

# Stability analysis of power system under n-1 contingency condition

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## Article Info

### Article history:

Received Mar 3, 2023

Revised Jan 8, 2024

Accepted Apr 4, 2024

### Keywords:

Contingency conditions

IEEE 30-bus

N-1 outage

Stability indices

Voltage instability

## ABSTRACT

Several voltage stability indices (VSIs) have been developed to assess the potential for voltage collapse. However, certain indexes are computationally costly. Meanwhile, some have been noted to underperform across various conditions. This work proposes a novel line index called the super voltage stability index (SVSI) to calculate the system's voltage stability margin (VSM). The suggested approach is based on the transmission system's two bus systems. The reactive power loss and N-1 contingency conditions to voltage sensitivity is a unique calculation approach used in this study to identify voltage instability. Day to day, the demand for electric power is being increased due to incessant increments in technology and population growth. Therefore, the power system networks are under pressure. The operational conditions of transmission system networks are affected at this point, which may result in voltage collapse. Regular monitoring of power supply is essential to avert voltage collapse. The effectiveness of the suggested index has been assessed using the IEEE 5 and 30-bus systems across diverse operating scenarios, including variations in active and reactive power loading as well as single line losses. The findings indicate that SVSI provides a more reliable indication of the proximity to voltage collapse when compared to conventional line VSIs.

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## 1. INTRODUCTION

Day-to-day incessant increment in technology and population growth in the universe, due to that, the demand for electricity increased. So, the networks are operated in highly stressed conditions. Also, weather conditions, faults, and miscommunication between control station operators will lead to rising voltage instability problems in the power systems, and the consequences of these problems will lead to voltage collapse or block out [1]–[3]. The main reason for voltage breakdown under these circumstances is a lack of reactive power. As a result, research into voltage instability and voltage collapse remains a prominent priority in power system management and planning [4], [5] provides a general explanation of power system stability, concepts, and classifications. Dynamic and static stability techniques may be used to analyse voltage stability. In comparison to dynamic analysis, static stability analysis requires less computational time. Therefore, the system is easy to analyse and model [4], [5].

In the literature, many traditional and new voltage stability indices (VSIs) approaches have been used to predict and monitor the system condition. Power voltage-reactive voltage (PV-QV) curves have been used to calculate the maximum allowable load of the transmission system [6]. These curves are drawn from the voltage equation of two bus system. Some of the traditional methods like modal analysis, sensitivity

analysis [7], continuation power flow method [6], singular value decomposition [8], bifurcation methods [9], [10], and tangent vector method [11] are used to measure the distance between current operating point to the collapse point. These traditional methods are complex and computationally consume maximum time.

VSI are used to address the drawbacks inherent in conventional voltage stability methods. These VSIs play a vital role in the power system by providing exact information about planning, control, accuracy, and speed of operation. The assessment of the system's voltage stability relies on VSI-based metrics, which derive a numerical value from the power flow solution [12]–[14]. Various types of VSIs, grounded in different power system concepts, have been proposed and tested on IEEE test systems as documented in the literature. These indices serve to evaluate voltage stability. The different types of concepts like:

- PMUs and local measurements: phasor measurement units are the advanced and smart devices to collect the information (i.e., current and voltage phasors) at the buses, and these are located at both the generator side and load end side of the power system. The data acquired from PMUs can be employed for predicting voltage collapse in the system [15]–[19].
- Voltage equation of a line: these indices [20]–[27] are formulated using transmission parameters, including real and reactive power, voltage, current, and reactance at the sending and receiving ends of the line. The stability margin of the power system is then determined by integrating VSI into the power flow solution.
- Jacobian matrix: the VSIs relying on the Jacobian matrix utilize the Jacobian matrix of the power flow equations, as mentioned in [7], [8], [28]–[30]. These indices offer a clear indication of the proximity to voltage instability, providing detailed information about sensitive locations and critical buses.
- Maximum power flow: the indices which can be derived based on the maximum power flow transfer in a line or the maximum power transfer theorem of the power system. The VSIs have been mentioned in the literature using the concept of power flow analysis in the power system [28], [31]–[35].
- Apart from the concepts mentioned earlier, the derivation of VSIs has been grounded in various factors, including the ABCD parameters [14], a hybrid indices [36], assessment of reactive power loss [37], based on the transmission areas and paths.

