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Research Article

Analysis of Oscillations during Out-of-Step Condition in Power Systems

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Power systems interconnected by weak tie lines can be subject to low-frequency oscillations because of disturbances which excites the low-frequency modes of the system; furthermore, these oscillations can be stable or unstable. The latter, if not treated, can cause severe oscillations that divide the network into smaller groups which oscillate against each other, leading to out-of-step (OOS) condition in the network. The detection of OOS condition is a challenge for power system operators in real time as it is difficult with conventional measuring instruments, to identify the instant at which the bus voltage angle between two areas connected by tie line falls out of synchronism. Conventionally, the detection of OOS condition has been carried out with impedance-based relays along with power swing blocking. With the advent of synchrophasor-based measurement units, it is now possible to measure the bus voltage angle in real time leading to direct detection of OOS condition in power system and intentional islanding. In this article, a systematic analytical study and EMT time-domain simulation study have been performed to simulate OOS condition in the power systems, and its detection is based on the voltage angle difference with wide-area measurement systems (WAMSs). The article has been carried out on a single machine infinite bus (SMIB) to monitor generator OOS, Kundur's two-area system to detect interarea OOS, and the IEEE39 bus system to identify OOS condition and with a new algorithm. Time-domain simulation studies carried out with OPAL-RT real-time simulator in HYPERSIM environment corroborates with analytical results.

1. Introduction

Oscillation in the power grid results from the power system's dynamic nature [1]. Among the oscillation modes mentioned in [2], the current attention is drawn to the interarea oscillation mode due to the severity of its results and the fact that it can occur in unexpected lines far from the existing disturbance. The lines in the interarea may not have sufficient damping for these low-frequency oscillations. So, the low-frequency interarea oscillations can cause stress on these weak tie lines and can lead to loss of synchronization by forming coherent groups of generators that oscillate with the same angular speed against others, which in turn leads to cascading failures and ends with network collapse [3, 4]. Maintaining the reliability and security of the power system network requires a basic understanding of oscillations and their dangers, namely, stable and unstable oscillations. Increasing the disturbance severity, which can be either faults, increase or decrease in generation, loss or increase in a large block of load, or changes in network configuration [5], gives rise to the risk of these oscillations leading to so-called out-of-step (OOS) [6].

The current challenge for grid operators is maintaining the stability of the network in the presence of low-frequency oscillations and preventing the OOS condition. Concerning the recent change in power generation toward renewable energy sources (RES), it is worth mentioning that these inverter-based resources, which do not have rotating mass coupled to the grid, lead to a decrease in inertia in the power system. The resulting low inertia in the power system has an impact on the OOS condition [7, 8]. The OOS condition in literature has been addressed in two cases. The first one is for synchronous generators and where the power plant falls out of synchronism after a disturbance contributed by the rotor angle of the generator. Secondly, the OOS condition between two coherent areas contributed by interarea mode. The OOS condition is driven in the power system mainly due to fault disturbances which can excite the generator rotor angle mode or the interarea mode in large interconnected systems. For the faulted system to be stable, the fault should be removed before a time, known as the critical clearing time (CCT). However, when fault clearing time is delayed due to the failure of the breaker, for example, it will lead to out-of-step condition [8].

Upon survey of the literature for OOS, the authors of [5] have proposed a method to protect ultrahigh voltage transmission lines from power oscillation due to wind generation integration and differentiate between symmetrical faults and power oscillation. The authors of [9] have compared the dynamic characteristics of an extensive transmission system with and without photovoltaic penetration, and its stability state has been observed. In [10], out-of-step oscillation has been observed due to sequence faults in a large power system despite clearing the faults at CCT, leading to the need for controlled splitting. Abedini et al. [11] have proposed the free measurement faster-than-real-time (FTRT) method to predict OOS oscillation based on equal area criterion EAC mathematical formulation. In [12], a real-time estimation has been developed to distinguish the OOS oscillation of the generator based on active power derivation. The proposed scheme has relied on the polarity of extracted angular velocity and acceleration data from EAC. In reference to [13], a new EAC approach to detect OOS has been tested by replacing the power-angle curve with the power-time curve.

Traditionally, OOS condition in the power system was detected using an impedance-based distance relay [14]. However, with the implementation of synchrophasor technology on a large scale in power grids, many parameters can be monitored to observe the low-frequency oscillations and detect OOS condition with the help of a phasor measurement unit (PMU) characterized by a phasor (magnitude and angle) output. In [5], an algorithm has been developed based on measuring the angle of the current between sending and receiving ends using the PMU. In [15], the proposed method has used the magnitude of positive sequence voltage obtained from PMU to develop fast and accurate intelligent devices (IDs) to detect symmetrical/asymmetrical faults during power oscillation. The authors of [16] have traced the trajectory of the generators power angle with respect to the frequency in the plane (δ-ω) to implement Zubov's boundary method for stable and OOS oscillation discrimination. In [10], the proposed algorithm can detect out-of-step oscillation in its first cycle and determine its location by obtaining the frequency of the bus voltages using PMU. The feature of the proposed algorithm [17] is independence from the details of the power system and only depends on the phase angle of the terminal voltage of generators collected from PMU.

The latest literature [18–22] have carried out research studies regarding the design of wide-area power system stabilizer (PSS) using PMU for damping interarea oscillations to improve the stability of the system. PSS effectively increases damping of low-frequency oscillations by shifting unstable mode to the left side of the complex plane. However, PSS cannot guarantee the stability of the system in case of large topological changes which in turn leads to OOS condition in the system. In this study, wide area-based OOS condition detection, during the unstable power swing (i.e., the time until which the system remains synchronized from the occurrence of the disturbance in case of an unstable power swing), has been proposed. In this way, this article is different from the damping of oscillation in power systems with PSS.

Though several methods have been proposed in the literature to avoid the mal operation and overcome the difficulties of the traditional impedance-based method with continuously increasing RES in the power system, to avoid the complex calculations required for setting of impedance-based traditional OOS relay, it is worthy to go for a measurement-based method. Thus, the first contribution in this article is an algorithm which is simple and does not need the complex data of the system; it only needs the bus voltage angle obtained directly from PMU without the requirement of any computational estimation. The second contribution is that the presented method can detect both generator mode and interarea mode, as previous studies have been concerned with either one of these modes in their research. Furthermore, a systematic study on the analysis of OOS condition from small to large power systems under different disturbance scenarios in the time domain as well as in the frequency domain (eigenvalues) has been performed. Thirdly, this article shall be helpful for monitor OOS in the power system which can be used to identify unintentional catastrophic tripping of transmission lines due to voltage angle separation between two coherent areas. The proposed OOS detection method can be considered to identify the instant at which the voltage angle separation of a generator (or between two coherent areas) falls out of synchronism, leading to instability in the power system.

To summarize, this article performs an OOS analysis of power oscillation in grid-connected generator and interconnected power systems. An out-of-step tripping algorithm has been developed and implemented in the presence of different disturbance scenarios, using the information output from wide-area measurements. Simulation studies have been performed on SMIB, Kundur's 2-area systems, and IEEE39-bus system in OPAL RT real-time simulator with 50 μ sec time step in HYPERSIM software. Results in the time domain have been verified with eigenvalue analysis.

2. Out-of-Step Background

Out of step is a condition in a power system where the phase angle between two buses in an interconnected power system or rotor angle of a generator and its generator bus exceeds 180 degrees [23]. OOS condition can occur between the generator and the network which is known as a local mode with frequency oscillation in the range (0.7–2) Hz or between coherent areas causing interarea oscillation mode in the network transmission lines with low-frequency (0.1–0.8) Hz [24]. The generator falls out of synchronism with the generator bus in case of OOS condition, and in case of an interconnected power system, the tie line oscillations shall not be stable. This article has focused on interarea OOS condition and on generator as well. The basics of the OOS condition can be analysed with steady-state power transfer equation, swing equation, and modal values explained as follows.

2.1. Steady-State Power Transfer. The transmitted active power through a transmission line in a grid, as shown in Figure 1 [25], is given as follows:

$$P_e = \frac{V_s.V_R}{X_s}.\sin\delta. \tag{1}$$

In equation (1), V_S and V_R are sending and receiving ends voltage of the line, δ is the voltage angle difference ($\delta_s - \delta_R$), and X_S is the equivalent reactance of the transmission line. Typically, there is a voltage angle difference between two ends of any transmission line to achieve the power transfer principle as a power-angle ($P-\delta$) characteristic [25]. However, if this angle difference oscillates under exposure to any disturbance, it should not reach the value of 180°. Otherwise, the oscillation will not dampen out, and this angle difference will keep increasing, leading to a loss of the synchronism of these two areas, according to equal area criterion (EAC) [26].

2.2. Swing Equation. In case of a disturbance to the generator connected to the bus, the rotor angle of the generator oscillates according to the swing equation [27]:

$$\frac{H}{\pi.f_0}\frac{d^2\delta}{\mathrm{d}t^2} = P_i - P_t, \tag{2}$$

where H is the area inertia per unit, δ is the electrical power angle in radians, which will vary with time, and P_i is the area input power and P_t is the electrical transmitted power. OOS condition occurs when the rotor angle oscillations cross 180 degrees away from the bus voltage angle to which it is connected.

