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An Efficient Method for Contingency Ranking Using Voltage Stability Index in Power System

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The power system is a complex network consisting of enormous equipment. Failure of any one of this equipment during its operation affects the reliability of the system and it also leads outage of equipment. The impact of outage states on the system reliability is taken into consideration in contingency selection and ranking method. The objective of contingency enumeration is to identify the contingencies which may lead to unreliability. In this paper, a computationally feasible approach to rank severe contingencies using New Voltage Stability Index (NVSI) is proposed. Illustrations using IEEE 30 and practical TNEB 69 bus system in India aim to exhibit the effectiveness of proposed method for considering different heavy loading condition with one outage (line/generator).

Keywords: Contingency ranking, NVSI, Voltage stability, Voltage stability index

1. Introduction

Contingency analysis which is an inevitable part of static security analysis is critical in power system and the power market scenario. Robust operation of a power grid requires anticipation of unplanned component outages that could lead to dramatic and costly blackouts. The contingency analyses spans over single element outage, multi-element outage and sequential outage. The network quantities are first calculated for all the contingencies and ranking is done based on the results of the approximate solutions. The majority of methods are based on the evolution by means of some Performance Index (PI). Ranking methods rank the contingencies in approximate order of severity, based on the value of a scalar performance index, which is the measure of system stress expressed in terms of network variables and are directly evaluated [1]. The voltage stability indices methods serve as the powerful tools for checking the limits after each contingency whether the system is secure. Different methods were proposed for voltage stability contingency ranking [2]. A method for ranking contingencies based on information from the base case and post- contingency operating states using Voltage Stability Margin (VSM) was proposed [3]. A new index based on P_Q_V curve of a specified bus, area, or overall system was proposed to provide useful information about the ranking of voltage weak nodes, classification of areas susceptible to voltage stability and also extended to contingency analysis and load shedding schemes [4]. The NSGA II and MNSGA II algorithms were proposed for network contingency to obtain the optimal values of the control variable by considering L-index [5].Total reactive generation gradient (TRGG) with respect to reactive/active power demand was used as voltage stability indicator for mitigation of cascaded voltage collapses. This proposed voltage stability index, TRGG, could guarantee the voltage security and stability, with a good physical meaning, and low computational burden. The capability to detect the most effective generators and maximize their reactive

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reserves was expressed as another advantage [6]. A method for online voltage stability monitoring for multiple contingencies using an enhanced Radial Based Function Network (RBFN) is proposed [7]. A supervised learning approach for fast and effective power system security assessment and contingency analysis has been utilized using voltage – reactive power Performance Index, PIVQ and line MVA performance index, PIMVA [8]. A fuzzy based method is utilized to rank contingency in power system using Fast Voltage Stability Index [9]. The voltage stability indices methods serve as the powerful tools for checking the limits after each contingency and to find whether the system is secure.

In this paper, a computationally feasible approach has been proposed to detect a severe system failure that does not require a prohibitively expensive enumeration. A New Voltage Stability Index (NVSI) can be utilized as an alarm indicating tool to prevent voltage collapse and cascading blackouts. The method has examined the line stability, i.e. it has detected the stressed condition of the lines and identified the weak areas prone to voltage collapse. For any state of loading each line will have a stability index and based on that value of stability index an idea about the stressful situation of that line could be achieved.

2. Notation

The notation used throughout the paper is stated below.

Indexes:

X	line reactance
Q_j	reactive power at the receiving end
V_i	sending end voltage
P_j	real power at the receiving end

3. Implementation of NVSI and its effects

3.1. Voltage stability index

A New Voltage Stability Index (NVSI) has been proposed which originates from the equation of a two bus network, neglecting the resistance of transmission line, resulting in appreciable variations in both real and reactive loading [10]. In general, the NVSI formulation connecting bus ‘i’ to bus ‘j’ can be given by

$$NVSI_{ij} = \frac{2X\sqrt{\left(P_j^2 + Q_j^2\right)}}{2Q_J X - V_I^2}$$

The value of NVSI must be less than 1.00 in all transmission lines to maintain a secure system. The proposed index is implemented in IEEE 30 bus system considering various loading conditions and also comparison is done with existing indices such as L_{mn} [11], FVSI [12] and LQP [13] which is used analysis the performance of this index.

3.2 Both Real and Reactive power loads change at a bus

It is well-known that simultaneous real and reactive load variations are more probable combinations in practical systems. Both real and reactive powers are raised gradually at node 4 to a level very close to instability. Gradual addition of load slowly makes a few lines critical. For a load of P = 1.986pu and Q = 0.736pu at node 4, it is found that line 2-4, which is directly connected to bus 4, is the most critical with a value of its stability index 0.920. Fig 1 show that the apparent power variation causes to increase NVSI value closer to unity which indicates that point leads to voltage collapse.