This study introduces the super voltage stability index (SVSI) as a method to assess the voltage stability margin (VSM) swiftly and accurately. Derived from the voltage equation of a two-bus system transmission network, this index provides a faster and more precise means to predict the power system's voltage stability. The primary goal of SVSI is to furnish operators with precise information about the state of the system networks, enabling informed decisions in advance to ensure system reliability and safety. This suggested index's efficacy has been assessed on conventional IEEE-5 bus and IEEE-30 bus systems, and the outcomes have been compared with those of the VSIs that are currently in use.

The paper's organizational structure can be outlined as follows: section 2 elaborates on various VSIs and their methodologies for measuring the stability margin from the current operating point to the system collapse point. The derivation and properties of the SVSI are discussed in section 3. Section 4 concludes the examination of the findings obtained from the IEEE test system under diverse circumstances. Finally, section 5 provides a conclusion to the overall topic.

## 2. CONCEPT OF VSIS

In power system research, voltage instability stands out as a top priority and a formidable challenge for electrical engineers and researchers. The following sections delve into various methods and practices applied to IEEE test systems, aiming to assess voltage instability and anticipate voltage collapse. This section specifically compares different line VSIs to gauge the stability status of the power system. Subsequent subsections briefly discuss various VSIs, including Lmn, fast voltage stability index (FVSI), and NVSI.

- Lmn: the line stability index is developed based on the quadratic voltage equation of a transmission line [24]. This technique is applicable to all lines in the system, not to a line. The Lmn equation for the  $i^{\text{th}}$  transmission line is given by:

$$Lmn = \frac{4XQ_R}{V_S \sin(\theta - \delta)^2} \quad (1)$$

Here, the Lmn value keeps on moving to reach the indicator “1” shows the system is unstable, and “0” represents the stable operating condition.

- FVSI: this method is employed for forecasting voltage collapse and conducting contingency analysis resulting from a line outage in a power system. The index is derived from the quadratic voltage equation of the transmission line, with the criterion being that the discriminant of the voltage equation must be greater than zero. If the (discriminant < 0), the roots of the quadratic equation become imaginary, resulting in voltage instability finally, it reaches voltage collapse [25]. FVSI can be defined by (2):

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

- NVSI: the derivation of NVSI involved the quadratic voltage equation at the receiving end bus in a two-bus system, neglecting the transmission system resistance [27]. Practically the efficacy of the index has tested on tamilnadu electricity board (TNEB) 69 bus system. This index can be used to identify weak areas and weak buses in the system under outage contingency conditions.

$$NVSI_{ij} = \frac{2X \sqrt{(P_j^2 + Q_j^2)}}{2Q_j X - V_i^2} \quad (3)$$

### 3. DEVELOPMENT OF PROPOSED INDEX (SVSI)

A simplified transmission system is employed to elucidate the concept underlying the proposed SVSI. Contemplate the two-bus systems depicted in Figure 1, where V1 represents the sending end voltage, V2 the receiving end voltage, and Z the impedance of the line.

$$I = \frac{V_1 \angle 0 - V_2 \angle \delta}{Z} \quad (4)$$

$$S = V_2 I^* \Rightarrow I = \left( \frac{S}{V_2} \right)^* = \left( \frac{P_2 - jQ_2}{V_2 \angle -\delta} \right) \quad (5)$$

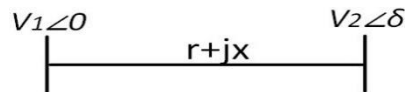


Figure 1. Visual representation of the single-line configuration within the transmission network

Substitute (4) in (5) will get (6):

$$\frac{V_1 \angle 0 - V_2 \angle \delta}{Z} = \left( \frac{P_2 - jQ_2}{V_2 \angle -\delta} \right) \quad (6)$$