2.3. Modal Values. Modes are the roots of the characteristic equation of the power system matrix, and these can be determined by eigenvalue analysis. With the use of eigenvalues, the nature of these oscillations mode can be indicated as follows [1]:

$$\lambda = \sigma \pm j\omega. \tag{3}$$

The damping coefficient is given as follows:

$$\tau = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}. \tag{4}$$

Moreover, the frequency of oscillations is given as follows:

$$f = \frac{\omega}{2\pi}. \tag{5}$$

The positive real part of the eigenvalue indicates an unstable system with a negative damping coefficient, and the imaginary part decides the oscillation mode.

The OOS condition due to this small signal stability cannot be identified easily with conventional measurements. Traditionally impedance-based distance relays with blinders were used to identify the OOS condition due to the interarea mode in the system.

2.4. Wide Area Measurement System (WAMS). With the advancement of synchrophasor technology, an enormous number of research studies have been directed to the wide-area measurement system (WAMS). WAMS is a network of PMUs connected by a communication system. All PMUs of various substations are connected to one phasor data concentrator (PDC) [28], which is a central computer that collects information from all PMUs and stores it for later use to predict how the future of the network will be. PDC can monitor the system in real time to warn the operators or send a trigger signal in case of any disturbance. The main feature of this technology is the GPS synchronization with a phasor measurement unit (PMU) to give output with time-stamped measurements [23]. PMU is a measurement device that can report data at various data rates (10, 30, 60, and 120 frames per second), to convert the input instantaneous values to the time-stamped samples as represented in Figure 2.

2.5. Traditional Algorithm. Traditionally, out-of-step condition was detected in the power system with impedance measurement, based on distance relay with a "blinders scheme" [29]. Power swing blocking (PSB) and out-of-step tripping (OOT) functions have been added to the impedance relay. In this scheme, if the impedance trajectory during the fault or oscillation travels from the right outer blinder to the right inner blinder (ΔZ) during time $\Delta t > \Delta t_{\text{setting}}$, the outer zone Z3 function will be blocked from tripping as the distance relay distinguishes stable power swing from fault. While OOT function permits the distance relay to trip immediately when the impedance trajectory leaves the right inner blinder as the relay identifies the OOS condition, as represented in Figure 3.

As aforementioned, blinders' scheme requires proper settings for ΔZ and $\Delta t_{\text{setting}}$ along with blinder locus depending on system configuration which may change at any time because of any contingency. Therefore, to implement this multiple functionality scheme, a thorough study of system stability and detailed analysis of the system in presence of different types of disturbances has to be carried out precisely which is difficult in a larger system. Otherwise, maloperation of relay may occur causing undesired triggering.

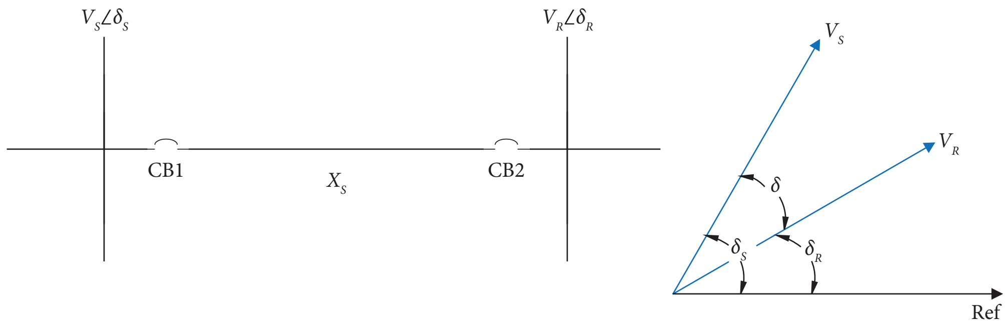

FIGURE 1: Sending and receiving ends of the transmission line.

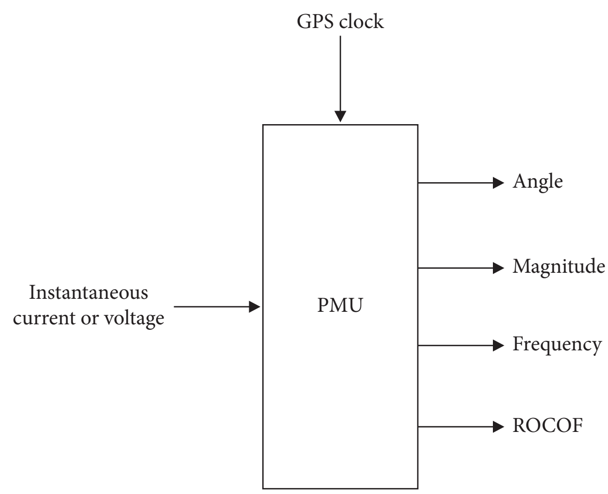

FIGURE 2: PMU input and output.

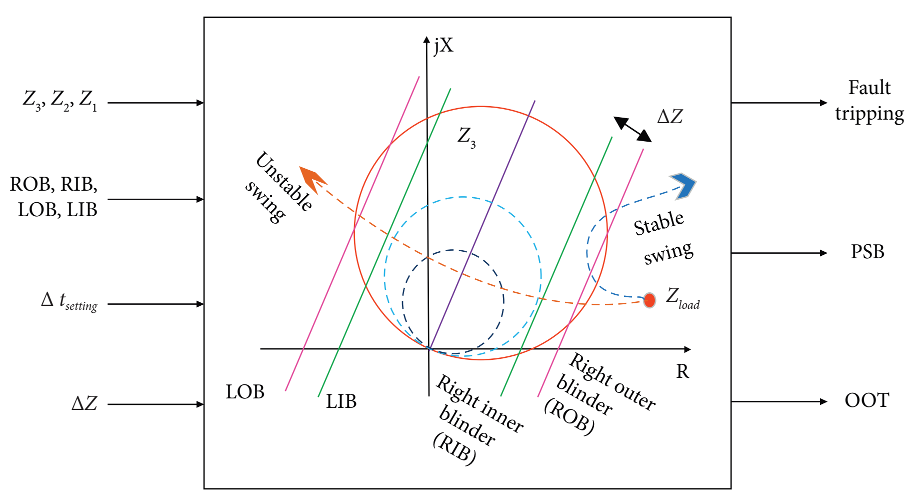

FIGURE 3: Blinder scheme.

2.6. Proposed Algorithm. Taking advantage of the PMU data stream at substations, the bus voltage angle can be measured from two PMUs at the ends of the tie line. The test configuration is shown in Figure 4.

The voltage angle difference $(\delta_s - \delta_R)$ has been implemented to trip at out-of-step condition after collecting PMUs data [30], as shown in Figure 5.

The voltage angle difference tool of the tie line has been carried out using MATLAB/Simulink and has been imported to HYPERSIM for observation.

Figure 6 demonstrates the proposed relay algorithm to detect OOS condition based on the voltage angle difference between the buses at both ends of the tie line. The trip decision is taken when the voltage angle difference is equal to

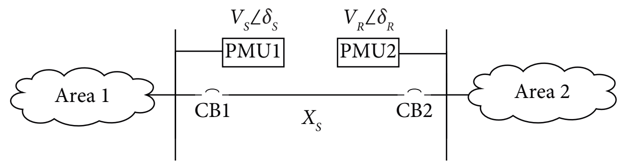

Figure 4: PMUs on buses on both ends of the tie line.

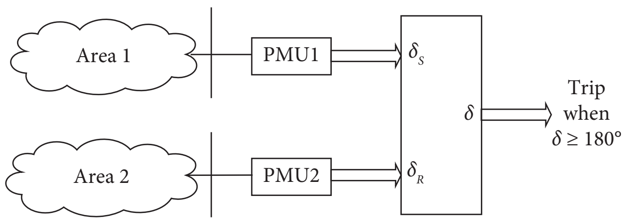

Figure 5: Implementation of OOS tripping.

or greater than 180°. The main advantages of the proposed approach are the simplicity, measurement based, and independent of the system topology.

3. Case Study

The study has been carried out on OPAL-RT real-time simulator using HYPERSIM environment, which is software that helps to simulate and test power systems with realistic visualization. PMU is a measurement device that can be utilized to obtain phasor quantities, which has been simulated in Simulink and imported into HYPERSIM, to collect bus voltage angle. Furthermore, HYPERSIM can provide the damping coefficient and the frequency of oscillations of the system from which eigenvalue can be calculated.

The analysis has been carried out on three configuration systems to monitor the behaviour of system stability under different disturbance scenarios. First, the effect of changing the generated power of SMIB on CCT, considering a three-phase fault, has been simulated at the sending end of one of the lines. Second, on Kundur 2 area system, three scenarios have tested changing inertia, load variation, and changing network configuration. Lastly, interarea oscillation has been created by 2 three-phase faults at different locations on the 39-bus system to observe the behaviour of out-of-step condition in the extensive system.

