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A New Algorithm for Predicting Out-of-step Using Rotor Speed-acceleration Based on Phasor Measurement Units (PMU) Data

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Abstract—Transient instability is one of the major threats to system security which can cause out-of-step condition. Out-of-step condition can result in mechanical and thermal damage to generators. Therefore, in the case of out-of-step, early detection and disconnection of the generator from grid is essential. In this article, using generator rotor speed-acceleration \((\omega - \alpha)\) data obtained from phasor measurement units (PMU) measurements, a new algorithm for predicting out-of-step condition for generators is proposed. The trend of the movement of the \((\omega - \alpha)\) locus curve in the plane provides a measure for predicting and detecting out-of-step status. The predictive ability of this method enables early tripping of the unstable generator, thereby avoiding hazard damage. The proposed algorithm is examined using an IEEE 39 bus system. The simulation results demonstrate the ability of the proposed algorithm for correct prediction of various unstable power swing conditions, with sufficient early prediction compared with the actual instability time.

1. INTRODUCTION

Rotor angle oscillation following a disturbance is 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 as exhibited 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 damage. When the out-of-step condition is detected, appropriate actions have to be taken to disconnect the generator from the grid. In complex modern power systems, sustained out-of-step conditions are not permissible and generator groups becoming out-of-step must be separated in the first cycle of out-of-step [1]. Various techniques are described in the literature to detect out-of-step conditions in regard to determining 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, and 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 the worst case scenarios and the performance is affected by the swing frequencies encountered [5, 6]. A new simple procedure for detecting out-of-step is proposed [7], in which the equal area criterion condition is mapped to the time domain. The classification between stable and out-of-step swings is carried out using the accelerating and decelerating energies representing the area under the power–time curve. A method based on wavelet transform is proposed [8] for detecting out-of-step condition for the blocking function of distance relays to distinguish between a power swing and a fault. Artificial intelligence techniques were used [9, 10] to develop methods for detecting out-of-step condition. A method based on the frequency deviation of voltage values measured at a local bus [11] is proposed for detecting out of-step condition. In this method, the angular velocity and acceleration are obtained using the measured frequency and then the unstable equilibrium point (UEP) is detected. Using the pattern recognition technique [12], 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. A real-time transient instability detection method based on perturbed voltage trajectories is presented [13], and a general Transient Stability Estimation Index (TSEI) is introduced [14] which determines the stability status based on quantifying the impact of parameters affecting the transient stability problem using a decision tree algorithm. Based on the energy equilibrium criterion in the time domain, an algorithm is introduced [15] to detect the out-of-step condition in power systems. Using local dynamic measurements of transmission line variables [16], the line potential energy along the post fault trajectory is proposed as a criterion for instability detection.

Using a combination of three direct methods for power system transient stability analysis [17]: controlling unstable equilibrium point (CUEP), Potential Energy Boundary Surface (PEBS), and extended equal area criterion (EEAC), a new integrated direct algorithm is proposed. Out-of-step relaying practices and their application for protection of small generation have been examined [18].

Generally, the methods for recognizing out-of-step condition can be divided into two categories: (1) detection and (2) prediction methods. Conventional methods mainly deal with detection while recently prediction methods have attracted some interest from researchers [19–21]. Due to the importance of out-of-step condition for synchronous generators from the point of view of mechanical and thermal damage, rapid detection of such situations is vital. For this purpose, detection of out-of-step may be too late and prediction methods appear to be necessary. Using decision trees [19], the transient stability of a generator is predicted based on the apparent impedance obtained from Phasor Measurement Units (PMU). A decision tree classifier is proposed to develop an out-of-step predictor [20]. A method for real-time prediction of transient stability using an energy approach and an Interactive Multiple model (IMM) algorithm is introduced [21].

In the present article, 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 the out-of-step condition of a generator. This method is also suitable for accurate detection of out-of-step condition after its prediction. The predictive ability of this method for out-of-step condition enables early tripping of an unstable generator to avoid hazard damage. All simulations for stability studies are carried out using Power Factory® software and the proposed predicting algorithm is developed in MATLAB. The proposed algorithm is implemented on the IEEE 39 bus New England system. The simulation results show that the proposed algorithm is able to correctly predict various unstable power swing conditions with sufficiently early prediction time compared with 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 in a generator when it loses its synchronism with other generators, and its rotor angle with respect to other generators increases monotonically due to increased power. Following the occurrence of a fault in the network, all generators are subject to a sudden decrease in electric power output, the magnitude of which depends on the location of the generator with respect to the fault. This sudden decrease in power output imposes greater power on the rotor, causing an increase in its speed and angle with respect to other generators. Equation (1) governs the dynamic of the generator during the transient period
FIGURE 1. Locus of $\omega - \alpha$ for a stable/unstable swing.

following a fault.

$$M \frac{d^2 \delta}{dt^2} = P_M - P_E = P_{acc} \quad (1)$$

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.

