VOLTAGE STABILITY EVALUATION USING MODAL ANALYSIS

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ABSTRACT
This paper analyses the voltage stability analysis of large power systems using a modal analysis technique. This method makes use of the power system Jacobian matrix to determine the eigenvalues necessary for the evaluation of the voltage stability of the power system. It identifies if the eigenvalues are positive or negative which is an indicator of the system stability. For a steady state power system, a positive eigenvalue shows that the system is stable while a negative eigenvalue indicates that the system is unstable. The analysis is performed for IEEE 14 Bus system. Then, the most critical mode is identified for each system. After that, the weakest bus, which contributes the most to the critical mode, are identified using the participation factor.

Keywords: Voltage Stability, Modal Analysis, Reduced Jacobian Matrix, Eigen value, Participation factor.

1. INTRODUCTION
The increasing number of power system blackouts in many countries in recent years; is a major source of concern. Power engineers are very interested in preventing blackouts and ensuring that a constant and reliable electricity supply is available to all customers. Incipient voltage instability, which may result from continues load growth or system contingencies, is essentially a local phenomenon. However, sequences of events accompanying voltage instability may have disastrous effects, including a resultant low-voltage profile in a significant area of the power network, known as the voltage collapse phenomenon. Severe instances of voltage collapse, including the August 2003 blackout in North - Eastern U.S.A and Canada, have highlighted the importance of constantly maintaining an acceptable level of voltage stability. The design and analysis of accurate methods to evaluate the voltage stability of a power system and predict incipient voltage instability, are therefore of special interest in the field of power system protection and planning.

The voltage stability of a power system refers to its ability to properly maintain steady, acceptable voltage levels at all buses in the network at all times, even after being subjected to a disturbance or contingency. A power system may enter a condition of voltage instability when the system is subjected to a steady increase in load demand or a change in operating conditions, or a disturbance (loss of generation in an area, loss of major transformer or major transmission line).

This causes an increased demand in reactive power. Voltage instability is characterized by gradually decreasing voltage levels at one or more nodes in the power system. Both static and dynamic approaches are used to analyze the problem of voltage stability. Dynamic analysis provides the most accurate indication of the time responses of the system [1]. Dynamic analysis is therefore extremely useful for fast voltage collapse situations, following large disturbances such as loss of generation and system faults, when specific information concerning the complex sequence of events leading to instability, is required. Dynamic simulations however, fail to provide information such as the sensitivity or degree of stability. More importantly, dynamic simulations are extremely time consuming in terms of CPU and engineering resources required for the computation and analysis of the several differential and algebraic equations needed for quantification of the phenomenon.

In most cases, the system dynamics affecting voltage stability are usually quite slow and much of the problem can be effectively analysed using the static approaches that examine the viability of a specific operating point of the power system. Static analysis methods, in addition to providing information such as sensitivity or degree of stability, involve the computation of only algebraic equations and are much more efficient and faster than dynamic approaches. The static analysis approach is more attractive than the dynamic method, and well suited to voltage stability analysis of power systems over a wide range of system conditions [1-4].

Many static approaches for voltage stability analysis are presented in the literature, most utilizing a variation of the same common principle. Some popular static methods are summarized and contrasted in this document. The modal analysis of the load flow Jacobian presented by Gao, Morisson and Kundur in 1992, is of particular interest. This method, in addition to providing an accurate estimate of the system proximity to instability using the system eigenvalues, identifies the
elements of the power system contributing the most towards incipient voltage instability (critical load buses, branches and generators). A prototype package for predicting incipient voltage stability is developed incorporating modal.

2. MODAL ANALYSIS

A. The Reduced Matrix Jr

In the Newton Raphson power flow there is the linear system model to represent the injected power in buses as shown in equation (1).

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = \begin{bmatrix}
J_{P\theta} & J_{PV} \\
J_{Q\theta} & J_{QV}
\end{bmatrix} \begin{bmatrix}
\Delta \theta \\
\Delta V
\end{bmatrix}
\]

(1)

When the power is kept constant the above equation will become as shown as in the equation (2)

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = \begin{bmatrix}
J_{P\theta} & J_{PV} \\
J_{Q\theta} & J_{QV}
\end{bmatrix} \begin{bmatrix}
\Delta \theta \\
\Delta V
\end{bmatrix}
\]

(2)

Q-V modal analysis method is proposed in [5] follows the reduced Jacobian matrix Jr to analyze eigenvalue and eigenvector of the power system. The relation between Jr, ΔQ and ΔV can be seen in equation (3).

\[ΔQ = JrΔV \quad (3)\]

The reduced Jacobian Matrix Jr can be found by solving the equation (4) below

\[J_r = [J_{QV} - J_{Q\theta}J_{P\theta}]^{-1}J_{PV} \quad (4)\]

\[J = \xi \Lambda \eta \Leftrightarrow J_r = \xi \Lambda^{-1} \eta \quad (5)\]

B. The Global VSI value

Voltage Stability Indexes (VSI) is needed to give the system security of the power system. Modal analysis is one of the global VSI that can measure the voltage stability [5-6].

