Identification of Weakest Buses in Electrical Power System Based on Voltage and Line Stability Indices

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Abstract- The identification of voltage collapse (VC) is crucial to prevent a possible collapse of the preventive control actions and voltage security evaluation. Selecting the critical buses in the network can assist in determining the locations where voltage collapses may occur. VC initially manifests at the weakest bus in a serious emergency case. So, for operational and planning purposes, it is essential to detect critical buses in an electric power system. The analysis of the power system in view of voltage stability (VS) was performed under different loading conditions using voltage stability indices (VSIs). The line voltage stability indices in terms of the fast voltage stability index (FVSI) and line stability index (LMN) are utilized in this paper to identify the weakest bus in the network. The suggested procedure is tested on a standard network (IEEE 14-bus system) at different overloading conditions (25 – 100 % overload) utilizing power system analysis toolbox (PSAT) software. The results proved that this index has a higher standard for predicting the point of voltage collapse and identification the weakest bus in the network, so consider more reliable and accurate relative to other indices.

Keywords Voltage stability, fast voltage stability index, line voltage index, voltage collapse.

Abbreviation:

VS	Voltage Stability
VSIs	Voltage Stability Indices
VC	Voltage Collapse
PSAT	Power System Analysis Toolbox
FVSI	Fast Voltage Stability Index
L_{mn}	Line Voltage Index
VSM	Voltage Stability Margin
DG	Distributed Generation
VCP	Voltage Collapse Point
PMU	Phasor Measurement Unit
RPC	Reactive Power Compensation
AVR	Automatic Voltage Regulator
WAMS	Wide Area Measurement System

1. Introduction

Voltage instability is considered as one of the main issues caused by increasing demand of electrical power, which presents especially significant challenges for power utilities. The Voltage instability of transmission and distribution networks may deteriorate the performance of the whole power system and severely restricting load growth. Consequently, a blackout due to VC occurs in the power system, whereas at this point the voltage becomes uncontrollable [1]. Accordingly, analyzing crucial buses and determining their closeness to VC is vital. The approximate location of VC was determined using the P-V and Q-V curve approaches that give more details on the mechanism of

instability. These methods have few disadvantages such as long computation time [2, 3].

As defined in [4, 5], VS refers to a power system's capacity to keep constant and appropriate voltages at all its buses in the event that its initial operating circumstances are disturbed. Failure of either power sources to create adequate reactive power or power system tie lines to transmit the necessary reactive power can result in voltage instability [6]. The needed reactive power can be provided to a network via Generators and compensators for reactive power such as shunt capacitors.

The main factors that cause voltage instability include increasing of load, tripping of power system components (such as generators, power transformers and transmission lines), exceeding the reactive power limits of some generators, and broken transformer on-load tap changers. To prevent voltage instability, weak buses and tie lines should be improved in the designing stage of the power system (by distributed generation units or other voltage supporting device), shunt capacitor switching, load shedding, and FACTS devices to increase the VSM. Typically, the final line of security among them is load shedding [7]. The most crucial functions of the VSIs are finding the critical buses and lines in the power systems, giving details on voltage instability, or obtaining the state of proximity to VC under different loading scenarios and contingencies, including loss of sources or lines. Additionally, it provides real-time data on voltage instability via phasor measurement unit wide area measurement system (PMU-WAMS) [8–10].

These indices are commonly used as the desired function to deal with several application problems, for example selection of the optimal location and the proper size of distributed generation (DG) units [11], reactive power compensation (RPC) [12, 13] and optimized power flow for the planning of power systems [14]. It was established to assess the effectiveness of a power system by calculating how close the system is to the voltage collapse point (VCP). Two factors must be taken into account in order to analyze VS in power systems: (i) proximity, which determines how near the system is to voltage instability; and (ii) the mechanism causing voltage instability, including the primary contributing factors to voltage instability, voltage vulnerable points, and impacted areas [15, 16].

Some investigations need the use of static model to select the critical buses and lines of the system or its load margin. Due to the easy of the analysis that yields an accurate result with lower computing work and offers certain crucial benefits through the dynamic study, a substantial number of studies have concentrated on the steady-state static scheme elements in the literature [17]. Different VSIs and indices have been presented by various authors in the literature as ways to assess how close a power system is to experiencing voltage instability.

In [18], the selection of weak bus and critical line in IEEE 30 bus and Tamil Nadu Electricity Board (TNEB) 69 bus system were determined by using A New Voltage Stability Index (NVSI) and fuzzy based load flow. The analysis of voltage stability by using fast voltage stability index (FVSI) to evaluate the maximum load ability point in power system are presented in [19, 20].

In this paper, VSIs i.e., FVSI and L_{mn} are analyzed for an IEEE 14 bus network. Buses can be kept under various loading scenarios to test these indices abilities to identify critical lines. The loading conditions include 25%, 50%, 75%, and 100% over loading cases. The values of FVSI and L_{mn} indices are studied for each loading case and the eigenvalue analysis has been used to observe the stability of the network considering, growth in load of the network. The results are compared to determine the critical lines and buses in the system considered. The usage of these indices by the operators will allow them to take manual or automated action to avoid VC as well as for designing and planning objectives.

