

Detection of Proximity to Voltage Collapse by Using L –Index

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ABSTRACT: Several systems are considered for the National Grid of Sudan show strong signs of voltage instability or voltage collapse. It is proposed in this work to investigate the proximity of power systems to voltage instability with special reference to the National Grid. This work describes real life application in detection of proximity to voltage collapse by using L-index method. The research challenge was found out an appropriate method for detection voltage collapse in an effective manner. This work reflects that through case study conducted in National Grid of Sudan. The work is started with L-index method or technique. The L-indices for a given load condition are computed for all load buses and the maximum of L-indices gives the proximity of the system to voltage collapse. This work reports an analytic synthesis of real experience acquired to solve problems concerning with detection voltage collapse in National grid. Our methods provided several results. The validity of results was discussed with the known IEEE 14-bus system, IEEE 30-bus system, in addition to other methods. In this paper after detection of proximity to voltage collapse a compensation method of mitigating the voltage collapse by supplying the reactive power at load buses is discussed and compares the results with and without compensation.

KEYWORDS: L-index method, voltage collapse, National Grid of Sudan, Voltage stability.

I. INTRODUCTION

Extensive work has achieved on static voltage stability, and several voltage stability indices were derived from static power flow analysis. Power systems operate most of the time under quasi-steady state conditions. Disturbances also occur in power systems. Examples of such disturbances are sudden changes in load demand, generator failures or change in transmission system configuration due to faults and line switching. Voltage stability is concerned with the ability of a power system to maintain acceptable voltages in the system under normal conditions and after being subjected to a disturbance [1]. Voltage stability analysis through simulation often requires examination of several system states and many contingency scenarios, for this reason, numerous works have been conducted recently for the prediction of voltage stability and collapse based on the steady state analysis by conventional ways [2-6]. Some of these focus on static voltage stability analysis with the use of instability measuring indicators. Among them the suitable and simple way of finding the stability margin and the limit by means of the popular L-index is as described in [7]. This index gives a sufficiently accurate and more practical means of the assessment and can express the stability analysis in a simple way. Huang & Nair [8] discuss a voltage stability indicator whose value changes between zero (no load) and one (voltage collapse). The indicator incorporates the effect of all other loads in the system on the evaluation of index at individual load buses. The overall voltage stability of the system could be identified by the largest value of the index evaluated amongst all the load buses. This indicator can also be used as a normalized quantitative measure, for estimation of the voltage stability margin from the operating point. The indicator uses information of a normal load flow. Static voltage instability is actually related to the reactive power imbalance. The reactive power support which the bus receives from the system, can limit loadability of that bus and hence the entire system. If the reactive power support reaches below the limit, the system will approach to maximum loading point or voltage collapse point due to high real and reactive power losses [9-11]. Hence, the reactive power supports should be local and adequate in order to avoid problem associated with its transmission [12, 13]. The advantage of the method lies in the simplicity of the numerical calculation and the expressiveness of the result. This paper discusses the formulation of the L-index in detail. The L-index simulation results are presented for IEEE 14-bus, IEEE 30-bus as benchmark and Sudan National Grid. In

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this paper after detection of proximity to voltage collapse compensation methods of mitigating the voltage collapse by supplying the reactive power at load buses is discussed and compare the results with and without compensation. . On comparison of the results at the load buses it is seen that with capacitor bank at the load buses voltage collapse is mitigated in spite of heavily loading the system. This paper is organized as follows. In section II, describes the problem formulation of the L-index. Section III presents the case study for IEEE 14-bus, IEEE 30-bus as benchmark and Sudan National Grid. In section IV, presents results and discussions, and finally section V a conclusion is drawn by discussing the results.

II. PROBLEM FORMULATION

In order to become of practical value the indicator L has to be extended to the multi-node system, there are two categories of nodes which have to be distinguished. One is characterized by the behaviour of the PQ-node which stands for a type of consumer node, the other comprise the generator nodes which may be given by a PV-node or by the slack node. The transmission system itself is linear and allows a matrix representation of the power systems. The power system can be expressed as [14]:

$$I_{bus} = Y_{bus} V_{bus} \tag{1}$$

Consider a system where,

n=total number of buses, with 1, 2...g generator buses (g)

g+1, g+2,...,g+s SVC buses(s),

g+s+1, g+s+2,..., n the remaining buses(r=n-g-s)

A load flow result is obtained for a given system operating condition, which is otherwise available from the output of on-line state estimator.

$$\begin{bmatrix} I^G \\ I^L \end{bmatrix} = \begin{bmatrix} Y^{GG} & Y^{GL} \\ Y^{LG} & Y^{LL} \end{bmatrix} \begin{bmatrix} V^G \\ V^L \end{bmatrix} \tag{2}$$

$$I^G = Y^{GG} V^G + Y^{GL} V^L$$

$$I^L = Y^{LG} V^G + Y^{LL} V^L$$

Where I^G, I^L and V^G, V^L represent currents and voltages at the generator nodes and load nodes and $j=g+1, g+2, \dots, n$.

