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# Comparative analysis of Shunt Compensation Devices Impact on Voltage Stability Enhancement

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**Abstract**: *The voltage stability can be assessed accurately using different methods viz. P-V curves, L-index and Fast Voltage Stability Index (FVSI). These indices can either reveal the critical bus or line of a power system. P-V curves, FVSI and L indices are used to identify the most critical n-1 contingency. The optimal location of the shunt compensator can be identified with maximum value of stability indices of all buses and lines.*

*The optimal capacity of the shunt compensator is computed using fictitious Generator at weakest bus. Power flow is carried out by placing the optimal sized shunt compensator at weakest bus and results shows the effectiveness of the shunt compensator. The comparative analyses have been carried out for the fixed shunt compensator, Synchronous Phase Modifier and Static Var Compensator against load variations.*

***Index Terms***: *Voltage Stability, SPM,SVC, Voltage stability indices, Comparative analysis of Shunt Compensation Devices, Shunt Compensation, Fast Voltage Stability Index, L-index, Impact of shunt compensation & Losses reduction with shunt devices.*

## I. Introduction

Power system stability is defined as a characteristic for a power system to remain in a state of equilibrium at normal operating conditions and to restore an acceptable state of equilibrium after a disturbance. Traditionally, the stability problem has been the rotor angle stability [1], i.e., maintaining synchronous operation. Instability may also occur without loss of synchronism, in which case of concern is the control and stability of voltage. “The voltage stability [2-3] is the ability of a power system to maintain steady acceptable voltages at all buses in the system at normal operating conditions and after being subjected to a disturbance.” Power system is voltage stable if voltages after a disturbance are close to voltages uncontrollably decrease due to outage of equipment (generator, line, transformer, bus bar, etc.), increment of load, decrement of production and/or weakening of voltage control.

The Voltage instability is nothing but under the stressed conditions a power system can exhibit new type of unstable behavior characterized by slow (or sudden) voltage drops, sometimes escalating to form a collapse. When the system crosses the maximum deliverable power limit the mechanism of load power restoration becomes unstable, reducing the power consumed instead of increasing. Voltage control and instability are local problems. However, the consequences of voltage instability may have a widespread impact.

Voltage stability can also be called “load stability”. The main factor causing Voltage instability is the inability of the power system to meet the demands for reactive power in the heavily stressed systems to keep desired voltages. Other factors contributing to voltage instability are the generator reactive power limits, the load characteristics, the characteristics of the reactive power compensation devices and the action of the voltage control devices.

The condition of voltage stability in a power system can be known using voltage stability indices[4-8]. These indices can either reveal the critical bus of a power system or the stability of each line connected between two bus in an interconnected network or evaluate the voltage stability margins of a system. They provide important information about proximity of the system to voltage instability and can be used to identify the weaker bus as well as the critical line with respect to a bus of a system. Usually their values change between 0(No Load) to 1 (Voltage Collapse).

The tools used to assess the voltage stability are P-V curves, FVSI and L-Indices.

### 1. P-V curves

The P-V curves are the most used method of predicting voltage security. They are used to determine the loading margin of a power system[5]. The power system load is gradually increased and, at each increment, is necessary recomputed power flows until the nose of the PV curve is reached. The margin between the voltage collapse point and the current operating point is used as voltage stability criterion.

### 2. L Index

The L index[5] is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. The L index describes the stability of the complete system and is given by:

$$L = \max_{j \in \alpha L}\{L_j\} = \max_{j \in \alpha L}\left|1 - \frac{\sum_{i \in \alpha G} F_{ji} V_i}{V_j}\right|$$

Where $\alpha L$ is the set of consumer nodes and $\alpha G$ is the set of generator nodes. $L_j$ is a local indicator that determinates the bus bars from where collapse may originate. The L index varies in a range between 0 (no load) and 1 (voltage collapse).

**3. Line Stability Index FVSI**

The line stability index FVSI [6] is based on a concept of power flow through a single line. For a typical transmission line, the stability index is calculated by:

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i X}$$

Where Z is the line impedance, X is the line reactance, $Q_j$ is the reactive power flow at the receiving end and $V_i$ is the sending end voltage. The line that gives index value closest to 1 will be the most critical line of the bus and may lead to the whole system instability. The calculated FVSI can also be used to determine the weakest bus on the system. The determination of the weakest bus is based on the maximum load allowed on a load bus. The most vulnerable bus in the system corresponds to the bus with the smallest maximum permissible load.

## II. Contingency Based Voltage Stability Improvement

Voltage stability is defined as the ability of a power system to maintain steadily acceptable bus voltage at each node under normal operating conditions, after load variation following a change in system configuration or when the system is subjected to contingencies [7] like line outage or generator outage. Single or multiple contingencies cause voltage violations which are known as voltage contingencies. The line outages may lead to the most severe violations in line flow which necessitates the line over load alleviation of the network.

