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Prediction of Voltage Collapse in Power System using Different Indices

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Abstract: ***After some damaging blackouts, voltage stability and collapse have become more concerned problems. This paper analyzes voltage stability indices, named L index and Modal Analysis, which determines the weakest node of the system.From these indicators, it is allowed to predict the voltage instability or the proximity of the system to a voltage collapse. The advantage of the method lies in simple and fast numerical calculations. Through these indicators of voltage stability, it is easy to find the most vulnerable area in a power system. Performance of these indices are also compared in this paper. The computation of indices is done in MATLAB environment and evaluated on IEEE 6 bus, IEEE 14 bus and IEEE 30 bus system, considering various operating conditions and line outages.***

Keywords: Voltage stability, Contingency analysis, Line outage, Critical bus, Voltage stability index.

1. Introduction

In the present competitive era, power system has become heavily loaded and more complex due to the increasing load demand. After the blackouts of Europe in 2003 [1], August 14th in New York, September 23rd in Sweden and Denmark, August 14th in New York, and September 30th inItaly [2], the basic reason of which was voltage collapse, worldwide power systems have becoming more concerned with voltage stability and voltage collapse problems. *Voltage Stability* is defined as the power system's ability to maintain acceptable voltage at every bus in the power system under normal operating conditions, after increasing load demand, change in system conditions or being subjected to any disturbance. If any of the above condition causes uncontrollable drop of voltage in a power system then the system can enter a voltage instability state.

Inability of a power system to meet reactive power demand is the main factor which causes instability. A system is *voltage stable* if V-Q sensitivity is positive for every bus in the system i.e. a system is said to be voltage stable if at a given operating condition for every bus in the system, the bus voltage magnitude increases as the reactive power injection at the same bus is increased; A system is *voltage unstable* if V-Q sensitivity is negative for atleast one bus in the system i.e. a system is voltage unstable if, for atleast one bus in the system, the bus voltage magnitude decreases as the reactive power injection at the same bus is increased. The sequence of voltage instability events that leads to a sudden voltage drop or a blackout in a particular part of the system, is called *voltage collapse*.

There are various indices that are used to evaluate proximity to voltage stability problems. These indices can indicate how close a system is to the voltage collapse. Some of the indices are based on bus admittance matrix, node voltage and active and reactive power flow through the line such as L index, LCPI, FVSI. Some indices are based on power flow jacobian matrix such as minimum eigenvalue [11]. Some of these indices are evaluated and their performances are compared in this paper.

2. Indices Formulation for Voltage Stability Margin

Various voltage stability indices have been proposed in the literature for the assessment of voltage stability in the power system. In this section, two of them are briefly discussed. The information of these indices are obtained from respective references.

The L index

The L index is proposed in Kessel and Glavitsch to assess the voltage stability of a particular bus in a system. This index is based on load flow analysis. It is formulated by using the elements of bus admittance matrix. Its value lies between 0, which indicates no load condition and 1, indicating voltage collapse condition i.e. the bus having highest value of L index is considered as the most critical bus of the system. For stability, index value should lie within a unit circle.

The formulation of index is incorporated from [3] and is discussed below:
For an N bus power system

$$I_{bus} = Y_{bus} * V_{bus} \quad (1)$$

By separating generator buses and load buses, the above equation can be written as

$$\begin{bmatrix} I_g \\ I_l \end{bmatrix} = \begin{bmatrix} Y_a & Y_b \\ Y_c & Y_d \end{bmatrix} \begin{bmatrix} V_g \\ V_l \end{bmatrix} \quad (2)$$

where, V_g, I_g are voltage and current at generator buses;
V_l, I_l are voltage and current at load buses
After the rearrangement of eq. (2), we get

$$\begin{bmatrix} V_l \\ I_g \end{bmatrix} = \begin{bmatrix} P_a & P_b \\ P_c & P_d \end{bmatrix} \begin{bmatrix} I_l \\ V_g \end{bmatrix} \quad (3)$$

where, P_a, P_b, P_c and P_d are sub matrices obtained from partial inversion of Y_{bus}

$$P_b = -[Y_d]^{-1}[Y_c] \quad (4)$$

The L index at K^th node is given as

$$L_K = \left|1 - \sum_{i=1}^{N_G} F_{Ki} \frac{V_i}{V_K} \angle(\theta_{Ki} + \delta_i - \delta_K)\right| \quad (5)$$

where
V_K = voltage magnitude of K^th generator
V_i = voltage magnitude of i^th generator
θ_{Ki} = phase angle of F_{Ki}
δ_K = phase angle of voltage of K^th generator
δ_i = phase angle of voltage of i^th generator
N_G = number of generating units

