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Assessment of Voltage Stability Indices to Predict the Line Close to Voltage Collapse

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Abstract: Voltage stability is the integral part of the power system stability. In this paper, assessment of various voltage stability indices (VSIs) are presented to predict the proximity of the distribution line close to voltage collapse. These line VSIs are based on the concept of voltage quadratic equation of the two bus system. The behaviour of VSIs have been tested on two test systems, i.e. IEEE 12-bus and IEEE 33-bus radial distribution systems (RDS) with increasing penetration of base load. These indices are differentiated to resolve their effectiveness in identifying the weakest line in the system. Results show that these indices evaluation can be used for placing Distributed Generation (DG) and capacitors in the system.

Keywords: distribution system, voltage stability indices, voltage collapse.

I. INTRODUCTION

In recent decades, it has been reported that the major cause for power system blackouts in the worldwide is due to voltage instability. It leads to abnormal low voltage in the system. Voltage stability refers to the ability of a power system to maintain steady voltage at all buses in the system after being subjected to a disturbance from a given initial operating condition [1]. Voltage instability is also referred to as voltage collapse. The causes of voltage instability are as follows:

1) Failure to meet the required reactive power demand.
2) Increase in load demand.
3) Disturbances in the electric network such as tripping of transmission lines, power transformers and generators.
4) Malfunctioning of on-load tap changing transformers.

These disturbances in power system cause serious social impacts and economic losses. The voltage collapse can be avoided by some measures as given below [2].

1) Integrating DG into the system.
2) Installing FACT devices.
3) Changing transformer tapping.
4) Load shedding and shunt capacitors switching.

The VSIs predict how close a system is to a voltage collapse. The application of these indices help in identifying the weak buses and lines in the system. If the value of VSI of the bus/line is close to the critical value, then it is considered as the weak bus/line in the system. The application of VSIs can be used to find the optimal location and sizing of DGs & capacitors and planning of the power system network [3-4].

In the literature review, various VSIs have been proposed by many researchers [5-7]. Some of these indices are functions of the bus voltage, line current and impedance of the network [8]. Some other indices use the concept of machine learning techniques [9], singular value decomposition techniques [10] and continuation techniques [11]. These indices evaluation gives different result. In this paper comparison of various line VSIs have been precisely investigated. To show the reliability of these VSIs, IEEE 12-bus and IEEE 33-bus RDS are considered as test systems with different loading conditions. The rest of the paper is arranged as follows. Section II reviews the various line VSIs. Section III discusses the results and finally the conclusion is drawn in section IV.

II. VOLTAGE STABILITY INDICES

In this section a brief study of various line VSIs are discussed. These indices are all developed based on the two bus representation of the system as shown in the figure 1.

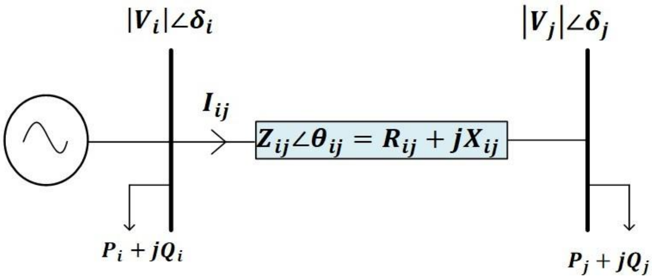

Fig. 1. Single line diagram of a two bus system

where,

V_i&V_j	Voltage at $i^{th}$and j^{th}buses.
δ_i&δ_j	Power angle at $i^{th}$and j^{th}buses.
θ_{ij}	Line impedance angle.
P_i&P_j	Real power load at $i^{th}$and j^{th}buses.
Q_i&Q_j	Reactive power load at $i^{th}$and j^{th}buses.
R_{ij}&X_{ij}	Resistance and reactance of the line connecting $i^{th}$and j^{th}buses.
I_{ij}	Branch current of each line connecting $i^{th}$and j^{th}buses.
$\delta = \delta_i - \delta_j$	Power angle difference between sending and receiving end buses.

