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A Novel Line Stability Index for Voltage Stability Analysis and Contingency Ranking in Power System Using Fuzzy Based Load Flow

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Abstract – In electric power system, the line stability indices adopted in most of the instances laid stress on variation of reactive power than real power variation of the transmission line. In this paper, a proposal is made with the formulation of a New Voltage Stability Index (NVSI) 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. The efficacy of the index and fuzzy based load flow are validated with IEEE 30 bus and Tamil Nadu Electricity Board (TNEB) 69 bus system, a practical system in India. The results could prove that the identification of weak bus and critical line in both systems is effectively done. The weak area of the practical system and the contingency ranking with overloading either line or generator outages are found by conducting contingency analysis using NVSI.

Keywords: Stability Indices, NVSI, Voltage stability, Contingency ranking and Fuzzy logic load flow.

1. Introduction

The voltage instability is considered as one of the critical issue in electric power system. The inherent complexity and interconnectivity forces a power system to operate closer to limits of stability, along with the added contribution to system instability by inadequate supply of reactive power which in turn leads to voltage collapse. Fast voltage stability analysis and prediction of collapse point are great challenges in power system. Many of the researchers in the recent-past focused on the effective online monitoring of status of the system and hence to solve the problem of voltage collapse. In this regard, voltage stability index of each transmission line becomes the useful measure of power system monitoring. The index could identify how far a system is from its point of collapse [1]. Performance indices to predict closeness to voltage stability boundary have been a permanent concern of researchers and power system operators, as these indices can be used online or offline to help dispatchers determine how close the system is to a possible voltage instability state [2]. Several voltage stability indices used to measure proximity to voltage collapse in off-line as well as on-line applications are described with great detail [3]. A fast method to compute the minimum singular value, together with corresponding left and right singular vectors of a power flow Jacobian matrix has been proposed [4]. A voltage stability indicator for identification of the weakest bus or area in power systems was derived from the Newton power flow equations [5]. An Incremental Condition Estimation (ICE) method for estimating the condition member of a triangular matrix was proposed [6]. If the off diagonal row of the triangular matrix is zero, it could not give exact result. This problem was overcome and also more accurate singular value has been obtained which was derived based on the non-iterative characteristic of the ICE method [7].

A local method based on the power transfer impedance matching principle has been proposed [8]. The voltage collapse occurs when the Thevenin's equivalent impedance, as seen from the load bus, and the apparent power are equal. The Tellegen's theorem makes it possible to simplify the determination of the Thevenin's parameters and enables derivation of the new index. This approach determined Thevenin's parameters from the consecutive phasor measurement [9]. A voltage stability index VMPI (Voltage Margin Proximity Index) considering the voltage limits, especially lower voltage limits, has been simulated [10]. A combined static and dynamic voltage stability method to predict dynamic voltage collapse in a practical power system using power transfer stability index has been proposed [11]. An equivalent node voltage stability index (ENVCI) has been derived from the information of local voltage phasors [12]. Many line stability indices were suggested in [13-16] for identifying the weak bus, to determine maximum load ability, voltage stability analysis and contingency ranking.

In this paper, a new line stability index has been proposed for on-line monitoring of different loading conditions and contingency ranking. This method does not consider the resistance of the transmission line. The

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uniqueness of this index is that it relates both real and reactive power. A fuzzy logic based fast decoupled load flow method has been considered for this work. Fuzzy deals with linguistic variables and the values lies between 0 and 1. Since the off diagonal elements of the Jacobian matrix are zero, it is able to obtain exact result. Precise results and minimized power mismatch errors are obtained based on the characteristics of the proposed fuzzy logic method. The results obtained from this method are compared with existing indices.

Subsequent discussion is organized as follows. The equivalent model and formulation of NVSI are presented in Section 2. Fuzzy logic based load flow are given in Section 3. Simulation results are given to demonstrate the feasibility and effectiveness of NVSI in Section 4. The identification of weak bus most critical line is explained in section 5 and contingency ranking followed by conclusions in section 6& 7.

