Finding and Ranking Load Bus Voltage Stability Severity Indexes Due to Load Reactive Power Changing Using User-Defined and Modified Voltage Stability Indices.

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Abstract: Recently the utility is facing severe voltage stability problems so that to satisfy end users exponential growth of energy demands. As a solution, considering high operational cost of constructing new power generation, transmission and distribution system the utility is connecting more loads on existing load buses up to their thermal limits. But in power system increasing inductive load brings voltage stability problem due to an armature reaction. Thus, if we connect an additional inductive load, the armature reaction is subtractive to the main field, resulting in voltages fall-down and hence yields further voltage collapses. In addition, since under heavy load the line absorbs more reactive power than it generates, leads to transmission line stresses and its fall down when it exceeds maximum thermal limits. Therefore, this article targets finding voltage stability margins of load buses and ranking them based on their severity indexes for reactive load power changing using user modified voltage stability indices and recommending further solutions

Keywords: voltage stability problems, power, voltage engineering

Introduction

For safe operation, control, and utilization an adequate and stable power system network is needed. In general, during operating condition power system network will lay on two different states called stable and unstable states. Under steady state condition all power system parameters such as; voltage, power, synchronous frequency and synchronous accelerating angles are assumed to be operating within its equilibrium condition or accepted standard and the network is said to be stable. However, due to creatine constraints such as; change in demand per time interval, power generation and transmission line constraints and environmental conditions power system network change from its steady state points. Thus, if power system components maintain its steady state condition before and after being subjected to a disturbance from a given initial operating point the network is said to be stable and if the

disturbance is uncontrollable the network is unstable. Some of the power system stability problems are; transient, angular and voltage stability problems. The first two are more related to power generation stability problems. In contrast voltage stability is more related to demand management, especially load reactive power demands.

1. Voltage stability

Voltage stability is an ability of power system network to keep up steady voltages at all buses before and after the network being subjected for disturbance from a given initial operating point. As different scholars research output shows that growth of world economy brought high industrial energy demands. Accordingly, power utilities are forced to connect additional loads on existing load buses up to maximum thermal constraints of the transmission line and bus MVA. These additional loads especially inductive load which are subtractive to main field flow due to armature reaction leads to falling in bus voltage, results in voltage stability problems. On top of it in order satisfy additional reactive demand there will be an excess flow of reactive power flow and yields in line outages due to its maximum thermal limits constraints [1], [2].

2.1 Sources of voltage stability problems

Exponential growth in industrial demand, the existing network configuration and power transmission line thermal unit constraints takes paramount in voltage stability problems. In addition, different researchers, scholars, and engineers identified the main factors which contribute to bus voltage instability problems. For instances; increased power interconnection, advancement in technology, high voltage power transmission over long distance, unfavorable geographical environment for power transmission line expansion, installing new loads considering electricity market, large penetration of wind generation and local uncoordinated controls systems and unsuitable placing of compensators [3], [4]. Therefore, considering these all scenarios which leads to voltage stability problems scholars also proposed different mitigation techniques

2.2 Mitigation techniques of voltage instability.

There are two types of voltage stability problem namely steady state and dynamic voltage stability. Steady state voltage stability deals with small change in load from normal operating condition up to point of voltage collapses. Whereas, dynamic voltage stability is more related to fast transient voltage stability problems including proper time domain analysis for problems like; power transmission line outages and power system faults. Since analyzing steady state and dynamic voltage stability problems at the same time too difficult. This article mainly focuses on the former cases. Some of the mitigation techniques are;

2.2.1 Fast voltage stability index(FVSI).

FVSI begins with energy conservation equation or power equation so that to find out the voltage quadratic equation, which predicts point of voltage collapses. The quadratic form of voltage at bus j based on power flow equation, power flow from generator bus to load bus is determined. For stable voltage at load bus the discriminants of quadratic equation should be greater than or equal to zero. considering it, the maximum point of voltage collapse FVSI at load bus is given as;

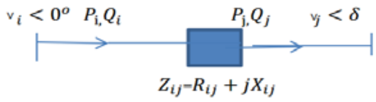

Figure. 1,Two bus power system network [4]

$$V_j = \frac{(V_i(\cos\delta + \frac{R}{X}\sin\delta) \pm \sqrt{(V_i(\cos\delta + \frac{R}{X}\sin\delta)^2 - 4Q_j(\frac{X^2+R^2}{X})}}{2}$$

