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Comparison Of Voltage Profile Improvement using Structural Characteristics based method with Modal Analysis method

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Abstract
The main aim of the paper is to compare eigensensitivity technique with modal analysis technique for voltage profile improvement of the given power system network. In eigen sensitivity technique, Y-admittance matrix is partitioned by applying the circuit theory concept and is used for identification of weakest buses which are the suitable locations for the reactive power compensators. In modal analysis technique eigen values and eigen vectors are obtained for the load flow solution of the given power system network. Bus participation factors are obtained from eigen vectors of the eigen values and are used to identify the weakest buses in the given network to employ the reactive power compensators to enhance the voltage profile of the system. Here, the Interactive Power System Analysis software was used to implement the Static Var Compensator (SVC) at weakest buses. The implementation of eigen sensitive technique and modal analysis were performed using MATLAB. Both the techniques were applied to an IEEE 14 bus system and the results were compared. On comparison it is observed that the eigen sensitivity techniqueimproves voltage profile better than the modal analysis technique with a lesser number of SVCs.

Keywords: Eigen sensitivity technique, modal analysis, Reactive power, StaticVar Compensator, Voltage profile

INTRODUCTION

In general meeting the increased power demand has become the greatest challenge in power system networks. Among various factors that influence the efficient operation of a power transmission network, change in reactive power with the active power transfer plays a vital role which in turn affects the voltage profile of the network. If not identified and rectified at the earliest it leads to cascading effects which results finally in a black out [1]. Hence it has become essential to maintain the voltage profile of the power transmission network. Various methods have been proposed for the compensation of reactive power which can be broadly categorised under two methods: mathematical optimization and sensitivity analysis technique. Mathematical optimization involves both analytic and heuristic techniques. Generally a function with voltage profile, loadability or with both with some limitations are defined. Non-convex nature is the greatest challenge in this sort of formulation [3]. Hence the importance lies in identifying the critical load buses for employing the compensators [2]. On the other hand in sensitivity techniques, the suitable locations for reactive power compensators are identified by reduced jacobian matrix after performing repetitive load flow analysis and by observing the bus participation factors close to the point of network singularity[4]. Hence in both, suitable locations are identified based on convergence of load flow analysis [4] [5]. In these two approaches though the network structure is considered, the circuit theory point of view is very important and plays an important role in system operation. The impedances associated between the buses and the way the buses are interconnected will influence the flow of active and reactive power since basically the network obeys the circuit theorems. Hence circuit theory approach has two significant merits. Firstly, the repetitive load flow analysis is not required for the identification of vulnerable buses. Secondly, impact of these critical buses on the network is well predicted due to the effect of circuit theorems on network operations.

Tajudeenetal., [6] discussed the voltage profile improvement by partitioning the Y-admittance and applying circuit theory on power system networks. The partitioned Y-admittance matrix and eigenvalue decomposition technique were used to identify the suitable locations for reactive power compensators. The results of this method were compared with classical Q – V sensitivity method. They also discussed the advantages of circuit theory concept over classical Q – V sensitivity method.

Tajudeenetal.,[7] discussed the relationship between generator affinity and voltage profile improvement. They focussed on reducing the electrical distance between generators and loads by locating pseudo generators in suitable bus locations.Gaoetal.,[5] proposed the Modal analysis technique to predict the voltage collapse of power system. Based on steady state system model smallest eigen values and their eigen vectors were obtained. Each minimum eigen value magnitude predicts the closeness of the system to voltage collapse. Yakout Mansour WilsunXuetal.,[4] have identified the critical buses resulting to voltage collapse by Modal or eigenvalue analysis of the system Jacobian matrix closer to voltage collapse point. They installed the RPCs at those locations to improve the operation. Tajudeenetal., H. Sikiru, Adisa A. Jimoh, YskandarHamam, John T. Agee and Roger Ceschi., [8] have discussed the role of inherent structural characteristics of power network and have shown the mathematical derivation of the same.