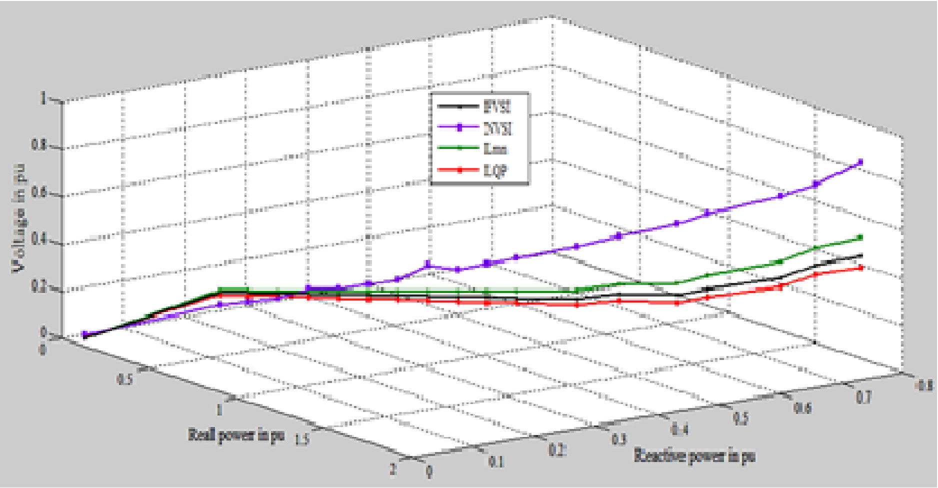

Fig.1. Simultaneous Real and Reactive power load variation Vs index value (bus 4)

Nevertheless, other indices do not provide proper information on how far the system is from voltage collapse.

3.3 Constant power factor load

In computing voltage stability index, the power factor of the load remains constant when the load increases. The real and reactive power loads are increased in proportion to their base case value.

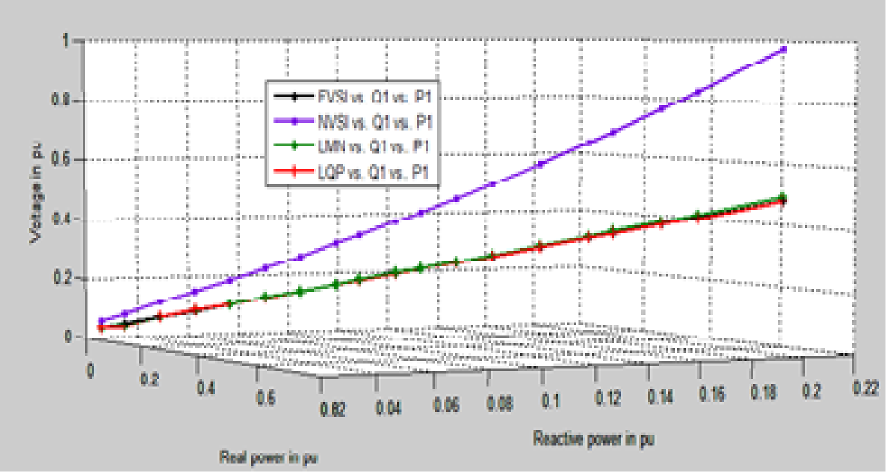

Fig.2.Real and Reactive power load variations with constant PF Vs index value

This procedure was performed on several buses where the power factor was retained as constant for base and heavy loading conditions for which the values for bus 10 are entered in Table 1. It evidently proves that the line 6-10 is in critical condition and other lines 2-5 and 9-10 are in stressed condition and from Fig.2 only NVSI is competent in showing variation of load.Table 1.Line Stability Indices at heavy loading with constant power factor

	Base case P=0.058pu &Q=0.02pu (PF=0.945)				P=0.628pu & Q=0.2165pu at bus 10(PF=0.945)			
Line	NVSI	L_{mn}	FVSI	LQP	NVSI	L_{mn}	FVSI	LQP
6-10	0.069	0.044	0.044	0.044	0.976	0.494	0.981	0.483
2-5	0.375	0.161	0.146	0.144	0.375	0.163	0.146	0.144
9-10	0.013	0.008	0.008	0.008	0.183	0.145	0.134	0.119

The voltage magnitudes found through the proposed method is compared with PV curve obtained using Continuous Power Flow (CPF) method in MATPOWER shown in Fig.3.

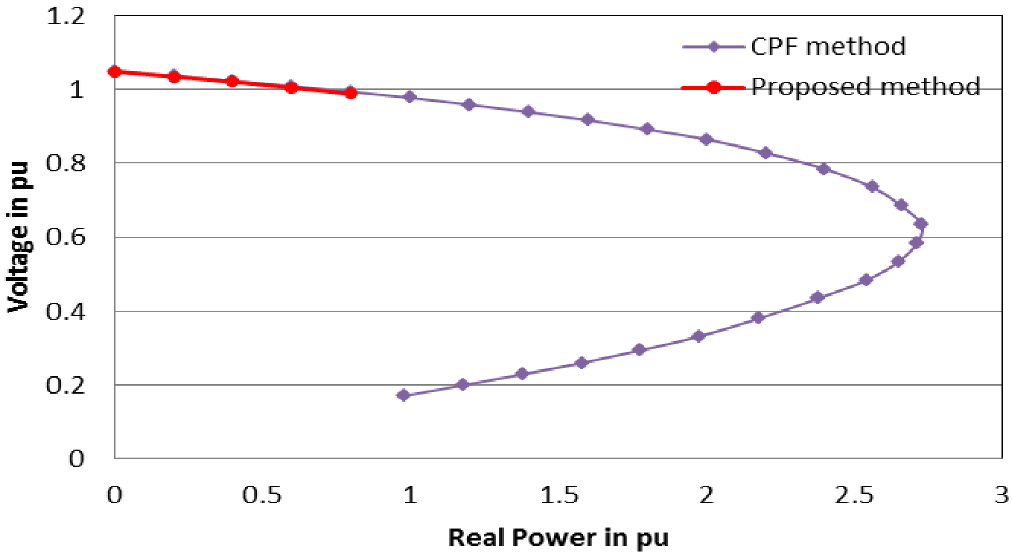

Fig. 3 Comparison of the voltage magnitudes

Even though the loading margin of the bus 10 using CPF is found as P=2.698pu with constant power factor, the proposed method has attempted to increase the load up to P=0.628pu to maintain voltage stability.