The values of F_{Ki} are got from matrix P_b. For a given loading conditions, L index is calculated for every load bus in the system. The maximum value of all the L indices (L_{max}) describes the system proximity to the voltage collapse. The value of L_{max} must be less than the maximum allowable voltage of a bus.

Algorithm for voltage stability analysis using L index

Step 1: Run the load flow program for the base case.
Step 2: Evaluate L index value for every bus in the system.
Step 3: Gradually increase the load in steps of 10% until the load flow solution fails to give the results and find the L index for every load bus and for every loading in the system.
Step 4: From the value of L index, obtain the rank of each load bus in the system such that the bus having highest value of L index to be ranked first implying the weakest bus in the system.
Step 5: The bus having L index value more near to 1(or, the bus having highest rank) is considered as the most critical bus of the system.

Modal analysis

This method of voltage stability analysis is proposed by Gao, Morison and Kundur in 1992. Modal analysis is based on power flow jacobian matrix. Detail aspects of this method are incorporated from [4]-[6]. This method computes eigenvectors of smallest eigenvalue of the reduced jacobian matrix incurred from load flow solution.

The system is voltage stable if all the eigenvalues of reduced jacobian matrix are positive; the system is voltage unstable if one of the eigenvalues is negative; if any of the eigenvalue of reduced jacobian matrix is zero then system is at the verge of stability. In this method, of minimum positive eigenvalue is used to predict the voltage collapse condition of the power system. From the eigenvector associated with minimum eigenvalue, bus participation factor is calculated and then the participation factor is used to find the weakest bus in the system. The power voltage equation is given by

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\delta} & J_{PV}\\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\delta\\ \Delta V\end{bmatrix} \quad (6)$$

where,
ΔP = incremental change of bus real power
ΔQ = incremental change of bus reactive power
$\Delta\delta$ = incremental change of phase angle of bus voltage
ΔV = incremental change of bus voltage magnitude
To reduce eq. (6), let ΔP = 0, we get

$$\Delta Q = J_R \, \Delta V$$

where
$J_R = \left[J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV}\right]$ = reduced jacobian matrix (7)

Now, the participation factor of bus i to mode k is given by
$P_{ik} = \emptyset_{ik} * \beta_{ki}$ (8)

where,
$\emptyset$ = right eigenvector of matrix J_R
β= left eigenvector of matrix J_R

Thus, eq. (8) reveals that which bus participates more to the voltage collapse.

Algorithm for voltage stability analysis using modal analysis

Step 1: Obtain the load flow solution for base case of the system and set the jacobian matrix (J).
Step 2: Compute the reduced jacobian matrix (J_R).
Step 3: Compute the eigenvalue of reduced jacobian matrix (λ). (If λ = 0 → the system will collapse; if λ > 0 → the system is voltage stable; if λ < 0 → the system is voltage unstable).
If system is voltage stable (λ > 0) then find how close is the system to voltage instability:
Step 4: Find the minimum eigenvalue of J_R.
Step 5: Calculate the right and left eigenvectors of reduced jacobian matrix (∅ and β).
Step 6: For minimum eigenvalue of the bus, find the participation factors for the corresponding mode and bus (P_{ik})
Step 7: The highest P_{ik} will indicate the most participated i^th bus to k^th mode in the system i.e. bus with maximum participation factor is considered as the weakest bus of the system.

3. Test Results and Discussions

The above explained voltage stability indices are tested on three test systems viz. IEEE 6 bus, IEEE 14 bus and IEEE 30 bus system.The test results are shown in this section in the tabular form and in the form of graphs.

3.1. Increasing the system load in steps from base case to peak loading

In this case, the L index of every bus is calculated under base case. Now increase the system load in steps of 10% and determine the L index value of each load bus in each step load increment. The test results are shown in this section.

