A study on Angle Stability Solution Using coordinated Facts Devices

Dr. K.T. Chaturvedi, Assistant Professor Dept. of Electrical Engineering UIT RGPV Bhopal
Kripashankar Pandeya UIT RGPV Bhopal

Abstract— This paper presents a Angle Stability Solution Using coordinated Facts Devices located in different areas of a power system. Analysis of initial conditions and a contingency analysis to determine the voltage stability margin and voltage variations at different critical nodes are held. The response is carried out by the coordination of multiple-type FACTS devices due to which the reactive power is compensated, improving the voltage stability margin at the critical nodes.

Index Terms— FACTS Devices, Transmission Loadability, Angle stability, Voltage Stability, Continuation Power Flow, Tangent Vector Technique, Real Power Flow Performance Index Sensitivity Factor

I. INTRODUCTION

Currently, electric power systems are experiencing structural changes due to the growing incorporation of renewable sources of energy. Another determinant factor in modifying the configuration of electric power systems is the liberalization of electricity market and restructuring the trade of energy. Also, in near future, the number of interconnections in electric power systems will increase. Thus, the future electric power systems will operate closer to their limits. Considering the aforesaid reasons, together with the major switching actions concerning the connection of renewable energy sources, the stability of future power systems is undertaking a more highlighted role. Being large scale and complex, are features of modern power systems. Also, because of deregulation, the configuration of interconnected networks is routinely in a state of change. Therefore, an indicator of stability, which covers the vast spectrum of states, is of interest. Such a methodology should reconcile the stochastic behavior of the renewable energy sources and the deterministic approach of stability analysis.

A methodology to indicate the small disturbance angle stability in future power systems is to make use of an iterative- stochastic approach. By applying such an approach, the probabilistic nature of sustainable energy sources is modeled and subsequently, for each sample of this model an iterative linear stability analysis is performed. This approach analyzes all possible combinations of loads and the sustainable electricity generations. Eventually, this method reveals the most vulnerable operating points of the system and consequently can be used as an indicator of small disturbance angle stability.

II. PROBLEM FORMULATION

Postfault rotor angle oscillations lead to power swings. Both unstable and stable swings can induce distance relay tripping. For unstable swings, a new computational procedure to locate all the electrical centers is developed. It simplifies the work associated with visual screening of all the R-X plots. For stable swings, a generic three tier hierarchy of stability related norms defined by branch norm, fault norm and system norm is proposed. Ranking by branch norm leads to ranking of power swings. Ranking by fault norm leads to ranking of faults or contingencies. Magnitude and rate of change of system norm can be used to detect an out-of-step condition. Results on a 10-machine system and a utility system with detailed models are also presented. Voltage stability is concerned with the ability of a power system to maintain acceptable voltage at all nodes in the system under normal conditions or after being subjected to a disturbance [1]. In order to detect the system conditions and to predict voltage instability, it is necessary to conduct a voltage stability study at all nodes. To prevent or correct voltage instability, solution methods based on the results of the power system study must be applied; these methods allow to improve the voltage stability margin and to avoid voltage collapse.

Study of Voltage Stability

The methods for studying voltage stability are used to find the operation state, the voltage stability margins and limits and to study the system variation and element responses. The voltage stability study can be conducted using analytical or monitoring methods.

1) Analytical Methods: These methods allow a detailed study of the variables, parameters and elements behavior of the power system, in order to find design solutions and operation criteria that allow the system to work far from the instability point. Each of these methods uses a mathematical technique, which is implemented in a computational tool with a great number of nodes, lines and loads. These methods are based on
conventional power flows, progressive power flows and dynamic analyses. Conventional power flow techniques are based on mathematical calculations made for each load condition of the power system and represent voltage variation at all nodes due to the change of the active and reactive power of the load. These techniques allow the calculation of the system operation state and the voltage stability limits and margins, in normal operation conditions and after contingencies. Some of these techniques are: sensitivity analysis [4], reduction of the Jacobian matrix (matrix singularity [5] and modal analysis [6]), network equivalent, vectorial difference [7] and energy-based techniques. Progressive flow techniques are static analysis methods based on consecutive power flow results used to find the voltage stability margins and limits of the nodes with higher numerical accuracy [8]; they use a prediction tangent vector to estimate a solution to another load value, which is then corrected [9]. These methods have been widely used because of their precision in the voltage stability limit calculation. Dynamic analysis techniques are based on the solution of algebraic equations in time-domain [1] and they are used for transient and small signal stability events analysis. These techniques allow to create different scenarios that include contingencies or normal operation states in order to determine the variables behavior and response of power system elements in the occurrence of an event [10].

