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Test of Significance and Fiducial Limit of Voltage Stability Index for Indian 205 Bus System

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Voltage delivery stability is frequently used to analyze power delivery systems. Under stressed condition, these indices denote the flexibility of voltage stability condition and predict the voltage collapse phenomenon by weak area clustering. The prediction of voltage collapse is very important for the smooth operation of power system, so that situation of voltage collapse could be avoided. For small transmission system, these indices work satisfactorily. In the present work, a large transmission system equivalent to 205 bus Indian transmission system has been examined. The Fast Voltage Stability Index (FVSI) proposed has been applying to test the system under consideration. Various aspects of power delivery system for example voltage profile, maximum load-ability limit, weakest bus and the different weak area clustering have been examined. Although the FVSI values obtained in the test result are capable of identifying the weak buses of the system, yet they vary in a non-linear manner i.e. for increasing values of load, the FVSI values first increase and then decrease.

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Keywords: Transmission systems; maximum load-ability; voltage stability index; weak area clustering; congestion.

NOMENCLATURE

dE/dV	: Variation of generator voltage to load voltage.
VCPI	: Voltage Collapse Proximity Indicator.
$(dQg)/dQ$	: Variation in total reactive power generator wrt reactive load change.
Q	: Reactive load change.
E	: Generation voltage.
V	: Load voltage.
X	: Reactance.
$V_{critical}$	: Critical voltage of the bus.
z_i	: Point impedance of the network.
z_L	: Load bus impedance.
$V_1\angle 0$	: Sending end (bus1) voltage.
$V_2\angle\delta$	: Receiving end (bus2) voltage.
$P_1 \& P_2$	: Sending end (bus1) and receiving end (bus2) active powers.
$Q_1 \& Q_2$	: Sending end (bus1) and receiving end (bus2) reactive power.
$S_1 \& S_2$	: Sending end (bus1) and receiving end (bus2) apparent/ real power.
δ	: Angle difference between sending end (bus1) and receiving end (bus2) voltage.
I	: Current.
FVSI	: Fast Voltage Stability Index.
V_i	: Sending end (bus1) voltage.
Z	: Impedance of the line.
X	: Reactance of the line.
Q_j	: Reactive power at the receiving end (bus2).

1. INTRODUCTION

Voltage stability analysis is a classical dilemma for power engineers and with interconnected ever growing system, the voltage stability problem has also become a serious issue. The main cause of voltage collapse is voltage instability, which may lead to partial or full power interruption in the system. Voltage instability is characterized by a high percentage of large and small induction motor loads. When such a system is subjected to sudden disturbance or fault, the motor begins to slow down and draws more reactive power. This increase in VAR consumption causes (i) increase in the reactive loss in the system and (ii) reduces the reactive power supplied by the line charging capacitor banks because of severe dip in the system voltage. The net effect is that system voltage may not recover even after clearing of the fault and may even fall further, thereby driving the system towards voltage collapse. For the last four decades, many system outages have been reported due to voltage instability [1].

Voltage stability is the capability of a power system to conserve ample voltage magnitudes at buses, such that when nominal load of the system is increased, the actual power transferred to the load will increase, and both power and voltage are manageable. The system gets into a condition of voltage instability when there is an occurrence of fault, natural disturbances, sudden increase in load or sudden change in system and this causes the bus voltage to drop rapidly. The operators and automatic system controllers fade to halt the decay. This voltage decay may take few seconds or ten to twenty minutes to resolve the instability condition. However, if this voltage decay continues further for the long time, voltage collapse will occur. Due to fiscal and environmental pressures, nowadays the systems are being forced to operate in stressed conditions causing the problem of maintaining the required bus voltages within acceptable limit, giving rise to voltage stability protection.