Therefore

$$V^L = [Y^{LL}]^{-1} I^L - [Y^{LL}]^{-1} Y^{LG} V^G \tag{3}$$

$$I^G = Y^{GL} [Y^{LL}]^{-1} I^L + (Y^{GG} - Y^{GL} [Y^{LL}]^{-1} Y^{LG}) V^G \tag{4}$$

Equations 3 and 4 in matrix form

$$\begin{bmatrix} V^L \\ I^G \end{bmatrix} = \begin{bmatrix} [Y^{LL}]^{-1} & [Y^{LL}]^{-1} Y^{LG} \\ Y^{GL} [Y^{LL}]^{-1} & Y^{GG} - Y^{GL} [Y^{LL}]^{-1} Y^{LG} \end{bmatrix} \begin{bmatrix} I^L \\ V^G \end{bmatrix}$$

Rearranging the above matrix we get,

$$\begin{bmatrix} V^L \\ I^G \end{bmatrix} = \begin{bmatrix} Z^{LL} & F^{LG} \\ K^{GL} & Y^{GG} \end{bmatrix} \begin{bmatrix} I^L \\ V^G \end{bmatrix} \tag{5}$$

Where $F^{LG} = -[Y^{LL}]^{-1} Y^{LG}$ are the required values which are obtained by repeated solutions of sparse linear equations. An L-index value away from 1 and close to 0 indicates improved system security. For an unloaded system with generator/ load buses voltage $1.0 \angle 0^\circ$, the L indices for load buses are close to zero, indicating that the system has maximum stability margin. For a given network, as the load/ generation increases, the voltage magnitude and angles change near maximum-power-transfer condition and the voltage stability index L_j (at bus j) values for load buses approaches unity, indicating that system is close to voltage collapse. While different methods give a general picture of the proximity of the system to voltage collapse, the L-index gives a scalar number to each load bus. Among the various indices for voltage stability and voltage collapse predication, the L-index gives fairly consistent results. The L-index for a given load condition is computed for all the load buses and the maximum of the L-indices gives the proximity of the system to voltage collapse.

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The L-index value for the j^{th} node can be rewritten as,

$$L_j = \left| 1.0 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \angle \theta_{ji} + \delta_i - \delta_j \right| \tag{6}$$

$$L_j = \left| 1.0 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} (F_{ji}^r + jF_{ji}^m) \right| \tag{7}$$

where

$$F_{ji}^r = F_{ji} \cos(\theta_{ji} + \delta_i - \delta_j)$$

$$F_{ji}^m = F_{ji} \sin(\theta_{ji} + \delta_i - \delta_j)$$

III. CASE STUDY

A single-line diagram of the IEEE 14-bus standard system extracted from [15]. It consists of five synchronous machines; two of them are providing both active and reactive power at buses 1 and 2, and the generators at buses 3, 4 and 5 are basically synchronous condensers; the base total loading level of the system is 259 MW and 81.3 MVar.

The IEEE 30-bus test case is one of the widely used test cases available from the power system test case archive [15, 16]. Bus 1 and 2 are providing both active and reactive power, and the generators at buses 3, 4, 5 and 6 are basically synchronous condensers. All the remaining buses are load buses. The base total loading level of the system is 283.4 MW and 126.2 MVar.

The simplified one line diagram of Sudan National Grid is given in the Appendix. The system consists of 45-bus in two parts: a 500 kV system at bus 17, 18, 26, 27 and a 220 kV system at the remaining buses; the 220 kV network forms the backbone of the transmission system in the Sudanese National Grid, the maximum power can be generated in the Sudan is a round 1700 MW which comes from four power plants, Roseires, Khartoum North, Garri, and Merow, it has 41 transmission lines, 35 load buses, 8 tap-changing transformers, the base total loading level of the system is 1550 MW and 807.1 MVar [6].

