Voltage Stability Assessment using Different Indices
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Abstract—The problem of voltage instability has been increasing day by day because of the increased demand of power. It is important to analyze the power system behavior with respect to voltage stability. This paper shows the performance of the stability indices. The two indices whose analysis are performed in the paper are line stability index and fast voltage stability index. The indices are tested on IEEE 14 bus standard test system. The simulation of the IEEE 14 bus system is implemented using PSAT toolbox. With the help of the above mentioned indices the most critical lines and the weakest buses can be identified. Lines having index value equal to one or close to one are considered as the most critical lines.

Keywords: Voltage stability, voltage collapse, voltage stability indices, power system analysis toolbox (PSAT)

I. INTRODUCTION
Voltage instability is relatively recent and challenging problem in a power system. Day by day it is gaining importance as the trend of operating power system close to their maximum limits increases. Present day power systems are being operated closer to their stability limits due to economic and environmental constraints.

Power system stability can be stated as the ability of the power system that enables it to maintain in state of equilibrium under normal operating condition and to regain an acceptable state of equilibrium after being subjected to a disturbance. Voltage stability is the ability of the power system to maintain voltage up to their limit, so that when the load admittance is increased, load power will increase, thus both power and voltage are controllable [1].

To maintain power system secure is therefore very important. Voltage instability is a major concern and it has been given much more attention by power system researchers and planners in recent years, and is being regarded as one of the major causes of power system insecurity. “Voltage collapse is the process by which the voltages fall to very low values as a result of an avalanche of events accompanying voltage instability” [2].

Voltage collapse may occur in the power system due to loss of voltage stability in the system. Therefore a proper attention should be given to the voltage stability analysis in order to identify critical buses in a power system. As a result many techniques have been proposed to identify critical buses and lines. Voltage stability index for a stressed power station from a reduced system model can be derived [3]. The index can identify how far a system is from its point of collapse. Line stability factors which could identify critical lines developed by [4]. How the singularity in the jacobian matrix can be avoided by reforming power flow and point of voltage instability by employing PV curve can be obtained [5]. In this paper, voltage stability indices i.e. line stability index and fast voltage stability index are analyzed. The capability of these indices to identify critical lines and buses can be done by keeping buses at different loading conditions. The load change is increased from the base load until load flow fails to converge.

II. THEORETICAL ANALYSIS OF VOLTAGE STABILITY INDEX
Voltage stability analysis can be performed on the system by analyzing the stability indices referred to a line. Two such indices are mentioned in this paper, they are line stability index and fast voltage stability index.

A. Line Stability Index:
M. Moghavemmi et al. [6] derived the line stability index which is based on the concept of power transmission on the single line. According to the Moghavemmi discriminator of the voltage equation should be set to zero or greater than zero to maintain stability. In order to derive the index a single line transmission network can be used, fig 1 illustrates the network.

The power flow at the receiving end can be expressed as

\[ S = \frac{|V_1| |V_2|}{|Z|} \angle (\theta - \delta + 62) - \frac{|V_2|^2}{|Z|} \angle \theta \]

From this power equation, real and reactive power can be separated as

\[ P_v = \frac{|V_1| |V_2|}{|Z|} \cos(\theta - \delta + 62) - \frac{|V_2|^2}{|Z|} \cos(\theta) \]

\[ Q_v = \frac{|V_1| |V_2|}{|Z|} \sin(\theta - \delta + 62) - \frac{|V_2|^2}{|Z|} \sin(\theta) \]

Where \( \theta \) is the angle of line impedance and \( \delta \) is the angle difference between the supply voltage and the receiving voltage. Putting \( \delta = 61 - 62 \) into (3) and solving it for \( V_2 \) yields quadratic equation of:

\[ |V_2|^2 \sin \theta - |V_1| V_2 \sin (\theta - \delta) + |Z| \sin(\theta) Q_2 = 0 \]

Using (5), the root of \( V_2 \) is obtained and yields to (6):

\[ \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \]

\[ V_2 = \frac{|V_1| \sin(\theta - \delta) \pm \sqrt{|V_1| \sin(\theta - \delta)^2 - 4 |Z| Q_2 |\sin(\theta)|}}{2 |\sin(\theta)|} \]

