A new algorithm for predicting out-of-step condition in large-scale power systems using rotor speed–acceleration

Ali Reza Sobbouhi and Mohammad Reza Aghamohammadi*†

Faculty of Engineering, Department of Electrical and Computer Engineering, Shahid Beheshti University, AC, Tehran, Iran

SUMMARY

Transient instability is one of the major threats to system security which can cause out-of-step condition. Out-of-step condition can cause mechanical and thermal damages to generator. Therefore, in the case of out-of-step, early detection and disconnection of generator from grid are very essential. In this paper, by using generator rotor speed–acceleration \( \omega/C_0 \alpha \) data obtained from PMU measurements, a new algorithm for predicting out-of-step condition of the generator in large-scale power systems is proposed. The trend of the movement of the \( \omega/C_0 \alpha \) locus curve in the plane can give us a measure for predicting and detecting out-of-step condition. The prediction ability of this method enables one for early tripping unstable generator avoiding hazard damages. The proposed algorithm is examined on two networks: IEEE 39 bus system and large-scale Iran power network. The simulation results demonstrate the ability of the proposed algorithm for correct prediction of various unstable power swing conditions with prediction time soon enough compared to the detection time. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: transient stability; out-of-step; rotor speed; rotor acceleration; speed–acceleration locus; prediction

1. INTRODUCTION

Rotor angle oscillations following occurrence a disturbance are inherent in synchronous machines. In the case of a severe disturbance such as a three-phase short-circuit fault, the oscillations do not damp out and may lead to an unstable condition denoted by out-of-step or loss of synchronism. Out-of-step protection is designed as an aid to protect electric machines against consequent mechanical and thermal damages. When the out-of-step condition is detected, appropriate actions have to be taken to terminate generator from grid. In complex modern power systems, sustained out-of-step conditions are not allowed, and generator groups going out-of-step are required to be separated in the first cycle of out-of-step [1]. There are various techniques available in the literature to detect out-of-step conditions for deciding whether or not splitting is needed in the system. An accurate out-of-step detection technique is important especially in improving power system reliability. Most popular conventional out-of-step detection techniques use a distance relay. Distance relay detection is based on the rate of movement of the apparent impedance. An out-of-step condition is detected by observing the behavior of the impedance loci. A typical out-of-step protection scheme is accomplished by blinders in the R–X diagram and a timer [2]. The blinder and timer settings require knowledge of the fastest power swing, the normal operating region and the possible swing frequencies; therefore, these settings are system dependent [3,4]. Such techniques require extensive offline stability studies for obtaining the settings and their complexity increases when applied to multi-machine systems. The performance also depends on the guidelines used for blinder and timer settings. The technique ensures better protection only in

*Correspondence to: Mohammad Reza Aghamohammadi, Faculty of Engineering, Department of Electrical and Computer engineering, Shahid Beheshti University, AC, Tehran, Iran.
†E-mail: Aghamohammadi@pwut.ac.ir

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the worst case scenarios, and the performance is affected by the swing frequencies encountered [5,6]. In [7] a new simple procedure for detecting out-of-step is proposed in which the equal area criterion is mapped to the time domain. The classification between stable and out-of-step swings is carried out using the accelerating and decelerating energies which represent the area under the power–time curve. In [8] a method based on the wavelet transform is proposed for detecting out-of-step condition for blocking function of distance relays to distinguish between a power swing and a fault. In [9] a method based on artificial intelligence with focusing on the development of the new Artificial Neural Network (ANN) for detecting generator loss of synchronism is proposed. [10,11] have employed artificial intelligence techniques to develop methods for detecting out-of-step condition. In [12] a method based on the frequency deviation of the voltage values measured at a local bus is proposed for detecting the out of-step condition. In this method, the angular velocity and acceleration are obtained by using the measured frequency, and then the unstable equilibrium point (UEP) is detected. In [13], a method is developed in which both neural networks and genetic algorithms (GA) are combined into a common frame work for predicting transient instability in power systems. In [14], by using pattern recognition technique a new sophisticated approach for out-of-step detection is proposed which is able to initiate early tripping for unstable swings while avoiding tripping on stable swings. In [15], an approach is presented for out-of-step relaying by using fuzzy classification in which by selecting the appropriate features, partitioning the pattern space into fuzzy subspaces and inducing a fuzzy if–then rule for each subspace, the relay is designed. In [16] with the computed rate of change of apparent impedance (or resistance) out-of-step relaying is involved. This reference introduces an impedance based law for out-of-step detection description. In [17] out-of-step relay scheme based on the direct method of lyapunov is used to determine the stability boundary in a two-machine system. In [18], a real-time transient instability detection method based on the basis of the perturbed voltage trajectories is presented. In [19], a general Transient Stability Estimation Index (TSEI) is introduced, which determines the stability status based on quantifying the impact of parameters affecting transient stability problem using decision tree algorithm.