2) Monitoring Methods: these methods are based on data measurements of the power system variables such as voltages, current, active power, reactive power and vector angles, to find the operation state, voltage stability limit and margin as well as the critical nodes of the system. They can be used as a tool for the on-line and off-line voltage stability detection and prediction.

III. SOLUTION OF VOLTAGE STABILITY

The methods used for the solution of the voltage stability are based on the prevention and correction of the problem. Prevention methods are aimed at maintaining voltage stability at all nodes, avoiding them to get close to the limit; correction methods are aimed at restoring the unstable conditions to return voltage stability to the nodes. These methods are divided in: reactive compensation, control of elements and power system changes. Control actions can be automatic or manual and must be used according to the time of response to improve in a short, middle or long-term stability.

1) Reactive Compensation: these techniques are based on the compensation of reactive power to the system, from power generation sources [11], transmission lines [12], transformers [13] and load nodes. The line compensation can be carried out with a constant value of reactive power, called static compensation, using switched elements to increase the voltages at the nodes; also, a variable compensation can be carried out, controlled by power electronic devices as FACTS; this is called dynamic compensation and is used to respond during transitory and small signal variations that occur in the power system due to disturbances.

2) Control of Elements: these techniques are used to avoid voltage instabilities and collapses in the power system by controlling elements that change the operation conditions as protection relays [14], current limiters [15] and TAP changers.

3) System Changes: these techniques are based on the entrance of elements or the shedding of loads to avoid voltage instability in the system. They are used to increase the power transmission capacity and to alleviate the power system overloads. These methods are divided in undervoltage load shedding [16], and system configuration changes [17].

4) Mixed: this is a technique based on the combination of the above mentioned techniques to create a voltage stability prevention and correction scheme using different elements [18].

IV. VOLTAGE STABILITY PROBLEM

Each node of a power system initially operates with a voltage stability margin as shown in Fig. 1(a). Once a contingency occurs, voltage decreases to a stable point as shown in Fig. 1(b) or it becomes unstable as shown in Fig. 1(c). Also when the node operates near the voltage stability limit, Fig. 1(b), a voltage collapse can occur after other events or operations that decrease the reactive transfer capacity to the critical nodes; therefore it is necessary a prompt response to increase the voltage stability margins as shown in Fig. 1(d).

![Fig. 1. PV curves and Voltage stability margins](image-url)
with a static or dynamic increasing of the voltage at the nodes. Some methods seek to solve voltage instability by the optimal location of FACTS devices close or in the critical nodes [19]; other methods are based on the coordination of FACTS devices, as in 1998, when a method to coordinate thyristor controlled series and shunt compensators (TCSC and SVC) was presented in order to improve angle and voltage stability, using a disturbance response method based on the Disturbances Auto-Rejection Control (DARC) theory [20]. In 2003, a secondary voltage control method was proposed to eliminate voltage violations at the nodes after a contingency, using the coordination of SVC and STATCOM devices to provide reactive power; the secondary voltage control is implemented by a learning fuzzy logic controller [21]. In 2005, the development of a control system and control strategies capable of governing multiple flexible AC transmission system (FACTS) devices in coordination with load shedding was proposed to remove overloads caused by lines outages in transmission networks, based on linearized expressions in steady state [21]. In 2005, a method for coordination of FACTS devices as SVC, TCSC and TCPST was presented, based on the optimal power flow to avoid congestion, to give greater security and to minimize the active losses in transmission lines [22]. FACTS devices location and coordination techniques mentioned above have been based on the voltage stability improvement in an area near the devices, improving voltages in steady state, preventing violations of the voltage limits, coordinating few quantity and types of FACTS devices, they do not allow to handle reactive power in the lines and aim at relocating the devices increasing the costs. Table I shows the comparison among the techniques used for the solution of voltage stability problems after a contingency. The rating of the indexes was done with numbers that indicate the low (1), middle (2) and high (3) levels of the objective functions of the proposed method.

