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Critical Nodes Identification Using Participation Factor

B.Rajasekhar
Department of Electrical and Electronics Engineering, Andhra University College of Engineering (A), Visakhapatnam, Andhra Pradesh 530003, India.

Dr.Ch.V.V.S. Bhaskara Reddy
Department of Electrical and Electronics Engineering, Andhra University College of Engineering (A), Visakhapatnam, Andhra Pradesh 530003, India.

Abstract

The objective of this work is to identify the critical nodes in the system for effective monitoring of the power system voltage stability. In this work, Participation Factors calculated from the eigen values and eigen vectors of the power flow jacobian is utilized to determine the critical nodes of the given power system. The results obtained from the studies have been compared with the results obtained using L-index and Q-V curves. In this work, an attempt to identify the cluster of nodes affected due to various contingencies is also considered. To show the effective ness of the proposed technique, studies have been carried on IEEE 5-bus and IEEE 14-bus systems.

Keywords: ***Eigen vectors, L-index, Participation Factors***

1. Introduction

Voltage stability problem is significant since it affects the power system security and reliability. Voltage stability [1] is related to the "ability of a power system to maintain acceptable voltages at all buses under normal conditions and after being subjected to a disturbance". Voltage instability is an aperiodic, dynamic phenomenon. As most of the loads are voltage dependent and during disturbances, voltages decrease at a load bus will cause a decrease in the power consumption.

A definition of power system stability as given in [1] is Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

For analysis purposes, voltage stability can be classified, in two ways: according to the time frame of their evolution (long-term or short-term voltage stability) or to the disturbance (large disturbance or small disturbance voltage stability).

Using Modal analysis [10] proposed by Gao, Morrison and Kundur in 1992, the reactive power margin and voltage instability contributing factors are calculated. Modal analysis depends on power flow Jacobian matrix. Real power is kept constant and reduced Jacobian matrix J_R of the system is calculated.

The matrix J_R represents the linearized relationship between the incremental changes in bus voltage (ΔV) and the bus reactive power injection (ΔQ). If the minimum Eigen value of J_R is greater than zero, the system is voltage stable. Using the left and right eigenvectors corresponding to critical mode, bus participation factors can be calculated. Branch participation factors are calculated from linearized reactive power loss. Buses and Branches with large participation factors are identified as critical buses. From the above methods we are using modal analysis and voltage stability index.

2. Critical node Identification

Minimum singular value or minimum eigenvalue helps to find the critical operating point. Modal analysis in which system is represented by using eigenvectors is also used. At the voltage collapse point, solution of power flow equations experiences convergence problem. So to avoid this convergence

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problem, voltage stability indices are proposed based on power flow equations. These indices gives information such as critical buses

2.1 Participation factor

The power-flow (load-flow) analysis involves the calculation of power flows and voltages of a transmission network for specified terminal or bus conditions. The system is assumed to be balanced. Associated with each bus are four quantities: active power P, reactive power, voltage magnitude, and voltage angle. The relationships between network bus voltages and currents can be represented by node equations [6].

The Newton-Raphson method is an iterative technique for solving nonlinear equations. Using this method, the model can be linearized around a given point the following way:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (2.1)$$

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = [J]\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (2.2)$$

Where J is called the Jacobian matrix, ΔP is the incremental change in bus real power, ΔQ is the incremental change in bus reactive power injection, $\Delta\theta$ is the bus voltage angle and ΔV is the incremental change in bus voltage magnitude.

2.1.1 Procedure for Participation Factor

The modal analysis mainly depends on the power- flow Jacobian matrix. The stepwise procedure for the modal analysis method used in this study is given below.

Step 1): Obtain the Load flow for the base case of the system and get the Jacobian matrix (J).

Step 2): Compute the reduced Jacobian matrix (J)

Step 3): Compute the Eigen values of $J_R\,(A)$

Step 4): Investigate Eigen values for voltage stability

a) if $\lambda_i = 0$,the system will collapse

b) if $\lambda_i > 0$,the system is voltage stable, proceed to step 5

c) if $\lambda_i < 0$, the system is voltage unstable

Step 5): Find minimum Eigen value of $J_R\,(\lambda_{min})$

Step 6): Calculate the right and left Eigen vectors of $J_R\,(\alpha,\beta)$

Step 7): Compute the Participation factors P_{ki} for (λ_{min}) is $\alpha_{ki} * \beta_{ik}$

Step 8): The highest P_{ki} will indicate the most participated k^{th} bus to i^{th} mode in the system

Step 9) Generate the Q-V curve to the participated k^{th} bus.

