A Novel Method for Contingency Ranking Based On Voltage Stability Criteria in Radial Distribution Systems

Manjunatha Babu Pattabhi^{1,2} · Bangalore Rangappa Lakshmikantha³ · Krishna Shanmukha Sundar³

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Abstract

Voltage stability margin regarding with contingency ranking in radial distribution system using novel method is proposed in this paper. Two new indices are derived to forecast the voltage stability in the radial distribution feeders. Here, $RSI_N(r)$ is the radial stability index calculated for each bus and utilized for forecasting the voltage stability. The second index is derived by finding the effect of receiving end voltage change on voltage stability index at a specific bus. Contingency planning by delta analysis method improves the reliability of the system. The proposed system is employed for optimally ranking the contingencies. Impact on voltage stability due to contingencies like loss of FACTS devices, loss of distributed generation (DG) sets and loss of lines is carried out on radial distribution feeders and compared the experimental results with the proposed method using MATLAB platform. The proposed indices are implemented on the test systems and outcomes are compared to existing indices on literature and it is viewed that the proposed indices are effective on predicting the system stability. Contingency due to a loss of DG set, due to a loss of reactive source, due to a loss of line, due to loss of DG set are the considered test cases. Voltage profile improvement using Static VAR Compensator (SVC)-DSTATCOM is also employed in this paper. The proposed system is also tested under 15, 28 bus system, IEEE-69 and 123 bus system.

Keywords Radial Stability Index (RSI) · Voltage Stability Improvement (VSI) · Radial distribution system · Radial System Sensitivity Index (RSSI) · Distributed generation (DG) · Delta Analysis

Abbreviations

V_s	sending end voltage
δ_s	Phase angle of sending end voltage
δ_r	phase angle of receiving end voltage
V_r	Voltage in receiver end
Z	impedance of branch
R	Resistance
X	reactance
P	Active power load
Q	reactive power load

Z_{equ}	Equivalent impedance of the branch connecting source to receiving end
R_{equ}	equivalent resistance of the branch connecting source to receiving end
X_{equ}	Equivalent reactance of the branch connecting source to receiving end
$RSI_{N(r)}$	radial stability index
g	Generator bus
l	load bus
RSI	Radial Stability Index
VSI	Voltage Stability Improvement
RSSI	Radial System Sensitivity Index
DG	Distributed generation
ROW	Right of way

✉ Manjunatha Babu Pattabhi
manjubabup@gmail.com

¹ BMS Institute of Technology and Management, Bengaluru, Karnataka, India

² Department of Electrical and Electronics Engineering, Visvesvaraya Technological University, Belagavi, Karnataka, India

³ Department of Electrical and Electronics Engineering, Dayananda Sagar Academy of Technology and Management, Bengaluru, Karnataka, India

Introduction

Due to the rapid industrial growth and spread of larger residential areas the stress on electrical distribution network is increasing many folds. Right of way (ROW) issue in the urban areas is one of the bottlenecks to expand the

distribution network with the demand. Voltage collapse is the limiting factor, as electrical utilities try for increasing the use of its distribution network capabilities for transporting real power. With the introduction of newer technologies like net metering, many end users are installing renewable energy systems and injecting power into the grid [6, 7, 26]. An unplanned disturbance if not handled properly would spread to the transmission system and would result in grid collapse [20]. The distribution networks of today not only passively deliver power from the transmission network, via the distribution network to the end customer but also inject power into the grid with the introduction of distributed generation. System operators should possess adequate knowledge on what are the action needs to be taken when system experiences a contingency. The classification of unsafe contingencies by its severity is called contingency classification and important for power system operators and planners [2, 9, 10, 19]. Many FACTS devices are also connected in distribution systems to maintain power factor, reduce power loss, and recover system voltage stability [16, 21, 24]. In [5, 23] the load flow equations of the radial network are modified and an innovative voltage stability index is proposed. A new voltage stability index is derived from squaring the received active and reactive power in load end from the load flow equations for radial networks. [4, 18, 25]. Introduction of the DG and FACTS devices in the distribution would reduce the system losses and also can enhance the system stability. Contingencies like loss of line or loss of embedded generator or loss of a reactive power device or unplanned maintenance to attend an emergency would increase the risk of voltage instability [4, 14]. At present only few electrical utilities are carrying out voltage stability and contingency analysis of distribution systems.

