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Determination of Voltage Stability Index using Eigen Ratio

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Abstract: Contingencies like faults and equipment outages are constantly faced by power system. When the system is operating under high stress, the system can face dynamic instability. Voltage collapse is one of the critical problems that show a large impact on power system operational security. Therefore, voltage stability monitoring is necessary. This paper provides the effective use of voltage stability indices like QV curve, voltage stability index (VSI), L index and eigen ratio, which gives information about how far the system is to voltage collapse. Test results through simulation are presented.

Keywords: Dynamic stability, VSI, L index, eigen ratio, voltage collapse

1. INTRODUCTION

Voltage stability is crucial in operation of interconnected power system. The ability of the power system to maintain acceptable voltages at all the buses in the system under normal operating conditions and even after being subjected to disturbance is defined as Voltage Stability [1]. But, nowadays the electric power networks are becoming more and more complex and highly stressed which may lead to voltage instability under some operating conditions. This voltage instability results in progressive fall of voltage which leads to voltage collapse. Voltage collapses usually occur if power system is heavily loaded or faulted or have shortage of reactive power. Voltage collapse is a system instability involving many power system components. In fact, voltage collapse may involve an entire power system. Voltage collapse is typically associated with reactive power demand of load not being met due to shortage in reactive power production and transmission. To determine the proximity of voltage collapse i.e. how far the operating condition is from voltage collapse point and which buses are the most vulnerable ones, voltage stability assessment is needed. Many voltage stability and voltage collapse prediction methods have been presented in the literature.

Haung and Nair[2] presented a voltage stability indicator called L index whose value changes from zero during no load to one at voltage collapse point, from which the proximity to voltage collapse can be determined. Jia Hongjie *et. al.,* proposed an improved L index in[3] showing two methods for calculating the index. In this two methods the calculation of L index is differentiated between generators and loads. To overcome the difficulty in obtaining the no load phasor during the calculation of L index, neural network based method is proposed in[4]. This method is capable of estimating voltage stability index at each load bus using direct measurements and accurately estimating the L index for different operating conditions. Vadivelu *et. al.,* [5] Proposed the use of a fast voltage stability index (FVSI) which determines the weakest bus in the system that has the lowest sustainable load. At each bus, the load is increased and at nose point the load is determined as maximum loadability point. The bus with the least maximum loadability point implies the weak bus. Subarami *et. al.,* [6] formulated voltage stability index from the voltage quadratic equation at the receiving bus. The discriminant of the characteristic equation is set to greater than or equal

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to zero which gives the condition for voltage stability. If the discriminant is small or equal to zero then the system approaches instability. Moghavenni *et. al.,* [7] proposed a voltage stability index that is based on the concept of maximum power transferred through the line. The ratio of power calculated from power flow calculations and the maximum power transfer is taken as the voltage performance index. This index is similar to that mentioned in[2], whose value varies from zero and one. Mohammed *et. al.,* [8] derived line stability index factor termed as LQP to assess the voltage stability. It indicates the stability of the system with respect to changes in the reactive power. LQP should be maintained less than unity to achieve stability of the system.