The problem of power system rotor angle stability is well understood and documented. This problem has now largely been overcome due to improvements in the design philosophy on machines and control strategies such as power stabilisers, fast excitation and protection systems. As real power is the key variable to analysis of rotor angle stability, reactive power is central to analysis of voltage stability. Reactive power, compared to the real power, is easier to generate but more difficult to transmit. It has been observed that balance of reactive power is highly essential to maintain bus voltage at nominal value. Bus voltages would dip if demand of reactive power is more than that generated. However, if reactive power support is adequate, bus voltage will recover. But there are situations in which additional reactive power support will not be able to prevent the bus voltage from decaying further thereby giving rise to the situation of voltage instability. System outages due to voltage instability have been reported for the last three decades and voltage stability improvement has become a challenging issue in planning a security assessment of power systems.

The most frequently used traditional method is based on P-V curve or Q-V curve of the system together with load characteristic. Another method is to calculate an index to find desired bus, the index giving an indication of imminent voltage collapse at that bus (weak bus). In the voltage stability analysis, the impact of disturbance is evaluated. Voltage stability, depending on simulated time, are categories into two category: (i) Static voltage stability, can be analyzed by solving algebraic equations and (ii) Dynamic voltage stability, occur when changes are very fast. The static voltage stability is usually correlated with reactive power imbalance. The loading ability of a bus in a system depends on the reactive power that it can receive from the system. As the system approaches towards maximum loading point, both real and reactive power losses increase, therefore reactive power support should be available locally.

In order to determine the closeness of the system to the voltage instability point, it is useful for an operator, if they are provided with simple voltage stability indicator. There are various indicators for voltage stability suggested in the literature and these are:

i. **Minimum singular value and condition number:** Near voltage instability point, the minimum singular value and the condition number (ratio of maximum to minimum singular values of Jacobian) of the system Jacobian (or Power flow Jacobian) assume zero and infinite values, respectively. These indices have been used for AC as well as AC-DC networks.
ii. **Sensitivity Methods:** Variation of generator voltage to load voltage (dE/dV) has also been used as proximity index. These becomes infinite (showing uncontrollability of load voltage) at the instability point.
iii. **Voltage Collapse Proximity Indicators (VCPI):** VCPI is having two different forms. The first is defined as the Variation of total reactive power generation (Q_g) change to the reactive load (Q) change i.e.

$$\text{VCPI} = \frac{dQ_g}{dQ} \tag{1.1}$$

The Variation becomes infinite at the critical loading point. Let the generation and load voltages be E $\angle\delta$ and V $\angle 0$ respectively and transfer reactance as X. Assume real power load P = 0, hence δ=0. So, it can be proved that

$$Q = \frac{EV}{X} - \frac{V^2}{X} \tag{1.2}$$

At critical loading point, the sensitivity becomes infinite. Thus, VCPI is a very sensitive indicator of imminent voltage collapse.

$$\frac{dQ}{dV} = 0 \tag{1.3}$$

$$V_{critical} = \frac{E}{2} \tag{1.4}$$

$$\frac{dQ_g}{dQ} = \frac{1}{\sqrt{1-Q/Q_{max}}} \tag{1.5}$$

Voltage V changes from E at no load to $E/2$ at maximum load; VCPI changes from unity at no load to infinity at maximum load (i.e. large reactive power is required at the sending end to support an incremental increase in load). Thus, VCPI is a very sensitive indicator for voltage collapse.

The second one is defined as the ratio of driving point impedance (z_i) of the network at a load bus i to the load bus impedance (z_L).

$$\text{VCPI} = \frac{z_i}{z_L} \tag{1.6}$$

This becomes unity at critical point (where complete black out occur) of the load.

Balamourougan et al. [2] in 2004 proposed a new technique which is used to predict voltage collapse. The author uses voltage magnitude, voltage angle of different buses and network admittance matrix, to determine voltage collapse. Musirin et al. [3] in 2002 proposed a novel Fast Voltage Stability Index to determine the maximum loading limit of the system before voltage collapse, so that essential precaution can be taken to omit system capacity contraventions. Maximum loading capacity is the threshold value of reactive power upto which a system can remain stable, can maintain steady state voltage stability. FVSI is computed at every line of the system to check the voltage stability of the line. These facts can be used by planning or operation engineers in verifying that any increase or decrease of reactive power in the system cannot exceed the maximum load-ability, which causes contravening the voltage stability limit.