A new index of voltage stability from load flow equations is presented in the literature for determining the bus that is prone to voltage instability for radial distribution networks [22]. For the analysis of voltage stability, an equivalent system of two buses of a distribution network is utilized. [11, 12]. But, the variation of indices with the placement of DG is not studied in the literature. An attempt is made to study the impact of placement of DG in the voltage stability indices proposed in [8, 22, 22].

A PQ or PV node is used for DG modeling, where the PQ node models are treated as negative injections into the system [15]. In future it will be mandatory for all utilities and system planners to conduct contingency analysis on distribution systems. In literature contingency ranking analysis is done for the transmission systems [1, 3] in detail but for the distribution system only limited literature is available.

Voltage stability margin regarding with contingency ranking in radial distribution system using novel method is proposed in this paper. Two new indices of voltage stability are derived to forecast the voltage stability for the radial

distribution feeders. Rest of the paper is organized in the following: Sect. 2 provides the radial stability index. Section 3 explains the derivation of proposed delta analysis method. Section 4 delineates the experimental results. Section 5 provides the conclusion.

Radial Stability Index (SI)

In [16] a voltage stability index has been proposed depending on the existence of real and reactive power solutions at receiving end. In [20], a voltage stability index is proposed for radial distribution system and given by Eq. (1). Figure 1 shows the electrical equivalent.

$$RSI(r) = 2V_s^2 V_r^2 - V_r^4 - 2V_r^2(PR + QX) - |Z|^2(P^2 + Q^2) \quad (1)$$

For stable operation of radial distribution networks, $RSI(r) \geq 0$ for $r=2, 3, 4$. where V_s is the sending end voltage, δ_s is the phase angle of sending end voltage, δ_r is the phase angle of receiving end voltage, V_r is voltage in receiver end, Z is impedance of branch, R is resistance, X is reactance, P is active power load, Q is reactive power load, voltage stability node index r ($r=2, 3, 4, \dots$).

Derivation of Proposed Radial Voltage Stability Indices

The stability index given in Eq. (1) is used to derive the Radial Voltage Stability Index. Sending voltage (V_s) in the equation $RSI(r)$ is made to unity and the branch resistance and reactance are modified with equal resistance and reactance as source bus to receiving bus. A resultant equation with the above mentioned changes is given as

$$RSI_N(r) = 2V_r^2 - V_r^4 - 2V_r^2(PR_{equ} + QX_{equ}) - |Z_{equ}|^2(P^2 + Q^2) \quad (2)$$

$$\begin{aligned} Z_{equ} & Z_{bus}(r,r), \\ R_{equ} & \text{Real part of } (Z_{bus}(r,r)), \\ X_{equ} & \text{Imaginary part of } (Z_{bus}(r,r)). \end{aligned}$$

where Z_{equ} is the equivalent impedance of the branch connecting source to receiving end, R_{equ} is the equivalent

Fig. 1 Electrical equivalent

resistance of the branch connecting source to receiving end, X_{equ} is the equivalent reactance of the branch connecting source to receiving end. $RSI_N(r)$ is radial stability index calculated for each bus and utilized for forecasting the voltage system stability. Once the receiving end voltages are known from the load flow then it can be calculated very easily.

The second index is derived by finding the effect of receiving end voltage change on voltage stability index (1) at a specific bus; $RSI(r)$ is differentiated with respect to change in the receiving end voltage V_r . Upon differentiation, obtain a change within $RSI(r)$ regarding with change on receiving end voltage V_r .

$$\frac{\Delta RSI(r)}{\Delta V(r)} = 4V_r - 4V_r^3 - 4V_r(PR + QX) = RSI_P(r) \quad (3)$$

Voltages, resistance, and reactance are modified with equal source voltage, resistance, and reactance as source to bus in deliberation. $RSI_P(r)$ is calculated for each bus and it can be used as an alternate index to forecast the voltage system stability.

Bus Electrical Radial System

The analysis of indices $RSI_N(r)$ and $RSI_P(r)$ is done on the 15 bus rural electrification distribution system. Table 9 in the Appendix 1 gives the line and load data. The index derived in Eq. (2) is compared with the index in Eq. (1) and the SI index proposed in [2]. SI index is the stability index consequent as divergence of load flow equations and it's valid only for the radial systems. Pattern of variation of indices with respected to bus number is plotted in the Fig. 2.