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A. Fast Voltage Stability Index (FVSI)

The FVSI is computed from the voltage quadratic equation at the receiving end bus on the system. Mathematically, it is expressed as follows [12].

$$V_j^2 - \left(\frac{R_{ij}}{X_{ij}}\sin(\delta) + \cos(\delta)\right)V_iV_j + \left(X_{ij} + \frac{R_{ij}}{X_{ij}}\right)Q_j = 0 \qquad (1)$$

To obtain the real roots for V_j, the discriminant of the equation is set greater than or equal to zero, i.e.,

$$\left[\left(\frac{R_{ij}}{X_{ij}}\sin(\delta) + \cos(\delta)\right)V_i\right]^2 - 4\left(X_{ij} + \frac{R_{ij}^2}{X_{ij}}\right)Q_j \geq 0 \qquad (2)$$

Rearranging the equation 2, we get,

$$\frac{4\,Z_{ij}^2Q_jX_{ij}}{V_i^2\left(R_{ij}\sin(\delta)+X_{ij}\cos(\delta)\right)^2} \leq 1 \qquad (3)$$

Since is a small value them,

$\delta \approx 0$, $R_{ij}\sin(\delta) \approx 0$ and $X_{ij}\cos(\delta) \approx X_{ij}$

Representing the bus-i as sending bus and bus-j as receiving bus, the FVSI is mathematically written as,

$$FVSI_{ij} = \frac{4\,Z_{ij}^2Q_j}{V_i^2X_{ij}} \qquad (4)$$

For stable operation of the system the value of FVSI should be maintained well less than one. The value close to one indicates that the particular line is close to instability point, leading to voltage collapse in the system.

B. Line Stability Index (L_{mn})

Moghavemmi et al. [13], have proposed Lmn based on the concept of power flow through a single line two bus system. It is computed by the equation given below,

$$L_{mn} = \frac{4X_{ij}Q_j}{\left(V_i\sin(\theta_{ij}-\delta)\right)^2} \qquad (5)$$

The effect of active power and shunt admittance on voltage stability is neglected in this index. The value of L_{mn}close to one indicates that the system is losing its stability leading to voltage collapse. Therefore for stable operation of the system, the value should remain less than one.

C. Line Stability Factor (LQP)

Mohamed et al. [14], formulated LQP based on the same concept of power flow has FVSI andL_{mn}. It is given by the equation below.

$$LQP = 4\left(\frac{X_{ij}}{V_i^2}\right)\left(Q_j + \frac{P_i^2X_{ij}}{V_i^2}\right) \qquad (6)$$

For stable operation of the system, LQP < 1.

D. Line Stability Index (L_p)

TheL_p has been formulated by Moghavvemi et al. [15]. This index is obtained based on the same concept as the previous indices. $L_p$is given by,

$$L_p = \frac{4\,R_{ij}P_j}{\left(V_i\cos(\theta_{ij}-\delta)\right)^2} \qquad (7)$$

For any value of L_p>1, the system is considered as unstable.

E. Novel Line Stability Index (NLSI)

NLSI is derived from the voltage quadratic equation at the receiving end bus. The expression for the NLSI is expressed as follows [16],

$$NLSI = \frac{P_jR_{ij}+Q_jX_{ij}}{0.25\,V_i^2} \qquad (8)$$

For stable operation of the system, the value of NLSI should be less than one.

F. Voltage Stability Index (L_d)

This index is derived from the voltage quadratic equation, same as previous indices. Authors in [17] had proposed L_d mathematically given as follows,

$$L_d = \frac{4\sqrt{\left(P_j^2+Q_j^2\right)\left(R_{ij}^2+X_{ij}^2\right)}}{V_i^2} \qquad (9)$$

The system is said to be in proximity to voltage collapsefor any value of L_d close to one.

G. Stability Index (L)

In [18], the authors have formulated the stability index based on the same concept asLp. For stable operation of the system, the value of L should be less than one. This index is given by,

$$L = \frac{4\left(V_iV_j - V_j^2\right)}{V_i^2} \qquad (10)$$

H. Stability Index (SL)

The most used line VSI is based on voltage quadraticequation [19-20]. It is expressed as follows,

$$SI = 2V_i^2V_j^2 - V_j^4 - 2V_j^2\left(P_jR_{ij} + Q_jX_{ij}\right) - Z_{ij}^2\left(P_j^2 + Q_j^2\right) \qquad (11)$$

Line is sensitive to voltage collapse, if its SI value isminimum.