Generally, the methods for recognizing out-of-step condition can be divided into two categories: (i) detection methods and (ii) prediction methods. Conventional methods mainly dealt with the detection methods, while recently the prediction methods have received some interest by researchers [20–24]. Because of the importance of out-of-step condition for synchronous generators from point of view of mechanical and thermal damages, fast detection of such situation is very vital. For this purpose, detection of out-of-step may be slightly late, and predicting methods appear to be necessary. In [20], a method for predicting the trend toward instability is proposed by using time-series analysis and fitting an autoregressive (AR) model for each generator rotor angle. Combination of AR model with equal area criterion (EAC) is proposed as another way to predict unstable swings [21]. In [22], transient stability of a generator is predicted based on the apparent impedance obtained from PMUs, using decision trees. This paper provides a new prediction method for instability by taking advantage of the data obtained by PMUs. Recently out-of-step protection has been considered for distributed generation (DG). In [23] a protection scheme which is accomplished on online data collecting during the growing phase to predict out-of-step is described. The phase difference between two points is obtained from solving an equation contains simultaneously sampled voltage data. Reference [24] proposes a predictive out-of-step method based on the observation of the voltage phase difference between the substations. This method is based on the artificial intelligence algorithm used in the improved tabu search for optimal placement of PMU to keep the system completely observable. In [25], out-of-step relaying practices and their application for protection of small generation have been examined. The settings of the generator out-of-step protection relays for gas and steam turbine generators used in a grid connected combined heat and power (CHP) power plant have been investigated in [26].

In this paper, by using rotor speed–acceleration data obtained from PMU measurements, a new algorithm based on the rate of change of speed–acceleration is proposed for predicting out-of-step condition of generator. The method is also able for accurate detection of out-of-step condition after its prediction. The prediction ability of this method for out-of-step condition enables one for early tripping unstable generator for avoiding hazard damages. All simulations for stability studies are carried
out using the Power Factory® software [27], and the proposed predicting algorithm is developed in MATLAB. The proposed algorithm is implemented on two networks: (ii) small-scale power system (IEEE 39 bus New England system) and (ii) large-scale realistic Iran power system (Neka power plant in Iran power network). The simulation results show that the proposed algorithm is able to correctly predict various unstable power swing conditions with prediction time soon enough compared to the detection time.

2. MECHANISM OF OUT-OF-STEP CONDITION

The concept of out-of-step mainly relates to the synchronism between generating units. An out-of-step condition occurs for a generator when it loses its synchronism with respect to other generators and its rotor angle increases monotonically with respect to other generators because of an accelerating power. Following occurrence of a fault in the network, all generators encounter with a sudden decrease in their electric output powers whose magnitude depends on the location of generator with respect to the fault. This sudden decrease in the output power imposes an accelerating power on the rotor causing increasing its speed and angle with respect to other generators. Equation (1) governs the dynamic of the generator during the transient period following a fault:

\[ M \ddot{\delta} = P_M - P_E = P_{acc} \]  

(1)

where \( M \) is the constant inertia, \( \delta \) is the rotor angle, \( P_M \) and \( P_E \) are the mechanical and electrical powers, respectively, and \( P_{acc} \) is the accelerating power of the generator.

In Equation (1), the mechanical damping is usually neglected which makes our results more pessimistic with higher stability margin. The electrical damping is implicitly included by modeling excitation system and AVR of synchronous generators.

It is worth noting that, in the stage of simulation studies, the rotor angle of a generator or power plant evaluated by swing Equation (1), is basically with respect to a 50-Hz synchronous machine. However, the stability criteria of each generator are based on its relative rotor angle with respect to either center of inertia (COI) of the power system or an arbitrarily selected reference machine within the system (e.g. machine \#R) which are evaluated as follows:

\[ \delta_{i-COI} = \delta_i - \delta_{COI} \]

\[ \delta_{i-R} = \delta_i - \delta_R \]

where:

- \( \delta_i \) Rotor angle of unit \#i evaluated by swing Equation (1) respect to 50 Hz
- \( \delta_R \) Rotor angle of reference unit \#R evaluated by swing Equation (1) respect to 50 Hz
- \( \delta_{COI} \) Rotor angle of the COI of power system respect to 50 Hz
- \( \delta_{i-COI} \) Rotor angle of unit \#i respect to the COI
- \( \delta_{i-R} \) Rotor angle of unit \#i respect to the reference machine \#R

Therefore, the synchronism and rotor-angle stability of machine \#i should be verified based on the variation of its relative rotor angle either \( \delta_{i-COI} \) or \( \delta_{i-R} \).

In the circumstances of online stability assessment, at each time instant, based on the phasors of generators terminal voltages (\( V < \theta \)) and generators currents (\( I < \phi \)) measured by PMU, generator rotor angles with respect to their terminal voltage can be estimated. It is worth noting that because of the inherent relative nature of rotor angle stability, the phase angles of generators terminal voltages should be measured simultaneously in real time by PMU using WAMS technique with respect to an arbitrarily selected reference bus.

Therefore, for evaluating the stability of generator \#i, beside this generator, the phase angle of at least one another generator bus should be measured as reference bus (\#R). So, by measuring the
voltage phase angles of bus #i and reference bus #R, the rotor angles of their corresponding generators can be estimated as follows:

\[ \theta_{iR} = \theta_i - \theta_R \]
\[ \delta_{iS} = \theta_{iR} + \delta_i \]
\[ \delta_R = \delta_{iS} - \delta_R \]

where:

\( \theta_i, \theta_R \) The voltage phase angle of generator buses #i and #R respectively which are measured by PMU with respect to 50Hz.