In order to maintain a stable system, \( V_2 \) needs to satisfy the stability criterion

\[ b^2 - 4ac \geq 0 \]

Thus, \( V_2 \) is expressed as

\[ |V_1| \sin(\theta - \delta)^2 - 4 |Z| Q_2 |\sin(\theta)| \geq 0 \]

And for |\( Z \) \sin(\theta) = X|,

\[ \frac{4 X |Q_2|}{|V_1| \sin(\theta - \delta)^2} \leq 1.00 \]

Thus, the line stability index can be defined as...
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L_mn = \frac{4 X |Q_2|}{|V_2|^2 (\sin(\theta - \delta))^2} \quad (9)

B. Fast Voltage Stability Index:

Fast voltage stability index proposed by I. Musirin et al. [6] is based on the concept of power flow through the single line. For a typical transmission line as shown earlier,

I = \frac{\frac{V_2 \delta_1 - V_1 \delta_2}{|Z_l|}}{I_{ref}} \quad (10)

I = \frac{\frac{p - jq_2}{V_2 \delta}}{V_1 \delta} \quad (11)

Taking (10) = (11), \delta = \delta_1 - \delta_2 and rearranging the equations will lead to

P_2 - jQ_2 = \frac{-|V_1|^2 \delta - 0 + i|V_1 V_2|\delta - 0}{|Z_l|} \quad (12)

From (12) the reactive power of receiving bus form the quadratic equation for the \( V_2 \) is evaluated as

\begin{align*}
|V_2|^2 - [V_1 V_2] [\frac{R}{X} \sin \delta + \cos \delta] + [\frac{R^2}{X} + X] Q_2 = 0 \\
[\frac{R}{X} \sin \delta + \cos \delta]|V_1|^2 \pm \sqrt{[\frac{R^2}{X} + X |V_1|^4 - 4[\frac{R}{X}]^2 Q_2} \\

\end{align*}

\begin{align*}
\frac{4 |Z|^2 Q_2}{|V_1|^2 (\sin \delta + X \cos \delta)} \leq 1.00 \\
\frac{4 |Z|^2 Q_2}{|V_1|^2 (R \sin \delta + X \cos \delta)} \leq 1.00 \quad (15)
\end{align*}

Since the angle difference is normally small and can be neglected, therefore R \sin \delta \sim 0 and X \cos \delta \sim X. Thus

\begin{align*}
\frac{4 |Z|^2 Q_2}{|V_1|^2 X} \leq 1.00 \\
\end{align*}

Finally, the line stability index FVSI is formulated as

FVSI = \frac{4 |Z|^2 Q_2}{|V_1|^2 X} \quad (17)

After implementing the above method if the value of the above indices is close to 1 that line is the most critical line of the bus and it will lead to system instability. The calculated FVSI is also used to calculate the weakest bus on the system. The concept of determining the weakest bus is based on the maximum load allowed on a load bus. The weakest bus in the network corresponds to the bus with the smallest maximum tolerable load.

<table>
<thead>
<tr>
<th>Index</th>
<th>Formulation</th>
<th>Relative Variables</th>
<th>Critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_mn</td>
<td>L_mn = \frac{4 X</td>
<td>Q_2</td>
<td>}{</td>
</tr>
<tr>
<td>FVSI</td>
<td>FVSI = \frac{4</td>
<td>Z</td>
<td>^2 Q_2}{</td>
</tr>
</tbody>
</table>

Table-1: After Implementing

III. ANALYSIS TOOLS

For the analysis purpose power system analysis toolbox (PSAT) is used. PSAT is one of the most important open source Matlab and GNU/Octave-based software package for the analysis of electric power systems. PSAT includes various operation such as power flow, continuation power flow, optimal power flow, small-signal stability analysis, and time-domain simulation, as well as several static and dynamic models. All the simulation has been implemented on the power system analysis tool.

IV. TEST RESULTS AND DISCUSSION

Fig. 2: Test Result
The analysis of the voltage stability indices were performed on the IEEE 14 bus test system. The simulation results are investigated in order to document the theory analysis. The system comprises of 5 generator buses, 11 load buses, and 20 interconnected branches. The configuration is shown in fig 2.

The different indices are tested for the different loading conditions of the IEEE 14 bus system. The increased loading will affect the lines connected to the buses. The loading of the bus can be slowly varied for its base value to its 10% loading, 20% loading and so on.

