MODERN PROTECTION RELAYS EQUIPPED WITH PMUS FOR OUT OF STABILITY

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ABSTRACT
This paper proposes a new inter area angle stability prediction algorithm. This algorithm does not require any prior knowledge of system state as it operates directly from measurements drawn from SPMUs. The proposed predictor foresees the system stability state before elapsing the first swing i.e. assessing system stability in advance. Applying the Synchronized Phasor Measurement Units (SPMUs) for the power systems, inter-area stability can be predicted in a proper time. Since the need for real-time Out-Of-Stability (OOS) algorithms becomes a very important issue in the modern power system networks. So that, the objective of this paper is producing an algorithm for Fast Stability Detection (FSD) before elapsing the first swing period using enhanced equal area criteria in time domain. For the above objective a comprehensive analysis with various faults are performed in a single machine infinite bus test system.

I. INTRODUCTION
Power systems are large interconnected nonlinear systems. They respond to a disturbance over a varying timescale, ranging from milliseconds even to hours. Wide range of contingencies and disturbances occur and abnormal operating conditions may be detected. A different corrective control schemes must be implemented in each type of contingency or disturbance at the right time [1].

Because of deregulation, many power systems around the world are being forced to operate closer to their stability limit because of the operational requirements in an open access environment and the environmental considerations. Power transfers across the inter-connected areas of a power system are unpredictable due to market price variations. Inter-connection unforeseen operating conditions and area instability can lead to system blackout [2].

The recent series of blackouts in different countries has further emphasized the need for operators to have better information regarding the actual state of the power system they are operating.

For the last two decades, advances in computer technology and communications provide the operators with the information needed for appropriate control action. At the same time, measurement systems based on Phasor Measurement Units (PMUs) are becoming proven technology and are seen by many utilities as one of the most promising ways of providing phasor information for wide area control [3].

Since many real-time operating decisions, both manual and automatic, are based on software applications using information derived from the phasor measurements through communication, these developments have shown immediate benefits in terms of increased accuracy, stability, and speed of convergence of control action decision making.

Current software and algorithms used in wide-area control are based on phasor measurements of bus voltage and generator reactive power [1]. In some applications, it is effective to use phase angle measurements to detect inter-area angle instability [1, 14].

The paper produced an enhancement for the time domain Equal Area Criterion that published in [11, 12]. The enhancement is detecting the stability conditions before first swing via the proposed FSD algorithm. I.e. no need to wait till elapsing the total first swing as required by the conventional Equal Area Criterion.

II. PROBLEM FORMULATION
If a severe disturbance, such as three-phase fault occurs in a tie-line between two areas of an interconnected power system, some of the generators of the power system may accelerate and may lose synchronism. If such disturbance is not cleared at a proper time, the loss of synchronism may extend to other areas' generators and a blackout may occur [4, 6-11]. The loss of synchronism after fault clearing is affected by the increase or decrease of the generator relative rotor angle beyond an identifiable threshold.
Prediction of rotor angle and/or electric power developed by the generator can be used to detect the first swing stability in advance, which gives time to controllers to apply the proper preventive control action. Based on electric power calculation via the SPMUs from the entire interconnected power system, transient stability can be detected via the FSD algorithm.

III. ENHANCED EAC FOR MODERN PROTECTION RELAYS

For improving and enhancing the time domain EAC algorithm shown in [5], the algorithm of Fast Stability Detection (FSD) can be constructed through several stages as shown in the following section. The algorithm is based on Synchronized Phasor Measurement Unit SPMU installed at each generating area of the power system (more details found in [14]). The real-time measurements taken by the SPMUs are analyzed to calculate the electric power developed by the generator then processed via the proposed FSD to take the adequate decision by the protection relay then, tripping action is executed via the circuit breaker tripping circuit as shown in figure.1. The constructive stages of the FSD algorithm are analyzed according to the following cases.

The first case is when the rotor angle corresponding to the instant of clearing time be lower than or equal π/2. The P-t curve and the corresponding P-δ curve are shown in figure.2. From the mentioned figure it can be concluded that the P-t curve must have only one peak in this case. Thus, the system stability is detected by the energy equilibrium by the cumulative summation of the total transient energy under P-t curve.