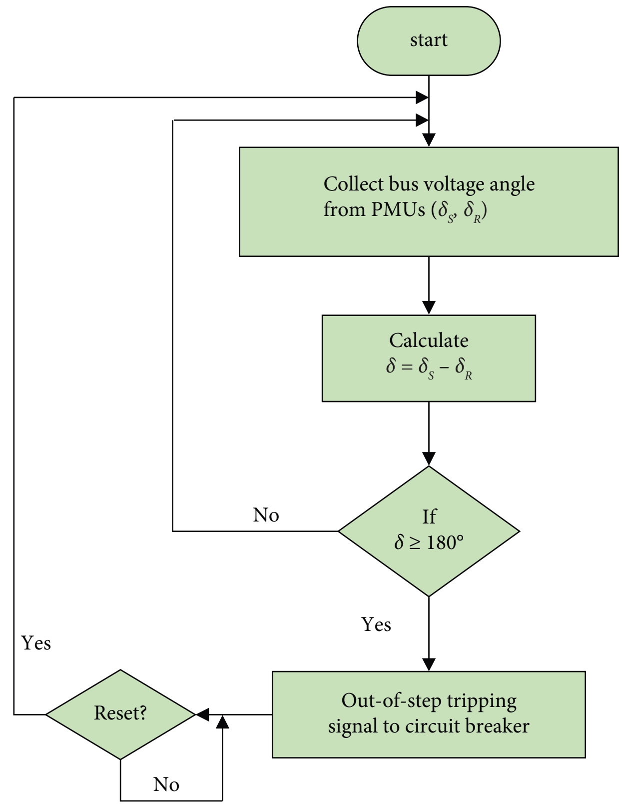

Figure 6: Proposed algorithm based on voltage angle difference.

3.1. Case Study I: Single Machine System (Generator Mode).

The study system in this case is a 60 Hz single machine connected to an infinite bus through two transmission lines (Figure 7). The parameters of SMIB are given in Table 1. A three-phase fault has been applied on line 2, at the sending end of the line at 1 sec. The fault has been cleared by tripping of the lines from both ends. The time of clearing the fault has been varied according to the different scenarios of power transmission. The OOS condition, at which the generator falls out of synchronism with a phase angle difference of 180 degrees, has been detected with PMU measurements from bus 2 and bus 3. The relay algorithm developed has been used to detect the OOS condition and trip the generator. The results have been analytically verified with the calculated values of CCT.

The CCT has been calculated as given in [31] using critical clearing angle (CCA) δ_c with the following equations:

$$
\begin{aligned}
\cos\delta_c &= \frac{P_0\left(\delta_{\max}-\delta_0\right)+P_{3\max}\cos\delta_{\max}-P_{2\max}\cos\delta_0}{P_{3\max}-P_{2\max}},\\
\text{du ring fault } P_{2\max}\sin\delta &= \frac{V_s V_R}{X_{df}}\sin\delta,\\
\text{after fault} P_{3\max}\sin\delta &= \frac{V_s V_R}{X_{af}}\sin\delta.
\end{aligned}
\tag{6}
$$

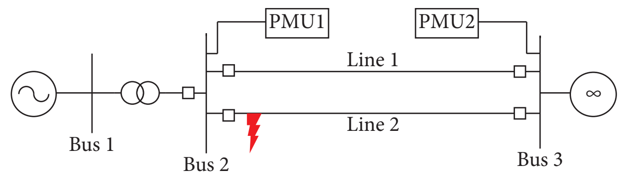

Figure 7: SMIB with fault on line 2.

Table 1: SMIB parameters.

Device	Parameter (p.u)
Transformer imp	0.05
Generator (X_d')	0.3
Generator (H)	6.112
Line 1 = line 2	0.3
$X_{\text{before fault}}$	0.5
$X_{\text{during fault}}$	inf
$X_{\text{after fault}}$	0.65
Network	Inf. bus voltage = 1

Table 2: Calculated and simulated CCT values with changing power.

Scenarios	Power flow (pu)	CCT (sec) In EAC and time domain
Scenario1	$0.9 + 0.430j$	0.265
Scenario2	$0.8 + 0.074j$	0.287
Scenario3	$0.6 + 0.450j$	0.400
Scenario4	$0.4 + 0.910j$	0.561

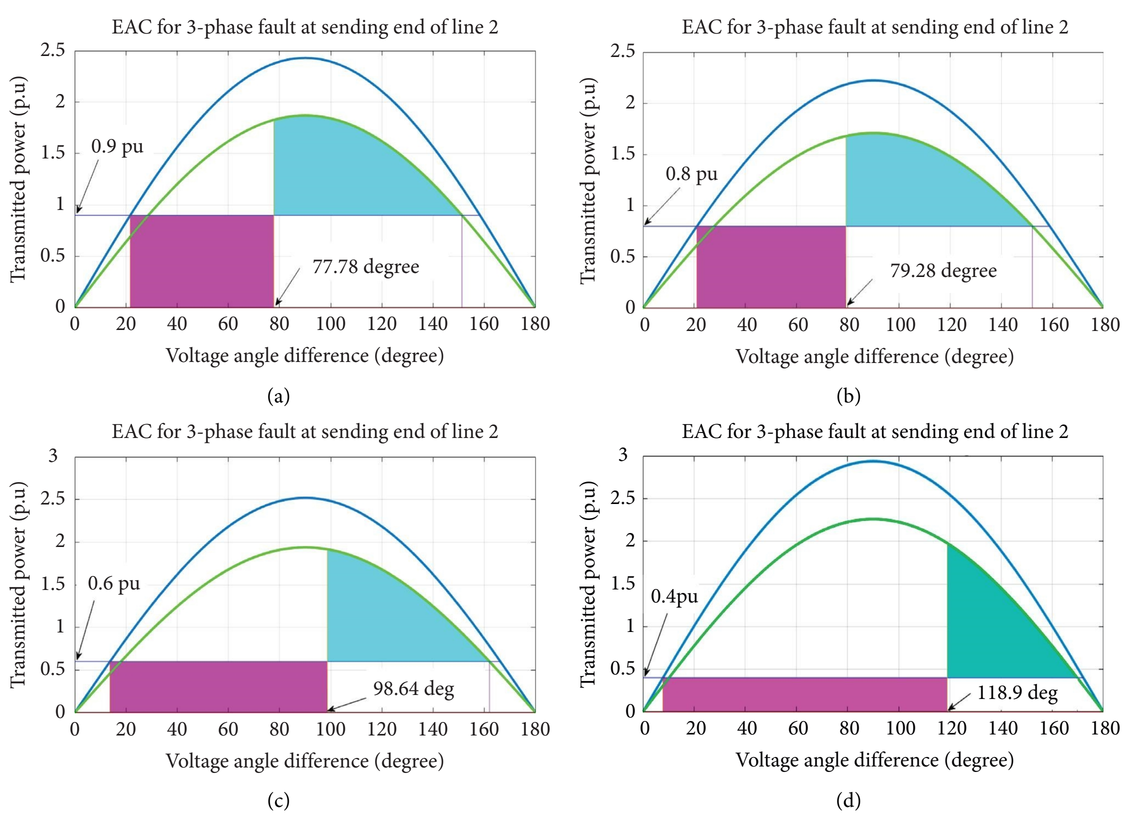

Figure 8: SMIB equal area criteria for different values of active power: (a) 0.9 pu, (b) 0.8 pu, (c) 0.6 pu, and (d) 0.4 pu.

X_{df} = inf because the fault occurs on sending end. X_{af} = the reactance of line 1.

$$t_c = \sqrt{\frac{2H(\delta_c - \delta_0)}{\pi f_0 P_0}}. \quad (7)$$

OOS condition has been evaluated in the power angle domain in the light of the same fault applied at 1 second for all generating scenarios in Table 2. To verify the OOS condition at CCT, equal area criteria have been plotted for all scenarios observing CCA for corresponding generated power.

Figure 8 demonstrates equal area criteria with the value of CCA required to get CCT. Table 2 shows the CCT from the time of the fault. The table illustrates that decreasing generated active power increases CCT. Thus, clearing time (CT) of the fault on or before these CCT will maintain the system's stability as verified in time domain (Figures 9 and 10).

Traditional transmission line relays are coordinated in such a way as to clear the fault at a predetermined time. Moreover, the integration of renewable energy and its generation relies on the renewable sources. This may cause instability issue and out-of-step condition when, for example, the relay has already been set to operate at 0.4 seconds (scenario 3 in Table 2) from the time of the fault.

Now, when the generated power raises up to 0.8 pu, which requires lesser time to clear the same fault, for the system to be stable, the transmitted power oscillates continuously, as in Figure 10.

To capture the previous said phenomenon in WAMS, bus voltage angle difference is measured through PMU at Bus 2 and Bus 3. Figure 11 plots stable and unstable bus voltage angle difference oscillations due to OOS condition. If there is any delay in clearing time (CT) of the fault, the system will be out-of-step, and there will be a loss synchronization when the voltage angle difference goes beyond 180° as in Figure 11, which compares clearing the fault on and after CCT.