(1)

To determine the real root, the discriminants set to greater or equal to zero

$$(V_i(\cos\delta + \frac{R}{X}\sin\delta)^2 - 4(Q_j(\frac{X^2+R^2}{X}) \geq 0 \qquad (2)$$

$$\Rightarrow \frac{4(Q_j(\frac{X^2+R^2}{X})}{(V_i(\cos\delta + \frac{R}{X}\sin\delta)^2} \leq 1$$

Since δ is small $\delta \approx 0, \cos\delta = 1, \sin\delta = 0$, Fast Voltage Stability Index (FVSI) can be written as follows;

$$FVSI_j = \frac{4Z^2 Q_j}{V_i X} \leq 1$$

(3)

Accordingly, if FVSI at bus j is approaching to unity bus j is considered as voltage unstable. if FVSI is greater than or equal to unity the intended bus is subjected for voltage collapse.

2.2.2 P-V and Q-V curve methods

It gives an information on to what extent the utility can increase load at load bus up to of point of voltage collapses. Two bus networks considering voltage stability equation and substituting per unit value for stable operation is given as [5], [6] [7] [8] [9]. Assuming constant power factor $k = \frac{q}{p}$, one can increase p and q at most

$$p \leq \frac{1}{2}((1+k^2)^{1/2} - k)$$

(4)

$$\frac{\Delta q}{\Delta v} = 0 \cdot$$

Where: p and q are the receiving end real and reactive power.

Apart from these two mechanisms, the proponents have applied different techniques to find the margin of voltage stability considering two bus power networks. Although, these techniques work perfectly for radially connected power network its application for large interconnected network seems unfeasible. Since power network is complex and meshed together having two or more buses connected end to end motivated the researcher to develop user modified voltage stability indices which comprises the effect of meshed network on voltage stability indices.

2. Developing user modified voltage stability indices.

Step 1: Consider N bus power system network having M loads and K generation unit. Y bus matrix is given as;

$$\begin{vmatrix} I_1 \\ \vdots \\ I_k \\ \vdots \\ I_N \end{vmatrix} = \begin{vmatrix} Y_{11} \ldots Y_{1K} \cdots Y_{1N} \\ \vdots \\ Y_{K1} \cdots Y_{KK} \cdots Y_{KN} \\ \vdots \\ Y_{N1} \cdots Y_{NK} \cdots Y_{NN} \end{vmatrix} \begin{vmatrix} V_1 \\ \vdots \\ V_K \\ \vdots \\ V_N \end{vmatrix}$$

(5)

According to energy conservation the current flowing in to load bus K is equal to zero. Which implies that:

$$I_K = Y_{K1}V_1 + Y_{K2}V_2 \cdots Y_{KK}V_K \cdots Y_{KN}V_N = 0 \quad (6)$$

Apparent power at load bus K is given as;

$$S_K = P_K + jQ_K = V_K I_K^{\bullet}$$

$$\Rightarrow I_K = \frac{P_K - jQ_K}{V_K^{\bullet}}$$

(7)

Relating two equations

$$\frac{P_K - jQ_K}{V_K^{\bullet}} = Y_{K1}V_1 + Y_{K2}V_2 \cdots Y_{KK}V_K \cdots Y_{KN}V_N$$

$$\Leftrightarrow P_K - jQ_K = V_K^2 Y_{KK} + V_K \sum_{i=1, i\neq K}^{N} (V_i Y_{Ki})$$

(8)

Expanding in to real and imaginary part, the power flow equation for load bus K is given as

$$P_K = V_K^2 Y_{KK} \cos\theta_{kk} + \sum_{i=1, i\neq K}^{N} V_K V_i Y_{Ki} \cos(\delta_k - \delta_j - \theta_{kj})$$

$$-jQ_K = V_K^2 Y_{KK} \sin\theta_{kk} + \sum_{i=1, i\neq K}^{N} V_K V_i Y_{Ki} \sin(\delta_k - \delta_j - \theta_{kj})$$

(9)

Let $\delta = \delta_k - \delta_j$ is small value and if we use the trigonometric rule of cos and sin

$$\cos(\delta - \theta_{kj}) = \cos\delta\cos\theta ij + \sin\delta\sin\theta ij$$