2. Problem Statement

The demand for electricity has increased during the last decade due to the ongoing growth of domestic, industrial, and commercial loads [21, 22]. To supply the consumer with sufficient power, the network has been continuously expanding to meet client expectations, reliability and equality must be met [23, 24]. Many consumers are suffering low voltage profiles at load end. To resolve this issue, wind power plant integration is proposed to connect with network at the centre of the loads [25, 26].

To select the optimal location of wind power, voltage stability and reduce power system losses are to be maintained. The most critical bus of the system considers the optimal location of wind power [27]. VSIs are carried out to calculate all buses voltages and select the weakest point of the system [28]. Power system planners and operators need to monitor the voltage profile at all times to avoid voltage collapse and blackout occurrences; thus, identifying the collapse point is necessary for them [29, 30]. In this paper an IEEE 14 –bus network has been tested and using simulation to achieve this purpose.

2.1. Voltage Stability in Power System

Voltage stability of the power system is essential as a tool for prediction and prevention, and the indications of instability phenomena are becoming more visible in the performance and analysis of the power system [31, 32]. The fundamental problem with planning and operating of power system is VS, which limits the amount of power that can be transferred. Voltage instability is the approach by which the voltage drops reach very small value in a significant part of the system because of event cascades.

The voltage of the power system is stable under normal operating conditions, but when subjected to a fault or disturbance, the voltage becomes unstable leading to progressive and unpredicted drop in voltage. VS is often referred to as load ability. If action is not considered to address this voltage instability, it will result in a drop in system voltage and ultimately a VC that could cause partial or complete system black out [33]. Insufficient reactive power taken from the generator and transmission line leads to voltage instability, thus reactive compensation can be

made most effective by using renewable sources at the critical bus in the network.

3. Voltage Stability Indices (VSIs)

The literature has provided a variety of VSIs. these indices have been categorized According to the following criteria [34].

1. Jacobin matrix and system parameters based VSIs

2. Line, bus and overall VSIs

The VCP and VSM may be calculated using Jacobin matrix based VSIs. But these methods are not appropriate for real-time VS testing because of their large calculation times and requirement of updating the Jacobin matrix after each topological change. On another side, the VSIs, which depend on system parameters, take few computing times, and provide sufficient data for real-time applications. VSIs are utilized to select the weakest buses and lines in an electrical system or initiate voltage instability countermeasures [35]. Because of this, it can be considered quite valuable to classify VSIs according to the line, bus and all indices that are described in this work.

3.1. Fast Voltage Stability Index (FVSI)

The Fast Voltage Stability Index proposed by Musirin (2002) [36], is based on a concept of power flow through a single line as shown in Fig. 1. It is a line index derived from the general equation for the current in a line between two buses, classified ‘s’ and ‘r’. Its mathematical expression is given as:

$$FVSI = \frac{4Z^2 Q_r}{V_s^2 X} \leq 1 \tag{1}$$

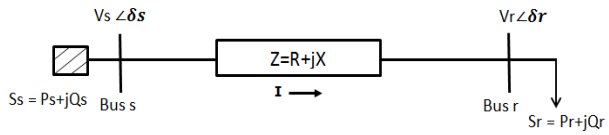


Fig. 1. Two-bus power system model.

Where:

bus 's' is sending end bus,

bus 'r' is receiving end bus,

Z is the line impedance,

R is the line resistance,

X is the line reactance,

V_s and V_r are the sending end and receiving end voltage respectively.

(P_s + jQ_s) and (P_r + jQ_r) are sending end and receiving end complex powers respectively.

All parameters and variables are per unit. A line is near to its point of instability if the computed FVSI value is near to 1, which might cause a VC in the network [37, 38]. To maintain a safety condition for the system's operation, the values of FVSI should be kept at levels much below 1. The system's weakest bus can be identified with the help of the analyzed FVSI.

3.2. Line Stability Index (L_{mn})

The line stability is derivative based on the concept of power transmission line. Moghavvemi and Omar (1998) derived this index [39]. In order to determine the stability of the line connecting two buses in an interconnected system that has been reduced to a single-line network, as illustrated in Fig. 1. The mathematical equation as presented may be used to determine the L_{mn}.

$$Lmn = \frac{4XQ_r}{|V_s|^2 \sin^2(\theta - \delta)} \leq 1 \tag{2}$$

Where:

'θ' is the line impedance angle,

'δ' is the angle among the sending and receiving end voltages.

If the stability index L_{mn} remains less than 1, the system is stable. The system becomes unstable when its value approaches or exceeds1.

4. Eigenvalues and Stability Analysis

When the system suffers from a sudden change, oscillatory stability problems are often associated with a pair of complex eigenvalues of the system equilibrium point (the operating point) that point in the direction of the right half-plane from the left half-plane and cross the imaginary axis of the complex plane. Weak modes, which are identified by the eigenvalues of the system equilibrium point, can set off by small and sudden disturbances. The weak modes have increased oscillation behaviour at their amplitudes, if the damping on this mode is missing [40].

