3, showing that the proposed method can detect power swing in all conditions accurately. Additionally, this table shows that the proposed method does not lose efficiency in compensated condition.

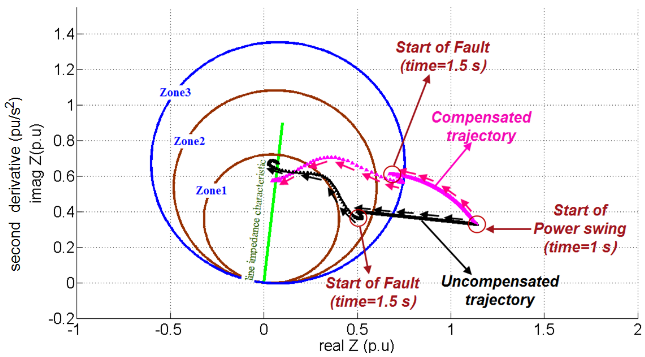


Fig. 7. Impedance trajectories for fault during power swing.

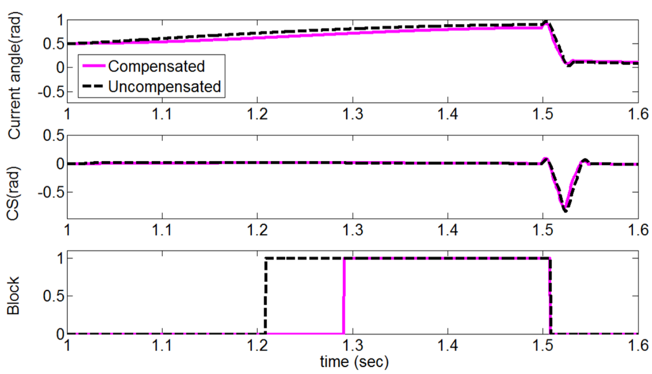


Fig. 8. Performance of the proposed PSB for fault during power swing.

Fault during power swing condition :
PSB should detect every fault and unblock distance relay ($Block = 0$) during power swing. This condition is examined in this section. Power swing condition and UPFC setting are the same as the previous case, but with a symmetrical fault occurring during power swing. A power swing occurs on the power system (Fig. 1) at $t = 1s$, which forces the impedance trajectories to move slowly toward the distance relay zones (Fig. 7). As explained earlier, power swing is detected by the proposed method based on the positive trend of currents angle when the impedance trajectory's movement during power swing is toward Zone 3.

The block command is set to 1 at $t = 1.21s$ for uncompensated and $t = 1.29s$ for compensated condition during power swing. However, a fault is initiated at $t = 1.5s$ at 75% of transmission line forcing the impedance trajectories to move rapidly toward the line impedance characteristic (Fig. 7). It is worthy to mention that, as a result of UPFC operation during a fault, distance relay experiences over-reaching (Fig. 7), so that the fault, which is at 75% of transmission line, is seen closer by the distance relay. Fig. 8 shows the performance of the proposed method: the fault causes a severe drop of the angle of current for both uncompensated and compensated conditions ($CS = -0.83$ for uncompensated and $CS = -0.77$ for compensated). Since the values of CS for compensated and uncompensated conditions become negative, the proposed method detects this event as fault and removes block command ($Block = 0$) at $t = 1.53s$ for both conditions. Moreover, 36 different cases (different modes of UPFC, different fault

TABLE IV
CS(P.U) VALUES AT FAULT INITIATION DURING POWER SWING IN DIFFERENT CASES

UPFC	R=0 m=100 $\delta = 90$	R=0 m=50 $\delta = 90$	R=0 m=100 $\delta = 130$	R=0 m=100 $\delta = 170$	R=6 m=75 $\delta = 90$	R=12 m=75 $\delta = 90$
Uncom	-0.840	-0.855	-0.501	-0.181	-0.80	-0.760
Mode1	-0.740	-0.765	-0.484	-0.170	-0.720	-0.696
Mode2	-0.754	-0.779	-0.541	-0.195	-0.735	-0.699
Mode3	-0.732	-0.758	-0.444	-0.163	-0.732	-0.695
Mode4	-0.732	-0.757	-0.450	-0.164	-0.731	-0.694
Uncom	-0.750	-0.775	-0.520	-0.175	-0.735	-0.698

distances ($m\%$), and different δ_1 in which fault occurs) are simulated and the results are tabulated in Table IV. According to the table, CS values are negative (smaller than $h_n = -0.05$), showing that the proposed method can detect fault during power swing for both compensated and uncompensated lines.

