Voltage Stability Enhancement of Power System using STATCOM and SSSC

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Abstract-- In this paper, voltage stability assessment with appropriate representations of STATCOM and SSSC is investigated and compared in the modified IEEE 14-bus test system. One of the major causes of voltage instability is the reactive power limit of the system. Improving the system's reactive power handling capacity via Flexible AC transmission system (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse. AC and DC representations of STATCOM and SSSC are used in the continuation power flow process in static voltage stability study. The appropriate representation provides more practical solutions in the dc parts of these devices. Static voltage stability margin enhancement using STATCOM and SSSC is compared in the modified IEEE 14-bus test system.

Index Terms-- *voltage stability, STATCOM, SSSC, DC representation*

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I. INTRODUCTION

Present power systems are now large, complex and interconnected systems, which consist of thousand of buses and hundreds of generators. New installations of power stations and other facilities are primarily determined based on environmental and economic reasons. In addition, new transmission lines are expensive and take considerable amount of time to construct. Given these conditions, in order to meet ever-increasing load demands, electric utilities have to rely on power export/import arrangements through the existing transmission system, deteriorating voltage profiles and system stability in some cases. This situation has resulted in an increased possibility of transient, oscillatory and voltage instability, which are now brought into concerns of many utilities especially in planning and operation. Moreover, the trend of the deregulated power system has led to some unexpected problems, such as voltage instability, etc.

Voltage instability is the cause of system voltage collapse, which makes the system voltage decay to a level from which they are unable to recover. The consequence of voltage collapse may lead to a partial or full power interruption in the system. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse. Introducing the sources of reactive power, i.e., shunt capacitors and/or Flexible AC Transmission System (FACTS) controllers at the appropriate location is the most effective way for utilities to improve voltage stability of the system.

The recent development and use of FACTS controllers in power transmission system have led to many applications of these controllers not only to improve the voltage stability of the existing power network resources but also to provide operating flexibility to the power system. FACTS devices have been defined by the IEEE as "alternating current transmission system incorporating power electronic-based and other static controllers to enhance controllability and increase power transfer

capability". There are five well-known FACTS devices utilized by the utilities for this purpose. These FACTS devices are Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor-Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC). Each of them has its-own characteristics and limitations. From the utility point of view, it would be useful if they can achieve voltage stability criterion with the help of the most beneficial FACTS device.

Based on the above observation, an effort made in this paper is to compare the merits and demerits of some FACTS devices, namely, STATCOM and SSSC, in terms of loading margin (LM) in static voltage stability study. Appropriate representations including DC equations of these devices are incorporated in the CPF process in the voltage stability study in order to consider the limits in the DC side. Voltage stability margin enhancement using these FACTS devices is also compared in the same test system. This leads to a more practical solution in terms of LM or voltage stability margin, which may be useful for utilities to select the mostbeneficial FACTS devices among STATCOM and SSSC.

II. VOLTAGE STABILITY ANALYSIS

PV and QV curves - Voltage profiles shown in the well-known PV and QV curves are of the practical use for determining the proximity to collapse so that operators can take proper preventive control actions to safeguard the system.

Q-V curve technique is a general method of evaluating voltage stability. It mainly presents the sensitivity and variation of bus voltages with respect to the reactive power injection. Q-V curves are used by many utilities for determining proximity to voltage collapse so that operators can make a good decision to avoid losing system stability. In other words, by using Q-V curves, it is possible for the operators and the planners to know the maximum reactive power that can be achieved or added to the weakest bus before reaching minimum voltage limit or voltage instability. The P-V curves, active power-voltage curve, are the most widely used method of predicting voltage security. They are used to determine the MW distance from the operating point to the critical voltage.

Singular value decomposition:

The main idea of the method is to find "How close is the Jacobian matrix to being singular"? One issue with this index is that it does not indicate how far in Mvars it is to the bifurcation point (singular Jacobian value). The more important use of the index is the relationship it provides for control. That is, if VAR compensation through capacitors, excitation control or other means is available, the index provides the answer to the problem of how to distribute the resource throughout the system for maximum benefit. A disadvantage of using the minimum singular value index is the large amount of CPU time required in performing singular value decomposition for a large matrix.