\( \theta_{iR} \) The voltage phase angle of generator bus #i with respect to the reference bus #R.

\( \delta_i \) Rotor angle of the generator #i with respect to its terminal voltage (bus #i) estimated using the operating variables of generator #i.

\( \delta_R \) Rotor angle of the reference machine #R with respect to its terminal voltage (bus #R) estimated using the operating variables of generator #R.

\( \delta_{iS} \) Rotor angle of the generator #i with respect to the reference bus #R.

\( \delta_{iR} \) Rotor angle of the generator #i with respect to the reference machine #R connected to bus #R.

Consequently, in an online stability assessment, in order to be able to verify synchronism and stability of generator #i, the rotor angle \( \delta_{iR} \) should be used as stability criteria.

In this paper, by using the results obtained from time domain stability simulation studies as online measured data, the rotor angle of generators with respect to an arbitrarily selected reference machine is evaluated and used for evaluating speed and acceleration of the generator in question.

Having estimated relative rotor angle of each generator, by using Equations (2) and (3), relative speed and acceleration of the generator with respect to the reference machine can be evaluated numerically in terms of time variation of rotor angle as follows:

\[ \omega = \frac{d\delta}{dt} \quad (2) \]
\[ \alpha = \frac{d^2\delta}{dt^2} \quad (3) \]

Figure 1 shows the locus of speed–acceleration \( (\omega - \alpha) \) of a specific generator during dynamic behavior leading to stability or loss of synchronism [12]. It is worth noting that the locus is actually

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**Figure 1.** Locus of \( \omega-\alpha \) for a stable/unstable swing.
drawn for relative speed but the curve is shifted to the right hand side by $\omega_0$. Point 1 represents the initial stable equilibrium point (SEP) before fault where ($\omega = \omega_0$, $\alpha = 0$).

Point 2 represents an immediate situation after fault occurrence in which speed has not changed yet but acceleration has suddenly increased to a positive value ($\omega = \omega_0$, $\alpha > 0$). From point 2 onward, because of positive acceleration, rotor speed and rotor angle start to increase according to the swing Equations (1) and (2). At the instant of fault clearance, immediately before fault clearance, rotor acceleration is positive, and its speed is greater than synchronous speed ($\omega > \omega_0$, $\alpha > 0$). Immediately after fault clearance, rotor acceleration generally becomes negative while its speed remains greater than $\omega_0$ ($\omega > \omega_0$, $\alpha < 0$).

In Figure 1, points 3 and 4 represent generator situation immediately before and after fault clearance, respectively. Jumping from point 3 to 4 is because of the sudden change in the accelerating power because of fault clearance.

In the post fault condition represented by the second quarter of the $(\omega - \alpha)$ plane because the rotor angle has increased and voltage has recovered because of fault clearance, generator is usually able to temporarily generate an electric power greater than its input mechanical power for a short time (e.g. 0.5 s.). This condition imposes a decelerating power on the generator which provides a chance for preserving its stability; otherwise the generator will certainly lose its stability.

As it can be seen in Figure 1, in the post fault condition from point 4 onward, depending on the generator potential for stability, its dynamic will be established in one of the two following trajectories A—leading to stability, or B—leading to instability.

1. If generator is able to reduce its speed to $\omega_0$ at a typical point like point 5, while it is still experiencing a decelerating power ($\alpha < 0$), it will follow the trajectory A with the chance of stability. In such condition, generator moves to points 6 and 7 experiencing a damped oscillation and finally settling at the equilibrium point 1.

2. If generator movement reaches to a typical point like point 8 where $\alpha = 0$ and $\omega > \omega_0$, then it will follow the trajectory B with the risk of loss of synchronism. Point 8 typically represents post-fault unstable equilibrium point UEP ($\alpha = 0$, $\omega > \omega_0$) of the generator. In such condition, generator moves toward point 9 experiencing a monotonic increase in angle and speed of the rotor.

3. OUT-OF-STEP CONDITION CRITERION

The advent of phasor measurement units (PMUs), together with advances in computational and communications facilities, provides an opportunity to perform online monitoring of system dynamics. The rotor angle in nature is a mechanical quantity which cannot be directly measured by PMU. On the other hand, rotor angle calculation needs numerical methods which need data of the whole structure of power system and is very time consuming [28]. Therefore, in this respect, estimation of rotor angle appears to be necessary. Having estimated relative rotor angle of the generator with respect to an arbitrary reference machine or COI, based on the terminal variables measured by PMU [29–31], at the consecutive interval times $t(i)$, $t(i+1)$ and $t(i+2)$, rotor speed and acceleration of the generator can be evaluated by Equations (4) and (7). These equations are based on discreet PMU data and piecewise linear assumption of rotor angle, speed and acceleration.

$$\omega(i) = \omega_0 + \frac{\delta(i + 1) - \delta(i)}{t(i + 1) - t(i)}$$  \hspace{1cm} (4)

$$\omega(i + 1) = \omega_0 + \frac{\delta(i + 2) - \delta(i + 1)}{t(i + 2) - t(i + 1)}$$  \hspace{1cm} (5)

$$t_r(i) = \frac{t(i + 1) + t(i)}{2}$$  \hspace{1cm} (6)

$$\alpha(i) = \frac{\omega(i + 1) - \omega(i)}{t_r(i + 1) - t_r(i)}$$  \hspace{1cm} (7)
For each generator, by using relative rotor speed and acceleration signals evaluated by the Equations (4) and (7), corresponding locus of speed–acceleration ($\omega - \alpha$) like the locus of Figure 1 can be drawn.