IV. RESULTS AND DISCUSSION

The L-index varies in the range between 0 (for no load) to 1 (voltage collapse point). This index was implemented using MATLAB. Results are obtained for the IEEE (14-bus, 30-bus) systems as benchmark and the Sudan National Grid (SNG).

A. IEEE 14-bus System

The IEEE 14-bus system is used as a benchmark test system. Result of a load flow simulation is used to illustrate how L-index predicts the voltage stability margin, and the results of the L-index computation are shown in table 1. It can be seen from the table 1 that the order of the worst load buses with the largest L-indices for the base and the critical case without compensation are almost the same. Therefore, bus 14 represents the weakest bus in the system.

Table: IEEE 14-bus L-index for the base case and voltage stability limit

Base case		Voltage stability limit	
Bus #	L-index	Bus #	L-index
14	0.0708	14	1
9	0.0598	9	0.7912
10	0.0569	10	0.7641
8	0.0348	11	0.3245
11	0.0325	8	0.3108
13	0.0302	13	0.2348
7	0.0299	12	0.1469
12	0.023	7	0.1385
6	0.0203	6	0.0959

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Figures 1, 2 shows the L-index versus the bus number without compensation; figure 1 represents L-index method for the base case and figure 2 represents L-index at voltage stability limit. For both case bus 14 represents the weakest bus in the system.

As indicated from Figs. 2 and 3, the maximum L-index at bus 14 is 1 and 0.588 respectively, therefore fig 3 after compensation the value will reduce from 1 to 0.588.