3.3 Load Change with Constant Power Factor at all buses

The proposed index is also examined through the load variation at all buses using loading factor (λ), maintaining constant power factor.

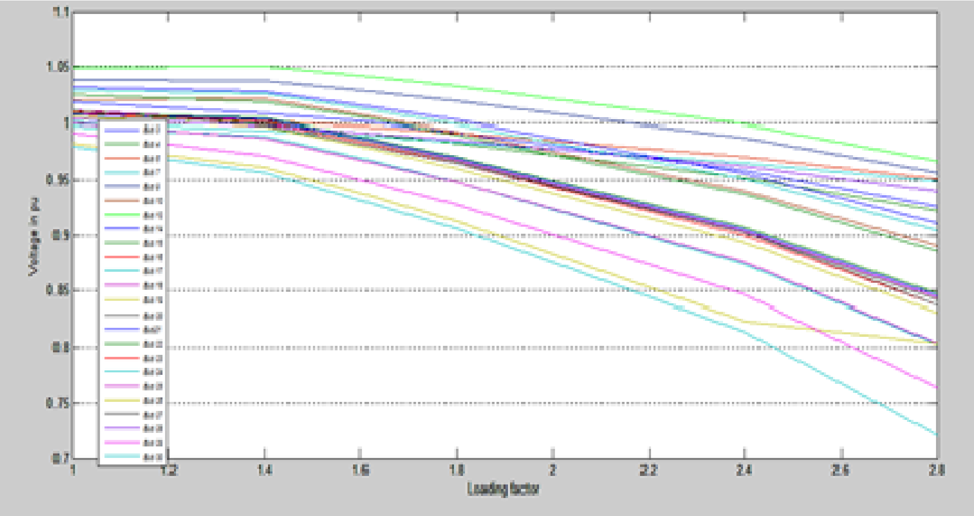

Fig. 4 Voltage Vs loading factor (λ) at all the buses

The loading factor is taken as 1 for base case and gradually increased, in all bus bars of the system, until maximum NVSI value is reached in any one the lines. The line 2-5 is first reached 0.989 as index value at λ =2.8. The voltage at all the buses with respect to load variation is shown in Fig.4 and this loading margin of individual buses may protect the system against voltage collapse. All the lines are sorted based on NVSI value and top 11 lines are selected to draw the Fig.5.

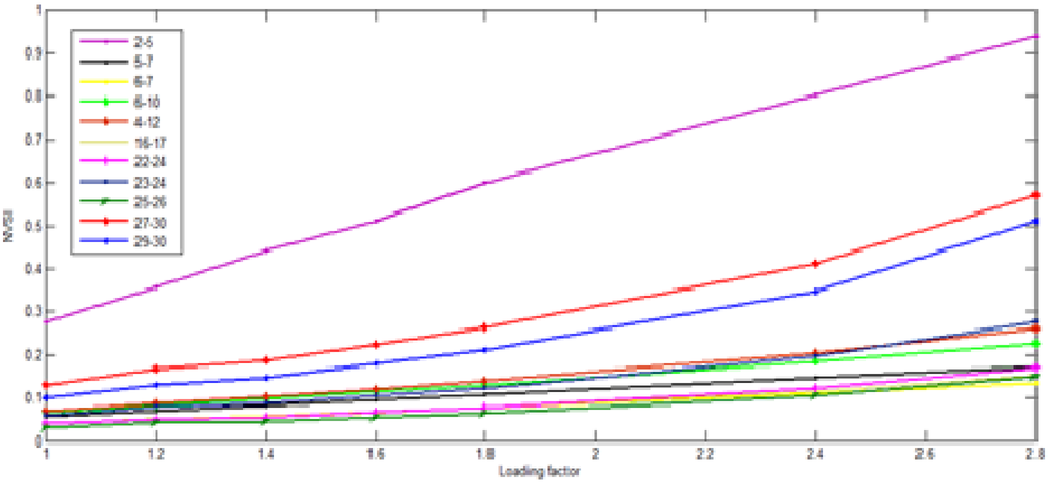

Fig. 5 NVSI Vs loading factor (λ) at selected lines

From these figures, we have to conclude that further increase of loading factor may cause voltage instability and both lines connected in bus 30 are in critical position. The values of index for 27-30, 29-30, are 0.570 and 0.511 respectively. Hence the index value of bus 30 is decided by line 27-30. Compare with other existing indices, the NVSI response for various loading conditions and it can used to rank the contingency in power system very effectively.

4. Contingency Ranking and Discussion

A well accepted contingency analysis procedure is based on splitting the process as different stages. The first stage is usually referred to as contingency ranking, and contingencies from a predefined list are analyzed and ranked by using a simple, computationally fast method. This paper tackles the contingency ranking problem, that is, the one of correctly ranking contingencies regarding their impacts on proposed index value. Contingencies with the highest index are the most severe and ranked at the top of the list. The line outage contingency is simulated by removing each line at a time. NVSI is computed for each line in the system for every line outage. The highest NVSI value from every line outage is extracted and sorted in descending order. The line outage with highest rank is identified as the most critical outage and hence a list of critical contingencies can be identified. The critical contingency ranking process is conducted for several loading conditions namely the heavy real loading, and heavily real and reactive loaded case. The generator outage contingency is also simulated in similar method. In this paper, contingency analysis is made through index for both standard IEEE 30 bus system and a practical TNEB 69 bus system in India [14].