Wartana, et al. [4] has suggested a multi objective based technique, which is used to upgrade the power system load-ability. The author finds out the optimal location of FACTS controller by using particle swarm optimization technique. The main objective of this paper is to maximise the system load-ability which is subjected to maintain the system security, integrity and stability. Madhvi et al. [5,6] explained the role of FACTS controller in the power system to remove congestion and suggested an optimization technique "Inspection Method" for the best location of FACTS Controller.

C. Reis [7], 2009 analysis the line stability indices and tested on in IEEE 14 and IEEE 57 bus bar test systems. The author's result concluded that by using this index the weakest bus and critical line of the system can be correctly identified. In [8], Musirin uses FVSI index to calculate maximum load-ability of a particular load bus in the system. The author tested this technique on IEEE Reliability Test System (RTS) and concluded that the proposed technique is able to calculate the maximum load-ability of the system. Subramani [9], calculated the distance between the current operating point and voltage collapse point within the power system. The indices can be used to detect the following things (i) the critical bus of a power system (ii) the stability of line connected between two buses in an interconnected network (iii) calculate the voltage stability margins of a system. Chattopadhyay [10] proposes a voltage stability index for radial distribution system.

In present paper, a case study is analysis on a large system i.e. Indian 205 bus transmission system so that weakest bus is to be analysis and according to that FACTS controller can be placed on the identified bus. The technique is successfully implemented on the system and the results have been shown in the paper.

2. INDEX FORMULATION

A two bus system power model for Fast Voltage Stability Index can be derived as follows

The symbols V_1 and V_2 represents sending end i.e. bus 1 and receiving end i.e. bus 2 (Fig. 1) voltages of the system, $P_1$and P_2 represents the sending end (bus 1) and receiving end (bus 2) active powers of the system, Q_1 and Q_2 represents the sending end (bus 1) and receiving end (bus 2) reactive power of the system, $S_1$and $S_2$are the sending end (bus 1) and receiving end (bus 2) apparent power of the system, δ = δ_1-δ_2 is the angle difference between sending end and receiving end voltage.

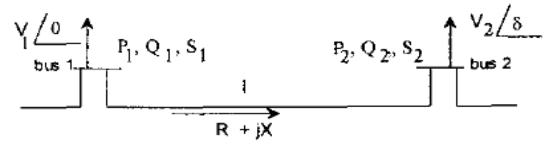

Fig. 1. Two bus system power model

The current that is flowing in the line is given by:

$$I = \frac{V_1\angle 0 - V_2\angle\delta}{R+jX} \tag{2.1}$$

Where V_1 is consider as a reference voltage of the line, hence angle is considered as 0. The real power at bus 2 is given by:

$$S_2 = V_2 I^* \tag{2.2}$$

The equation (2.2) can be rearranged as;

$$I^* = (S_2/V_2) \tag{2.3}$$

The apparent power and voltage at bus 2 is given by $S_2 = P_2 + jQ_2$ and $V_2 = V_2\angle\delta$ respectively. Putting these two values in eq (2.2), we get

$$I = \frac{P_2 - jQ_2}{V_2\angle -\delta} \tag{2.4}$$

Equating equation (2.1) in equation (2.4), we get

$$V_1V_2\angle -\delta - V_2^2\angle 0 = (R + jX)(P_2 - jQ_2) \tag{2.5}$$

Now, separating real and imaginary part of equation (2.5), we obtain

$$V_1V_2\cos\delta - V_2^2 = RP_2 + XQ_2 \tag{2.6}$$

and,

$$-V_1V_2\sin\delta = XP_2 - RQ_2 \tag{2.7}$$

By rearranging eq (2.7), we get

$$P_2 = \frac{RQ_2 - V_1V_2\sin\delta}{X} \tag{2.8}$$

Now, putting equation (2.8) in equation (2.6) produce a quadratic equation in terms of V_2

$$V_2^2 - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \quad (2.9)$$

By solving it, we obtain, $V_2 = \frac{aV_1 \pm \sqrt{(aV_1)^2 - 4(X + \frac{R^2}{X})Q_2}}{2}$