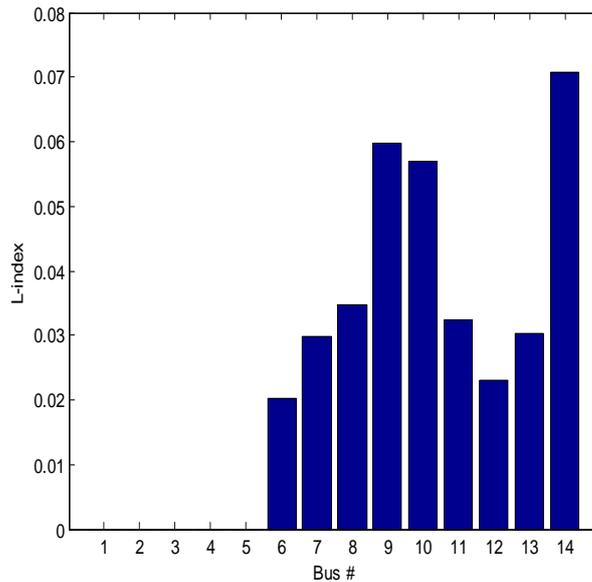


Fig. 1 IEEE 14-bus L-index for the base case without compensation

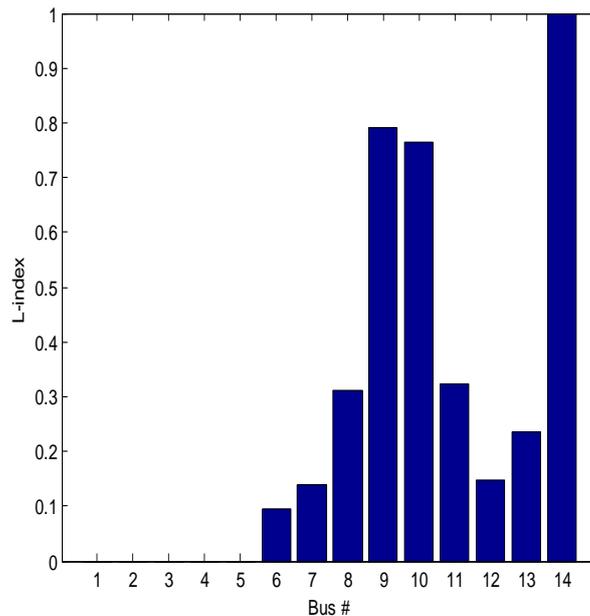


Fig. 2 IEEE 14-bus L-index for voltage stability limit without compensation

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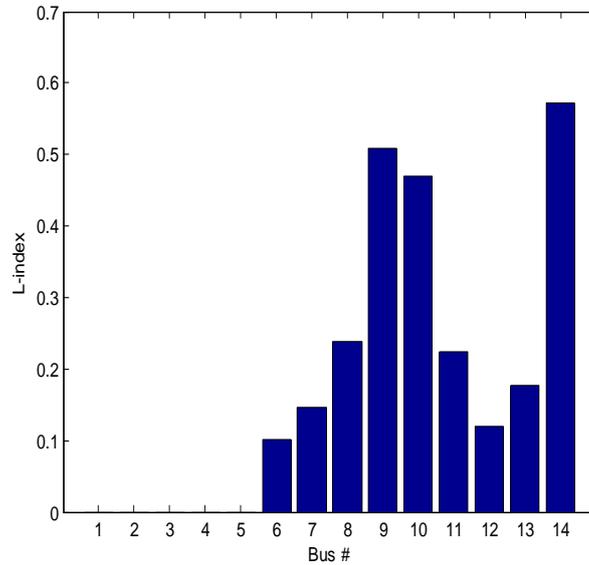


Fig. 3 IEEE 14-bus L-index for voltage stability limit with compensation

B. IEEE 30-bus System

The IEEE 30-bus system is used as a benchmark; table 2 shows the order of the worst load buses with the largest L-indices for the base case and voltage stability limit without compensation are the same. Therefore, bus 30 represents the weakest bus in the system.

Table 2: IEEE 30-bus L-index for the base case and voltage stability limit

Base case		Voltage stability limit	
Bus #	L-index	Bus #	L-index
30	0.1366	30	1
29	0.1164	29	0.8306
26	0.1146	26	0.7471
19	0.1057	25	0.5882
24	0.1036	24	0.5691
18	0.1019	19	0.5479
20	0.1009	27	0.5284
23	0.0985	18	0.5242
25	0.0983	23	0.518
21	0.0934	20	0.5154
22	0.0929	21	0.4741
15	0.0883	22	0.4726
27	0.0868	15	0.4408
17	0.0863	17	0.4228
14	0.0854	14	0.4172
10	0.0821	10	0.3967
16	0.0795	16	0.3835
11	0.0741	11	0.3628
12	0.0672	12	0.3118
7	0.0667	13	0.239
13	0.0594	9	0.236
9	0.0532	7	0.1466
28	0.0529	28	0.1287
8	0.0505	8	0.1152

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Figures 4, 5 shows the L-index versus the bus number without compensation; figure 4 represents L-index method for the base case and figure 5 represents L-index at voltage stability limit. For both cases bus 30, 29 and 26 represents the weak buses; therefore bus 30 is weakest bus in the system. In case of comparing between fig. 5 and 6 the maximum L-index at bus 30 is reduce from 1 in fig. 5 to 0.475 in fig. 6 it seem very clear the effect of compensation.