III. VOLTAGE ANALYSIS AND RESULTS

To demonstrate the effectiveness of the various VSIs discussedin section II, they have been tested on two test systems.IEEE 12-bus and IEEE 33-bus RDS are considered as two testsystems. The backward/forward sweep load flow method isutilized for study purpose. In this paper, the study of variousline VSIs is demonstrated in four cases. They are as follows.

Case 1: System with base case load.
Case 2: System with 125% of base case load.
Case 3: System with 150% of base case load.
Case 4: System with 175% of base case load.

The simulation was carried out using MATLAB software inorder to verify the most sensitive line index in identifying theline which is close to voltage collapse.

A. IEEE 12-bus system

This test system comprises of one generator bus and 11 load buses, and 11 connecting lines, as shown in the figure 2. It has a total load of 435 kW and 405 kVAr. In Table I, the voltage profile (p.u) and the index value of line VSIs is provided for the base case load of the test system. The index value greater than one refers to system being unstable, except SI index. The lowest value of SI index of a line indicate that particular line is the most weak bus in the system. Similarly, a low value of the voltage profile of a bus indicates that particular bus is close to voltage collapse. It is observed from the table 1, that the voltage at bus 12 is having the lowest bus voltage. The FVSI, LQP, Lp, NLSI, Ld and L index values are in the range of stable system. The Lmn value at line 7 is more than one, indicating the system is unstable. But the value of the bus voltage at which that particular line is connected has better value than the voltage at bus 12. Among all the indices, the SI show that the line which is connected to lowest voltage bus is the weakest line in the system.

The study has been carried out for the increased loading conditions i.e., 125%, 150% and 175% of the base load. The increment is considered in both active and reactive power load of the system simultaneously. Table II, II and IV show the results obtained for the case 2, 3 and 4 respectively. It is found that, except SI remaining line VSIs identify the line 6 or 7 as the weak line the system. In actual, the bus voltage at which these lines have connected are having higher voltage value than the voltage at bus 12. It is observed that the line with minimum value of SI occurs at line connecting 11 and 12 buses. Simultaneously, the voltage at bus 12 is having lower value. It is clear that among all the line VSIs, SI performs better in identifying the line close to the voltage collapse.

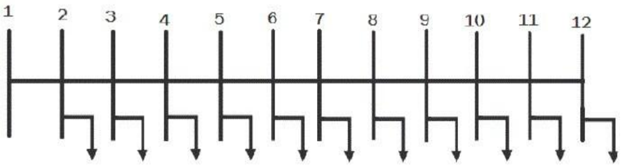

Fig. 2. Single line diagram of IEEE 12-bus system

B. IEEE 33-bus system

This test system consists of one generator bus, 32 load buses and 32 connecting lines. The single line diagram of IEEE 33- bus system is shown in figure 3. The total real and reactive power load of the test system is 3.715 MW and 2.3 kVAr respectively.

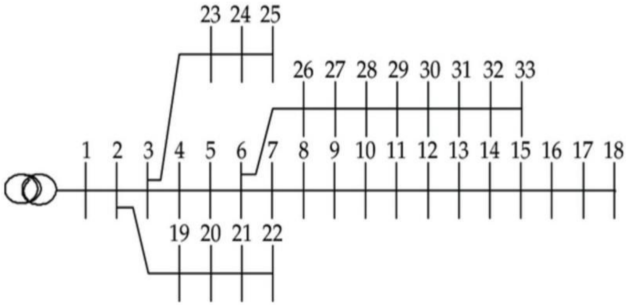

Fig. 3. Single line diagram of IEEE 33-bus system

Voltage collapse is the process by which the voltage profile falls to a very low value. From the voltage profile obtained for 33-bus test system. It is observed that, the voltage level falls more from bus 7 to 18, and from bus 27 to 33. In this test system, study has been carried out these low voltage buses. For stable operation of the system, the value of the line FVSI, Lmn, LQP, Lp, NLSI, Ld and L should be less than one. The minimum value of SI indicate the system is close to voltage collapse. The voltage profile and the line VSIs obtained for the base case load of the test system is shown in Table V. It is observed that all the line VSIs are in the range of stable condition. The voltage at bus 18 is having lowest voltage (p.u) i.e., 0.9038. The FVSI, Lmn, LQP, Lp, NLSI, Ld and L show line 7, 28, 29, 15, 29, 8, 8, and 17 as most sensitive line in the system respectively. But the receiving end bus voltage at which these lines are connected have voltage higher than 0.9038, except line 17. The minimum value of SI is obtained at line 17, which is connecting line between bus 17 and 18. The voltage at this bus is lower as compared with that of other buses in the test system.

