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Strategies for detection of out-of-step phenomenon for power system protection and control

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Power systems, nowadays, are subjected to severe oscillations during the post disturbance span of time because of its operation at very narrow stability margins. Out-of-step condition is a consequence of transient instability and protection against out-of-step condition is a major issue for the power industry. In order to operate a system safely and to protect from the damages caused to system components such as generators, transmission lines and switching equipment, proper out-of-step detection and necessary protective action has to be provided. This paper explains the various out-of-step detection strategies which can be augmented to the numerical relaying algorithms, their computational simplicity and reliability and also discusses the issues and challenges related to implementation.

Keywords: *Distance protection, numerical relays, out-of-step detection, phasor measurement, power swing and transient instability*

1.0 INTRODUCTION

The integration of the out-of-step detection function into a numerical relaying algorithm is done to differentiate the stable and unstable power swings and to initiate system area separation or islanding if required, at predetermined points in the network. This has to be executed by satisfying the voltage and phase angle constraints. If load generation balance cannot be achieved in some areas, adequate load shedding is necessary to avoid a complete blackout. The measured apparent impedance during a power swing is of oscillatory nature and may initiate the distance zone tripping, which is not desirable. Very often, the distance relays are utilized to provide the out-of-step protection function and the detection is basically done by observing the movement of the impedance loci. In large interconnected networks, the operation of conventional out-of-step relays are found to be unsatisfactory, because the network topology and conditions considered when the relay characteristics are defined become outdated quickly and thus the electromechanical swings that occur may be completely different from those obtained during simulations.

The another major concern is that even though it is possible to decide between the stable and unstable swing, still the algorithm should be most reliable and it should execute the classification in a reasonable time.

2.0 CONCEPT OF POWER SWING AND OUT-OF-STEP PHENOMENON

Power swing is defined as a variation in three phase power flow which occurs when the generator rotor angles are advancing or retarding relative to each other in response to changes in load magnitude and direction, line switching, loss of generation, faults and other system disturbances [1]. During a power swing, a change is observed in the relative phase angle between the group of generators. If the generators do not slip poles and

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the system reaches a new state of equilibrium or an acceptable operating condition, it is considered as a stable power swing. If a generator or a group of generators experience pole slipping i.e. if the system does not return to a stable state of equilibrium, it is considered as an unstable swing.

Figure 1 shows a simple transmission system in which power $P_{initial}$ is transferred over two parallel lines. $P_{initial}$ is given by

$$P_{initial} = \frac{EV}{X} \sin \delta \quad ....(1)$$

where X is the total reactance of the two parallel lines, E is the internal voltage of the generator, V is the voltage of the infinite bus or the reference bus, δ is the angle between two sources.

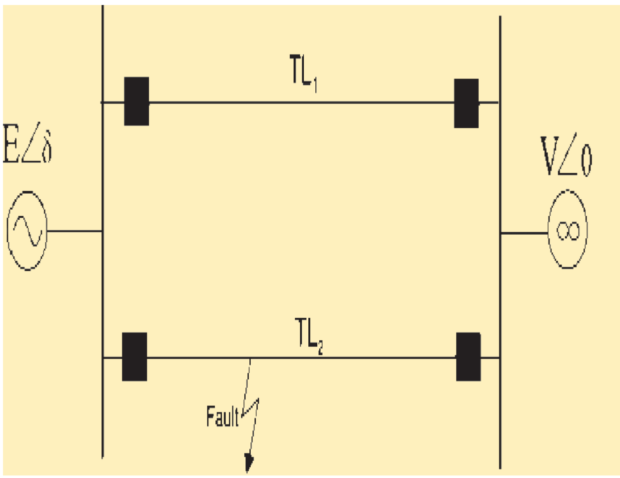

FIG. 1 SINGLE MACHINE INFINITE BUS SYSTEM

Any disturbance causes an imbalance between input mechanical power and output electrical power in the system and as a consequence electromechanical oscillations are developed. These oscillations are electrically characterized by the fluctuation of voltages, currents and hence the power flows in the system and this is referred to as a power swing. Dynamic behavior of the system can be determined by swing equation

$$\frac{Md^2\delta_m}{dt^2} = P_M - P_E = P_A \quad ....(2)$$

where M is the inertia constant, δ_m and δ are the mechanical and electrical angles respectively, P_M, P_E and P_A are mechanical, electrical and accelerating powers respectively. Figure 2 and 3 shows the plots of P_E and P_M versus power angle δ for stable and unstable systems. In Figure 2, the angles δ_0 and δ_c are the pre-fault and post-fault clearing angles respectively. Here the stability criterion A_1=A_2 is satisfied as the power angle loci reaches the point 4. Thereafter the acceleration of the angle δ is negative which causes a return to a stable point [2].