&

$$\sin(\delta - \theta_{kj}) = \sin\delta\cos\theta ij - \cos\delta\sin\theta ij$$

(10) since the angle of each bus voltage is very small implies their difference is also very small (approaches to zero). In addition to that for practical power network the transmission line reactance is >> greater than resistance $\theta ij \approx 90$. Which implies that;

$$\cos\delta\cos\theta ij + \sin\delta\sin\theta ij \approx 0$$

& Then real and

$$\sin\delta\cos\theta ij - \cos\delta\sin\theta ij \approx -1$$

imaginary par of equation 10 will be changed as;

$$P_K = V_K^2 Y_{KK} \cos\theta_{kk}$$

$$-jQ_K = V_K^2 Y_{KK} \sin\theta_{kk} - \sum_{i=1, i\neq K}^{N} V_K V_i Y_{Ki}$$

(11)

Then considering imaginary part only the modified voltage stability index equation for load bus K for N bus network (MVSI) will be determined using pythagorize method as follows;

$$V_K^2 - \frac{V_K}{Y_{KK}\sin\theta_{kk}} \sum_{i=1, i\neq K}^{N} V_i Y_{Ki} + \frac{Q_K}{Y_{KK}\sin\theta_{kk}} = 0$$

(12)

$$V_K = \frac{\frac{1}{Y_{KK}\sin\theta_{kk}} \sum_{i=1, i\neq K}^{N} V_i Y_{Ki} \pm \sqrt{\left(\left(\frac{1}{Y_{KK}\sin\theta_{kk}} \sum_{i=1, i\neq K}^{N} V_i Y_{Ki}\right)^2 - 4\frac{Q_K}{Y_{KK}\sin\theta_{kk}}\right)}}{2}$$

(13)

But to have real solution the discriminant should be greater than or equal to zero.

$$\left(\frac{1}{Y_{KK}\sin\theta_{kk}} \sum_{i=1, i\neq K}^{N} V_i Y_{Ki}\right)^2 - 4\frac{Q_K}{Y_{KK}\sin\theta_{kk}} \geq 0$$

(14)

Which means;

$$MVSI_k = \frac{4Q_K Y_{KK} \sin\theta_{kk}}{(\sum_{i=1, i\neq K}^{N} V_i Y_{Ki})^2} \leq 1$$

(15)

Thus, for stable operation MVSI should be less than or equal to one. According if bus MVSI magnitudes are approaching or greater than unity the intended bus is subjected for voltage instability. Finally, buses will be ranked in descending order, from most sever to least according to MVSI magnitudes.

From this modified equation, we can also deduce that one can increase reactive power on load bus for maximum of;

$$Q_K \leq \frac{(\sum_{i=1, i\neq K}^{N} V_i Y_{Ki})^2}{(4 * Y_{KK} \sin\theta_{kk})}$$

(16)

3. Methodology

To find out the voltage stability margin of IEEE bus standard system and ranks them according to their severity indexes using modified voltage stability indices the following steps are followed.

4.1 Selecting IEEE standard bus.

IEEE 57 bus standard network is considered. It exists base 100 MVA and base voltage of 69 KV, 18 KV and 13.8 KV in three different regions. All transformers are considered as a transmission line represented by their series reactance and bus one is considered as slack bus. Finally, all units are given by per unit value as per selected base values.

4.2 Software used for modeling

MATLAB interfaced free power system stability analysis toolbox software called PSAT 2.1.9 is used for modeling the selected network. It is a MATLAB toolbox which is used for electric power system analysis and control. The command line version of PSAT is also GUI Octave compatible with MATLAB. It is a tool that performs power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation. All operations are assessed by means of graphical user interfaces (GUIs) and a Simulink based library provides user-friendly tools for network design.