This analysis has been done with increasing load conditions. Table VI, VII and VIII show the results obtained for case 2, 3, and 4 respectively. Even with increase in load conditions, the line VSIs show same line as weak line. Among all the line VSIs, SI performs better in identifying the line close to voltage collapse. This help to key out the line which is weak in the system.

Table I. Comparative study for line vsis evaluated at base case on IEEE 12-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	Ld	L	SI
1–2	0.99433	0.00001	0.0020	0.0009	0.0039	0.0031	0.0034	0.0225	0.9986
2–3	0.98903	0.00001	0.0010	0.0005	0.0030	0.0021	0.0022	0.0212	0.9765
3–4	0.98058	0.00006	0.0031	0.0016	0.0082	0.0055	0.0061	0.0339	0.9543
4–5	0.96982	0.00011	0.0023	0.0014	0.0078	0.0047	0.0052	0.0434	0.9223
5–6	0.96654	0.00000	0.0006	0.0002	0.0013	0.0010	0.0010	0.0135	0.8842
6–7	0.96375	0.00001	0.0021	0.0008	0.0031	0.0028	0.0030	0.0115	0.8716
7–8	0.95531	0.00028	2.3567	0.0019	0.0071	0.0090	0.0105	0.0347	0.8590
8–9	0.94728	0.00054	0.0214	0.0023	0.0091	0.0105	0.0122	0.0334	0.8288
9–10	0.94446	0.00006	0.0293	0.0009	0.0038	0.0046	0.0051	0.0119	0.8035
10–11	0.94356	0.00001	0.0442	0.0005	0.0023	0.0027	0.0029	0.0038	0.7947
11–12	0.94335	0.00000	0.0113	0.0002	0.0007	0.0009	0.0010	0.0009	0.7923

Table II. Comparative study for line vsis evaluated at 125% of base case on IEEE 12-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	Ld	L	SI
1–2	0.9928	0.00001	0.0024	0.0011	0.0051	0.0038	0.0042	0.0284	0.9982
2–3	0.9861	0.00001	0.0012	0.0006	0.0040	0.0026	0.0027	0.0268	0.9704
3–4	0.9754	0.00007	0.0035	0.0020	0.0114	0.0069	0.0077	0.0429	0.9425
4–5	0.9618	0.00014	0.0026	0.0017	0.0115	0.0059	0.0065	0.0551	0.9024
5–6	0.9576	0.00000	0.0007	0.0003	0.0017	0.0013	0.0013	0.0173	0.8552
6–7	0.9541	0.00001	0.0025	0.0010	0.0041	0.0035	0.0038	0.0147	0.8397
7–8	0.9434	0.00035	1.3252	0.0025	0.0090	0.0115	0.0135	0.0444	0.8240
8–9	0.9332	0.00070	0.0191	0.0030	0.0123	0.0134	0.0157	0.0428	0.7870
9–10	0.9296	0.00007	0.0294	0.0012	0.0050	0.0060	0.0066	0.0153	0.7562
10–11	0.9285	0.00001	0.0492	0.0006	0.0029	0.0035	0.0038	0.0049	0.7456
11–12	0.9282	0.00000	0.0139	0.0003	0.0009	0.0011	0.0013	0.0011	0.7427