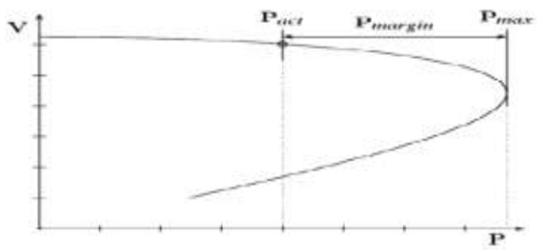

Fig.1.Power margin

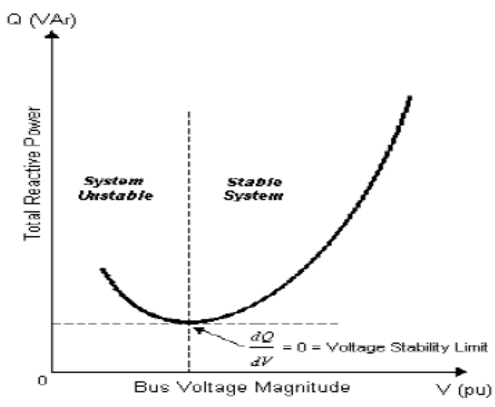

Fig. 2. Q-V curve

III. STATIC VOLTAGE STABILITY

Voltage instability is mainly associated with reactive power imbalance. The load ability of a bus in the power system depends on the reactive power support that the bus can receive from the system. As the system approaches the maximum loading point or voltage collapse point, both real and reactive power losses increase rapidly. Therefore, the reactive power supports have to be local and adequate.

There are two types of voltage stability based on the time frame of simulation i.e. static voltage stability and dynamic voltage stability. Static analysis involves only the solution of algebraic equations and therefore is computationally less extensive than dynamic analysis. Static voltage stability is ideal for the bulk of studies in which voltage stability limit for many pre-contingency and post-contingency cases must be determined.

In static voltage stability, slowly developing changes in the power system occur that eventually lead to a shortage of reactive power and declining voltage. This phenomenon can be seen from the plot of the power transferred versus the voltage at receiving end. The plots are popularly referred to as P-V curve or “Nose” curve. As the power transfer increases, the voltage at the receiving end decreases. Eventually, the critical (nose) point, the point at which the system reactive power is short in supply, is reached where any further increase in active power transfer will lead to very rapid decrease in voltage magnitude. Before reaching the critical point, the large voltage drop due to heavy reactive power losses can be observed. The only way to save the system from voltage collapse is to reduce the reactive power load or add additional reactive power prior to reaching the point of voltage collapse.

Usually, placing adequate reactive power support at the “weakest bus” enhances static-voltage stability margins. The weakest bus is defined as the bus, which is nearest to experiencing a voltage collapse. Equivalently, the weakest bus is one that has a large ratio of differential change in voltage to differential change in load (dV/dP_{Total}). Changes in voltage at each bus for a given change in system load is available from the tangent vector, which can be readily obtained from the predictor steps in the CPF process. In addition to the above method, the weakest bus could be obtained by looking at right eigen vectors associated with the smallest eigen value as well.

Reactive power support can be done with FACTS devices. Each FACTS device has different characteristics; some of them may be problematic as far as the static voltage stability is concerned. Therefore, it is important to study their behaviors in order to use them effectively and efficiently. There are two types of FACTS devices considered in this study, namely, STATCOM and SSSC. Details including basic structures and terminal characteristics including DC parts of these FACTS devices are presented in the following section.

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A. STATCOM

STATCOM is the Voltage-Source Inverter (VSI), which converts a DC input voltage into AC output voltage in order to compensate the active and reactive power needed by the system. Figs. 3 and 4 show the schematic diagram and terminal characteristic of STATCOM, respectively. From Fig.3, STATCOM is a shunt-connected device, which controls the voltage at the connected bus to the reference value by adjusting voltage and angle of internal voltage source. From Fig. 4, STATCOM exhibits constant current characteristics when the voltage is low/high under/over the limit. This allows STATCOM to delivers constant reactive power at the limits compared to SVC.