4.3 Modeling power system network for voltage stability analysis

The steady state IEEE 57 bus standard system model using PSAT software Simulink is given as;

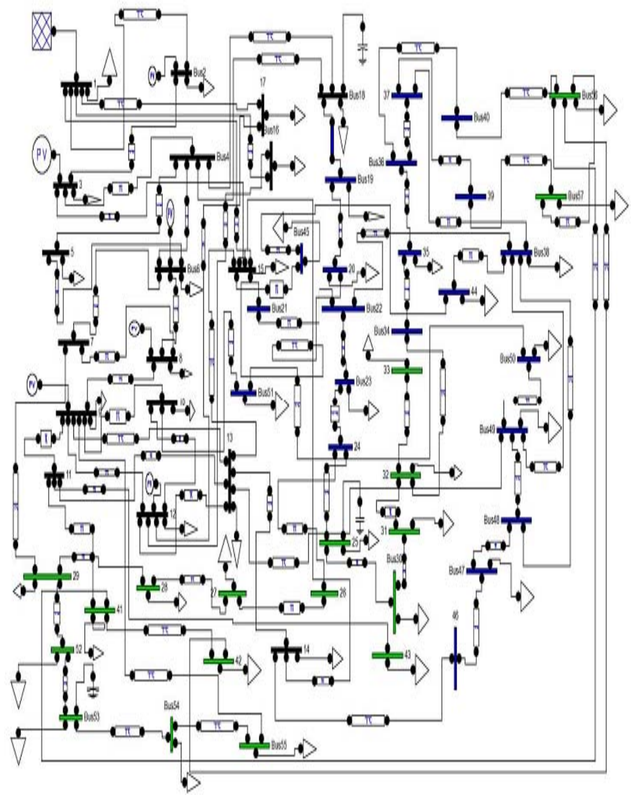

Figure.2, IEEE 57 bus standard system model using PSAT

4.4 Performing load flow analysis and checking base case bus voltage profile.

First, after loading PSAT model to its main directory Newton Raphson load flow simulation is performed for base case. N-R iterative method approximates set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's expansion. In general, it helps to find out an iterative output solution for bus voltages, voltage angle, real and reactive power flow. Based on, the power flow simulation result for standard IEEE 57 bus, 42 loads and six generation, base case voltage profile is given in fig below

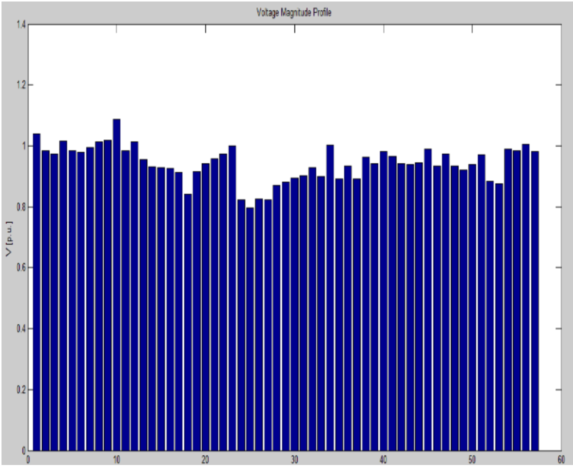

Figure.3, Voltage profile of IEEE 57 bus standard system for base case load flow

The per unit voltage profiles of all buses are almost within acceptable IEEE standard, 0.95 to 1.05 per unit value. It implies that the network is voltage stable for base case load flow. However, due to continuous change in energy demand per time interval the load flow of network also keeps on changing for real system, results in voltage stability problems. Therefore, considering load variation is very crucial for voltage stability analysis.

4.5 Applying continuation power flow analysis

To meet unevenly growth of energy demands utility are forced to connect additional load on existing load buses up to their maximum limits, results in voltage stability problems. So, it mandatory to know that for what extent we load the buses and its effect on bus voltage stability. Newton Raphson based continuation power flow is an ideal technique to find maximum loading factor of a given power system network.

4.5.1 Continuation power flow result of IEEE 57 bus;

The simulation result shows that utility can increase loads for a load factor λ=1.3406. Which means total real and reactive power loads are increased from base case value of 1251 MW and 273.35 MVAR to 1590.96MW & 372.955 MVAR respectively. Overall system power loss also increased from 29.5609 MW &14.34094-MVar to 61.18532084 MW&157.1006865 MVAR respectively. In addition, the total power flow from generation to load through transmission line is also increased irrationally so as to satisfy increased load demand, maintaining energy conservation, see Appendix. However, due to increased loading most IEEE 57 load buses are subjected for voltage stability problems. The graphical relationship between bus voltages and maximum loading factor is given in figure below.