This main aim of this paper is to show the implementation of partitioning of Y-bus matrix for the given power system network. By using eigen sensitivity techniquetechnique, weakest load buses are identified and SVCs are installed at the weakest buses and the voltage profile improvement is observed. On the other hand, weakest buses are identified using modal analysis technique and SVCs are implemented at the weakest buses and the improvement in voltage profile is compared with that of Eigen sensitivity technique. Section II describes the y-bus partitioning and eigen sensitivity techniquetechnique and its implementation results. Section III discusses the modal analysis technique and its implementation results on IEEE 14 bus system. Section IV discusses the advantages of Eigen sensitivity technique over modal analysis and shows the comparative results of these methods. Section V concludes the voltage profile improvement is better using eigen sensitivity techniqueas compared with modal analysis.

RELATIONSHIP BETWEEN GENERATOR LOCATION AND LOAD BUSES IN GIVENPOWER SYSTEM

As per circuit theory,

$$V = Z * I \quad (1)$$

Where,

V - Voltage

I - Current

Z - Impedance of the line

From which I is given by

$$I = Z^{-1} * V \quad (2)$$

Where $Z^{-1} = Y_{bus}$

$$\text{Hence } I = Y_{bus.*} V \quad (3)$$

Y_{bus} is partitioned [6] with respect to generator and load buses as shown in equation (4)

$$Y_{Bus} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \quad (4)$$

Where,

Y_{GG}- coupling of generator-generator with dimension G×G

Y_{LG}& Y_{GL} - generator-load buses coupling

Y_{LL}- Load-load coupling with dimension L × L

L and G- Numbers of load and generator buses respectively

Substituting (4) into (3), the equation is

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (5)$$

Where,

I_L – Load currents

I_G – generator currents

V_G – Generator voltages

V_L – Load voltages

On rearranging the equation (5)

$$\begin{bmatrix} V_G \\ I_L \end{bmatrix} = \begin{bmatrix} Z_{GG} & E_{GL} \\ N_{LG} & R_{LL} \end{bmatrix} \begin{bmatrix} I_G \\ V_L \end{bmatrix} \quad (6)$$

Where,

Z_{GG}– total generator impedances

E_{GL} – electrical attraction of generators to load buses

N_{LG}– negative transpose of E_{GL} matrix

R_{LL} –equivalent admittance of load buses with influences of buses associated with generators on network eliminated.

Hence the structural characteristics of load buses have influence on the flow of active and reactive power in a network. This degree of influence of the load buses on load flow is termed as electrical attraction region between the load buses. Electrical distance between the generator and the various load buses determines their electrical attraction. Electrical distance is a function of impedance between the nodes. The electrical attraction between the generator and load bus is less when the impedance between them are large. Hence the effect of load buses structure on the voltage of the network is a significant information in the matrix. Hence the eigen sensitivity techniqueis used in order to have a clear insight into the electrical attraction between the load buses[6].

The eigen value sensitivity technique of the matrix R_{LL} is

$$R_{LL} = NDN^{*} = \sum_{i=1}^{n} v_i \lambda_i u_i^{*} \quad (7)$$

Where,

N - Orthonormal matrix with left and right eigen vectors u_i and υ_i respectively.

D - Diagonal matrix with eigenvalues λ_i i = 1, 2…, n as its diagonal elements.

Expanding (5) gives

$$[V_L] = [R_{LL}]^{-1}[I_L - N_{LG} * I_G] \quad (8)$$

Substituting (6) into (7) gives

$$[V_L] = [\sum_{i=1}^{n} \frac{v_i u_{i*}}{\lambda_i}][I_L - N_{LG} * I_G] \quad (9)$$

The eigen values are obtained for the R_{LL} matrix which consists of only the load buses. The buses with least eigen values are considered to be the weakest buses which affects the voltage profile of the overall network. Also these are the buses at which the reactive power compensators are needed to meet the reactive power demand. These locations once identified remain fixed and hence finding the locations remains critical.

EIGEN SENSITIVITY TECHNIQUE AND ITS IMPLEMENTATION

The eigen sensitivity technique is implemented on IEEE 14 bus system.