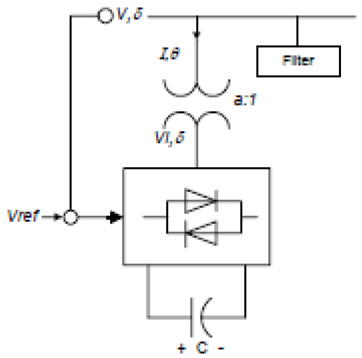

Fig.3. Basic structure of STATCOM

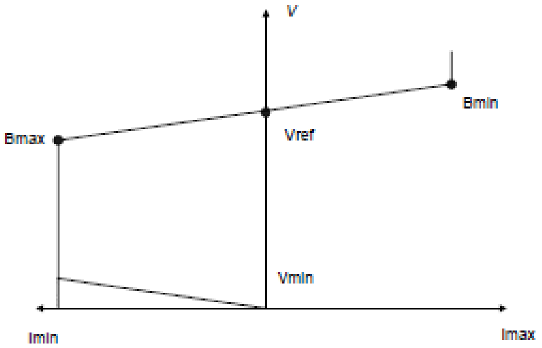

Fig.4. Terminal characteristics of STATCOM

B. SSSC

SSSC is a solid-state synchronous voltage source employing an appropriate DC to AC inverter with gate turnoff thyristor. It is similar to the STATCOM, as it is based on a DC capacitor fed VSI that generates a three-phase voltage, which is then injected in a transmission line through a transformer connected in series with the system. The main control objective of the SSSC is to directly control the current, and indirectly the power, flowing through the line by controlling the reactive power exchange between the SSSC and the AC system. The main advantage of this controller over a TCSC is that it does not significantly affect the impedance of the transmission system and, therefore, there is no danger of having resonance problem. Figs. 5 and 6 show basic structure and the representing model of SSSC with control and state variables, respectively. From Figs. 5 and 6, it can be seen that SSSC can absorb/deliver both active and reactive power by controlling voltage and angle at the DC voltage. However, the amount of active power is normally small since the value of R_C is small.

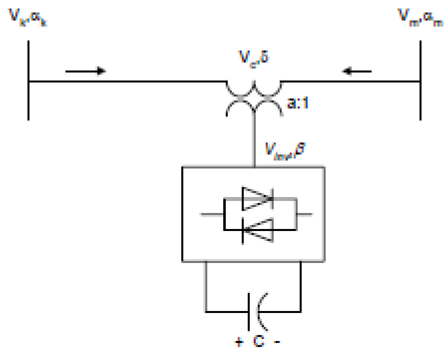

Fig.5. Basic structure of SSSC

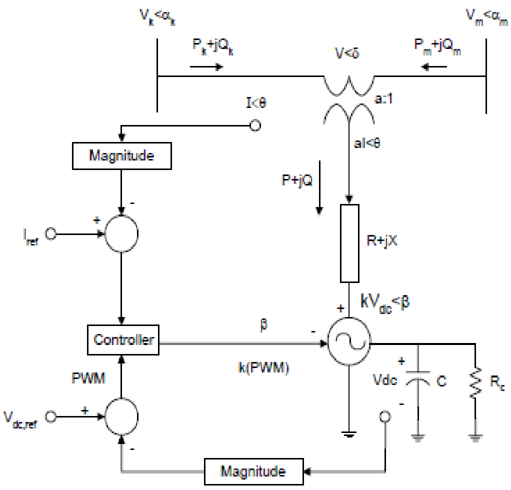

Fig.6. Stability Model of SSSC.

C. Voltage Stability Study with FACTS Devices Using CPF

To incorporate FACTS devices in the power system, equations and state variables of FACTS devices are introduced in the load flow equations and in the corrector step in the CPF process. The way to solve the new load flow equations is similar to that in conventional load flow equations but with equations of FACTS devices. Each FACTS device has its own equations and state variables. Table I shows state variables of STATCOM and SSSC based on FACTS equations. The number of state variables is as same as the number of FACTS equations required in the load flow formulation.

TABLE I. STATE VARIABLES OF STATCOM, TCSC AND SSSC

Type of FACTS	State Variables

STATCOM	P, V_{dc}, I, θ, Q, α
SSSC	I, θ, P_k, P_m, P, Q_k, Q_m, Q, V_{dc}, V, δ, β

Where P, Q and I are the active power, reactive power and current received/ delivered by FACTS devices. V_{dc}, α, β, θ are DC voltage magnitude, DC voltage angle for STATCOM, DC voltage angle for SSSC and current angle, respectively. V and $B_e$are the voltage and susceptance of series components, respectively. Sending and receiving ends are represented by k and m, respectively.

There are 6 and 12 AC and DC state variables for STATCOM and SSSC, respectively. Flowchart of voltage stability with FACTS using the CPF method is illustrated in Fig 7. From Fig. 7, it can be observed that equations of FACTS devices are added in the load flow equations. The new load flow equations are then used in the corrector step in CPF process. In the following section, the IEEE 14-bus test system and analysis tools used in the paper are presented in brief.

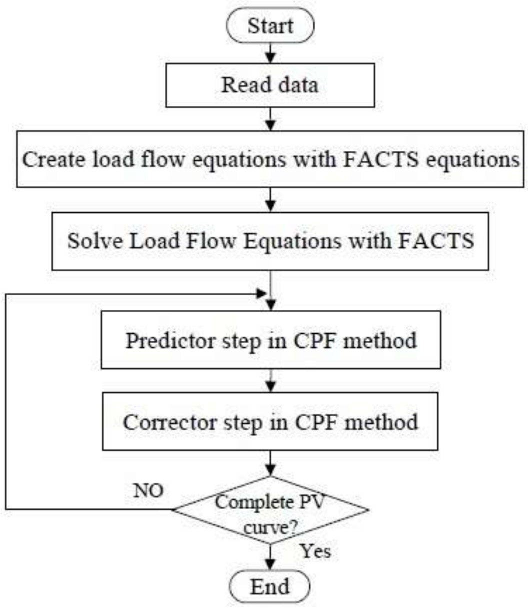

Fig. 7. Flowchart of CPF process with FACTS.