An essential component of the system is the state matrix. It can be used to determine the stability of the system at its operational point. The eigenvalues of this state matrix represent the poles of the system and therefore can be utilized to determine the stability of the system. To determine the eigenvalues, (λ) of the state matrix, the mathematical Eq. (3) can be applied:

$$|A - \lambda I| = 0 \tag{3}$$

If A is an n x n matrix, it will have n eigenvalues. If these eigenvalues are complex, they take the form in Eq. (4):

$$\lambda = \sigma \pm jW \tag{4}$$

The real part denotes the damping of the corresponding mode while the imaginary portion denotes the frequency of the oscillation [41]. The stability of the operating point (W0, δ0) may be assessed using an eigenvalues analysis. If all the eigenvalues are located on the imaginary axis of the complex plane's left side, the operating point is stable;

otherwise, it is unstable. The associated modes are unstable if any of the eigenvalues appear on or to the right of this axis.

Table 1. Case Study to Identify Weakest Buses in the System

Case Study	Description
1	(Base case study) Study the behavior of system under normal operating condition
2	Voltage stability indices by load growth (25-100) %

5. Results and Discussions

In this section, Voltage stability analysis has been considered to identify weakest buses considering the IEEE standard 14-bus power systems at 100 MVA base. Fig. 2 shows the considered network under test. It consists of 14 buses, 4 transformers, 5 synchronous generators connected to Buses 1, 2, 3, 6 and 8 provide both active and reactive power. Three static synchronous compensators are connected at Buses 3, 6 and 8 which are utilized only for providing reactive power. It has 11 loads and 20 lines. The parameters of the considered network are listed in Table 2.

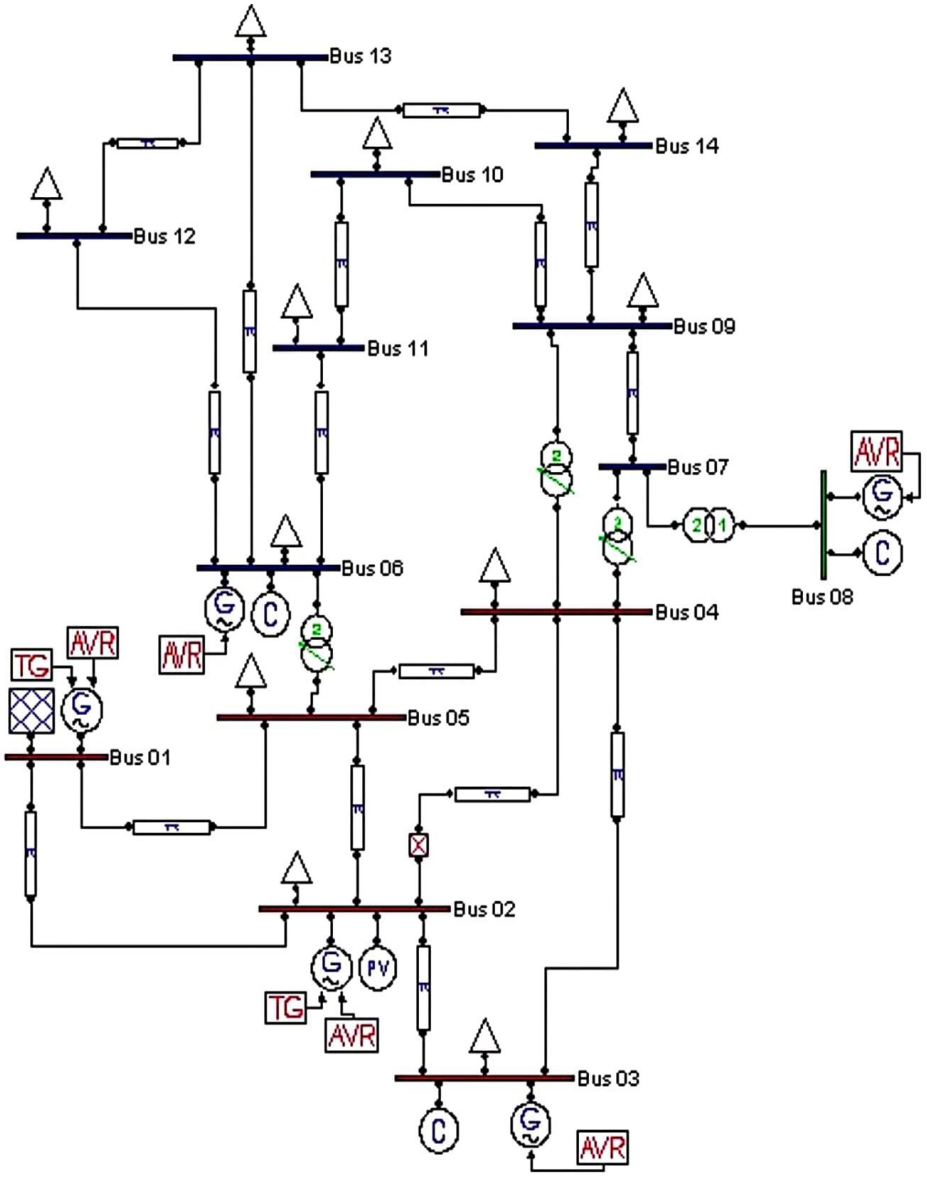


Fig. 2. IEEE 14-bus test system simulated on PSAT.