Whereas, the second case is when the rotor angle corresponding to the instant of clearing time is greater than π/2. The P-t curve and the corresponding P-δ curve are shown in figure.3. According to this case, the P-t curve will comprise two power peaks. So that, (in the region of \( P_m < P_e \)) if the power reached to peak then reduced. After that if increased again before reaching the value of steady state mechanical input power, the system is considered stable and no need to calculate the total transient energy of the first swing. But, if in the same region, the power decreased to be equal the mechanical input power, then increased again, the system is considered as critically stable system. Otherwise, is considered unstable case. Comprehensive results covering all cases will be depicted in later section.
IV. STAGES OF ENHANCED EAC FOR MODERN PROTECTION RELAYS

The constructive stages of the FSD algorithm according to the above analysis can be described as shown below:

Stage 1:
Measuring the bus voltages and the summation of all currents connected to the bus via the installed SPMU located at the H.V side of the generator/step up transformer set as shown in figure.4 to calculate the corresponding electric power delivered by the generator as shown in equation.1. Real power losses through the step up transformer are negligible.

\[ P_e = \text{real} \{ V \cdot I \} \]  

Stage 2:
Monitoring the electric power at each measured sample to detect the instant of maximum power to start the FSD algorithm derived from the analysis in the previous section to assess the stability in advance.

As shown in figure.7, when the instant electric power is achieved the FSD algorithm is sealed-in and monitoring the decrement of the electric power according to the calculated samples \( P_e(t) < P_e(t-1) \). If the electric power is increased again - according to the calculated samples \( P_e(t) > P_e(t-1) \) - before reaching the steady mechanical power the FSD
algorithm produces an output operand “Stable System” without waiting till elapsing the whole first swing and area comparison. **Timer with two cycles for ON-delaying and other two cycles for OFF-delaying is used for stable sealing-in for the algorithm.** This stable output operand is used for blocking the protection relay during normal power swing events to prevent the mal-operation of the protection relay. This blocking signal is very important to the relay’s manufacturers for reliable relay operation during power swing events instead of using traditional blinder method for detecting out-of-stability and power swing blocking conditions.

**Stage 3:**
If the conditions of FSD algorithm are verified, the algorithm produces an output operand “System Stable” before the first swing period and without completing the comparison of decelerating and accelerating areas. If the logic of the FSD algorithm is not verified, the algorithm compares the accelerating and decelerating areas to detect system stability to produce the relevant output operand. Refer to figure.7.

Figure.7: Detecting the instant of maximum electric power

Figure.8: Output operands of the FSD algorithm

Figure.9 shows comprehensive logic diagram of the FSD algorithm with dashed lines to partitioning the algorithm into the mentioned stages for easy tracking.

**V. TEST SYSTEM SIMULATION**

The employed test system for validating the FSD algorithm is the single machine infinite bus shown in figure.10. The system comprises of two parallel overhead transmission lines. A three phase short circuit at the sending end bus with several durations is simulated using Matlab programs created by the authors. Due to the unavailability of PMUs, off-line simulations are performed to get results that can be used as PMU measurements. Figure.9 depicts the adaptation of FSD algorithm on a sample system.

Figure.10: Single machine infinite bus test system
Figure 9: Shows comprehensive logic diagram of the FSD algorithm with dashed lines for easy tracking.
VI. SIMULATION RESULTS

The system is simulated for several three-phase short circuit- as it is the worst fault- durations at send end as per summarized table 1.

Table 1: Summarizing table for the several fault cases

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Clearing Time (ms)</th>
<th>Clearing Angle (Deg.)</th>
<th>Maximum Power Angle (Deg.)</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>38.4446</td>
<td>50.1335</td>
<td>1.682</td>
<td>-1.682</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>44.8276</td>
<td>66.2513</td>
<td>6.789</td>
<td>-6.789</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>55.4505</td>
<td>87.1790</td>
<td>15.28</td>
<td>-15.28</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>70.2734</td>
<td>122.0731</td>
<td>27.14</td>
<td>-27.14</td>
</tr>
<tr>
<td>5</td>
<td>410</td>
<td>71.9868</td>
<td>128.9595</td>
<td>28.51</td>
<td>-28.51</td>
</tr>
</tbody>
</table>

The above testing results are compared to what is obtained from conventional off-line simulation method as shown in table 2. The two results are found identical which proves the validity and adequateness of the FSD algorithm. But, the proposed method is online and made to be used for protection relay algorithm for online system protection and more reliable relay operation during power swing events. Whereas, the conventional method is offline and required system load flow and integration which is not adequate for online application and also, relay algorithm.

VII. CONCLUSIONS

Modern power system networks are employing the synchronized phasor measurement units for monitoring, and controlling power system variables. One of the benefits of these SPMUs is to detect system stability of power systems. The created FSD algorithm in this paper is to assess system stability before elapsing the first swing. i.e. assessing stability in advance which makes the FSD algorithm adequate for real-time stability assessment.

During stable power swing events, the FSD algorithm produces stable output operand that is used for blocking the protection relay preventing the mal-operation of the protection relay. This blocking signal is very important to the relay's manufacturers for reliable relay operation during power swing events instead of using traditional blinder method for detecting out-of-stability and power swing blocking conditions.

REFERENCES