4.1 IEEE 30 Bus System

The proposed index is effective in segregation of severe contingencies. The lines 9-11, 12-13 and 25-26 outages result in islanding of buses 11, 13 and 26. The line 1-2 outage results in an infeasible operating state for heavy loading conditions. These outages are treated as high ranking and not shown in Tables. Contingencies involving radial branches could be automatically considered as a severe one, since they may imply in loss of generation/load. On the other hand, they may also result in small impact on the system's maximum loading. In fact, this is the usual case for realistic systems. In this paper, no special care was taken on the radiality characteristic of branches and only their impact on the system's maximum loading was taken into account. The generator constraint is only included in this paper.

Case 1: Heavy reactive load at one bus with (N-1) line outage

The reactive load is increased to 0.35pu at bus 10 and (N-1) contingency analysis, that is one line outage at a time, is conducted. The NVSI value at line 6-10 is 0.667 for this heavy reactive load.

Table 2 Contingency ranking for heavy reactive loading with single line outage

Rank	Q=0.35pu at bus 10 and also one line outage at a time.		
	Outage line	Critical line	NVSI
1	1-3	6-10	0.933
2	3-4	6-10	0.923
3	2-5	6-10	0.840
4	2-6	6-10	0.819
5	4-12	6-10	0.813
6	28-27	6-10	0.790
7	9-10	6-10	0.789
8	6-28	6-10	0.784
9	12-14	6-10	0.782
10	6-9	6-10	0.780

The top ten outages which are tabulated in Table 2 increase the index value very closer to its maximum. The index value is increased to 0.933 when the line 1-3 outage leads to instability and the Fig.6 is shown NVSI value for all the transmission lines at this condition.

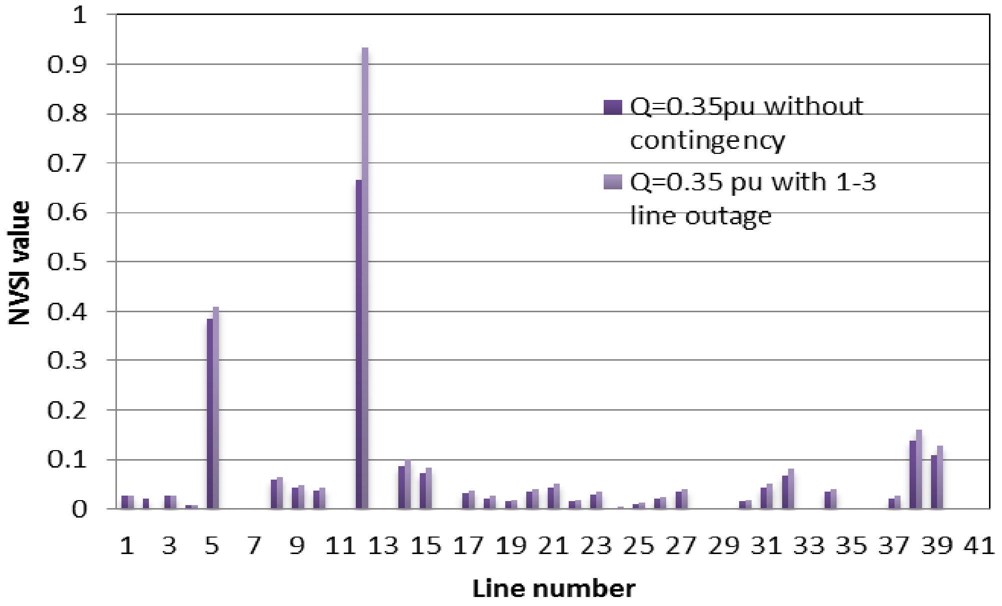

Fig.6 Line number Vs NVSI value for line 1-3 outage with heavy reactive loading at bus 10.

From this, 1-3 line outage causes to increase the NVSI value near to unity in 6-10 due to either increase the line flow in line 6-10 or decrease the bus voltage at bus 10. Comparatively the index value is raised much in 6-10 line, makes it as critical. The voltage variation at all buses for three different conditions i.e., base load case, heavy reactive load case and heavy reactive loading with line 1-3 outage are compared in Fig. 7.

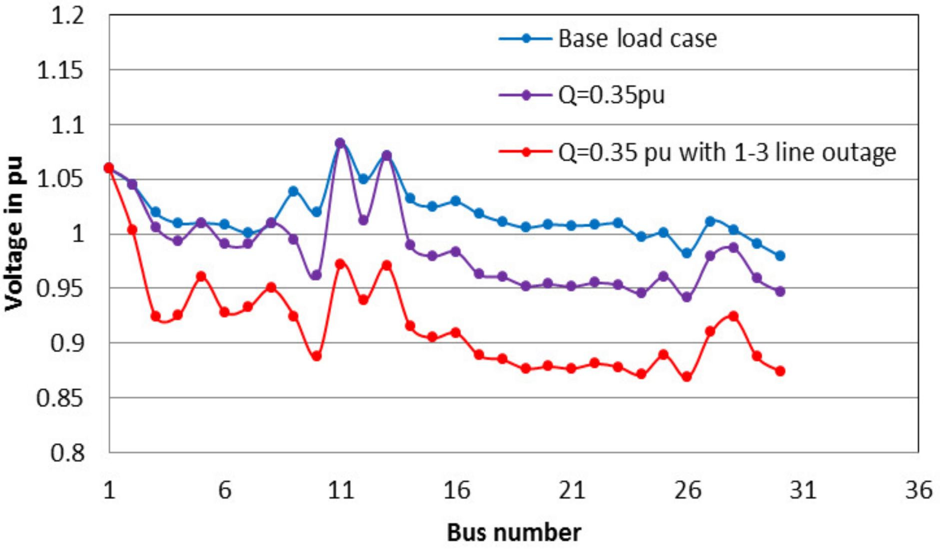

Fig. 7 Bus number Vs Voltage for line 1-3 outage with heavy reactive loading at bus 10

From this, the heavy loading with line outage reduce the voltage at all buses and except slack bus all generator buses are converted as load buses. The line flows are also violated in 2-6 and 2-4 lines.

