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Research Article

Synchrophasor-Based Out-of-Step Prediction in Large Grids

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Out-of-step (OOS) condition is a potential problem in the power system and uncontrolled islanding is one of the severe consequences of out-of-step condition which leads to cascaded tripping of the system. To avoid this undesired cascaded tripping, early prediction of out-of-step condition is essential before losing the synchronization of generators and between the system areas. Controlled islanding is the last emergency action that can be taken by splitting the system intentionally into coherent islands. Conventionally, OOS condition has been detected with impedance-based measurement techniques which have their own limitations. With the implementation of a wide-area measurement system with synchrophasor measurement units (PMUs) in the power system, it is now possible to measure the bus voltage angle at a much faster rate than with SCADA. In this paper, synchrophasor-based bus voltage angle measurement has been used for early prediction of OOS condition in power systems. A new algorithm has been formulated for both generator and tie lines based on the trajectory of first and second derivatives of the bus voltage phase angle for early detection of OOS condition. The prediction speed of proposed method is found to be between 5% and 70% of time to OOS, after disturbance clearance. The proposed algorithm has been mathematically formulated and evaluated with three benchmark systems in real-time simulation environment with an OPAL-RT real-time simulator and a HYPERSIM platform.

1. Introduction

Out-of-step (OOS) condition is a phenomenon described by the loss of synchronization of generator with the system or angular separation of 180 degrees between coherent areas in large power system. The OOS condition follows unstable oscillations in a postdisturbed power system [1, 2]. In such a condition, the intentional tripping of the generator or the tie line which goes out-of-step is essential to avoid total collapse of the system. Presently, the actual detection of OOS condition is available with impedance-based OOS relays [3, 4], which can detect OOS after its occurrence and does not predict OOS effectively, where byoperators do not have time for corrective measures to prevent the OOS condition. The prediction of out-of-step condition immediately after a disturbance helps operators to get some time prior to the occurrence of OOS (i.e., 180-degree angular separation), to trigger a remedial action scheme (RAS) [5], and to prevent the angular separation and for restoring system stability in the system. The work presented in this paper is regarding the prediction of OOS condition in large power system after a disturbance in the system.

OOS condition is expected in all generators connected to the power system, as well as in the tie lines which are subjected to disturbance. The OOS condition in generators and in interconnected power systems are analyzed in the literature, mainly by equal area criterion (EAC) and linearized analysis that compute the eigenvalues. It is understood that, in the case of OOS condition in the generator, the basic governing equations for the estimation of oscillations are the swing equation which mainly depends on the parameters of the local generator mass, damping, and friction of the generator, as well as the fault clearing time. However, in the case of an interconnected large system, the excitation of tie line oscillations needs to be addressed which are prone to OOS unstable conditions, which if not addressed could lead the system towards uncontrolled islanding and eventually to a blackout [6].

Traditionally, generator out-of-step protection has been implemented with distance relay [7–10] with additional functions, to differentiate between fault and stable as well as unstable power swings, namely, power swing blocking (PSB) and out-of-step tripping (OST). These relays need model-based predetermined settings which fail in the event of any network configuration changes. Moreover, it mainly detects the OOS condition at the time of its occurrence without any prior expectation. Thus, several alternative methods have been suggested in the literature to overcome the difficulty.

The recent methods for detection of OOS condition can be classified as model-based and measurement-based schemes. The study of [11] has introduced a predictive model-based algorithm named faster-than-real-time by estimating Thevenin's equivalent subsequent to the disturbance. The study of [12] has suggested a method to improve differential protection function in case of OOS condition. Transmission line model-based details have been used to develop the algorithm. However, model-based techniques need comprehensive offline stability studies of specific system configurations and operating conditions which can be highly complex and not adaptive to system changes.

To avoid the complexity of model-based methods, several literatures have proposed measurement-based algorithms. Generator terminal voltage and current are used in reference [13] to estimate the rotor speed. The estimated rotor speed with respect to time has been monitored for OOS protection. The study of [14] has suggested a new formation of equal area criterion (EAC) in terms of time domain with local measurements of current and voltage at the relay location. These measurements are inputs to a mathematical calculation algorithm, where generator inertia is used and if renewable energy sources are integrated into a power system, the algorithm will fail. EAC has been also proposed in the study of [15], where out-of-step condition has been estimated by tracking the acceleration and deceleration areas on the power-angle curve using local measurements of current and voltage for the least-squares method. Terminal voltage of the generator has been used in the study of [16], where OOS detection decision is taken if the real part of the measured voltage is negative and the imaginary part crosses zero. Furthermore, in these methods, the phasor has been mathematically estimated but with the help of a wide-area measurement system (WAMS). PMU-based algorithms can be developed for real-time OOS detection without any estimation. In [17], wide area measurement data are continuously collected to plot power angle-frequency trajectory for testing its crossing with the Zubov's approximate boundaries. However, these boundaries need a repeatable calculation to be set using power system parameters which are not updated in real time according to the system changes. The frequency variation characteristics approach of PMU-based bus voltage measurements has been implemented in [18] for tie line OOS protection. The concept is based on comparing voltage frequency difference of transmission line ends with frequency threshold. If it exceeds this value, the tie line will be tripped. OOS protection for the generator has been widely addressed in the literature by EAC or rotor angle-based detection algorithms which cannot be used for out-of-step of interarea oscillation. However, very limited works have been carried out to protect the system from OOS of interarea mode.

Recent works are going towards the prediction of out-of-step condition in order to control the oscillations and enhance the stability to avoid OOS condition. An artificial intelligence prediction approach has been suggested in [19] which requires offline transient stability simulation for training purposes. In [20], the algorithm which has been proposed is based on EAC in time domain for OOS generator prediction using electrical power forecasted by the curve fitting method. In another literature [21], the generator rotor angle is estimated continuously from computed instantaneous active power using local current and voltage measurements at the generator terminals. This method is used to estimate the stability of a single generator in the system based on the polarity of angular velocity and acceleration of the generator rotor angle.

Voltage angle difference has recently been used in the literature for out-of-step of interarea oscillation which is the present concern for maintaining the power system reliability in addition to the generator stability. The authors of [22, 23] have proposed a wide area measurement-based prediction algorithm based on slip frequency, and acceleration, of voltage angle difference between two terminal generators with thresholds limits. Warning signal activates as a first step in case of detecting power swing (PSD), depending on comparing slip and acceleration locus with constant values (thresholds) within 3 cycles. In the second step, predictive OOS tripping approach (OOST) has been developed based on tracking slip-acceleration locus and crossing OOST characteristics. In [24], the algorithm depends on checking the value of first two derivatives of angular difference if they are positive, activating the OOS protection. But they can also be positive in a stable case so the authors had to add blocking logic for such a condition. Coherent generator identification based on the correlation coefficients has been used in [25] for OOS prediction. However, the OOS center on tie-line has been identified at a time of 180-degree separation of bus voltage angles. The author of [26] has proposed a technology to predict out-of-step in interconnected power systems relying on system integrity protection schemes (SIPSs). Positive sequence voltage angle of terminal generators is collected by a synchrophasor vector processor (SVP) and the voltage angle difference is calculated. By tracking the slip-acceleration curve of a voltage angle difference, at the time of crossing the predetermined boundaries, out-of-step has been predicted. OOS settings using boundaries or characteristics are not the best choice as they require simulations study to be set. Moreover, these methods can predict the existence of interarea mode in the system but not the location of angular separation.

Generally, in literature, OOS prediction has been addressed separately for generator and for tie lines; however, this work addresses both. A similar type of study based on bus voltage angle based on the center of inertia (COI) of generators has been reported in [27], by extending the concept of EAC for single machine infinite bus to interarea [28]. The criteria for early prediction of out-of-step condition are based on the polarity of the slope of the tangent to the (angular speed-acceleration) locus curve. This method requires a PMU at all the generator buses, for the calculation of COI angle from the bus voltage angle of all generators, and requires the slope of its acceleration with respect to slip. Furthermore, it does not clearly address the main interarea mode oscillations, which is the main concern for the stability of large interconnected systems.

Overcoming the aforementioned limitations is a key research priority. A generalized early warning method that can be used to predict OOS condition for both generator and tie-line under various types of disturbances remains challenging for the researchers. Specially, the main interarea mode oscillations need to be located earlier, where an OOS tie line can be predicted. The complexity of offline analysis must also be eliminated by developing a setting-free prediction tool. Thus, a real-time implementation logic is required to avoid estimation calculations, and hence, the OOS prediction method can be independent of the network parameters. A comprehensive comparison of detection and prediction of OOS as well as generator and tie line detection application has been summarized in Table 1.