A stability analysis approach for determining the voltage stability of the system is PV curves[9]. The active power is increased in steps and bus voltage is observed which decreases and reaches the nose point. These curves are useful in determining how much load shedding should be done to obtain stable condition. Other traditional method to determine voltage stability is QV curves[10]. These curves predicts the verge of voltage instability which is termed as nose point. As the load increases, the bus voltage decreases and reaches a point where $\frac{dQ}{dV} = 0$, this point denotes the beginning of voltage instability. The limitations of QV curves are presented by Haoen Li in [11]. To overcome these limitations, voltage stability index is developed to determine voltage stability margins of all the load buses. VSI based on time synchronised measurements is presented to overcome some of the limitations like slow data sampling rate and slow data communications. VSI for a simple power system modal is devised which is used to simplify a large system network [12]. The efficient use of PMU data for determining the voltage stability index is well explained in [13]. Voltage stability margin (VSM) is proposed in [14]. This method determines the margin between voltages of bus and nearby generators which is represented as the stability index. The negative and positive sign of this index, $\frac{dQ}{dV}$ indicates voltage stability and voltage instability respectively. Bonneville power administration proposed wide area control systems (WACS) in [15] that gives the implementation of reactive power compensation of the power system for transient stability. Gao [16] proposed that the eigen values provide a relative measure of proximity to voltage instability as they are obtained from the power flow Jacobian matrix. Eigen values are associated with a mode of voltage and reactive power variation. Young huei hong *et. al.,* [17] proposed an efficient algorithm that calculates smallest singular value of Jacobian matrix. This smallest singular value serves as an indicator of the proximity to voltage stability limit. An eigen value decomposition from the reduced Jacobian matrix has been proposed in [18]. This paper also demonstrates that the singular value and the eigen value provides same information of voltage stability. Modal analysis for voltage stability is developed in [19] which depends on the participation factors values that can be found from the eigen vectors of the Jacobian. From the participation factors, the weakest bus or node is found in the system. To improve the stability of the system an Artificial Immune system is implemented. The modal and sensitivity methods are used to observe the stability of the system [20]. The sensitivity factor is obtained from the power loss equation. Comparison between modal analysis and sensitivity analysis is proposed in this paper.

The present paper compares the above indices and also proposes a new method based on eigen values through which the proximity to voltage collapse is determined.

2. STABILITY INDICES FORMULATION

In this section different voltage stability indices are discussed and the formulae for each stability index is given

A. L index

Kessel developed voltage stability index named L index, it is a quantitative measure which gives a scalar quantity that estimates the distance of the actual state of the system to the stability limit. The L index describes the stability of the system and is given by

$$L_j = 1 - \frac{V}{V_{oc}} \tag{1}$$

$$L_j = 1 - \frac{V}{\sum_{i=1}^{g} F_{ji} V_j} \tag{2}$$

V_{oc} is the open circuit voltage obtained from the system admittance matrix by making load current (I_L) equal to zero, i is the set of generator buses and j is the set of load buses. F_{ji} is given by

$$F_{ji} = -Y_{LL}^{-1} Y_{LG} \tag{3}$$

During no load, the voltage is almost equal to one and so the value of index is equal to zero and when the load is increased, voltage decreases and may drop to zero which makes the value of L index to be one. Thus, L index varies in a range between zero and one. The bus with the highest value of L index can be considered as the most vulnerable bus.

$$L = \max(L_j) \tag{4}$$

B. Q-V curves

One of the basic methods to obtain the proximity to voltage collapse is to build Q-V curve. The power system load (reactive power) is gradually increased in steps. Power flows are calculated for each incremental load, so that the bus voltage corresponding to that load is determined. Increase in load is stopped when the slope becomes infinity i.e., $\frac{dQ}{dV} = 0$. This point is called nose point which is indicated by the singularity of Jacobian matrix [1].

C. Voltage Stability Index

The process of obtaining the Q-V curve is time consuming, therefore voltage stability index mentioned in [3], is faster than Q-V curves. From the power solution, Jacobian matrix is obtained in which ΔP is made equal to be zero because voltage stability depends on Q and V. The reduced Jacobian matrix (J_r) is formed. Bus voltage magnitude and reactive power injection are directly related by J_r.

$$\Delta V = J_R^{-1}\, \Delta Q \tag{5}$$

$$\frac{\Delta Q_i}{\Delta V_i} = i^{th} \text{ diagnol element of } [\det(J_r) \times [\text{adj}(J_r)]^{-1}] = \Gamma_{QiVi} \tag{6}$$

Γ_{QiVi} is defined as voltage stability index at bus i. As the system approaches instability, the value of determinant reduces. The singularity of the Jacobian matrix makes the value of determinant to be zero and $\frac{dQ_i}{dV_i} = 0$. Hence VSI (Γ_{QiVi}) can be used as an indicator of voltage stability.