According to Eq. (1), during dynamic behavior, the speed and acceleration of the generator can be evaluated in terms of the change in rotor angle as follows.

$$\omega = \frac{d\delta}{dt} \quad (2)$$

$$\alpha = \frac{d^2 \delta}{dt^2} = \frac{1}{M} (P_M - P_E) \quad (3)$$

Figure 1 shows the locus of speed-acceleration ($\omega - \alpha$) of a specific generator during dynamic behavior leading to stability or loss of synchronism [11].

Point 1 represents the initial stable equilibrium point (SEP) before the fault in which ($\omega = \omega_0$, $\alpha = 0$). Point 2 represents an immediate situation after fault occurrence in which speed has not yet changed but acceleration has suddenly increased to a positive value ($\omega = \omega_0$, $\alpha > 0$). From point 2 onward, due to positive acceleration, both rotor speed and rotor angle start to increase according to Eqs. (1) and (2). 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 and its speed remains greater than $\omega_0$ ($\omega > \omega_0$, $\alpha < 0$).

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

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

As can be seen, in the post fault condition from point 4 onward, depending on the generator’s 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 the generator speed can be reduced to $\omega_0$ at point 5 while it is still undergoing decelerating power ($\alpha < 0$), it will follow trajectory A with the possibility of stability. Under this condition, the generator moves to points 6 and 7 with reduced oscillation and finally settling at equilibrium point 1.

2. If generator movement reaches to $\alpha = 0$ and ($\omega > \omega_0$) (e.g., point 8) it will follow trajectory B leading to the loss of synchronism. Point 8 is a typical point representing the UEP ($\alpha = 0$, $\omega > \omega_0$) of the generator. Under such a condition, the generator moves toward point 9 with monotonic increase in angle and speed of the rotor.

3. OUT-OF-STEP CONDITION CRITERION

The advent of PMU, 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 require data of the whole structure of the power system and is very time consuming [22]. Therefore, in this respect, estimation of rotor angle appear to be necessary. Having estimated the rotor angle of the generator using terminal variables measured by PMU [23–25], at consecutive interval times $t(i)$, $t(i + 1)$, and $t(i + 2)$, generator rotor speed and acceleration can be evaluated by Eqs. (4)–(7). These equations are based on discreet PMU data and piecewise
linear assumption of rotor angle, speed, and acceleration.

\[
\omega (i) = \omega_0 + \frac{\delta (i + 1) - \delta (i)}{t (i + 1) - t (i)} \quad (4)
\]

\[
\omega (i + 1) = \omega_0 + \frac{\delta (i + 2) - \delta (i + 1)}{t (i + 2) - t (i + 1)} \quad (5)
\]

\[
t_v (i) = \frac{t (i + 1) + t (i)}{2} \quad (6)
\]

\[
\alpha (i) = \frac{\omega (i + 1) - \omega (i)}{t_v (i + 1) - t_v (i)} \quad (7)
\]

For each generator, by using rotor speed and acceleration signals evaluated by Eqs. (4)–(7), the corresponding locus of speed-acceleration \((\omega - \alpha)\) like the locus of Figure 1 can be drawn.

During the dynamic behavior of a generator, if the curve of its \((\omega - \alpha)\) locus reaches a point such as point 5 \((\alpha < 0, \omega = \omega_0)\), the stability condition will be satisfied.

Regarding the behavior of the \((\omega - \alpha)\) locus for stable condition, the stability criteria can be derived as follows.

If the \((\omega - \alpha)\) locus of a generator crosses the line \(\omega = \omega_0\) at the negative part \((i.e., \alpha < 0)\) then it can be concluded that the generator will remain stable.

Such a situation causes the rotor angle to return to a stable point with reduced oscillations. However, it should be noted that only one cross section of the line \(\omega = \omega_0\) does not guarantee the total stability of the generator. In order to ensure complete stability of the generator, this criterion should be examined for repeated intersection of the line \(\omega = \omega_0\), which corresponds to stability for generator multi-swings.

If the \((\omega - \alpha)\) locus of a generator reaches a point such as point 8 \((\alpha = 0, \omega > \omega_0)\), the stability condition will not be satisfied. Regarding the 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 crosses the line \(\omega = \omega_0\) at the positive part \((i.e., \alpha > 0)\) then it can be concluded that the generator will lose its stability and become out-of-step.

Such a situation results in the rotor angle passing through unstable point UEP with monotonic increase, which is referred to as out-of-step condition.

