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Detection and Prevention of Aperiodic Small Signal Angle Instability at an Early Stage

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This paper explores the method of early detection and prevention of aperiodic small signal rotor angle (ASD) instability. A criterion for ASD stability detection is tested on a synthetic system. Sensitivity analysis is utilized to seek the node that would have the most influence on the generator undergoing said instability. The assessment of a suggested countermeasure is carried out to determine whether the system will sustain the stable state. Three case studies on the synthetic system, in the form of generator fault, three phase symmetrical fault and double line to ground fault, are also performed to test the method of early detection.

Keywords: Stability, Rotor angle, PMU, Sensitivity analysis

I. INTRODUCTION

A stable, secure power system is of paramount importance for a sustainable and progressive society. Instability-triggered power system failures bring significant power supply shortages across large regions. Blackouts can persist for several hours and affect hordes of consumers. The restoration of normal operating conditions is a complex method that involves a lot of effort and time from staff in the control room. Such issues can be avoided if these instabilities can be detected and prevented at an early stage. The developments in the field of phasor measurement technology have created new avenues to explore real time stability assessments which would provide the operators with sufficient time window to take actions against an imminent instability. The stability assessment techniques need to be valid for a wide range of changes that trigger the instability. Since extensive work has been done on voltage instability and frequency instability, this paper shall focus on Angle instability, or more specifically, the aperiodic small signal angle instability.

A comprehensive classification and definition have been given for each form of instability in [1],[2]. In [3], [4] a method is provided for long-term voltage instability detection using wide-area snapshots to calculate sensitivities in a system with complete observability. The calculated sensitivities are traced and to guarantee a quick computing speed, the representation of an algebraic system is used.

In [5], [6] the phasor measurements of the system and the Thevenin equivalents are used to calculate the maximum power stability margins and to develop a technique for long term voltage instability identification.

For transient stability, [7] provides an early forecast technique for transient voltage sags of critical nature induced by rotor swings, using complete system observability and the SIME method i.e. single machine infinite bus equivalent method.

In [8], long term instability or more specifically, aperiodic small signal angle instability was studied. An effective algorithm for calculating power margins of generators based on Thevenin impedance calculations was proven to be suitable for offering an early warning in real time against this form of instability.

In order to decrease the number of nodes to be processed through the sensitivity analysis, an algorithm has been suggested in [9]. A method is provided in [10] to determine Thevenin impedance using synchro phasor snapshots in real time.

In addition, in order to ascertain whether an applied countermeasure would restore stability, the rotor angle dynamics for each generator in the grid should be anticipated. A technique for such a forecast was provided in [11] using real-time synchro phasor snapshots of the system.

The early step at angular stability detection to enable online applications was suggested in [12]. It describes a technique based on real-time surveillance of synchronization and damping torques. The technique uses neural network approach multilayer feed forward approach. Mainly, the estimation of transient stability is regarded in the paper, but surveillance of the synchronizing torque element based on real-time rotor angle, velocity and electromagnetic torque measurements makes it possibly applicable for an aperiodic small angular stability (ASSAS) evaluation.

Another technique regarded in [13] utilizes wide area measurements to define ASSAS boundaries in the system for each generator in terms of maximum injectable power and maximum rotor angle. Specified activities on the decreased admittance matrix are suggested to achieve these critical values.

Using techniques such as Decision Trees, Computational Intelligence and Neural Networks for the real-time evaluation of oscillatory stability, among other things, is under consideration in [14], [15]. In [14], the methodology for calculating countermeasures to prevent oscillatory instability suggests the use of generalized optimal power flow where the function to be targeted is defined as the difference between the actual load flow and the features of the desired countermeasure calculation.

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These techniques provide promising early-stage outcomes for identifying oscillatory instability, but have common inconvenience of necessarily being intensively trained before appropriate functioning is feasible.

The time frame between emerging instability and system crash may range from a few seconds to dozens of seconds depending on system setup and the magnitude of synchronizing torque deficit. In the event of a small synchronizing torque deficit, the early stage of instability cannot be detected by tracking the primary system parameters, as their variation is very smooth and progressive. At the same moment, very early identification of ASSAI would provide adequate time for suitable countermeasures to be taken. Nevertheless, this sort of instability has not been the focus of the studies on real-time stability evaluation over the past decade. Very few approaches were established for on-line ASSAI assessment in [16]-[19].