After a thorough analysis of OOS by the authors of [29], the authors of this paper present a response-based early prediction method for OOS condition in interconnected power system, based on trajectory of acceleration and slip of bus voltage angle difference obtained from PMU measurements. This method is independent of network variations and can be easily implemented in real time. The basic principle of this proposed method is based on the bus voltage angle's rate of change and its derivative. The rate of change of angle difference and its acceleration are computed in real time from the instantaneous bus voltage phase angle difference to identify the unstable condition in a derivative plane. The benefit of this method is its independence from fault-clearing time and network parameters. To summarize, the main contributions of this study are as follows:

(i) A straightforward OOS early prediction method derived from bus voltage phase angle difference which avoids tedious network analysis and offline calculations

(ii) A simpler method that can be directly applied to interconnected large-area power systems without any network reduction as well as for generator protection.

(iii) A novel out-of-step prediction method, which utilizes the wide area information obtained from PMU which can be used as an alarm for controlled islanding.

The proposed method of early prediction of OOS has been validated in the time domain on three benchmark (SMIB, two-area, and IEEE39 bus) systems. The time domain simulation study has been performed on an OPAL-RT real-time simulator with 50 μs time step in a HYPERSIM EMTP environment.

2. Voltage Phase Angle Difference and Its Slip-Acceleration for Prediction of OOS

In this section, the background for the detection of type of oscillation is presented. For lossless lines, the steady state power transfer through a transmission line is given by the following equation:

$$P_e = \frac{V_1.V_2}{X_s}.\sin(\delta), \quad (1)$$

where V_1 and V_2 are the terminal bus voltages of the line, δ is the bus voltage angle difference (δ_1-δ_2), and X_s is the equivalent reactance of the transmission line. The same equation can be considered for synchronous generator with internal emf V_1, terminal voltage V_2, rotor angle δ, and internal impedance X_s.

Any perturbation to the system shall result in power swings in tie lines (rotor angle θ in case of the generator) which can be represented as oscillations of δ across tie lines (and θ around the synchronous rotating reference frame ω_s for the generator). The first and second derivatives of the oscillation of δ are utilized to develop a criterion to identify the unstable oscillation in this section.

2.1. Stable Oscillation Identification.

2.1. Stable Oscillation Identification. In the case of stable power swings, the phase angles of the tie line oscillate near the interarea frequency range (0.1–0.8) Hz [30], as shown in Figure 1.

These stable damped oscillations can be ideally expressed by a sinusoidal curve with exponentially damped magnitude by the following expression:

$$\delta(t) = e^{-\alpha t}.\sin(\beta t), \quad (2)$$

where β is the oscillation frequency and α is a quantity that characterizes the damping magnitude.

Taking the first derivative of (2), the following expression can be derived:

$$\frac{d\delta(t)}{dt} = e^{-\alpha t}.(\beta.\cos(\beta t) - \alpha.\sin(\beta t)). \quad (3)$$

Also, the second derivative of (2) is as follows:

$$\frac{d^2\delta(t)}{dt^2} = e^{-\alpha t}.\left(-2.\alpha.\beta.\cos(\beta t) + \left(\alpha^2 - \beta^2\right).\sin(\beta t)\right). \quad (4)$$

By plotting the first and second derivatives in the time domain, we obtain Figure 2.

It can be noticed that every time the second derivative crosses zero from negative to positive, the first derivative is negative. This feature can be noticed clearly by tracking the locus on the first derivative-second derivative plane which is always moving from a negative to positive value, crossing the horizontal axis from the left side. In other words, it goes from the third quadrant to the second as it is shown in Figure 3.

2.2. Unstable Oscillation Identification. In the case of unstable oscillation, the voltage angle difference may increase exponentially along with oscillation behavior and crosses

Table 1: A comparison between previous literature and the proposed method.

Category	Ref	Detection/prediction of OOS	Generator/interarea
Model-based	[11]	Prediction	Generator
	[12]	Detection	Interarea
Local measurement-based	[13–16]	Detection	Generator
	[20, 21]	Prediction	Generator
WAMS-based	[17]	Detection	Generator
	[18]	Detection	Interarea
	[19, 28, 29]	Prediction	Generator
	[22–27]	Prediction	Interarea
	Proposed method	Prediction	Generator and inter-area

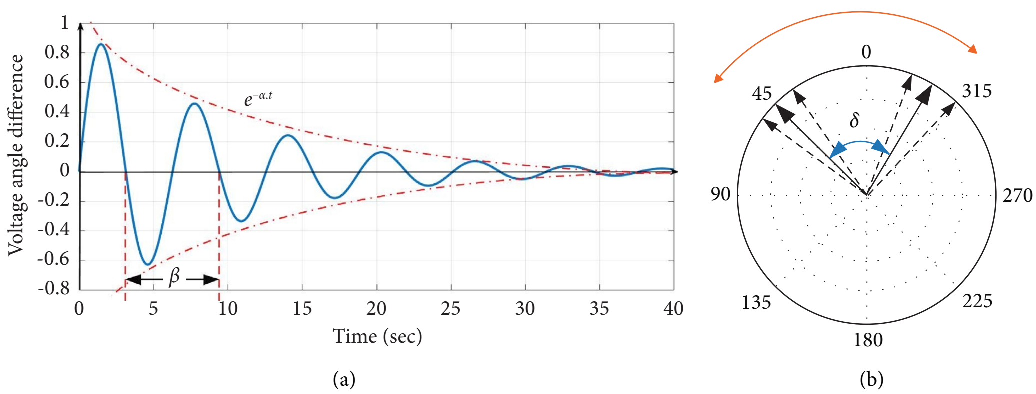

Figure 1: Stable oscillation after disturbance in the system: (a) voltage angle difference oscillation; (b) bus voltage angles oscillation.

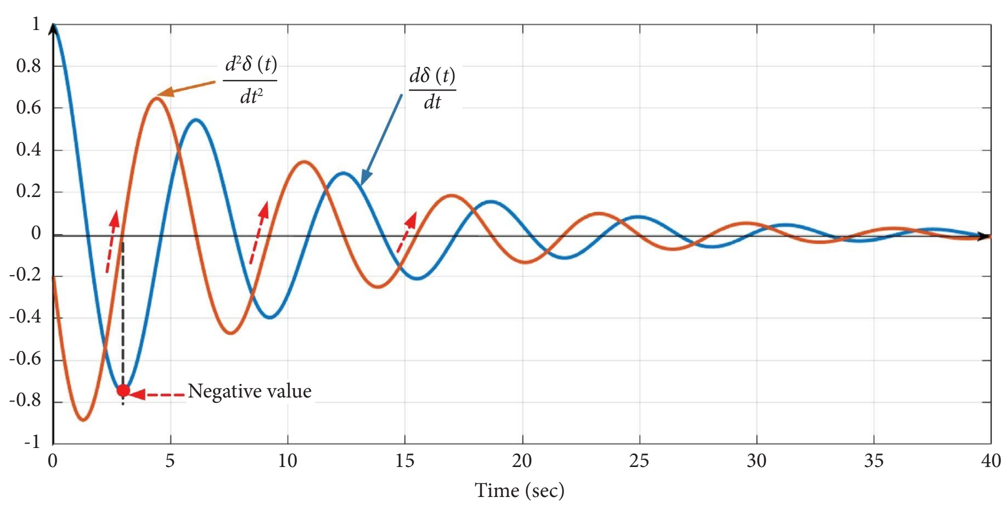

Figure 2: Stable oscillation of first and second derivatives.

a point of 180° separation [29]. At this point, the system falls out of synchronism known as out-of-step (OOS) condition. Theoretically, the out-of-step curve can be represented by an undamped exponential function. As there is some oscillation along with the exponential factor, an additional sinusoidal function is mathematically added to the equation. Therefore, the unstable oscillation shown in Figure 4 can be represented by the following equation:

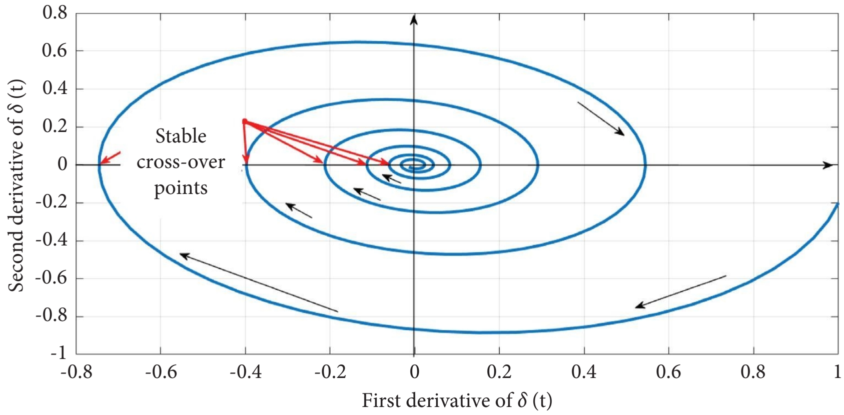

Figure 3: Pattern of stable trajectory in the first-second derivative plane.

$$\delta(t) = e^{\alpha t} + \sin(\beta t), \tag{5}$$

where α is a quantity that characterizes the slop and β is the oscillation frequency.

