NEW VOLTAGE STABILITY INDEX (NVSI) FOR VOLTAGE STABILITY ANALYSIS IN POWER SYSTEM

SARAT KUMAR SAHU, S.SURESH REDDY & S.V.JAYARAM KUMAR

Professor, MVGR College of Engineering NBKRIST JNTUCEH, VizianagaramVidyanagar, Hyderabad, India

ABSTRACT

The phenomenon of static voltage instability and voltage collapse is of much importance in the present day power scenario. An index for assessing the weak bus in the system was developed in the paper. The paper also addresses a methodology to find the appropriate type of FACTS device and its location for the improvement of static voltage stability as well as increase in the power transfer capability of existing lines.

A New Voltage Stability Index (NVSI) is developed based on the condition number of the standard power flow Jacobian matrix. The proposed index has been tested on standard IEEE 14 bus test system and the results obtained are compared with the results obtained from the other stability indices. A novel strategy for the type and placement of the FACTS devices based on the analysis of the results obtained from various techniques is proposed.

KEY WORDS: Voltage Stability, FACTS, Voltage Collapse, Voltage Stability Index

INTRODUCTION

The present day power system is a complex network comprising of transmission lines interconnecting all the generator stations, transformers and all the loading points in the power system[1]. These lines carry large blocks of power which can be directed in any desired direction on the various paths of the transmission system to achieve the preferred economic and performance objectives. Power system studies comprises of generation, transmission and distribution. The major concern of the power utilities is to supply electrical power to customers without any interruption. The power flow solution, which is closely linked to voltage stability, is a significant tool, which is required to compute the total power that needs to be transferred to the customers.

Since voltage stability determines the quality of the available power, it has been acknowledged as the important issue for power system utilities. In recent years, voltage instability has been considered as important restraining factor to power transmission. Over the last ten to fifteen years, the electric utility industry has become increasingly worried with voltage instability and collapse incidents. This concern is based on quite a lot of voltage collapse incidents as described in an IEEE report [2].

Voltage stability studies are mainly categorized into two main types, namely the dynamic stability studies, and the static stability studies. Most of the studies focus in the static stability as dynamic stability is difficult to simulate or analyze due to the presence of nonlinear loads. There are many methods currently in use to help in the analysis of static voltage stability.

Some of them are PV analysis, QV analysis, Modal Analysis, Fast Voltage Stability Index (FVSI), multiple load flow solutions based indices, voltage instability proximity indicator [9], Line stability index, Line stability Factor, Reduced Jacobian Determinant, Minimum Singular Value of Power Flow Jacobian, and other voltage indices methods.

In this paper a New Voltage Stability Index (NVSI) is developed for the identification of the weakest bus or pilot
bus in the system. The performance of FACTS controller connected at the weakest bus is assessed by comparing voltage profile and steady state voltage stability margin of the system.

VOLTAGE INSTABILITY

The phenomenon of progressive decrease and final collapse of the terminal voltage as a result of an incremental increase in load is referred to as voltage instability. Voltage Collapse which may take several seconds to minutes is the result of a complex interaction between induction motor type loads and certain voltage regulators, such as tap-changing transformers. The reason for voltage collapse is that decreasing terminal voltage results in increase in load current and poor load power factor which leads to further decline in the terminal voltage. The voltage stability limit identifies for a given system the specific voltage and power condition at which the next increment causes a voltage collapse.

“A system enters a state of voltage instability when a disturbance like an increase in load demand, or change in system condition causes a progressive and uncontrollable decline in voltage”. The major reason for voltage instability is the inability of the power system to meet the demand for reactive power. The heart of the problem is generally the voltage drop associated due to the active power and reactive power flows through inductive reactance associated with the transmission network. Voltage stability can be described as “The capability of the system to maintain the adequate voltage under normal operating conditions and after the disturbances arise”. Huge transmission system interconnections, increase in load demands, insufficient generation, lack of transmission corridor expansions, economical and environmental pressures have led power systems to operate with its equipment very close to their stability limits. Voltage instability and voltage collapse situation are very likely to take place, imposing significant limitations on power system operation.