The small addition of load fails to converge the load flow solution and indicates that the loading is critical and very close to system instability. At a time only one bus is taken into consideration and load on the other buses keep constant at base load.

A. Reactive Power Load Changes:

Fig. a shows the variation of line stability index (Lmn) vs bus number for the base case of the IEEE 14 bus system. From the graph, it shows that line L4-9 is the highest index value. By increasing the reactive load on the bus number 4, the line L4-9 is going to be critical first.

Fig. 3: Variation of Line Stability Index

Fig. 3 shows the variation of line stability index (Lmn) vs. bus number for the 10% loading of the IEEE 14 bus system. The reactive load is slowly increased, only in one bus of the IEEE 14 bus system at a time, from the base case till its maximum permissible load, keeping the load on the other buses constant at base load.

The reactive power variation has been done on the bus number 14 from the value of 0.1 p.u to 0.7 p.u, and this will lead to value of 0.965 as the line stability index as depicted in the figure, the line 13-14 connecting to the bus 14 is going to be critical first as compared to other lines as the index value is close to 1. Fig.3 shows the variation of line stability index (L13-14) for different value of reactive power Q (MVAR) in p.u. at bus number 14.

Fig. 4: L (13-14) vs. Reactive Load Variation for 14 Buses

Fig.5 shows the variation of line stability index L (6-11) for different value of reactive power Q (MVAR) in p.u. at bus number 11.

Fig. 5: L (6-11) vs. Reactive Load

From the above mentioned plot, line 13-14 is the critical line referred to bus 14 and the line 6-11 is the critical line referred to bus 11.

Fig. 6 shows the variation of FVSI vs. bus number for the base Case of the IEEE 14 bus system. From the graph, it shows that line L4-9 is having the highest index value. By increasing the reactive load on the bus number 4, the line L4-9 is going to be critical first.

Fig. 6: Variation of FVSI vs. Bus Number

The variation of the reactive load on the bus number 4 keeping the load on the other buses constant at base load is shown below by FVSI method. From the Fig.7, it shows that the line 2-4 is the critical line referred to bus 4.

Fig. 7: FVSI Method

V. CONCLUSION

This paper presents the methods to identify the critical lines and buses based on the proposed methods. Two such indices
were formulated; line stability index and fast voltage stability index to identify lines based on different loading conditions up to maximum loading condition. The results are tested on the standard IEEE 14 bus test system.

<table>
<thead>
<tr>
<th>Bus</th>
<th>Phase(deg)</th>
<th>P Gen</th>
<th>Q gen</th>
<th>P load</th>
<th>Q load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000</td>
<td>3.5206</td>
<td>0.2821</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>-0.1357</td>
<td>0.4000</td>
<td>0.9483</td>
<td>0.3038</td>
<td>0.1778</td>
</tr>
<tr>
<td>3</td>
<td>-0.3321</td>
<td>0.0000</td>
<td>0.5971</td>
<td>1.3188</td>
<td>0.2660</td>
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<tr>
<td>4</td>
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<td>0.0000</td>
<td>0.0000</td>
<td>0.6692</td>
<td>0.0560</td>
</tr>
<tr>
<td>5</td>
<td>-0.2270</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.1064</td>
<td>0.0244</td>
</tr>
<tr>
<td>6</td>
<td>-0.3696</td>
<td>0.0000</td>
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<td>0.1050</td>
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<td>0.0000</td>
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<tr>
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<td>0.2086</td>
<td>0.0700</td>
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Table 2: Load Flow Results

<table>
<thead>
<tr>
<th>Bus</th>
<th>Q-max</th>
<th>Q-min</th>
<th>Tap setting</th>
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<tbody>
<tr>
<td>2</td>
<td>50</td>
<td>-40</td>
<td>Bus 5-6</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>0</td>
<td>Bus 4-9</td>
</tr>
<tr>
<td>6</td>
<td>24</td>
<td>-6</td>
<td>Bus 4-7</td>
</tr>
<tr>
<td>8</td>
<td>24</td>
<td>-6</td>
<td>Bus 7-8</td>
</tr>
</tbody>
</table>

Table 3: Tap Setting and Reactive Power Limits

REFERENCES