It is simulated using PSAT toolbox and the Newton-Raphson Method was used to run the power flow. As given in Table 1, the simulations are performed considering the two case studies, in each case the stability of the system has been checked, using PSAT toolbox, depending on the analysis of VSIs (FVSI and L_{mn}) and Eigen values of the system, which have various values as described below:

- If the real part of the Eigen value is negative, the system is stable.
- If it has positive value, the system is unstable.
- If it has zero value, the system is critically stable.

Table 2. Input data for the IEEE 14- bus system model

Bus No	Generation		Load	
	Active (MW)	Reactive (MVAR)	Active (MW)	Reactive (MVAR)
1	352.0304	28.1968	0.00	0.00
2	40	94.8602	30.38	17.78
3	0.00	59.7360	131.88	26.60
4	0.00	0.00	66.92	5.60
5	0.00	0.00	10.64	2.24
6	0.00	44.4329	15.68	10.50
7	0.00	0.00	0.00	0.00
8	0.00	33.4022	0.00	0.00
9	0.00	0.00	41.30	23.24
10	0.00	0.00	12.60	8.12
11	0.00	0.00	4.90	2.52
12	0.00	0.00	8.54	2.24
13	0.00	0.00	18.90	8.12
14	0.00	0.00	20.86	7.00

The behaviour of the system under standard operating conditions has been taken into consideration, as shown in Table (1) taking Case Study 1 into consideration to be able to determine the strength of each bus using the maximum load ability concept. In case study 2, the load growth assessment was tested by increasing all loads in the system from (25 - 100) % of the base load. This was done to compare the voltage stability indices and to select the higher values, which refer to the critical buses in the network.

A. Case study 1: Base case study

In this case, e-simulation with nominal loading conditions has been performed to obtain VSIs i.e., FVSI and L_{mn} for each bus in the system. Fig. 3 displays the FVSI and L_{mn} values for each line. For any of the transmission lines, neither the FVSI nor the L_{mn} exceed 1.0, and the two values of the indices are significantly less than one (1). In this case no weak bus is found as indicated by the low values of voltage stability indices and line (4-9) has the highest value of both L_{mn} and FVSI.

The stability of the system will be checked by using Eigen values of the system and tabulating the values with the positive or zero values with its dominant state. The system can be known either stable or critical stable or unstable as given in Table 3. Fig. 4 shows and Table 3 gives that the system has 55 Eigen values, and all Eigen values are negative except the Eigen value - λ 44 - is zero and thus the system is critically stable.

Table 3. Eigen values and dominant state of Case 1

Description of the system	Positive Eigen value	Dominant States of Positive Eigen value	Zero Eigen value	Dominant States of Zero Eigen value
Base case	–	–	Eig As 44	Delta of synchronous1

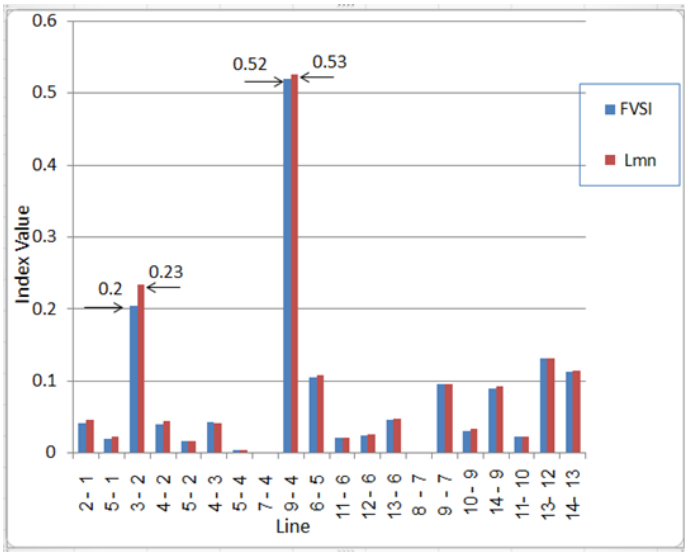


Fig. 3. Index values of all the Transmission lines at nominal loading condition.

