

## Study on Impact of Load Changes on Voltage Stability Assessment

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### Abstract

Electric power system is one of the most complex man made systems. Voltage stability is the one of the instabilities among the various types of instabilities experienced by electric power systems. With the development of the technology, different types of loads with different load densities are increasing in the power system. As a result, it is necessary to assess the effectiveness of the various procedures used to monitor the power systems. In this paper a study is proposed to analyze the effect of different types of load variations on voltage stability monitoring indices. It is considered to carry out the studies on IEEE 14 and IEEE 30 bus test systems.

### Introduction

Power system is a huge network consists of hundreds of nodes and thousands of lines connected to them. Operation of power system is becoming difficult day by day due to increased complexity, competition, social and environmental factors, and Imbalance in load-generation growth. All these factors are causing the power system stability problems. Voltage stability problem is one of the major concerns in power system operation. Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all nodes in the system under normal condition and after being subject to a disturbance [1].

The study of voltage stability has been analyzed under different approaches that can be basically classified into dynamic and static analysis [2]. Static analysis is carried on the assumption that at each instant the system is in steady state. Dynamic analysis involves differential algebraic models which observe the interaction of generators, tap changers, etc.

Static approach involves computation of only algebraic equations and it is faster than dynamic approach. Static analysis is preferred over dynamic since it takes less computational time. The results from the conventional power flow are used in the static analysis. There are several methods used for the static analysis they are, The P-V curves and Q-V

curves are the most used method of predicting voltage security. The loading margin of system can be known from this method [3]. But this method is not efficient since lot of computation involved for complex networks. Modal analysis proposed by Gao et al. [4] that computes the eigenvalue and eigenvectors of the reduced Jacobian matrix. If one

of the eigen values is negative, the system is considered to be voltage unstable. Minimum singular value method proposed by Thomas and Lof [5] is used to calculate the voltage stability margin by observing how close is the Jacobian matrix to become singular. In this paper effect of load types and its variations on voltage stability assessment are analyzed using different indices. From this analysis, one can choose the effective indices to predict the proximity of voltage instability.

These indices provide information about proximity of voltage instability in a power system. Usually, their values changes between 0 and 1. In this paper studies have been carried out using IEEE 14 and IEEE 30 bus test systems.

### II. VOLTAGE STABILITY INDICES

Voltage stability indices define the status and condition of voltage stability in a power system. The distance between actual state and voltage collapse point can be easily identified by defining critical buses or critical lines of a system. Some of the indices are discussed in this section:

A) L- Index Kessel et.al [6] has derived voltage stability index based on power flow solution. Using this index proximity of the actual system from the collapse point can be known. The L index describes the stability of a system. Consider a network with 'n' node consists of consumer node (PQ node) and generator nodes (PV nodes).

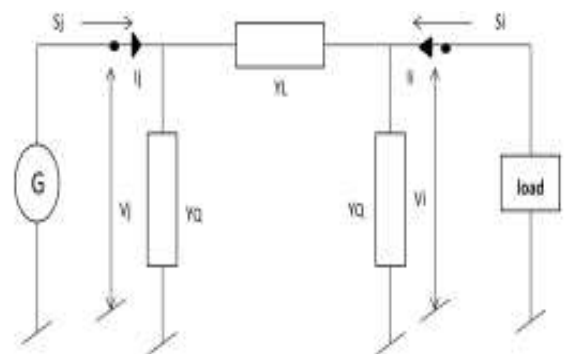


Figure 1: Line Model

The relation between voltages and currents can be represented using hybrid matrix given by

$$\begin{bmatrix} V^L \\ I^G \end{bmatrix} = [H] \cdot \begin{bmatrix} I^L \\ V^G \end{bmatrix} = \begin{bmatrix} Z^{LL} & F^{LG} \\ K^{GL} & Y^{GG} \end{bmatrix} \cdot \begin{bmatrix} I^L \\ V^G \end{bmatrix} \quad (1)$$

Where,

$V^L, I^L$  Vectors of voltages and currents at consumer nodes

$V^G, I^G$  Vectors of voltages and currents at generator nodes

$Z^{LL}, F^{LG}$

$K^{GL}, Y^{GG}$  Submatrices of the H-matrix

The L Index is given by

$$L = \max_{j \in \alpha_L} \left| 1 - \frac{\sum_{i \in \alpha_G} F_{ji} V_i}{V_j} \right| < 1 \quad (2)$$

Where,  $V_i$  : Voltage at generator bus

$V_j$  : Voltage at load bus.