Where,

a = $\frac{R}{X}\sin\delta + \cos\delta$

But to get real roots of V_2, the discriminant should be greater or equal to zero, i.e.

$$(aV_1)^2 - 4(X + \frac{R^2}{X})Q_2 \geq 0 \quad (2.10)$$

As δ is very very small, then

$\delta \approx 0$, R$\sin\delta \approx 0$ and X$\cos\delta \approx X$

Voltage stability indices can be manipulate to predict the voltage stability condition of the power system. The mathematical formulation is derived by Musirin et al. [3]. The index can either be used for voltage stability analysis with or without contingency or can be assigning to a bus or line. In this work, the voltage stability index is evaluated for all lines and corresponding buses. The index value evaluated close to 1.0 will signify the limit of voltage instability. The voltage stability index is given by

$$FVSI = \frac{4Z^2Q_j}{V_i^2X} \quad (2.11)$$

Where V_i =Sending end (bus1) voltage, Z = impedance of the line, X = reactance of the line, Q_j =Reactive power at the receiving end (bus2). The index value evaluated should be always less than one for a healthy power system.

3. TEST SYSTEM

A test system equivalent to an Indian 205 bus transmission system is studied for research justification with modified data. A MATLAB program is developed and bus having least value of maximum load-ability limit list has been calculated. This least load-ability limit of a particular bus will determine the weakest bus of the transmission system and therefore, it requires the proper placement of a FACTS controller.

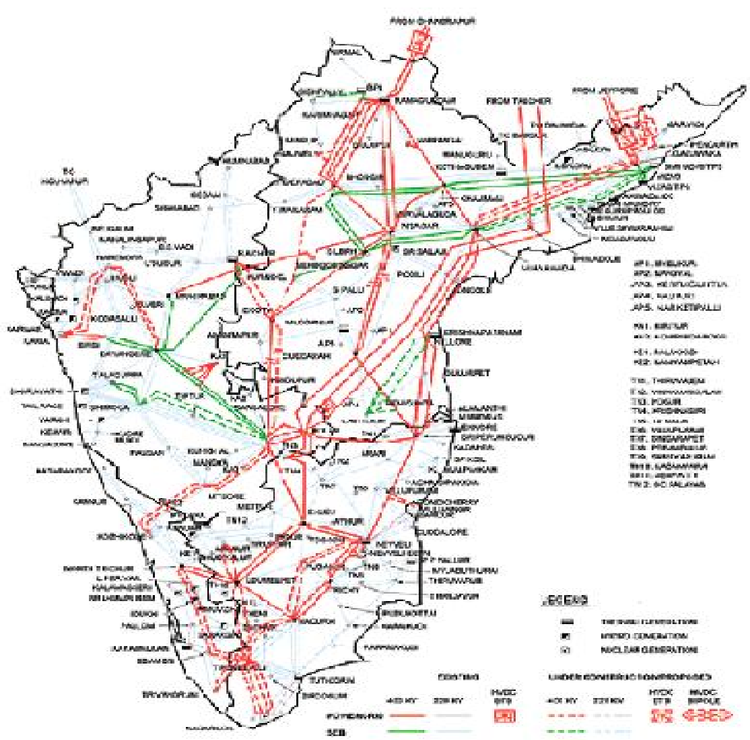

Fig. 2. Zonal-wise grid map of real-life 205-bus system

The grid map of Indian 205 bus Transmission System is shown in Fig. 2. This system is consists of twenty two generators on buses number 1 to 22. This system is having 118 loads, which is consuming total real and reactive powers of 8323 MW and 6469 MVAR respectively through 240 transmission lines. This system is also having 33 shunt compensators and 22 reactors. There are 47 numbers of transformers in the system.