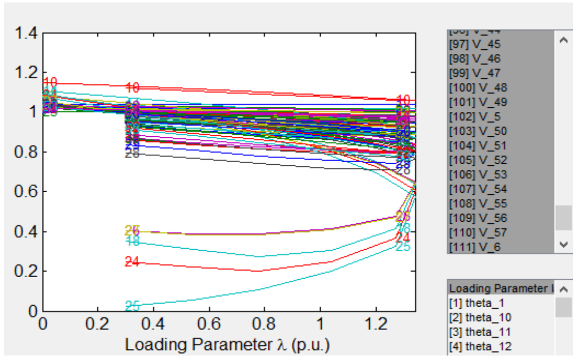

Figure. 4, Load Voltage profile vs maximum loading

Here, it shows that most of load bus voltages drops as load-factor increases and subjected for voltage instability and voltage collapses. Especially, bus 26, 18, 24 and bus 25 more viable for voltage instability. But, generalizing voltage stability from bus voltage only is not enough. In practice voltage instability problem on a bus is a function the surrounding environment like; voltage of other buses, reactive power loading magnitude and line admittances. Therefore, using modified voltage stability indices is an appropriate technique so that to predict critical bus considering different scenarios.

4.6 Identifying and ranking critical buses using MVSI for continuation power flow

To come up on this intended goal, PSAT-MATLAB interfaced coding is done based on the flow chart given below.

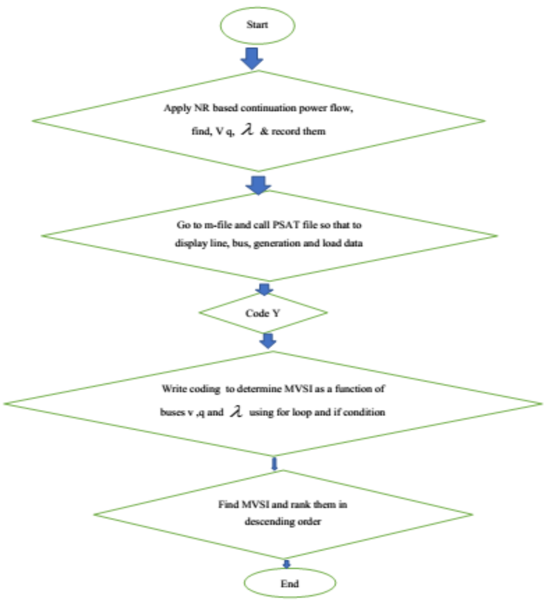

Figure. 5, MATLAB coding flow chart for bus ranking using MVSI for continuation power flow.

PSAT defines and gives its own bus name followed by original bus name as given in table below. Therefore, load bus ranking of IEEE 57 bus for CPF result using MVSI is given in table below

Table 1, Bus ranking of IEEE 57 standard 42 load buses

Bus name	Voltages	Reactive power	MVSI	Bus rankings
[56]-8	1.005	3.7269	0.8271	1
[57]-9	0.96343	0.06256	0.4374	2
[4]-12	1.015	-0.03486	0.2707	3
[12]-2	1.0063	-0.04022	0.2707	4
[54]-6	0.97586	-0.04424	0.2291	5
[9]-17	1.0091	-0.07239	0.1488	6
[8]-16	1.007	-0.07373	0.1369	7
[42]-47	0.8955	-0.07641	0.1229	8
[46]-50	0.88894	-0.0925	0.0937	9
[7]-15	0.97877	-0.09384	0.0803	10
[44]-49	0.89957	-0.09518	0.0788	11
[49]-53	0.8689	-0.10333	0.0788	12
[47]-51	0.95061	-0.11261	0.0693	13
[23]-3	1	-0.11663	0.0655	14
[32]-38	0.87308	-0.11663	0.0625	15
[5]-13	0.96554	-0.12065	0.0604	16
[22]-29	0.94671	-0.12468	0.0583	17
[45]-5	0.97686	-0.12468	0.0506	18
[6]-14	0.95507	-0.13138	0.047	19
[39]-44	0.89365	-0.13138	0.0411	20
[37]-42	0.82002	-0.13674	0.0342	21
[51]-55	0.94735	-0.15417	0.0303	22
[20]-27	0.893	-0.185	0.0292	23
[52]-56	0.80529	-0.21181	0.0292	24
[11]-19	0.92356	-0.2279	0.0277	25
[36]-41	0.88509	-0.26276	0.0277	26
[29]-35	0.78605	-0.27214	0.0268	27
[25]-31	0.57342	-0.28152	0.0259	28
[53]-57	0.79105	-0.29493	0.0259	29
[16]-23	0.86482	-0.31236	0.025	30
[18]-25	0.6382	-0.35509	0.0229	31
[48]-52	0.88951	-0.35526	0.0211	32
[2]-10	0.96738	-0.36196	0.0208	33
[21]-28	0.92243	-0.42229	0.0205	34
[27]-33	0.64306	-0.55367	0.017	35
[50]-54	0.90111	-0.61667	0.0164	36
[24]-30	0.6058	-0.6703	0.0161	37
[10]-18	1.057	-1.0323	0.0139	38
[13]-20	0.89188	-1.2199	0.0098	39
[38]-43	0.93058	-1.2199	0.0089	40
[26]-32	0.64764	-1.9707	0.0077	41
[26]32	0.64764	-1.9707	0.0077	41