The steps to be followed for eigen sensitivity technique are as follows:

1. Form the admittance matrix $Y_{bus}$for the given power system network.
2. Partition the Y_{bus} matrix such that forming the submatrices with respect to generators and load buses following equation (5).
3. Obtain the eigen values of the sub matrix R_{LL}.
4. Identify the weakest bus from the eigen values found such that the buses with the least eigen values are the weakest buses.
5. Implement the reactive power compensators at the weakest buses and observe the improvement in voltage profile.

A. IMPLEMENTATION RESULTS OF EIGEN SENSITIVITY TECHNIQUE:

Implementation of the eigen sensitivity technique and identification of weak buses are carried out by using MATLAB software. The installation of SVC at suitable locations and verifying the improvement in voltage profile is performed by using IPSA (Interactive Power System Analysis) software. The bus data and the line data of IEEE 14 bus system is given in Appendix A.

The corresponding eigen values of the load buses are listed in Table. 1 and is shown in Fig. 1

Table. 1. Eigen Values of Load buses for IEEE 14 bus system

Bus No.	Eigen Values (Diagonal elements)
4	16.2101 – 56.80i
5	7.1322 – 34.31i
7	2.9631 -20.97i
8	7.5444-11.34i
9	0.0001-0.02i
10	3.9294-10.49i
11	0.6485-2.73i
12	0.3178-5.56i
13	2.4066-5.16i
14	1.3534-4.77i

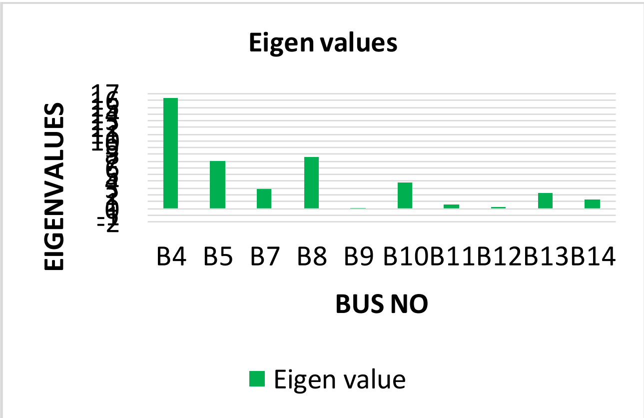

Fig. 1.Eigenvalues of C_{LL} sub matrix

From the table data, it is clear that bus 9 has the smallest eigen value followed by bus 12 and bus 11. Hence these buses are considered as critical or the weakest buses in the system. The ranking of the weakest buses is given in Table. 2.

Table. 2. Weakest buses ranking by eigen sensitivity technique

Bus No.	Ranking of the weakest buses
9	1
12	2
11	3

Implementation of SVC's at suitable locations and the improvement in the voltage profile are carried out in such a way that with single SVC at bus 9, the first weakest bus and the resulting voltage profile is observed. Later two SVC's one at bus 9 and second SVC at bus 12 was installed and checked for the profile improvement. Similarly the implementation of three SVC's was carried out one at bus 9, second at bus 12 and third at bus 11 which are the first, second and third weakest buses respectively and the profile improvement is observed and are listed for with and without SVC in Table. 3.

Table. 3. Voltage magnitude with and without SVC placement

Bus No.	Vm without SVC	Vm with single SVC at bus 9	Vm with two SVCs at buses 9, 12	Vm with three SVCs at buses 9, 12, 11
1	1.0600	1.0600	1.0600	1.0600
2	1.0406	1.0450	1.0450	1.0450
3	1.0100	1.0100	1.0100	1.0100
4	0.9958	1.0131	1.0147	1.0155
5	1.0046	1.0201	1.0222	1.0231
6	0.9887	1.0247	1.0356	1.0396
7	0.9670	1.0128	1.0149	1.0165
8	0.9670	1.0128	1.0149	1.0165
9	0.9533	1.0141	1.0164	1.0183
10	0.9514	1.0082	1.0121	1.0166
11	0.9660	1.0128	1.0201	1.0303
12	0.9710	1.0095	1.0297	1.0311
13	0.9644	1.0048	1.0179	1.0208
14	0.9382	0.9912	0.9984	1.0008