B. Simulation results of IEEE 39-Bus power system (detailed model of UPFC)

This section provides simulation results related to IEEE 39-Bus (Fig. 9) simulated in PSCAD. The power system is simulated by using a sampling frequency 30.72 KHz and then measured voltage and current are pre-filtered by low-pass filter for preventing aliasing phenomenon. In order to model distance relay and PSB, sampling rate of measured voltage and current are decreased by integer factor 16 and are sent to DFT (Discrete Fourier Transform) to estimate their phasors. According to the output of DFT, angle of current is obtained. The detailed model of UPFC consists of two major parts, the electrical part and the control part. In the electrical part, there are four multi-level converters, four phase shifting transformers and a dc capacitor; whereas in the control part, there are measurements, PI controllers, calculation blocks and limiters. UPFC is located at the right end of protected line (between Bus14 and Bus4 at Bus14 side). The natural power flow (without UPFC) at Bus14 is $P_2 = 9.5p.u$ and $Q_2 = 2.55p.u.$ ($V_{base} = 345KV$ and $S_{base} = 100MVA$). Two different conditions are analysed: the first one deals with power swing condition and the second one is related to fault condition.

1) Power swing condition: In order to trigger this condition, a three-phase fault is simulated at $t = 1s$ in the line between Bus19 (B19) and Bus33 (B33), and is cleared by the circuit breakers at both ends of the line. This event puts the power system in power swing condition. Fig. 10 shows the impedance trajectory, CS parameter and block command during this condition. The impedance trajectory enters Zone 3 at $t = 1.94s$ and the proposed method detects this event as a power swing based on the positive trend of the current angle, issuing a blocking command ($Block = 1$).

2) Fault condition: This section analyzes the performance of the proposed method for detecting a fault condition. Fig. 11 shows the simulation results for this case. According to Fig. 11, a three-phase fault is detected by the negative value of CS at fault initiation setting the block command to zero. Hence, the proposed method can detect fault during power swing

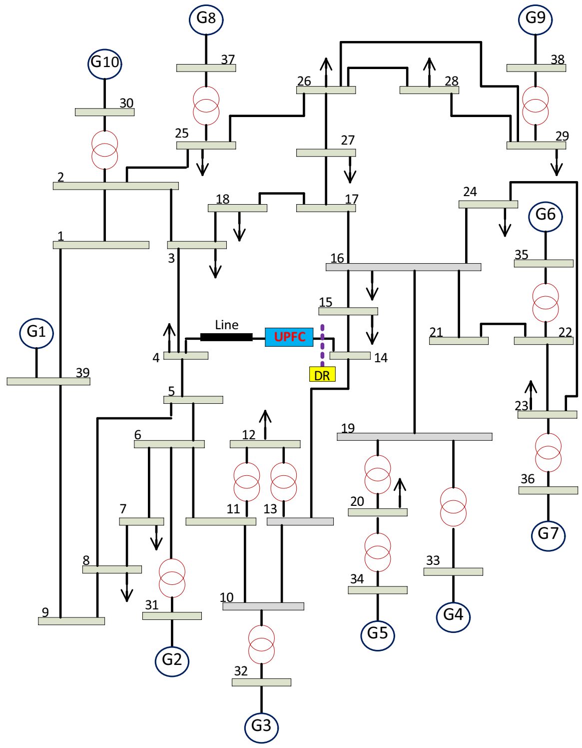


Fig. 9. IEEE 39-Bus power system.

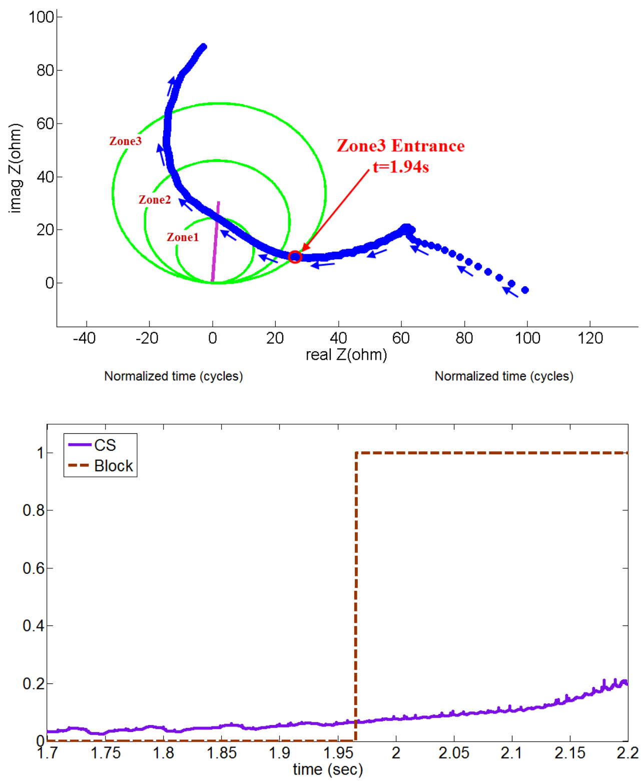


Fig. 10. Simulation results of IEEE 39-Bus for pure power swing condition.