The phenomenon of voltage instability is attributed to the power system as its maximum transmissible power limit, shortage of reactive power resources and inadequacy of reactive power compensation tools. The main factors contributing to the voltage collapse are the generator reactive power limit, voltage control limit, load characteristics, reactive power compensation device characteristics and its actions. In power system operation voltage stability problems are not new to the electric utility industry and commercial field. Voltage instability has been responsible for major network collapses. Voltage stability problems in power systems may occur for a variety of reasons, from voltage control problems arising due to automatic voltage regulators (AVR) and under-load tap-changer (ULTC) transformers, to instabilities created by different types of bifurcations. These bifurcations are characterized by changes in the eigen values of the system equilibrium, as certain parameters change in the system.

VOLTAGE STABILITY INDICES

Performance indices to predict the system proximity to voltage collapse are very essential, as these indices can be effectively used to carry out off-line or on-line studies to evaluate how close the system is to instability. Once the performance indices are evaluated, a search for appropriate location for placing remedial control and reactive power support devices can be obtained [3]. Finally, this effort will yield an improved system performance that avoids potential damages due to different contingencies and variations in loading.

There are many methods currently in use to help in the analysis of static voltage stability. Some of them are PV analysis [4], QV analysis, Modal Analysis [5, 6,7], Fast Voltage Stability Index (FVSI)[8], multiple load flow solutions based indices, voltage instability proximity indicator [9], Line stability index [10], Line stability Factor[11,13], Reduced Jacobian Determinant, Minimum Singular Value of Power Flow Jacobian, and other voltage indices methods. Different methods of analysis were determined as they serve different function of analysis on the same network, but they have a
common goal, which is the prediction of voltage collapse of the system.

**PROPOSED METHODOLOGY**

A New Voltage Stability Indicator was developed, which is based on the condition number of the standard power flow Jacobian matrix. The condition number of a symmetric positive definite matrix is defined as the ratio of maximum eigen value to the minimum eigen value. The condition number gives a good indication of the sensitivity of the inverse of the matrix to small perturbation in the original matrix. The ratio of the condition number at critical loading (The reactive power loading at a particular bus where the load flow solution diverges) to the condition number at base case loading gives a good measure of voltage stability limit. The power flow solution is obtained at the base case loading. The eigen values of the standard power flow Jacobian are computed. The condition number at the base case loading is computed as

\[
K_{base} = \frac{\text{Maximum Eigen Value}}{\text{Minimum Eigen Value}}
\]

(1)

The load is gradually increased at the chosen load bus until the load flow solution diverges. The reactive power load prior to which the solution fails to converge is called critical loading at that bus. The condition number at the critical loading is computed using equation 1. This gives the condition number at critical loading, \(K_{critical}\).

The New Voltage Stability Index (NVSI) is defined as the ratio of the condition number at critical loading (The reactive power loading at a particular bus where the load flow solution diverges) to the condition number at base case loading.

\[
\text{NVSI} = \frac{K_{critical}}{K_{base}}
\]

(2)

The following steps are implemented for finding the maximum loadability and weak bus identification

1. Obtain the solution of the load flow problem at the base case using standard Newton - Raphson method.
2. Compute the maximum and minimum eigen values of standard power flow Jacobian matrix from the eigen value analysis.
3. Compute the condition number as the ratio of maximum to minimum eigen value at base case load.
4. Gradually increase the reactive power load at any one of the load bus until the load flow solution diverges. The reactive power load prior to which the solution diverges is known as critical load.
5. Compute the condition number as the ratio of maximum to minimum eigen value at critical reactive power loading.
6. Compute the ratio of condition number at critical load to the condition number at base case load. This is the NVSI for the voltage stability limit at a particular bus.
7. Repeat steps 4 to 6 for every load bus in the system.
8. Obtain the voltage at the critical loading, which is known as critical voltage of that particular load bus.
9. Sort the NVSI obtained for various load buses obtained in step 6 in descending order. The bus with highest value of the NVSI is termed as weakest bus.
The Placement Problem