4. RESULTS

Maximum load-abilities of each load bus are calculated. The bus having least maximum load-ability limit was evaluated as the weakest bus of the system. It is found that for some buses, the load flow did not converge up to 100 iterations. However, the load flow converged within 500 iterations for those buses (this is the one disadvantage of the index, yet this index is able to find out the weakest bus of the system). But this happened for only some buses so those buses are considered as inadmissible. The weakest bus found this way may be considered as the optimum location for the placement of a FACTS controller. The simulation results for Indian 205 bus Transmission System is given in Table 1.

Table 1. Maximum Load-ability limit Calculation for 205-bus Indian Transmission System

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
1 to 22	Generator bus	-	-
23	3242	0.9998	0.8234
	-7633	0.9999	1.3339
24	574.8	0.9999	0.8202
	-1489	0.9999	1.4843
25	545	0.9996	0.8192
	-1650	0.9999	1.4483
26	429	0.9828	0.6994
	-811	0.9996	1.4126
27	807.5	0.9999	0.6450
	-2916	0.9997	1.5739
28	139.8	0.9996	0.6802
	-298	0.9990	1.3867
29	219.3	0.9984	0.5695
	-1044	0.9996	1.5898
30	202	0.9960	0.5724
	-1073	0.9994	1.6037
31	259.7	0.8834	0.6879
	-816	0.9994	1.4589
32	188.8	0.9748	0.6424
	-729	0.9997	1.6472
33	295	0.9916	0.7008
	-661	0.9999	1.4633
34	195.5	0.9405	0.5975
	-1216	0.9996	1.5943
35	262.4	0.9854	0.6789
	-740	0.9996	1.4789
36	393.2	0.9568	0.6774
	-3047	0.9999	1.8445
37	184.3	0.6215	0.6527
	-1635	0.9998	1.9942
38	99.8	0.8999	0.4157
	-2210	0.9998	2.4590
39	158.9	0.9996	0.7201
	-387	0.9997	1.4271
40	710.9	0.9559	0.7915
	-2818	0.9998	1.5410

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
41	180.5	0.9994	0.7466
	-852	0.9999	1.6929
42	681	0.9997	0.5674
	-2740	0.9999	1.6288
43	1788	0.9984	0.6267
	-7727	0.9999	1.6165
44	80.5	0.9895	0.5819
	-479	0.9993	1.7772
45	379.9	0.9980	0.6933
	-717	0.9992	1.3252
46	347	0.9981	0.6230
	-1316	0.9996	1.6169
47	357.8	0.9634	0.6362
	-1440	0.9997	1.6117
48	140.6	0.9988	0.6991
	-259	0.9987	1.3372
49	333.3	0.9989	0.6797
	-963	0.9997	1.5015
50	162.6	0.9989	0.6922
	-330	0.9996	1.3576
51	252.9	0.9997	0.6474
	-613	0.9994	1.4345
52	66.4	0.9991	0.7301
	-295	0.9994	1.5386
53	147.4	0.9991	0.7756
	-269.7	0.9999	1.3319
54	305.3	0.9600	0.6640
	-1343	0.9997	1.7229
55	1242	0.9919	0.5211
	-11005	0.9999	1.9911
56	271.7	0.9997	0.7168
	-562	0.9988	1.3596
57	452.5	0.9998	0.6646
	-1233	0.9997	1.4144
58	219.2	0.9780	0.6928
	-491	0.9999	1.3604
59	494.5	0.8144	0.6049
	-3105	0.9998	1.8180
60	434	0.7637	0.6024
	-2341	0.9999	1.6478
61	309.1	0.9549	0.7143
	-800	0.9998	1.4287
62	238.8	0.6897	0.6619
	-2108	0.9997	1.9077
63	239.6	0.9819	0.6622
	-1989	0.9999	1.7128
64	686	0.9988	0.6241
	-1771	0.9999	1.3820
65	521.4	0.9831	0.5313
	-1683	0.9999	1.4108
66	269.8	0.9982	0.6136
	-2796	0.9998	1.9998
67	214.1	0.9998	0.7850
	-939	0.9998	1.5109