Therefore for stability  $L < 1$  is a must condition. B ) Voltage Collapse Proximity Indicator(VCPi): Using maximum power transfer theory of a line chebbo et al.[7] derived a Z ratio model. Consider a two bus system Which consists of constant voltage source with internal impedance  $Z_s \angle \beta$  and a load impedance of  $Z_l \angle \phi$  .According to maximum power transfer theorem maximum power will be delivered from source to load when  $Z_s = Z_l$  i.e.,  $Z_s / Z_l = 1$

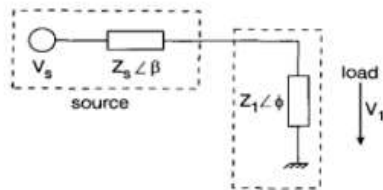


Figure 2 : Two Bus system

When this condition is generalized for a n bus system it can be used as a voltage collapse proximity indicator .Therefore the Thevenin's equivalent impedance between bus i and ground is

$$Z_{ii} \angle \beta_i \text{ and } Z_i \angle \phi_i$$

Where,

$Z_i \angle \phi_i$  is the load impedance

$Z_{ii} \angle \beta_i$  is the  $i^{th}$  diagonal element of  $[Z] = [Y]^{-1}$

Therefore a permissible power is supplied to a particular bus i

is possible when the ratio  $Z_{ii} / Z_i$  is less than or equal to 1.

Thus for stable and secure operation of system

$$Z_{ii} / Z_i \leq 1 \quad (3)$$

C) Fast Voltage Stability Index (FVSI): The stability index is derived by I.Musirin et.al [8] using power flow concept

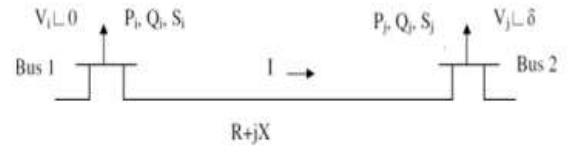


Figure 3: Two Bus power system model

Consider a two bus system with bus i as sending bus and bus j as receiving bus ,as shown in figure 3,the voltage stability index is derived from the quadratic equation of receiving bus voltage ,a stable condition is obtained when the discriminant of the equation greater than or equal to zero.

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \quad (4)$$

Where,

$Q_j$ : receiving end reactive power

$Z$  : Impedance of the line

$X$ : Reactance of the line

$V_i$ : Voltage at 'i' th bus

The value of FVSI should be less than or equal to 1, the value reaching 1 indicates the line is nearer to the instability and voltage collapse is going to occur. D) Line Stability Index (Lmn): Mogavvemi [9] derived a stability index based on power transmission concept taking  $\pi$  model of a network .Consider the figure shown with a sending bus 'i' and receiving bus 'j',write the receiving end voltage quadratic equation and to achieve stability the discriminant of the equation should be greater than or equal to zero.

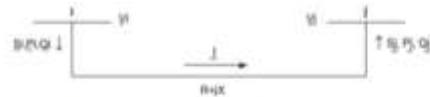


Figure 4: Typical one-line diagram of transmission line. The line stability index for the above model is defined as

$$\frac{4XQ_j}{(V_i \sin(\theta - \delta))^2} \leq 1 \quad (5)$$

$$Lmn = \frac{4XQ_j}{(V_i \sin(\theta - \delta))^2} \leq 1 \quad (6)$$

Where  $\theta$  is the line impedance angle and  $\delta$  is the angle difference between the supply voltage and the receiving end voltage. Until the line stability index Lmn is less than 1 the system is stable if the index reaches 1the system is going to collapse and on the verge of instability. E) Line Stability Factor (LQP) The line stability factor is derived by Mohammed et.al [10] from reactive power flow in a line .Consider the Figure 5

