CONTINGENCY SCREENING AND RANKING BASED ON LINE OUTAGES FOR VOLTAGE STABILITY ASSESSMENT

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Abstract- Voltage stability has recently become a challenging problem for many power systems. Voltage instability is one phenomenon that could happen in power system due to its stressed condition. The result would be the occurrence of voltage collapse which leads to total blackout to the whole system. Investigation and online monitoring of power system stability have become vital factors to electric utility suppliers. Contingency screening and ranking (CS&R) is one of the important components of on-line voltage stability assessment. The objective of CS&R is to quickly and accurately select a short list of critical contingencies from a large list of potential contingencies and rank them according to their severity. Suitable preventive control actions can be implemented considering contingencies that are likely to affect the power system performance. An effective method for contingency ranking is proposed in this paper. This method calculates the voltage stability margin considering line outages. The basic methodology implied in this technique is the investigation of each line of the system through calculating line stability indices. The point at which VSI close to unity indicates the maximum possible connected load termed as maximum loadability at the point of bifurcation. This technique is tested on the IEEE system and results proved that the contingency ranking indicates the severity of the voltage stability condition in a power system due to line outage.

Index Terms - voltage stability, sensitive lines, critical line outage, contingency ranking, Voltage Stability Index, weak area cluster.

I INTRODUCTION

Continuing interconnections of bulk power systems brought about by economic and environmental pressures, has led to an increasingly complex system which must be operated closer to the limits of stability [Chiang, H-D, 1990]. This situation becomes worst when contingencies occur in the stressed network. Contingencies caused by line, generator and transformer outages are identified as the most common contingencies that could violate the voltage stability condition of the entire system. Past researches have shown that contingency analysis can be time consuming particularly for a bulk power system. For instance, if one minute is spent to analyse a single line outage, then the IEEE 30-bus system would require 41 minutes to simulate all the line outages. The computation burden can be alleviated by conducting contingency ranking that is normally carried out based on the severity of the line outages. This may reduce the credible contingency set. This process is repeated for different cases in order to accurately rank the contingencies.

Many papers have discussed different techniques to simulate and rank the contingencies for example automatic contingency selection based on a pattern analysis as reported by Rodrigues [Rodrigues, 1999]. This technique is capable to identify the potential harmful contingencies. Voltage based contingency selection techniques reported in reference [Ekwue, 1998] is able to identify the critical line outages. The change in load margin between nominal and contingency based on
Voltage collapse can also be identified via sensitivities obtained from the single nose of a PV curve as reported by Greene [Greene, 1999]. Fast methods for contingency ranking techniques using the Jacobian matrix manipulation in the load flow study [Gubina, 1996], [Mohamed A, 1998] are alternative methods towards minimizing computation burden and the number of contingencies to be simulated. This paper presents a new contingency ranking technique using a line-based voltage stability index. The study involves voltage stability analysis and line outages simulation which subsequently derived the correlation between critical line outages and sensitive or weak lines. 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 the results from this study could also identify the weak cluster in a power system network.

II INDEX FORMULATION

Voltage Stability Index abbreviated by L\textsubscript{ij} referred to a line is formulated in this study as the measuring unit in predicting the voltage stability condition in the system. The mathematical formulation is very simple that could speed up the computation. The L\textsubscript{ij} is derived from the voltage quadratic equation at the receiving bus on a two-bus system [I. Musirin, 2002]. The general two-bus representation is illustrated in Figure 1.

\[
V_2 = \frac{R}{X} \sin \delta + \cos \delta \frac{V_1}{V_2} + \left( \frac{X + \frac{R^2}{X} Q_j}{V_2} \right) \geq 0
\]

\[
V_2^2 \left( \frac{R}{X} \sin \delta + \cos \delta \right)^2 V_1 V_2 + \left( X + \frac{R^2}{X} Q_j \right) \leq 1
\]

\[
L_{ij} = \frac{4Z^2 Q_j X}{V_i^2 \left( R \sin \delta + X \cos \delta \right)^2}
\]

Where, 
\( Z \) = line impedance \\
\( X \) = line reactance \\
\( Q_j \) = reactive power at the receiving end \\
\( V_i \) = sending end voltage

Any line in a system that exhibits L\textsubscript{ij} closed to unity indicates that the line is approaching its stability limit and hence may lead to system violation. L\textsubscript{ij} should always be less than unity in order to maintain a stable system.