Line outage in power system lead to the voltage collapse which implies the contingency in the system. Line outage contingencies are ranked so that the line which highly affects the system when there is an outage occurs in this line in terms of voltage instability could be identified. The contingency ranking process can be conducted by computing the line stability index of each line for a particular line outage and sort them in descending order. The contingency which is ranked the highest implies that it contributed to system instability.

### A. Contingency ranking based on voltage stability indices

Contingencies are ranked according to their margins to voltage collapse. A margin to voltage collapse is defined as the largest load change that the power system may sustain at a bus or collection of buses from a well defined operating point. The margin may be measured in MVA, MW, or MVAR.

A new contingency ranking technique using a voltage stability index. The study involved voltage stability analysis and line outages simulation which subsequently derived the correlation between critical line outages and sensitive or weak lines obtained from the voltage stability analysis.

The results have shown that there is a correlation between critical line outages and sensitive lines obtained from voltage stability analysis. The technique was tested on the IEEE Reliability Test System and verified by comparing the results obtained from other techniques. The results from this study could also identify the weak cluster in a power system network.

Here is this paper IEEE 9 Bus, 30 Bus, 118 Bus Test Systems are simulated in POWER WORLD and MATLAB software. By the outage of transmission line between two buses and simulated for all the cases. By considering the severe most contingency which is ranked first is taken and connected shunt compensation at buses. By this connection of shunt compensation there is an improvement in voltage magnitude & stability.

### B. Optimal Placement of Shunt Compensator

The severe most n-1 contingency is identified based on P-V Curves, L-Index & FVSI. The weakest bus is detected based on the same indices, which can be used for the optimal placement of shunt compensator (Shunt Capacitor, SPM and SVC).

**1. IEEE 9 Bus System**

Contingency ranking is made based on P-V curves, L-Index and FVSI for (n-1) contingency. The 7-5 line outage is severe most (n-1) contingency based on P-V curves, L-Index and FVSI. The 8th bus is most critical bus based on P-V curves, L-Index and FVSI.

**2. IEEE 30 Bus System**

Contingency ranking is made based on L-Index and FVSI values for (n-1) contingency. The 25-27 line outage is severe most (n-1) contingency based on P-V curves & L-Index. The 1-3 line outage is severe most (n-1) contingency based on FVSI. The 26th bus is most critical bus based on P-V curves & L-Index and 27th bus is most critical bus based on FVSI.

**3. IEEE 118 Bus System**

Contingency ranking is made based on P-V curves, L-Index and FVSI for (n-1) contingency. The 53-54 line outage is severe most (n-1) contingency based on P-V curves, L-Index and FVSI. The 53rd bus is most critical bus based on P-V curves, L-Index and FVSI.

### C. Optimal Capacity of Shunt Compensator

The optimal location and size of FACTS devices [8-10] has retained the interest of worldwide researchers in power systems. In the stationary mode, FACTS devices are used to control the power flow in the transmission lines as well as the bus voltages. The required objectives can be of technical order or of an economic nature. Various mathematical methods and criteria are used to optimal allocation of these devices in the power systems.

We have concluded that optimal placement should be done at critical point where the values are near to the collapse point. In order to calculate the size of the compensator The Capacity of the Shunt Compensator is obtained by using P-Q bus to P-V bus Conversion Method. In this method the weakest bus can be converted to Voltage Controlled bus by placing a Fictitious Generator, which generates only Reactive Power corresponding to the Reference Voltage i.e. 1 P.U. After connecting a Fictitious Generator at weakest bus, the power flow is performed using N-R Method. The capacity or Size of the Compensator is obtained at that bus corresponding to reference voltage (1 p.u.).

When Fictitious Generator is connected in shunt to IEEE 9 bus system based upon P-V Curves, L-index & FVSI values at 8th bus we get 207 MVAr. Again the load flow is done, at 5th bus voltage value is near to the critical point the same process is repeated i.e., calculation of P-V Curves L-index and FVSI values. Now the Fictitious Generator is connected in shunt to IEEE 9 bus system at 8th & 5th buses now we get 205 MVAr & 97MVAr values respectively i.e., size or capacity of shunt compensator.

When Fictitious Generator is connected in shunt to IEEE 30 bus system based upon P-V Curves & L-index values at 26th bus we get 37 MVAr. Again the load flow is done, at 25th bus voltage value is near to the critical point the same process is repeated i.e., calculation of P-V Curves & L-index values. Now the Fictitious Generator is connected in shunt to IEEE 30 bus system at 8th & 5th buses now we get 37 MVAr & 5 MVAr values respectively i.e., size or capacity of shunt compensator. When Fictitious Generator is connected in shunt to IEEE 30 bus system based upon FVSI values at 27th bus we get 35 MVAr value respectively i.e., size or capacity of shunt compensator.