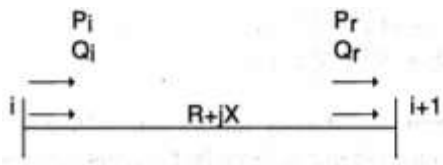


Figure 5: Power flow from node i to node i+ 1

consider  $Q_r$  is the reactive power flow from a reference node 'i' to 'i+1' and writing power balance equation and solve for quadratic equation we get,

$$LQP = 4 \left( \frac{X}{V_i^2} \right) \left( Q_r + P_i^2 \left( \frac{X}{V_i^2} \right) \right) \leq 1 \quad (7)$$

Where,  $X$  is the line reactance,  $Q_j$  is the reactive power flow at the receiving bus,  $V_i$  is the voltage on sending bus and  $P_i$  is the active power flow at the sending bus.

To achieve secure and stable system the stability factor should be less than or equal to 1. The weakest bus can also be found from the stability index.

### III. TEST RESULTS AND DISCUSSIONS

The IEEE 14-Bus and IEEE 30-Bus systems are selected to illustrate the stability indices behaviour for different loading patterns. Two kinds of testing criteria are adopted viz. (i) Case-i: Change of load at all the buses and (ii) Case-ii: Change of load at only one bus (critical). Also load various are considered in three patterns viz. (a) Change of load with constant power factor, (b) Change of load at constant rate, and (c) Random change of load.

#### A .IEEE -14 Bus Test Results:

Under normal condition when the node indices and line indices are calculated from the conventional power flow it indicated Bus 14, 10 and 9 had highest index among all other and the line 10, 9 and 14 are highest.

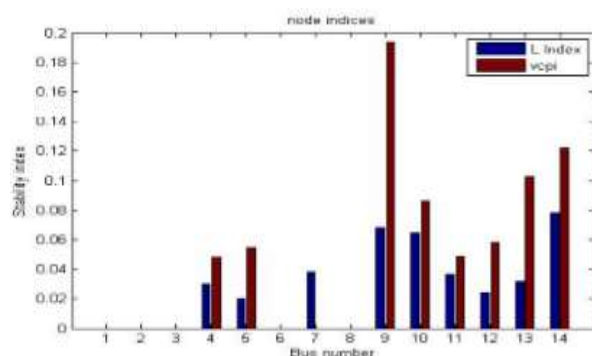


Figure 6: Node indices of IEEE 14 Bus system

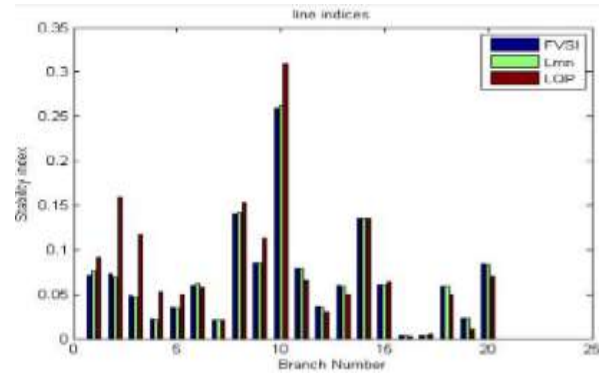


Figure 9: Load change Vs. Line indices for constant power factor

Table II. Line indices with load change at all buses constant power factor

Line	FVSL	Lmn	LQP	Status
10(5-6)	1.004	1.177	1.869	Most critical
2(1-5)	0.752	0.73	1.308	Critical
14(7-8)	0.514	0.514	0.514	

#### b) Change of Load at all buses at Constant Rate:

In this case the load at all buses is incremented in equal steps.

Table III shows critical buses and the corresponding voltages and the effect of changing load on the node indices. Both indices resemble approximately the same bus as a critical bus.

Figure 10 is the graphical representation of table III at different loads.

Table IV shows the line stability indices at various steps of loading at all buses. Here three indices are taken to know the impact of load change and lines 10, 2 and 3 are depicted as critical line. Figure 11 gives the pictorial representation of various indices.