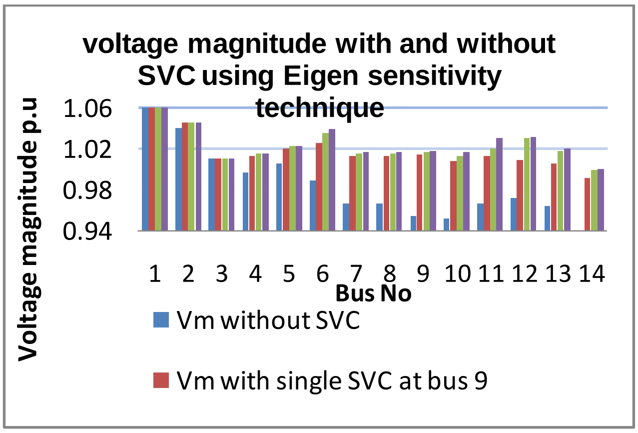

Fig. 2 comparison of voltage magnitude with single, two and three SVCs placement at weakest buses

The corresponding fig. 2 gives a comparative observation of the voltage magnitude when single SVC is at bus 9, two SVC's at 9,12 and three SVC's at buses 9,12,11 are placed. The Fig. 1 shows that there is a better improvement in the voltage magnitude of the buses when SVC's are implemented rather than without SVC. Also it shows that the voltage magnitude increases with the increase in the number of SVC's at suitable locations.

REACTIVE POWER BASED VOLTAGE SENSITIVITY METHOD

This technique is an effective tool in analyzing the closeness to the voltage collapse point. In this method eigen values and eigen vectors are obtained for the reduced Jacobian matrix obtained from the load flow studies.

Eigen values are associated with a mode of voltage and reactive power variation, which is capable of providing a relative measure to voltage instability.

Bus participation factor is used to identify the weakest buses in the given power system network. Bus participation factor values can be obtained from eigen vectors of the eigen values.

The Power balance equations at bus k [5] are

$P_k = V_k \sum_{n=1}^{N} Y_{kn} * V_n \cos(\delta_k - \delta_n - \theta_{kn})$ (10)

$Q_k = V_k \sum_{n=1}^{N} Y_{kn} * V_n \sin(\delta_k - \delta_n - \theta_{kn})$ (11)

Where

P_k and Q_k-Active and reactive power at bus k respectively

V_k and V_n - voltage magnitude at buses k and n respectively

δ_k and δ_n- voltage phase angle at buses k and n respectively

θ_{kn}- angle between the two buses k and n

Y_{kn} - line admittance between the buses k and n

In general real power and reactive power both affect the voltage stability of a system. Similar to Q-V approach, real power is kept at constant value and voltage stability is evaluated at every point with the consideration of the incremental relationship between Q-V. The equation relating ΔQ and ΔV is given by (12), assuming $\Delta P = 0$, then

$[\Delta Q] = [J_R]\,[\Delta V]$ (12)

Where,

$[\Delta V] = [J_R^{-1}]\,[\Delta Q]$ (13)

$J_R = \xi * \Lambda * \eta$ (14)

Eigen values are effective in predicting the closeness to voltage instability. Positive eigen values predict that the system is stable. Negative eigen values predict that the system is unstable. Zero eigen value denotes that the system is neither stable nor unstable and is at the margin. Hence it is necessary to concentrate on the least eigen value inorder to measure the closeness of the system to voltage instability.

Bus participation factor [9] isgiven by $P_{kj} = \xi_{jk} * \eta_{jk}$

This factor is extensively used for the determination of weakest bus. P_{kj}denotes the contribution of j^{th}eigen value to Q-V sensitivity at k^{th} bus.

A. Steps to identify the weakest buses using modal analysis technique [5] :

1. For the given load flow solution Obtain the Jacobian matrix and reduced Jacobian matrix on assuming incremental real power to be zero.
2. Eigen values of a reduced Jacobian matrix are obtained.
3. From the reduced Jacobian matrix right and left eigen values are evaluated.
4. For minimum eigen value obtain bus participation factors
5. Identify the weakest bus from the bus participation factor. Buses with highest participation factors are the weakest buses.
6. Implement the reactive power compensators at the weakest buses and observe the improvement in the voltage profile.