During dynamic behavior of a generator, if the curve of its ($\omega - \alpha$) locus reaches a point like point 5 ($\alpha < 0$, $\omega = \omega_0$), the stability condition will be satisfied. Regarding the behavior of ($\omega - \alpha$) locus for stable condition, the stability criteria can be derived as follows.

*If the ($\omega - \alpha$) locus of a generator intersects the $\alpha$ axis at the negative part (i.e. $\alpha < 0$) then it can be concluded that the generator will remain stable. Such situation causes the rotor angle return to a stable point with damped oscillations.*

However, it should be noted that only one intersection of the $\alpha$ axis does not guarantee the full stability of the generator. In order to ensure complete stability of the generator, this criterion should be examined for repeated intersection of the $\alpha$ axis which is corresponding to stability for multi swings of generator.

If the ($\omega - \alpha$) locus of a generator reaches a point like point 8 ($\alpha = 0$, $\omega > \omega_0$), the stability condition will not be satisfied. Regarding behavior of the ($\omega - \alpha$) locus for an unstable condition, the instability criteria can be derived as follows.

*If the ($\omega - \alpha$) locus of a generator intersects the $\omega$ axis at the positive part (i.e. $\omega > \omega_0$) then it can be concluded that the generator will lose its stability and become out-of-step.*

Such situation causes rotor angle pass through unstable equilibrium point (UEP) with monotonic increase which is referred to as out-of-step condition.

### 4. PREDICTION OF OUT-OF-STEP CONDITION

Because of the importance of out-of-step condition for synchronous generators from the point of view of mechanical and thermal damages, fast detection of such situation is very vital. For this purpose, only detection of out-of-step may be slightly late, and so predicting methods appear to be necessary.

Regarding the typical curve for the ($\omega - \alpha$) locus of a generator shown in Figures 2 and 3, the trend of the locus movement toward stable point 5 and unstable point 8 can be predicted by the slope of the curve of ($\omega - \alpha$) as shown in Figures 2 and 3, respectively. The slope of the locus curve of ($\omega - \alpha$) based on the linear model of Equations (2) and (3) can be evaluated by Equation (8):

$$m(i) = \frac{\alpha(i + 1) - \alpha(i)}{\omega(i + 1) - \omega(i)} = \frac{\Delta \alpha(i)}{\Delta \omega(i)} = \frac{1}{M} \frac{\Delta \text{P}_{\text{sec}}(i)}{\Delta \omega(i)}$$

where $m(i)$ is the slope of the tangent line to the locus curve of ($\omega - \alpha$) at interval time $t(i)$.

![Figure 2. Trajectory of ($\omega-\alpha$) locus curve for stable condition.](image-url)
Based on the slope of the tangent line to the curve of \((\omega/C_0, \alpha)\), the proposed algorithm for predicting out-of-step condition can be verified.

After a fault, when the locus curve comes into the second quarter of \((\omega/C_0, \alpha)\) plane where \(\alpha < 0\), \(\omega > \omega_0\), by tracing the slope of the \((\omega, \alpha)\) curve the trend of rotor angle toward stability or instability can be predicted.

In the second quarter of \((\omega, \alpha)\) plane where \(\alpha < 0\), as long as the tangent line to the locus curve crosses the negative part of the vertical line \(\omega = \omega_0\) at a typical point \(M\) (e.g. points \(M1\) or \(M2\)) as shown in Figure 2, there is no sign for predicting movement of rotor angle toward unstable or out-of-step conditions.

The equation of the tangent line can be evaluated by Equation (9), and the distance of point \(M\) from the point \((\alpha=0, \omega=\omega_0)\) can be evaluated by Equation (10).

\[
\alpha - \alpha(i) = m(i) \times (\omega - \omega(i)) \\
\]  
\[
d_M = \alpha(i) + m(i) \times (\omega_0 - \omega(i)) \\
\]

The stability criterion can be mathematically interpreted by Equation (11):

\[
d_M \times \alpha > 0 \\
\]

where \(d_M\) is the distance of the point \(M\) from the point \((\alpha=0, \omega=\omega_0)\), and \(\alpha\) is acceleration of the rotor at the point of estimation.

4.1. Out-of-step prediction criterion

In the second quarter of \((\omega, \alpha)\) plane where \(\alpha < 0\), if the tangent line to the locus curve crosses the positive part of the vertical line \(\omega = \omega_0\) at a typical point \(M\) (e.g. points \(M4\) or \(M5\)) as shown in Figure 3, it can be used as a sign for predicting movement of rotor angle toward out-of-step condition.