Solving (3) and will get real and imaginary parts are written in (7) and (8):

$$V_1 V_2 \cos \delta - V_2^2 = R P_2 + X Q_2 \quad (7)$$

$$V_1 V_2 \sin \delta - V_2^2 = X P_2 - R Q_2 \quad (8)$$

From (7) and (8) separating the  $\cos \delta$  and  $\sin \delta$  terms and equating to  $\sin^2 \delta + \cos^2 \delta = 1$ , will get a quadratic as given in (6):

$$2V_2^4 + V_2^2 [(X + R)(P_2 + Q_2) - V_1^2] + [(R^2 + X^2)(P_2^2 + Q_2^2)] = 0 \quad (9)$$

Tten  $V_2^2 = x$  The quadratic equation will be given:

$$x = x^2 + x[(X + R)(P_2 + Q_2) - V_1^2] + [(R^2 + X^2)(P_2^2 + Q_2^2)] = 0 \quad (10)$$

The roots of the above equation are:

$$V = \sqrt{\frac{-[(X+R)(P_2+Q_2)-V_1^2] \pm \sqrt{[(X+R)(P_2+Q_2)-V_1^2]^2 - 8[(R^2+X^2)(P_2^2+Q_2^2)]}}{4}} \quad (11)$$

The condition has at least one solution:

$$[(X + R)(P_2 + Q_2) - V_1^2]^2 - 8[(R^2 + X^2)(P_2^2 + Q_2^2)] \geq 0 \quad (12)$$

Apply square root on both sides of (12). The solution for the equation leads to SVSI for the transmission line  $i, j$  is given in (13):

$$SVSI_{i,j} = \frac{\sqrt{2(R^2 + X^2)(P_2^2 + Q_2^2)}}{(R + X)(P_2 + Q_2) - V_1^2} \leq 1 \quad (13)$$

To observe (13), the index SVSI depends on the transmission resistance of the line. For a practical or standard system, the resistance values are assumed to be negligible or zero. So, the resistance value is set to be "0", and (13) rewritten as modified SVSI is given.

$$SVSI_{i,j} = \frac{\sqrt{2X^2(P_2^2 + Q_2^2)}}{X(P_2 + Q_2) - V_1^2} \leq 1 \quad (14)$$

The formulation of the proposed line stability index is presented, and its key attributes are outlined as:

- The proposed technique is developed from the quadratic voltage equation of a transmission two-bus system.
- This technique can be applied to all types of networks, and this can give the exact information of all the lines in a system.
- The accuracy of this index is high, and the time to compute this index is very low compared to existing techniques.
- The proposed index can be applicable for both the online and offline operators to provide secure operation of the power system.
- The index value depends on the system impedance.

#### 4. RESULTS AND DISCUSSION

Predicting a system's voltage collapse point or boundary is the aim of voltage stability analysis (VSA). SVSI is used in this study to predict the voltage collapse point. The IEEE 5- and IEEE 30-bus test systems are used for the thorough study. As shown in Figure 2 [15], the IEEE 30-bus system consists of 6 generating buses (PV) and 24 load buses (PQ) coupled by 41 transmission lines.