Table 1: Voltage stability indices for 6-bus system with peak system loading

Rank	Bus	L index	Bus	Modal analysis
1	3	0.6643	3	0.4374
2	5	0.4847	4	0.323
3	6	0.4809	6	0.1635
4	4	0.4761	5	0.076

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Table 2: Voltage stability indices for 14-bus system with peak system loading

Rank	Bus	L index	Bus	Modal analysis
1	14	0.8031	14	0.1478
2	13	0.7781	13	0.137
3	12	0.7647	12	0.1357
4	10	0.7117	11	0.1169
5	11	0.7015	10	0.1107
6	9	0.6563	4	0.1017
7	4	0.6389	9	0.0938
8	5	0.5097	5	0.0726
9	7	0.5097	7	0.0656
10	6	0.2089	6	0.0093
11	8	0.1884	8	0.0088

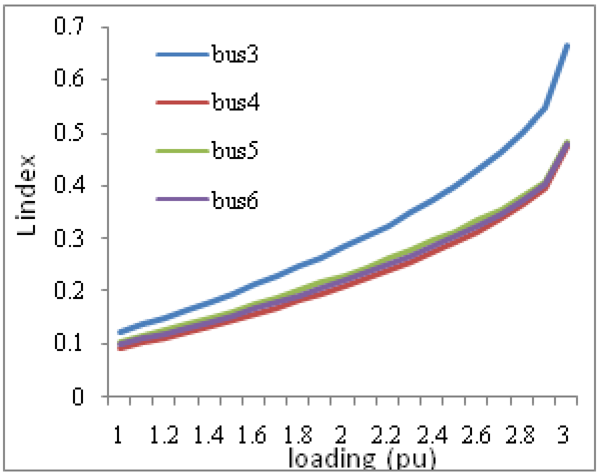

Figure 1: L index for 6-bus system

Table 1,2,3 show both the voltage stability indices with peak loading for 6-bus, 14-bus and 30-bus test systems. From this data, it is easy to find the most critical bus of the respective system. Table 1 shows that bus 3 has maximum value of L index means this is the most vulnerable bus of the system. Also bus 3 has maximum participation factor which also reveals that this bus participates more for voltage collapse which affects the whole system. Table 2 shows that bus 14 is the critical bus of the system since this is the bus which is having maximum value of L index as well as participation factor. Similarly, in table 3 bus 30 has maximum participation factor and highest L index value.

Table 3: Voltage stability indices for 30-bus system with peak system loading

Rank	*Bus*	*L index*	*Bus*	*Modal analysis*
1	30	1.1112	30	0.3175
2	29	0.8794	29	0.235
3	26	0.8099	26	0.1379
4	25	0.6534	27	0.1046
5	24	0.6113	25	0.0855
6	27	0.6111	24	0.0269
7	19	0.5785	23	0.0137
8	23	0.5601	22	0.0108
9	18	0.5593	21	0.01
10	20	0.547	19	0.0082
11	21	0.508	20	0.008
12	22	0.5076	18	0.0076
13	15	0.49	10	0.0063
14	14	0.474	17	0.006
15	17	0.4622	15	0.0057
16	16	0.436	16	0.004
17	10	0.4357	14	0.0037
18	12	0.3881	28	0.0025
19	7	0.3247	9	0.0021
20	9	0.2505	12	0.002
21	28	0.2201	4	0.000601
22	6	0.2041	6	0.000543
23	4	0.179	3	0.000496
24	3	0.1485	7	0.000194