By deriving the equation twice,

$$\begin{aligned} \frac{d\delta(t)}{dt} &= \alpha \,.\, e^{at} + \beta.\cos(\beta t), \\ \frac{d^2\delta(t)}{dt^2} &= \alpha^2 \,.\, e^{\alpha t} - \beta^2.\cos(\beta t). \end{aligned} \tag{6}$$

These two derivatives behave differently than they do in the stable state, as initially over a short period of time, the first derivative starts increasing exponentially with positive values, while the second derivative oscillates with positive and negative values as shown in Figure 5.

What distinguishes this case is that the second derivative crosses zero from negative to positive when the first derivative is positive. At this moment the locus on the (first derivative-second derivative) plane which is given in Figure 6 crosses from negative to positive on the right side from fourth quadrant to first quadrant. From the pattern of the locus moving from the fourth to the first quadrant, the undamped nature of the curve δ can be identified.

2.3. Voltage Phase Angle-Based Algorithm. As explained in sections 2.1 and 2.2, by obtaining the voltage angle difference δ and evaluating its derivation with respect to the time referred to as slip (S_f) and the derivative of slip with respect to the time as acceleration (A), it is possible to distinguish between stable and unstable oscillations and to predict an out-of-step condition in the system when the trajectory crosses from fourth quadrant to first quadrant on the right side of the derivatives plane.

In the case of a synchronous generator, the rotor angle θ cannot be directly measured by synchrophasor measurements; however, the generator bus voltage angle δ which follows the rotor angle closely can be utilized for calculation. With PMU direct bus voltage, angle measurements of the tie line ends δ_1 and δ_2 can be acquired continuously.

Based on these measurements, a predictive algorithm for out-of-step condition has been developed based on the slip-acceleration criterion using the following equations:

$$\begin{aligned} \delta &= \delta_1 - \delta_2, \\ S_f &= \frac{d\delta}{dt}, \\ A &= \frac{dS_f}{dt} = \frac{d^2\delta}{dt^2}. \end{aligned} \tag{7}$$

Stable and unstable interarea oscillations can be identified based on slip-acceleration criterion as follows, where n is the sample at time interval t.

Criterion of stable oscillations: $\left\{ \begin{array}{l} A^{n-1} < 0 \longrightarrow \\ A^n > 0, S_f^n < 0 \end{array} \right\}$

Criterion of unstable oscillations: $\left\{ \begin{array}{l} A^{n-1} < 0 \longrightarrow \\ A^n > 0, S_f^n > 0 \end{array} \right\}$

The proposed algorithm is given in Figure 7.

2.4. OOS Prediction Performance Evaluation. In order to evaluate the prediction time of OOS from the instance of disturbance for various systems, a time scale representation is shown in Figure 8. As shown in Figure 8(a), after a disturbance in the normal state, the system moves into stable oscillations before it recovers to a new stable state, in case of the damped oscillations. However, in case of unstable oscillations, the system moves into a chaotic state after 180 degree angular seperation as shown in Figure 8(b). The prediction time required by the algorithms is represented by Y secs after the disturbance clearance and the rest of the time to OOS can be used for RAS. It is obvious that a small value of prediction time Y is desired for prediction algorithms. As the time to OOS varies from one system to another, it is convenient to express prediction speed as the ratio of actual time taken for prediction to time for OOS after disturbance.

$$\text{Prediction speed} = \frac{\text{time to predict}}{(\text{time to OOS from disturbance})}. \tag{8}$$

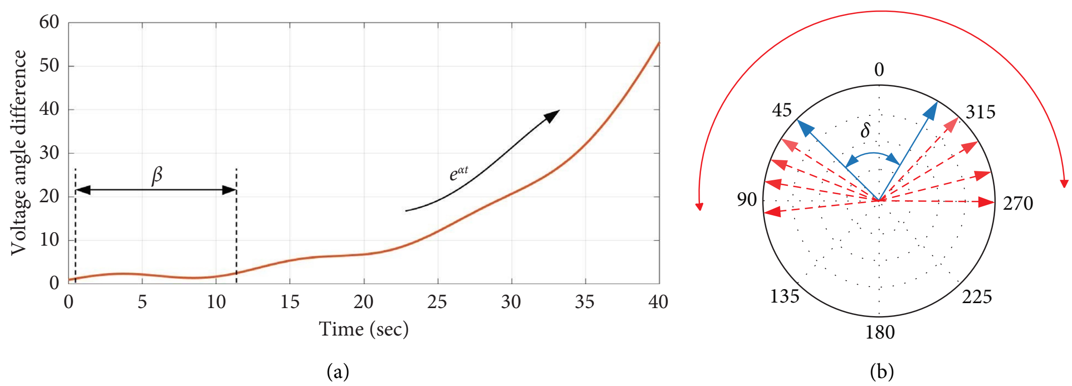

Figure 4: Unstable oscillation after disturbance in the system: (a) voltage angle difference oscillation; (b) bus voltage angles oscillation.

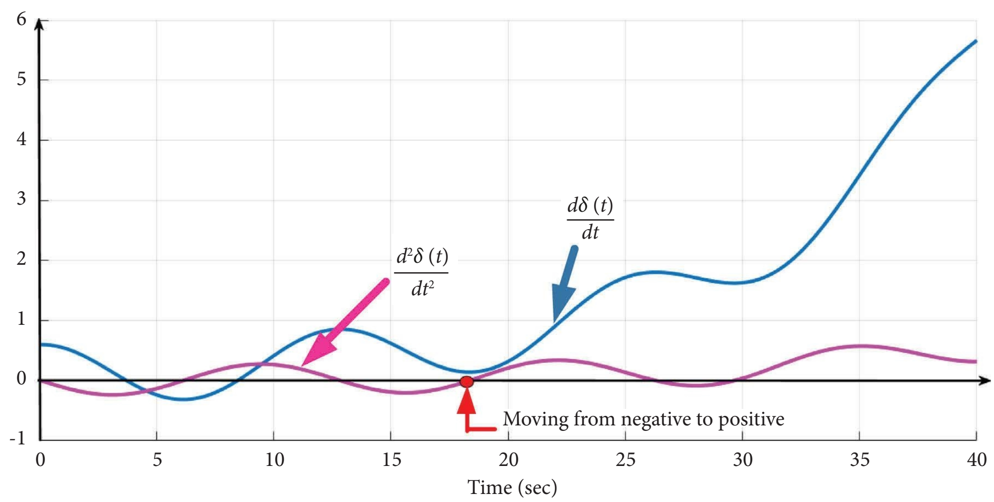

Figure 5: Unstable oscillation of first and second derivatives.

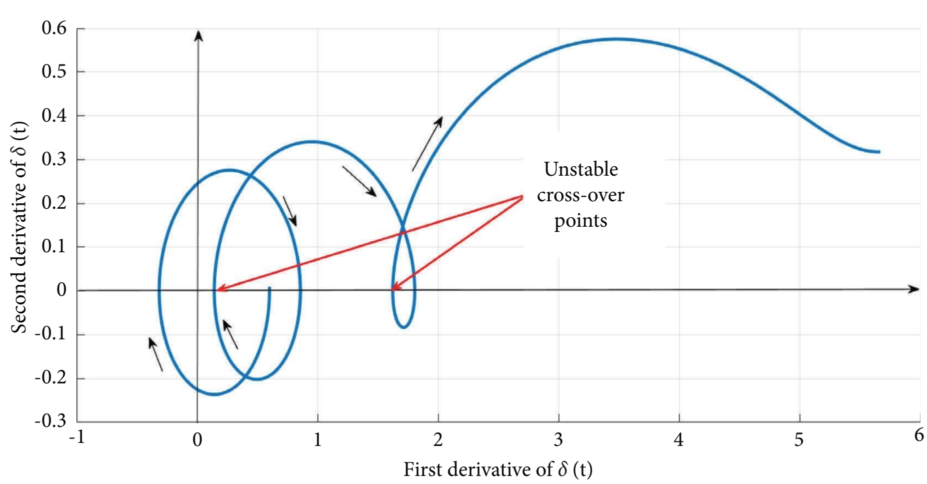

Figure 6: Pattern of out-of-step trajectory in the first-second derivative plane.