The eigen values of the reduced Jacobian matrix are given in Table. 4 and are shown in Fig. 3

Table. 4 Eigen values for IEEE 14 bus system by modal analysis technique

No of eigen values	Eigen values (diagonal elements)
1	63.8159
2	37.7514
3	21.8703
4	18.2592
5	15.9504
6	11.8042
7	1.5302
8	4.2092
9	5.6087
10	7.3408

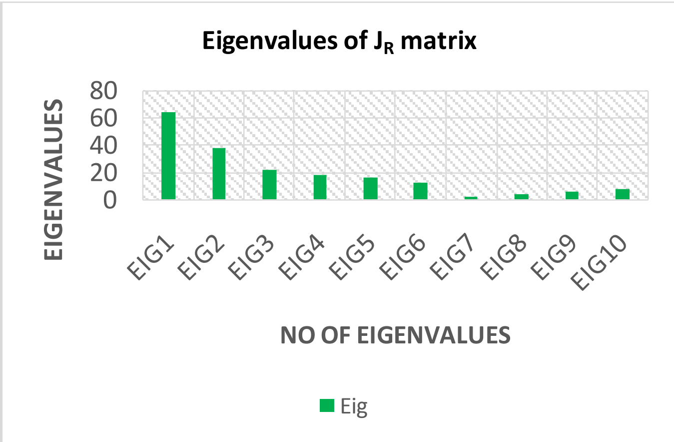

Fig. 3.Eigenvalues of reduced Jacobian matrix J_R

From Table. 4 it is clear that eigen value 7 is the least value and the bus participation factors corresponding to that value is required to be evaluated for the load buses. Thus evaluated participation factors are shown in fig. 4 from which the weakest buses are identified.

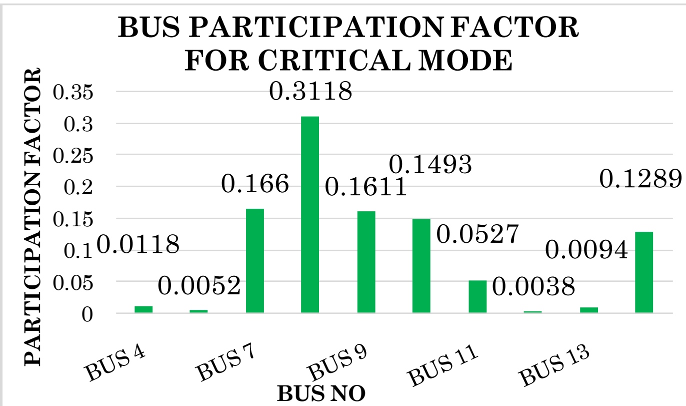

Fig. 4 Bus participation factors for IEEE 14 bus system

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From the above Fig. 2 the highest participation factor is for bus 8 which is identified as the first weakest bus in the system followed by buses 7 and 9 which are the second and third weakest buses respectively. Hence the ranking of the buses are as shown in table. 5.

Table. 5 Ranking of weakest load buses by modal analysis technique

Bus No.	Ranking of the weakest buses
8	1
7	2
9	3

Hence the best suitable locations of the SVC installation for reactive power compensation to improve the voltage profile is identified as bus 8,7,9. Initially the voltage profile improvement is observed in the system with a single SVC placement at bus 8.

Then the same is repeated with placement of two SVC's one at bus 8 and the second SVC at bus 7. Similarly observed the profile improvement with three SVC's one each at bus 8, 7 and 9 and all the three results were compared with that of without SVC placement and shown in fig. 5. The results reveal that the improvement in voltage is less than 1 p.u for single and two SVC placement but is better with SVC placement than without SVC. Also it denotes that there is a significant improvement in the voltage profile with the increase in the number of SVC's and is evident from the Table. 6 and the corresponding fig. 5.