D. Eigen Values

Gao [6] gave relation for eigen values and voltage stability, the magnitude of each eigen value, determines the weakness of the corresponding voltage. Smaller the magnitude, weaker is the corresponding modal voltage. If the magnitude is zero then the modal voltage will collapse. If one of the eigen value is zero, which means the Jacobian matrix is singular then the system is unstable.

In addition to magnitude of eigen values, eigen ratio can be used to determine the voltage collapse point. From the eigen values of reduced Jacobian matrix the maximum and minimum eigen values are considered as $|\lambda_{max}|$ and $|\lambda_{min}|$ respectively. The ratio $\frac{|\lambda_{max}|}{|\lambda_{min}|}$ is calculated. The ratio increases gradually with increase in load and when the collapse point reaches, the ratio increases drastically. The increase in the eigen ratio is taken as a measure to find collapse point.

3. RESULTS AND DISCUSSION

The IEEE 14-bus system is used as test system [8]. It consists of four generator buses, nine load buses; the base total loading level of the system is 259 MW and 81.3 Mvar.

1. Result of a load flow solution is used to illustrate how L index predicts the voltage stability margin, the results of L index are shown in Table 1.

Table 1
IEEE 14-bus L index for base case and voltage stability limit

Base case		*Voltage stability limit*	
Bus	*L index*	*Bus*	*L index*
14	0.0476	14	0.3284
10	0.0383	5	0.3258
9	0.0378	4	0.3080
11	0.0232	9	0.3044
13	0.0221	10	0.2850
7	0.0209	7	0.2170
12	0.0152	11	0.1419
4	0.0126	13	0.0987
5	0.0084	12	0.0510

From Table 1 it can be seen that the value for L index for both base case (0.0476) and voltage stability limit (0.3284) is highest for 14^{th} bus. Therefore, bus 14 is the most vulnerable bus in the system.

2. To obtain QV curve, the reactive power load at all load buses is increased in steps of 3% maintaining the power factor. To meet the increased load generation is also increased in steps of 5%. Voltage values for corresponding load is noted. The figure shows the variation of voltage with the reactive load for all load buses.