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
68	479.4	0.8744	0.6986
	-2982	0.9998	1.6270
69	262.6	0.9997	0.6696
	-990	0.9995	1.4198
70	245.9	0.9996	0.6943
	-518	0.9985	1.3160
71	283.8	0.9994	0.7064
	-516	0.9992	1.2899
72	262	0.9945	0.6716
	-786	0.9993	1.3557
73	515.1	0.8572	0.5675
	-1401	0.9998	1.3728
74	435.6	0.8914	0.6569
	-1461	0.9999	1.4673
75	398.45	0.9727	0.5553
	-1978	0.9999	1.6282
76	281.3	0.9064	0.7214
	-1875	0.9997	1.6265
77	313.3	0.8673	0.6824
	-1357	0.9998	1.5433
78	354	0.9510	0.5998
	-1961	0.9997	1.6518
79	425.2	0.9995	0.6547
	-1160	0.9995	1.4420
80	187	0.8700	0.5187
	-1885	0.9999	2.1373
81	226.9	0.8398	0.6667
	-2144	0.9998	1.8569
82	453.8	0.9998	0.6875
	-846	0.9999	1.3716
83	806	0.9990	0.6690
	-3280	0.9999	1.6429
84	370.6	0.9996	0.8193
	-1268	0.9999	1.4344
85	199.1	0.9127	0.6066
	-1387	0.9998	1.9252
86	977	0.9977	0.6596
	-4322	0.9998	1.6099
87	1589	0.9994	0.6942
	-3703	0.9998	1.4034
88	452	0.9983	0.7001
	-593	0.9998	1.3130
89	778.4	0.9997	0.6490
	-2553	0.9999	1.5181
90	88.7	0.9996	0.7634
	-562	0.9992	1.5770
91	475	0.9981	0.7852
	-1611	0.9998	1.4023
92	1286	0.9995	0.7874
	-4434	0.9998	1.4376
93	545.1	0.9996	0.7220
	-807	0.9996	1.3269
94	231.9	0.9996	0.6328
	-1032	0.9995	1.7111

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
95	298	0.9977	0.7623
	-498	0.9997	1.3171
96	279.1	0.7947	0.6778
	-1181	0.9997	1.6531
97	430	0.9998	0.7376
	-680.8	0.9999	1.2863
98	304.99	0.9063	0.6962
	-1145.3	0.9999	1.5568
99	1327	0.9996	0.5512
	-9410	0.9999	1.8456
100	390.4	0.9998	0.6824
	-881	0.9999	1.3513
101	846	0.9999	0.7361
	-1559	0.9996	1.3198
102	680.6	0.9999	0.8073
	-2621.5	0.9999	1.4343
103	1392.4	0.9999	0.5858
	-7342	0.9999	1.6893
104	565.2	0.9998	0.6884
	-1570	0.9996	1.4171
105	459	0.9998	0.6851
	-2357	0.9999	1.6057
106	442.2	0.9996	0.7163
	-942	0.9999	1.3179
107	789	0.9997	0.6617
	-3425	0.9998	1.6202
108	548.3	0.9513	0.7822
	-1122	0.9997	1.3450
109	221.7	0.9999	0.8295
	-619	0.9999	1.4046
110	1570.8	0.9999	0.7459
	-5737	0.9999	1.4584
111	576.3	0.9997	0.6844
	-1356	0.9998	1.3613
112	301.05	0.9999	0.8245
	-793	0.9994	1.3514
113	660.6	0.9997	0.7674
	-2610	0.9998	1.5154
114	381	0.9997	0.7179
	-922	0.9994	1.3696
115	331.5	0.9999	0.7294
	-811	0.9990	1.3568
116	479.8	0.9999	0.7384
	-2333	0.9999	1.5876
117	652.8	0.9997	0.7191
	-5410	0.9999	1.7861
118	505.92	0.9673	0.5108
	-2893	0.9999	1.6579
119	513	0.9998	0.7723
	-1863	0.9999	1.3764
120	268	0.9990	0.6371
	-949.8	0.9999	1.4835
121	473.62	0.8436	0.6145
	-1221	0.9997	1.3217