In the case of an unstable system as in Figure 3, area A_1 is larger than A_2 and thus the stability criterion is not satisfied. As the locus of the angle reaches δ_{UEP}, the acceleration is positive resulting in an out-of-step condition. This is called an unstable power swing. If the power swings are severe, it is desirable to separate the system by tripping certain transmission line lines so that the subsystem will eventually settle at stable states.

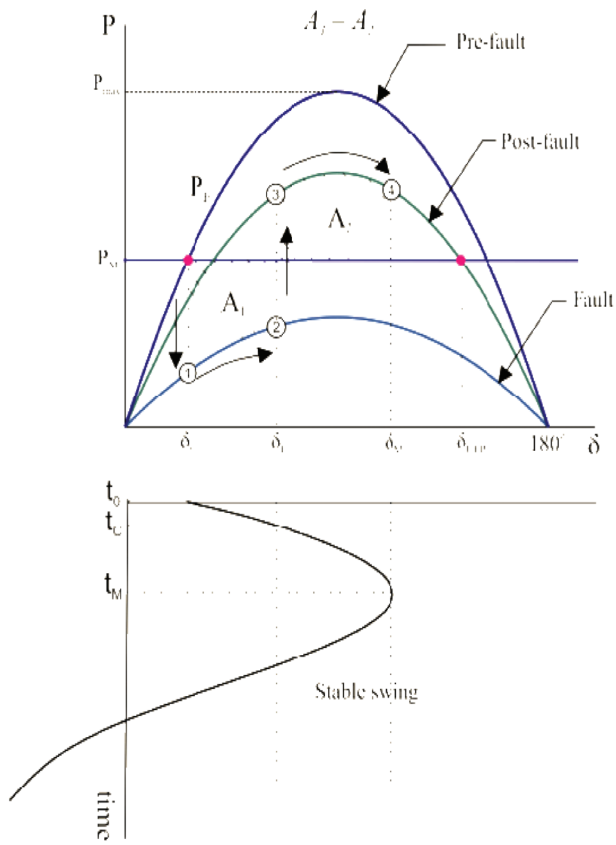

FIG. 2 POWER-ANGLE CURVE AND ANGLE (STABLE SYSTEM)

This basically helps in two ways: first is to get rid of a complete system collapse and second is to make the system restoration easier.

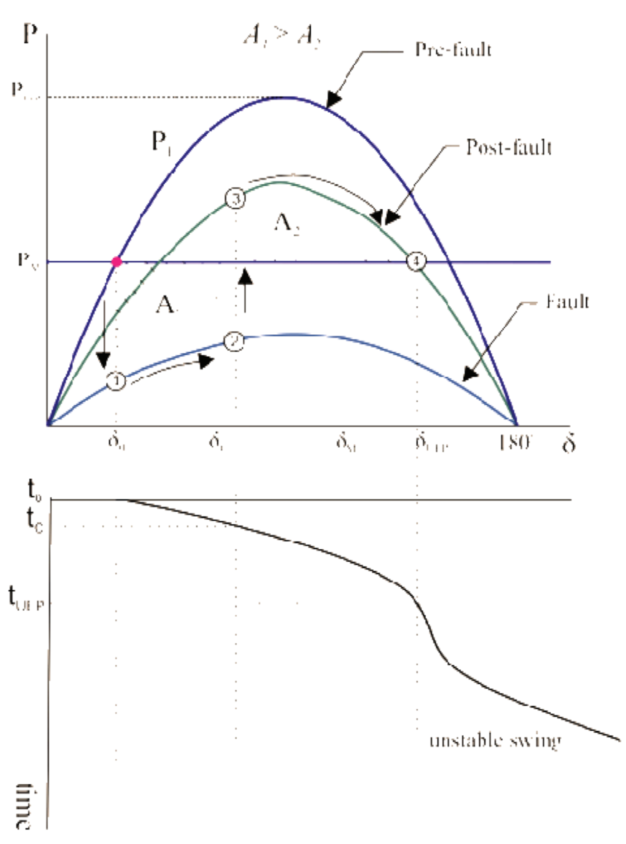

FIG. 3 POWER-ANGLE CURVE AND ANGLE (UNSTABLE SYSTEM)

3.0 NEED FOR AN OUT-OF-STEP DETECTION FUNCTION

As mentioned in the previous section, the system separation during an out-of-step condition helps in avoiding a complete system collapse. The needs for augmentation of a power swing detection algorithm to distance relaying are as follows. Power swings can cause mal-operation of generator protection, zone 1 distance, phase over current and phase under voltage elements. For secure operation of the power system, all these elements have to be made secure by providing a power swing detection function and In order to avoid a complete system collapse in case of an unstable power swing, out-of-step detection must be provided so as to generate an out-of-step tripping (OST) or blocking function wherever required.