Case 2: Heavy real and reactive load at one bus with (N-1) line outage

The proposed index is successfully implemented to rank the line outage for both real and reactive load changing at one particular bus without maintain the PF.

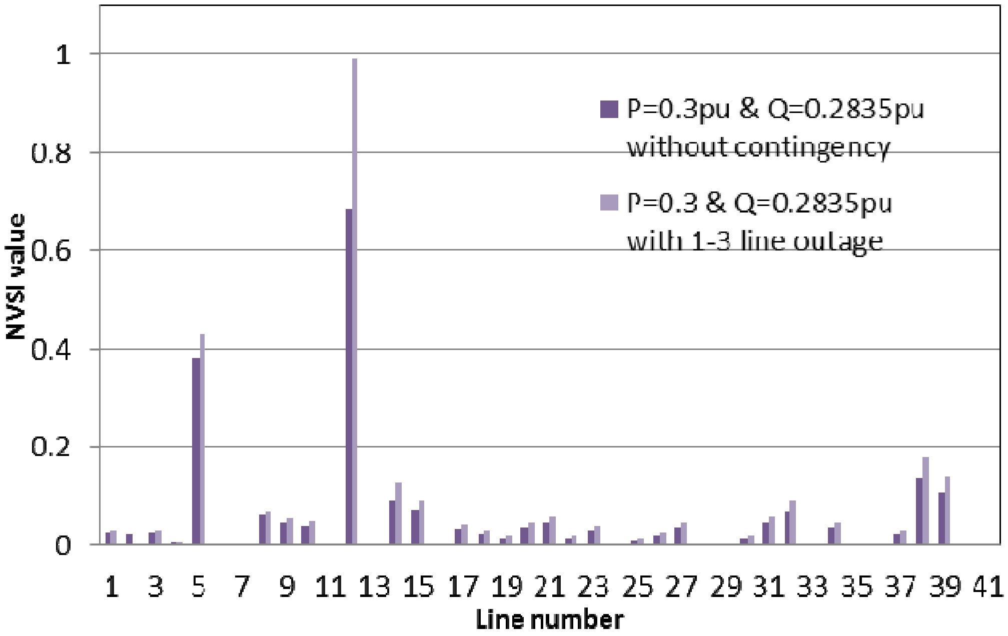

Fig. 8 Line number Vs NVSI value for line 1-3 outage with heavy real and reactive loading at bus 10

Fig. 8 shows that the system is running with heavy real and reactive loading without maintain constant power factor at bus 10, the index value of line 6-10 is raised from 0.691 to 0.989 when the line 1-3 outage has also happened in the system.

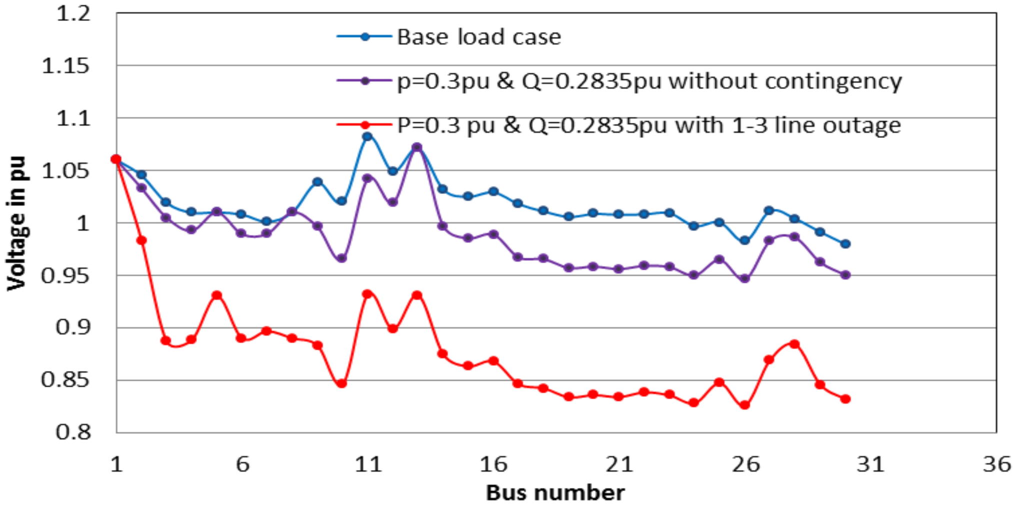

Fig. 9 Bus number Vs Voltage for line 1-3 outage with heavy real and reactive loading at bus 10

The voltage variation at all buses is reduced from heavily loaded to heavily loaded with one line outage condition at bus 10 in Fig. 9. Table 3 shows that the critical line is 6- 10 for all these line outages with heavy loading at bus 10.

Table 3 Contingency ranking for heavy real and reactive loading with Single line outage

Rank	**P=0.30pu & Q=0.2835pu at bus 10 and also one line outage at a time**		
	Outage line	**Critical line**	**NVSI**
1	1-3	6-10	0.989
2	3-4	6-10	0.959
3	2-5	6-10	0.934
4	2-6	6-10	0.930
5	4-12	6-10	0.905
6	2-4	6-10	0.885
7	4-6	6-10	0.879
8	5-7	6-10	0.873
9	6-9	6-10	0.824
10	19-20	6-10	0.818

Case 3: Heavy real and reactive load at one bus with single generator outage

The real and reactive power increases from their base value (P=0.058 & Q=0.02pu with power factor 0.945) to heavy real P=0.5pu and reactive power Q=0.172pu loading without change the power factor at bus 10. Except slack bus, other buses are examined for this case. From Table 4, the generator at bus 5 outage increases the index value at lines 6-10 from 0.72 to 0.82 and it is ranked as 1. The results obtained from this contingency ranking were used to identify weak clusters in the system. The voltage value is dropped from 1.021pu to 0.9169 at bus 10 in this condition.