There are some severe unstable situations in which the curve of \((\omega, \alpha)\) does not come into the second quarter of \((\omega, \alpha)\) plane. Figure 4 shows a typical \((\omega, \alpha)\) curve for such situation. The key point for occurrence of such situations is based on this fact that generator will never experience a decelerating power at the post fault condition. This situation can be arisen because of two conditions, (i) fault clearing time is longer than the time at which the generator reaches to its unstable equilibrium point UEP \((t_{\text{clear}} > t_{\text{UEP}})\) and (ii) weak network structure at the post fault condition in which generator is not able to experience an electric power more than its mechanical power (a decelerating power). Because in such situation, the \((\omega, \alpha)\) curve never enters the second quarter of the \((\omega, \alpha)\) plane so,
the detecting method based on the crossing the axis $\alpha=0$ by the $(\omega - \alpha)$ curve is not able to detect such unstable situation.

The criterion for detecting such instability condition can be also derived based on the slope of the tangent line to the $(\omega - \alpha)$ curve in the first quarter of $(\omega - \alpha)$ plane. After a fault, if the locus curve remains into the first quarter of $(\omega - \alpha)$ plane where $(\alpha > 0, \omega > \omega_0)$, by tracing the slope of the $(\omega - \alpha)$ curve, the trend of rotor angle toward instability can be predicted as follows.

If the tangent line to the locus curve crosses the negative part of the vertical line “$\omega = \omega_0$” at a point M (e.g. points M6 or M7) as shown in Figure 4, it can be used as a sign for predicting movement of rotor angle toward out-of-step condition.

The instability criterion for both scenarios of out-of-step condition shown in Figures 3 and 4 can be mathematically interpreted by Equation (12).

$$d_M \times \alpha < 0$$

5. SIMULATION STUDIES

In order to demonstrate the effectiveness of the proposed approach, it is applied on two small and large systems. All stability simulations are carried out using Power Factory® software. The function of PMU is simulated only as the output phasors of Power Factory® software. All calculations necessary for
evaluating \((\omega - \alpha)\) curves based on the proposed algorithm are carried out by the developed program in MATLAB code using the simulation results obtained from stability studies. The proposed algorithm is verified for different types of faults including three-phase short circuit, line to ground and double line to ground, but only the results of solid three-phase short circuit and line to ground are presented in this paper. In this study, after several simulation studies, the reference value for the arming repeater “\(r_0\)” is adopted as 3. For each fault scenario first, by performing stability simulation using Power Factory® software, stability condition of all generators is evaluated. One important point which should be clarified is that the proposed approach is basically an online approach without need to any additional information about the occurrence of fault in the network. In a realistic power system all generators which are important or have a probable risk of instability should be equipped with PMU and the proposed algorithm for predicting their instability in the case of a fault occurrence. In order to evaluate speed
and acceleration of the generators in question, based on the sampled data from simulation results, their rotor angles with respect to a reference machine (Gen. #39) are evaluated every 10 ms for a time duration of 2 s. Then rotor speed and acceleration of the generators are evaluated numerically using Equations (2) and (3). The function of PMU is simulated only as the output phasors of Power Factory software.

Corresponding to each unstable scenario, the time duration lasting for the unstable generator to pass through the point UEP \((\alpha=0, \omega > \omega_0)\) is defined as the actual time for generator to go out-of-step (TOFS) after fault occurrence. TOFS is measured from the time of fault occurring. In simulation study, TOFS can be evaluated by using simulation results and tracing the variation of \((\omega - \alpha)\) locus until reaching the point of UEP \((\alpha=0, \omega > \omega_0)\) like a typical point as 8 in Figure 1. For unstable scenarios, this time duration which is associated with the unstable generator is shown in the 7th column of Table I. For each fault scenario, by using corresponding simulation results, rotor angle and consequently rotor speed and acceleration are evaluated from which the curve of the \((\omega - \alpha)\) locus is drawn. By applying the proposed algorithm the predicted time for out-of-step (TPOFS) of the unstable generator is evaluated. In Table I, associated to each unstable scenario, the 10th column shows the predicted time (TPOFS) by the proposed method for out-of-step. This duration is the minimum time lasting for generator to show some indication in its behavior \((\omega - \alpha)\) alarming its movement toward the corresponding unstable equilibrium point UEP \((\alpha=0, \omega > \omega_0)\).

Also in order to show the effectiveness of the proposed approach compared to other methods, the results are compared with the result of a conventional out-of-step distance relay. Figure 6 shows typical characteristic of the distance relay.

5.1. A) Small-scale power system

In this part, the proposed approach is applied on IEEE 39-bus New England system including 10 generators. In order to demonstrate the ability of the proposed approach, more than five hundreds cases with different fault location and duration are tested from which six scenarios are reported in Table I. The second and fourth scenarios are for three-phase short-circuit fault, the fifth and sixth scenarios are for a severe three-phase short-circuit fault and the first and third scenarios are for single-phase short-circuit fault. It should be noted that for each fault scenario, the stability and out-of-step state of all generators should be verified by the proposed algorithm. However, in different unstable scenarios depending on the fault situation, basically the unstable generators may differ from each other. In this study, generators 2, 5 and 7 constitute unstable generators of the four unstable scenarios.