But from practical point of view it is very difficult to conclude that the demand on all power system network bus increases at the same time. This necessitates changing reactive power load at a bus and checking voltage stability indices.

4.7 Increasing a load bus reactive power at a time and ranking them using MVSI magnitude.

Continuation power flow can also apply for changing reactive power on a given bus at a time considering predictor corrector is used to determine critically voltage unstable bus. in this case lambda is used as initial parameter and the tangent vector which changes fast as power flow is considered as tangent vector. Continuation power flow output will be recorded when the selected tangent vector= 0 as given in the flow chart.

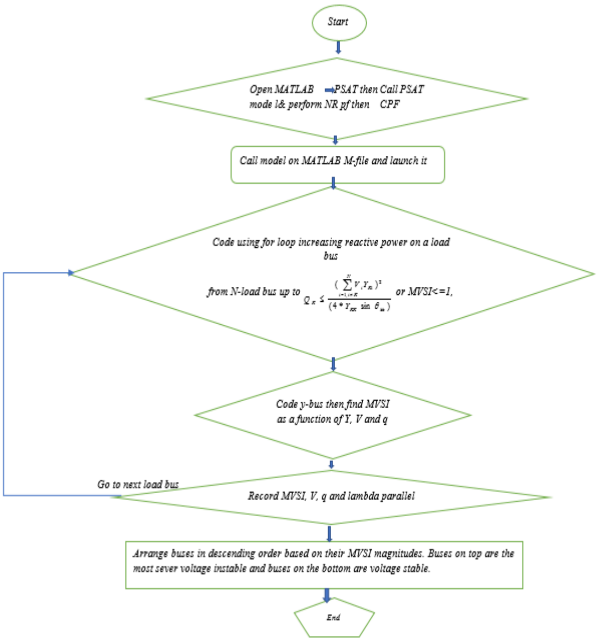

Figure. 6, Flow chart of MATLAB coding to find out bus rankings based on MVSI

Before applying user defined formula (MVSI) on a large and complex power system network first its feasibility is checked by small IEEE bus standard system

4.7.1 Testing and comparing user defined methods

The user modified voltage stability indices formula is first applied on IEEE 6 and IEEE 14 standard load buses. Both 6 and 14 standard system networks were initially built inside the library of PSAT software.

Therefore, based on the flow chart the critical bus ranking for both standard network is given in table 2 and table 3 respectively.

Table 2, Ranking of IEEE 6 bus standard network using MVSI

Bus name	MVSI	Q	V	Remarks	Bus rankings
1	0.795	3.1322	1.05	PV	-
2	1.3835	5.451	1.05	PV	-
3	0.7188	2.8322	1.05	PV	-
4	1.3326	-5.2503	0.53596	Load bus	1
6	0.9077	-3.5762	0.83564	Load bus	2
5	0.6592	-2.5973	0.73347	Load bus	3