Table III. Comparative study for line vsis evaluated at 150% of base case on IEEE 12-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	Ld	L	SI
1–2	0.9913	0.00001	0.0027	0.0014	0.0065	0.0046	0.0051	0.0345	0.9978
2–3	0.9832	0.00001	0.0014	0.0007	0.0051	0.0031	0.0033	0.0326	0.9641
3–4	0.9702	0.00009	0.0039	0.0025	0.0154	0.0084	0.0093	0.0522	0.9304
4–5	0.9536	0.00017	0.0029	0.0021	0.0166	0.0071	0.0080	0.0672	0.8822
5–6	0.9485	0.00000	0.0008	0.0004	0.0021	0.0016	0.0016	0.0212	0.8261
6–7	0.9442	0.00001	0.0029	0.0013	0.0052	0.0043	0.0047	0.0181	0.8078
7–8	0.9311	0.00043	0.2134	0.0030	0.0112	0.0141	0.0166	0.0546	0.7892
8–9	0.9187	0.00086	0.0171	0.0037	0.0161	0.0166	0.0195	0.0528	0.7456
9–10	0.9143	0.00009	0.0286	0.0014	0.0062	0.0074	0.0082	0.0189	0.7097
10–11	0.9129	0.00001	0.0526	0.0008	0.0036	0.0044	0.0047	0.0061	0.6974
11–12	0.9126	0.00000	0.0164	0.0003	0.0011	0.0014	0.0016	0.0014	0.6941

Table IV. Comparative study for line vsis evaluated at 175% of base case on IEEE 12-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	Ld	L	SI
1–2	0.9897	0.00002	0.0030	0.0016	0.0080	0.0054	0.0059	0.0406	0.9973
2–3	0.9801	0.00001	0.0015	0.0009	0.0064	0.0037	0.0039	0.0385	0.9577
3–4	0.9647	0.00010	0.0043	0.0029	0.0205	0.0098	0.0110	0.0618	0.9181
4–5	0.9451	0.00020	0.0032	0.0025	0.0241	0.0084	0.0095	0.0798	0.8617
5–6	0.9391	0.00000	0.0009	0.0004	0.0026	0.0019	0.0019	0.0253	0.7970
6–7	0.9340	0.00001	0.0033	0.0015	0.0064	0.0051	0.0056	0.0216	0.7758
7–8	0.9184	0.00052	0.0911	0.0036	0.0136	0.0168	0.0199	0.0654	0.7544

8–9	0.9037	0.00103	0.0154	0.0044	0.0210	0.0199	0.0235	0.0634	0.7046
9–10	0.8985	0.00011	0.0274	0.0017	0.0076	0.0089	0.0099	0.0228	0.6640
10–11	0.8968	0.00002	0.0547	0.0009	0.0044	0.0053	0.0057	0.0074	0.6500
11–12	0.8964	0.00000	0.0188	0.0004	0.0014	0.0017	0.0020	0.0017	0.6464

Table V. Comparative study for line vsis evaluated for base case on IEEE 33-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	L_d	L	SI
7–8	0.9323	0.00597	0.0041	0.0035	0.0476	0.0130	0.0136	0.0569	0.7545
8–9	0.9260	0.00027	0.0005	0.0004	0.0075	0.0022	0.0023	0.0270	0.7343
9–10	0.9201	0.00027	0.0008	0.0004	0.0038	0.0022	0.0024	0.0251	0.7166
10–11	0.9192	0.00000	0.0002	0.0001	0.0004	0.0003	0.0003	0.0038	0.7137
11–12	0.9177	0.00001	0.0004	0.0001	0.0009	0.0008	0.0008	0.0066	0.7080
12–13	0.9115	0.00163	0.0072	0.0012	0.0031	0.0038	0.0039	0.0267	0.6894
13–14	0.9092	0.00053	0.0037	0.0017	0.0034	0.0037	0.0039	0.0100	0.6831
14–15	0.9078	0.00004	0.0003	0.0002	0.0022	0.0012	0.0015	0.0063	0.6787
15–16	0.9064	0.00011	0.0003	0.0003	8.6267	0.0017	0.0018	0.0061	0.6741
16–17	0.9044	0.00188	0.0097	0.0010	0.0026	0.0034	0.0041	0.0090	0.6682
17–18	0.9038	0.00024	0.0043	0.0007	0.0024	0.0027	0.0028	0.0027	0.6359
25–26	0.9475	0.00000	0.0001	0.0001	0.0013	0.0004	0.0004	0.0878	0.8808
26–27	0.9450	0.00000	0.0001	0.0001	0.0044	0.0006	0.0006	0.0108	0.8059
27–28	0.9335	0.00040	0.0014	0.0005	0.0028	0.0023	0.0026	0.0478	0.7961
28–29	0.9253	0.00062	0.0151	0.0014	0.0030	0.0042	0.0043	0.0349	0.7579
29–30	0.9218	0.00057	0.0049	0.0045	0.0201	0.0075	0.0106	0.0153	0.7310
30–31	0.9176	0.00145	0.0058	0.0020	0.0063	0.0063	0.0067	0.0180	0.7199
31–32	0.9167	0.00009	0.0016	0.0011	0.0052	0.0030	0.0033	0.0040	0.7080
32–33	0.9164	0.00010	0.0014	0.0006	0.0010	0.0012	0.0014	0.0012	0.7057