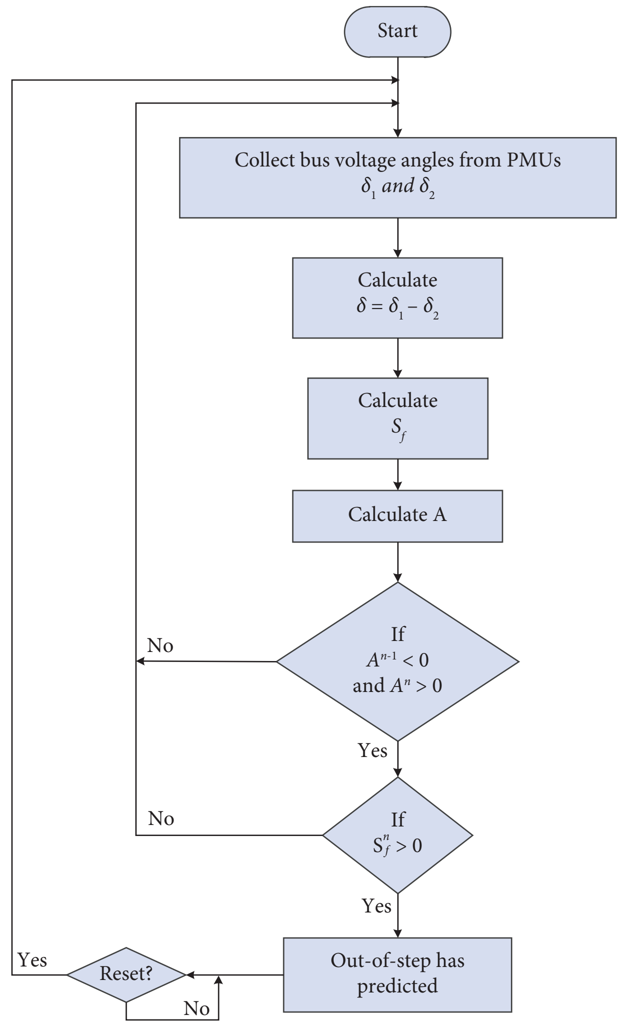

FIGURE 7: The PMU-based algorithm for out-of-step prediction.

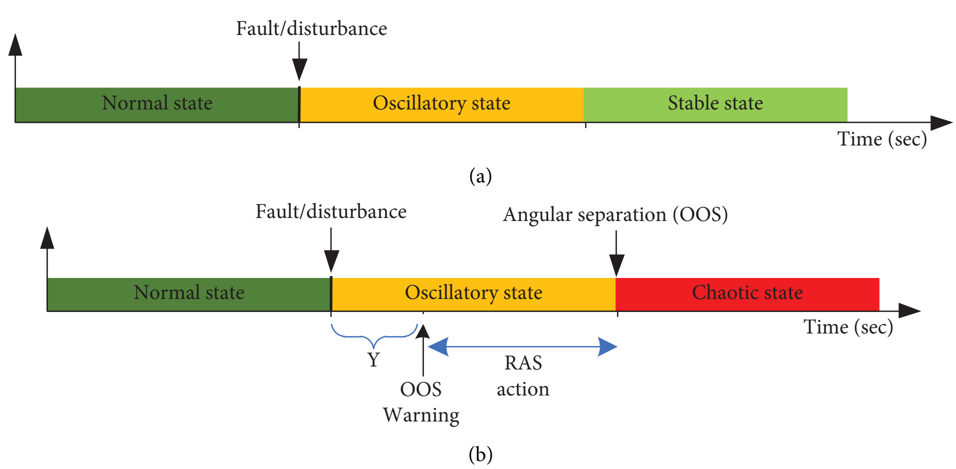

FIGURE 8: Transition of power system state: (a) stable condition; (b) unstable condition.

The prediction speed shall be helpful for quantitative comparison on performance of the predictive algorithms.

3. Simulation and Verification

In order to evaluate the proposed approach and algorithm performance, a detailed study has been carried out on three benchmark systems: single machine infinite bus, two-area system, and IEEE39-bus system, with several scenarios in a OPAL-RT real-time simulator's HYPERSIM environment with a simulated PMU reporting at a time interval of 15 msec.

3.1. Single Machine Infinite Bus. The study system in this case is a 60 Hz single machine connected to an infinite bus through two transmission lines as shown in Figure 9. PMUs have been considered at Bus 2 and Bus 3. Thus, the bus voltage angle of the line ends can be collected to predict out-of-step.

Different faults scenarios have been applied on line 2 at 1 sec for various power flow scenarios in the transmission line as given in Table 2, where T_{oos} is the time of out-of-step occurrence, T_P is the prediction time, R is the fault resistance, and X is the location of the fault. The fault has been cleared by tripping the faulted line from both ends. The time of clearing the fault (T_{ct}) has been varied according to the scenarios. The green shaded portion in the table indicate the stable and unstable conditions for the same power flow. The out-of-step condition has been successfully detected earlier than 180° separation using the developed algorithm for all unstable cases.

For example, in scenario 2, a three-phase fault has been applied on line 2 at two different locations from bus 2 and was cleared at 1.299 sec. In the case of the fault at 90% of line 2, stable oscillations were observed in line 1 and the voltage angle difference curve oscillates with a frequency of 0.85 Hz (obtained by fast Fourier transformer (FFT)), as can be observed from Figure 10 (red legend). While Figure 11 representing slip and acceleration curve in time domain demonstrates that, at the time when acceleration crosses zero from negative to positive, slip is always negative. Furthermore, the slip-acceleration locus curve in Figure 12 crosses from the third quadrant to the second in the derivatives plane.

However, in the case of the three-phase fault at 10% of the line, the voltage angle difference in Figure 10 (blue legend) increases exponentially beyond 180° to go out-of-step at 2.108 sec. But using the proposed algorithm, the out-of-step condition can be predicted at 1.46 sec, as in Figure 13, when the slip-acceleration locus curve cross from the fourth quadrant to the first, as demonstrated in the slip-acceleration plane, Figure 14.

Table 2 summarizes the behavior of the system under different scenarios of stable and out-of-step condition and early prediction of OOS condition before actual 180-degree separation, with the proposed method.

3.2. Kundur's Two-Area System. The second case study has been carried out on a 50 Hz Kundur's two-area system as shown in Figure 15.

Each area has two generators and five buses and they are connected by two lines with a bus. Two loads are connected with buses 4 and 6, and detailed parameters are given in [1]. Two PMUs have been used to capture voltage angle from bus 3 and bus 7 in the light of three different types of system variations (loads, inertia, and network configuration) for early detection of OOS condition in interarea oscillation which tends to go out-of-step.

Scenario 1. Load variation.

In this scenario, interarea oscillation has been excited by varying the load in the system to simulate out-of-step condition. Load 2 on bus 6 has been increased by 30% and 50% at 1 sec and the developed algorithm has been used to predict out-of-step condition earlier.

Figure 16(a) shows stable interarea oscillation in case of the 30% load increase. The bus voltage angle difference oscillates at 0.68 Hz and stabilizes after a few seconds. It can be noticed in Figure 16(b) that the slip is always negative when acceleration moves from negative to positive and the slip-acceleration locus is crossing the horizontal axis from the left side in Figure 16(c).

While out-of-step condition between area 1 and area 2 has been predicted in case of the 50% load increase, as the slip-acceleration locus curve is crossing the horizontal axis from the right side before out-of-step occurs, as it is illustrated in Figure 17(c). The results are tabulated in Table 3.

Scenario 2. Inertia variation.

The recent change in power generation toward renewable energy sources (RESs), which do not have rotating mass coupled to the grid, leads to a decrease in inertia in the power system. Thus, these inverter-based resources have been considered in this study and simulated by varying generator 3 inertia for two values (6.175 and 3.175) in the presence of a three-phase fault on line (5-6) at 1 sec and cleared by removing the fault at 1.08 sec for both inertias. The results are given in Table 4.

Figure 18 demonstrates stable interarea oscillations (0.91 Hz). Whereas, Figure 19 shows that low inertia causes OOS condition between area 1 and area 2, which has been predicted at 2.877 sec using the proposed algorithm.

Scenario 3. Network configuration variation

In this scenario, a three-phase fault has been applied on line (5-6) at 1 sec. In the first case, the fault was cleared without removing the line at 1.09 sec; in another case, the fault was cleared by removing the line at 1.09 sec which is considered changing the network configuration.

Figure 20 illustrates stable interarea oscillations (0.39 Hz) that have been excited after removing the fault. While OOS has been predicted at the time of right crossing of slip-acceleration locus curve with the horizontal axis shown in Figure 21, the time intervals are given in Table 5.