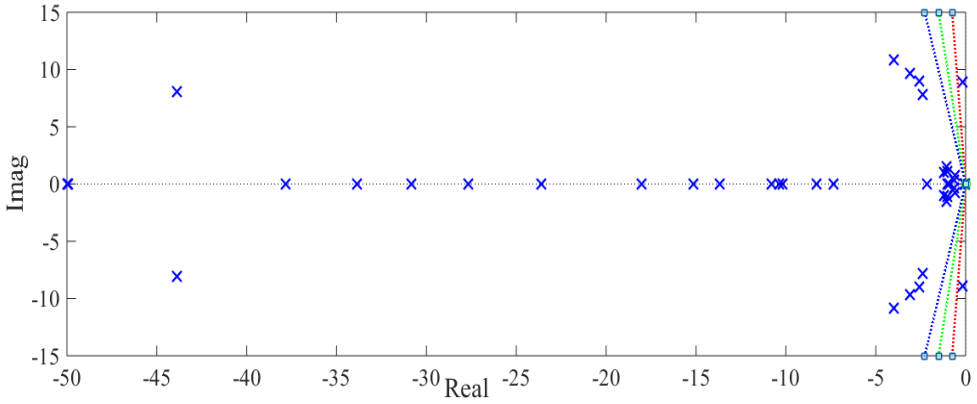


Fig. 4. Computed Eigen values in case of nominal loading condition.

B. Case study 2: Load Growth for all Buses

It is essential for the considered power system to ensure that it can remain secure, dependable, and cost-effective, while accommodating the occurrence of future load growth. Hence, this case has been resolved to assess how the system behaves when a load increase occurs. In this current case, the nominal load was increased in steps by various percentages for both active and reactive power loads at each load of buses. The percentage increments in this case evaluated by four steps are 25%, 50%, 75%, and 100% of the system load. In the first step, the load is increased by 25% of the based load. It is noticed that the values of FVSI and L_{mn} increased more but all are less than 1 as shown in Fig. 5.

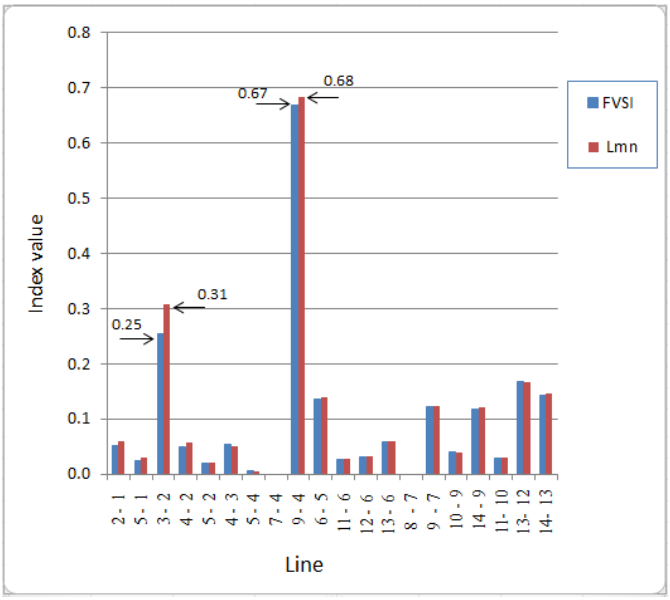


Fig. 5. Index values with load increased by 25% of base load.

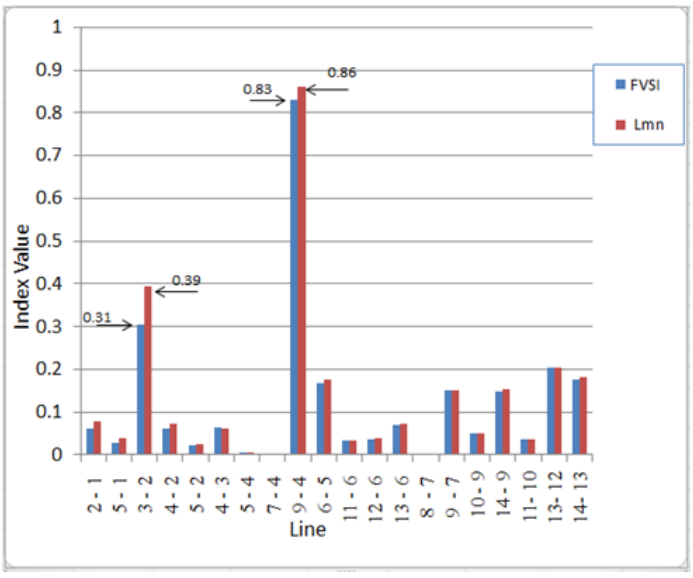


Fig. 6. Index values with load increased by 50% of base load.

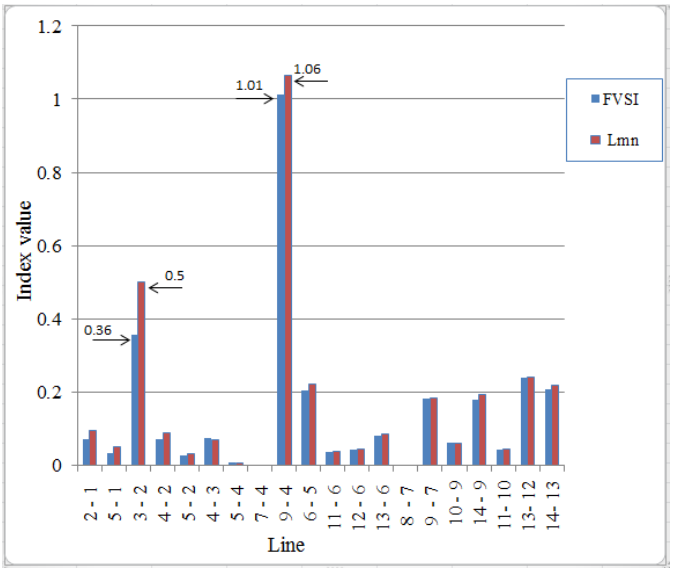


Fig.7. Index values with load increased by 75% of base load.