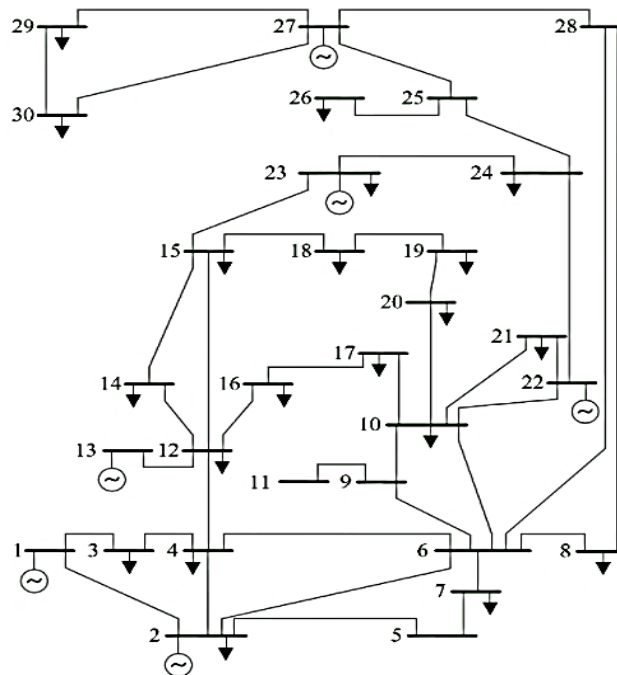


Figure 2. The standard IEEE 30-bus system

To attain the power flow solution within the system, a Newton-Raphson load flow program is utilized. The power flow solution is then employed to compute the SVSI for each transmission line in the system. The approach involves incrementally raising the load from the base case until convergence is achieved. Sequential testing of all buses in the system is conducted to assess the accuracy and performance of the proposed index. In this context, stability criteria are established, where a particular line with an SVSI index value close to 1 is deemed critical, and an index value of 0 signifies stability. The determination of the weakest lines is based on the criticality of index values. The entire process is visually represented in the flow chart presented in Figure 3. Additionally, the same methodology is applied to the remaining indices, namely Lmn [24], FVSI [25], and NVSI [27].

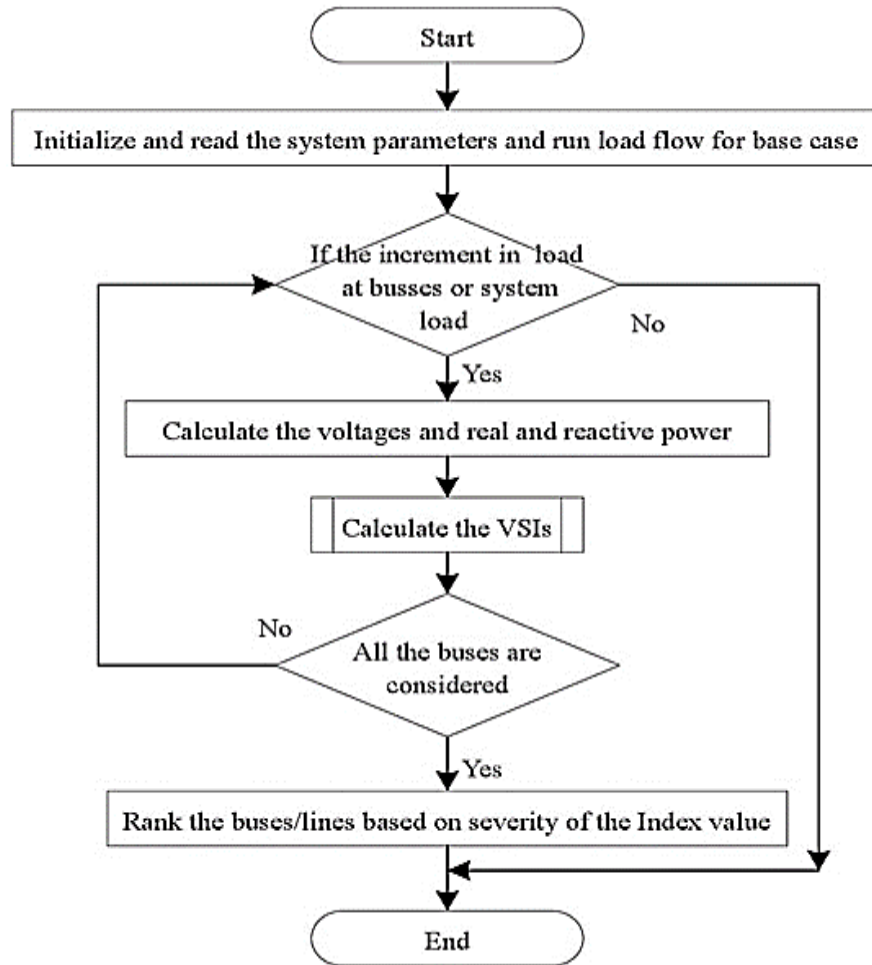


Figure 3. Flow chart for the identification of critical lines under loading condition

The IEEE 5-bus and IEEE-30 bus systems have been used to test the proposed index under a variety of operational conditions [15]. The outcomes are then contrasted with those generated by the recognised indices, Lmn [25], FVSI [26], and NVSI [28]. The computation of the SVSI index is conducted across various operating conditions, revealing that the suggested method yields values close to 0 for baseload conditions, and it increases from 0 to 1 as the system's loading increases. The suggested approach is close to one when the system is near to VSM or voltage collapse. The test results for different cases under different conditions are given:

- Active power loading
- Reactive power loading
- System loading
- Line outage condition

**4.1. Baseload condition**

The effectiveness of the proposed technique is assessed using IEEE 5-bus and IEEE 30-bus test systems. A comparison is made with existing indices, namely Lmn, FVSI, and NVSI, under base case loading conditions, as illustrated in Figure 4 for the IEEE 5-bus and Figure 5 for the IEEE 30-bus system. Notably, both figures depict that when the system is voltage stable, all indices-FVSI, Lmn, NVSI, and the proposed index-converge near zero.