4.0 METHODS FOR OUT-OF-STEP DETECTION

Detection of power swings are done with many different techniques each having its own advantages and drawbacks. An overview of these different methods is presented in this section.

4.1 Rate of change of impedance method

During a power swing, locus of the measured impedance move slowly on the impedance plane and the rate of change of impedance depend on the slip frequency of the system. Conventional schemes make use of this difference between the rate of change of impedance during a power swing and a fault to identify whether it is a power swing or a fault.

4.1.1 Concentric characteristic schemes

The simplest method for measuring the rate of change of impedance is to determine the elapsed time required by the impedance vector to pass through a region bounded by two impedance characteristics [3]. In this method, there will be a quadrilateral or circular shaped concentric impedance elements provided with a timer for the measurement of impedance trajectory time from when the locus reaches the outer element to the time it reaches the inner element. If this time is more than the preset delay the power swing blocking function is enabled (Figure 4).

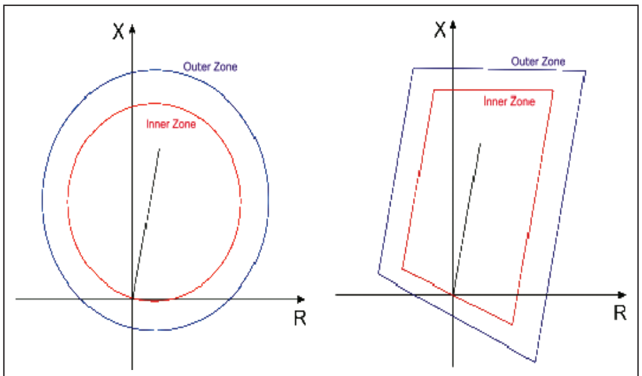

FIG. 4 POWER-ANGLE CURVE AND ANGLE (UNSTABLE SYSTEM)

The main advantage in this method is that before reaching any one of the impedance tripping zones the power swing condition is checked, thereby allowing the distance elements to be blocked if desirable [4]. The drawback of concentric circular characteristic is load encroachment i.e. the characteristic will limit the reach of the higher impedance zone. The limiting requirement in the application of concentric quadrilateral characteristics is that the resistive reach of the outer zone should not enter into the load characteristics.

4.1.2 Blinder schemes

Blinder schemes are generally of two types, classified on the basis of number of blinders. Dual Blinder Scheme is also based on the similar principle as that of the concentric characteristic schemes. It measures the time interval Δt, the impedance trajectory takes to cross the distance between the outer blinder and inner blinder [3]. When the time measured is more than the time delay set, it declares a power swing. Also this scheme can be utilized to have an out-of-step tripping function when the trajectory moves the way out of the distance zones. Figure 5 shows the basic example of a dual blinder scheme. The main advantage of this method is that it can be used independent of the distance characteristic zones.

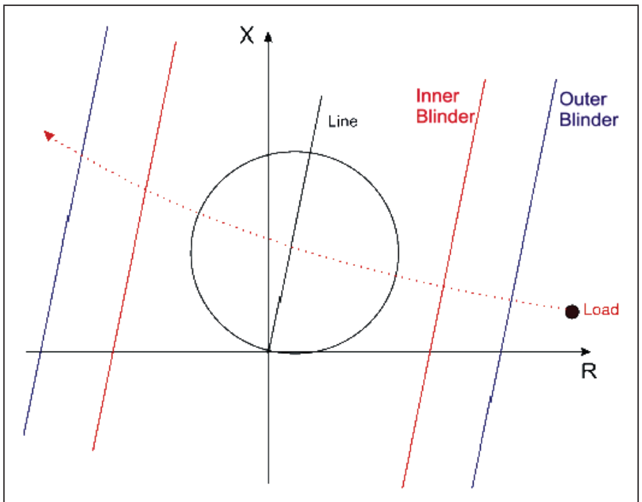

FIG. 5 DUAL BLINDER SCHEME

Single blinder scheme have only one set of blinder characteristics is used and an auxiliary tripping logic can be used for an out-of-step tripping function.