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
122	283	0.9148	0.6335
	-1067	0.9995	1.5197
123	305.8	0.9999	0.7429
	-706	0.9996	1.3765
124	1144.9	0.9999	0.7233
	-5203	0.9999	1.4668
125	717.46	0.9989	0.7170
	-3513	0.9998	1.4852
126	957	0.9998	0.7782
	-3334	0.9999	1.3876
127	744.9	0.9870	0.6957
	-1200	0.9994	1.3447
128	1125.8	0.9999	0.7454
	-1459	0.9996	1.2979
129	888	0.9988	0.6428
	-1603	0.9997	1.3823
130	839.5	0.9811	0.7165
	-1788	0.9998	1.3721
131	595	0.9994	0.7272
	-732	0.9996	1.3206
132	684	0.9999	0.8362
	-1070	0.9995	1.3117
133	307.93	0.8723	0.8684
	-1108	0.9999	1.3940
134	735.7	0.9998	0.7754
	-2117	0.9999	1.3789
135	419.1	0.9997	0.7822
	-2099	0.9998	1.5499
136	247.7	0.7061	0.6684
	-1243	0.9999	1.7510
137	603.6	0.9998	0.7866
	-3055	0.9998	1.5484
138	774.6	0.9998	0.7669
	-1189	0.9999	1.3500
139	1224.8	0.9999	0.7091
	-2712	0.9998	1.3481
140	1205.8	0.9998	0.6334
	-3938	0.9998	1.4442
141	1682	0.9998	0.5992
	-6951	0.9999	1.5341
142	1403.7	0.9997	0.5765
	-10940	0.9999	1.8214
143	1509.3	0.9999	0.6606
	-6791	0.9999	1.5605
144	690	0.9997	0.7898
	-2283	0.9999	1.4031
145	1722	0.9998	0.6838
	-6807	0.9999	1.4996
146	1273.7	0.9997	0.6415
	-5454	0.9998	1.5893
147	582.3	0.9998	0.6696
	-1219	0.9999	1.3370
148	579.9	0.9830	0.6944
	-1217	0.9997	1.3412

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
149	1427	0.9991	0.6141
	-5690	0.9999	1.5198
150	571.9	0.9996	0.7328
	-1900	0.9999	1.4448
151	1473	0.9998	0.6918
	-7000	0.9999	1.5743
152	526	0.9999	0.7353
	-1026	0.9998	1.3364
153	698.28	0.9894	0.6219
	-2613	0.9997	1.5585
154	423.5	0.9997	0.7691
	-1227	0.9999	1.3302
155	1455.9	0.9998	0.6335
	-5253	0.9998	1.5086
156	737.4	0.9998	0.7677
	-4337	0.9999	1.5333
157	640.83	0.9940	0.5619
	-4600	0.9999	1.7728
158	872.7	0.9769	0.8475
	-2581	0.9999	1.3591
159	664.7	0.9996	0.6719
	-2377	0.9997	1.4947
160	1217.4	0.9998	0.7735
	-4645	0.9999	1.3843
161	1598.8	0.9998	0.6982
	-2799	0.9998	1.3318
162	970.1	0.9997	0.7441
	-2523	0.9998	1.4117
163	1341.4	0.9609	0.7250
	-3502	0.9999	1.4886
164	1477	0.9999	0.7343
	-4200	0.9999	1.4857
165	375.2	0.9983	0.7499
	-1070	0.9998	1.4428
166	2651	0.9999	0.7893
	-7193	0.9999	1.4027
167	649.3	0.9998	0.6952
	-1284	0.9999	1.3280
168	2388	0.9995	0.7953
	-8248	0.9999	1.4684
169	1409.5	0.9999	0.7526
	-3232	0.9999	1.3460
170	1666.7	0.9998	0.6070
	-5805	0.9999	1.4550
171	509.7	0.9999	0.8004
	-2394	0.9997	1.4183
172	1528.6	0.9999	0.7607
	-4641	0.9998	1.3545
173	1587	0.9999	0.5929
	-7186	0.9999	1.6132
174	564	0.9997	0.7689
	-2624	0.9998	1.5305
175	516.5	0.9996	0.6871
	-1481	0.9997	1.4538