2. Problem Formulation

The voltage stability index is one of the powerful tools used to indicate the voltage stability condition formulated based on a line or bus. In this paper, a New Voltage Stability Index (NVSI) is proposed and comparison has been made with the existing indices such as Fast Voltage Stability Index (FVSI), line stability index symbolized by Lmn and Line Stability Factor (LQP) [13-15] as follows.

2.1 Fast Voltage Stability Index (FVSI)

The FVSI was derived from the voltage quadratic equation at the receiving bus on a two-bus system [13].

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{1}$$

2.2 Line Stability Index (Lmn)

This index was formulated based on a power transmission concept in a single line. The line stability index Lmn[14] is given

$$L_{mn} = \frac{4Q_j X}{[\|V_i\| \sin(\theta - \delta)]^2} \tag{2}$$

2.3 Line Stability Factor (LQP)

The LQP was used in the comparison since this factor is more sensitive to change in reactive power. The formulation begins with the power equation in a power system and finally LQP [15] is expressed as

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \tag{3}$$

All the above said indices have effectively shown the variation of reactive power load but not real power load. Most of these indices have been derived from the receiving end reactive power equation of transmission line. Instead of that, the index solved by considering the receiving end real power equation, it depends the resistance of the transmission line. However, the resistance values are negligible or even zero in standard and practical line data, and hence the index remains either infinite or zero. To overcome this pitfall, the resistance value of the transmission line is assumed as zero initially for solving the New Voltage Stability Index (NVSI).

2.4 The proposed New Voltage Stability Index (NVSI)

NVSI may be mathematically explained as follows [17].

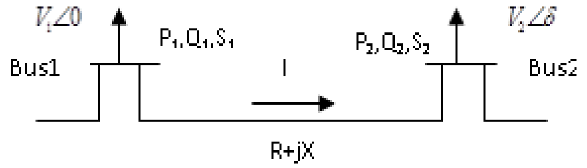

Fig. 1. Line model.

From the Fig. 1, current flowing between bus 1 and 2,

$$I = \frac{V_1\angle 0 - V_2\angle\delta}{R + jX} \tag{4}$$

$$I^* = \frac{\overline{V}_1^* - \overline{V}_2^*}{R - jX} \tag{5}$$

Comparatively resistance of transmission line is negligible. The equation may be rewritten as

$$I^* = \frac{\overline{V}_1^* - \overline{V}_2^*}{-jX} \tag{6}$$

And the receiving end power,

$$S = V_2 I^* \tag{7}$$

Incorporating Eq. 6 in 7 and solving

$$P_2 = -\frac{V_1 V_2}{X}\sin\delta \tag{8}$$

$$Q_2 = -\frac{V_2^2}{X} + \frac{V_1 V_2}{X}\cos\delta \tag{9}$$

Eliminating δ from Eqs. 8 & 9 yields

$$\left(V_2^2\right)^2 + (2Q_2X - V_1^2)V_2^2 + X^2(P_2^2 + Q_2^2) = 0 \qquad (10)$$

This is an equation of order two of V2. The condition to have at least one solution is:

$$(2Q_2X - V_1^2)^2 - 4X^2(P_2^2 + Q_2^2) \geq 0$$

$$\frac{2X\sqrt{(P_2^2 + Q_2^2)}}{2Q_2X - V_1^2} \leq 1 \qquad (11)$$

Taking the suffix “i” as the sending bus & “j” as the receiving bus, NVSI can be defined by

$$NVSI_{ij} = \frac{2X\sqrt{(P_j^2 + Q_j^2}}{2Q_jX - V_i^2} \qquad (12)$$

Variable definition follows.

Z : line impedance
X : line reactance
Q_j : reactive power at the receiving end
V_i : sending end voltage
θ : line impedance angle
δ : angle difference between the supply voltage and the receiving voltage.
P_i : sending end real power
P_j : real power at the receiving end.

The procedure to estimate the NVSI in all transmission lines in power system is shown in Fig. 2. The value of NVSI must be less than 1.00 in all transmission lines to maintain a stable system. In this paper, the performance of the proposed index is examined using different test conditions. Comparison results prove that the NVSI is very suitable for voltage stability assessment than other indices.