However this scheme is usually utilized where out-of-step tripping blocking is not required because the swings passing through the line section will cause distance zones to operate. Figure 6 shows the single blinder scheme. The major advantage of the single blinder scheme is that it is least affected by load encroachment.

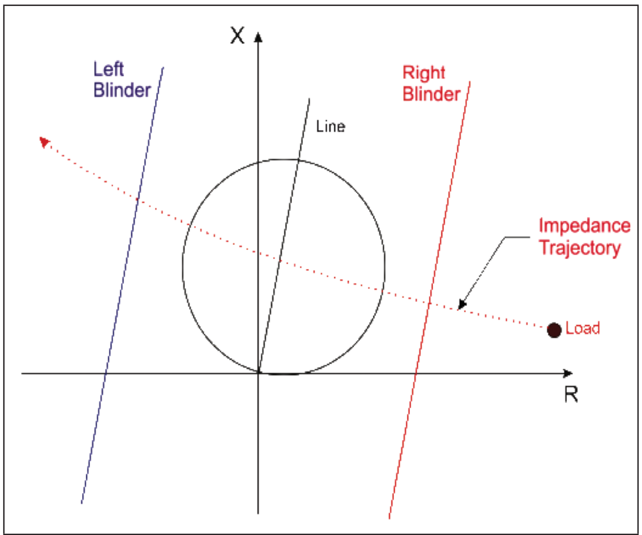

FIG. 6 SINGLE BLINDER SCHEME

The major issues in blinder techniques are to set the blinders and to determine the preset delay because the settings are often system specific in nature. Therefore setting the blinders for all possible system condition is very difficult. This scheme requires extensive system studies.

Generally, the schemes which utilizes the rate of change of impedance has drawbacks such as they can only detect an out-of-step condition after crossing the blinder on the opposite side and these methods does not aid in determining the right angle (time) to split the system.

4.2 Out-of-step detection using rate of change of apparent resistance augmentation or the rdot scheme

In this method, the rate of change of apparent impedance is replaced with the apparent resistance augmented with the rate of change of apparent resistance and the characteristic is defined in the $R\text{-}R_{dot}$ plane [5]. In order to avoid severe voltage dips throughout the whole system, the out-of-step tripping initiation is required prior to the point where voltage at the electrical center reaches to a minimum value. Control algorithm based on resistance to define the out-of-step detection is given by

$$Y = (R - R_1) + T_1 \frac{dR}{dt} \leq 0 \quad ....(3)$$

where R is the apparent resistance measured by the relay, Y is the control output and R_1 and T_1 are relay setting parameters. Figure 7 shows the characteristics of R_{dot} relay in the R-R_{dot} plane.

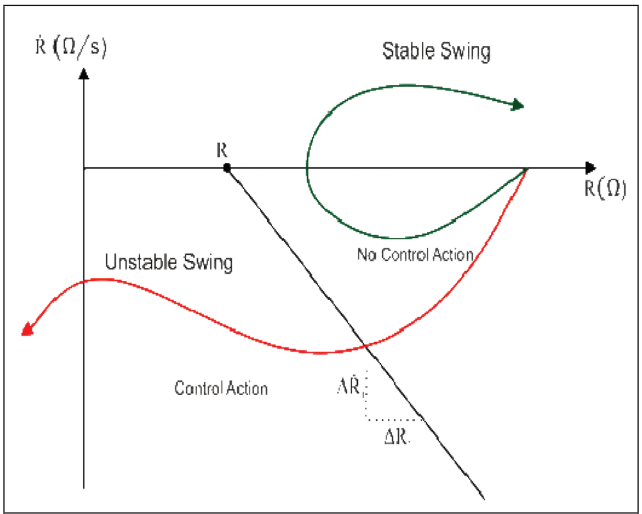

FIG. 7 OUT-OF-STEP DETECTION USING RATE OF CHANGE OF APPARENT RESISTANCE AUGMENTATION

As mentioned in the equation (3) Y becomes the switching line in this scheme of detection and the relay develops an output when the power swing trajectory crosses the switching line. This scheme also demands extensive system studies through simulations.

4.3 Method based on continuous impedance calculation

In this technique, algorithm monitors the progression of the impedance locus in the R-X plane and it declares a swing based on the fundamental characteristics of a power swing such as continuity and smoothness [3]. The basic scheme is shown in Figure 8.

The main advantage of this method is that it can handle slip frequencies up to 7 Hz and does not require any special settings contributed by power swing studies and complex simulations. The drawback is that in order to handle very slow moving trajectories this scheme has to be supplemented by a concentric characteristic.