Table III. Voltage and Node indices at all buses with constant increment

Bus	Voltage	L index	VCPI	Status
14	0.6964	0.5641	0.5421	critical
9	0.7241	0.4729	0.4315	
10	0.7386	0.4408	0.4158	

Table IV. Line indices at all buses with constant increment

Line	FVSI	Lmn	LQP	status
10(5-6)	0.953	1.068	1.598	Most critical
2(1-5)	0.913	0.93	1.736	Most critical
3(2-3)	0.646	1.015	1.338	Most critical

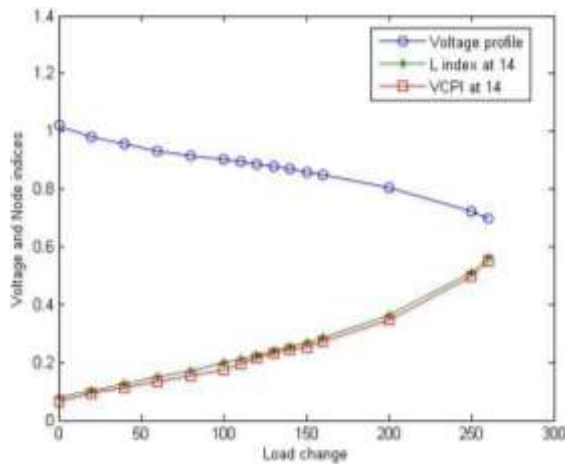


Figure 10: Load change Vs. Voltage and node indices with constant increment

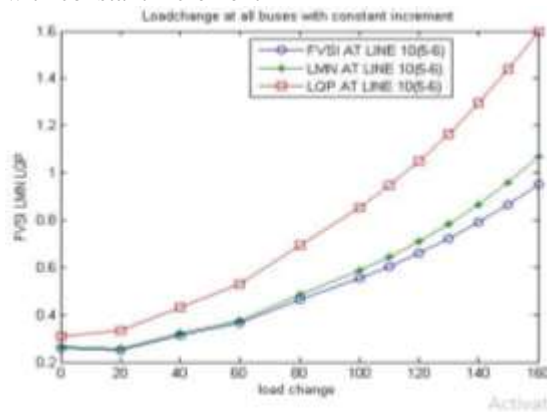


Figure 11: Load change Vs. Line indices at constant increment

c) Load change at all buses randomly : A practical power system consists of many loads and all the loads may not change in same fashion hence random loading taken as reference to show how it affects the voltage stability assessment. Table V shows the list of critical line when randomly loaded. Bus 10 is critical from a particular random loading. Figure 12 show the voltage profile and the variation of different node indices with the loading factor.

Table V. Voltage and node indices with random load

Bus	Voltage	L index	VCPI	Status
10	0.7539	0.4178	0.3954	Critical
9	0.7751	0.3935	0.3869	
14	0.7712	0.3759	0.3541	

Table VI. Line stability indices at random load

Line	FVSI	LMN	LQP	Status
10(5-6)	1.086	1.241	1.851	Most critical
12(6-12)	1.543	1.435	1.36	Most critical
13(6-13)	1.009	0.944	0.873	Most critical