3.3. IEEE 39-Bus System. In this section, IEEE 39 bus system has been simulated to validate the proposed method to predict OOS condition. The system has a frequency of 60 Hz and

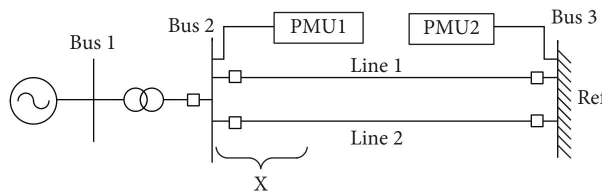

Figure 9: SMIB system.

Table 2: OOS prediction time for SMIB.

S	Power flow (p.u)	TF (sec)	Fault type	RF (Ω)	X	TCT (sec)	TOOS (sec)	TP (sec)	Prediction speed
1	0.9+0.43j	1	ABG	0	20%	1.1	S	∞	∞
						1.26	2.12	1.43	19.7%
2	0.8+0.07j		ABCG	0.1	90%	1.299	S	∞	∞
					10%		2.10	1.46	20.1%
3	0.6+0.45j		ABCG	0.9	5%	1.44	S	∞	∞
				0.01			2.07	1.61	26.9%
4	0.4+0.91j		ABG	0	20%	1.592	S	∞	∞
			ABCG				3.01	1.84	17.5%

The green shaded portion in the table indicate the stable and unstable conditions for the same power flow.

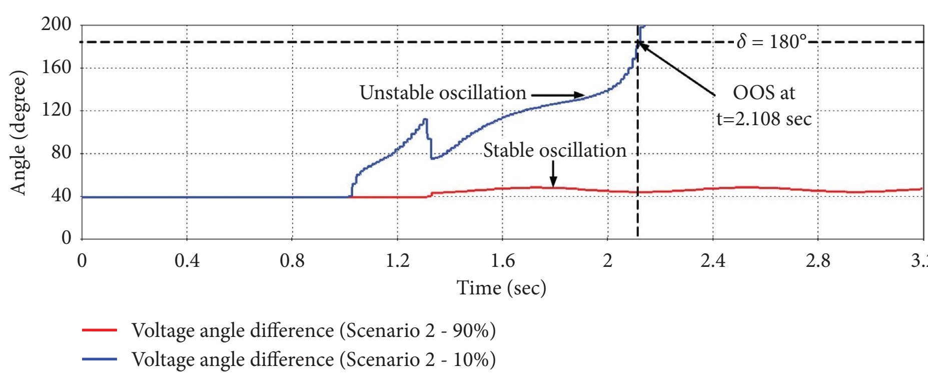

Figure 10: Voltage angle difference of scenario 2.

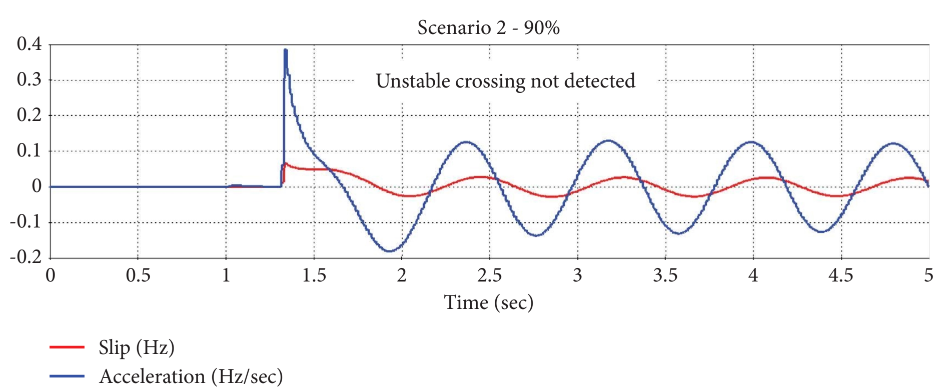

Figure 11: Stable slip and acceleration oscillation of 90% fault location.

consists of 10 generators, 12 transformers, and 34 transmission lines, and the detailed parameters are in reference [31]. All generators are implemented with full excitation and turbine governor system. To simulate the OOS condition, two faults have been simultaneously applied at 1 sec to excite interarea oscillation. One fault is on line 25-2 and has been cleared by isolating the line at 1.1 sec; the other fault is on line 21-22 and has been cleared by removing the line at 1.12 sec as well.

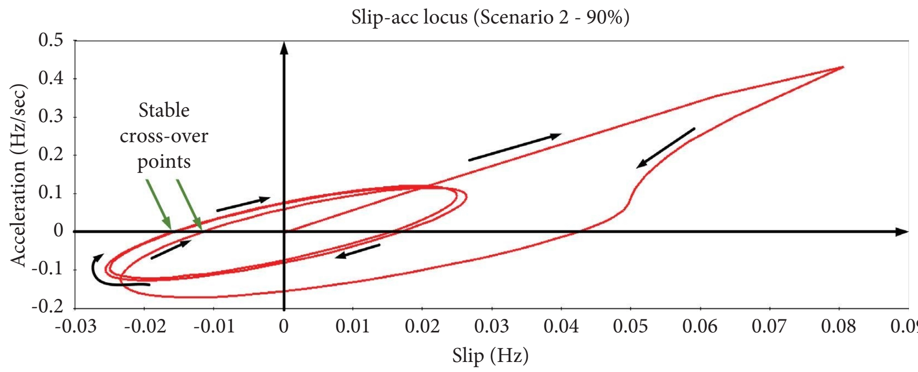

Figure 12: Stable slip-acceleration locus of 90% fault location.

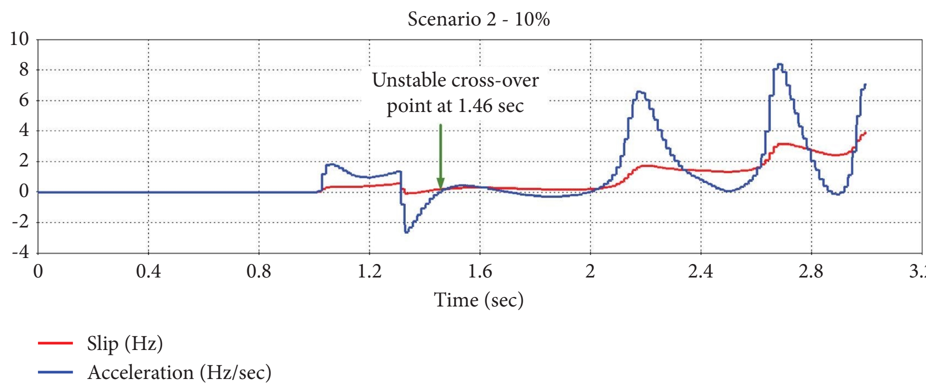

Figure 13: Unstable slip and acceleration oscillation of 10% fault location.

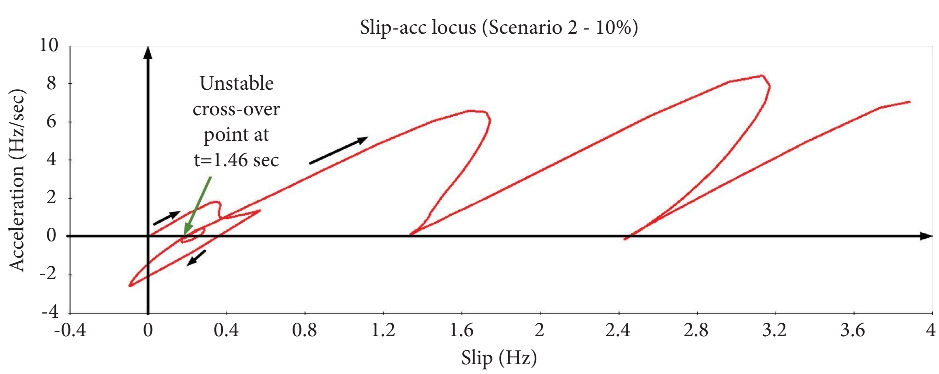

Figure 14: Unstable slip-acceleration locus of 10% fault location.