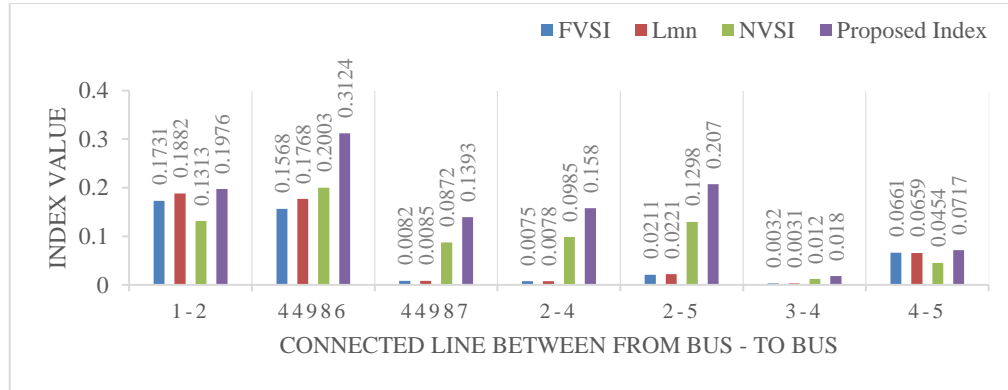


Figure 4. Initial loading condition for the IEEE 5-bus system

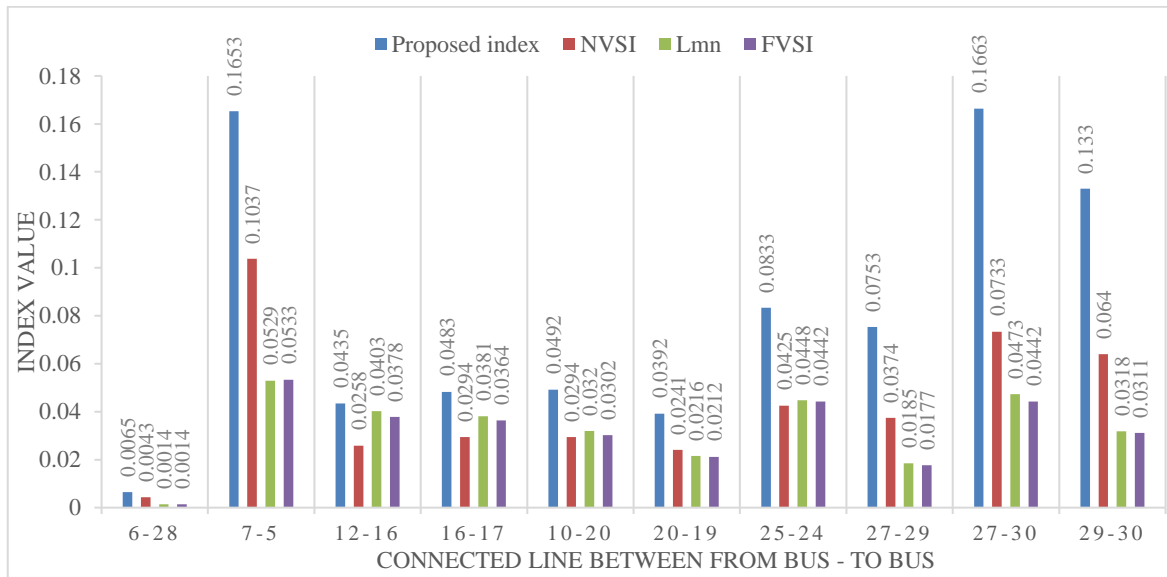


Figure 5. Initial loading condition for the IEEE-30 bus system

**4.2. Assessment of active power loading**

In this study, the proposed index is examined under the impact of real power loading, with a continuous increase in loading at each bus until reaching the VSM or collapse point. As shown in Tables 1 and 2, the proposed index approaches the critical value closer to unity at the maximum active power loading point. In contrast, the values of alternative indices [24], [25], [27] deviate significantly from the critical threshold, indicating their inability to precisely evaluate the voltage collapse point. Critical lines are pinpointed based on the severity of the voltage margin, computed using the proposed index. In Table 1, bus five is loaded to the maximum point, causing the proposed index for lines 2-5 to rise to 0.9981. Similarly, in Table 2, bus seven is loaded to the maximum, resulting in the index value for lines 2-6 increasing to 0.9937. This signals an authoritative state for these lines, highlighting the need for appropriate control measures to restrict loading and prevent voltage collapse. On the other hand, the indices [24], [25], [27] are unable to measure the critical state of these lines. From the above discussion, it is noticed that the other indices [24], [25], [27] show inaccurate results of voltage stability.

Table 1. VSIs for a 5-bus system under heavy active power loading on a single-load bus

Load bus	Loading	Critical line	Proposed index	NVSI	Lmn	FVSI
3	5.1	1-3	0.9774	0.4557	0.0239	0.0175
4	6.1	1-3	0.9921	0.4602	0.0269	0.0196
5	3.8	2-5	0.9981	0.4151	0.0391	0.0315

Table 2. VSIs for IEEE-30 bus system under heavy active power loading on a single load bus

Load bus	Loading	Critical line	Proposed index	NVSI	Lmn	FVSI
5	2.7	1-2	0.9857	0.3298	0.0841	0.0682
7	7.7	2-6	0.9937	0.4575	0.0866	0.0732
14	13.8	6-10	0.9976	0.749	0.3965	0.4008
15	10.8	6-10	0.9628	0.7025	0.3434	0.3437
16	22.5	6-10	0.9992	0.7145	0.3271	0.3265
17	7.8	6-10	0.9915	0.7039	0.3143	0.3126
20	22.8	6-10	0.9999	0.7042	0.3014	0.3009
21	5	6-10	0.984	0.6834	0.2772	0.2741