Table. 6. Voltage magnitude with and without SVC placement by modal analysis technique

Bus No.	Vm without SVC	Vm with single SVC at bus 8	Vm with two SVC's at buses 8,7	Vm with three SVC's at buses 8,7,9
1	1.0600	1.0600	1.0600	1.0600
2	1.0406	1.0438	1.0450	1.0450
3	1.0100	1.0100	1.0100	1.0100
4	0.9958	1.0056	1.0124	1.0164
5	1.0046	1.0130	1.0187	1.0226
6	0.9887	1.0047	1.0160	1.0285
7	0.9670	0.9976	1.0198	1.0271
8	0.9670	1.0237	1.0304	1.0326
9	0.9533	0.9786	0.9967	1.0195
10	0.9514	0.9752	0.9923	1.0135
11	0.9660	0.9861	1.0004	1.0174
12	0.9710	0.9880	1.0000	1.0135
13	0.9644	0.9821	0.9947	1.0090
14	0.9382	0.9607	0.9767	0.9962

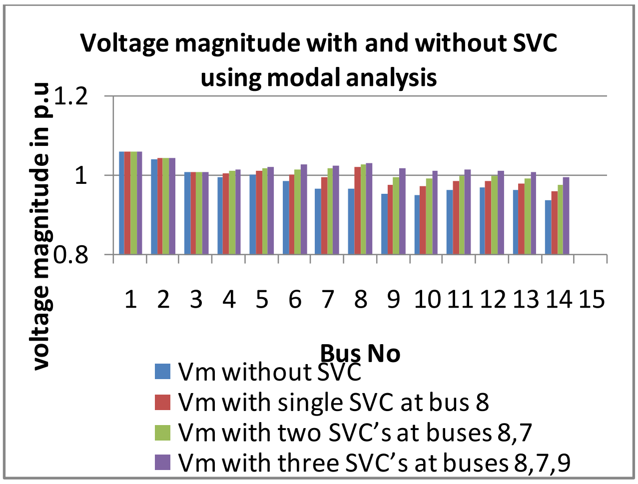

Fig. 5 Comparision of voltage magnitude with and without SVCs using modal analysis technique

On considering the modal analysis technique, variation in the real power is assumed to be constant. This assumption will not be valid for the network under stressed condition. This becomes very clear when the network is with an unbalanced condition of reactive power. Hence the eigen sensitivity technique is more advantageous compared to this method. The same is shown by means of comparison of the results of these two methods which is carried in next section.

COMPARISON OF THE RESULTS

On implementing the eigen sensitivity techniquetechnique on modified IEEE 14 bus system it is observed that the weakest buses as per first, second, and third ranking were identified to be 9, 12 and 11 respectively. The implementation of SVC's have improved the voltage profile. Also the profile improvement was enhancing with the increase in the number of SVC's.On the other hand, the analysis carried out by modal analysis have revealed the buses 8, 7 and 9 to be the order in ranking the weakest buses. On implementing the SVC's at the weakest buses have shown the improvement in voltage profile. But on comparing the results of Eigen sensitivity technique with that of modal analysis the improvement of voltage is better in eigen value method with two SVC's whereas to achieve a similar improvement of voltage profile in modal analyis it requires three SVC's. The results comparing the two methods are shown in the following tables with the corresponding plots.

Table. 7 Comparison of voltage magnitudes by eigen sensitivity technique and modal analysis method with single SVC

Bus No	V_m Without SVC	V_m using Eigen value decompositon method	V_m using modal analysis method
1	1.0600	1.0600	1.0600
2	1.0406	1.0450	1.0438
3	1.0100	1.0100	1.0100
4	0.9958	1.0131	1.0056
5	1.0046	1.0201	1.0130
6	0.9887	1.0247	1.0047
7	0.9670	1.0128	0.9976
8	0.9670	1.0128	1.0237
9	0.9533	1.0141	0.9786
10	0.9514	1.0082	0.9752
11	0.9660	1.0128	0.9861
12	0.9710	1.0095	0.9880
13	0.9644	1.0048	0.9821
14	0.9382	0.9912	0.9607