4. PREDICTION OF OUT-OF-STEP CONDITION

Due to the importance of out-of-step condition for synchronous generators from the point of view of mechanical and thermal damage, rapid detection of such a situation is vital. For this purpose, simple detection of out-of-step may be too late and so predictive 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 \((\omega - \alpha)\) in Figures 2 and 3, respectively. The slope of the locus curve of \((\omega - \alpha)\) based on the linear model of Eqs. (2) and (3) can be evaluated by Eq. (8).

\[
m (i) = \frac{\omega (i + 1) - \omega (i)}{\omega (i + 1) - \omega (i)} = \frac{\Delta \omega (i)}{M \Delta \omega (i)} \quad (8)
\]

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

Based on the slope of the tangent line to the curve of \((\omega - \alpha)\), the proposed algorithm for predicting out-of-step condition can be verified.
Following a fault, when the locus curve is in the second quarter of the \((\omega - \alpha)\) plane where \(\alpha < 0\), by tracing the slope of the \((\omega - \alpha)\) curve the trend of the rotor angle toward stability or instability can be predicted.

In the second quarter of the \((\omega - \alpha)\) plane where \(\alpha < 0\), providing the tangent line to the locus curve crosses the negative part of the vertical line \(\omega = \omega_0\) at point \(M\) (e.g., points M1 or M2) as shown in Figure 2, there is no means of predicting the trend of rotor angle toward unstable or out-of-step conditions. The equation of the tangent line can be evaluated by Eq. (9) and the distance of point \(M\) from the point \((\alpha = 0, \omega = \omega_0)\) can be evaluated by Eq. (10).

\[
\alpha - \alpha(i) = m(i) \times (\omega - \omega(i)) \tag{9}
\]

\[
d_M = \alpha(i) + m(i) \times (\omega_0 - \omega(i)) \tag{10}
\]

The stability criterion can be mathematically interpreted by Eq. (11).

\[
d_M \times \alpha > 0 \tag{11}
\]

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

**Out-of-Step Prediction Criterion**

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

There are some severe unstable situations in which the curve of \((\omega - \alpha)\) does not appear in the second quarter of the \((\omega - \alpha)\) plane. Figure 4 shows a typical \((\omega - \alpha)\) curve for such a situation. The key point for occurrence of such situations is based on the fact that the generator will never undergo decelerating power under post fault condition. This situation can arise due to two conditions: (1) fault clearance time is longer than the time taken by the generator to reach its UEP \((t_{\text{clear}} > t_{\text{UEP}})\); and (2) a weak network structure under post fault
condition in which the generator’s electric power is less than its mechanical power (reducing power). Since in such situation the \((\omega - \alpha)\) curve never appears in the second quarter of the \((\omega - \alpha)\) plane, the detection method based on crossing the axis \(\alpha = 0\) by the \((\omega - \alpha)\) curve is unable to detect such an unstable situation.

The criterion for detecting such an instability condition can also be derived based on the slope of the tangent line to the \((\omega - \alpha)\) curve in the first quarter of the \((\omega - \alpha)\) plane. After a fault, if the locus curve remains in the first quarter of the \((\omega - \alpha)\) 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 point M (e.g., points M6 or M7) as shown in Figure 4, this can be used as a sign for prediction of movement of the 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 Eq. (12).

\[
d_M \times \alpha < 0 \tag{12}\]

Regarding the serious consequences of incorrect action for out-of-step relay, in order to prevent any mal-prediction by the proposed approach, out-of-step relay will be activated when the criterion for out-of-step condition is armed more than once. For this purpose, an arming repeater “\(r\)” is defined as equal to the number of consecutive armings of the criterion. For activation of out-of-step relay, a reference value “\(r_0\)” is defined for the arming repeater which should be satisfied as \((r > r_0)\).

Figure 5 shows the flowchart of the proposed approach for predicting out-of-step condition.

The application of the proposed method has no limitation with respect to single-swing or multi-swing instability because it is based on the basic concept of out-of-step. However, in the case of a serious instability situation in which the fault clearing time \((t_{\text{clear}})\) is much greater than the critical clearing time \((\text{CCT})\) \((t_{\text{clear}} >> \text{CCT})\), the accuracy of prediction will

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Generator number} & Z_a(p.u.) & Z_b(p.u.) & Z_c(p.u.) & Z_d(p.u.) \\
\hline
7 & 0.1127 & 0.3616 & 0.0285 & 0.0714 \\
2 & 0.1592 & 0.486 & 0.0648 & 0.162 \\
6 & 0.1758 & 0.5315 & 0.0769 & 0.192 \\
\hline
\end{array}
\]

\textbf{TABLE 2.} Setting of out-of-step distance relay for generators of IEEE 39 bus system.
be lower than the case in which clearing time is slightly greater than CCT.