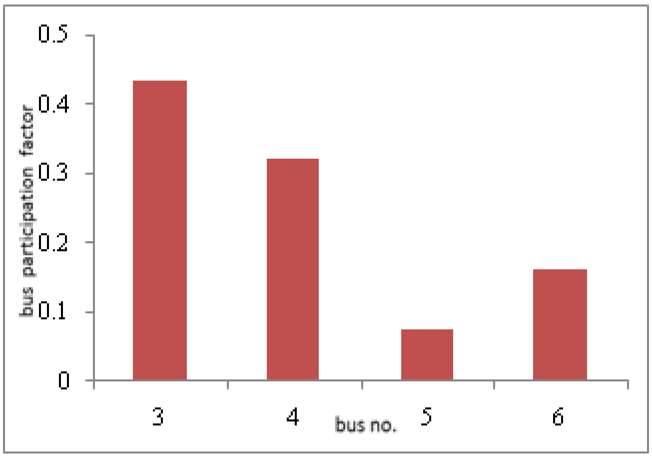

Figure 2: Bus participation factor for critical operating case for 6-bus system

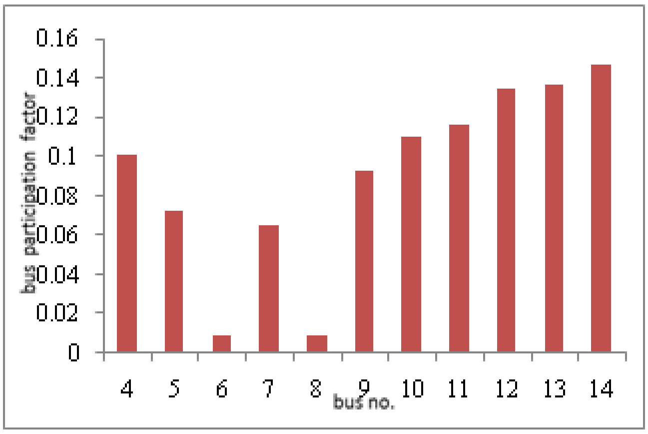

Figure 3: Bus participation factor for critical operating case for 14-bus system

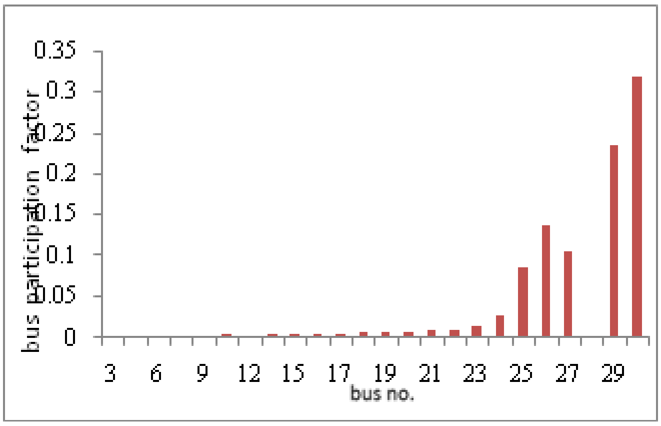

Figure 4: Bus participation factor for critical operating case for 30-bus system

3.2. Increasing the Reactive Load at Single Node

Voltage stability of a system is highly sensitive to the reactive power flow at any bus of the system. So, in this case, reactive power of a load bus is increased in steps keeping other buses at base case loading [7]. By this, we find the maximum permissible reactive power of each load bus i.e. how much of reactive load can each bus handleswhile maintaining the stability.

Table 4: Voltage stability indices for 6-bus system with heavy reactive load

Rank	Bus	L index	Bus	Modal analysis
Q = 0.79 p.u. at bus 3				
1	3	0.9552	3	0.7278
2	4	0.4683	4	0.2394
3	6	0.1738	6	0.0288
4	5	0.1460	5	0.0039
Q = 0.96 p.u. at bus 5				
1	5	0.9839	5	0.7944
2	6	0.2852	6	0.1610
3	3	0.1656	4	0.0284
4	4	0.1470	3	0.0162

Table 5: Voltage stability indices for 14-bus system with heavy reactive load

Rank	Bus	L index	Bus	Modal analysis
Q = 0.53 p.u. at bus 14				
1	14	1.1170	14	0.3743
2	13	0.6548	13	0.1179
3	12	0.6085	12	0.0953
Q = 0.61 p.u. at bus 13				
1	13	0.9733	13	0.2536
2	12	0.8494	12	0.1930
3	14	0.7075	14	0.1310
Q = 0.48 p.u. at bus 12				
1	12	1.0125	12	0.3572
2	13	0.7343	13	0.1703
3	14	0.5862	14	0.0964