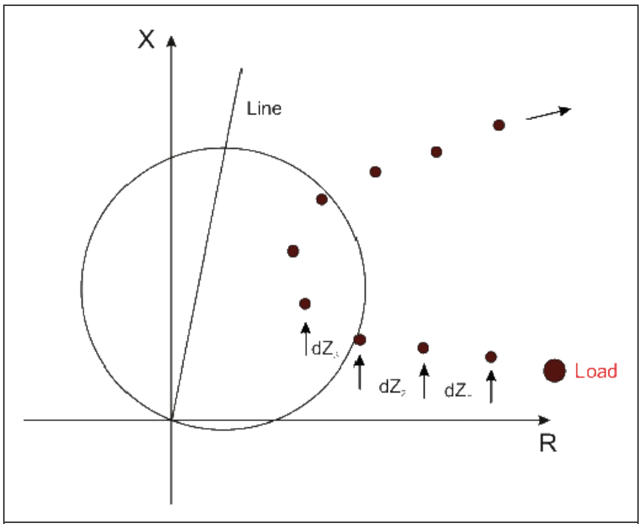

FIG. 8 POWER-ANGLE CURVE AND ANGLE (UNSTABLE SYSTEM)

4.4 Method based on swing centre voltage and its rate of change

Swing Center Voltage (SCV) is defined as the voltage at the location of a two source equivalent system where the voltage value is zero when the angles between the two sources are 180° apart [6]. Figure 9 shows the voltage phasor diagram for a general two machine system.

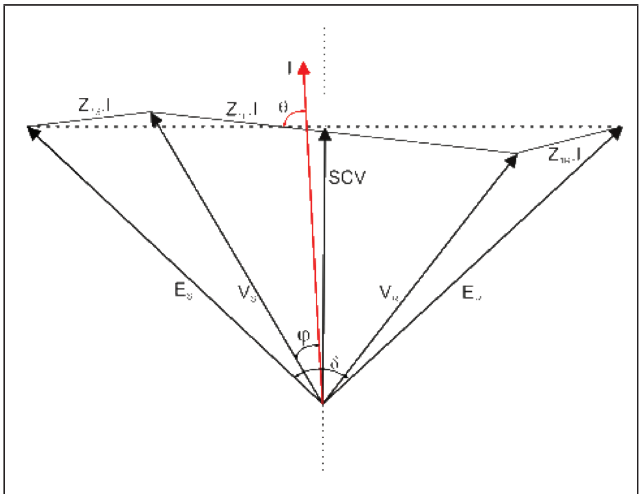

FIG. 9 POWER-ANGLE CURVE AND ANGLE (STABLE SYSTEM)

The Swing Center Voltage (SCV) is approximated as

$$SCV \cong |V_S| \cos\emptyset \quad ....(4)$$

by using the measurements locally available, where V_s is the magnitude of the locally measured voltage and ϕ is the angle between V_s and the local current measurement I as shown in Figure 8. The main information on the nature of the power swing for the purpose of out-of-step detection is given by the rate of change of SCV. If the source voltages E_S and E_R are approximated to the positive sequence voltage E_1, the positive sequence swing center voltage can be written as:

$$\mathrm{SCV}_1 = E_1 \cos\left(\frac{\delta}{2}\right) \quad ...(5)$$

The time derivative of SCV1 is given by

$$\frac{d(SCV_1)}{dt} = -\frac{E_1}{2}\sin\left(\frac{\delta}{2}\right)\frac{d\delta}{dt} \quad ...(6)$$

Equation 6 shows that when the angle between the two machines is zero, rate of change of SCV_1 is also zero and when δ is equal to 180°, the rate of change of SCV_1 is maximum, which forms the basis for this scheme.

The major advantage of this technique is that the swing center voltage is independent of the source and line impedances of the system and it depends directly on the angle between the two sources, δ. The disadvantage is that the detection is usually made at a separation angle near to 180° and the approximation done in the algorithm will work only if the system impedance angle is close to 90°. Also for a multi machine system this method is not reliable since the voltage measurement at relay location does not give an accurate approximation of the swing center voltage.

4.5 Out-of-step detection using frequency deviation of voltage

In this method, frequency is computed using the voltage angle measured at the local bus and using this frequency, angular acceleration is calculated and Unstable Equilibrium Point (UEP) is detected [7].