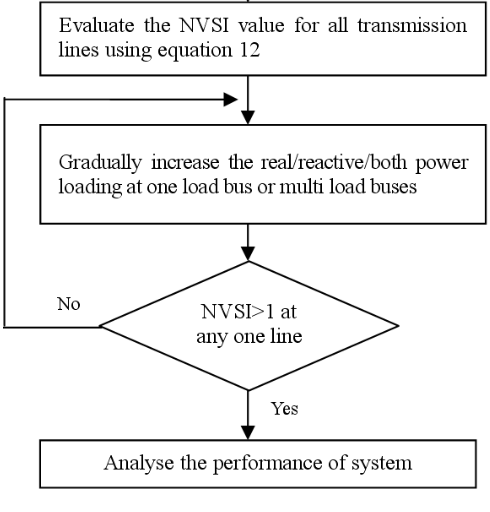

Fig. 2. Procedure for calculating NVSI

3. Fuzzy Load Flow Analysis

The NVSI provides complete description of the system performance. In this paper, Fuzzy based load flow method is utilized for analyzing the NVSI with different loading conditions. A variant of Mamdani-type Fuzzy method for membership function [17] is improved with computation time. In this, ‘Fuzzy Logic’ is used to update the ‘ δ ’ and ‘V’.

$$\left[\frac{\Delta P}{\|V\|}\right] = [B'][\Delta\delta] \qquad (13)$$

$$\left[\frac{\Delta Q}{\|V\|}\right] = [B''][\Delta V] \qquad (14)$$

The above equations can be expressed in fuzzy as

$$\Delta f = B.\Delta y$$

Δy –Real or Reactive power mismatches per voltage vector

Δy –Correction of voltage angle or magnitude vector.

The recurrent update of the state vector of system is performed with the function,

$$\Delta y = fuzzy(\Delta f) \qquad (15)$$

The proposed fuzzy load flow is based on the previous fast decoupled load flow equation but the membership function of linguistic terms, are labeled as three linguistic terms (large negative (LN), Zero(ZR), and large positive (LP)) instead of seven fuzzy linguistic terms [17]. Computation time for different linguistic terms is listed in Table 1.

Table 1. Computation Time for Different Linguistic Terms

Type	Computation time	
	IEEE 30 bus	TNEB69 bus
3 linguistic terms	0.205ms	0.248ms
7 linguistic terms	0.224ms	0.255ms
9 linguistic terms	0.229ms	0.261ms
13 linguistic terms	0.231ms	0.272ms

Membership function of three linguistic terms is considered for this work and the individual membership function is titled as shown in Fig. 3. The proposed algorithm can handle large-scale power system because it significantly reduces the computational burden by reducing linguistic terms.

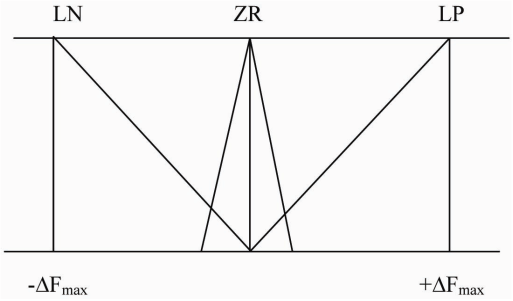

Fig. 3. The membership functions of linguistic terms

4. Numerical Result and Discussion

4.1 Results of an IEEE system

IEEE 30 bus system which has 5 generator buses, 9 load buses and 20 inter connected lines has been considered to evaluate NVSI.

4.1.1 Real power load changes at one particular bus

When real power is increased to 227.6MW from base value at bus 4 and all other demands remain same, the Table 2 indicates the NVSI reaches 0.934 in line 2-4 but only meager variation in Lmn.

Table 2. Line stability indices in bus 4 with heavy real loading

Line	Base Case		P=227.6MW at bus 4	
	NVSI	Lmn	NVSI	Lmn
2-4	0.026	0.028	0.934	0.122
5-7	0.380	0.382	0.615	0.386
6-7	0.236	0.234	0.236	0.236

The line which is closer to unity is treated as critical line because a small increase of demand on this bus may lead severe outages. Based on the comprehensive analysis of this result, a main conclusion has been reached, that is, the Lmn does not indicate real power variation.