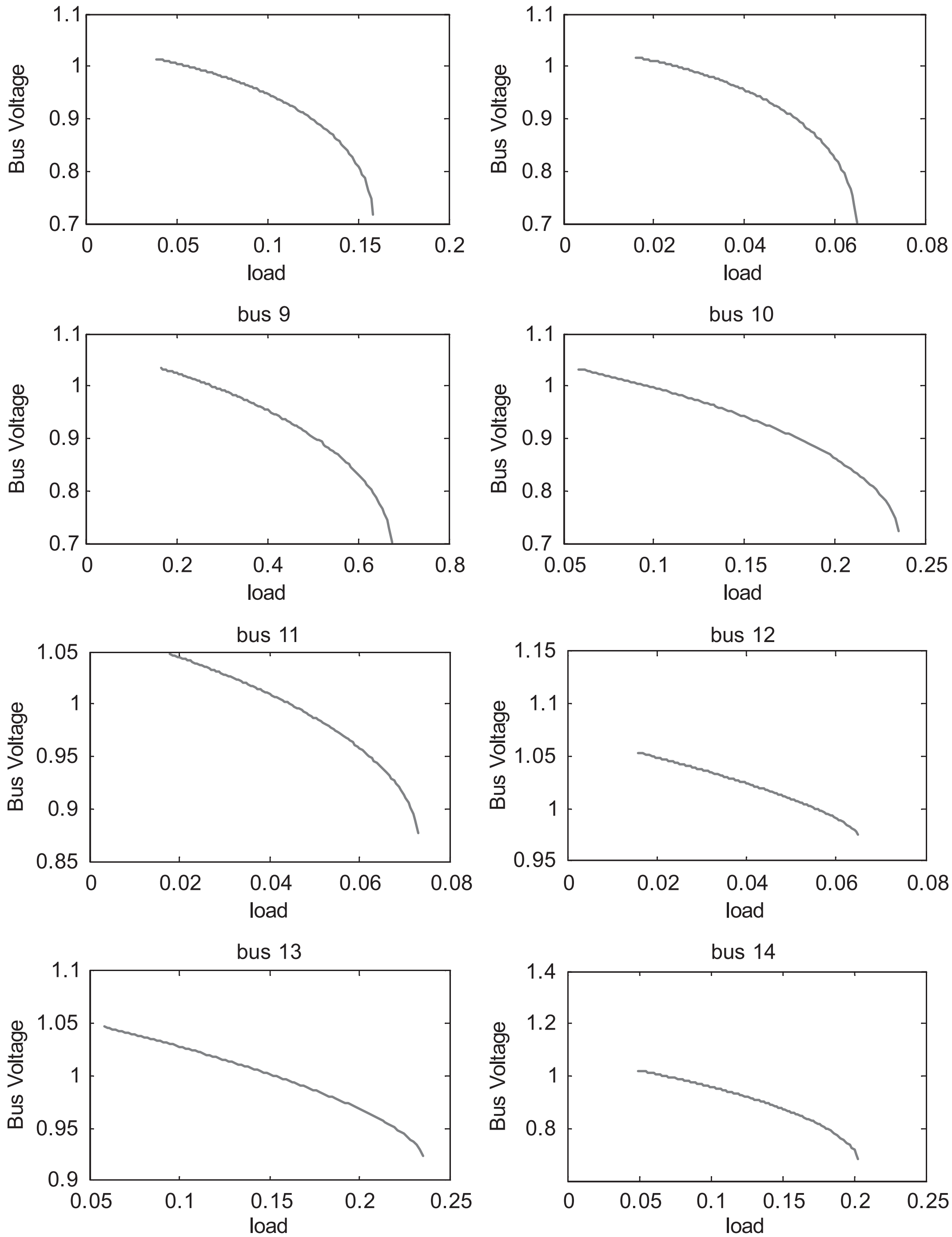

Figure 1: Q-V curve of all load buses

From Figure 1 it is seen that as load is increased in steps, the bus voltages decreases and reaches a point where $\frac{dQ}{dV} = 0$, this point is called nose point.

3. Voltage stability index (VSI) is calculated with the mentioned formula above. The load is increased at regular steps and the corresponding values VSI is noted to plot a graph between VSI and load. The figure shows the variation of VSI with reactive power load for bus 14.

   From Figure 2 it is clear that the load reactive power cannot be increased beyond nose point. The value of VSI at which the nose point is reached is 3.9727.