V. PROPOSAL

The proposed methodology consists on compensating the reactive power in an interconnected power system of several areas as shown in Fig. 2, by a coordinated control strategy of a wide quantity of different FACTS devices located in several parts of an interconnected power system in order to increase the voltage stability margin during critical voltage variations created by a contingency. This methodology is based on a fast injection and the direction of power through the transmission path of lower losses to increase the reactive power supply to the critical nodes of a power system. This method avoids load shedding, increases the time for other slower reactive control elements to operate, can be applied to global power systems and does not need to relocate FACTS devices so the costs are not increased. The coordination of FACTS devices to improve voltage stability is made in several stages: FACTS selection, design and implementation.

A. FACTS Selection

The FACTS controllers used in power systems are classified in: shunt controllers (SVC, STATCOM, BESS, SMES, SSG, TCBR, TCR, TSC, TSR, SVG, SVS), series controllers (SSSC, TCSC, TSSC, TCSR, TSSR, TCPST), combined shunt and series connected controllers (UPFC, TCPST, IPC) and other types (TCVL, TCVR) [23]. These devices allow controlling power flow, increasing transmission line capacity, improving stability and reducing reactive losses. The devices that should be used for voltage stability solution are those that allow reactive power injection and power transfer with lower losses.

B. Design

The design stage is based on the determination of the coordinated control strategies of the FACTS devices. The steps to find the control strategies are shown in Fig. 3.

1) Initial Conditions: the initial conditions of a system are calculated to determine the operation state and the voltage stability margin of each node.

2) Contingency Analysis: a contingency analysis to determine nodes with voltage instability or near the limit is carried out. The selection of the
3) **Voltage Analysis:** based on the selection of the most critical contingencies and the nodes for the variables measurement, a dynamic study of the voltages after the contingency to determine the system response is carried out.

4) **Coordination of FACTS:** the control strategy of FACTS devices is developed to improve voltage stability at critical nodes of the system. These devices should allow the reactive power supply to the weak nodes and the directing of the reactive power flow.

5) **Operation Verification:** after determining the control strategy, an appropriate response for the selected contingencies should be verified and voltages must be adjusted in order to comply with the system constraints.

**C. Implementation**

The implementation stage is based on the operation form of the coordinated control strategy of FACTS devices. The operation form of the control strategy is shown in Fig. 4.

![Fig. 4. Operation form of the voltage stability control strategy.](image)

**TABLE I**

**COMPARISON OF THE TECHNIQUE FOR THE SOLUTION OF VOLTAGE STABILITY**

<table>
<thead>
<tr>
<th>FACTS</th>
<th>Ref.</th>
<th>Time of Response</th>
<th>Cost</th>
<th>Large Systems</th>
<th>Quantity of Coordinated FACTS</th>
<th>Different Types of FACTS</th>
<th>Reactive Power Injection</th>
<th>Reactive Power Direction to Critical Nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Coordinated</td>
<td>[S][20]</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Present Coordinated</td>
<td>[O][34]</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
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most critical contingencies and the nodes for the measurement of the entrance variables of the control strategy are carried out.

**2) Determination of Instability Type and Magnitude:** one of the most important parts of the control strategy is the determination of the type of instability and the magnitude of a disturbance occurred in the system, because it is necessary to establish the time for the operation of the devices and the reactive power quantity to be transferred to the critical nodes.

**3) Determination of the Coordinated Control:** after determining the type and magnitude of the event, the coordinated actions of the available devices are determined, transmitting through the transmission path of lower losses to reduce reactive losses and to allow a higher reactive supply to the nodes.

**4) Sending Signals to Controllers:** the operation signals for FACTS controllers are sent according to the obtained control decisions; they control the operation of capacitor and inductors of each FACTS device, allowing the reactive injection and power flow direction to the critical nodes.

**5) Devices Operation:** the devices operate based on the signals sent and inject reactive power or allow the pass of the power flow to a specific node based on the transmission path of lower losses.

**REFERENCES**