It has been shown in [20] that critical limits for stable state stabilization are close to the limits of convergence of load flow. Thus, the inference about the system's stable state could be made on the basis of the calculation of power flow. However, the use of this technique for real-time stability evaluation is hardly possible, as it needs a full and accurate grid model at any time of operation, and load flow calculations for large-scale energy systems are excessively time-consuming for online analysis.[21]

Further artificial intelligence techniques were explored in [22], with the same constraint of being extensively trained for specific systems. References [23]-[25] provide the reference data for generators.

A prevalent objective of the preceding papers is to give early warnings and raise awareness of the scenario, but they do not indicate which actions to take after an early warning has been provided regarding an imminent situation. An algorithm which includes both detection of instabilities and proposal of countermeasures can be viewed as a first step towards a self-healing power system.

The methodology is explained in section II. The synthetic test system is presented in section III and the methods are demonstrated on it. Section IV presents the case studies applied on the system to ascertain the generality of the method.

II. METHODOLOGY

A. Early detection of ASD instability

A method was developed in [13] which utilized the injection impedance of the generator and the Thevenin impedance as viewed from the generator end to form a stability criterion.

$$Z_{inj} >= \frac{Z_{th} sin(\theta_{inj})}{sin(\phi_{th})} \qquad (1)$$

Here Z_{th} is the Thevenin impedance of the network and Z_{inj} is the injected impedance of the generator. The calculations for Z_{th} through the manipulation of network admittance matrix is explained in [2]. To ascertain the validity of equation (1), the time at which the generator becomes unstable is to be determined. The criterion for a stable active power margin for each generator is given by [2] as:

$$P_{inj} = \frac{E_{th} V cos(\theta_{th}+\delta)}{Z_{th}} - \frac{V^2 cos(\theta_{th})}{Z_{th}} \qquad (2)$$

$$P_{inj,max} = \frac{-E_{th} V}{Z_{th}} - \frac{V^2 cos(\theta_{th})}{Z_{th}} \qquad (3)$$

$$\triangle P_{inj} = P_{inj,max} - P_{inj} \qquad (4)$$

$$\% \triangle P_{inj} = \frac{\triangle P_{inj}}{P_{inj,max}} . 100\% \qquad (5)$$

Where Vo and E_{th} corresponds to magnitude of constant steady state voltage and Thevenin voltage respectively, Z_{th} and θ_{th} stand for magnitude and angle of Thevenin impedance respectively and δ is angle between E_{th} and Vo. The point at which the power margin in (4) becomes zero indicates instability.

If there exist multiple sources in the system, Thevenin voltage for each source needs to be calculated. To simplify this approach, the methodology given in [9] is utilized.[9] presents Thevenin voltage for multiple sources and introduces a Grid transformation coefficient matrix (GTC) to relate steady state voltage and the Thevenin voltage.

$$[E_{th}] = [GTC].[V_0]$$

Monitoring the system using the above equation provides the time at which ASD instability occurs. The detection time needs to be lesser to provide a sufficient time window for further operations.

B. Identification of the optimal node for the application of a countermeasure

Sensitivity analysis identifies the most influential node for countermeasure application. [12] provides an equation which computes the change in the Thevenin impedance to the change in nodal admittance, measuring the ability of a node to affect the unstable generator.

$$S_{k,m} = \frac{\frac{\Delta Z_{th}}{sin(\phi_{th})}}{\Delta Y_{m,m}} \qquad (6)$$

Here k represents the index of the generator and m denotes node index, ϕ_{th} being the Thevenin impedance angle.

C. Assessment of the suggested countermeasure

After the application of any form of countermeasure, the system will be at a new operating point. The Thevenin impedance and GTC matrix shall change as well. If the time of countermeasure application be t_{0+} then [14] suggests that due to the inertia of the rotor, the angles before and after the instant of application can be assumed to be equal.

$$\delta_{t_{0-}} = \delta_{t_{0+}} \qquad (7)$$

A new value of the injected power can thus be calculated as following:

$$P_{inj_{t0+}} = \frac{E_{th_{t0+}} V cos(\phi_{th_{t0+}} + \delta_{t0+} - \theta_{th_{t0+}})}{Z_{th_{t0+}}} - a \qquad (8)$$

$$\text{Where, } a = \frac{V^2 cos(\phi_{th_{t0+}})}{Z_{th_{t0+}}}$$

[14] provides an algorithm to predict the values of voltage angle after this point.