To verify the results in small signal stability criteria, eigenvalues have been calculated using damping ratio and oscillation frequency, which have been obtained from the model identification method in SCOPE VIEW software from Figures 9 and 10. The stability conditions have been evaluated by using eigenvalues in case of fault clearing time (CT) equal to CCT and greater than CCT.

As shown in Table 3 the real parts of the eigenvalues are negative when clearing the fault happens at CCT, indicating a stable system. Unlikely, when CT > CCT, the real parts of the eigenvalues are positive which denotes the OOS condition for different scenarios considered.

From this case study, it can be inferred that the OOS condition in generator detected with phase angle difference from PMU measurements in real time confirms to the EAC criterion, which is difficult to implement in generators otherwise.

3.2. Case Study II: Kundur Two Area System (Interarea Mode). The second case study has been carried out on Kundur's two area system. It is a 50 Hz power system consisting of two symmetrical areas, as shown in Figure 12. Each area has two generators and five buses in addition to the two middle lines with a bus; thus, there are 11 buses. Two loads are connected with buses 4 and 6, and detailed parameters are in [30]. The transmitted power from bus 4 to 6 has been measured, and two PMUs have been connected with bus 3 and bus 7. Thus, the tie lines' transmitted power and voltage angle difference have been observed to identify out-of-step conditions during the scenarios of varying loads, inertia, and network configuration.

3.2.1. Scenario I: Load Variation. In this scenario, the OOS condition has been simulated in two area systems by varying the load in the system so that the interarea mode oscillations are excited. The initial condition for tie line power transfer of 410 MW has been set and load 2 on bus 6 has been varied by increasing the load by 30% and 50% at 1 sec. Figure 13 shows how the power oscillations due to interarea mode for the two cases. It can be observed that the system remains stable in case of a 30% change where as it turns unstable for 50% change.

Therefore, the OOS condition for 50% change has to be detected in real time so as to prevent the collapse of the system. Figure 14 represents the effect of load variation, on the voltage angle difference between bus 7 and bus 3, measured through PMU for both cases. It can be observed that, for the unstable case at 180-degree separation, two areas lose their synchronization and run under out-of-step conditions. Eigenvalue analysis for this scenario has been performed and tabulated in Table 4 to verify the time-domain results.

3.2.2. Scenario II: Change in Inertia. In this section, the effect of inertia has been observed by applying a three-phase fault on one of the lines between bus 5 and bus 6 at 1 sec; then, the fault has been cleared at 1.08 sec [30]. Under this condition, two subscenarios have been studied, giving the inertia of generator 3 two values (6.175 and 3.175). Figure 15 shows a comparison between stable and unstable transmitted power during a change of inertia.

Low inertia increases the oscillation of the generator rotor, consequently causing unstable power flow in the interconnected system and increasing the bus voltage angle difference of the tie lines, as shown in Figure 16.

It can be noted from equation (7) that CCT relies on system inertia and decreasing inertia requires decreasing the time of clearing the fault [8]. Noting that, in this article, in both scenarios, clearing the fault has been carried out at 1.08 sec, causing the out-of-step condition in case of inertia 3.175. Therefore, under the same fault condition, low inertia causes OOS condition, which has to be considered to protect

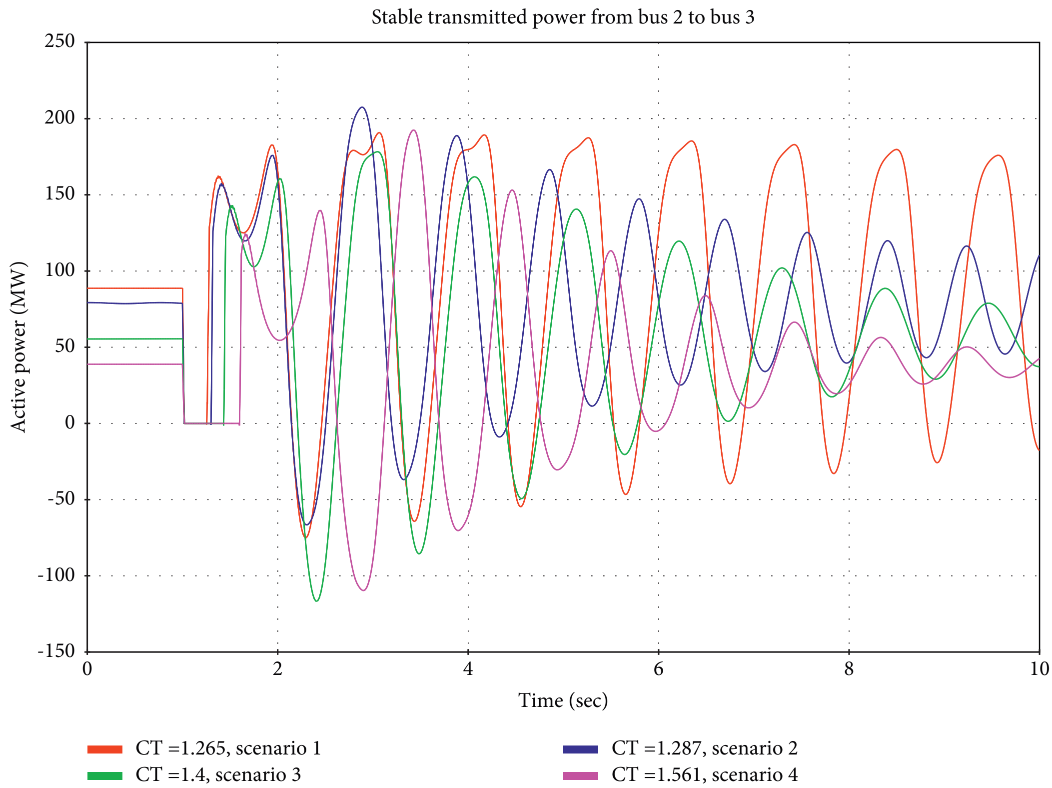

FIGURE 9: Transmitted power from bus 2 to bus 3 for different generated power when CT = CCT.

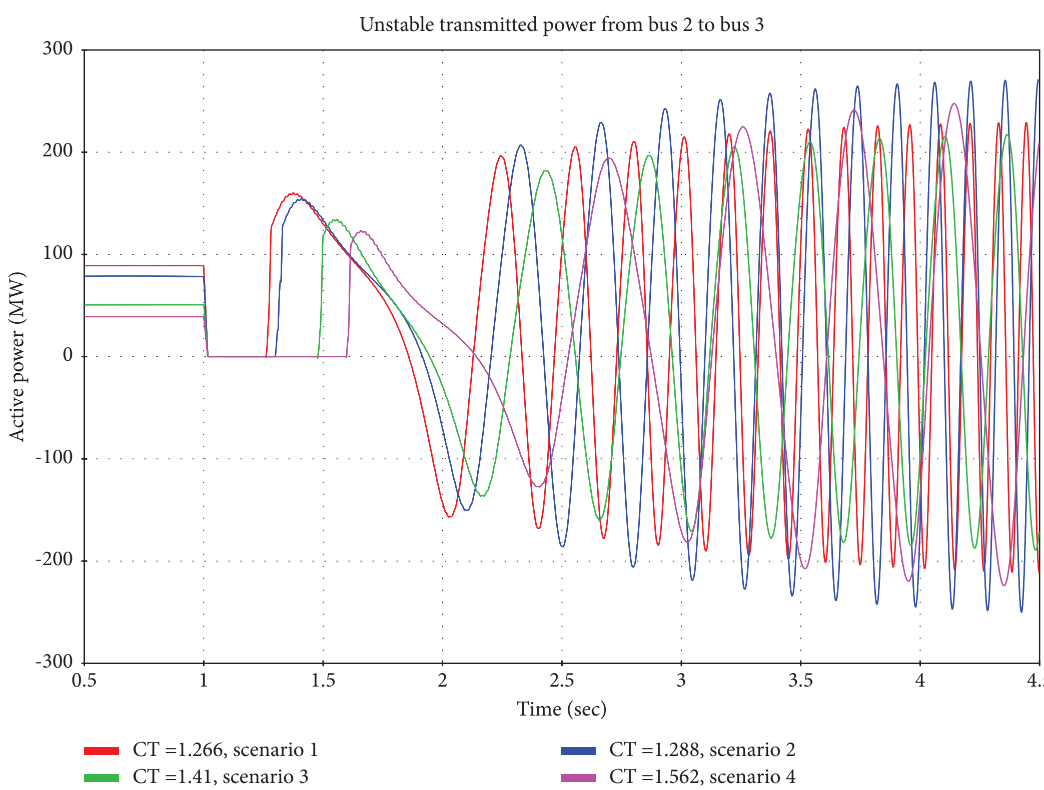

FIGURE 10: Transmitted power from bus 2 to bus 3 for different generated power when CT > CCT.