IV. TEST SYSTEM

The modified IEEE 14-bus test system is used throughout the study. A single line diagram of the modified IEEE 14 bus test system is depicted in Fig. 8, which consists of five synchronous machines, including one synchronous compensator used only for reactive power support and four generators located at buses 1, 2, 6 and 8. The modification from the original IEEE 14-bus test system is that generators located at buses 6 and 8 were changed from synchronous compensators to generators. In the system, there are twenty branches and fourteen buses with eleven loads totaling 259 MW and 81.4 Mvar.

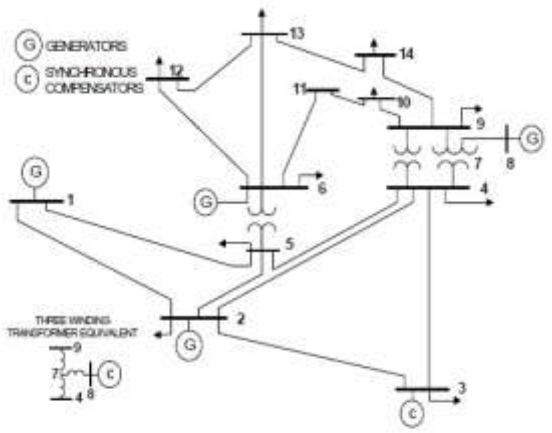

Fig.8. Single diagram of the IEEE-14 bus system

In this paper, all of the results including STATCOM, TCSC and SSSC are produced with the help of a program that is developed in MATLAB. Current control mode is used for SSSC and voltage control mode for STATCOM.

V. RESULTS AND DISCUSSION

1) *Shunt Compensation Device*. The best location for shunt reactive power compensation, as far as the improvement of static voltage stability margin is concerned, is the weakest bus of the system. Bus 14 is the weakest of the system, introducing STATCOM in this bus will increase the LM to the maximum value. In order to get a rough estimate of reactive power supportneeded at the weakest bus and corresponding LM, asynchronous compensator with no limit on reactive power was used at the weakest bus. Another method of determining the capacities is to find the relationship between the maximum Loading Factor and the corresponding capacities that the devices can deliver without having the voltage collapse.

2) Series Compensation Devices. However, based on exhaustive studies by inserting one SSSC at a time, the series compensation device should be placed at line 1-5 to obtain the highest LM. Sizing of SSSC can be found by voltage stability study. The size of these series devices can be found from the active and reactive power requirement at the collapse point.

TABLE II. LOADING MARGIN WITH VARIOUS FACTS DEVICES

	Base case	STATCOM	SSSC
LM(p.u.)	0.9278	1.2643	0.9452

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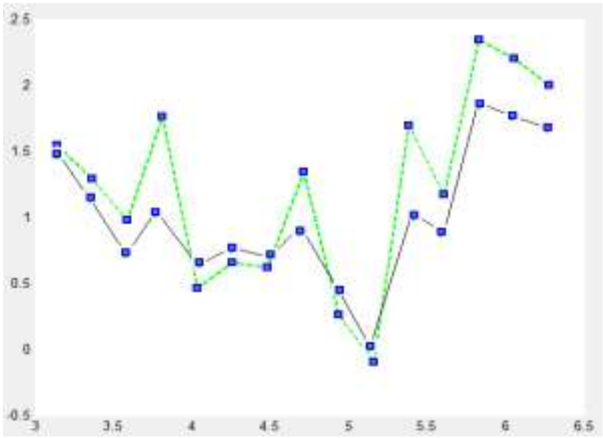
Voltage(p.u.)



Bus Number

----- STATCOM ____ SSSC

Fig.9. Voltage profile of system with STATCOM and SSSC

VI. Conclusion

In this paper, voltage stability assessment of the modified IEEE 14-bus test system with STATCOM and SSSC is studied. STATCOM provide higher voltage stability margin than SSSC. The test system requires reactive power the most at the weakest bus, which is located in the distribution level. Introducing reactive power at this bus using STATCOM can improve loading margin the most. Real and reactive power losses of these devices are lowest in case of STATCOM, the highest LM case.

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