### 4.3. Assessment of reactive power loading

The performance of the suggested index under reactive power loading is evaluated by progressively increasing the reactive power for each bus until reaching the critical point. The proposed index is computed and compared with other indices [24], [25], [27]. Comparative results for both IEEE 5-bus and IEEE 30-bus systems are detailed in Tables 3 and 4. Examining Table 3, bus 3 experiences the maximum loaded condition, leading to a proposed index value of 0.9979 for line 4-5, indicating a critical state for this line. Referencing Table 4, bus 21 is under maximum loaded conditions, resulting in a proposed index value of 0.9953 for lines 14-15, signifying a critical condition for this line. Consequently, the proposed index proves adept at detecting unstable voltage conditions under reactive power loading. In contrast, indices Lmn [24] and FVSI [25] yield values exceeding their critical thresholds, falsely suggesting a voltage instability condition in the power system.

Table 3. VSIs for five bus system under heavy reactive power loading of single-load bus

Load bus	Loading	Critical line	Proposed index	NVSI	Lmn	FVSI
3	23.2	4-5	0.9979	0.9319	0.8222	1.0716
4	57.8	4-5	0.9984	0.9333	0.8321	1.0727
5	22.6	2-5	0.9955	0.6702	0.8638	0.8672

Table 4. VSIs for IEEE-30 bus system under heavy reactive power loading of single load bus

Load bus	Loading	Critical line	Proposed index	NVSI	Lmn	FVSI
7	28.4	6-9	0.9888	1.0075	0.9075	0.9828
17	23	12-16	0.9961	0.7667	0.9815	1.0637
21	9.8	14-15	0.9953	0.4389	1.2668	1.3432
24	11.3	24-25	0.989	0.6324	0.8671	1.0189
30	16.8	29-30	0.9771	0.4753	0.5747	0.7914

### 4.4. Assessment of system loading

The flexibility of the proposed index has been demonstrated under various operating conditions, as detailed in the preceding subsections. To assess its effectiveness under maximum loading conditions, this study explicitly elaborates on MVA loading conditions. Here, both the real and imaginary powers are loading at all buses are incrementally raised until convergence is achieved. Illustrated in Figure 6, the calculated index values at this juncture are 0.9977 for IEEE-5 bus systems and 0.9875 for IEEE-30 bus systems, respectively. These values indicate that the voltage collapse point is imminent. In contrast, other indices [25], [26], [28] remain below their critical values, underscoring their inability to identify unstable voltage conditions. Table 5 provides details on the loading factor and critical lines obtained for the systems under consideration.