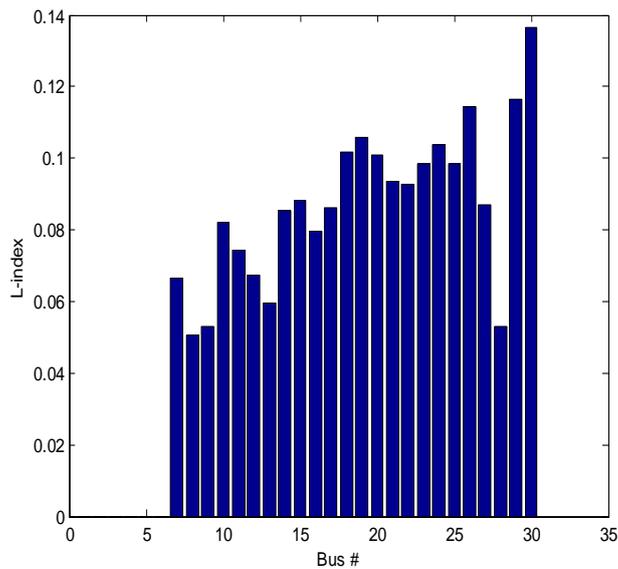


Fig. 4 IEEE 30-bus L-index for the base case without compensation

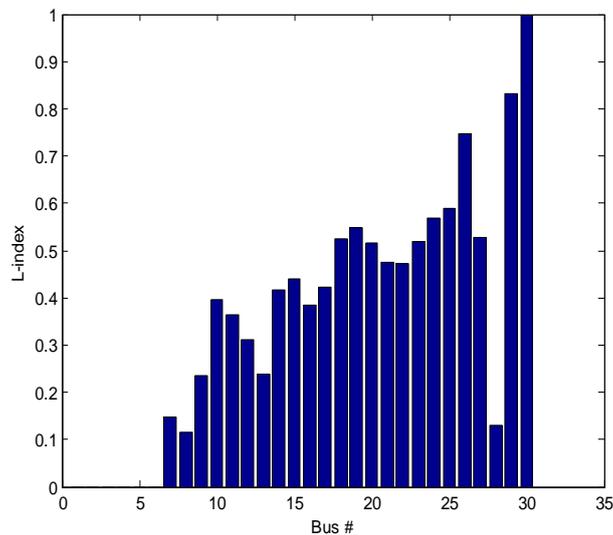


Fig.5 IEEE 30-bus L-index for voltage stability limit without compensation

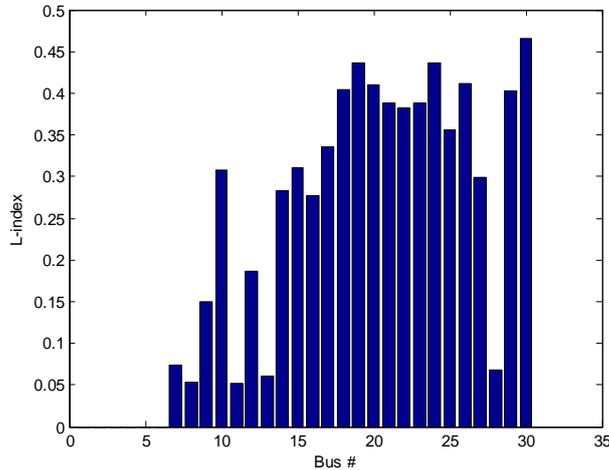


Fig.6 IEEE 30-bus L-index for voltage stability limit with compensation

C. Sudan National Grid

A single line diagram showing the Sudan National Grid is attached in appendix A. After intensive simulation of base and critical cases, the L-index computation of the worst buses in the system is listed in the table 3, which provides the results of the base and critical cases. It can be seen from the table 3 that the order of the worst buses with the largest L-indices for the base and the critical cases without compensation are almost the same. Based on these results it can be conclude that the buses of central areas which are representing 29, 28 and 30 are weakest buses for both cases.

Figures 7, 8 shows the L-index versus the bus number without compensation; figure 5 represents L-index method for the base case and figure 8 represents L-index at voltage stability limit. For both case the weakest bus is # 29 and further, it can be seen that buses 28 and 30 are standing out as the most critical. Therefore, the central area represents the weakest buses in the grid. Thus indicating an improvement in the voltage stability margin for the system. A comparison is also made between figs. 8 and 9 it is very clear that the maximum value of l-index is reduced from 0.9781 at bus 29 in fig. 8 to 0.489 in fig. 9 a reduction of about 50%, which indicating an improvement in the system voltage stability margin.

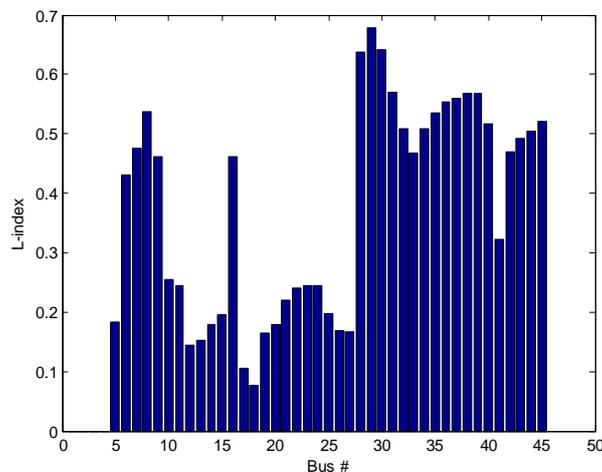


Fig. 7 Sudan National Grid L-index for the base case without compensation

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Table 3: Sudan National Grid L-index for the base case and voltage stability limit