Table 3, Ranking of IEEE 14 bus standard network using MVSI

Bus name	MVSI	Q	V	Remarks	Bus rankings
4	1.7865	-1.8108	0.6548	Load bus	1
9	1.5898	-1.6115	0.59981	Load bus	2
14	0.6863	-0.69566	0.56855	Load bus	3
13	0.6656	-0.67468	0.8123	Load bus	4
10	0.5104	-0.51737	0.61942	Load bus	5
5	0.3173	-0.32161	0.65233	Load bus	6
12	0.2656	-0.26917	0.8633	Load bus	7
11	0.1828	-0.18528	0.76813	Load bus	8
3	3.904	-3.9572	0.92738	Load bus	9
6	0.6449	-0.65371	0.95754	Load bus	10
2	0.201	-0.20375	0.99653	Load bus	11

Therefore, since user modified voltage stability indices (MVSI) is well-tested on small IEEE standard buses and its result is almost similar with the output of other research with better quality. Because we can easily apply this method for large complex system. Finally, the ranking of IEEE 57 bus standard system is given in the table below.

Table 4,IEEE 57 bus standard ranking based on their MVSI indices severity.

PSAT defined	Bus name (original)	Bus voltages	Load reactive power	Lambda new	MVSI	Rankings

Bus						
23	3	1	-0.7667	1.3406	1.0399	-
44	49	0.8798	-0.5457	1.3209	0.9596	1
54	6	0.97399	-1.0679	1.3402	0.9283	-
4	12	1.0147	-1.6942	1.3406	0.9105	-
6	14	0.94931	-0.35315	1.3348	0.8985	2
7	15	0.97594	-0.48204	1.3372	0.8725	3
45	5	0.9687	-0.33547	1.3396	0.8516	4
5	13	0.96397	-0.33369	1.3386	0.8469	5
22	29	0.93958	-0.33186	1.3366	0.8435	6
46	50	0.84316	-0.67518	1.3185	0.7888	7
47	51	0.93502	-0.43477	1.3363	0.7582	8
11	19	0.79111	-0.2825	1.322	0.7281	9
10	18	0.97724	-0.27707	1.3307	0.7091	10
12	2	0.98078	-2.1602	1.3352	0.7077	-
9	17	0.99926	-0.81373	1.34	0.707	11
37	42	0.74201	-0.26854	1.3197	0.6916	12
39	44	0.88805	-0.2325	1.3347	0.5914	13
51	55	0.93415	-0.22799	1.3382	0.5794	14
32	38	0.84572	-0.45649	1.3372	0.5503	15
29	35	0.74138	-0.20044	1.3333	0.5276	16
36	41	0.85585	-0.20398	1.3304	0.5209	17
52	56	0.77259	0.77259	1.3304	0.4838	18
16	23	0.84487	-0.17144	1.3581	0.4503	19
42	47	0.86397	-0.78241	1.3396	0.4397	20
53	57	0.75	-0.16924	1.3303	0.4327	21
18	25	0.52302	-0.16566	1.1409	0.4147	22
25	31	0.46893	-0.16398	1.1284	0.409	23
48	52	0.87463	-0.15411	1.3373	0.3919	24
21	28	0.91316	-0.15392	1.3355	0.3915	25
57	9	0.94983	-2.4235	1.3325	0.3781	-
2	10	0.96352	-0.2115	1.3395	0.3746	26
20	27	0.89015	-0.14468	1.339	0.3671	27
27	33	0.53019	-0.11971	1.2574	0.3091	28
49	53	0.80506	-0.55396	1.3283	0.301	29
24	30	0.43485	-0.10931	1.2119	0.2829	30
50	54	0.89065	-0.11135	1.3391	0.2828	31
13	20	0.87219	-0.07104	1.3376	0.1806	32
38	43	0.92523	-0.0671	1.339	0.1703	33
26	32	0.56761	-0.05574	1.3243	0.1449	34
8	16	1.0032	-0.68127	1.3404	0.1008	35
56	8	1.005	3.5292	1.3406	0.073	-

Excluding generation buses, the ranking of load bus in descending order is given in the table. Thus, ranking is performed from the most to least sever voltage unstable load buses based on the magnitudes of MVSI indices. For instances bus; 49, 14, 15,5, 13,29, 50 ,19 and 18 are the most sever voltage unstable buses and needs an additional reactive power compensation. Finally, from the result researcher is concluding that the user defined and modified voltage stability indices can easily apply for both small and complex power system network so that to determine the load bus voltage stability severity and its rankings.

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