The traditional criteria used to decide which type and place to install reactive power compensating devices are based on the protection philosophy adopted in the company, including selectivity and coordination analysis. More recently, criteria based on the benefits of these devices to system reliability have been increasingly used in this type of analysis. In this section, the proposed approach is described as follows: The weak bus and weak line are identified by analyzing the results obtained through the line stability indices such as FVSI, and proposed method. By using the line stability indices, the pilot bus or the weak bus is identified as the bus which has the lowest reactive power loading margin. The voltage at that particular bus is lowest which is called critical voltage. Any further increase in the reactive power load at that bus makes the system to be unstable. On the other hand by using the same indices, we can also determine the weak line with respect to a bus. Any increase in the reactive power loading at that bus will cause instability in the line associated with it.

Based on the analytical study of both the results, for a given system the weak bus or pilot bus is determined and also the weak line which causes the system to collapse with an increase in the reactive power loading is obtained. A shunt FACTS device such as SVC or STATCOM can be employed to provide the reactive power support to the system at the weak bus. A series FACTS device such as TCSC or a hybrid device such as UPFC can be connected in series with the weak line to improve the transfer capability of the line and also to maintain the stability of the line.

RESULTS & DISCUSSIONS

Simulation studies are carried out on IEEE-14 bus test system. This system has 5 generator buses, 9 load buses and 20 interconnected branches. Initially power flow studies are carried out on IEEE 14-bus system with the reactive load at load buses gradually increased, only in one bus at a time, from the base case until its maximum allowable load, keeping the load at the other bus fixed at base load. After the load flow analysis was completed, the stability indices are found out. The voltage stability analysis is performed on IEEE 14-bus test system. From Table-1, it is observed that bus 14 is ranked high with a reactive power loadability of 0.72p.u. It indicates that this bus sustains the lowest load. Bus 5 is ranked highest with a maximum load-ability of 2.4032p.u. Bus 5 can be treated as most secure bus and bus 14 as most insecure bus in the system. A shunt FACTS device such as SVC or STATCOM can be placed at bus 14 to provide necessary reactive power support.

Table 2 gives the idea of weakest line in the system with respect to a bus. The line connected between buses 14 and 13 is most critical with variation in reactive power loading at bus 4 and 5 as its FVSI value is close to 1. Similarly the other lines also show criticalness with respect to other load buses. Instead of connecting a pure shunt FACTS device such as STATCOM at bus 14, a hybrid device such as UPFC can be connected in the line 14 - 13; close to bus 14 such that it regulates the voltage at bus 14 and also improve the power transfer along the line 14 - 13. Similarly the line

<table>
<thead>
<tr>
<th>Rank</th>
<th>Bus No</th>
<th>Voltage(PU)</th>
<th>FVSI</th>
<th>Qmax(PU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14</td>
<td>0.81956</td>
<td>0.99410</td>
<td>0.72</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.71140</td>
<td>0.99850</td>
<td>1.4836</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>0.73331</td>
<td>0.99916</td>
<td>1.5989</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>0.691640</td>
<td>0.87649</td>
<td>1.6056</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0.69164</td>
<td>0.99950</td>
<td>1.6392</td>
</tr>
<tr>
<td>6</td>
<td>13</td>
<td>0.85565</td>
<td>0.99984</td>
<td>1.7365</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>0.779300</td>
<td>0.99889</td>
<td>1.7977</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0.885300</td>
<td>0.99958</td>
<td>2.4032</td>
</tr>
</tbody>
</table>
connected between buses 11 and 10 is also critical with respect to both the buses 9, 10 and 11. Since bus 9 is ranked highest and there is no need of voltage support required at that bus, a TCSC can be incorporated between lines 11 and 10.