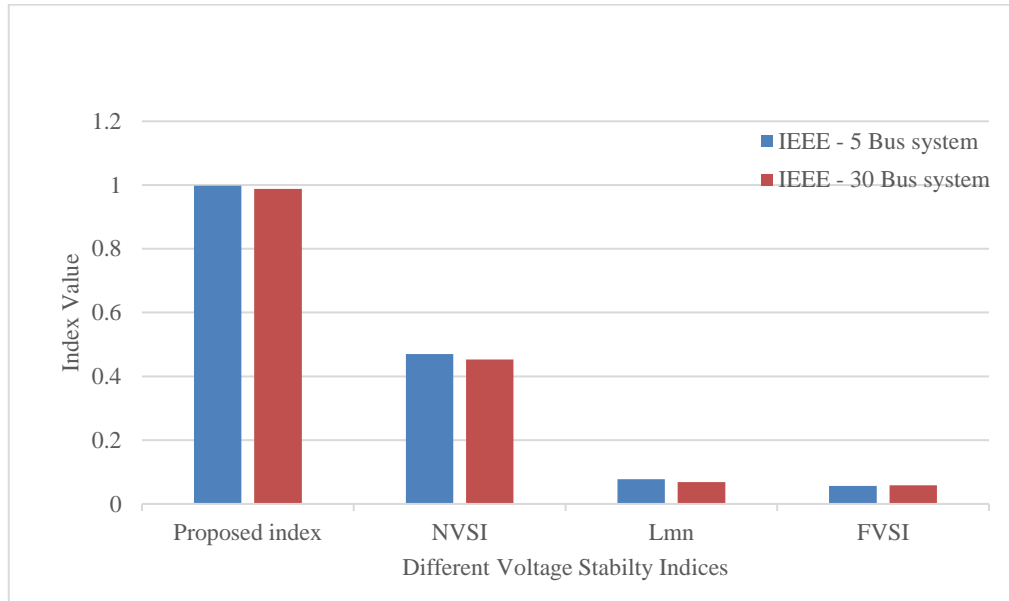


Figure 6. Critical levels for different VSIs under heavy load condition

Table 5. VSIs under heavy load condition

	IEEE-5 bus system	IEEE-30 bus system
Loading factor	2.5	1.58
Critical line	1-3	2-6
Proposed index	0.9977	0.9875
NVSI	0.4695	0.4528
Lmn	0.0774	0.0683
FVSI	0.0565	0.0582

**4.5. Contingency analysis**

Conducting a contingency analysis is crucial in a system to assess the impact of lines and system components. This analysis provides valuable insights into system stability, reliability, and security, prompting the implementation of necessary control measures. In this context, the general N-1 contingency criterion is applied to evaluate the efficacy of the proposed stability index under single-line outage conditions. The comprehensive procedure for contingency analysis is illustrated in the flow chart presented in Figure 7, which closely resembles the one used in VSA. During this analysis, the real and imaginary power loading at all buses is incrementally raised until convergence is achieved. As depicted in Figure 6, the recommended index values at this juncture are 0.9977 for IEEE-5 bus systems and 0.9875 for IEEE-30 bus systems, indicating the proximity of the voltage collapse point. Contrastingly, other indices [25], [26], [28] fall significantly below their critical values, highlighting their incapacity to identify unstable voltage conditions. The highest index value during any outage condition indicates a severe contingency.