III VOLTAGE STABILITY ANALYSIS

Voltage Stability Analysis is performed to predict the point of voltage collapse using the proposed L\textsubscript{ij}. It is performed on IEEE 30-bus system. Initially load flow program was developed.
to obtain the power flow solution. The results are used to calculate the $L_{ij}$ for each line in the system. The load flow analysis is performed from base case to convergence. All load buses in the system are consecutively tested in order to determine the overall system performance accurately. Results from this experiment indicate the point of voltage stability, weak bus and critical lines in the system. The critical line refers to a particular bus is determined by the $L_{ij}$ value close to 1.00 while the weak bus is determined by the maximum permissible load for the individual bus in the system. Load ranking is done by sorting the maximum permissible load in ascending order. The lowest value of maximum permissible load characterizes the highest rank of bus which is the weakest one in the system. The bus which ranked lowest is the most secure bus in the system.

**IV LINE OUTAGE CONTINGENCY ANALYSIS**

In order to observe the impact of line outage in the system, contingency analysis is performed on the system. Contingency analysis is conducted by removing the lines in the system in sequence for every predetermined case. The predetermined cases are as follows; (i): base case, (ii): $Q_3 = 1.432$ p.u.,(iii):$Q_{14} = 0.4115$ p.u., (iv):$Q_{15} = 0.7485$ p.u. and (v):$Q_{30} = 0.155$ p.u., the predetermined cases set at half of the maximum permissible load obtained from the VSA. The procedure for contingency analysis is almost similar to the one in voltage stability analysis. The only difference is that, load flow computation is done with a line removed at a time and there is no need to increase the reactive power load in the system. The line outage contingency is simulated by removing each line at a time. $L_{ij}$ was computed for each line in the system for every line outage. The highest $L_{ij}$ value from every line outage was extracted and sorted in descending order. The line outage with highest rank is identified as the most critical outage and hence a list of critical contingencies can be identified.

**V RESULTS AND DISCUSSION**

**A. VOLTAGE STABILITY ANALYSIS**

Result for the voltage stability analysis that aimed to determine the voltage stability condition, weak bus and load ranking in the system. Fig.2 illustrates the response for critical line on each bus against the reactive load variation. These lines are the dominating lines that exhibited the highest $L_{ij}$ value for every tested bus. The line that exhibits the higher rate of change of $L_{ij}$ is considered as the critical line refer to a bus while the value closed to 1.00 is assigned as the maximum permissible load. The critical lines extracted from every load bus are plotted together on the same graph in order to identify weak bus in the system. Weak bus is determined by looking at the maximum permissible load rather than the $L_{ij}$ values since beyond this limit system will be already unstable.

**Table 1. Bus ranking based on maximum loadability using $L_{ij}$**

<table>
<thead>
<tr>
<th>Rank</th>
<th>Bus</th>
<th>Load (p.u)</th>
<th>Voltage (p.u)</th>
<th>Line No</th>
<th>$L_{ij}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30</td>
<td>0.311</td>
<td>0.6597</td>
<td>38</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>39</td>
<td>0.5748</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17</td>
<td>0.8264</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>0.9998</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>0.823</td>
<td>0.7784</td>
<td>18</td>
<td>0.9998</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>0.7462</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>22</td>
<td>0.4663</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>0.4147</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>1.497</td>
<td>0.6747</td>
<td>2</td>
<td>0.5239</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>0.9997</td>
</tr>
</tbody>
</table>

The result for bus ranking based on maximum loadability is tabulated in table 1. It is obvious that the line index increases as the reactive power loading is increased. Line 38 is the most critical line corresponds to any load change at bus 30. Bus 30 has the
smallest maximum permissible load of 0.311 p.u. and it is ranked as the highest. On other hand, line 4 is the most critical line which corresponds to load change at bus 3. Since bus 3 has a maximum permissible load of 2.864 p.u., it is the most secure bus in the system. From this result, a proper planning can be done according to the bus capacity in avoiding voltage collapse in the system. Fig.3 illustrates the voltage profile for critical line on each bus against the reactive load variation.