In Table I, the 7th column shows the actual time of out-of-step (TOFS) based on the time duration necessary for passing system through the point of UEP, the 8th column shows the detection time of out-of-step (TOFS) by the conventional method based on the distance relay and the 10th column shows the prediction time of out-of-step (TPOFS) based on the proposed method. As it can be seen the detection time by the distance relay is far from the actual time of out-of-step while the predicted time by the proposed method is close to the actual time and almost is less than it. The 11th column shows the difference between the actual time of out-of-step (TOFS) and the predicted time of out-of-step (TPOFS).

### Table I. Stable and unstable scenarios in IEEE 39 bus New England system.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Line name</th>
<th>Line %</th>
<th>Generator number</th>
<th>Fault duration (s)</th>
<th>Stable/unstable</th>
<th>Actual TOFS (s) based on UEP</th>
<th>TOFS (s) based on distance relay</th>
<th>Prediction TPOFS (s) by the proposed method</th>
<th>TOFS-TPOFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25-2</td>
<td>50</td>
<td>7</td>
<td>0.3</td>
<td>S</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>25-2</td>
<td>50</td>
<td>7</td>
<td>0.425</td>
<td>U</td>
<td>0.6868</td>
<td>1.3968</td>
<td>U</td>
<td>0.5268</td>
</tr>
<tr>
<td>3</td>
<td>23-22</td>
<td>15</td>
<td>5</td>
<td>0.25</td>
<td>S</td>
<td>—</td>
<td>—</td>
<td>S</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>23-22</td>
<td>15</td>
<td>5</td>
<td>0.28</td>
<td>U</td>
<td>0.6618</td>
<td>0.9600</td>
<td>U</td>
<td>0.5318</td>
</tr>
<tr>
<td>5</td>
<td>23-22</td>
<td>15</td>
<td>5</td>
<td>0.33</td>
<td>U</td>
<td>0.5218</td>
<td>0.6800</td>
<td>U</td>
<td>0.4618</td>
</tr>
<tr>
<td>6</td>
<td>7-6</td>
<td>20</td>
<td>2</td>
<td>0.51</td>
<td>U</td>
<td>0.5818</td>
<td>1.1818</td>
<td>U</td>
<td>0.3218</td>
</tr>
</tbody>
</table>
Table II shows the corresponding setting for distance relay to detect out of step based on the procedure developed in [29].

Figure 7 and Figure 8 show variations of rotor angle/speed/acceleration and the \((\omega - \alpha)\) locus curve, respectively, for the scenario 1.

Figure 9 and Figure 10 show variations of rotor angle/speed/acceleration and the \((\omega - \alpha)\) locus curve, respectively, for the scenario 2.

Figure 11 and Figure 12 show the same variations, respectively, for the scenario 3.

Figure 13 and Figure 14 show the same variations, respectively, for the scenario 4.

Table II. Setting of out-of-step distance relay for generators of IEEE 39 bus system.

<table>
<thead>
<tr>
<th>Generator no.</th>
<th>(Z_a) (p. u.)</th>
<th>(Z_b) (p. u.)</th>
<th>(Z_c) (p. u.)</th>
<th>(Z_d) (p. u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>0.1127</td>
<td>0.3616</td>
<td>0.0285</td>
<td>0.0714</td>
</tr>
<tr>
<td>2</td>
<td>0.1592</td>
<td>0.486</td>
<td>0.0648</td>
<td>0.162</td>
</tr>
<tr>
<td>5</td>
<td>0.5837</td>
<td>1.799</td>
<td>0.2208</td>
<td>0.552</td>
</tr>
</tbody>
</table>

Figure 7. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 1 of Table I.
Figure 8. Curve of $(\omega - \alpha)$ locus for scenario 1 of Table I.

Figure 9. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 2 of Table I.

Figure 10. Curve of $(\omega - \alpha)$ locus for scenario 2 of Table I.

Figure 11. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 3 of Table I.
Figure 12. Curve of \((\omega - \alpha)\) locus for scenario 3 of Table I.

Figure 13. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 4 of Table I.

Figure 14. Curve of \((\omega - \alpha)\) locus for scenario 4 of Table I.

Figure 15 and Figure 16 correspondingly show the variation, respectively, for the scenario 5.

Figure 17 and Figure 18 show the same variations, respectively, for the scenario 6 of Table I.

Figure 19 comparatively shows the \((\omega - \alpha)\) locus curves of the unstable generator in the scenarios 4 and 5 of Table I. As it can be seen, in scenario 5 by increasing \(t_{\text{clear}} \gg \text{CCT}\), calculating the tangent line to the \((\omega - \alpha)\) curve in the third quarter becomes difficult with lower accuracy.