4.1.2 Reactive power load changes at one particular bus

Load variation in a power system, is difficult to predict accurately. It will cause reactive power rise in a power system due to its inductive property. The reactive power at a single bus is subjected to change for analyzing the performance of the NVSI.

Table 3. Line stability indices in bus 4 with heavy reactive loading

Line	Q=132.6MVAR at bus 4			
	NVSI	Lmn	FVSI	LQP
2-4	0.934	0.984	0.986	0.927
3-4	0.455	0.486	0.399	0.368
5-7	0.415	0.386	0.363	0.313

The reactive load is increased to 132.6 MVAR from the base value at bus 4 made line 2-4 as critical line. The complete analyses from the Table 3, not only NVSI, all other indices also effectively indicate the reactive power load variation.

4.1.3 Both Real and Reactive power load changes at one particular bus

It is well-known that simultaneous real and reactive load variations are more probable combinations in practical systems.

The line which is connected between bus 2 and 4 can be stressed when the real and reactive power are increased to 187.6 MW and 63.6 MVAR at bus 4 with a value of its stability index 0.98. The table 4 shows that the NVSI is only influenced by both the real and reactive power variations, while other indices are not revealed.

Table 4. Line stability indices in bus 4 with heavy real and reactive loading

Line	P=187.6MW & Q=63.6MVAR at bus 4			
	NVSI	Lmn	FVSI	LQP
2-4	0.980	0.642	0.558	0.510
2-5	0.437	0.188	0.168	0.167
6-7	0.310	0.145	0.1532	0.156

4.1.4 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 load increases are proportional to their base case value.

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

Table 5. Line Stability Indices in Bus 10 with Constant Power Factor

Line	P=55.5MW & Q=19.4MVAR at bus 10			
	NVSI	Lmn	FVSI	LQP
6-10	0.910	0.457	0.486	0.446
2-5	0.487	0.288	0.286	0.226
9-10	0.313	0.186	0.196	0.167

4.1.5 Multi load changes at different buses (10, 15&24)

A practical power system network comprises of hundreds of buses and thousands of transmission lines. Practically load will be added or removed across many buses simultaneously at any instance.

Therefore, the buses 10, 15 and 24 are subjected to analysis of real and reactive load variation at multi buses. The real loads increases to 22.8MW, 18.2MW and 19MW and the reactive load raises to 21.5MVAR, 21MVAR and 28MVAR respectively. Several lines in Table 6 show a rise in all the indices, which indicate the severity of stressed condition.

Table 6. Line stability indices for multi loading condition.

Line	Reactive load increases at different buses			
	NVSI	Lmn	FVSI	LQP
22-23	0.968	0.786	0.817	0.756
22-24	0.964	0.746	0.847	0.734
14-15	0.908	0.783	0.878	0.721
6-10	0.508	0.352	0.372	0.334

4.2 Results of a practical system

The above said procedure is repeated for TNEB 69 bus system, a practical system in India [18] for ensuring the performance of NVSI. This system has 14 generator buses, 55 load buses and 99 inter connected lines.

4.2.1 Real power load changes at one particular bus

The heavy range of real power increment at one bus is a rare event in controlled practical system. Any switching may cause the unusual power increment in one bus which leads to operate the system very closer to voltage instability. Hence, the real power variation at one node is treated as special case to examine the factors influencing NVSI.

In this system the line 5-6 is prone to enter critical stage when the real power is raised from base value 99MW to 500MW and the lines 48-52, 1-6 are also in stressed condition. The NVSI index is found to be more sensitive to real power variation as compared with the other indices and the voltage magnitude variation is shown in Fig. 4. A small increment in real power more than P=500MW at bus 6 will lead system instability, which is clear from Table 7.

Table 7. Line stability indices with heavy real power loading at bus 6.