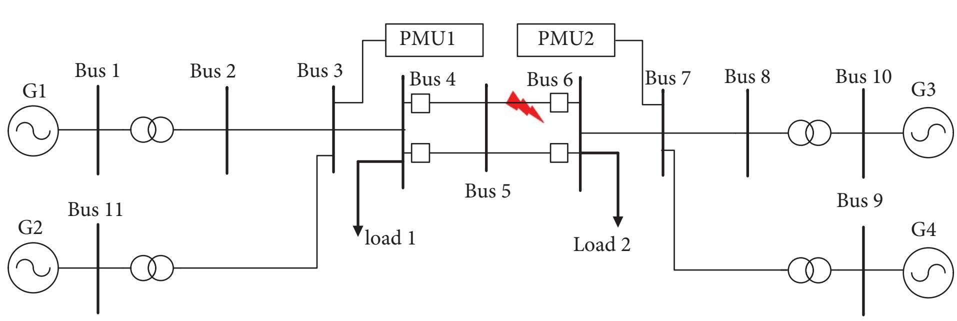

Figure 15: Kundur two-area system.

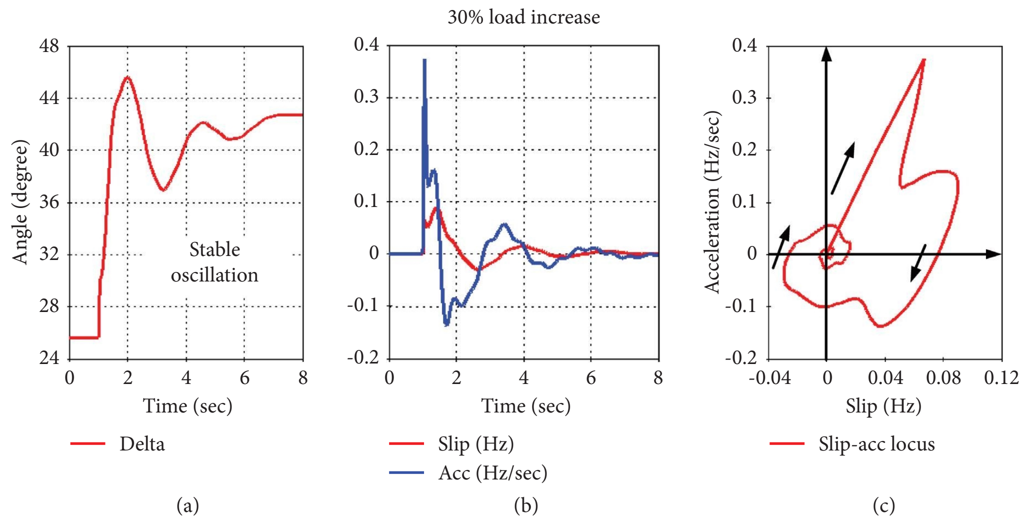

Figure 16: Stable interarea oscillation in case of 30% load increase.

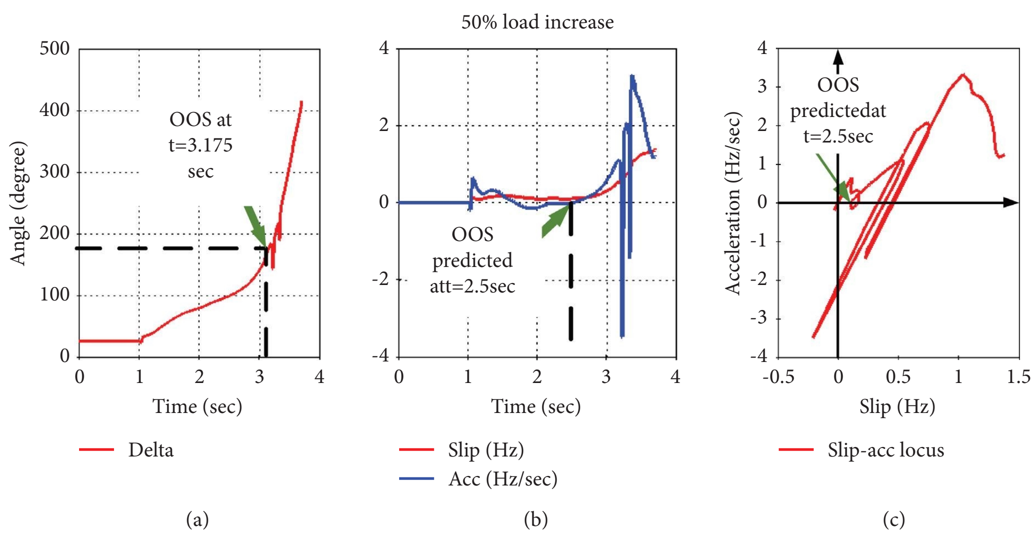

Figure 17: OOS prediction in case of 50% load increase.

Table 3: OOS prediction time for load variation.

Load variation (%)	OOS time (sec)	OOS prediction time (sec)	Prediction speed
30	Stable	∞	∞
50	3.175	2.5	68.9%

Table 4: OOS prediction time for inertia variation.

Inertia value	OOS time (sec)	OOS prediction time (sec)	Prediction speed
6.175	Stable	∞	∞
3.175	4.37	2.877	54.6%

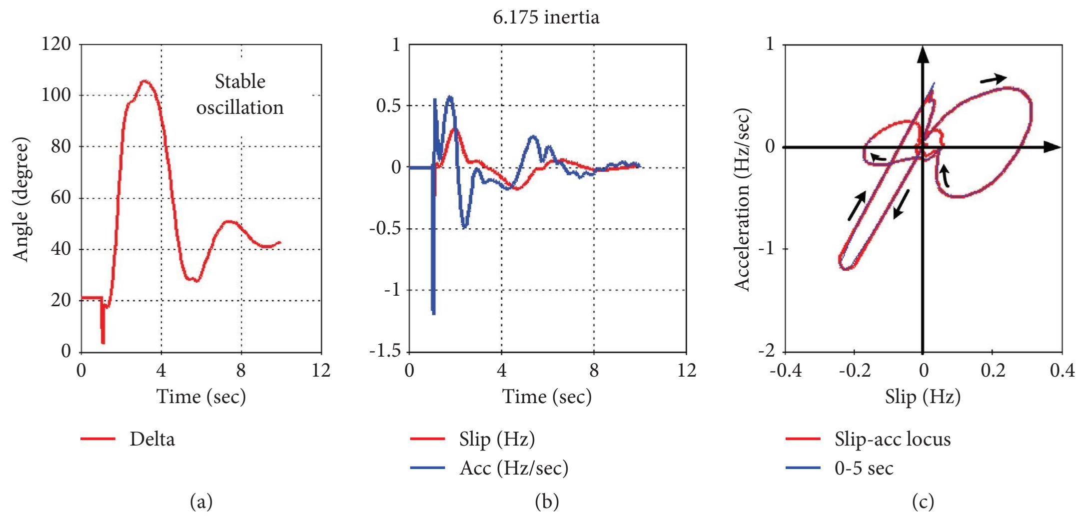

FIGURE 18: Stable interarea oscillation in case of 6.175 inertia.

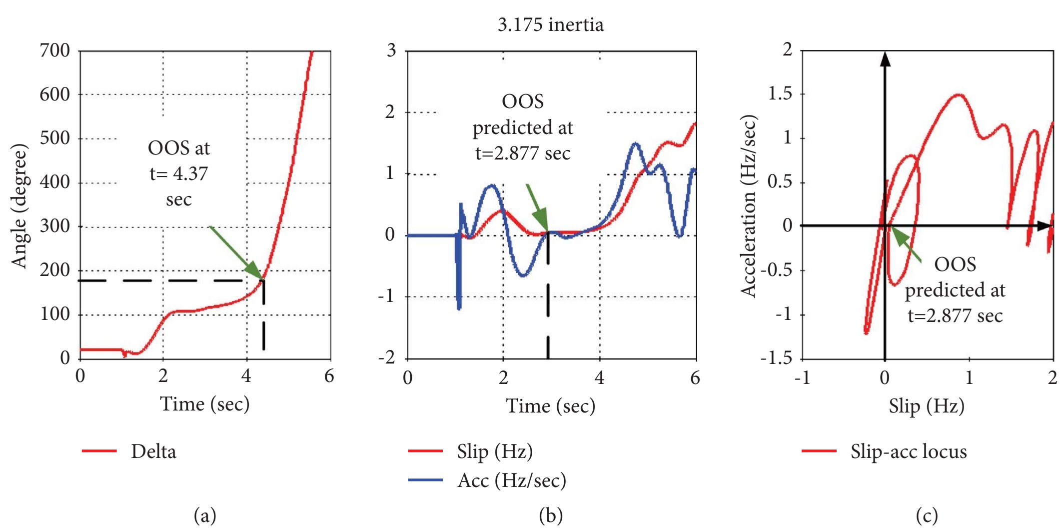

FIGURE 19: OOS prediction in case of 3.175 inertia.