Table 4 Contingency ranking for heavy real and reactive loading with Single generator outage

Rank	**P=0.50pu & Q=0.172pu at bus 10 and one generator outage.**		
	Outage generator	**Critical line**	**NVSI**
1	Bus 5	6-10	0.880
2	Bus 8	6-10	0.861
3	Bus 11	6-10	0.808
4	Bus 2	6-10	0.807
5	Bus 13	6-10	0.805

Case 4: Heavy reactive load at one bus with single generator outage

Table 5 Contingency ranking for heavy reactive loading with Single generator outage

Rank	**Q=0.38pu at bus 10 and one generator outage.**		
	Bus No. of generator outage	**Critical line**	**NVSI**
1	Bus 5	6-10	0.954
2	Bus 11	6-10	0.851
3	Bus 2	6-10	0.823
4	Bus 8	6-10	0.817
5	Bus 13	6-10	0.800

For this case, only reactive load is increased to 0.38pu at bus 10 and successive generator outages except slack bus. High severity is experienced when the outage generator at bus 5 has happened. All other generator outages with rank are shown in Table 5.

4.2 TNEB 69 Bus System

The line outage of the lines 33-44, 37-38, 39-42, 44-46, 48-49, 48-50 and 68-69 leads to isolation of buses, implicates the line outages occupying high ranking contingencies, originating from serious dearth of power generation or sudden removal of load. The outages in the lines 47-48, 15-28, 28-29, 41-48, 60-64, and 65-68 in the base case make the system reach instability, occupying next level of contingency ranking and hence are not shown in Table 6 ,7,8,and 9.

Case 1: Heavy Reactive load at one bus with (N-1) line outage

Reactive load is increased at the bus 48 from 0.68pu to 2pu with successive line outages (except above said lines) and also the reactive power limits at generators are considered.

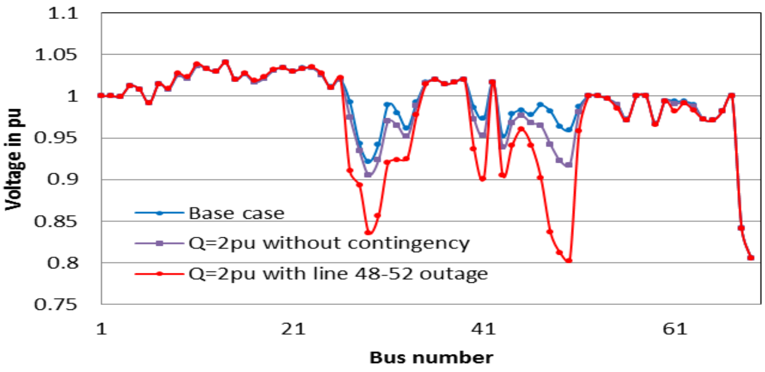

Fig.10 Bus number Vs Voltage for line 1-3 outage with heavy reactive loading at bus 48

The line outage is ranked based on NVSI values and only tabulated for first 10 ranks in Table 6. The lines 27-48 and 41-48 are identified as critical lines. The voltage at all buses and the NVSI value for all transmission lines in this Indian practical system when reactive load increased 0.2pu at bus 48 with line 48-52 line outage are shown in Fig. 10 & Fig.11.

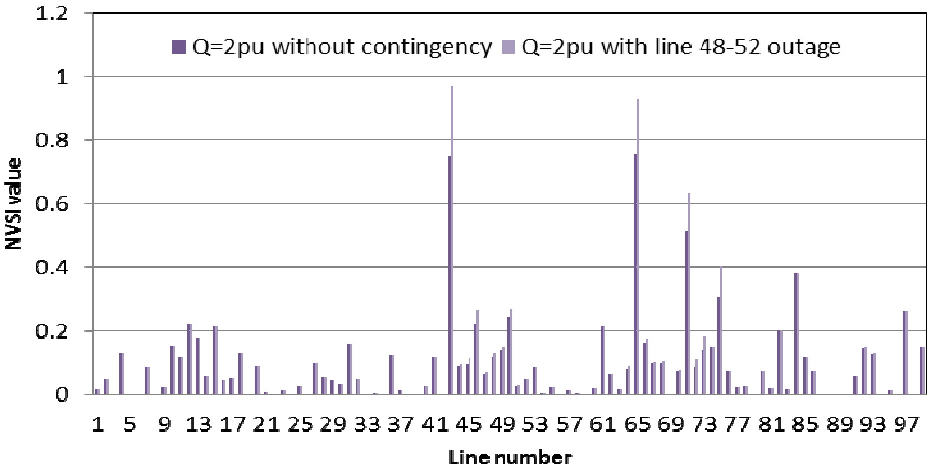

Fig. 11 Line number Vs NVSI value for line 48-52 outage with heavy reactive loading at bus 48.

The line outage leads the line flow violation at line 65-66. It may cause further outages and the line 41-48 is also in critical position.

Case 2: Heavy real and reactive load at one bus with (N-1) line outage

The real and reactive power loads are increased from base case values (P=1pu &Q=0.63pu) to heavy loading condition (P=2pu &Q=1.26pu) with maintain constant power factor. The heavy loading system provides the load flow results, but the line 48-52 or 29-30 outages with this heavy loading condition does not provide result .Other than this, top 8 line outages are ranked in Table 6 and line 40-41outage is considered for further analysis. The voltage magnitudes at all buses for base case, this heavy loading condition, and heavy loading with line 40-41 outage that are shown in Fig.12.