Line	P=500 MW at bus 6			
	NVSI	Lmn	FVSI	LQP
5-6	0.999	0.246	0.221	0.243
48-52	0.835	0.204	0.176	0.204
1-6	0.777	0.205	0.142	0.137

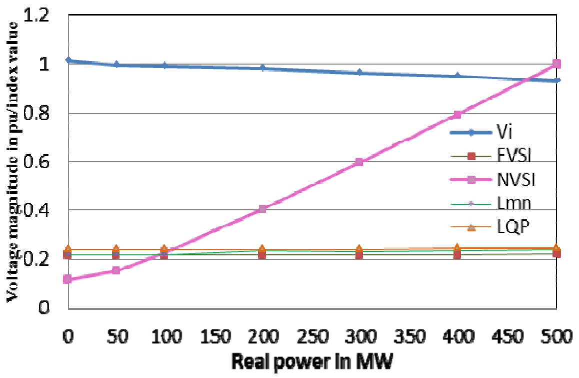

Fig. 4. Voltage magnitude, NVSI and other indices with respect to real power variation at bus 6.

4.2.2 Reactive power load changes at one particular bus.

Reactive power cannot be transmitted over a long distance since it would require a large voltage gradient to do so [20] or through power transformer due to excessive reactive power losses.

Reactive power supply should be located in close proximity to its consumption to maintain voltage levels within an acceptable range. This analysis may help to identify where the compensation is required.

From Table 8, it is inferred that the line 5-6 attains its stability limit when the reactive power is elevated from its base value 60MVAR to 265MVAR at bus 6, NVSI & the other indices show similar variation with the reactive power increment. This increment of reactive load has reduced the voltage magnitude to 0.8961pu at bus 6 which is shown in Fig. 5, indicating that the need of capacitive reactance for compensation to maintain the voltage.

4.2.3 Both Real and Reactive power load changes at one particular bus

When both real and reactive power are boosted from their base value to 300MW & 200MVAR respectively, the line 5-6 of bus 6 leads to critical state.

Table 8. Line stability indices in bus 6 with reactive power loading

Line	Q=256 MVAR at bus 6			
	NVSI	Lmn	FVSI	LQP
5-6	0.923	0.984	0.945	0.941
1-6	0.755	0.789	0.753	0.723
48-52	0.638	0.486	0.399	0.368

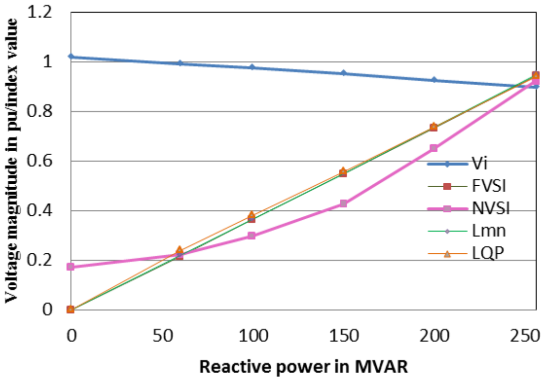

Fig. 5. Voltage magnitude, NVSI and other indices with respect to reactive power variation at bus 6.

Table 9. Line stability indices in bus 6 with heavy real and reactive loading

Line	P=300MW,Q=200MVAR at bus 6			
	NVSI	Lmn	FVSI	LQP
5-6	0.996	0.776	0.786	0.801
1-6	0.709	0.629	0.633	0.610
8-52	0.456	0.206	0.291	0.264

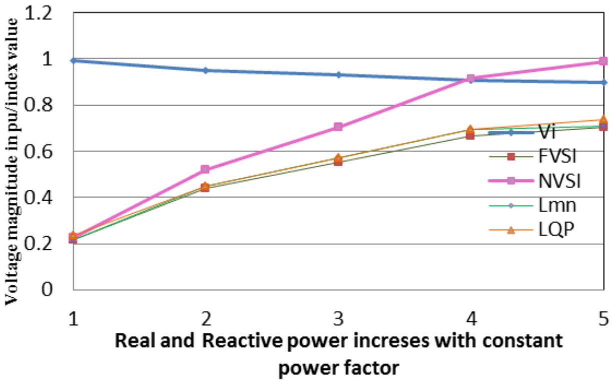

Fig. 6. Voltage magnitude, NVSI and other indices with respect to both real and reactive power variation at bus 6.

At this state the value of NVSI is 0.996 and its difference is revealed from the other indices with the above Table 9.

Both real and reactive power variation influence the NVSI than other indices successfully show in Fig. 6. The X axis values in graph are (1(99MW,60 MVAR), 2(149,93), 3(209,123), 4(249,173), 5(300,200)).