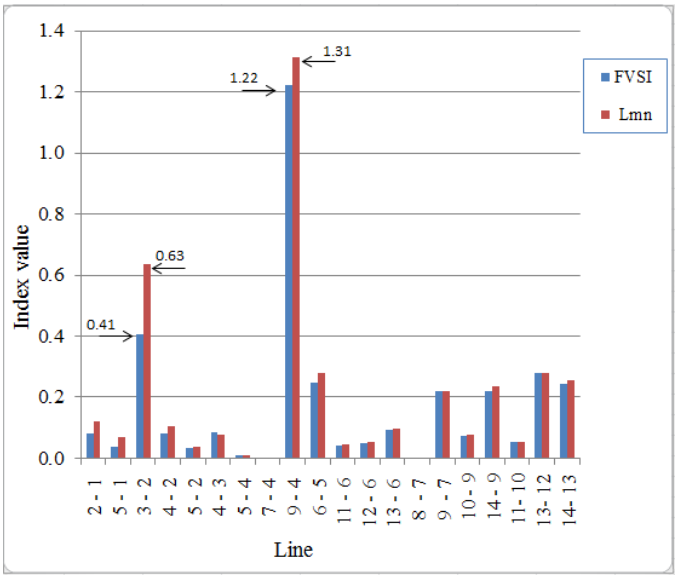


Fig. 8. Index values with load increased by 100% of base load.

Increase of the line loads by 25% of base load indicates that both lines from lines (4-9) and (2-3) appear as the top two most sensitive lines. It can be observed in Fig. 6 that by increasing the load by 50% of the nominal load, lines (4-9) and (2-3) are of the higher index values, thus buses 9 and 3 are considered the most critical buses in the system. By increasing the load value with 75% of the base load, the values of FVSI and L_{mn} index for lines (4-9) and (2-3) exceed 1. Thus, the system reaches the conditions to its collapse point as shown in Fig.7. The VSI values for each the transmission lines when the last load growth by 100% of base load are shown in Fig.8, both FVSI and L_{mn} indices exceed 1 and indicate that the weakness is in lines (4-9) and (2-3).

Table 4. Eigen values and dominant state of Case 2

Description of the system	Positive Eigen value	Dominant States of Positive Eigen value	Zero Eigen value	Dominant States of Zero Eigen value
First Step	Eig As 16 Eig As 17	E1q of Synch1-vf of exc1 E1q of Synch1-vf of exc1	Eig As 38	delta of Synchronous 3
Second Step	Eig As 18 Eig As 19	E1q of Synch1-vf of exc1 E1q of Synch1-vf of exc1	Eig As 37	delta of Synchronous 3
Third Step	Eig As18 Eig As 19	E1q of Synch1-vf of exc1 E1q of Synch1-vf of exc1	Eig As 37	delta of Synchronous 3
Fourth Step	Eig As 16 Eig As 17	E1q of Synch1-vf of exc1 E1q of Synch1-vf of exc1	Eig As 35	delta of Synchronous 3

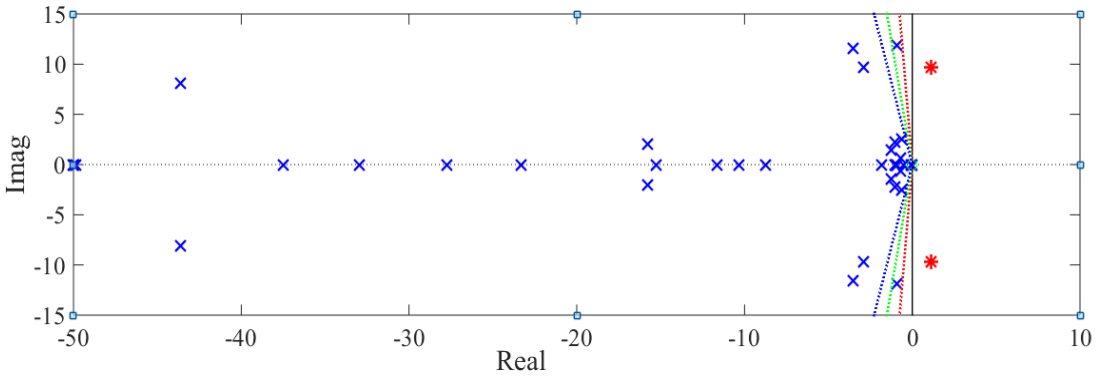


Fig. 9. Computed Eigen values in case of load increasing by 25% of base load.