Figure 10 shows the trajectory of angular velocity (ω_c) versus acceleration (α_v) of instantaneous voltage v(t). In this method, the difference in the swing curve in the angular velocity versus acceleration plane is used to differentiate between a stable and an unstable power swing.

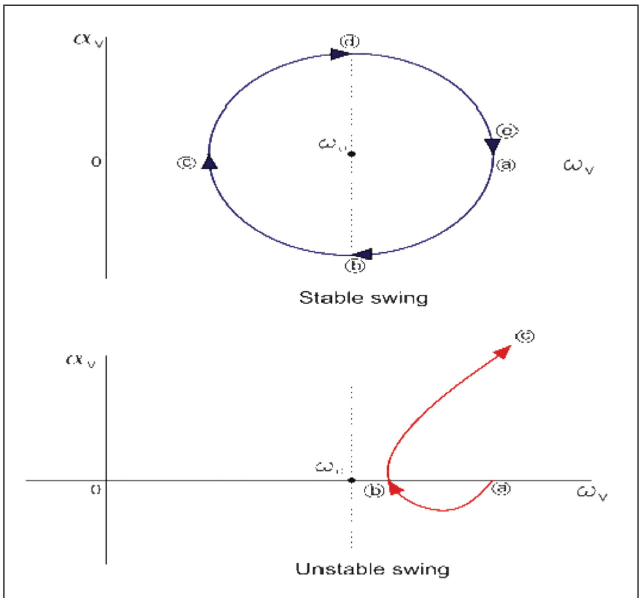

FIG. 10 TRAJECTORY OF ANGULAR VELOCITY (ΩV) VERSUS ACCELERATION (AV) OF INSTANTANEOUS VOLTAGE V(T)

When the polarity of the angular acceleration changes from negative to positive and the angular velocity is greater than ω_0, an out-of-step condition is detected. In this method, the local measurements from the PT or CVT is passed through an antialiasing filter, then digitized and fed to the out-of-step detection algorithm. Since this method relies on the system voltage signal (local measurements) which can change vary rapidly, it may result in false tripping due to switching transients. Also a wide area application of this protection has not been reported so far. Another main problem in this technique is the determination of ω_0, when there is load generation unbalance since ω_0 is no longer constant.

4.6 Detection based on the equal area criterion in the power angle domain

This method is based on the well-known equal area criterion. The swing equation is given by

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = \Delta P = P_m - P_e \quad ....(7)$$

Rewriting and integrating

$$\frac{d\delta}{dt} = \int_0^t \frac{\omega_s}{2H}\Delta P\, dt \quad ....(8)$$

Integrating this equation from the fault inception time t_0 to the fault clearing time tc and fault clearing time t_c to t_{max}, and combining, we have

$$\sum_{t_0}^{t_c} \Delta P \Delta t + \sum_{t_c}^{t_{max}} \Delta P \Delta t = 0 \quad ....(9)$$

which is the basis for this technique. The detection is based on the comparison of the two areas A_1 and A_2. If area A_1 and A_2 are equal, a stable swing is declared and if A_1 is greater than A_2 it is declared as an unstable swing. The equal area criterion based methods suffer in providing the critical clearing angle (CCA) and critical clearing time (CCT) for the power swings simultaneously and these methods need step by step integration techniques for the computation of critical clearing time.

4.7 Detection based on the equal area criterion in the time domain

In this technique, the classical equal area criterion is mapped to the time domain from the power angle domain and a graphical identification of the out-of-step condition is made in the time domain by point-by-point analysis. The accelerating and decelerating area in the power versus time trajectory is computed and if the areas corresponding to transient are equal, the system becomes stable [8]. If the accelerating area is greater than decelerating area the system becomes unstable. Figure 11 shows the PE-T curves for a stable and an unstable system. For a stable case, area A_1 is equal to A_2 and for an out-of-step condition; area A_1 is greater than A_2.

In order to get the area A_1, the limit of integration is set from t_0 to t_1, where t_0 is the fault inception time and t_1 is the time at which the electrical power Pe exceeds Pm line. Area A_2 is obtained by setting the limit of integration from t_1 to t_{max}, where t_{max} is the time at which δ is equal to δ_{max}. In order to get rid of the noise and other dynamic disturbances, the presence of instability is declared only when the disturbance magnitude (variation of the electrical power from the pre-fault value) is greater than 10%.