Figure 12 : Voltage and Node indices at random load

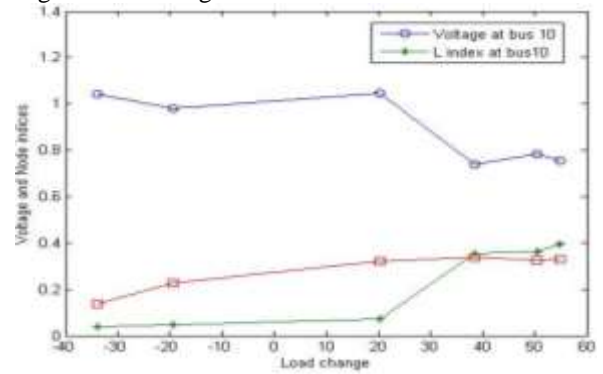
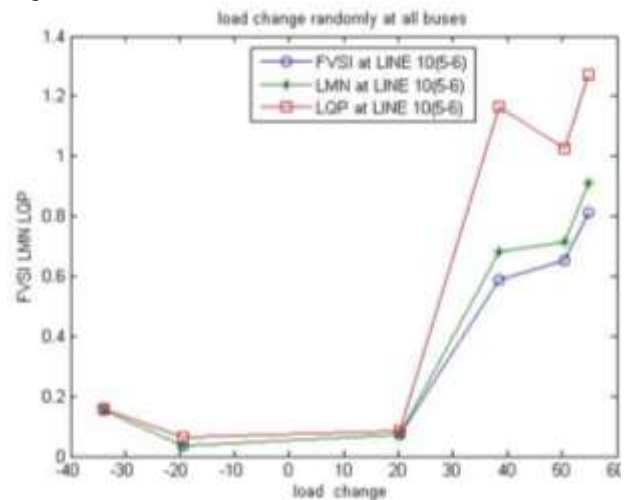


Figure 13: Line indices at random load



a) Load change at 14th bus with constant power factor:

In this case the load at particular node changed keeping the power factor constant. Among all the nodes the result is plotted for node 14. Table VII indicate node 14 as critical bus and the effect of loading on several node indices. The table also shown bus 9 and 10 becomes critical if the load increased further. Figure 14 shows the graphical representation of Table VII.

Table VII. Voltage and Node indices at 14th bus with constant power factor

Bus	Voltage	L index	VCPI	Status
14	0.628	0.7947	0.7542	Critical
9	0.9122	0.1887	0.1629	
10	0.9226	0.165	0.1245	



Figure14: Load change Vs. Node indices at 14th bus with constant pf

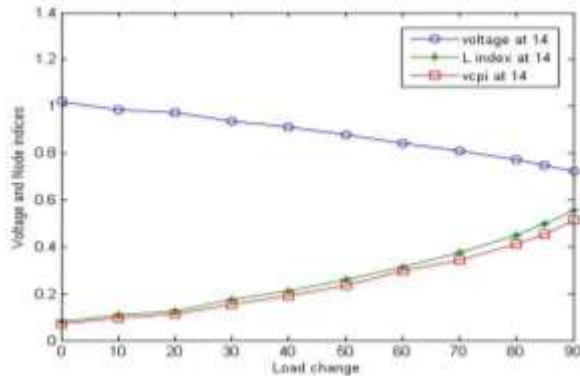
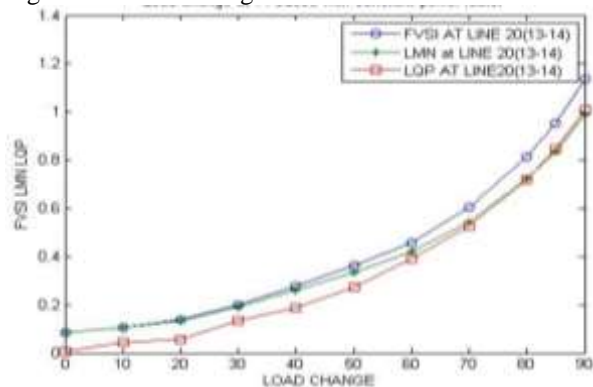


Table VIII shows the line indices of some of the buses when the load is changing at 14th bus. The line 20, 17 are mostly effected when the load changes at 14th bus the three indices shows same variation at almost same loading .Figure 8 shows the graphical representation of Table VIII.

Table VIII. Line indices at 14th bus with constant power factor

Line	FVSI	Lmn	LQP	status
20(13-14)	1.135	0.987	1.122	Most critical
17(9-14)	0.929	0.799	1.009	Most critical
10(5-6)	0.453	0.482	0.765	Critical

Figure 15: Load change Vs. Line indices at 14th bus



b ) Load Change At 14th Bus with Constant Increment: In this case the load at selected bus is varied in equal increments keeping all other buses unchanged. Table IX shows the result only 14th bus is critical. Figure 16 shows the voltage profile when the load is varied till the collapse point is reached. Table X shows the line indices for when the load is varying the line 20 and 17 are most critical line. Figure 17 gives the line indices with the varying load.