Table 6: Voltage stability indices for 30-bus system with heavy reactive load

Rank	Bus	L index	Bus	Modal analysis
Q = 0.34 p.u. at bus 30				
1	30	0.9382	30	0.5653
2	29	0.5594	29	0.2402
3	27	0.3127	27	0.0796
Q = 0.37 p.u. at bus 29				
1	29	0.8361	29	0.4719
2	30	0.6676	30	0.2971
3	27	0.3320	27	0.0915
Q = 0.326 p.u. at bus 26				
1	26	0.8760	26	0.6967
2	30	0.3197	25	0.0986
3	25	0.3064	30	0.0551

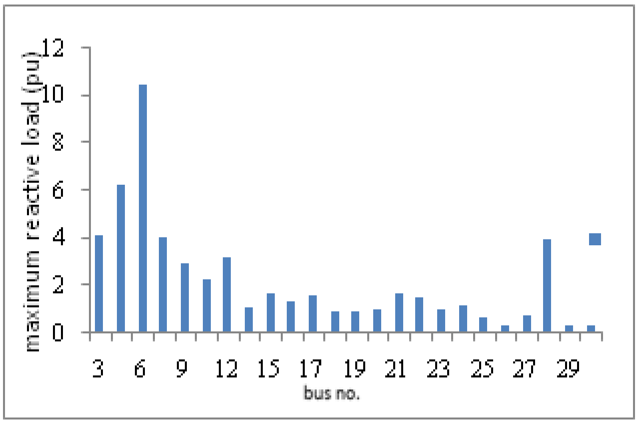

Figure 5: Maximum permissible reactive loading in p.u. for load buses of 30-bus system

3.3. Contingency Analysis

Contingency analysis is done by outage of one of the lines connecting different nodes. If contingency is there, the bus voltage stability can be affected. The results are shown in this section.

Table 7: Voltage stability indices for 6-bus system with contingency

Line out from-to	*Rank*	*Bus*	*L index*	*Bus*	*Modal analysis*
1-4	1	3	0.6505	3	0.4414
	2	4	0.5722	4	0.4088
	3	6	0.3376	6	0.1160
	4	5	0.2838	5	0.0338
4-6	1	3	0.6365	3	0.5119
	2	6	0.5377	4	0.4010
	3	5	0.5315	6	0.0619
	4	4	0.4568	5	0.0252
2-3	1	3	0.9607	3	0.5576
	2	4	0.6332	4	0.3251
	3	6	0.5012	6	0.0843
	4	5	0.4805	5	0.0329

Table 8: Voltage stability indices for 14-bus system with contingency

Line out from-to	*Rank*	*Bus*	*L index*	*Bus*	*Modal analysis*
6-7	1	14	0.8270	5	0.1442
	2	5&7	0.8202	14	0.1299
	3	9	0.8201	9	0.1283
4-12	1	12	0.8130	12	0.1967
	2	13	0.6905	13	0.1450
	3	14	0.6841	14	0.1401
4-13	1	13	0.8301	13	0.2213
	2	14	0.7084	14	0.1695
	3	12	0.6555	12	0.1539
9-10	1	10	0.8734	10	0.2994
	2	11	0.7244	11	0.2086
	3	12	0.6270	12	0.1222
9-14	1	14	1.2843	14	0.3978
	2	13	0.8993	13	0.1682
	3	12	0.8424	12	0.1412

Table 9: Voltage stability indices for 30-bus system with contingency

Line out from-to	*Rank*	*Bus*	*L index*	*Bus*	*Modal analysis*
1-3	1	30	0.9774	30	0.2954
	2	29	0.7790	29	0.2255

	3	26	0.7351	26	0.1454
8-28	1	30	1.1037	30	0.3115
	2	29	0.8796	29	0.2341
	3	26	0.7965	26	0.1375
27-30	1	30	0.9013	30	0.1546
	2	29	0.5690	26	0.0609
	3	26	0.3690	24	0.0545
10-17	1	30	1.0863	30	0.3094
	2	29	0.8617	29	0.2306
	3	26	0.7929	26	0.1389

4. Conclusion

This paper has compared the performance of voltage stability indices including L index and modal analysis based on minimum eigenvalue of reduced jacobian matrix. These indices were tested on three test bus systems. From the above results, it can be concluded that the used indices are promising tools for the identification of weakest bus in the system. From this information, one can easily get the exact position for the installation of FACTS devices.

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