4.2.4 Constant power factor load

The Table 10 is framed by changing both real and reactive power such that the power factor of system remains constant for both base load and increased loading conditions.

Table 10. Line Stability Indices in Bus 6 with Constant Power Factor.

Line	P=315 MW & Q=190 MVAR at bus 6			
	NVSI	Lmn	FVSI	LQP
5-6	0.989	0.740	0.702	0.707
1-6	0.710	0.601	0.557	0.537
48-52	0.435	0.205	0.196	0.227

The lines 5-6, 1-6 and 48-52 are under stressed condition in this case. Various points in X axis of Fig. 7, denote both the real and reactive load vary simultaneously without change in the power factor at bus 6. The X axis values are(1(99MW,60MVAR),2(200,120),3(250,151),4(300,181), 5(315,190)).

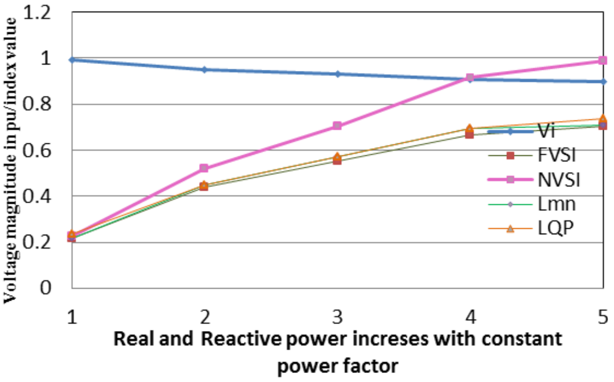

Fig. 7. Voltage magnitude, NVSI and other indices with constant power factor load variation at bus 6.

4.2.5 Multi Load changes at different buses (6, 7, and 8)

When load is added or removed from various buses at the same time its impact on the system is unique. The real and reactive loads at buses 6, 7 and 8 are increased from their base values to 280MW & 195MVAR, 210MW & 170MVAR and 120MW & 110MVAR respectively. Table 11 shows the lines 5-6 as most critical line for this condition and other two lines 1-6 and 48-52 are also in danger zone.

Table 11. Line stability indices for multi loading condition.

Line	Reactive load increases at different buses			
	NVSI	Lmn	FVSI	LQP
5-6	0.952	0.764	0.731	0.767
1-6	0.724	0.611	0.571	0.637
48-52	0.375	0.433	0.419	0.421

In TNEB 69 bus system, the line 5-6 is treated as critical line in different kind of load variation at bus 6.

5. Weak Bus and Most Critical Line Identification

The weakest bus identification for the operating point under analysis is the objective of the voltage security assessment. An iterative and sequential technique was presented, to determine the different routes being used for active power flow transmission to the weakest load bus, to identify the most loaded transmission path, and redirect the power flow to other routes which are less loaded for voltage security reinforcement [21]. A feed forward back propagation network has been proposed to identify the weakest lines and information about the rank of lines with respect to the stability index (Lmn) [22]. In this technique, the maximum loadability of reactive power at all the buses in network is determined for identifying the weak bus or most critical line of the system.

In this paper, instead of existing indices the NVSI is

Table 12. Weakest bus in test systems

Case	Reactive power loadability					
	High			Low		
	Q Value (MVAR)	Bus No	Line No	Q Value (MVAR)	Bus No	Line No
IEEE 30 bus system	128.87	7	Bus 5-7	26.41	30	Bus 27-30
TNEB 69 bus system	1708.52	54	Bus 52-54	80.15	68	Bus 65-68

proposed for weak bus and most critical line identification. For this, the reactive power loading at one particular bus is increased gradually till its NVSI reaches 0.9 and repeated for all transmission lines. The weakest bus is defined as the bus which has very low reactive power maximum loadability and the most critical line means the line which is connected in the weakest bus, reaches the stability index closer to unity.

Table 12 clearly shows that the weakest bus in both the IEEE 30 and India practical TNEB 69 bus system. The buses 30, 22 are considered as the weakest buses and the respective lines 27-30, 65-68 are treated as critical lines in IEEE 30 and TNEB 69 bus system. The maximum load ability of these buses is 80.15 MW and 206.15 MW respectively and it indicates that a small addition of load operates the system very closer to instability region.