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
176	515.1	0.9999	0.7051
	-1159.8	0.9999	1.3714
177	1403.9	0.9999	0.7872
	-4329	0.9999	1.4010
178	1202.2	0.9999	0.7608
	-3193	0.9998	1.3546
179	583.4	0.9998	0.7802
	-1502	0.9994	1.4068
180	383.5	0.9998	0.6987
	-714	0.9995	1.3195
181	2179.6	0.9999	0.7667
	-7569	0.9999	1.3724
182	1153.3	0.9999	0.7912
	-4301	0.9998	1.3985
183	1129.8	0.9999	0.7120
	-3494	0.9998	1.4407
184	285	0.8300	0.7616
	-1793	0.9997	1.5511
185	596.5	0.9995	0.6525
	-2700	0.9999	1.4393
186	496.5	0.8051	0.6166
	-2619	0.9998	1.5157
187	2076.2	0.9562	0.7052
	-3418	0.9998	1.3139
188	1735.8	0.9904	0.7781
	-5729	0.9999	1.3865
189	751.4	0.9998	0.7387
	-2879	0.9999	1.4635
190	1551.3	0.9999	0.7123
	-8394	0.9999	1.5875
191	902.4	0.9999	0.7436
	-3488	0.9999	1.4656
192	1126.7	0.9999	0.6837
	-2961	0.9999	1.3877
193	1113.2	0.9998	0.7104
	-4518	0.9999	1.4965
194	1098.7	0.9998	0.6676
	-3484	0.9999	1.4728
195	601.7	0.9411	0.6937
	-2707	0.9998	1.5759
196	716.6	0.9993	0.6275
	-2446	0.9999	1.4191
197	2180.3	0.9999	0.7880
	-7827	0.9999	1.4016
198	955.2	0.9997	0.6632
	-6540	0.9999	1.6581
199	1595	0.9996	0.7831
	-5501	0.9999	1.3915
200	1765.9	0.9999	0.7667
	-5881	0.9999	1.3655
201	1773.4	0.9999	0.9316
	-8067	0.9999	1.5965
202	1631.2	0.9999	0.7809
	-6156	0.9999	1.3897

Bus number	Maximum Load-ability limit (MVAR)	Voltage Index	Voltage Magnitude (V)
203	2201.2	0.9978	0.8084
	-6546	0.9999	1.3927
204	2229.6	0.9999	0.7773
	-6470	0.9999	1.3645
205	1317.8	0.9999	0.8189
	-4264	0.9999	1.3792

5. CONCLUSION

In the present work, a thorough study of voltage stability analysis for 205 bus transmission system which covers almost entire south India has been presented.

The voltage stability analysis using Fast Voltage Stability Index (FVSI) has been carried out for 205 bus transmission system and it has been observed that FVSI values vary continuously for variation in load and varies in a non-linear manner as R/X ratio is high and the system is very large. However, the drawback of index chosen is its value increases sometime even if we decrease the load on any bus. In the present work, negative load has been applied for different buses and FVSI shows collapse point. Positive load represents a load and negative load represents a generator for testing the system. Although FVSI varies in a non-linear manner, yet it is capable of suggesting weak buses of the system. The FVSI value indicates the collapse point when load is further increased to the maximum load-ability of the bus. Weak bus of the system is identified as

i. A bus is loaded slowly and FVSI is calculated.
ii. When FVSI becomes 0.9999, corresponding load is noted.
iii. The same process is repeated for all the buses and corresponding value of maximum load-ability is noted.
iv. These noted values of maximum load-ability of all buses have been compared.
v. The bus having least value for maximum load-ability is reported as weakest bus.

In the present work, 52, 44, 90, 38, 28 respectively are identified as weak buses of the system as it has least value of maximum load-ability. Maximum load-ability at 142th bus is -10940 and it indicates that a large size generator is to be connected to this bus.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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