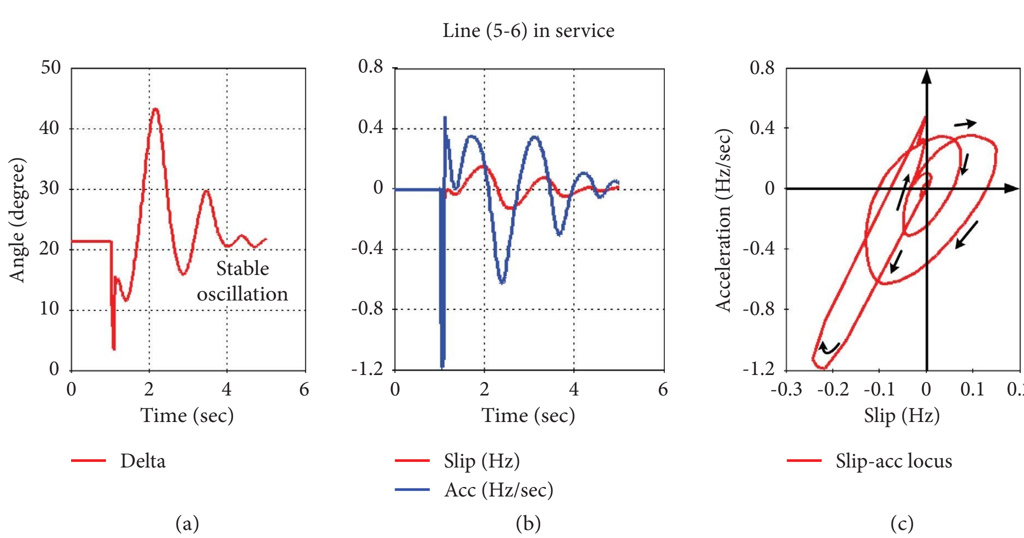

FIGURE 20: Stable interarea oscillation in the case of line (5-6) is in service.

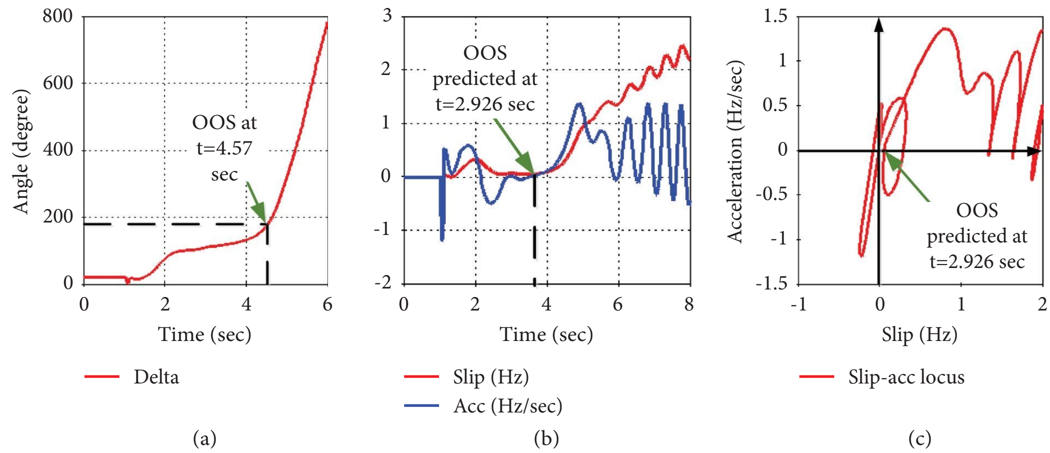

Figure 21: OOS prediction in case of line (5-6) is out of service.

Table 5: OOS prediction time for configuration variation.

Line (5-6)	OOS time (sec)	OOS prediction time (sec)	Prediction speed
In service	Stable	∞	∞
Out of service	4.57	2.926	52.7%

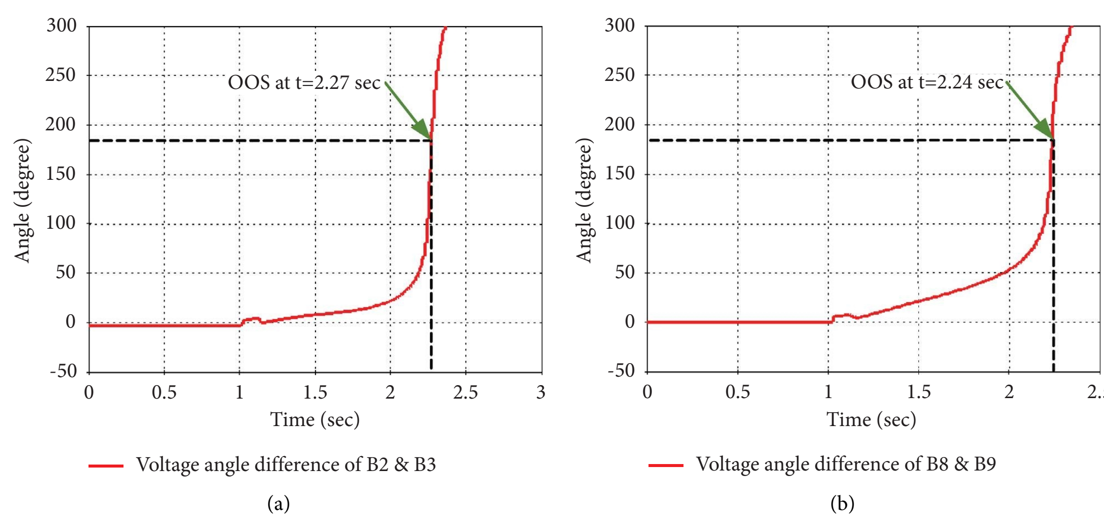

Figure 22: Voltage angle difference of the tie lines: (a) line (2-3); (b) line (8-9).

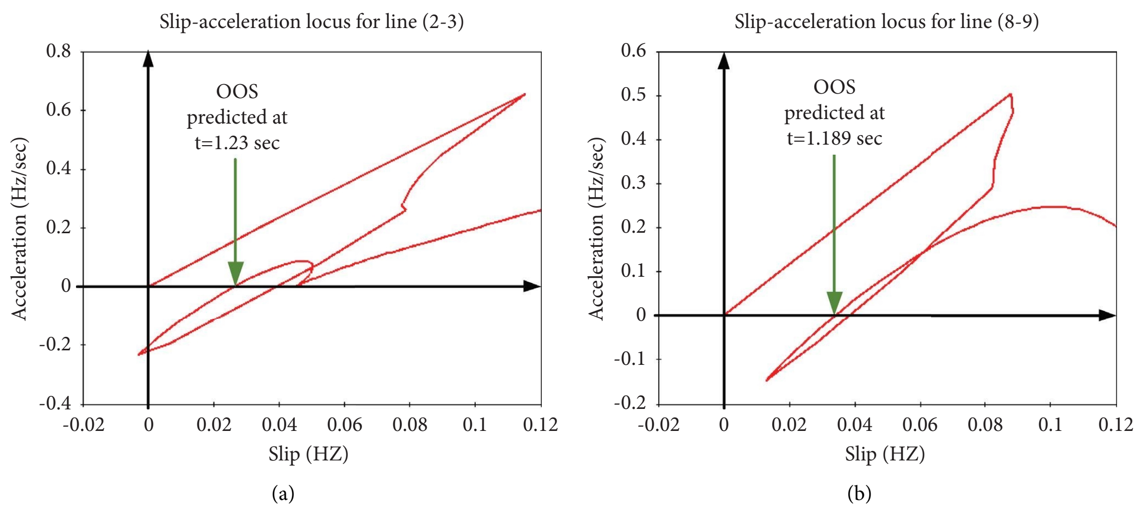

Figure 23: Slip-acceleration locus of the tie lines: (a) line (2-3); (b) line (8-9).