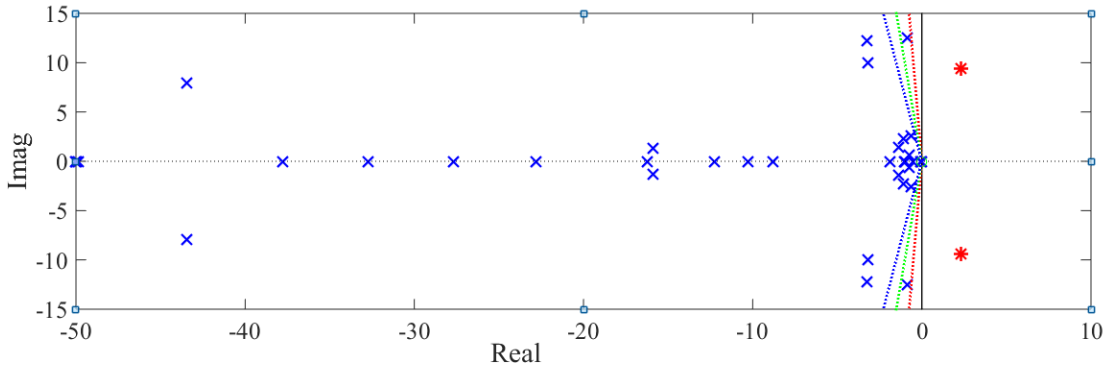


Fig. 10. Computed Eigen values in case of load increasing by 50% of base load.

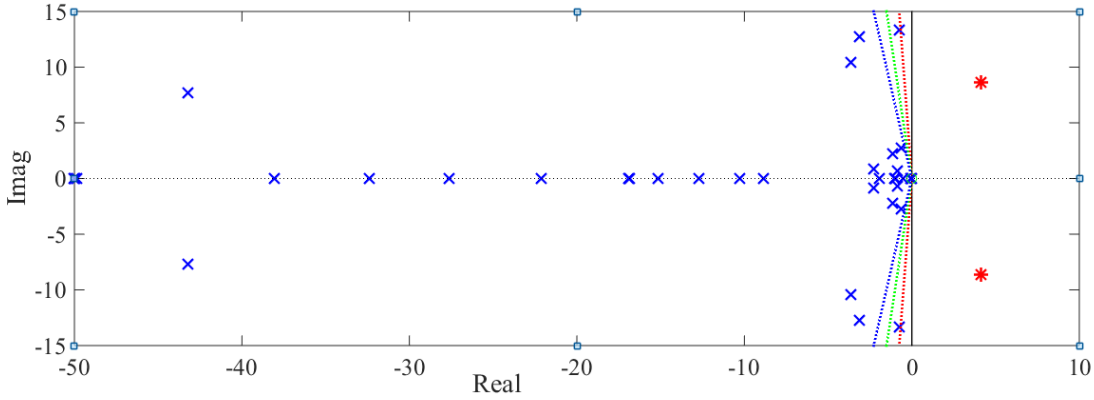


Fig. 11. Computed Eigen values in case of load increasing by 75% of base load.

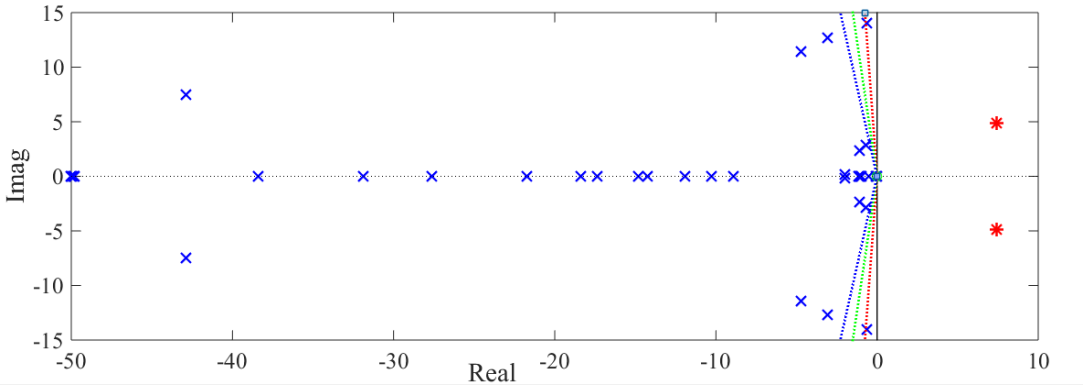


Fig.12. Computed Eigen values in case of load increasing by 100% of base load.

The Stability of the network in this state will be checked by using its Eigen values and tabulating the Eigen values with the positive or zero values with its dominant state for four steps, as given in Table 4. Figures 9, 10, 11, 12 show and Table 4 gives that the system has 55 Eigen number, two of them with red colure having positive values and one is zero. The system became unstable in this case with the participation elements link the quadrature-axis part of transient voltage of synchronous generator associated at bus1 and field voltage of automatic voltage regulator (AVR) of the identical generator with instability of the network for all configurations.