5. SIMULATION STUDIES

In order to demonstrate the effectiveness of the proposed approach, it is applied on the IEEE 39 bus New England system with ten generators. All stability simulations are carried out using 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 fault, including three-phase short circuit, line to ground, and double line to ground, and line to ground are presented. In this study, after several simulation studies, the reference value for the arming repeater “\(r_0\)” is adopted as 3. For each scenario, by initially performing stability simulation using Power Factory® software, the rotor angle and stability condition of the generator are evaluated. In order to evaluate speed and acceleration of the generator, the rotor angle is evaluated every 10 ms based on the sampled data for a time duration of 2 s.

Corresponding to each unstable scenario, the time duration for the generator to go out-of-step is denoted as time out-of-step (TOFS) and evaluated using simulation results and tracing the variation of \((\omega - \alpha)\) until reaching the point of UEP \((\alpha = 0, \omega > \omega_0)\) like a typical point such as 8 in Figure 1. This time duration shown in the fifth column of Table 1 is regarded as the actual time for the generator to become out-of-step after fault occurrence. For each fault scenario, by using corresponding simulation results the curve of the \((\omega - \alpha)\) locus is drawn and by applying the proposed algorithm the predicted time for out-of-step (TPOFS) is evaluated. In Table 1, the seventh column shows the predicted TPOFS associated to each fault scenario. This duration is the time required for the generator to show some indication in its behavior \((\omega, \alpha)\) specifying its movement toward the corresponding UEP \((\alpha = 0, \omega > \omega_0)\). Also in order to show the effectiveness of the proposed approach compared with other methods, it is compared to a conventional out-of-step distance relay. Figure 6 shows typical characteristics of the distance relay.

In order to demonstrate the ability of the proposed approach, more than 500 cases with different fault locations and durations were tested, from which five scenarios are reported in Table 1. The second and fourth scenarios are for three-phase short circuit faults, the fifth scenario is for a serious
three-phase short circuit fault, and the first and third scenarios are for a single-phase short circuit fault.

In Table 1, the seventh column shows the actual TOFS based on the time the system passes through the point of UEP; the eighth column shows the detection TOFS by the conventional method based on the distance relay; and the tenth column shows TPOFS based on the proposed method. As can be seen, the detection time using distance relay is far from the actual time of out-of-step while the prediction time by the proposed method is close to the actual time and almost lower. The 11th column shows the difference between the actual and predicted TOFS.

Table 2 shows the corresponding setting for distance relay to detect out-of-step based on the procedure developed in [26].

Figures 7–12 show variations of rotor angle, speed, acceleration, and the ($\omega - \alpha$) locus curve of the stable/unstable generator corresponding to the five fault scenarios.

As can be seen, the proposed approach is able to predict the condition of out-of-step much more rapidly than the conventional distance relay. Also it is able to predict out-of-step condition earlier than the actual time of out-of-step at which the system passes through the UEP point.

The time difference of the proposed approach with respect to the actual time for reaching UEP seems to be adequate for preventative action to be taken for early tripping of the generator.

In order to compare the simulation results to those reported in the literatures, reference [27] 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). Also, compared with [11], the proposed algorithm has better prediction time. Reference [19] claims prediction of out-of-step 0.2 s after fault clearance, however it needs considerable offline study, while the proposed algorithm is based on the concept of out-of-step and can work in real-time. In [28], the out-of-step prediction algorithm is based on the rotor angle passing through 180°, this time being close to the “Actual TOFS based on UEP” column in Tables 1 and 3, while the proposed algorithm has much better results which are shown in the “TPOFS by proposed method” column in Table 1.

6. CONCLUSIONS

In this article, 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. It is assumed that the rotor angle is known 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 was examined on generators using the IEEE 39 bus test system with promising results, showing its ability for correct and early prediction of out-of-step conditions. The algorithm was examined for several fault scenarios of varying severity resulting in both stable and unstable conditions. In all cases, it works properly and predicts correctly out-of-step condition before the generator reaches its UEP point. Also, the proposed approach was compared to the conventional out-of-step distance relay and results show its ability for earlier prediction. The simulation results show that the time difference between detection and prediction of instability achieved by the proposed algorithm is relatively satisfactory for early tripping of the generator before becoming out-of-step and consequent damage.

REFERENCES


**BIOGRAPHIES**

Ali Reza Sobbouhi received his B.Sc. degree from Power and Water University of Technology (PWUT), Tehran, Iran in 2012 and his M.Sc. degree from Sharif University, Tehran, Iran in 2014. His fields of interest include power system dynamics and control, and artificial intelligence applications to the problems of power systems.

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