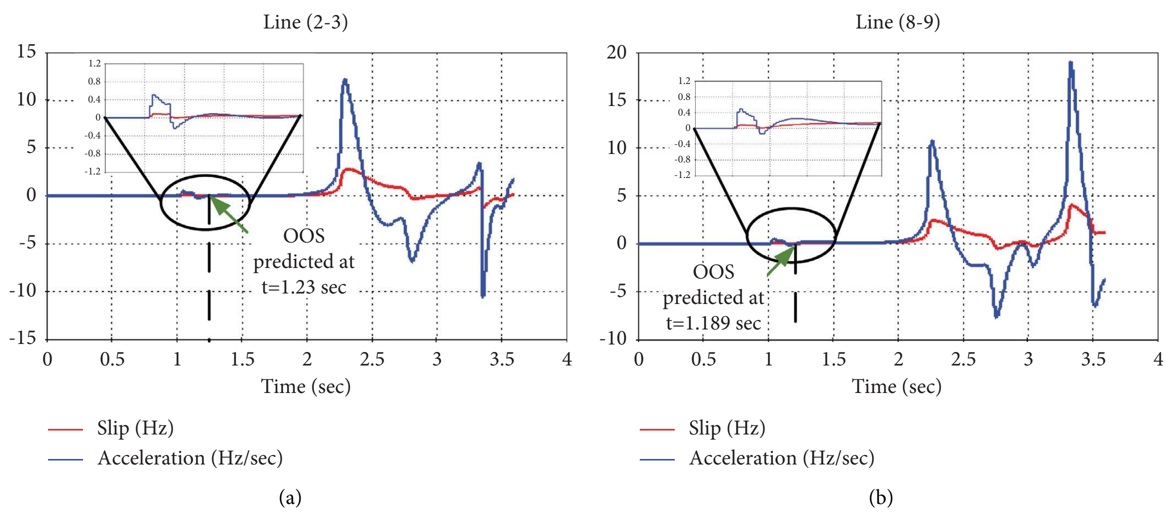

Figure 24: OOS prediction time of the tie lines: (a) line (2-3); (b) line (8-9).

In terms of bus phase angle, the response of the system has been observed and the coherency has been identified. Two groups of oscillating generators were coherently formed against each other.

Group I: G2, G3, G4, G5, G6, G7, G8, and G9

Group II: G1 and G10

It has been found in time domain simulation that the tie lines 2-3 and 8-9 are connecting these coherent groups which tend to go OOS as the voltage angle difference of these tie lines is exponentially increasing and crossing beyond 180° at 2.27 sec and 2.24 sec, respectively as shown in Figures 22(a) and 22(b).

However, using the proposed approach, OOS condition can be predicted earlier than the occurrence of OOS at tie lines 2-3 and 8-9 between group I and group II. At the time of the right crossing of the slip-acceleration locus curve on the horizontal axis as shown in Figure 23(a) and 23(b), OOS has been predicted at 1.23 sec and 1.189 sec, respectively. This can be verified in the time domain from Figure 24. The prediction speed of the proposed technique is 9.5% for lines 2-3 and 6.2% for lines 8–9.

Furthermore, as an unavoidable action, by tripping the tie lines (2-3) and (8-9) at the time of out of step, the system is islanded into two controlled islands as shown in Figure 25. The generator frequency in both areas after islanding is stabilized at 60 Hz, as observed in Figure 26.

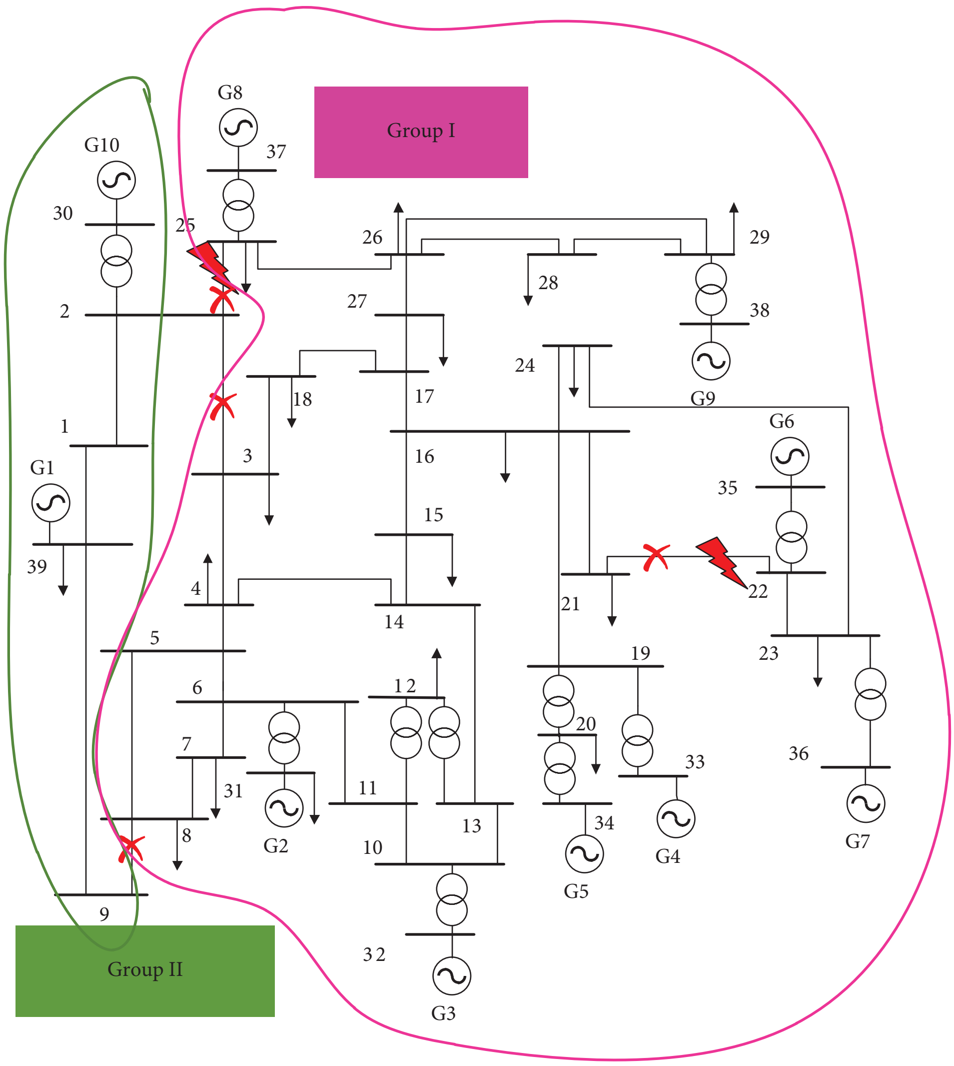

FIGURE 25: Splitting action into two islands.

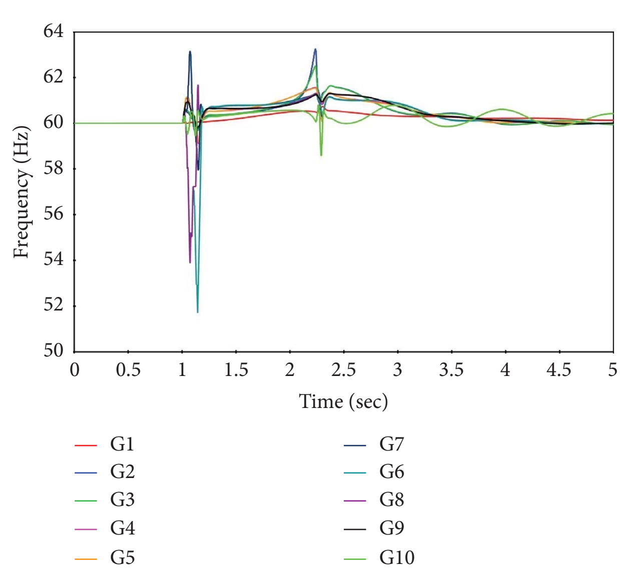

FIGURE 26: Stabilizing the frequency after splitting.

4. Conclusions

The proposed approach in this paper is a synchrophasor-based prediction method for OOS condition in power systems. This work's findings can assist the operators in taking corrective measures to prevent OOS and enhance the system stability. Having advanced warning of potential OOS events can also improve grid management by minimizing equipment damage, preventing outage, and increasing the system reliability. The method is based on the trajectory of first and second derivatives of bus voltage angle difference which has been validated for both generator and interarea oscillation. The concept which has been used for this purpose is the polarities checking at each phasor time step for slip and acceleration of the tie line bus voltage angle difference. This method successfully discriminates between stable and unstable oscillations and no power swing blocking is required as in the case of conventional impedance-based OOS detection schemes, and based on the proposed prediction technique, a controlled islanding has been implemented whereby island stability has been achieved after separation.

The key achievements of this research wok can be summarized as follows:

(i) Early detection of OOS in the system post-disturbance and before the loss of synchronization

(ii) The proposed method is able to predict OOS after any type of disturbance as it is a disturbance-independent method

(iii) The prediction speed is 5%–70% of time to OOS, after disturbance/fault clearance

The limitation of this method is that it can fail to predict OOS when voltage angle difference increases exponentially without oscillations, which are extremely rare in the power system, and in case of the prediction failure, the proposed technique can be used as a relay to trip the tie line and separate the system into islands. The proposed method has been successfully validated in three benchmark systems considering several scenarios. The results show the successful performance of the proposed approach for early prediction of OOS.

Data Availability

The data used to support the findings of the study are included in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research work is entirely the product of the authors' initiatives.

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