6. Contingency Ranking

Contingency Analysis which is an inevitable part of static security analysis is critical in power system and the power market scenario. The contingency analyses spans over single element outage, multi-element outage and sequential outage. The voltage stability indices methods serve as the powerful tools for checking the limits after each contingency whether the system is secure. 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. A method for ranking contingencies based on information from the base case and post- contingency operating states using Voltage Stability Margin (VSM) was proposed [23]. A new index based on P_Q_V curve of a specified bus, area, or overall system has been 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 [24]. The NSGA II and MNSGA II algorithm is proposed for network contingency to obtain the optimal values of the control variable by considering L-index [25].

The proposed index is effective in segregation of severe contingencies. 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 occupy 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 13 and 14.

Table 13. Contingency Ranking for Overloading with Single Line Outage

Rank	Q=200MVAR at bus 48 and also one line outage at a time.			P=205MW & Q=163MVAR, at bus 44 and also one line outage at a time.		
	Outage line	Critical line	NVSI	Outage line	Critical line	NVSI
1	48-52	27-48	1.126	28-29	48-52	1.210
2	29-30	27-48	1.115	29-30	48-52	1.112
3	40-41	41-48	1.084	60-64	48-52	1.064
4	30-31	27-48	1.048	30-31	48-52	1.053
5	15-27	27-48	0.978	48-51	48-52	0.928
6	48-51	41-48	0.902	31-32	48-52	0.905
7	27-48	41-48	0.863	27-48	48-52	0.884
8	32-31	41-48	0.846	44-47	48-52	0.871
9	31-47	41-48	0.820	34-35	48-52	0.860
10	32-43	41-48	0.812	35-36	48-52	0.848

Table 14. Contingency Ranking for Overloading with a Generator Outage

Rank	Q=220 MVAR at bus 48 and one generator Outage at a time			P=100MW,Q= 190 MVAR at bus 48 & one generator outage at a time		
	Generator Outage	Critical line	NVSI	Generator Outage	Critical line	NVSI
1	Bus 31	48-52	1.022	Bus 36	41-48	1.004
2	Bus 36	48-52	1.019	Bus 57	48-52	0.966
3	Bus 13	41-48	1.012	Bus 58	48-52	0.931
4	Bus 57	27-48	0.977	Bus 60	48-52	0.928
5	Bus 58	41-48	0.972	Bus 15	48-52	0.903
6	Bus 60	41-48	0.966	Bus 53	48-52	0.899
7	Bus 14	41-48	0.964	Bus 14	48-52	0.893
8	Bus 15	41-48	0.962	Bus 21	48-52	0.892
9	Bus 67	41-48	0.927	Bus 13	48-52	0.889
10	Bus 21	41-48	0.924	Bus 67	48-52	0.886

The following observations and analyses can be made from the Table 13

Case1: Q load is increased at the bus 48 to 200 MVAR with successive line outages (except above said lines) and also consider reactive power limits at generators. The line outage is ranked based on NVSI values and only tabulated for first 10 ranks. The lines 27-48 and 41-48 are identified as critical lines.

By analyzing the single line diagram, it is found that the line outages which create isolation and the line outages which cause power flow divergence are placed in marked area of Fig. 8. Comparatively; less number of generators is placed in this area. Therefore when the load increases at the bus 48, is located in this area, out of top 10, 7 line outages are in this marked area. Hence the marked area is