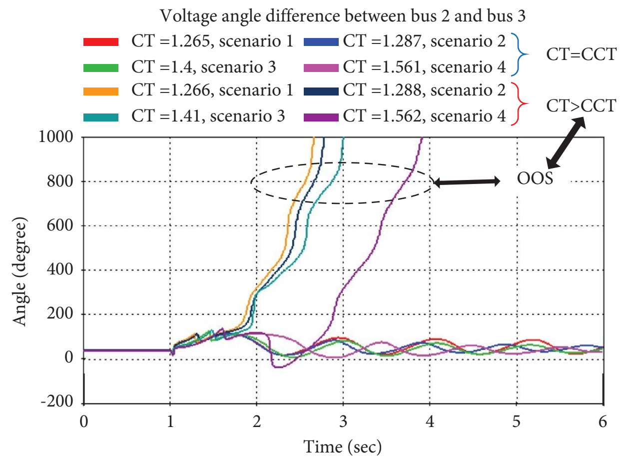

Figure 11: Voltage angle difference between bus 2 and bus 3 for different generated power in cases CT = CCT and CT > CCT.

Table 3: SMIB eigenvalues.

Scenario Power flow (SMIB)	$\lambda = \sigma \pm j\omega$ (stable) (CT = CCT)	$\lambda = \sigma \pm j\omega$ (unstable) (CT > CCT)
$0.9 + 0.43j$	$-0.3474 + 4.950j$	$0.2287 + 87.96j$
$0.8 + 0.074j$	$-0.335 + 4.390j$	$0.2243 + 65.97j$
$0.6 + 0.45j$	$-0.7100 + 4.390j$	$0.0591 + 29.53j$
$0.4 + 0.91j$	$-0.6500 + 4.020j$	$0.056 + 16.960j$

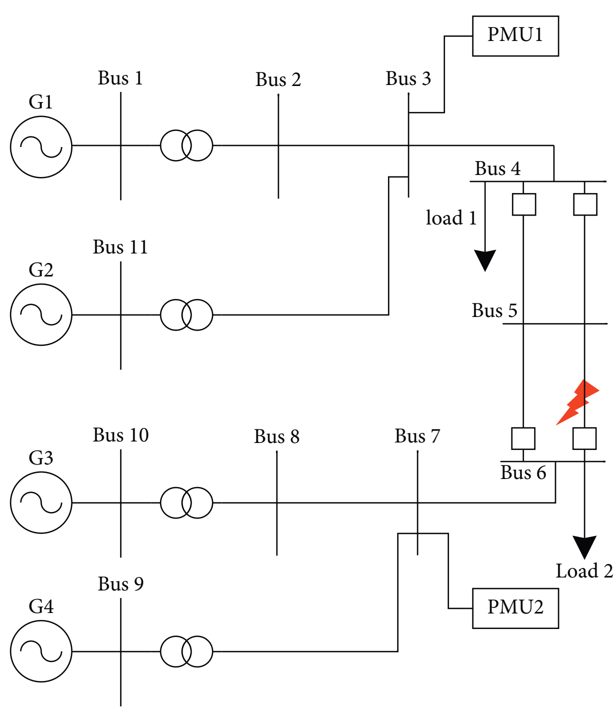

Figure 12: Kundur two area system.

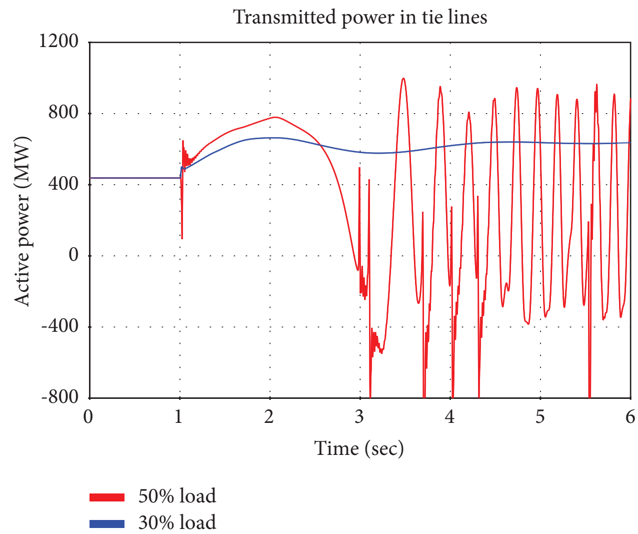

FIGURE 13: Power oscillations in tie lines for cases of 30% and 50% load increase.

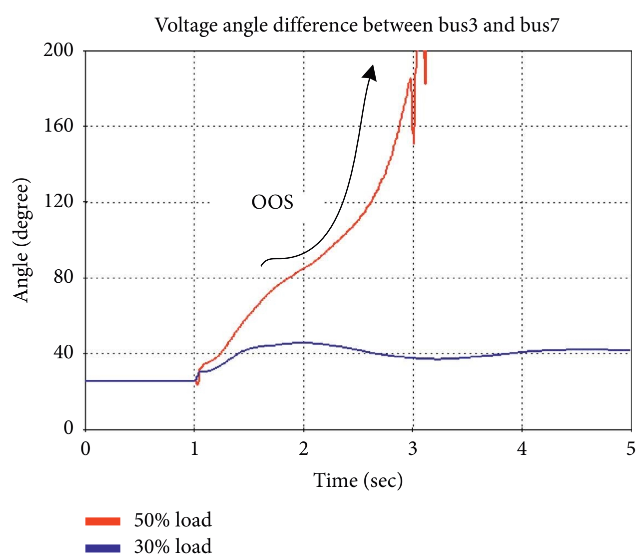

FIGURE 14: Voltage angle difference between bus 3 and bus 7 in cases of 30% and 50% loading increase.

TABLE 4: Two-area system eigenvalues.

Scenario	$\lambda = \sigma \pm j\omega$ (stable)	$\lambda = \sigma \pm j\omega$ (unstable)
Change inertia	$H = 6.175$ $-0.240 + 3.080j$	$H = 3.175$ $0.0704 + 17.59j$
Change load	30% variation $-0.5650 + 2.390j$	50% variation $0.188 + 37.57j$
Network change	AG fault $-0.2521 + 1.696j$	ABCG fault $0.0277 + 15.4j$

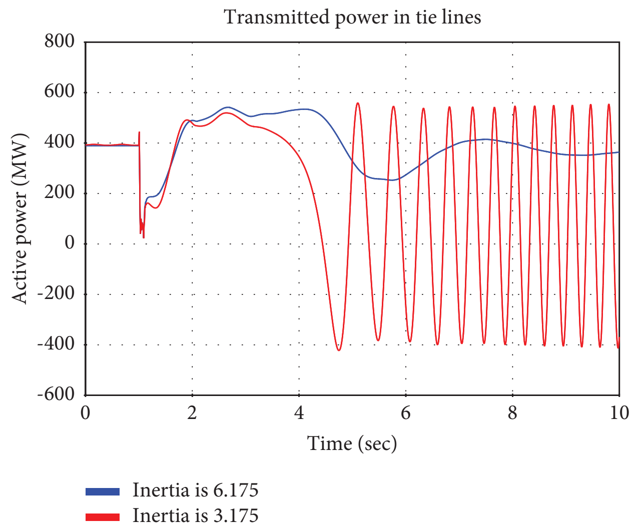

Figure 15: Effect of changing inertia on transmitted power.

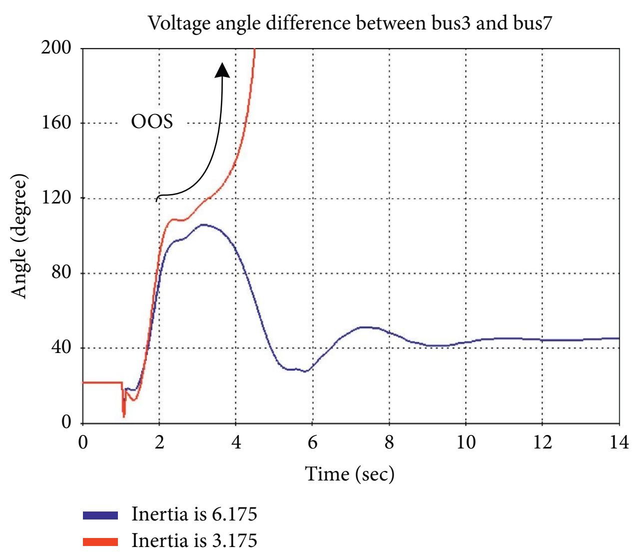

Figure 16: Effect of changing inertia on voltage angle difference.

the grid from this condition and its results. The results in this scenario have been verified by the eigenvalues calculated and tabulated in Table 4.

3.2.3. Scenario III: Change in Network. In this section, the changing network is represented by losing one of the lines between bus 4 and bus 6 due to a 3-phase fault and a line to ground fault and cleared at 1.07 sec, as shown in Figure 17.

The tie line power remains stable after removing the line to the ground fault. However, in the case of the 3-phase fault, caused out-of-step between area 1 and area 2 and bus voltage angle difference to cross 180°, as given in Figure 18, eigenvalue analysis has been carried out for both conditions, and Table 4 demonstrates unstable condition with positive real parts of the eigenvalues.