$\delta =$

$$arccos[\left(\frac{E_{th_{t0+}}.V}{Z_{th_{t0+}}}cos\left(\gamma_{th_{t0+}}+\phi_{th_{t0+}}\right)-b\right)c] \qquad (9)$$

Where, $b = P_{inj_{t0+}} + P_{inj_0}$; $c = \frac{Z_{th_{t0+}}}{E_{th_{t0+}}.V} + \theta_{th_{t0+}} - \phi_{th_{t0+}}$

The new voltage angle will be used to calculate new values of GTC and Thevenin voltages, which in turn will spawn subsequent voltage angle values, until a stopping criterion $\triangle\,\delta < \epsilon$ is established. To speed up the process, an iterative approach based on Newton method is proposed in [14]. Thus, the equations (6) and (7) reduce to

$$\frac{dP(\delta)}{d\delta} = J(\delta) \qquad (10)$$

$$\Delta\delta = J^{-1}\Delta P \qquad (11)$$

For each iteration,

$$\Delta P_k = P_{gen} - P_k \qquad (12)$$

$$\Delta\delta_k = J^{-1}\Delta P_k \qquad (13)$$

$$\delta_{k+1} = \delta_k - \Delta\delta_k \qquad (14)$$

Where the Jacobian matrix is given as:

$$J = \begin{bmatrix} \frac{\partial P_{gen1}}{\partial\delta_1} & \frac{\partial P_{gen1}}{\partial\delta_2} & : & \frac{\partial P_{gen1}}{\partial\delta_N} \\ \frac{\partial P_{gen2}}{\partial\delta_1} & \frac{\partial P_{gen2}}{\partial\delta_2} & : & \frac{\partial P_{gen2}}{\partial\delta_N} \\ \dots & \dots & : & \dots \\ \frac{\partial P_{genN}}{\partial\delta_1} & \frac{\partial P_{genN}}{\partial\delta_2} & : & \frac{\partial P_{genN}}{\partial\delta_N} \end{bmatrix}$$

[14] states that power injected by a given generator is dependent on its own voltage angle to a considerably larger extent than on the voltage angle variations of any other source in the grid. If this proposal is fair, the influence of voltage angles of the other generators can be neglected. Hence, the Jacobian matrix can be further reduced by ignoring the off-diagonal elements. Non convergence of the iterations will indicate a persisting ASD instability that the countermeasure failed to prevent.

III. SIMULATION AND RESULTS

An 8-bus synthetic system similar to the one used in [14] is modelled in ATP-EMTP as shown in figure 1.

The system consists of two generators at nodes X0003 (G1) and 7 (G2). The external grid is represented by a Separate generator at node 8. ASD instability is triggered by increasing the load at node 2 at 5 seconds. To simulate PMU measurement of voltage and current, the values of the magnitude and angles of these variables were stored in an output file using ATP-EMTP for every 20ms. In such a way, a snapshot of the system per cycle of the frequency is obtained. Figure 2 depicts the voltage angles of the two generators. An early detection algorithm is developed using equation (1) in MATLAB, which detects the instability at 5.214 seconds. Using equation (2), one can compute the time of instability for G1, which is 32.667 seconds.

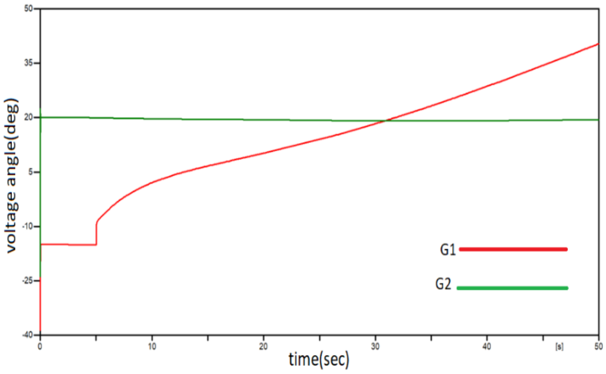

Fig.2. Voltage angles of generators G1 and G2

Sensitivity analysis is carried out on the load buses and node 2 is identified as the most influential node. Table I presents the values of sensitivities calculated for the nodes.

After the identification of an optimal node, a counter measure in the form of reactive power injection is applied at node 2. The admittance Y_{22} is decreased and the stability of this applied countermeasure is assessed using equations (6) to (12) in MATLAB. The stopping criterion for the Jacobian loop is set as $\triangle\,\delta < 10^{(-5)}$.