Table 6 Contingency ranking for heavy real and reactive loading with Single line outage

Rank	P=2pu & Q=1.26pu (PF=0.846) at bus 48 and also one line outage at a time.		
	Outage line	Critical line	NVSI
1	40-41	41-48	0.872
2	30-31	27-48	0.848
3	15-27	27-48	0.818
4	48-51	41-48	0.802
5	27-48	41-48	0.763
6	32-31	41-48	0.746
7	31-47	41-48	0.720
8	32-43	41-48	0.712

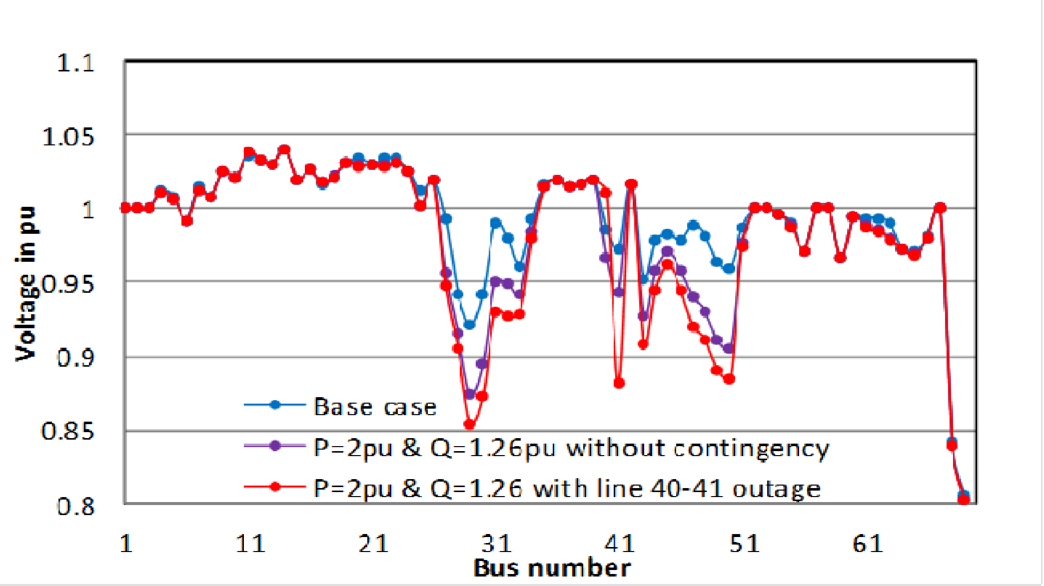

Fig.12 Bus number Vs Voltage for line 40-41 outage with heavy real & reactive loading at bus 48.

The NVSI values are much raised in the lines which are connected with bus 48 from heavy loading case to heavy loading with 40-41 line outages shown in Fig.13. The line 27-48 is also in critical condition.

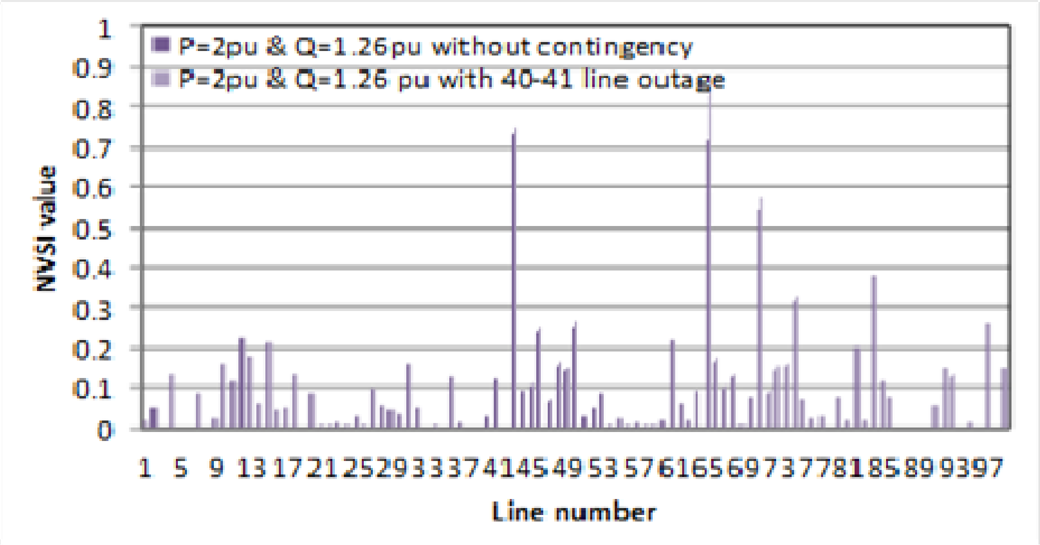

Figure 13 Line number Vs NVSI value for line 40-41 outage with heavy real & reactive loading at bus 48

Case 3: Heavy reactive load at one bus with one generator outage

In the bus 48, if reactive power is raised to 2.20pu with one generator outage repetitively for all the generators, the lines 41-48, 27-48, and 48-52 are picked as critical lines as shown in Table 7. The system touches instability when the generator outage occurs at bus 39 which is placed in weak area in the base case.