From Fig. 3 it can be observed that the variation of $RSI_N(r)$ which is derived from $RSI(r)$ Eq. (1) and the conventional radial distribution stability indices $RSI(r)$ Eq. (1), SI [2] is almost the same. Pattern of variation of indices are important than the absolute values. Once the pattern of variation is matching then the proposed indices can be used for any bus system. It can be observed that the 12th bus is

Fig. 2 15 bus radial distribution system

Fig. 3 Pattern of variation of indices

forecasted from bus that is susceptible to voltage instability from 3 indices.

L-index is one of the most primitive voltage stability index proposed on literature [10]. L-Index is used to predict the voltage stability of radial and meshed power systems.

$$L_j = \left| 1 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \right|$$

here “g”:- implies generator bus, “l”:- implies load bus. An L-index value among 1 and near with 0 implies great voltage stability margin. The buses with maximum value of L-index (near with 1) are deemed from critical lines. The pattern of variation of index $RSI_P(r)$ given by Eq. (3) and L-Index proposed in [10] is plotted in Fig. 4.

It is evident from the Fig. 4 that the pattern of variation of the indices is same. Most sensitive bus towards voltage instability as predicted from L-Index and $RSI_P(r)$ is 12th bus.

28 bus electrical radial system

The analysis of indices $RSI_N(r)$ and $RSI_P(r)$ is done on the 28 bus rural electrification distribution system. Table 10 in the Appendix 1 gives the line and load data. The index derived in Eq. (2) is compared with the index in Eq. (1) and the SI index proposed in [2]. Figure 5 shows the 28 bus radial distribution system. Figure 6 shows the plot of pattern of variation of indices with respect to bus number.

From Fig. 6 it can be observed that the variation of $RSI_N(r)$ which is derived from $RSI(r)$ equation and the conventional radial distribution stability index SI [2] is almost the same. It can be observed that the 18th bus is forecasted from bus that is susceptible to voltage

Fig. 4 Plot of pattern of variation of RSI_P(r) and L-Index

Fig. 7 Plot of pattern of variation of RSI_P(r) and L-Index

Fig. 5 28 bus radial distribution system

Fig. 6 Pattern of variation of indices

instability from 3 indices. Similarly, pattern of variation of indices as plotted in Fig. 7 is plotted for Eq. (3) and L-Index proposed [10]. L-Index is one of the most

primitive indexes utilized for predicting the voltage stability of both radial and meshed systems. It is evident from the Fig. 7 shows variation pattern of the indices is similar and 18th bus is predicted as most instable bus by both L-Index and RSI-P(r). From Figs. 4 and 7 it can be concluded that RSI_P(r) can be used as an alternate index to forecast the voltage stability of the radial bus systems.

Derivation of Proposed Delta Analysis Method

The linearized power flow equations is given below

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{pmatrix} H & N \\ M & L \end{pmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \quad (4)$$

$$\Delta P = J_{11} \Delta \theta + J_{12} \Delta V \quad (5)$$

$$\Delta Q = J_{21} \Delta \theta + J_{22} \Delta V \quad (6)$$

Rewriting Eq. 5 in terms of $\Delta \theta$ we get

$$\Delta \theta = J_{11}^{-1} \Delta P - J_{11}^{-1} J_{12} \Delta V \quad (7)$$

Substituting $\Delta \theta$ in Eq. (6) we get

$$\begin{aligned} \Delta Q &= J_{21} J_{11}^{-1} \Delta P - J_{21} J_{11}^{-1} J_{12} \Delta V + J_{22} \Delta V \\ (J_{21} J_{11}^{-1} J_{12} - J_{22}) \Delta V &= J_{21} J_{11}^{-1} \Delta P - \Delta Q \\ \Delta V &= [J_{21} J_{11}^{-1} J_{12} - J_{22}]^{-1} [J_{21} J_{11}^{-1} \Delta P - \Delta Q] \end{aligned} \quad (8)$$

Substituting ΔV in Eq. 3 we get

$$\Delta RSI(r) = \left[4V_r - 4V_r^3 - 4V_r(PR + QX) \right] \left[J_{21}J_{11}^{-1}J_{12} - J_{22} \right]^{-1} \left[J_{21}J_{11}^{-1}\Delta P - \Delta Q \right] \quad (9)$$

Equation 9 gives the relationship between the change under RSI index through the change of P and Q . This equation is utilized for determining the sensitivity of voltage stability index regarding with injection of reactive power on specified bus. Whenever the system experiences contingency, it would result in the change on real power and reactive power connected to system which in turn changes the voltage system stability. Equation 9 is used for predicting the change in voltage stability at a node due to the change in real and reactive power on system. Due to contingency, there may be a loss of generation (tripping of a DG set) or loss of reactive power source (disconnection of shunt FACTS devices) or both. The change in voltage stability index due to a loss of DG set or due to loss of shunt FACTS device or due to tripping of line can be obtained from Eq. 9. $\sum [\Delta RSI(r)]$ is calculated to compare and rank different contingencies in the system. A higher value of $\sum [\Delta RSI(r)]$ indicates the particular contingency would create greater impact on the system and ranked one.