The Newton Raphson Power Flow equations can be written in the form:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_1 & J_2\\ J_3 & J_4\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (2.1)$$

By letting $\Delta P = 0$ in equation (2.3)

$$\Delta P = 0 = J_1\Delta\theta + J_2\Delta V \quad (2.3)$$

$$\Delta\theta = -J_1^{-1}J_2\Delta V \quad (2.4)$$

$$\Delta Q = J_3\Delta\theta + J_4\Delta V \quad (2.5)$$

Substituting 2.6 in 2.7

$$\Delta Q = \left[J_4 - J_3J_1^{-1}J_2\right]\Delta V \quad (2.6)$$

$$\Delta Q = \left[J_R\right]\Delta V \quad (2.7)$$

Where

$$J_R = \left[J_4 - J_3J_1^{(-1)}J_2\right] \quad (2.8)$$

J_R is the reduced Jacobian matrix of the system. Equation 3.9 can be written as

$$\Delta V = J_R^{-1}\Delta Q \quad (2.9)$$

The matrix J_R represents the linearized relationship between the incremental changes in bus voltage ΔV and bus reactive power injection ΔQ for constant active power. The Eigen values and Eigen vectors of the reduced order Jacobian matrix J_R are used for the voltage stability characteristics analysis. Voltage instability can be detected by identifying modes of the Eigen values of matrix J_R. The magnitude of the Eigen values provides a relative measure of proximity to instability. The Eigenvectors on the other hand present information related to the mechanism of loss of voltage stability.

Proceeding as per [12] the i^{th} modal voltage variation is:

$$\Delta V_{min} = \frac{1}{\lambda_i}\Delta Q_{min} \quad (2.10)$$

The implications of (3.12) can be stated as follows:

1. If $\lambda_i = 0$ the i^{th} modal voltage will collapse because any change in that modal reactive power will cause infinite modal voltage variation.
2. If $\lambda_i > 0$ the i^{th} modal voltage and i^{th} reactive power variation are along the same direction, Indicating that the system is voltage stable.
3. If $\lambda_i < 0$ the i^{th} modal voltage and the i^{th} reactive power variation are along the opposite directions, indicating that the system is voltage unstable.

The system is considered voltage unstable if at least one of the Eigen values is negative. A zero Eigen value of J_R means that the system is on the verge of voltage instability. Furthermore, small Eigen values of J_R determine the proximity of the system to being voltage unstable.

2.2 Procedure For L-indeX

Using Kirchoff's Law, n-bus power system can be expressed as

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = H\begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix}\begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (2.11)$$

Where,

V_L, I_L are the voltage and current vectors at the load buses

V_G, I_G are the voltage and current vectors at the generator buses

Z_{LL} F_{LG} K_{GL} Y_{GG} are the sub-matrices of the hybrid matrix H.

The H matrix [14] can be evaluated using a partial inversion of the Y bus matrix, where the voltages at the load buses are exchanged against their currents. For any consumer node j, $j \in \alpha_L$ an equation for V_i can be derived from the matrix

$$V_j = \sum_{i\in\alpha_L} Z_{ji}.I_i + \sum_{i\in\alpha_G} F_{ji}.V_i \quad (2.12)$$

Which can be converted to

$$V_j^2 + V_{0j}V_j^* = \frac{S_j^{+*}}{Y_{jj}^{+}} \quad (3.28)$$

with the substitutions for the equivalent voltage V_{0j},the transformed admittance Y_{jj}^{+} and the transformed power S_j^{+}. Assuming that these effects can be estimated and controlled a local indicator Li can be worked out for each node j analogous to the line model

$$L_j = \left|1 + \frac{V_{0j}}{V_j}\right| = \left|\frac{S_j^{+}}{V_{jj}^{+*}.V_j^2}\right| = ... \quad (2.13)$$

For stable situations the condition $L_j \leq 1$ must not be violated for any of the nodes j. Hence a global indicator L describing the stability of the complete subsystem is given by

$$L = \underset{j\in\alpha_L}{MAX}\left(L_j\right) \quad (2.14)$$

One way of determining L is

$$L = \underset{j\in\alpha_L}{MAX}\left|1 - \frac{\sum_{i\in\alpha_G} F_{ji}.V_i}{V_j}\right| \quad (2.15)$$

Whereby α_L is set of consumer nodes and α_G is the set of generator nodes

Thus the important outcome of the presented theory is for stability to be guaranteed

$$L < 1 \quad (2.16)$$

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2.3 Interpretation:

The indicator L is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. The local indicators L_j permit the determination of those nodes from which a collapse may originate.

It can be shown that the derived theory is exact when two conditions are fulfilled i.e. that the stability limit is reached for L=l. The first requires that all generator voltages remain unchanged, amplitude- and phase wise.

The second calls for nodal currents which respond directly proportional to the current Ii and indirectly proportional to the voltage V_j at the node J under consideration. In general these two conditions are satisfied in an approximate manner only.