Base case		Voltage stability limit	
Bus #	L-index	Bus #	L-index
29	0.484	29	0.9781
30	0.4616	28	0.9038
28	0.4573	30	0.8951
31	0.4161	31	0.7637
38	0.4157	38	0.7134
39	0.4157	39	0.7134
37	0.4104	37	0.7029
36	0.407	36	0.6963
35	0.3949	8	0.6882
8	0.3946	40	0.6749
45	0.3851	35	0.6723
40	0.3808	45	0.6683
32	0.377	44	0.6489
34	0.377	32	0.6371
44	0.3747	34	0.6371
16	0.366	43	0.6312
43	0.3654	42	0.6029
7	0.3543	7	0.5987
42	0.3503	9	0.5923
33	0.3491	33	0.5838
9	0.3449	6	0.5346
6	0.3228	16	0.5292
41	0.2467	41	0.3992
23	0.2069	10	0.3017
24	0.2069	11	0.2903
22	0.2031	23	0.2673
10	0.2005	24	0.2673
11	0.1946	22	0.2621
21	0.1861	21	0.2395
15	0.1603	25	0.2328
25	0.1591	15	0.221
20	0.1516	5	0.2191
14	0.1466	26	0.2058
5	0.1442	14	0.2047
19	0.1404	27	0.2032
26	0.1343	20	0.1946
27	0.1327	19	0.1802
13	0.1248	13	0.1769
12	0.1186	12	0.1674
17	0.087	17	0.12
18	0.0636	18	0.0878

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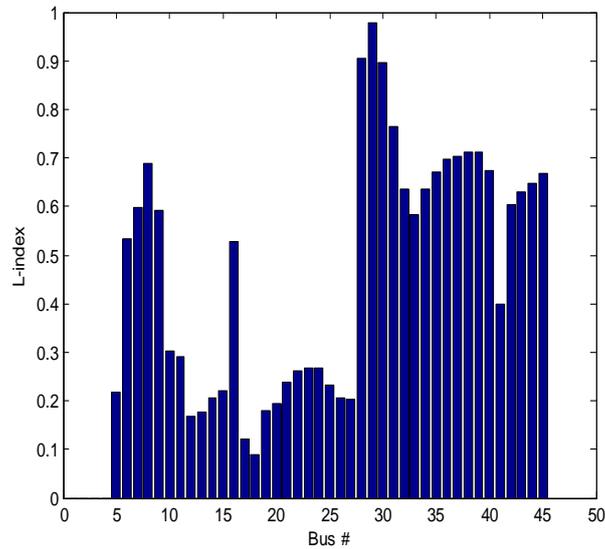


Fig. 8 Sudan National Grid L-index for voltage stability limit without compensation

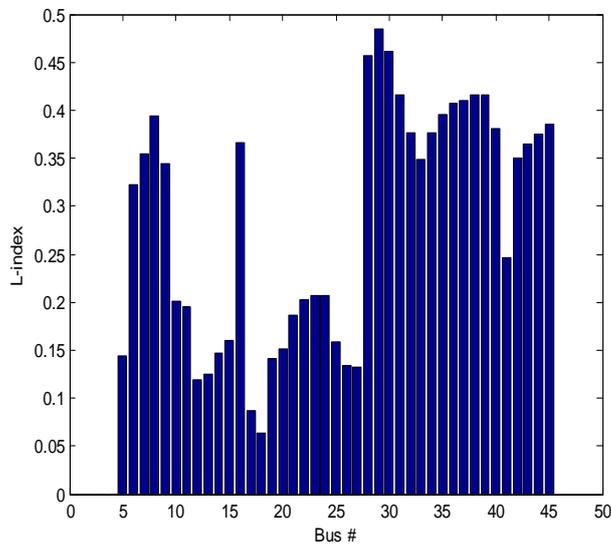


Fig. 9 Sudan National Grid L-index for voltage stability limit with compensation

V. CONCLUSION

This paper has discussed the formulation of L-index method in detail. The higher values for L- indices are indicative of most critical buses and thus maximum of L-indices is an indicator of proximity in the system to represent voltage collapse. Simulation results of the L-index were carried out on IEEE 14-bus system, IEEE 30-bus system (as benchmark) and the Sudan National Grid system. The results clearly indicate that L-index is stable in all cases above. The L-index based voltage stability index is simple to compute and it provides a quantitative means to review the voltage stability of the system at any given operating point. On comparison of the results at the load buses it is seen that with a capacitor bank at the load buses voltage collapse is mitigated in spite of heavily loading the system in case of comparing the status of compensated and uncompensated it is seen that the power transfer capability of the bus has

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been increased after the addition of shunt capacitor. The comparison can best be achieved with help of the graph showing the Lindex in figures of compensated and uncompensated and this method of compensation is lowest cost compare with the other methods.

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APPENDIX