Experimental Results

Test case 1: Contingency due to a loss of DG set

It compares the impact of contingency of DG set on voltage system stability both the proposed and the conventional system. For comparison, the 15 bus system is taken. Figure 2 portrays that one-line diagram with the location of the DG set. The DG set location and rating is selected randomly. Table 9 in Appendix 1 provides the load and line data. Loading of the system is increased five times over the base case indicated in the Table 9 to increase the load on the system. DG set is modeled as a PQ load with negative injection and rating is chosen as 100 kW.

To compare the effectiveness of proposed through conventional method, $\Delta RSI(r)$ for a loss of DG set is calculated from Eq. 9 ($\Delta Q = 0$). From the conventional method, $\Delta RSI(r)$ is calculated as difference in RSI at all the buses before and after removal of DG set. Results are tabulated in Table 1. Figure 8 shows the 15 bus system with a DG set connected at 12th bus.

It may be view as Table 1, which $\Delta RSI(r)$ from proposed delta analysis and conventional methods are matching closely. It can be observed from the calculated value of $\Delta RSI(r)$ from delta analysis and conventional method is maximum at 12th bus. Delta analysis can be used to in contingency planning to find the effect of any loss of DG set connected to the system. The absolute value of RSI(r) can

Table 1 Comparison of $\Delta RSI(r)$ calculated from delta analysis and conventional method for Test case-1

Sl. No	Bus No	$\Delta RSI(r)$ Delta Analysis Method	$\Delta RSI(r)$ Conventional Method
1	2	0.0048502	0.0045587
2	3	0.010573	0.0093636
3	4	0.011335	0.0095223
4	5	0.011993	0.0085358
5	6	0.0063141	0.0081011
6	7	0.0066826	0.0067091
7	8	0.005188	0.0083352
8	9	0.0051896	0.0079434
9	10	0.015373	0.0097142
10	11	0.022064	0.011376
11	12	0.02691	0.01488
12	13	0.011985	0.0084123
13	14	0.011597	0.0083965
14	15	0.006468	0.0066497

Fig. 8 15 bus system with a DG set connected at 12th bus

be obtained from adding RSI(r) at a bus with $\Delta RSI(r)$, if the absolute value becomes negative then the system becomes unstable. So, $\Delta RSI(r)$ can be used to predict the bus are having higher probability to become unstable and also predicts the system reliability.

Test case 2: Contingency due to a loss of reactive source

This section compares the impact of contingency of reactive source set on voltage system stability from proposed method and conventional method. 15 bus radial distribution systems are considered for test. Table 9 on Appendix 1 gives line and load data. Loading of the system is increased five times the base case. A reactive power compensating device can be anything like FACTS devices or Static capacitors is placed the bus no. 13 as shown in Fig. 9. Reactive

Fig. 9 15 bus system with a reactive power source connected at 13th bus system

power compensation device location and rating (100kVAr) is selected randomly.

To compare the effectiveness of proposed using the conventional method $\Delta RSI(r)$ for a loss of reactive power compensation device, which is connected to bus no. 13 is calculated from Eq. 9 with $\Delta P = 0$. From the conventional method, $\Delta RSI(r)$ is calculated as difference in RSI at all the buses before and after reactive power compensation device contingency. Results are tabulated on Table 2.