**Figure 2.** $L_{ij}$ Vs Reactive load variation ($Q$)

are with highest index. When $Q_{15}= 0.7485$ p.u. it is observed that lines 13, 16, 18 and 34 are with highest index. When $Q_{30} = 0.155$ p.u. it is observed that lines 13, 16 and 34 are with highest index. This indicates that as the loading increased, the number of line outages which could cause voltage collapse also increases and hence the risk for the system to experience voltage instability condition becomes higher. Results showed that ranking is consistent for all cases are accurately done. For instance, lines 13, 16 and 34 are ranked the highest for all cases, which implies that these lines are the most critical lines. These lines become very sensitive because the removal of lines 13 and 16 could cause the generators floating at bus 11 and 13 respectively and may lead the system into total voltage collapse.

**C. CORRELATION BETWEEN SENSITIVE LINES AND CRITICAL LINES OUTAGES**

The correlation between the critical line outage obtained from the contingency ranking and weak lines from the voltage stability analysis was observed by comparing both results. VSA was conducted on the system by evaluating $L_{ij}$ for each line. The analysis was conducted at the operating condition $Q_3 = 1.432$ p.u. The values of $L_{ij}$ obtained from the voltage stability analysis were sorted in descending order and the top twenty lines with high $L_{ij}$ were tabulated in Table 3. These lines were recognized as the sensitive lines in the system. In order to identify the weak cluster, correlation between sensitive lines and critical line outages are done.

Similar loading conditions were retabulated in table 3. From table 3, lines 1, 2, 3, 4, 5, 6, 7, 13, 16, 18, 33, 34, 37 and 38 belonged to both categories. This implies that the lines which are sensitive in terms of their voltage stability condition are also the critical lines i.e., if line outage occurs to any of these lines may lead the system into total voltage collapse.
D. WEAK CLUSTER IDENTIFICATION

The results obtained from the contingency ranking were further used to identify weak clusters in the system. Illustrating the results obtained from the contingency ranking of the test system shows some of the weak cluster in the system. The results from Table 3 are illustrated in Figure 4 and weak clusters are identified. The lines which caused critical contingencies are highlighted and a continuous path is observed from bus 1 to bus 6. It is identified as the major weak cluster based on critical line outages. Removal of any one of these lines along this path would violate the system stability and could possibly cause cascaded blackout in the system. A radial distribution network is also appeared along this path. Four other weak clusters are also identified, they are line 13 which is connecting a generator (buses 9 and 11), lines 16 and 18 which are two continuous lines connecting buses 12, 13 and 15. The lines 33 and 34 which are also two continuous lines connecting buses 24, 25 and 26 and the lines 37 and 38 which are also two continuous lines connecting buses 27, 29 and 30. Therefore, the removal of any lines in the weak clusters must be avoided in maintaining a secure power delivery.

The results of comparative studies between the manual contingency ranking and automatic contingency can be observed in table 4. It is obvious that the automatic contingency analysis and ranking technique is much faster than the conventional method which in turn minimize the human error during the process.
VI CONCLUSION

A rigorous investigation was carried out to see the effectiveness of reactive load variation on the line stability index. The VSI determines the maximum load that is possible to be connected to a bus in order to maintain stability before the system reaches its bifurcation point. This point is determined as the maximum loadability of a particular bus which beyond this limit system violation will be experienced. From this information, proper monitoring of a weak node can be conducted in maintaining a secure electric utility so that the load connected to the respective bus will not exceed the maximum allowable load to maintain a stable system.

This technique has successfully reduced the computation time for contingency analysis and ranking, which avoids the misranking due to long computation time and human factor constraint.

REFERENCES


BIographies

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