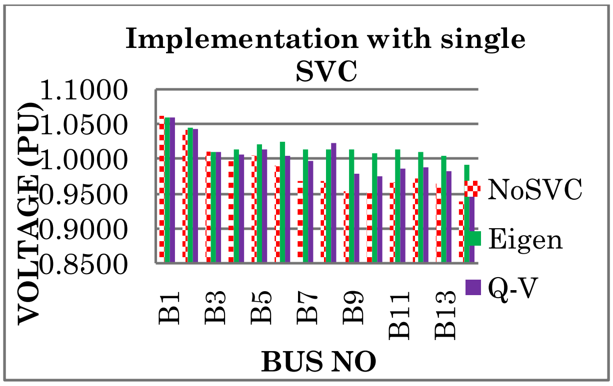

Fig. 6 Comparison of voltage magnitudes without SVC and with single SVC using eigen sensitivity technique and modal analysis method

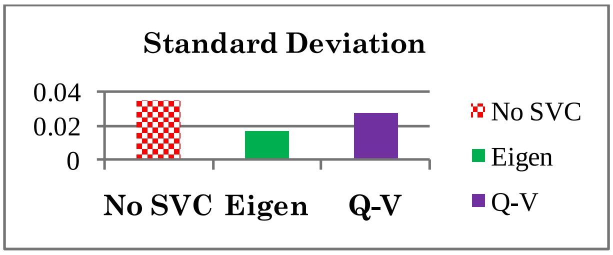

Fig. 7Standard deviation for both methods when single SVC is placed

Table. 8: Comparison of voltage magnitudes without SVC and with two SVCs using both the methods

Bus No	V_m Without SVC	V_m using Eigen value decompositon method	V_m using modal analysis method
1	1.0600	1.0600	1.0600
2	1.0406	1.0450	1.0450
3	1.0100	1.0100	1.0100
4	0.9958	1.0147	1.0124
5	1.0046	1.0222	1.0187
6	0.9887	1.0356	1.0160
7	0.9670	1.0149	1.0198
8	0.9670	1.0149	1.0304
9	0.9533	1.0164	0.9967
10	0.9514	1.0121	0.9923
11	0.9660	1.0201	1.0004
12	0.9710	1.0297	1.0000
13	0.9644	1.0179	0.9947
14	0.9382	0.9984	0.9767

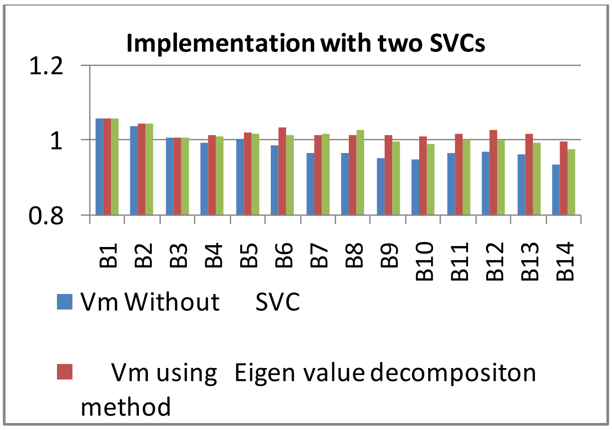

Fig. 8 Comparison of voltage magnitudes without SVC and with two SVCs using both the methods

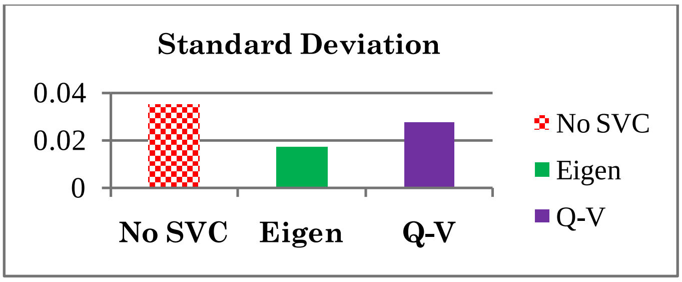

Fig. 9.Standard deviation for both methods when two SVCs are placed

Table. 9: Comparison of voltage magnitudes without SVC and with three SVC using eigen sensitivity technique and modal analysis method