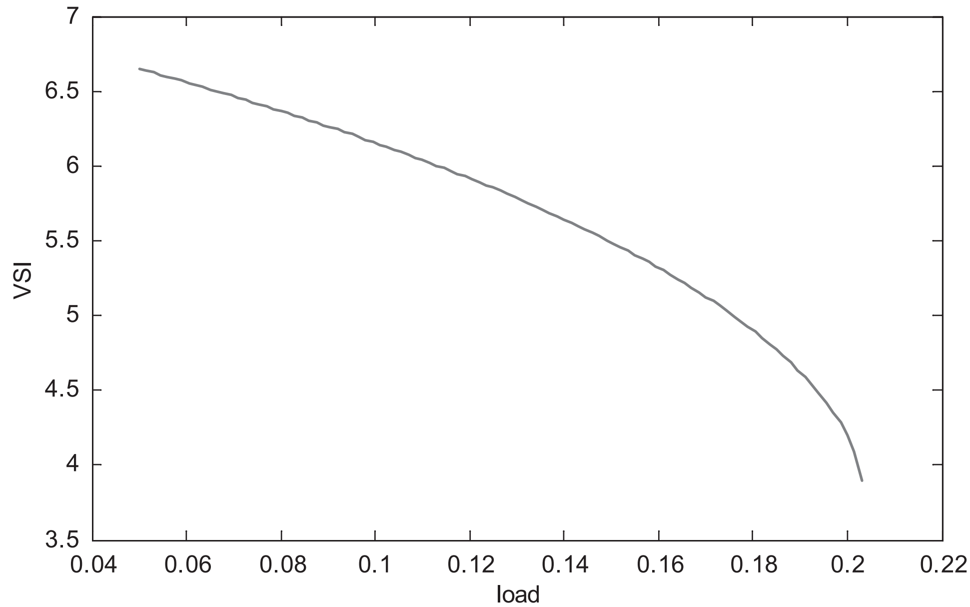

Figure 2: Variation of VSI with load

4. For the reduced Jacobian matrix, the eigen values are calculated, because the voltage stability always depends on reduced Jacobian. From the eigen values, the ratio of maximum and minimum eigen values is calculated. To illustrate the variation of eigen ratio as voltage instability is reached, the load reactive power is increased in steps. Figure 3 shows the variation of eigen ratio at every step.

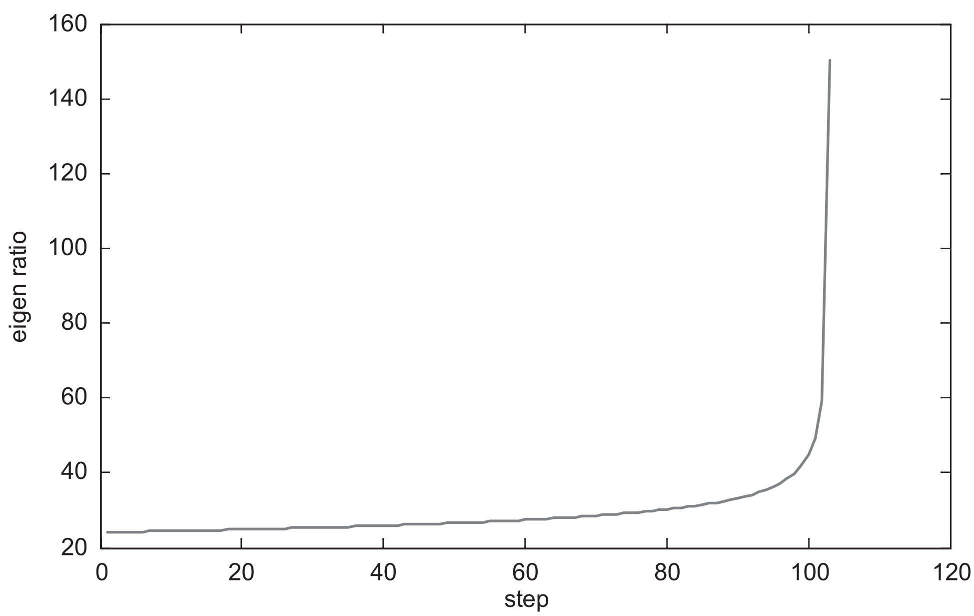

Figure 3: variation of eigen ratio

From Figure 3 it is seen that the value of eigen ratio suddenly increases at particular load which is considered to be the point of voltage instability. The value of eigen ratio at the point before the instability is 59.0036 and this value is changed to 229.4863, which shows the point of voltage instability.

The comparative performance of above mentioned voltage stability indices is presented in the Figure 4. The figure shows the voltage margin calculated from QV curve, L index and eigen ratio.