Disconnecting any electrical element from the network under any condition may expose it to the consequence of OOS. In such an unavoidable case, a protection system from OOS has to be built into the power system to ensure the security.

Table 4 presents positive real part eigenvalues in case load = 50%, $H = 3.175$, and loss line of the network, indicating OOS condition.

In all scenarios when an OOS condition exists because of any of the disturbances mentioned previously in the system, splitting action should be taken, by creating two independent islands to protect the system from collapsing.

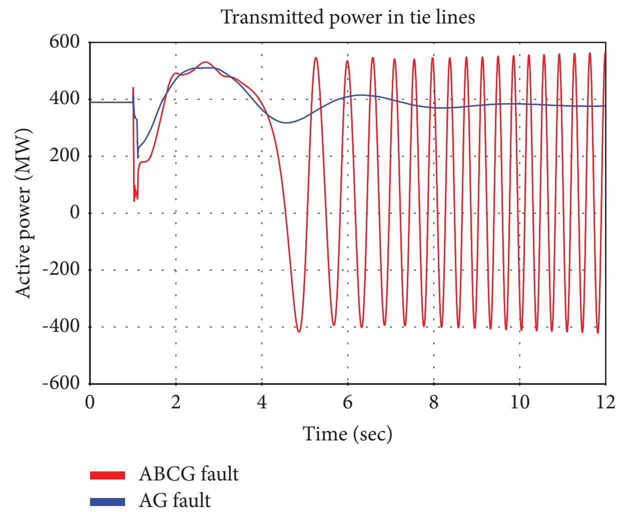

Figure 17: Effect of changing network configuration on transmitted power.

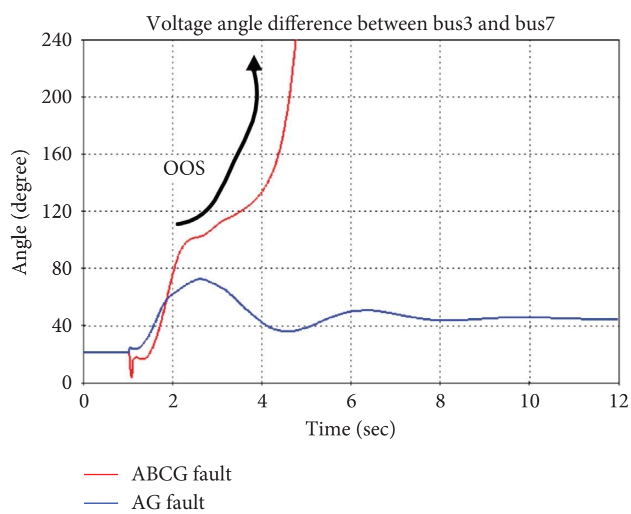

Figure 18: Effect of changing network configuration on voltage angle difference.

This solution has been analysed on the extensive system as follows using the proposed voltage angle difference method.

3.3. Case Study III: IEEE39 bus System. This section aims to analyze out-of-step oscillation in the IEEE39 bus system and identify the coherent group. The system has a 60 Hz frequency and consists of 10 generators, 12 transformers, and 34 transmission lines (Figure 19), and the detailed parameters are in [32]. Two scenarios have been simulated: first a three-phase fault and second a three-phase faults at two locations simultaneously in the system.

3.3.1. Scenario I. First, a fault was applied on line 21-22 at 1.0 sec and cleared by tripping the line at 1.12 sec. All generator's frequency has been measured, which is the best parameter that can be monitored to check if there is an oscillation in the system. Stable oscillations have been observed for this scenario as shown in Figure 20. Therefore, no OOS condition has been detected in the system. The eigenvalue calculation given in Table 5 verifies the stable condition.

3.3.2. Scenario II. In the second scenario along with the previous fault on line 21-22, one more fault on line 26–29 at 1 sec and has been applied and cleared by isolating that line at 1.1 sec. The response of the system in terms of generator frequency is shown in Figure 21 in three parts by grouping the coherent oscillations. It can be observed that the generators frequency is no longer stable leading to OOS condition in the system. Eigenvalue in Table 6 confirms the time-domain response.

3.3.3. Comparison of Scenarios. After finding out coherent generators, tie lines have to be identified; thus, in time-

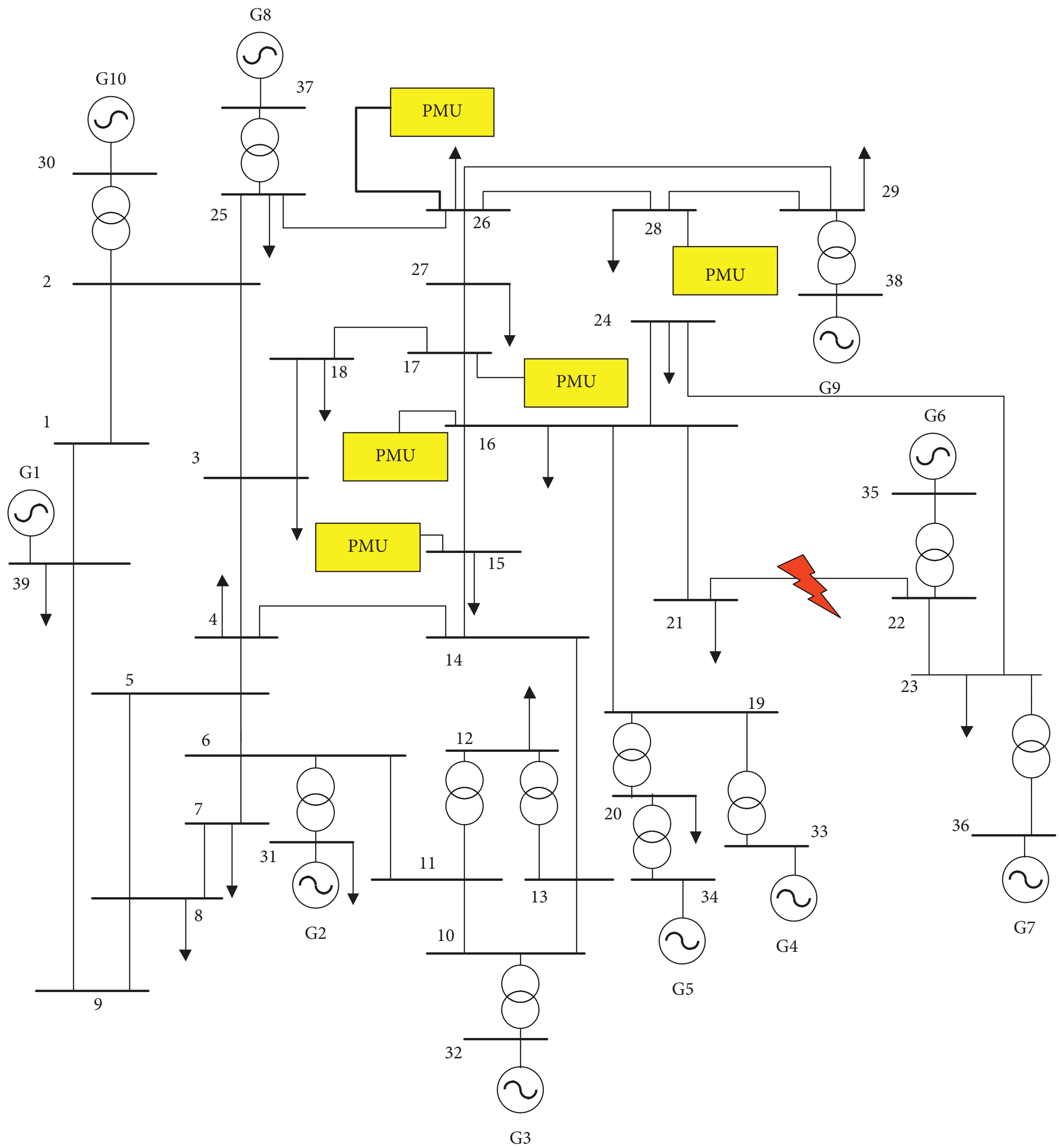

Figure 19: IEEE39-bus system.