Incremental change in reactive power will affect the incremental voltage by substituting equation (3) with equation (5) we can get equation (6):

\[ΔV = \xi \Lambda^{-1} \eta ΔQ OR \quad ΔV = \sum_i \frac{\xi_i \lambda_i}{\eta_i} ΔQ \quad (6)\]

Where

- \(\lambda_i\) is ith eigen value
- \(\xi_i\) is the ith column right eigenvector
- \(\eta_i\) is the ith row left eigenvector

Therefore, the ith modal reactive power variation is

\[ΔQ_{mi} = k_i \xi_i \]

where \(k_i\) is a normalization factor such that

\[k_i^2 \sum_i \xi_i^2 = 1\]

The ith modal variation can be written

\[ΔV_{mi} = \frac{1}{\lambda_i} ΔQ_{mi} \quad (7)\]

The voltage stability can be defined by the mode of eigenvalue \(\lambda_i\). The minimum eigenvalue in a power system is the global VSI value. Larger value of \(\lambda_i\) will give smaller changes in the voltages when the small disturbance happen. When the system is weaker, the voltage becomes weaker. A system is stable when the eigenvalue of Jr is positive. The limit is reached when one of the eigenvalue reach zero. If one of the eigenvalue is negative the system is unstable.

C. Bus Participation

Left and right eigenvectors corresponding to the critical modes in the system can provide information concerning the mechanism of voltage instability. The bus participation of the bus can be defined as

\[P_{bi} = \xi_i \eta_i \quad (8)\]

Bus participation factors show the voltage stability of nodes in the power system. Bus participation factors show in a matrix form called participation matrix. The row of the matrix indicates the bus number and the matrix column indicate the system mode. The bigger value of the bus participation factor indicates the more affecting bus to the power system.

D. Voltage Stability Assessment

It is useful to establish and facilitate a systematic and complete method for voltage stability analysis and prediction of incipient voltage instability in the power network. As seen previously P-V/Q-V curves cannot be used alone in large practical networks since there is no way to precisely determine beforehand, for many different operating points and contingencies, exactly which nodes and areas are susceptible to instability. Methods such as minimum singular value do not readily provide information in to the main factors contributing to voltage instability.

The modal analysis technique however can be seen as extremely useful since it provides a relative proximity of the system to voltage instability as well as the key contributing factors to instability such as the weakest or critical buses and transmission branches. A
simple systematic technique for initial assessment of
modal analysis for voltage stability prediction can be
done as follow:
1. Initiate the normal operating condition using the load
flow analysis
2. Perform the modal analysis to get the global VSI
(Minimum eigenvalue)
3. Find the weakest bus in the power system
4. Repeat the step 2 and 3 to do the real time monitoring

3. SIMULATION AND EXPERIMENTAL
VERIFICATION

A) Circuit Diagram and Description

FIG 1: The IEEE 14-bus test system

B) Circuit Description
A IEEE 14-bus test system as shown in Fig. 3 is used for
voltage stability studies. The test system consists of five
generators (bus no. 1,2,3,6 and 8) , eleven PQ bus or
load bus(bus no. 4,5,7,9,10,11,12,13 and 14) and 20
transmission lines. The Modal analysis method has been
successfully applied to the IEEE 14 bus power system.
The eigen value analysis are done for selected buses in
order to identify the weakest bus. A power flow program
based on Matlab is developed to:
1. Calculate the load flow solution.
2. Analyze the voltage stability based on modal analysis.

The modal analysis method is applied and the voltage
profile of the buses is presented from the load flow
simulation. Then, the minimum eigenvalue of the
reduced Jacobian matrix is calculated. After that, the
weakest load buses, which are subject to voltage
collapse, are identified by computing the participating
factors. The results are shown as follows.

FIG 2: Voltage profile of all buses
Figure 2 shows the voltage profile of all buses of the
IEEE 14 Bus system as obtained from the load flow. It
can be seen that all the bus voltages are within the
acceptable level (± 5%). Since there are 14 buses among
which there is one swing bus and 4 PV buses, then the
total number of eigenvalues of the reduced Jacobian
matrix JR is expected to be 9 as shown in table.

TABLE 1: IEEE 14 Bus system eigenvalues

<table>
<thead>
<tr>
<th>Bus</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eig</td>
<td>65.</td>
<td>39.</td>
<td>21.</td>
<td>18.</td>
<td>16.</td>
<td>11.</td>
<td>2.6</td>
<td>5.5</td>
<td>7.5</td>
</tr>
<tr>
<td>value</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Note that all the eigenvalues are positive which means
that the system voltage is stable. From Table 1, it can be
noticed that the minimum eigenvalue $\lambda = 2.6943$ is the
most critical mode. The participating factor for this
mode has been calculated and the result is shown in
Figure 3.
The result shows that, the buses 14, 10 and 9 have the highest participation factors for the critical mode. The largest participation factor value (0.327) at bus 14 indicates the highest contribution of this bus to the voltage collapse. Therefore it is identified that the weakest bus on the IEEE 14 bus power system is bus no.14.

4. CONCLUSION
In this paper, The Modal analysis technique is applied to investigate the stability of the power systems and that method computes the smallest eigenvalue and the associated eigenvectors of the reduced Jacobian matrix using the steady state system model. The magnitude of the smallest eigenvalue gives us a measure of how close the system is to the voltage collapse. Then, the participating factor can be used to identify the weakest node or bus in the system associated to the minimum eigenvalue. The obtained results agreed about the weakest buses that contribute to voltage instability or voltage collapse. The modal analysis feature was tested on IEEE-14 bus test system. The technique was demonstrated as an extremely useful method for steady state voltage stability analysis, providing relative measure of the system to the stability limit, and correctly predicting the critical buses and weak transmission branches in the power network.

REFERENCES