When Fictitious Generator is connected in shunt to IEEE 118 bus system based upon L-index & FVSI values at 53rd bus we get 31 MVAr value respectively i.e., size or capacity of shunt compensator.

## III. Optimal Placement Of Static Var Compensator

### A. Optimal Shunt Compensation

The severe most n-1 contingency is identified based on P-V Curves, L-Index & FVSI. The weakest bus is detected based on the same indices, which can be used for the optimal placement of shunt compensator (Shunt Capacitor, SPM and SVC). Voltage Stability can be improved by placing shunt compensator at weakest bus, capacity or size of the compensator equal to the value which is obtained from the Fictitious Generator.

### B. Synchronous Phase Modifier (SPM)

Synchronous Phase Modifier[11] is an effective method of achieving variable shunt compensation, but it has -10% active power losses (Iron and Mechanical). In second case a synchronous phase modifier is connected at the weakest bus, the results shows the effectiveness of the SPM on mitigating voltage variations and stability indices against load variations with a small increment in the power losses.

### C. Static Var Compensator (SVC)

In steady state an SVC [10] can be treated as a reactive power injection source, which can be presented as the following mathematical statement:

$$Q_{SVC} = V_t (V_t - V_{ref}) X_{SL}$$

Where $X_{SL}$ is the slope of voltage control characteristic, $V_t$ is the terminal voltage of SVC and $V_{ref}$ is the reference voltage. Doing some calculation the above Equation can be rewritten as:

$$Q_{SVC} = B_{SVC} \times V_{ref}^2$$

The value of $B_{SVC}$ can be varied between minimum and maximum susceptance the so-called capacitive susceptance and inductive susceptance, where the desired reactive power can be maintained.

The reactive power generated by SVC is given by

$$Q_{SVC}^{min} \leq Q_{SVC} \leq Q_{SVC}^{max}$$

IEEE 9, 30 and 118 Bus test systems have been simulated in Power World software and MATLAB programming. Simulation results have been presented below.

## IV. Comparative Analysis Of Simulation Results: Shunt Capacitor, Spm & Svc On Voltage Stability Improvement

Comparative Analysis of Simulation Results: Shunt Capacitor, SPM & SVC on Voltage Stability Improvement

### A IEEE 9 Bus System Results

IEEE 9 Bus test system is simulated in power world software the compensator is connected at the severe most bus for voltage stability enhancement. Three kinds of compensators viz. shunt capacitor, SPM and SVC have been connected and comparative bar graphs of these controllers have been drawn using simulation results as shown below.

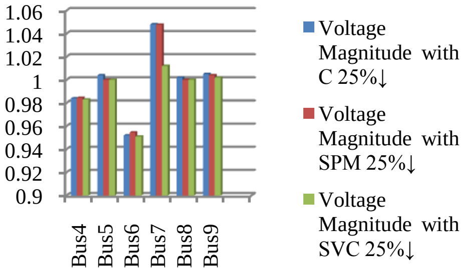

**Figure 1:** Comparison bar chart of voltages for C, SPM & SVC against load decrement of 25%

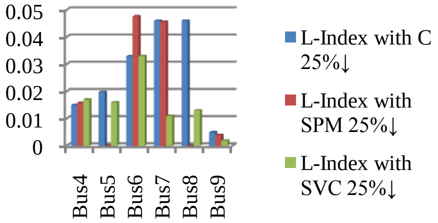

**Figure 2:** Comparison bar chart of L - Index for C, SPM & SVC against load decrement of 25%

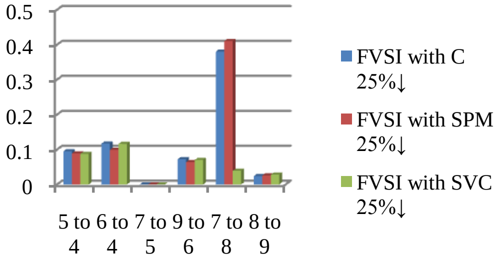

**Figure3:** Comparison bar chart of FVSI for C, SPM & SVC against load decrement of 25%

**Table 1:** Comparison of Losses of Shunt Capacitor, SPM & SVC against load variations

| ΔLoad | 0.25↓ | | 0.25↑ | | 0.5↓ | | 0.5↑ | |
|---|---|---|---|---|---|---|---|---|
| Device | MW | MVAr | MW | MVAr | MW | MVAr | MW | MVAr |
| C | 36 | 71.8 | 32 | 90.6 | 41 | 83 | 32 | 127 |
| SPM | 35 | 68.9 | 31 | 97.3 | 38 | 75 | 32 | 134 |
| SVC | 36 | 69.4 | 32 | 90.5 | 40 | 78.9 | 32 | 127 |