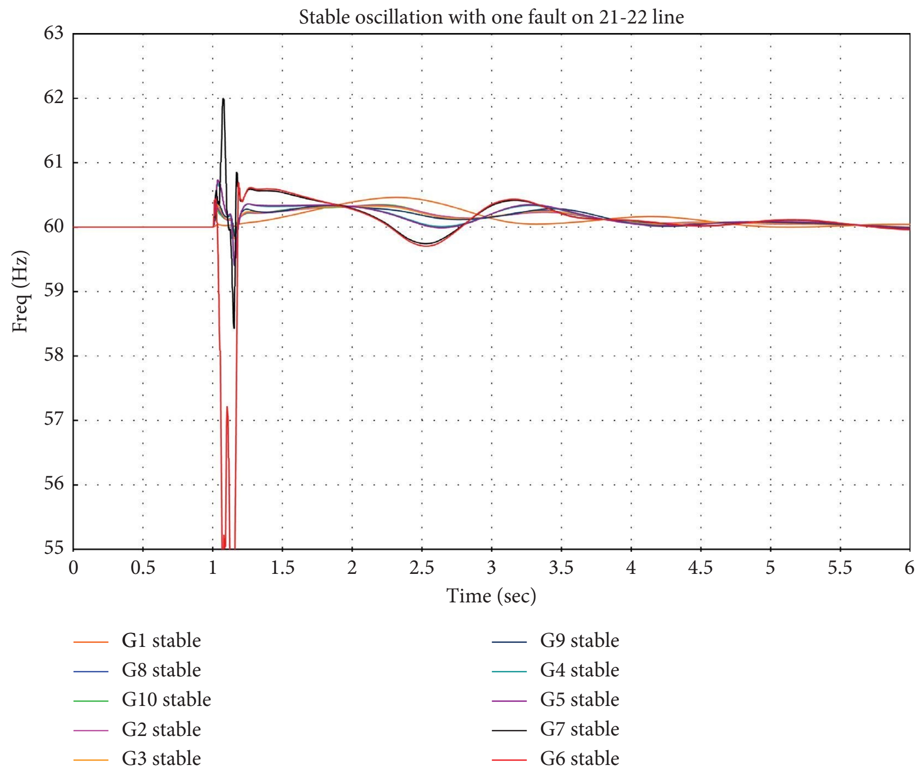

FIGURE 20: Stable generators' frequency.

TABLE 5: 39-bus system negative real part of eigenvalues.

Study case	$\lambda = \sigma \pm j\omega$ (stable)
39-bus system	Single fault $-0.3850 + 1.82j$

domain simulation, the oscillation frequency of system buses has been observed to monitor the coherency of buses as well. Along with that, the bus voltage angles difference across the lines connecting the coherent groups have been observed. The lines (15-16, 16-17, and 26–28) are going out of step, as shown in Figure 22.

Figure 22 compares both the scenarios transmitted active power and voltage angle difference of the three tie lines. In the case of a single fault, the power and angle difference for all the tie lines become stable after oscillating for some time. However, in the case of two simultaneous faults, the tie line bus voltage angle difference exceeds 180 degrees leading to OOS condition. Keeping the system operating in this condition will cause significant damage to the network and collapse of the system, so separating actions should be taken immediately when the voltage angle difference reaches 180° to maintain the security and reliability of the system. Thus, the three tie lines have been tripped with the developed algorithm, creating three stable islands with continuing the supply to the loads as in Figure 23.

This solution protects the system from collapsing and prevents any power outage for the consumers. Figure 24(b)

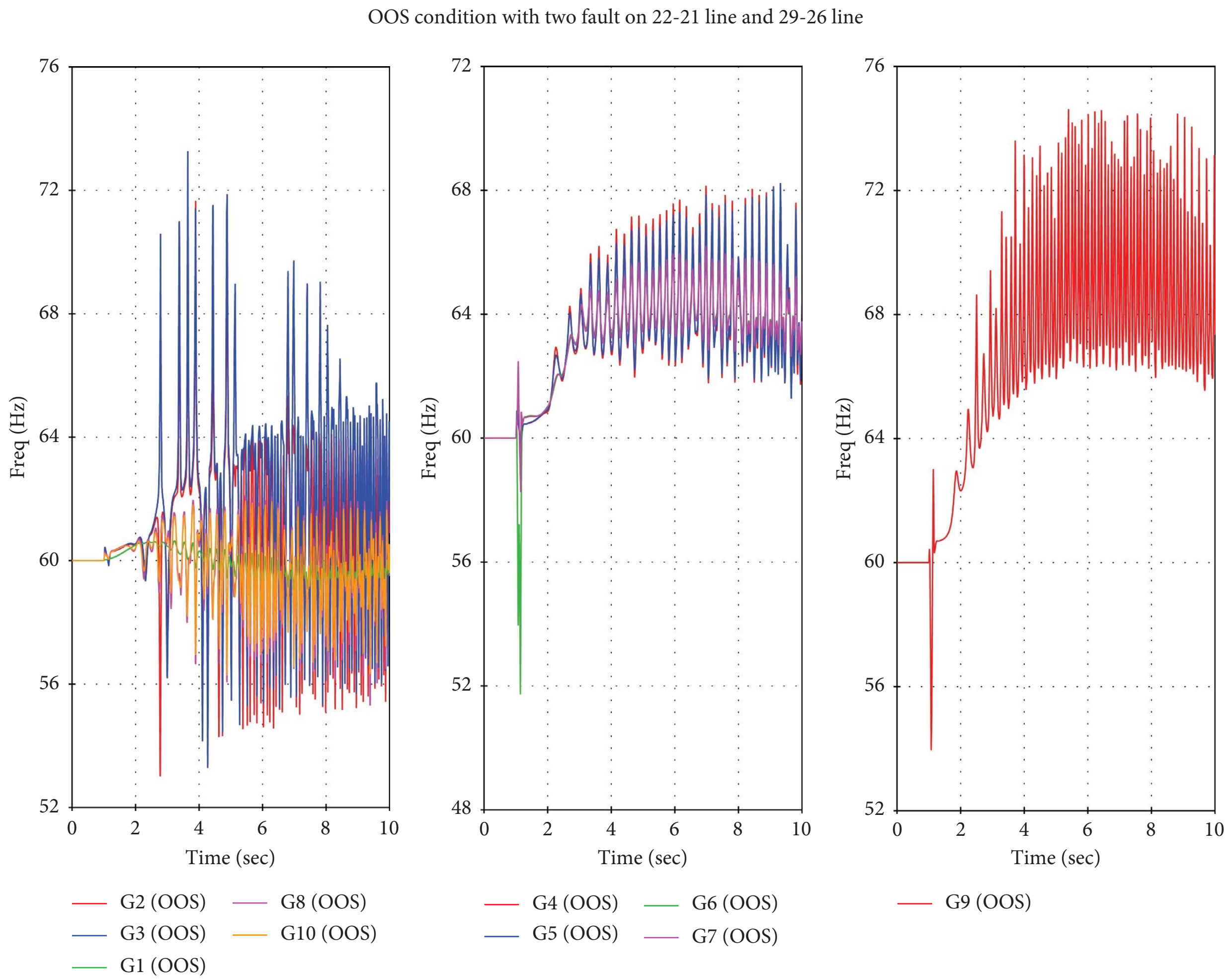

Figure 21: group of generator oscillates with the same frequency.

Table 6: 39-bus system eigenvalues (OOS).

Study case	$\lambda = \sigma \pm j\omega$ (unstable)
39-bus system	Two faults $0.1327 + 33.175j$