Bus No	V_m Without SVC	V_m using Eigen value decompositon method	V_m using modal analysis method
1	1.0600	1.0600	1.0600
2	1.0406	1.0450	1.0450
3	1.0100	1.0100	1.0100
4	0.9958	1.0155	1.0164
5	1.0046	1.0231	1.0226
6	0.9887	1.0396	1.0285
7	0.9670	1.0165	1.0271
8	0.9670	1.0165	1.0326
9	0.9533	1.0183	1.0195
10	0.9514	1.0166	1.0135
11	0.9660	1.0303	1.0174
12	0.9710	1.0311	1.0135
13	0.9644	1.0208	1.0090
14	0.9382	1.0008	0.9962

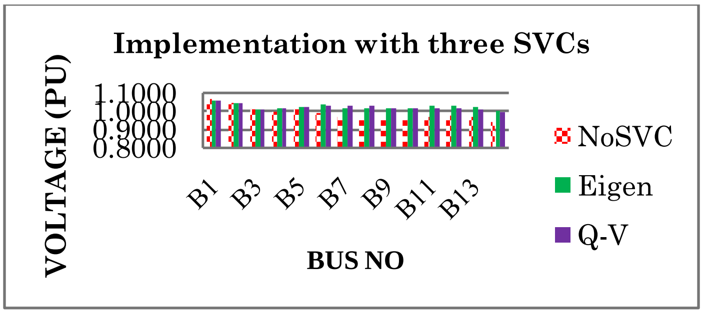

Fig. 10 Comparison of voltage magnitudes without SVC and with three SVCs using both the methods

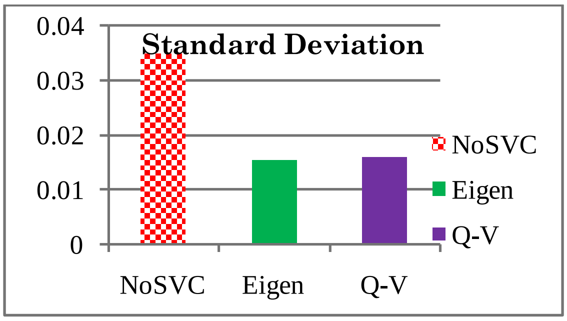

Fig. 11Standard deviation for both methods with 3 SVCs

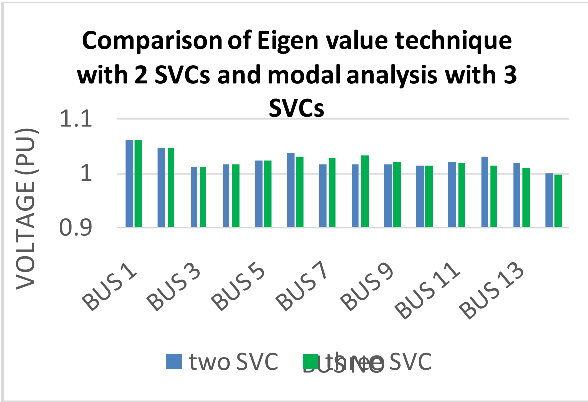

Fig. 12 Comparison of results of eigen sensitivity technique with 2 SVCs and modal analysis method with 3 SVCs

From Fig. 12, it is evident that with the eigenvalue decomposition method when 2 SVC's are installed the voltage profile improvement is well whereas in modal analysis technique inorder to achieve a similar improved voltage profile 3 SVC's are required. Thus it can be observed that using the eigen sensitivity technique results in the requirement of a fewer number of SVCs. This is because in eigen sensitivity techniquetechnique the interconnection of the buses and the impedances associated between them are considered which will influence greatly the flow of active and reactive power. In this method unlike the modal analysis the active power flow is included inherently in the computation which is very important particularly under the stressed condition of the network.

CONCLUSION

Hence the eigen sensitivity techniquetechnique have improved the voltage profile better than the modal analysis technique even with the placement of single SVC. With the installation of two SVC's at the first two weakest buses the results show that the voltage profile have improved significantly in eigen sensitivity techniquetechnique rather than modal analysis in which still the voltage magnitudes are less than 1 p.u. In modal analysis for achieving similar results it is required to have more number of SVC's than the eigen sensitivity technique. Hence the number of SVC's are reduced in eigen sensitivity techniquewith a better improvement in the voltage profile.

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