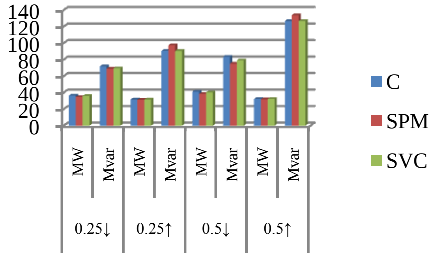

**Figure 4:** Comparison bar chart of Losses of Shunt Capacitor, SPM & SVC against load variations

### B. IEEE 30 Bus System Results

IEEE 30 Bus test system is simulated in power world software and the compensator is connected at the severe most bus for voltage stability enhancement. Three kinds of compensators viz. shunt capacitor, SPM and SVC have been connected and comparative bar graphs of these controllers have been drawn using simulation results as shown below. Figure 6.5 shows the Comparison bar chart of voltages for C, SPM & SVC against load decrement of 25%.Figure 6.6 shows the Comparison bar chart of L - Index for C, SPM & SVC against load decrement of 25%.

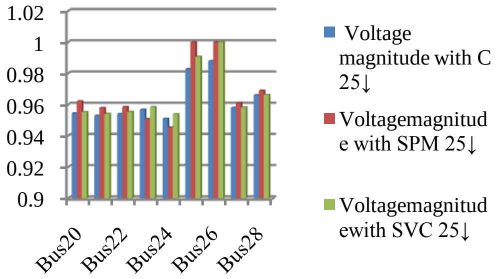

**Figure 5:** Comparison bar chart of voltages for C, SPM & SVC against load decrement of 25%

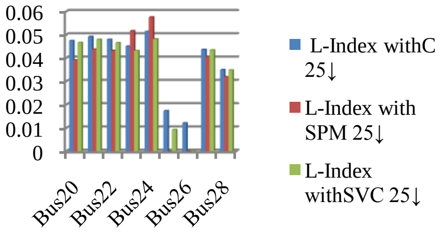

**Figure 6:** Comparison bar chart of L - Index for C, SPM & SVC against load decrement of 25%

### C. IEEE 118 Bus System Results

IEEE 118 Bus test system is simulated in power world software and the compensator is connected at the severe most bus for voltage stability enhancement. Three kinds of compensators viz. shunt capacitor, SPM and SVC have been connected and comparative bar graphs of these controllers have been drawn using simulation results as shown below.

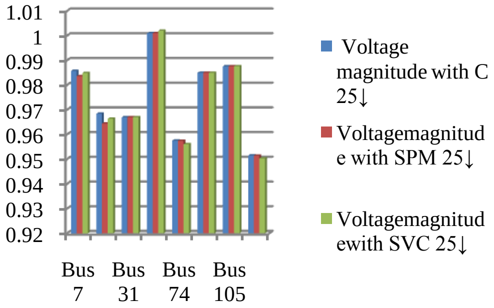

**Figure 7:** Comparison bar chart of voltages for C, SPM & SVC against load decrement of 25%

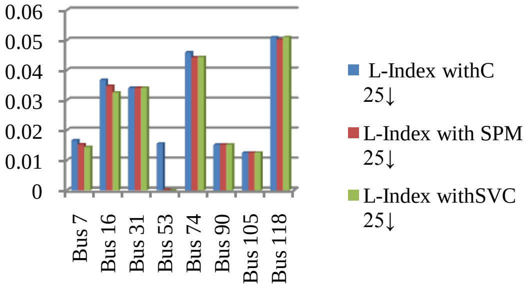

**Figure 8:** Comparison bar chart of L - Index for C, SPM & SVC against load decrement of 25%

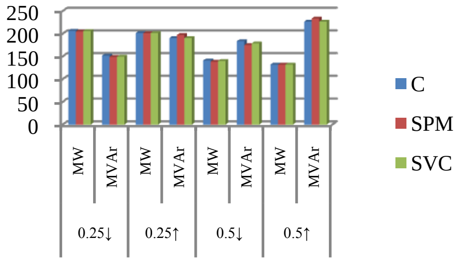

**Figure 9:** Comparison bar chart of Losses of Shunt Capacitor, SPM & SVC against load variations

## V. Conclusions

The simulation result shows the effectiveness of shunt compensator on voltage stability improvement, since FVSI and L-Index have been decreased considerably. The fixed shunt compensator is quite effective for the base load conditions and it is most economical method but it is ineffective against load variations i.e. off peak and peak load intervals. Load variations lead to voltage variations in fixed compensated systems; in order to minimize these variations variable compensators are most essential. SPM (Synchronous Phase modifier) and SVC are quiet effective for providing such variable compensation which will minimize voltage variations.

Simulation result also shows that the SVC is more advantageous than Shunt Capacitor and SPM since losses are minimum and it has effectively mitigated the voltage variations against the load variations hence it is quiet effective compensator for off peak and peak loads.

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