Table IX. Voltage and Node indices at 14th bus with constant increment loading

Bus	voltage	L index	VCPI	Status
14	0.5919	0.9067	0.8642	Most critical
9	0.8647	0.2492	0.2264	
10	0.8831	0.2135	0.1943	

Figure 16 : Loading factor Vs Voltage and node indices

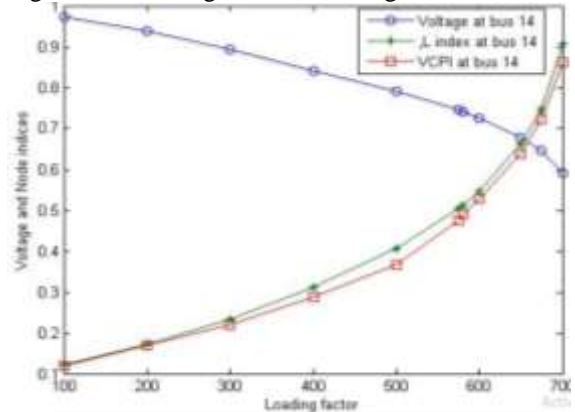
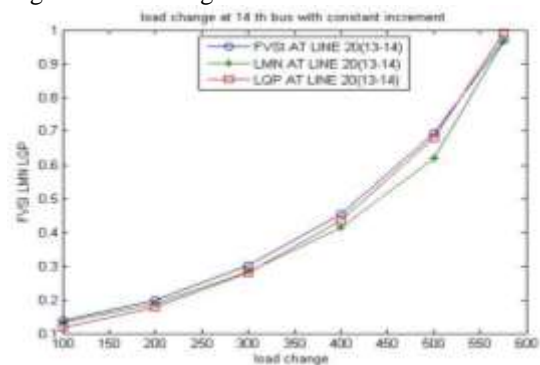


Table X. Line indices at 14th bus with constant increment

Lines	FVSI	Lmn	LQP	Status
20(13-14)	1.111	0.968	1.099	Most critical
17(9-14)	0.909	0.783	0.987	Most critical
10(5-6)	0.45	0.478	0.757	

Figure 17: Loading factor Vs. Line indices



c) Load change at 14th Bus with random loading: In this case the load at 14th bus is changed in random manner till the collapse point is reached and the impact on indices and voltage profile is studied. Table XI shows 14th bus as critical bus and 9 and 10 will be critical if load increases further. Figure 18 gives graphs of voltage profile. Table XII indicates line indices variation with the random loading at 14th bus.

Figure 18: Loading factor Vs. Voltage and node indices

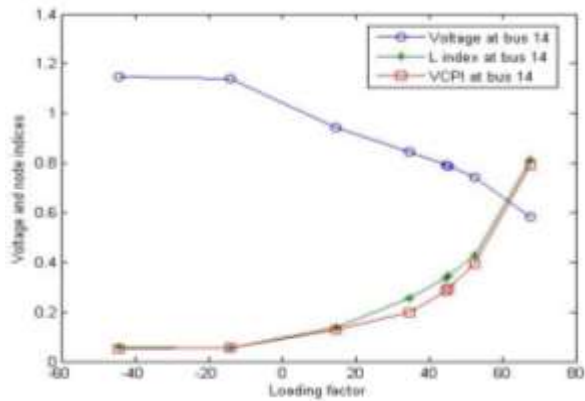


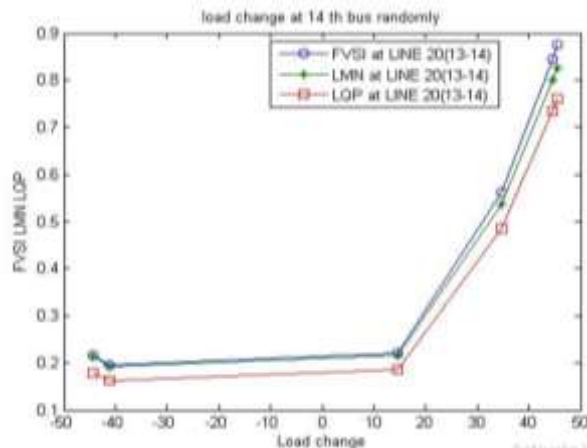
Table XI. Voltage and Node indices at 14th bus