It can be viewed as Table 2, which $\Delta RSI(r)$ from proposed delta analysis and conventional methods are matching closely. It can be observed from the calculated value of $\Delta RSI(r)$ from delta analysis and conventional method is maximum at 13th bus. In practice reactive power elements are connected in the distribution systems for improvement of voltages, reduction of line losses and for improvement of voltage stability. When there is a contingency associated with a reactive power source as done in the above test case the system may become

Table 2 Comparison of $\Delta RSI(r)$ calculated from delta analysis and conventional method for Test case-2

Sl. No	Bus No	$\Delta RSI(r)$ Delta Analysis Method	$\Delta RSI(r)$ Conventional Method
1	2	0.0042278	0.0040557
2	3	0.0092161	0.0083178
3	4	0.011534	0.0085912
4	5	0.012203	0.0088801
5	6	0.0055038	0.0071955
6	7	0.005825	0.0059583
7	8	0.0045222	0.0074036
8	9	0.0045236	0.0070554
9	10	0.0099827	0.0083169
10	11	0.01097	0.0072921
11	12	0.011329	0.0066996
12	13	0.015116	0.0098654
13	14	0.0118	0.0087352
14	15	0.005638	0.0059055

unstable. Delta analysis method can be used to calculate $\Delta RSI(r)$ at each bus taking into the consideration of loss of reactive element at any bus. The buses which are having higher change in $\Delta RSI(r)$ are considered as more prone to voltage instability. Even the absolute value of RSI can be obtained from adding $\Delta RSI(r)$ to $RSI(r)$. Contingency planning with delta analysis method would also improve the system reliability.

Test case 3: Contingency due to a loss of line

This section compares the impact of contingency of a line on voltage system stability both from proposed method and conventional method. For test, 15 bus radial distribution network portrays on Fig. 1 is considered. A DG set of 2250 kW is connected at 12th bus, the rating of the DG set is taken randomly. It is assumed that there is a fault on the line between 3rd node to 12th node. The relay protecting the line will sense the fault and isolate the faulty section by opening the circuit breaker (CB) shown in the Fig. 10. After the fault has cleared successfully, the system restores to a new state. After the removal of the line connecting the bus 3 to bus 12, the numbers of the nodes are changed as 13th node becomes 10th, 14th node becomes 11th and 15th node becomes 12th node respectively for carrying out voltage stability analysis.

It can be observed from Table 3. $\Delta RSI(r)$ from proposed delta analysis method and conventional methods are matching closely. Pattern of variation of indices before and after contingency is shown in Fig. 11. From the pattern of variation of indices, it can be seen that the pattern of $RSI(r)$ before contingency is below than the pattern of $RSI(r)$ after contingency which means that the system voltage stability is increased with the loss of line. The same may be confirmed from Fig. 12, as the individual bus voltages increases the voltage system stability improves. The reason for this, due to line loss the total load fed by the source will be reduced and the system voltage magnitudes will be improved which improve the overall voltage

Fig. 10 15 bus system with a fault on a spur

Table 3 Comparison of $\Delta RSI(r)$ calculated from delta analysis and conventional method for Test case-3

Sl. No	Bus No	$\Delta RSI(r)$ Delta Analysis Method	$\Delta RSI(r)$ Conven- tional Method
1	2	0.01028	0.00371
2	3	0.021539	0.01215
3	4	0.023786	0.01561
4	5	0.025781	0.01442
5	6	0.017713	0.01211
6	7	0.020612	0.01666
7	8	0.011283	0.01155
8	9	0.011286	0.01796
9	13	0.025738	0.01427
10	14	0.024557	0.01425
11	15	0.018268	0.01524

Fig. 11 Pattern of variation of RSI(r) before and after the contingency

system stability. In contrary, if DG set connected at the 12th bus is of higher capacity, then due to loss of this line the voltage stability of the system will be reduced. The reason may be attributed to the fact that loss of line is resulting in a loss of active power source from the system which will effect the overall voltage stability of the system To illustrate this fact, simulation is done with DG set of rating 3750KW at 12th bus. Pattern of variation of RSI(r) is plotted in Fig. 12 and bus voltages are plotted on Fig. 14. Figure 13, it may be viewed that pattern of RSI(r) before contingency is above than the pattern of RSI(r) after contingency. The same can be observed in Fig. 14, the bus voltages after contingency decreased compared to bus voltages after contingency.

In real time the faults on the distribution systems are unavoidable. The analysis done in the above test case is

Fig. 12 Bus voltages before and after contingency **Fig. 13** Pattern of variation of RSI(r) before and after the contingency **Fig. 14** Bus voltages before and after contingency

Fig. 15 15 bus system with DG set connected at bus no. 7, 9 and 12

Table 4 Indicating the location of DG sets connecting in the 15 bus system

Sl. No	Name of the DG set	Connected bus no
1	DG-I	12
2	DG-II	9
3	DG-III	7

very practical. It can be observed that the delta analysis method is effectual at predicting the voltage system stability. The loss of a line or loss of multiple lines can be simulated and voltage stability with the contingencies can be studied.