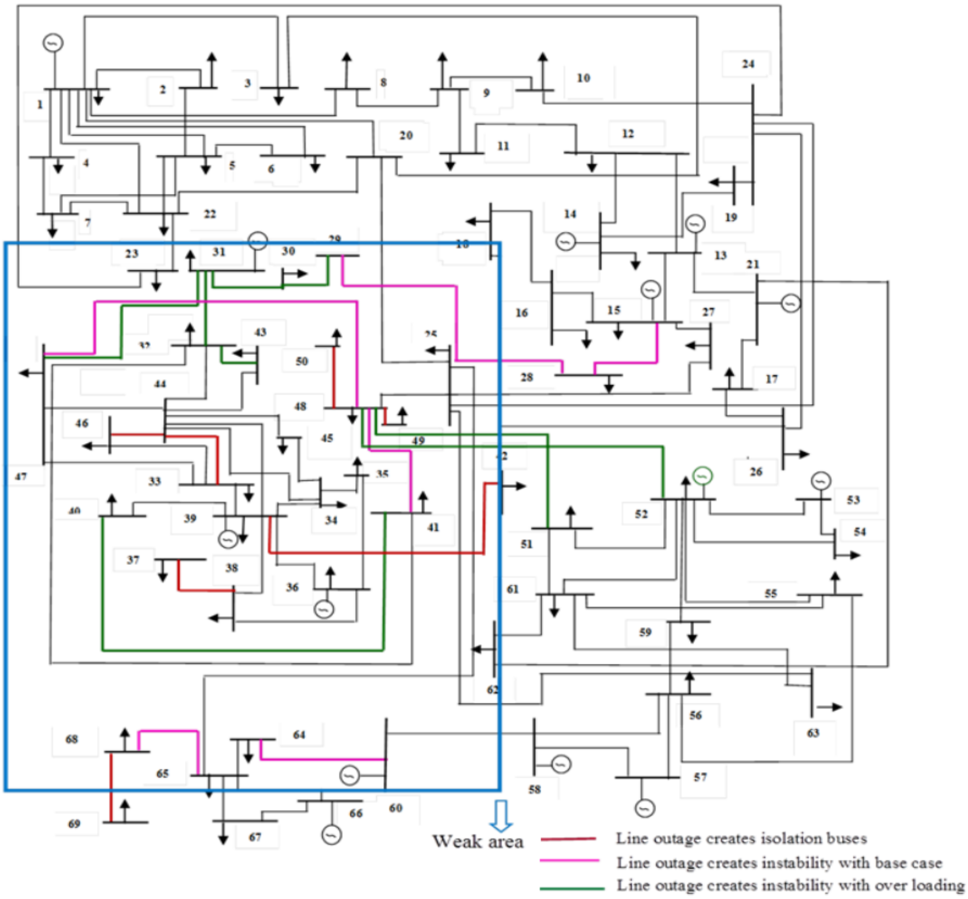

Fig. 8. 69 bus TNEB system

treated as weak area of this system.

Case 2: The system is tested, single line outage at a time, recursively for all the lines, with the real and reactive power respectively shot up to 205MW and 163 MVAR at bus 44. The line 48-52 turns out to be the critical line for most of the outages.

The following observations and analyses can be made from the Table 14

Case 3: In the bus 48, if reactive power is raised to 220 MVAR with one generator outage repetitively for all the generators, the lines 41-48, 27-48 and 48-52 are picked as critical lines. The system touches instability when the generator outage occurs at bus 39 which is placed in weak area in the base case. Other two top generator outages at bus 31 and 36 are also placed in weak area. Removal of any one generator in marked area will denote the high degree of sensitivity near the voltage collapse point and once again the weak area is justified.

Case 4: P and Q loads increased to 100 MW & 190 MVAR 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. Overloading of the transmission line may cause the cascading outages which leads voltage collapse at one or more areas. In Indian scenario, most of the transmission line transmit power at its maximum and also maintain equilibrium condition at all instants to avoid voltage instability. Line stability index will give the information about the system, 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 critical lines. The NVSI can be calculated within very short period(less than one second) when any component failure occurs in the system, while the process of system losing voltage stability take 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 area which needs more monitoring to maintain voltage stability at many nodes.

7. Conclusion

The paper has developed a notable advantage by introducing the new voltage stability index (NVSI). The index has been implemented in the conventional fast decoupled load flow method using fuzzy logic. The merits of the index are that it relates both real and reactive power whereas other indices relate only the reactive power of the system. Moreover usage of fuzzy logic method produces more accurate and exact results. The number of mappings is reduced from 7 to 3 outperforming the existing methods. The elapsed time of simulation is reduced due to the less number of mappings. This innovative technique can be used in the real time systems. NVSI index is more reliable compared to the other indices as the standard of prediction of voltage instability is high thus safe guarding the system from the point of voltage collapse. The contingency ranking is vital in predicting the occurrence of voltage instability thus preventing the system from collapse.

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