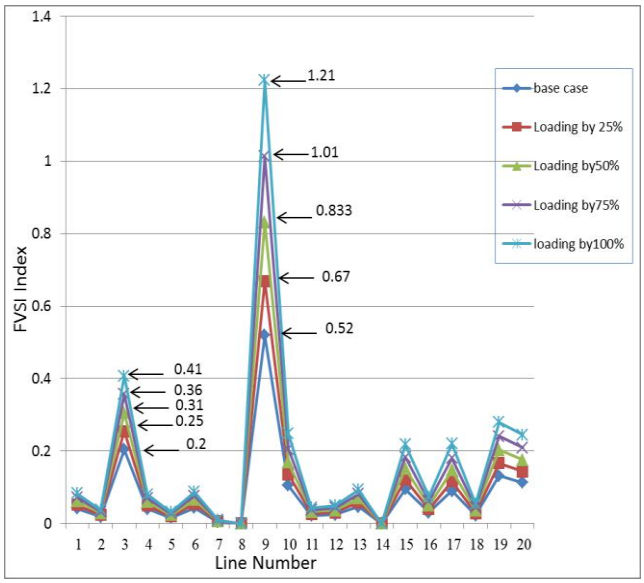


Fig. 13. FVSI index for different loading cases.

Comparing the results in two loading scenarios for the voltage stability analysis, which objected to evaluate the voltage stability state and weakest buses in the network are shown in Figs. 13 and 14. From Fig. 13, lines 9 and 3 respectively are the highest value of FVSI for every tested loading case. Line 9 between buses 4 and 9 gives an increment with more than 1 for most cases, so it is considered as the most sensitive line in the network as highlighted in [42]. To detect the weakest buses in the system, the critical lines derived from each bus for the study cases 1 and 2 are plotted together on the same graph. The system becomes stable when the values of these lines indices are near to 0 and reach the voltage collapse point close to unity. It is obvious that the FVSI grows with increasing in the load power consumption in all cases and becomes prominently higher in case of increasing the loads by 25%, 50%, 75% and 100% of base case, especially in these cases the system becomes far from stability where the value of FVSI is high.

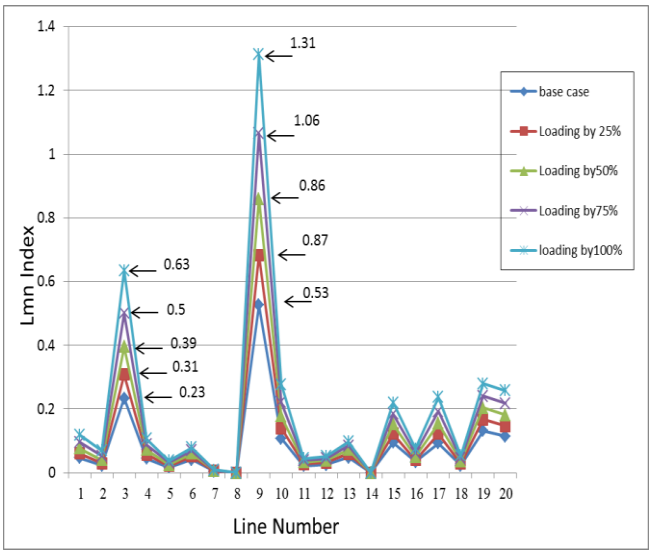


Fig. 14. L_{mn} index for different loading cases.

The line stability index for case study 1 and case study 2 are shown in Fig.14. The results are compared together to identify the most sensitive bus in the network. Here it is the line (4-9) having the top values and exceed 1 so considered as the weakest line in the network. The results indicate that both the lines (4- 9) and (2- 3) have the highest value of FVSI and L_{mn} are proximately the same, thus both buses 9 and 3 are the most sensitive buses in the network. The analysis of VSIs and Eigen values prove that the system become unstable with increasing loading and the most sensitive bus in the network has been identified, which leads to the whole system to voltage collapse.

6. Conclusion

The main purpose of this study is to identify critical or unstable bus in the electrical power network based on VSIs (FVSI and L_{mn}), which are formulated at different loading scenarios. Simulations were performed for IEEE 14 – bus to achieve this purpose using PSAT toolbox. VSIs (FVSI and L_{mn}) are computed, and voltage stability was noticed. Based on various loading conditions, a comparison of two indices is presented. The analysis leads to the conclusion that FVSI and L_{mn} are interchangeable terms and similar to one other. These indices (FVSI and L_{mn}) are accurate and reliable than other indices because it can forecast the point of voltage collapse and identify the weakest bus in the network. When the system is stable These indices indicate values near to 0, and they cross over 1 when the voltage reaches to collapse point. Five scenarios for the power system under test and their impacts on its stability are presented in this study. The value of each indices rises when we increase the overloading from base load to 25%, 50%, 75% and 100 %. According to the results of the simulation the system reaches to unstable from 25% to 100% overloading and both indices (FVSI and L_{mn}) pass the value 1. The eigenvalue analysis has been used to observe the stability of the network considering, growth in load of the network. According to the results the critical buses in the network are buses 9 and 3, thus these buses are considered as the optimal location of wind power plant. Eigenvalues describe the condition of the system through both normal operation and overloading in addition to (VSIs). To help power system operators keep a margin for stability and prevent voltage collapse.

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