Test case 4: Contingency ranking due to loss of DG set

This section discusses the procedure of ranking the contingencies for maintaining the system stability based on delta analysis method derived in Sect. 2. The contingency which reduces the voltage stability of the system as compared to other contingency is ranked one. For test, 15 bus radial distribution network as shown in Fig. 15 is considered 3 no's of DG sets each of rating 100KW are connected as given in Table 4.

$\Delta RSI(R)$ given in Eq. 8 is calculated for loss of each individual DG set and the results are summarized in Table 5. $\sum [\Delta RSI(r)]$ is calculated for each loss of DG set. It can be seen that the $\sum [\Delta RSI(r)(DG - I)] > \sum [\Delta RSI(r)(DG - III)] > \sum [\Delta RSI(r)(DG - II)]$. Critical ranking of the contingency will be in the order of DG - I (First), DG - III (Second) and DG - II (Third).

The change in the bus voltages before and after contingency of individual DG set is plotted in the Figs 16, 17 and 18 below.

The effect of any contingency on the voltage stability of the entire system may be arrived very easily from delta analysis method.

Voltage profile improvement using SVC – DSTATCOM

Presently, DSTATCOMs are widely placed in the distribution systems for improvement of the voltages, reduction of line losses and improvement of voltage stability. 15 bus distribution system is analyzed with placement of 1500kVAr SVC at bus no's 12th, 13th and 14th. It can be observed from

Table 5 Comparison of $\Delta RSI(r)$ calculated from delta analysis and conventional method for Test case-4

Sl. No	Bus No	$\Delta RSI(r)$ Due to loss of DG-I	$\Delta RSI(r)$ Due to loss of DG-II	$\Delta RSI(r)$ Due to loss of DG-III
1	2	0.0040429	0.002425	0.0029544
2	3	0.0089751	0.0036572	0.0044556
3	4	0.0096368	0.0039269	0.0047841
4	5	0.010216	0.0041628	0.0050716
5	6	0.0052375	0.0031416	0.0079597
6	7	0.0055832	0.003349	0.010402
7	8	0.004294	0.0050423	0.003138
8	9	0.0043114	0.0070904	0.0031507
9	10	0.013236	0.0039324	0.0047909
10	11	0.019282	0.0042991	0.0052376
11	12	0.024014	0.0044757	0.0054528
12	13	0.010208	0.0041596	0.0050677
13	14	0.0098664	0.0040204	0.0048981
14	15	0.0053706	0.0032214	0.0081619
$\sum [\Delta RSI(r)]$		0.1342739	0.0569038	0.0755251

Fig. 16 With loss of DG at 12th bus

Fig. 17 With loss of DG at 9th bus

Fig. 18 With loss of DG at 7th bus

the Fig. 19 below it is considerable development on voltage profile, then DSTATCOMs location in the 15 bus system.

Presently, DSTATCOMs are widely placed in the distribution systems for improvement of the voltages, reduction

of line losses and improvement of voltage stability. 15 bus distribution system is analyzed with placement of 1500kVAR SVC at bus no's 12th, 13th and 14th. It can be observed from the figure below it is considerable development on voltage profile, then DSTATCOMs location in the 15 bus system.

IEEE 69 Bus System

Pattern of variation of indices for the IEEE-69 bus system is depicted in Fig. 20. The indices varied with the bus number of 0 to 69. In the bus number of 1 to 29, the index value like SI, RSI(r) and RSI-N(r) is varied with the value of 1 to 0.7. In the bus number of 29 to 50, the index value like SI, RSI(r) and RSI-N(r) gives the value of 1. In the bus number of 50 to 70, the index value like SI, RSI(r) and RSI-N(r) is varied with the value of 1 to 0.85.

Pattern of variation of indices for the IEEE-69 bus system is depicted in Fig. 21. The indices varied with the bus number of 0 to 69. In the bus number of 1 to 29, the index value like RSI_P(r) and L-Index is varied with the value of 0 to 0.58. In the bus number of 29 to 50, the index value like RSI_P(r) and L-Index gives the value of 0. In the bus number of 50 to 70, the index value like RSI_P(r) and L-Index is varied with the value of 0 to 0.11. The bus voltage of IEEE 69 bus system is depicted in the Fig. 22. The voltage value of the IEEE 69 bus system is varied with the value of 1 to 0.958. Application of proposed system on test system is shown in Table 6. Average Root Mean Square (ARMS) and relative errors of output calculation are depicted in Table 7.