5.2. B) Large-scale power system

In this part, effectiveness of the proposed approach is demonstrated on Iran power system as a realistic large-scale power system including 471 generating units. For this network, Neka steam power plant with the rated power of 440 MW is adopted for examining the proposed algorithm to
predict out-of-step condition. Figure 20 shows situation of this power plant in Iran 230–400-kV power network. In this paper, for stability simulation studies whole Iran power system including 1063 buses, 993 lines and 471 generators with all details including AVR are modeled. The power frequency in Iran power network is 50Hz. However, for the large-scale Iran power system, because the stability of Neka power plant is concerned, therefore, only the data gathered from its PMU has been processed for instability prediction by the proposed algorithm. In order to demonstrate the capability of the proposed approach, a variety of several stable and unstable conditions (more than two hundreds) are examined from which only seven fault scenarios including different location and duration for faults are reported as shown in Table III.
In Table III similar to Table I, the 6th column shows the actual time of out-of-step (TOFS) based on the time of passing system through the point of UEP, the 7th column shows the detection time of out-of-step (TOFS) by the conventional method based on the distance relay and the 9th column shows the prediction time of out-of-step (TPOFS) based on the proposed method. As it can be seen the detection
time by the distance relay is far from the actual time of out of step, while the prediction time by the proposed method is less than it.

Table IV shows the corresponding setting for distance relay of Neka power plant to detect out of step based on the procedure developed in [32].

Table III. Stable and unstable scenarios for Neka power plant in Iran power network.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Line name</th>
<th>Line %</th>
<th>Fault duration (s)</th>
<th>Fault/ Stable</th>
<th>Actual TOFS (s) based on UEP</th>
<th>TOFS (s) based on distance relay</th>
<th>TPOFS (s) by the proposed method</th>
<th>TOFS TPOFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LN926</td>
<td>25</td>
<td>0.50</td>
<td>S</td>
<td>—</td>
<td>S</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>LN926</td>
<td>25</td>
<td>0.85</td>
<td>U</td>
<td>0.5918</td>
<td>1.2735</td>
<td>U. 0.4918</td>
<td>0.100</td>
</tr>
<tr>
<td>3</td>
<td>BN930</td>
<td>60</td>
<td>0.50</td>
<td>S</td>
<td>—</td>
<td>S</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>BN930</td>
<td>60</td>
<td>0.75</td>
<td>U</td>
<td>0.5718</td>
<td>0.9818</td>
<td>U. 0.4818</td>
<td>0.090</td>
</tr>
<tr>
<td>5</td>
<td>NW928</td>
<td>25</td>
<td>1</td>
<td>U</td>
<td>0.6718</td>
<td>1.1318</td>
<td>U. 0.3318</td>
<td>0.340</td>
</tr>
<tr>
<td>6</td>
<td>LW927</td>
<td>25</td>
<td>0.5</td>
<td>S</td>
<td>—</td>
<td>S</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>LW927</td>
<td>25</td>
<td>0.7</td>
<td>U</td>
<td>0.5418</td>
<td>1.2768</td>
<td>U. 0.4618</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Table IV. Setting of out-of-step distance relay for Neka power plant in Iran power system.

<table>
<thead>
<tr>
<th>Z_a(p. u.)</th>
<th>Z_b(p. u.)</th>
<th>Z_c(p. u.)</th>
<th>Z_d(p. u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8013</td>
<td>4.998</td>
<td>1.235</td>
<td>3.0875</td>
</tr>
</tbody>
</table>

Figure 21. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 1 of Table III.

Figure 22. Curve of (ω—α) locus for scenario 1 of Table III.
Figure 21 and Figure 22 show variations of rotor angle, speed, acceleration and the $(\omega - \alpha)$ locus curve, respectively, for a three-phase short-circuit fault for the Neka power plant of the scenario 1.

Figure 23 and Figure 24 show the variations, respectively, for a three-phase short-circuit fault of the scenario 2.

Figure 25 and Figure 26 show the variations, respectively, for a three-phase short-circuit fault of the scenario 3.

Figure 27 and Figure 28 show the variations, respectively, for a three-phase short-circuit fault of scenario 4.

Figure 23. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 2 of Table III.

Figure 24. Curve of $(\omega - \alpha)$ locus for scenario 2 of Table III.

Figure 25. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 3 of Table III.
Figure 29 and Figure 30 show the variations, respectively, for a severe three-phase fault for the scenario 5.

Figure 31 and Figure 32 show the variations, respectively, for a single-phase short-circuit fault for the scenario 6.

Figure 33 and Figure 34 show the variations, respectively, for another single-phase short circuit of the scenario 7.
As it can be seen from both small and large-scale power systems, the proposed approach is able to predict the condition of out-of-step much sooner than the conventional distance relay. Also it is able to predict out-of-step condition sooner than the actual time of out of step at which system pass through the UEP point.

The time difference of the proposed approach with respect to the actual time for reaching UEP point seems to be enough for taking some protective action for early tripping of the generator.

In order to compare the simulation results with the results reported in the literatures, reference [33] reports that its algorithm can predict instability 0.205 s prior to the instability detected by the distance

Figure 29. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 5 of Table III.

Figure 30. Curve of (ω–α) locus for scenario 5 of Table III.