**Table 2: Weak Line Identification for IEEE 14-Bus System**

<table>
<thead>
<tr>
<th>Line</th>
<th>FVSI</th>
<th>Q Variation at Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-13</td>
<td>0.99995</td>
<td>4</td>
</tr>
<tr>
<td>14-13</td>
<td>0.99958</td>
<td>5</td>
</tr>
<tr>
<td>11-10</td>
<td>0.99889</td>
<td>9</td>
</tr>
<tr>
<td>11-10</td>
<td>0.99850</td>
<td>10</td>
</tr>
<tr>
<td>11-10</td>
<td>0.99916</td>
<td>11</td>
</tr>
<tr>
<td>12-13</td>
<td>0.87649</td>
<td>12</td>
</tr>
<tr>
<td>3-4</td>
<td>0.99984</td>
<td>13</td>
</tr>
<tr>
<td>4-9</td>
<td>0.99410</td>
<td>14</td>
</tr>
</tbody>
</table>

**Table 3: Bus Ranking Based on Proposed NVSI**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Bus No</th>
<th>Voltage (PU)</th>
<th>NVSI</th>
<th>Qmax (PU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0.66981</td>
<td>2.4359</td>
<td>1.5776</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>0.67353</td>
<td>2.3281</td>
<td>1.0257</td>
</tr>
<tr>
<td>3</td>
<td>09</td>
<td>0.68618</td>
<td>2.3249</td>
<td>2.1414</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>0.68250</td>
<td>1.9506</td>
<td>1.7280</td>
</tr>
<tr>
<td>5</td>
<td>13</td>
<td>0.68738</td>
<td>1.5983</td>
<td>2.5868</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>0.69206</td>
<td>1.5694</td>
<td>1.6048</td>
</tr>
<tr>
<td>7</td>
<td>04</td>
<td>0.67303</td>
<td>0.8810</td>
<td>5.0720</td>
</tr>
<tr>
<td>8</td>
<td>05</td>
<td>0.67255</td>
<td>0.8159</td>
<td>4.9392</td>
</tr>
</tbody>
</table>

Voltage stability characteristics can be identified by computing the eigen values of the standard power flow Jacobian matrix. The IEEE 14-bus test system is considered for analysis to identify the weak bus. The proposed NVSI is calculated for each bus and ranking is given in a descending order. The bus with highest NVSI is ranked high implying the weak bus in the system. Table 3 gives the bus ranking for IEEE 14-bus test system. The maximum and minimum eigen values at the base case are 63.53051 and 2.58381 respectively. The condition number at base case is 24.58792.

![Figure 1: Voltage Profile of Test System with and without UPFC](image-url)
From the comparison analysis of line stability indices, and the proposed method, it was identified that bus 14 and bus 10 are more vulnerable to voltage collapse as they have the lowest reactive power margin. So a suitable FACTS device can be placed to improve the system stability. The system discussed above is simulated for assessing the impact of the Unified Power Flow Controller (UPFC) for voltage profile improvement and increase in the maximum permissible loading. From Fig. 1 it is evident that the voltage of the IEEE-14-bus has been improved with the use of UPFC. At Bus ’14’, the voltage is 0.81956p.u without UPFC.

The voltage at bus ’14’ is increased to 0.92892p.u when UPFC is incorporated between bus ’13’ and bus ’14’ close to bus ’14’. The reactive current drawn by the shunt source of UPFC is 0.9p.u The gain of the regulator is 50 and the time constant is 0.1seconds. The UPFC was set for 30% compensation. When the percentage of compensation is increased the voltage at bus 14 also increases.

CONCLUSIONS

The phenomenon of static voltage stability and the point of voltage collapse are studied in this paper. The main motivation of the study is occurrence of the several voltage collapse incidents during the last few decades all round the world. An index known as New Voltage Stability Index to determine the distance between the operating point and collapse point in terms of reactive power loading at the load bus was proposed. The proposed index to measure the static voltage instability is verified and its performance is compared with the available voltage stability indices. Results obtained from the proposed method show close agreement with the available techniques to evaluate the static voltage stability limit. Some broad guide lines were presented for the type and placement of the FACTS devices based on the analysis of the results obtained from various techniques in the study.

REFERENCES