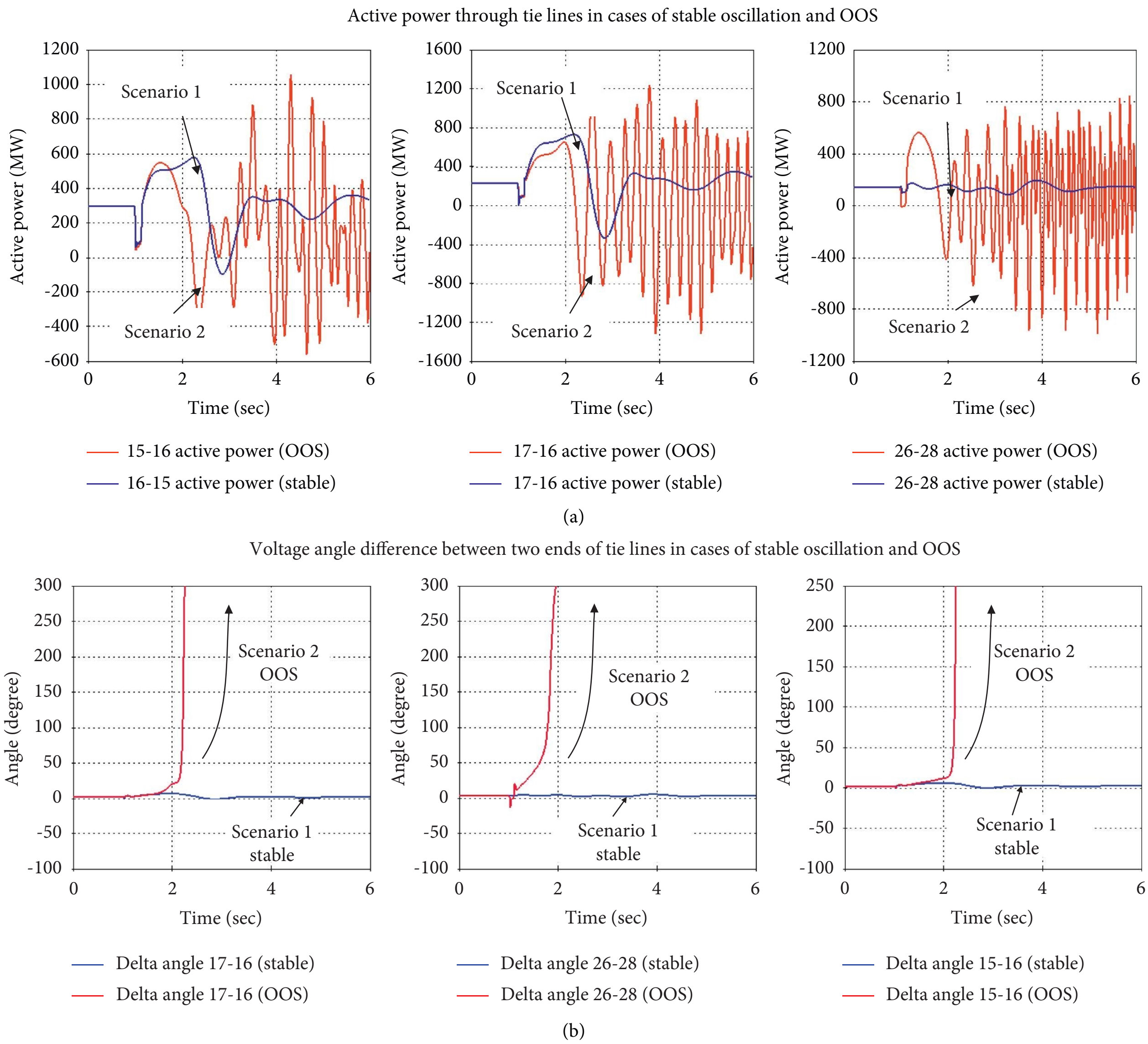

Figure 22: Comparison between stable and out-of-step conditions: (a) tie lines' active power and (b) voltage angle difference.

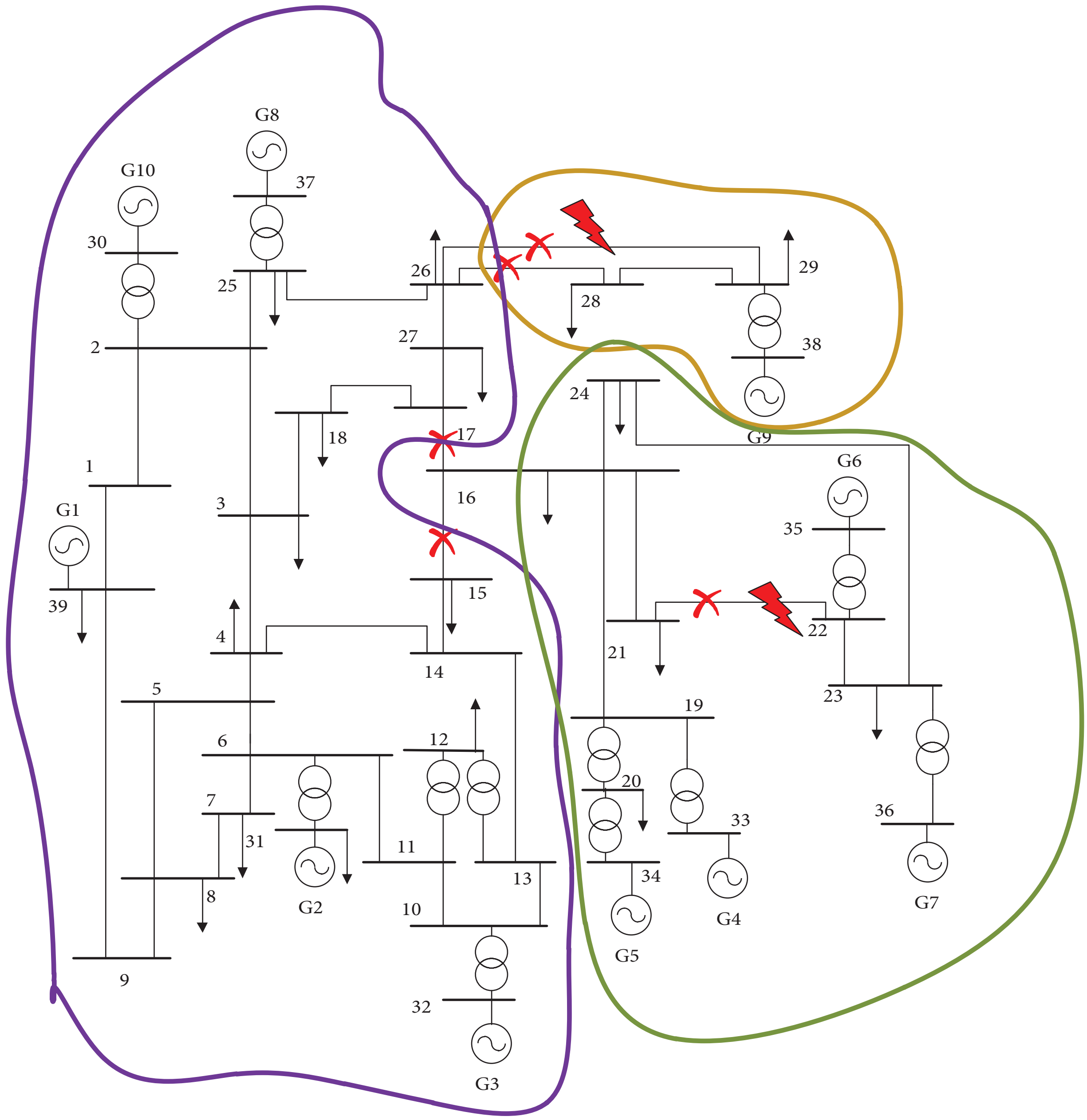

Figure 23: Separating the 39-bus system into three islands.

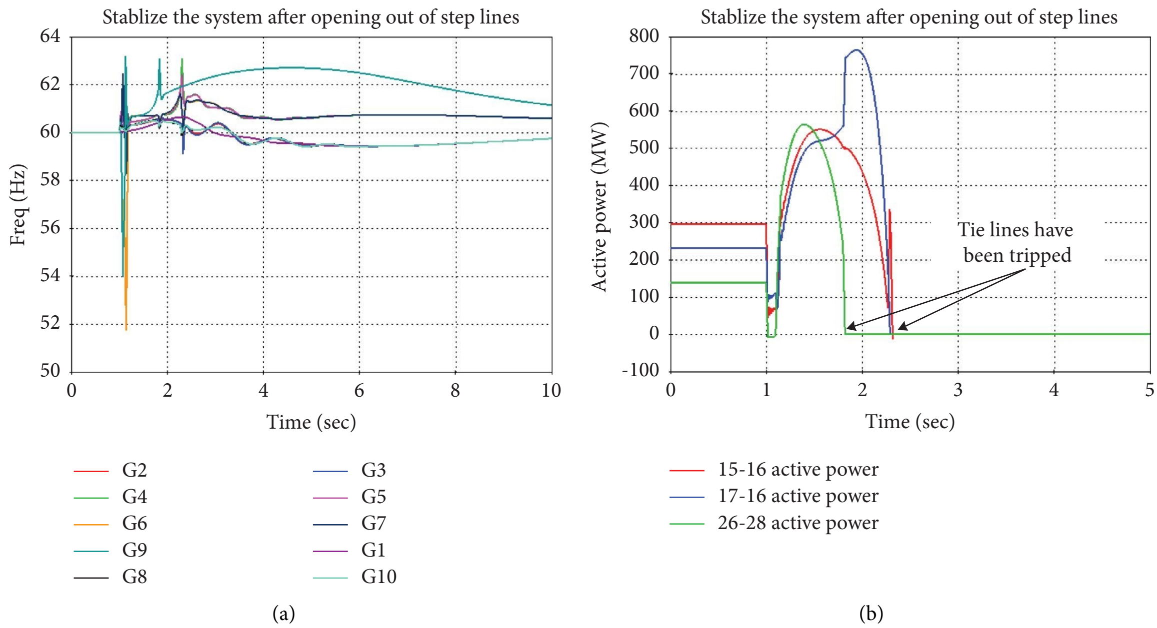

FIGURE 24: Stable islands after separation.

shows that, after opening, the three tie lines as the figure illustrate that no power flow through these lines. Consequently, the generators' frequency has stopped oscillating and going to be stable after a few second (Figure 24(a)).

4. Conclusions

Power swings in the power system are triggered due to faults and topological changes in the system. Power swing strigger oscillations in the system which can be stable or unstable. The unstable oscillations lead to a condition where a generator or two coherent areas oscillate against each other leading to a 180-degree phase angle separation named as out-of-step condition. The tripping of a generator or tie lines is essential for maintain the stability of system. A detailed investigation of OOS condition has been carried out in time domain simulation on three benchmark systems for generator mode and interarea mode, by simulating the systems in real-time simulator platform from OPAL-RT with HYPERSIM environment. The results of the article were compared with small signal stability analysis by eigenvalue technique.

Furthermore, a PMU-based OOS condition detection with bus voltage angle has been considered in this work which can be easily implemented in WAMS. This method is better than the conventional impedance-based detection of OOS condition which is prone to maloperation during power swings in the power system. Also, this method is independent of the network variations in the power system. The results from this article in the time domain corroborate with the analytical work considered in the article.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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