accurately. In order to examine the efficiency of the proposed method in different conditions (different fault resistances (R) and fault locations($m\%$)), different cases are examined, with the respective results tabulated in Table V. CS values are negative in both the compensated and uncompensated conditions, showing that the proposed method can detect fault during power swing for different fault locations and fault resistances.

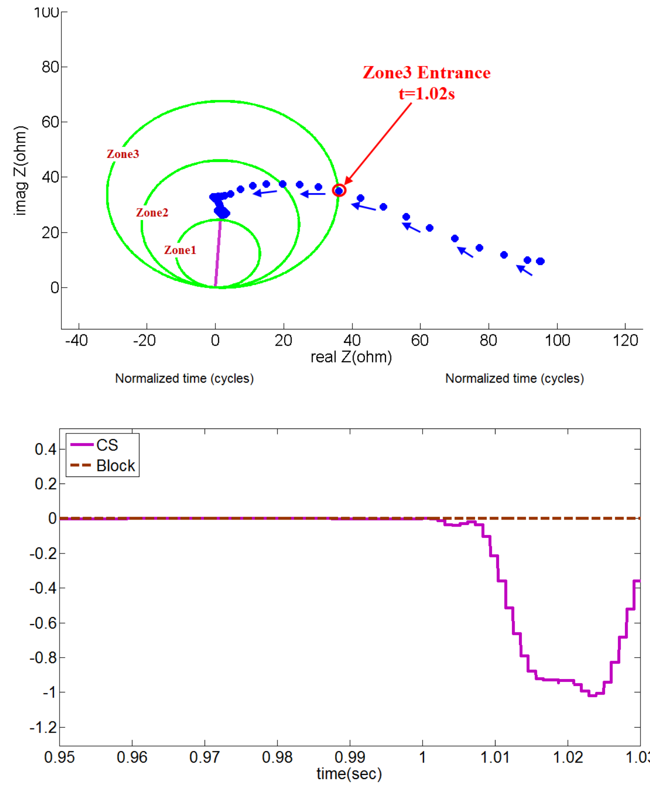


Fig. 11. Simulation results of IEEE 39-Bus for fault condition.

TABLE V
CS(KA) VALUES AT FAULT INITIATION IN IEEE 39-BUS POWER SYSTEM

Power System	$m=$ 25%	$m=$ 50%	$m=$ 100%	$R=$ 0Ω	$R=$ 5Ω	$R=$ 10Ω
Uncompensated	-1.79	-1.47	-1.23	-1.23	-0.98	-0.82
Compensated	-1.71	-1.39	-1.12	-1.12	-0.91	-0.75

IV. CONCLUSION

The first section of this paper demonstrated that the power swing blocker methods based on center of impedance trajectory and maximum rate of change of active and reactive powers are not applicable in UPFC-compensated transmission lines. Thus, it can also be concluded that the negative impact of UPFC on PSB so every power swing blocking method should be examined in compensated condition in order to be qualified. The second section of this paper proposes a new method for PSB, which is based on the phase angle of current and it is applicable in both uncompensated and compensated conditions. The trend of the angle of current to time reference at relay point (local measurement) is considered as an event detection index. According to the mathematical analysis, the variation of angle of current during power swing relates directly to the variation of δ_1. If $\Delta\delta_1$ is positive, the variation of angle of current is also positive and vice versa. On the other hand, it is shown that when a fault occurs, a downfall in the angle of current is present demonstrating the negative trend of this parameter. According to these results, a new method is proposed based on three conditional statements: if the impedance trajectory is inside Zone 3, the direction of the impedance movement is towards the inside Zone 3 and if the trend of the phase angle of current is positive, then power swing is present and the proposed PSB issues blocking command. It is worthy to note that the blocking command is kept until the impedance trajectory is inside Zone 3. Moreover, the proposed PSB can detect fault and unblock distance relay. If the impedance trajectory is inside Zone 3 and the trend of phase angle of current is negative, the proposed method detects that a fault has occurred and removes the blocking command of the distance relay. The proposed PSB is simulated for both single machine to infinite bus and IEEE 39-Bus power system, using both phasor and detailed model of UPFC during power swing and fault. According to the simulation results, the proposed PSB show acceptable performance in both compensated and uncompensated conditions.

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