Table VI. Comparative study for line vsis evaluated at 125% of base case on IEEE 33-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	L_d	L	SI
7–8	0.9134	0.00771	0.0054	0.0045	0.0518	0.0168	0.0176	0.0739	0.6949
8–9	0.9053	0.00035	0.0007	0.0006	0.0090	0.0029	0.0031	0.0353	0.6705
9–10	0.8977	0.00036	0.0010	0.0006	0.0048	0.0029	0.0031	0.0330	0.6494
10–11	0.8966	0.00000	0.0003	0.0001	0.0005	0.0004	0.0004	0.0050	0.6459
11–12	0.8947	0.00001	0.0006	0.0002	0.0012	0.0010	0.0011	0.0087	0.6391
12–13	0.8867	0.00214	0.0106	0.0016	0.0040	0.0050	0.0051	0.0352	0.6169
13–14	0.8838	0.00071	0.0044	0.0023	0.0047	0.0048	0.0052	0.0133	0.6095
14–15	0.8819	0.00005	0.0004	0.0002	0.0028	0.0016	0.0019	0.0083	0.6043
15–16	0.8801	0.00015	0.0004	0.0004	4.3883	0.0022	0.0024	0.0081	0.5989
16–17	0.8775	0.00249	0.0107	0.0014	0.0035	0.0045	0.0055	0.0120	0.5919
17–18	0.8767	0.00031	0.0057	0.0009	0.0031	0.0036	0.0037	0.0036	0.5410
25–26	0.9330	0.00000	0.0001	0.0001	0.0013	0.0005	0.0005	0.1136	0.8502
26–27	0.9297	0.00001	0.0001	0.0001	0.0051	0.0007	0.0007	0.0140	0.7574
27–28	0.9150	0.00052	0.0016	0.0007	0.0037	0.0030	0.0033	0.0621	0.7453
28–29	0.9045	0.00081	0.0167	0.0018	0.0040	0.0054	0.0057	0.0455	0.6991
29–30	0.8999	0.00075	0.0065	0.0059	0.0226	0.0098	0.0139	0.0201	0.6668
30–31	0.8946	0.00190	0.0080	0.0026	0.0079	0.0082	0.0088	0.0236	0.6535
31–32	0.8934	0.00012	0.0020	0.0014	0.0070	0.0040	0.0043	0.0052	0.6394
32–33	0.8931	0.00013	0.0018	0.0008	0.0014	0.0016	0.0018	0.0016	0.6367

Table VII. Comparative study for line vsis evaluated at 150% of base case on IEEE 33-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	L_d	L	SI
7–8	0.8935	0.0096	0.0070	0.0056	0.0544	0.0208	0.0221	0.0923	0.6358
8–9	0.8834	0.0004	0.0009	0.0007	0.0104	0.0036	0.0038	0.0446	0.6077
9–10	0.8741	0.0005	0.0013	0.0007	0.0058	0.0037	0.0040	0.0418	0.5835
10–11	0.8727	0.0000	0.0003	0.0001	0.0006	0.0005	0.0006	0.0063	0.5796