Table-I: Results for sensitivity analysis

Nodes	Changed admittance elements	Sensitivity calculations
1	Y11=0.5097i	13.862
2	Y22=0.82216i	53.632
3	Y33=0.145i	0.0005
4	Y44=1.07221i	0.368
5	Y55=0.145	0.0005

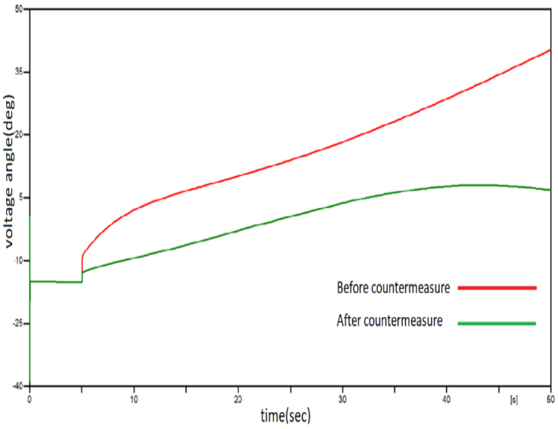

Fig.3. Voltage angles of generators when the countermeasure is applied

The iterations successfully converge, proving the countermeasure to be effective. Figure 3 portrays the situation of the generator after application of countermeasure at the time of detection.

IV. CASE STUDIES

A. Three Phase Fault

A symmetrical three phase fault is simulated on line 2 of the system at 5 seconds, for a duration of one second. Figure 4 represent the voltage angle dynamics during the fault. Violation of the early detection condition stipulated by equation (1) occurs at 5.235 seconds.

The GTC matrix and the Thevenin voltage are calculated on the basis of which equation (2) identifies an ASD instability at 80.913 seconds.

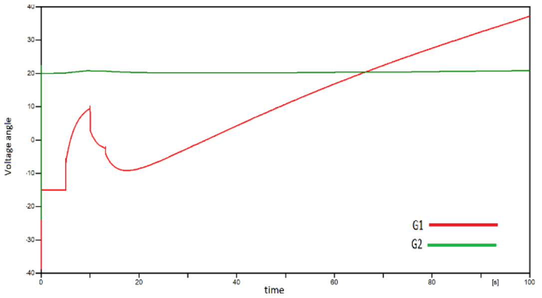

Fig.4. Voltage angles during 3 phase faults

B. Generator Fault

A fault is initiated at 5 seconds at the terminals of generator

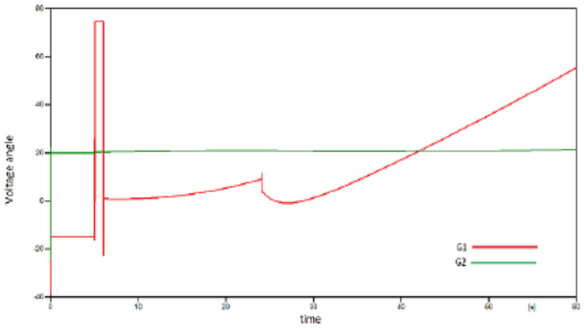

Fig.5. Voltage angles during generator fault

G1. The fault is cleared after one second. Figure 5 depicts the generator voltage angle under fault conditions. Equation (1) is violated at 5.093 seconds of the simulation time, indicating an imminent ASD instability. Equation (2) verifies the claim, ascertaining that the power stability margin is crossed at 48.926 seconds.

C. Single Line to Ground Fault

Line 2 undergoes a SLG fault which is cleared in one second. The early detection algorithm detects instability at 5.125 seconds. The power stability margin is crossed at 75.663 seconds.

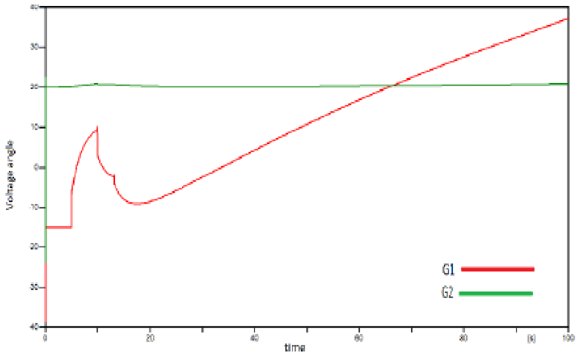

Fig.6. Voltage angles of generators during SLG fault

V. CONCLUSION

The paper implements the methods of early detection and prevention of aperiodic small signal angle instability on a synthetic 8 bus system. Simulated PMU measurements are generated for the calculations of the injection impedance of the generator, similar to taking snapshots of the system every 20ms. Sensitivity analysis yields the optimum node for countermeasure application and the countermeasure is assessed using Newton iterative method. New methods of triggering of angle instability like generator fault, three phase fault and double line to ground fault are all detected by the early detection algorithm in a reasonable time, providing a sufficient window of time for preventive actions.

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