Figure 31. Variation of (a)—rotor angle, (b)—rotor speed and (c)—acceleration of generator in scenario 6 of Table III.

As it can be seen from both small and large-scale power systems, the proposed approach is able to predict the condition of out-of-step much sooner than the conventional distance relay. Also it is able to predict out-of-step condition sooner than the actual time of out of step at which system pass through the UEP point.

The time difference of the proposed approach with respect to the actual time for reaching UEP point seems to be enough for taking some protective action for early tripping of the generator.

In order to compare the simulation results with the results reported in the literatures, reference [33] reports that its algorithm can predict instability 0.205 s prior to the instability detected by the distance

relay, while the proposed algorithm can predict out-of-step much sooner than the conventional distance relay (on average 0.8 s faster). With comparison to reference [12], the proposed algorithm has better prediction time. Reference [22] claims that it can predict out-of-step 0.2 s after fault clearance. However, the method of reference [22] needs lots of offline study, while the proposed algorithm is based on the concept of out-of-step and can work in real time. In [34] out-of-step perdition algorithm is based on passing the rotor angle through 180°; this time is close to the “Actual TOFS based on UEP” column.
in Tables I and III, while, the proposed algorithm has much better results which are shown in “TPOFS by proposed method” column in Tables I and III.

6. CONCLUSIONS

In this paper, a new algorithm for predicting out-of-step condition is presented. The algorithm works based on the locus of the speed and acceleration of the generator evaluated by the measured variables at the terminal of the generator by PMU. In this paper, it is assumed that the rotor angle is available by estimation from generator terminal variables measured by PMU. The proposed algorithm is able to both predict and detect out-of-step condition. The performance of the algorithm has been examined on Neka power plant in Iran power system with promising results showing its ability for correct and early prediction of out-of-step conditions. The algorithm has been examined for several scenarios of faults with different severity resulting in stable and unstable conditions. In all cases, it works properly and predicts correctly out-of-step condition before generator reaching UEP point. Also, the proposed approach has been compared with the conventional out-of-step distance relay, and results show its ability for sooner prediction. The simulation results show that the time difference between detection and prediction of instability achieved by the proposed algorithm is relatively enough for early tripping of the generator before becoming out-of-step and consequent damages.

7. LIST OF SYMBOLS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANN</td>
<td>Artificial Neural Network</td>
</tr>
<tr>
<td>AR</td>
<td>Autoregressive</td>
</tr>
<tr>
<td>AVR</td>
<td>Automatic Voltage Regulator</td>
</tr>
<tr>
<td>CCT</td>
<td>Critical Clearing Time</td>
</tr>
<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>COI</td>
<td>Center Of Inertia</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>EAC</td>
<td>Equal Area Criterion</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithms</td>
</tr>
<tr>
<td>PMU</td>
<td>Phasor Measurement Unit</td>
</tr>
<tr>
<td>SEP</td>
<td>Stable Equilibrium Point</td>
</tr>
<tr>
<td>TOFS</td>
<td>Actual Time of Out-Of-Step</td>
</tr>
<tr>
<td>TPOFS</td>
<td>Predicted Time of Out-Of-Step</td>
</tr>
<tr>
<td>TSEI</td>
<td>Transient Stability Estimation Index</td>
</tr>
<tr>
<td>UEP</td>
<td>Unstable Equilibrium Point</td>
</tr>
<tr>
<td>WAMS</td>
<td>Wide Area Measurement System</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Generator Rotor Speed</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Generator Rotor Acceleration</td>
</tr>
<tr>
<td>R</td>
<td>Resistance</td>
</tr>
<tr>
<td>X</td>
<td>Reactance</td>
</tr>
<tr>
<td>M</td>
<td>Constant Inertia of Generator</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Generator Rotor Angle</td>
</tr>
<tr>
<td>$P_M$</td>
<td>Generator Mechanical Power</td>
</tr>
<tr>
<td>$P_E$</td>
<td>Generator Electrical Power</td>
</tr>
<tr>
<td>$P_{acc}$</td>
<td>Generator Accelerating Power</td>
</tr>
<tr>
<td>$\delta_i$</td>
<td>Rotor Angle of Unit #i</td>
</tr>
<tr>
<td>$\delta_R$</td>
<td>Rotor Angle of Reference Unit #R</td>
</tr>
<tr>
<td>$\delta_{COI}$</td>
<td>Rotor Angle of The Center of Inertia of Power System</td>
</tr>
<tr>
<td>$\delta_{i-R}$</td>
<td>Rotor Angle of Unit #i Respect to The Reference Machine #R</td>
</tr>
<tr>
<td>$\delta_{i-COI}$</td>
<td>Rotor Angle of Unit #i Respect to The Center of Inertia</td>
</tr>
<tr>
<td>$V&lt;\theta$</td>
<td>Phasor of Generator Terminal Voltage</td>
</tr>
</tbody>
</table>
REFERENCES


27. DIGSILENT power factory®, http://www.digsilent.de/


32. SIEMENS, Report E D SE PTI/sk0632/SER07-B, extensive studies and enhancement of Iranian HV power system, section report on dynamic analysis for improved system, Aug. 2009, Tehran, Iran.