IEEE 123 System

The indices proposed are valid for distribution systems. Indices are derived from the already existing and time tested indices proposed in the literature. Most of the distribution systems available are of short length so the negligence of shunt admittance is valid. Voltage stability indices derived in this paper are for the distribution systems with no shunt admittance. IEEE-123 bus system data shows that each line is having shunt admittance. So in order to apply the proposed method the shunt admittance is neglected which is a valid assumption. Only shunt admittance is not considered this is only assumption. Pattern of variation of indices with Bus No is given in Fig. 23.

This graph shows that the patterns of variation of 3 indices are near to comparison. L-Index is given by

$$L_j = \left| 1 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \right| \quad (10)$$

where $F_{LG} = [Y_{LL}]^{-1} [Y_{LG}]$. On careful observation it can be seen that as calculation of FLG matrix requires inverse of Y

Fig. 19 Voltage profile before and after placement of DSTAT-COMs

Fig. 20 Pattern of variation of indices for the IEEE-69 bus system

bus and as Y bus is spare for large bus systems. MATLAB program results are NaN. So, RSI_P(r) is compared with other indices as shown in the below graph.

Pattern of variation of indices are shown in Fig. 24. Bus Voltages on IEEE 123 Bus System (R-Phase) is provided in Table 8. Voltage profile of IEEE 123 bus system is shown in Fig. 25. Fig. 24 Pattern of variation of indices

Conclusions

The research done in this paper focuses on the improvement of easier and effectual method to forecast the voltage system stability when any type of contingency occurs in the system, ranking the contingencies so much system planners and

Fig. 21 Pattern of variation of RSI_P(r) and L-Index for the IEEE-69 bus system

operator is alert when any contingency occurs. The proposed method of Delta analysis is tested taking different possible contingencies experienced by the system in the real time. Contingency analysis is done taking four contingencies, with the loss of active power source, with the loss of reactive power source, with the loss of line and with the loss of multiple sources for contingency ranking. The results presented would lead to the following conclusions,

- (1) To forecast the voltage system stability, the proposed system is tested under four different bus system like 15, 28 bus system, IEEE 69 and 123 bus system.
- (2) To forecast the voltage stability of radial systems, two new indices are proposed. The results plotted for proposed indices and conventional indices are in close

Fig. 22 Bus voltage for IEEE-69 bus system

Table 6 Application of proposed system on test system

Test System	Metrics	IEEE 69 bus system
Mohammedi et al. (2013)	Loss reduction	-
	System load ability	3.20
Mohammedi et al. [17]	Loss reduction	53.80%
	System load ability	4.24
Proposed system	Loss reduction	71.90%
	System load ability	2.17

agreement. Hence, the proposed indices are used as new voltage stability indices.

- (3) Test results obtained by implementation of Delta analysis method for different test cases are matching with the conventional method.
- (4) Once $\Delta RSI(R)$ is calculated it can be used to find the ranking of any contingency quickly. It will helpful in real time and planning studies for maintaining the reliability of the supply.

It can be concluded that delta analysis method is a powerful tool for predicting the voltage system stability and

improving the system reliability. Future work can be done on dynamic voltage stability analysis by considering generator dynamics and dynamic load models. Dynamic analysis can be done for contingencies and ranking can be given for buses and branches. The improvement in voltage stability by various reactive power compensation devices can be observed.

Appendix 1

Tables 9 and 10

Data Availability Data sharing does not apply to this article as no new data has been created or analyzed in this study.

Code availability Not applicable.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

Consent to participate Not applicable.

Conflicts of interest Authors declare that they have no conflict of interest.

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Table 7 Average Root Mean Square (ARMS) and relative errors of output calculation

Error Terms (%)	Parameters	Average		Maximum	
		Kenari et al. [13]	Proposed	Kenari et al. [13]	Proposed
Relative error (%)	Mean calculation	0.09	0.075	0.012	0.08
	SD calculation	1.07	1	1.39	1.111
ARMS error (%)	Cumulative distribution function (CDF) estimation	0.086	0.079	0.125	0.109

Fig. 23 Pattern of variation of indices with Bus No

Fig. 24 Pattern of variation of indices

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Table 8 Bus Voltages on IEEE 123 Bus System (R-Phase)