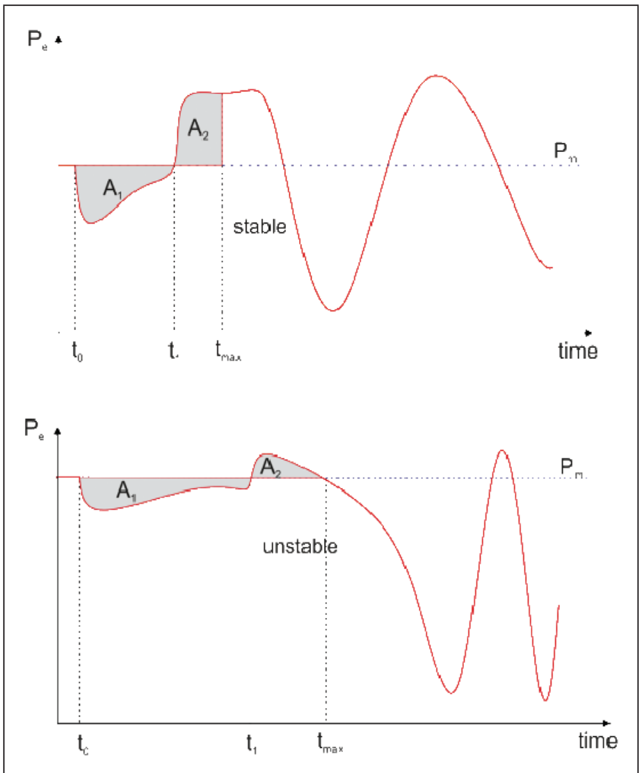

FIG. 11 PE V/S T CURVE FOR STABLE AND UNSTABLE CASES

In this method the main concern is with the opening of the circuit breaker since the unstable condition is detected close to 180°. Therefore, the breaker operation has to be delayed until the angle of separation reaches a favorable angle so as to reduce the re-striking voltage level. These methods also cannot provide the Critical Clearing Angle (CCA) and Critical Clearing Time (CCT) for the power swings simultaneously and need step by step integration techniques for the calculation of critical clearing time.

4.8 Method of detection using transient stability index

This method is based on the geometric characteristics of the system trajectory which is utilized to determine the instability of the system. In order to detect an out-of-step condition, an instability index is defined based on the nature of surface (concave or convex) on which the post fault trajectory lies [9]. The inputs to this algorithm are generator angles, angular velocity and angular acceleration which can be measured at the generator terminals. The transient instability index μ is defined as

$$\mu = \frac{[-\dot{\omega}(t-\Delta t)\ \omega(t-\Delta t)]\begin{bmatrix}\delta(t-\Delta t)-\delta\\ \omega(t-\Delta t)\end{bmatrix}}{[-\dot{\omega}(t-\Delta t)\ \omega(t-\Delta t)]\begin{bmatrix}\delta(t)-\delta\\ \omega(t)\end{bmatrix}} \quad ....(10)$$

i.e. the computation is very straightforward and it requires only measurements at generator terminals. This method detects the out-of-step condition or the instability based on the characteristics of the surface on which the post disturbance trajectory exists (concave or convex). If the value of the index μ is greater than one, then the surface belongs to concave nature and the system is stable else if the value of μ is less than one it is a convex surface and instability is declared.

4.9 Synchrophasor measurement based out-of-step detection

With the advent of phasor measurement units, time synchronized voltage angle measurements at different locations can be accomplished and can be transmitted across fast communication channels and can be utilized for out-of-step relaying. Basically two approaches are proposed in the literature [10]. One approach consists of time synchronized measurement of phase angle between the voltages between the transient reactance of the two machines and when a disturbance occur new phase angle is computed and the equal area criterion is verified in real time by the algorithm implemented. Second approach is based on a predictive algorithm where the positive sequence phasor of two or more most significant buses are measured and when a disturbance occur, the phase angle between the signal pairs is computed in real time. Here the predictive algorithm is used to differentiate between a stable swing and an unstable swing. For both of the approaches it requires identification of group of coherent machines. The procedure for detection of out-of-step condition is as follows:

- With the wide area measurements obtained, the coherency of the group of machines is identified.
- The equivalent Center Of Angle (COA) is computed for each group of coherent machines.
- Based on the center of angle (COA) difference, stability or instability is declared.

Figure 12 shows the equivalent COA diagram for the groups of machine based on the coherency identification.