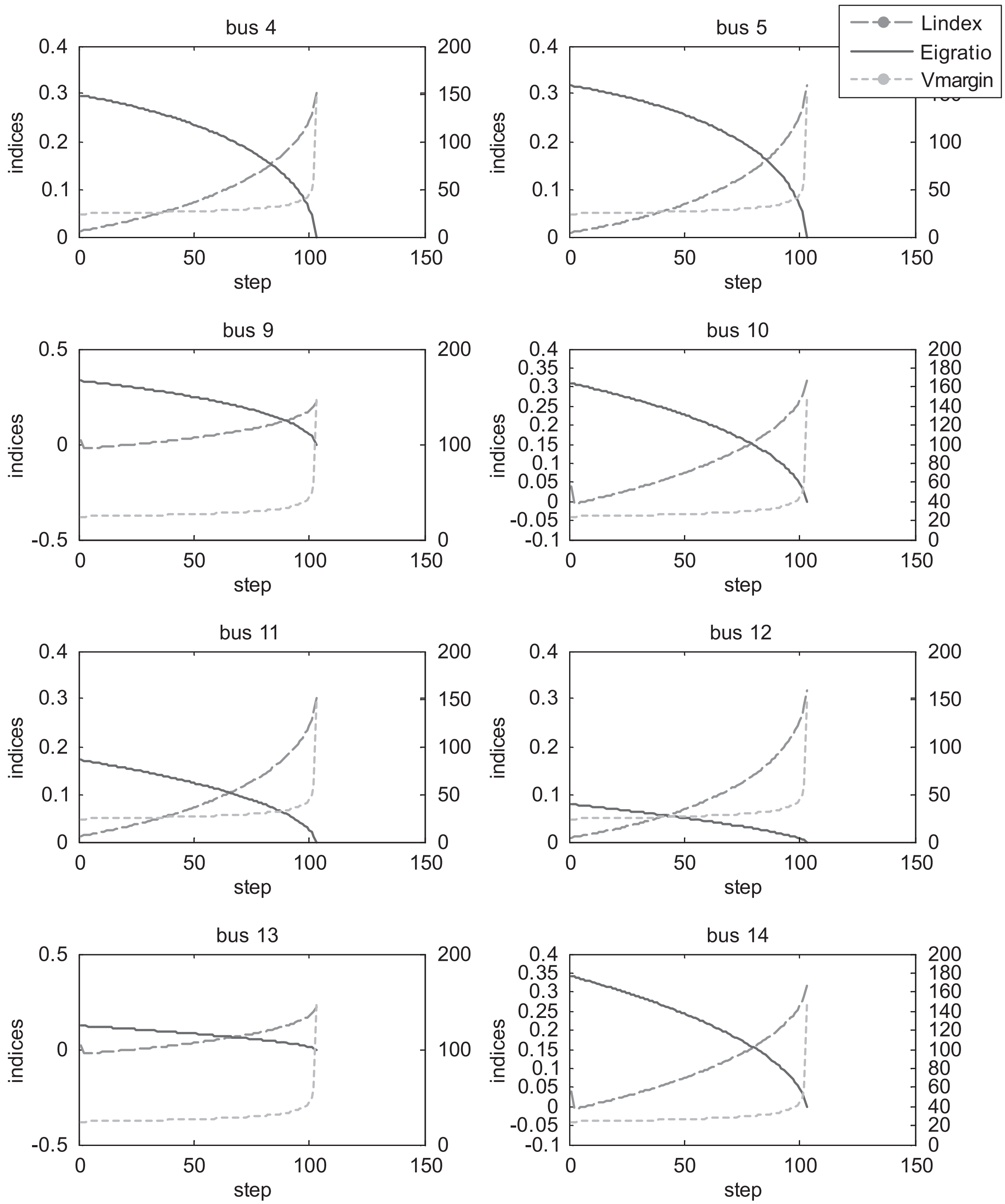

Figure 4: Variation Voltage margin, L index, eigen ratio at each step of load

It is observed from the figure 4 that all the plots reach the specified criterion as the nose point is reached.

4. CONCLUSION

A brief overview of different methods for determining the proximity to voltage collapse and the method to find the most vulnerable bus is shown in this paper. A new method which uses the eigen ratio as an index to find voltage instability is also presented. Simulation results for all the above methods are observed for an IEEE 14 bus system.

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