Bus No	Voltages	Bus No	Voltages	Bus No	Voltages	Bus No	Voltages
1	1	26	0.974029853	51	0.97075052	76	0.942141631
2	0.996919791	27	0.974772472	52	0.97075052	77	0.943808369
3	0.994943116	28	0.974286054	53	0.971171645	78	0.943808369
4	0.99350905	29	0.97403958	54	0.944049085	79	0.943808369
5	0.981351036	30	0.973793139	55	0.944036202	80	0.94334346
6	0.974772472	31	0.973611559	56	0.94402694	81	0.9418762
7	0.973892151	32	0.973423503	57	0.9443403	82	0.941736495
8	0.972537989	33	0.973372924	58	0.944418655	83	0.941468733
9	0.972427936	34	0.970826874	59	0.94437622	84	0.943867546
10	0.972310983	35	0.970783947	60	0.943855538	85	0.943825067
11	0.972233081	36	0.970332121	61	0.943855538	86	0.94378259
12	0.971962444	37	0.978216285	62	0.943704902	87	0.943527029
13	0.971962444	38	0.974184966	63	0.943539226	88	0.941643245
14	0.971962444	39	0.973914871	64	0.94334346	89	0.94090931
15	0.980791305	40	0.973431393	65	0.94334346	90	0.940757853
16	0.978328329	41	0.973296261	66	0.943958512	91	0.94378259
17	0.978282813	42	0.973361903	67	0.943919467	86	0.94378259
18	0.974772472	43	0.973342453	68	0.943893592	87	0.943527029
19	0.973895277	44	0.973323003	69	0.944880479	88	0.941643245
20	0.973488322	45	0.973323003	70	0.945342377	89	0.94090931
21	0.973253587	46	0.97323219	71	0.945585511	90	0.940757853
22	0.972589972	47	0.97323219	72	0.945875748	91	0.94378259
23	0.971171645	48	0.971040215	73	0.943490907		
24	0.971171645	49	0.970948214	74	0.942851248		
25	0.974322422	50	0.970858932	75	0.942397568		

Fig. 25 Voltage profile of IEEE 123 bus system

Table 9 Line data and nominal load data of 15 bus system

Branch No	Sending end node	Receiving end node	Branch resistance	Branch reactance	Nominal load Receiving end	
					P KW	Q kVAr
1	1	2	1.35310	1.32350	44.2	44.2
2	2	3	1.17031	1.14471	70	70
3	3	4	0.84122	0.82280	141	141
4	4	5	1.52350	1.02771	44.2	44.2
5	2	8	2.01320	1.35789	70	70
6	8	9	1.68682	1.13781	44.2	44.2
7	2	6	2.55731	1.72489	141	141
8	6	15	1.0891	0.73411	141	141
9	6	7	1.25151	0.84421	70	70
10	3	10	1.79561	1.21121	141	141
11	10	11	2.44851	1.65161	70	70
12	11	12	2.01328	1.35789	44.2	44.2
13	4	13	2.23090	1.50489	70	70
14	4	14	1.19711	0.80751	141	141

Table 10 Line data and nominal load data of 28 bus system

Branch No	Sending end node	Receiving end node	Branch resistance	Branch reactance	Nominal load Receiving end	
					P KW	Q kVAr
1	1	2	1.8227	0.761	141	90
2	2	3	2.231	0.9480	80	50
3	3	4	1.3671	0.5691	80	60
4	4	5	0.920	0.381	100	60
5	5	6	3.6441	1.521	80	50
6	6	7	2.7332	1.142	90	40
7	7	8	1.4584	0.6073	90	40
8	8	9	2.7332	1.141	80	50
9	9	10	3.6441	1.522	90	50
10	10	11	2.761	0.781	80	50
11	11	12	1.381	0.390	80	40
12	12	13	4.134	1.175	90	50
13	13	14	4.134	0.8564	70	40
14	14	15	3.0272	0.778	70	40
15	15	16	2.752	1.167	70	40
16	16	17	4.128	0.778	60	30
17	17	18	2.752	0.778	60	30
18	2	19	3.44	0.9725	70	40
19	19	20	1.376	0.389	50	30
20	20	21	2.752	0.778	50	30
21	21	22	4.9536	1.4004	40	20
22	3	23	3.5776	1.0114	50	30
23	23	24	3.0272	0.8558	50	20
24	24	25	5.504	1.556	60	30
25	6	26	2.752	0.778	40	20
26	26	27	1.376	0.389	40	20
27	27	28	1.376	0.389	40	20
1	1	2	1.8216	0.758	140	90