Table 7 Contingency ranking for heavy reactive loading with single generator outage

Rank	**Q=2.20pu at bus 48 and one generator outage.**		
	Outage generator	**Critical line**	**NVSI**
1	Bus 31	48-52	0.998
2	Bus 36	48-52	0.990
3	Bus 13	41-48	0.980
4	Bus 57	27-48	0.977
5	Bus 58	41-48	0.972
6	Bus 60	41-48	0.966
7	Bus 14	41-48	0.964
8	Bus 15	41-48	0.962
9	Bus 67	41-48	0.927
10	Bus 21	41-48	0.924

Other two top generator outages at buses 31 and 36 are also placed in weak area. Removal of any one generator in weak area denotes the high degree of sensitivity near the voltage collapse point and once again the weak area is justified.

Case 4: Heavy real and reactive load at one bus with one generator outage

When P and Q loads are increased to 2.00pu & 1.90pu at bus 48 and one generator outage at a time successively for all generators, either the line 41-48 or 48- 52 becomes critical line as shown in Table 8.

Table 8 Contingency ranking for heavy real and reactive loading with Single generator outage

Rank	P=2.00pu,Q= 1.90pu at bus 48 & one generator outage at a time		
	Outage generator	**Critical line**	**NVSI**
1	Bus 36	41-48	0.987
2	Bus 57	48-52	0.966
3	Bus 58	48-52	0.931
4	Bus 60	48-52	0.928
5	Bus 15	48-52	0.903
6	Bus 53	48-52	0.899
7	Bus 14	48-52	0.893
8	Bus 21	48-52	0.892
9	Bus 13	48-52	0.889
10	Bus 67	48-52	0.886

The results obtained from the contingency ranking are used to identify weak clusters in the system. Illustrating the results obtained from the contingency ranking on the single line diagram of the practical test system has been able to identify some weak clusters in the system.

5. Conclusion

Overloading of the transmission line may cause the cascading outages which lead to voltage collapse at one or more areas. In the Indian scenario, most of the transmission lines transmit power at their maximum and also maintain equilibrium condition at all instants to avoid voltage instability. Line stability index gives the information about the system and the stages of various contingency conditions. The results of simulation indicate that the NVSI can be utilized to judge voltage stability by identifying the weak bus and the critical lines. The NVSI can be calculated within a very short period (less than one second) when any component failure occurs in the system, while the process of system losing voltage stability takes a few seconds and even longer. Since NVSI can be used in a real time or online environment, it can easily identify the bus or the area which needs more monitoring to maintain voltage stability at many nodes.

References

[1] Singh SN, Srinivastava I,Sharma J.Fast voltage contingency screening and ranking using cascade neural network, Electrical power system research 2000,vol 53,pp 197-205

[2] Vaahedi, E, Fuchs, C, Xu,W, Mansour,Y, Hamadanizadeh, H & Morison GK, 'Voltage Stability Contingency Screening And Ranking', IEEE Transaction on Power System, vol. 14, no. 1,pp. 256–265, 1999.Contingency Screening And Ranking', IEEE Transaction on Power System, vol. 14, no. 1,pp. 256–265, 1999.

[3] Dester, M, & Csatro, CA, 'Multi _criteria Contingency Ranking Method for Voltage Stability', Elsevier, Electric Power systems Research,vol.79, no.1,pp. 220-225, 2009.

[4] Lee,CY, Tsai, SH & Wuc, YK, 'A new approach to the assessment of steady-state voltage stability margins using the P-Q-V curve' ,Elsevier, Electrical Power and Energy Systems, vol. 32,no. 10 pp.1091-1098,2010.

[5] Ramesh,S, Kannan,S & Baskar,S, 'Application of modified NSGA-II algorithm to multi-objective reactive power planning', Elsevier Applied Soft Computing,vol.12, no.2,pp. 741-753,2012.

[6] Amraee,T, Ranjbar,AM, Feuillet,R & Mozafari,B, 'System protection scheme for mitigation of cascaded voltage collapses' , IET Generation, Transmission & Distribution, vol. 3, no. 3, pp. 242–256,2009.

[7] Saikat Chakrabarthi, Benjamin Jeyasurya, ' Multi contingency voltage stability monitoring of a power system using an adaptive radial basis function network' Electrical Power and Energy Systems ,vol.30,no 1,pp 1-7,Jan 2008.

[8] Kusam verma,K.R.Niazi, 'Supervised learning approach to online contingency screening and ranking in power systems' Electrical Power and Energy Systems,vol.38,pp 97-104,2012.

[9] A. Y. Abdelaziz, A. T. M. Taha, M. A. Mostafa, 'Fuzzy Logic Based Power System Contingency Ranking' I.J. Intelligent Systems and Applications, vol.03,pp 1-12,2013.

[10] R.Kanimozhi, K.Selvi, A Novel Line Stability Index for Voltage Stability Analysis and Contingency Ranking in Power System Using Fuzzy Based Load Flow, Journal of Electrical Engineering and Technology,vol 8,pp 694-703,2013.

[11] Moghavvemi, M & Faruque,O 1998, 'Real-Time Contingency Evaluation and Ranking Technique', IEEE Proceedings on Generation, Transmission and Distribution, vol. 145, no.5, pp. 517-524.

[12] Musirin, I & Rahman,TKA 2002, 'Estimating Maximum Loadability for Weak Bus Identification Using FVSI,' IEEE Power Engineering Review, vol. 22, no.13, pp.50-52.

[13] Mohamed,A & Jasmon,GB 1989, 'Voltage Contingency Selection Technique for Security Assessment', IEE Proceeding Generation, Transmission and Distribution, vol. 136, no.1, pp.24-28.

[14] Tamil Nadu Electricity Board Statistics at a Glance 2009-2010, Planning Wing of Tamil Nadu Electricity Board, Chennai, India.