11–12	0.8703	0.0000	0.0007	0.0002	0.0015	0.0013	0.0014	0.0110	0.5717
12–13	0.8604	0.0027	0.0156	0.0020	0.0049	0.0064	0.0066	0.0448	0.5466
13–14	0.8568	0.0009	0.0052	0.0029	0.0063	0.0062	0.0066	0.0169	0.5383
14–15	0.8545	0.0001	0.0005	0.0003	0.0035	0.0021	0.0025	0.0106	0.5324
15–16	0.8523	0.0002	0.0005	0.0006	2.7367	0.0029	0.0030	0.0103	0.5262
16–17	0.8490	0.0032	0.0113	0.0018	0.0046	0.0058	0.0071	0.0153	0.5184
17–18	0.8480	0.0004	0.0071	0.0012	0.0040	0.0046	0.0048	0.0046	0.4439
25–26	0.9176	0.0000	0.0002	0.0001	0.0013	0.0006	0.0007	0.1415	0.8190
26–27	0.9136	0.0000	0.0002	0.0002	0.0058	0.0009	0.0009	0.0176	0.7087
27–28	0.8955	0.0006	0.0019	0.0008	0.0048	0.0037	0.0042	0.0775	0.6944
28–29	0.8825	0.0010	0.0176	0.0023	0.0051	0.0068	0.0071	0.0571	0.6407
29–30	0.8769	0.0009	0.0082	0.0075	0.0244	0.0123	0.0175	0.0253	0.6036
30–31	0.8703	0.0024	0.0109	0.0033	0.0097	0.0104	0.0112	0.0298	0.5885
31–32	0.8689	0.0002	0.0024	0.0018	0.0091	0.0050	0.0055	0.0066	0.5725
32–33	0.8684	0.0002	0.0022	0.0011	0.0017	0.0021	0.0023	0.0021	0.5695

Table VIII. Comparative study for line vsis evaluated at 175% of base case on IEEE 33-bus system.

From bus – To bus	V_j,(p.u)	FVSI	Lmn	LQP	Lp	NLSI	L_d	L	SI
7–8	0.8722	0.01159	0.0090	0.0067	0.0560	0.0252	0.0271	0.1126	0.5772
8–9	0.8601	0.00053	0.0011	0.0009	0.0117	0.0044	0.0047	0.0549	0.5458
9–10	0.8489	0.00055	0.0016	0.0009	0.0068	0.0046	0.0049	0.0516	0.5190
10–11	0.8472	0.00000	0.0004	0.0001	0.0007	0.0007	0.0007	0.0078	0.5147
11–12	0.8443	0.00002	0.0009	0.0003	0.0018	0.0016	0.0017	0.0137	0.5059
12–13	0.8324	0.00336	0.0235	0.0025	0.0059	0.0079	0.0082	0.0556	0.4784
13–14	0.8279	0.00112	0.0058	0.0036	0.0085	0.0077	0.0082	0.0211	0.4693
14–15	0.8252	0.00008	0.0006	0.0003	0.0042	0.0026	0.0031	0.0133	0.4629
15–16	0.8225	0.00023	0.0006	0.0007	1.5560	0.0036	0.0038	0.0129	0.4561
16–17	0.8186	0.00400	0.0116	0.0022	0.0059	0.0072	0.0089	0.0192	0.4477
17–18	0.8174	0.00050	0.0088	0.0015	0.0050	0.0058	0.0060	0.0058	0.3441
25–26	0.9014	0.00000	0.0002	0.0001	0.0013	0.0007	0.0008	0.1718	0.7872
26–27	0.8965	0.00001	0.0002	0.0002	0.0063	0.0011	0.0011	0.0215	0.6597
27–28	0.8748	0.00079	0.0021	0.0010	0.0061	0.0045	0.0051	0.0944	0.6433
28–29	0.8592	0.00124	0.0181	0.0028	0.0064	0.0083	0.0088	0.0700	0.5829
29–30	0.8525	0.00116	0.0103	0.0092	0.0258	0.0152	0.0216	0.0312	0.5416
30–31	0.8446	0.00296	0.0146	0.0041	0.0115	0.0128	0.0139	0.0368	0.5249
31–32	0.8428	0.00020	0.0029	0.0022	0.0115	0.0062	0.0068	0.0082	0.5073
32–33	0.8423	0.00020	0.0027	0.0013	0.0021	0.0026	0.0028	0.0026	0.5040

III. CONCLUSION

The main objective of the paper was to predict the weak line in the power system based on the line VSIs assessment. The line VSIs includes FVSI, Lmn, LQP, Lp, NLSI, Ld, L and SI. These indices are based on the concept of voltage quadratic equation. Simulations were performed on the IEEE 12-bus and IEEE 33-bus test systems. The voltage collapse problem was analysed in view of increasing load. The results obtainedwereconsistentinnature.Fromtheresultsitcanbe appropriate concluded that the index in identifying the weak line in the test system was SI. Thus SI index can be used as anindicatorforplacingcompensationdevices.Furtheranalysis canbedonebyconsideringdynamicloadmodels.

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