Bus	Voltage	L index	VCPI	status
14	0.5845	0.8123	0.7925	critical
9	0.8699	0.2239	0.2147	
10	0.8875	0.1933	0.1864	

Table XII. Line indices at bus 14 with random loading

Line	FVSI	Lmn	LQP	Status
20(13-14)	1.182	1.106	1.034	Most critical
17(9-14)	0.988	0.911	0.902	Most critical
10(5-6)	0.306	0.317	0.486	

Figure 19: Loading factor Vs Line indices for random load



B) IEEE 30 -Bus result: The same load pattern is repeated for the IEEE -30 Bus test system. The results are tabulated in the below Table XIII and XIV. Table 13 show the voltage profile and node based indices when load at all buses are changed at different load scenarios. Table XIV shows line based indices using three different indices at three different load patterns.

Case i : Change of load at all buses :

Table XIII. Voltage and Node indices at all load scenarios

Bus	Voltage	L index	VCPI	Status
26	0.5409	1.0303	0.954	Most critical
30	0.58	1.0138	0.942	Most critical
29	0.6063	0.8947	0.864	Critical
30	0.5875	0.9765	0.8948	Critical
26	0.6155	0.7297	0.7154	Critical
29	0.6326	0.7122	0.6941	
30	0.6124	0.9125	0.8926	Most critical
23	0.6341	0.7754	0.7315	Critical
24	0.7526	0.6768	0.6431	

From the table XIII it is evident that the node 30 and line 38 are critical among all other nodes with the load changes in any fashion. Along with the critical buses and lines other buses are also shown in the table which becomes critical if the loading increases further

Table XIV. Line indices at all load scenarios

Lines	FVSI	Lmn	LQP	Status
36(28-27)	1.44	1.599	1.865	Most critical
34(25-26)	1.011	0.912	0.788	Most critical
38(27-30)	0.777	0.654	0.829	Critical
36(28-27)	1.171	1.233	1.387	Most critical
38(27-30)	0.936	0.837	0.851	Critical
34(25-26)	0.655	0.625	0.485	
38(27-30)	1.021	1.014	1.346	Most critical
36(28-27)	0.754	0.764	0.841	Critical
39(29-30)	0.624	0.634	0.752	

Case ii: Change of load at only one bus: The load at selected bus here 30th bus is changed keeping all other buses unchanged. Table XV indicates 30th node is the critical bus when the load is changing in all different patterns.

Table XV. Voltage and Node indices at critical bus

Critical Bus	Voltage	L Index	VCPI	Status
30	0.6373	0.8907	0.8526	Most critical
29	0.7479	0.5529	0.5414	
30	0.5776	1.0776	0.9564	Most critical
29	0.7853	0.3951	0.3421	
30	0.655	0.603	0.577	
29	0.314	0.318	0.372	

Table XVI. Line indices at critical bus

<i>Critical line</i>	<i>FVSI</i>	<i>Lmn</i>	<i>LOP</i>	<i>Status</i>
38(27-30)	1.063	0.874	1.149	Most critical
37(27-29)	0.418	0.36	0.403	
38(27-30)	1.043	0.944	0.924	Most critical
39(29-30)	0.436	0.36	0.403	
38(27-30)	0.655	0.603	0.577	
36(28-27)	0.314	0.318	0.372	

#### IV CONCLUSION

This paper presents a study on impact of load changes on voltage stability assessment. Different node based and line based indices are simulated with different types of load patterns on IEEE 14 and IEEE 30 bus test systems. From the simulations, it was observed that node based indices are varying slowly and the change is abrupt near the collapse. However, the line based indices are varying almost the constant rate and giving better indication. But, in reality, although the line based indices crosses 1 or 0, it may not always result in system instability. Hence, from the studies it is observed that, instead of using a single indices, it is better to used more than one that to one line based and one node based indices will give better information when compared to single indices based approach.

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