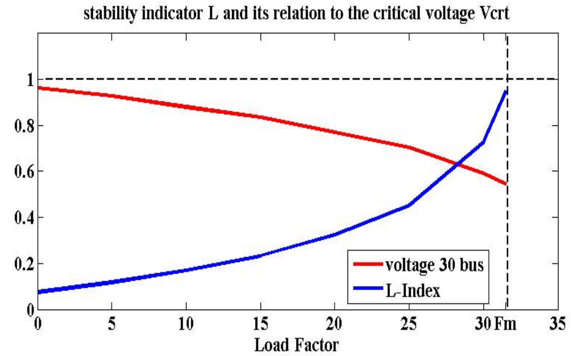

Fig.3.1: Stability indicator L and its relation to the critical voltage Vcrt

In this figure the indicator L for the 30-node AEP test system as well as the voltage at the critical node as a function of a load factor are plotted. This load factor is a multiplier by which the powers Sj of all consumer nodes and the active power Pi at the generator nodes are increased keeping the voltages Vi of the generator nodes constant. It is seen that the indicator L exceeds the theoretical value of 1.0 for the limiting load factor Fmax=32.5 MVAR. The effect of this error with respect to F is very small since the rate of change dL/dF is quite high. This numerical result proves quite well that the various assumptions are valid and justified. The accuracy of the load level where the system becomes unstable is very good, in particular when the level at which the prediction is made is very high.

3. Case study for IEEE 5-bus system

The IEEE 5-bus standard system is considered for the analysis and it consists two generators

L-index values

Table 3.1

Load bus numbers	L-index values	Weak bus ranking
2	0.0453	
3	0.0711	3
4	0.0725	2
5	0.0806	1

By considering constant power load model, the L-Index values are calculated for all load buses in table 3.1. from this table the max value of L is taken as the first weak bus and next values are taken as second and third weak buses. From the table 5,4and 3 are the first three weak buses

Participation factor values

Table 3.2

Load bus numbers	Participation factor values	Weak bus ranking
2	0.1810	
3	0.2981	3
4	0.3113	2
5	0.3199	1

By considering constant power load model, the participation factor values are calculated for all load buses in table 3.2. From this table the max value is taken as the first weak bus and next values are taken as second and third weak buses. From the table 5,4 and 3 are the first three weak buses.

Comparison of Participation factor and L-index

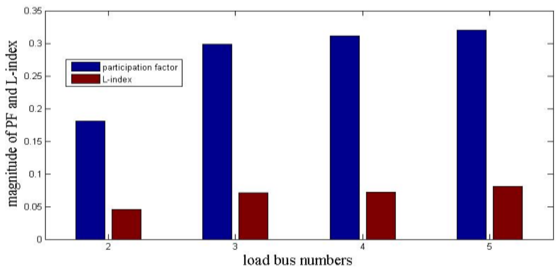

Figure 3.1 plot for participation factor and L-index Vs load buses

From the above figure it is clear that 5th bus is the weakest in all load buses, by comparing two methods the result is 5,4 and 3 are first three weak buses

4. Case study for IEEE 14-bus standard system

The IEEE 14-bus standard system is considered for the analysis and it consists two generators and three synchronous condensers

4.1 L-index values

Table 4.1

load bus numbers	L-index	Weak bus ranking
6	0.0196	
7	0.0236	
8	0.0226	
9	0.0382	3
10	0.0387	2
11	0.0229	
12	0.0158	
13	0.0223	
14	0.0491	1

By considering constant power load model, the L-Index values are calculated for all load buses in table 4.1. from this table the max value of L is taken as the first weak bus and next values are taken as second and third weak buses. From the table 14,10 and 9 are the first three weak buses

4.2 Bus Participation factors

Table 4.2

Load bus numbers	Participation factors	Weak bus ranking
6	0.0359	
7	0.149	
8	0.0523	
9	0.2518	3
10	0.2751	2
11	0.1871	
12	0.0774	
13	0.1009	
14	0.3164	1

By considering constant power load model, the participation factor values are calculated for all load buses in table 2.2. From this table the max value is taken as the first weak bus and next values are taken as second and third weak buses. From the table 14,10 and 9 are the first three weak buses.

4.3 Comparison of Participation factor and L-index

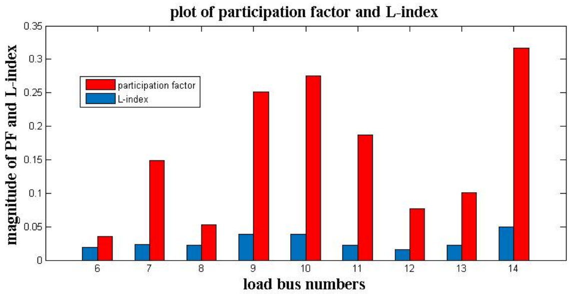

Figure 4.1: Participation factor and L-index Vs load bus numbers

From the above figure it is clear that 14th bus is the weakest in all load buses, by comparing two methods the result is 14,10 and 9 are first three weak buses

5. Conclusion

In this work critical nodes are identified for Case studies IEEE 5-bus system and IEEE 14-bus system for base case and for line outage.

Modal analysis is used and the maximum loadability is identified at the smallest minimum Eigen value of the reducued system Jacobian matrix J_R. This method gives bus participation factors that are used to identify the critical nodes. These critical nodes are compared with the L-index**.**

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