Conducting contingency analysis on the IEEE 5-bus system revealed critical outcomes under the single line outage scenario with a specified load at bus 4. The reactive loading of the buses was configured to half of the maximum allowable load, as indicated in Table 3, while other buses maintained constant reactive loads at base levels. Referring to Table 6, the SVSI of line 1-2 is computed as 1.462716 during the outage of line 1-2. This signifies a highly critical contingency, resulting in voltage collapse. Conversely, the remaining indices are away from the unity, implying that the system is in stable condition. So, the proposed index has high accuracy, and it is proficient in monitoring the different conditions of lines under different contingency conditions. The proposed index is used for power system control and planning applications, and it will help operators to take appropriate decisions to avoid voltage collapse. The contingency results for the IEEE 30-bus system under the line outage with a pre-specified load at bus seven has given in Table 7. SVSI of line 1-2 is calculated as 4.047185 at an outage of line 1-2, which shows that the contingency is very serious and it caused the voltage collapse.



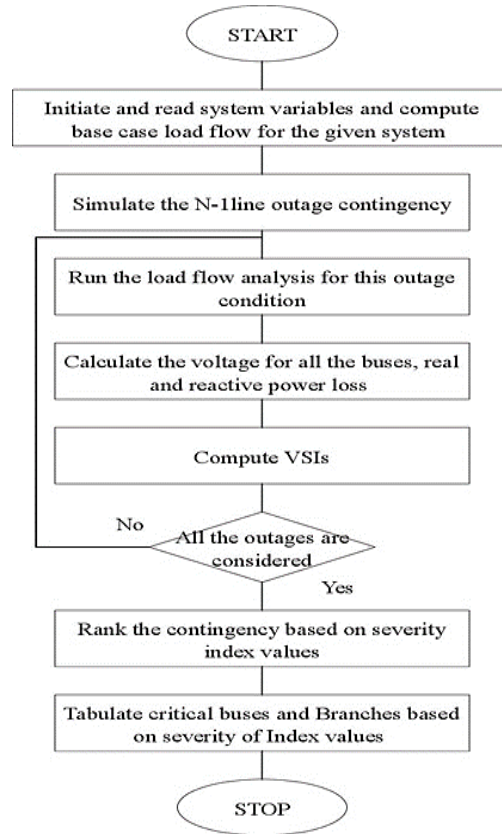


Figure 7. Procedure to identify critical lines under contingency condition

Table 6. Critical line ranking of IEEE 5-bus system under line outage

Rank	Line outage	Critical line	Proposed index	NVSI	Lmn	FVSI
1	1-2	1-2	1.462716	0.631911	0.398684	0.266438
2	5-7	2-5	0.586132	0.338176	0.055934	0.117039
3	3-2	2-3	0.372747	0.234368	0.174889	0.152385
4	6-2	4-5	0.30128	0.168824	0.172267	0.154062

Table 7. Critical line ranking of IEEE 30-bus system under line outage

Rank	Line outage	Critical line	Proposed index	NVSI	Lmn	FVSI
1	1-2	1-2	4.047185	1.273736	1.227086	0.58379
2	4-5	3-4	0.651076	0.371453	0.117363	0.100823
3	6-5	2-6	0.632904	0.355472	0.071811	0.060536
4	2-1	1-3	0.627432	0.277633	0.101473	0.084854
5	5-2	2-5	0.618643	0.338645	0.024515	0.020449
6	36-12	28-27	0.609969	0.437569	0.176096	0.172684

## 5. CONCLUSION

This study introduces the SVSI, which was assessed on standard IEEE test systems under various contingency scenarios, and the findings were compared with existing VSIs. The comparison demonstrated that the proposed index exhibits high accuracy and greater reliability compared to its counterparts. Derived from the quadratic voltage equation of the transmission line, this index's applicability extends to all network types, providing precise information about all lines within a system. A "0" index value indicates a stable voltage condition, while an increasing value towards unity indicates voltage instability, potentially leading to collapse. The index value is contingent on the system impedance. The results presented in the preceding section affirm that the proposed SVSI is effective in measuring VSMs and identifying critical lines. The proposed index facilitates the calculation of voltage stability for different lines, ranking critical lines under single-line outage contingency conditions. This index ensures secure operation of the power system in both online and offline modes.

## ACKNOWLEDGMENT

The authors are extremely grateful to the chancellor, vice-chancellor, Vellore Institute of Technology, Vellore for providing the excellent infrastructure facilities and encouragement which have made this research work possible.





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