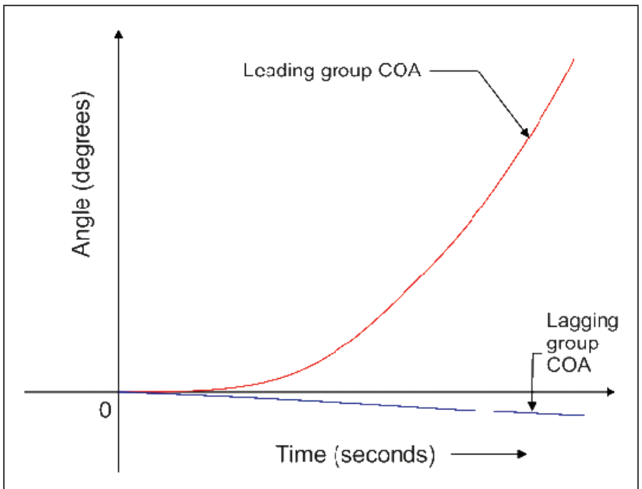

FIG. 12 EQUIVALENT COA DIAGRAM

The difference between the equivalent center of angles are compared with the set value to determine stability.

4.10 Detection using state plane trajectories analysis

In this method, the computation of the critical clearing angle is done using the principle that the total energy at the fault clearing instant should be equal to maximum potential energy of the system and the critical clearing time can be obtained by the time calibration of the relative speed versus power angle curve. Consider a power system is described with the following differential equation.

$$\ddot{\delta} = f(\delta, \dot{\delta}) \quad ....(11)$$

Representing as set of first order differential equations, we have,

$$\dot{x_1} = x_2 \qquad \dot{x_2} = f(x_1, x_2) \quad ....(12)$$

The state plane is the plane with coordinates x_1 and x_2 and the solution of equation 12 with respect to the time can be plotted in the state plane and is called the state plane trajectory. If the initial state of the system is known, the nature of the post disturbance dynamics can be easily predicted by observing the trajectory. The determination of singular points is an important stage in plotting the state plane trajectories and the stable and unstable equilibrium points are called the vortex and the saddle point respectively.

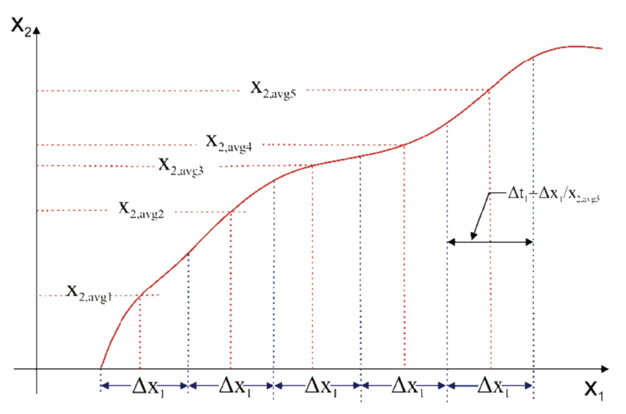

FIG. 13 CALCULATION OF TIME FROM THE STATE PLANE TRAJECTORY

The out-of-step detection algorithm mainly constitutes four stages. First stage is to find the state plane plot during disturbance. In the second stage, the time scale values are calculated. The third stage is to find the critical trajectory for the post disturbance condition and in the fourth stage critical clearing angle (CCA) and critical clearing time (CCT) are calculated. Time calculation from the state plane trajectory is shown in Figure 13. Out-of-step detection is made by comparing the critical clearing time and the fault clearing time. If critical clearing time is more than the fault clearing time, an unstable swing is declared.

One of the advantages of state plane trajectories analysis is that it is much faster than the two blinder scheme because of the simultaneous computation of the critical clearing angle and time and another advantage is that this method does not require any offline studies.

5.0 CONCLUSIONS

This paper has discussed the out-of-step phenomenon, the need for the proper detection and preventive action and also illustrated the different power swing detection methods that can be implemented standalone or augmented to a distance relaying algorithm. In summary, there are many different power swing detection methods that can be used to improve the system reliability and security from out-of-step conditions, each having its own benefits and drawbacks. The method of state plane trajectories and the method utilizing swing center voltage allow successful application of the power swing detection without having the knowledge of dynamic behavior of the system. Also state plane trajectories analysis technique provides a faster prediction of the out-of-step condition before the machine actually start slipping poles. At present, power engineers depend on the offline simulation studies and results to determine the out-of-step tripping locations which can be improved so that the desired system separation can be determined in real time. Also wide area measurements, now available through the state-of-the-art synchrophasor technology, are very useful and very reliable since the detection of small angle swings at a particular location serves to detect, characterize and differentiate the power swings and to provide blocking and tripping signals. Therefore, application of hybrid techniques will be useful for the instability detection to make use of the advantages of direct methods and wide area measurements using synchrophasor technology.

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