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# Sensitivity Factor Based Optimal Location of SVC on Transmission Network

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## *Abstract*

*In modern days power system are becoming highly unpredictable, so low voltages and blackout are becoming common scenario. The voltage limits are affected because the system is operated close to its stability limits. To improve the voltage profile new generating plants have to be developed, which are restricted due to economic an environmental limitations. To overcome these limitations and use the existing network to the maximum, FACTS devices are used. In this paper, SVC a FACTS device is used to improve the voltage profile of the network. To decide the location of the SVC, voltage sensitivity analysis method is used. FACTS devices are used to compensate both real and reactive power. To demonstrate this IEEE 14 bus and 39 bus are considered. The complete simulation is done using PSAT version 2.1.6 in Matlab 7.10.0 (R2010 a).*

***Keywords***: *sensitivity factor, SVC, transmission network*

## 1. Introduction

Power systems components mainly consist of generators, transmission lines, transformers, switches, active or passive compensators and loads. Power system networks are complex systems that are nonlinear, non-stationary, and prone to disturbances and faults. Reinforcement of a power system can be accomplished by improving the voltage profile, increasing the transmission capacity and others.

The electrical energy demand increases continuously leading to an augmented stress of the transmission lines higher risks for faulted lines. The extension of the transmission grid needed to further guarantee secure transmission is difficult for environmental and political reasons. The blackouts in different parts of the world in the last two years have shown that the current situation is not satisfactory and a way to increase transfer capability and controllability in order to ensure secure power transmission has to be found. An option to achieve this is the utilization of flexible AC transmission systems (FACTS).

The FACTS devices (Flexible AC Transmission Systems) could be a means to carry out this function without the drawbacks of the electromechanical devices such as slowness and wear. FACTS can improve the stability of network, such as the transient and the small signal stability, and can reduce the flow of heavily loaded lines and support voltages by controlling their parameters including series impedance, shunt impedance, current, and voltage and phase angle.

Controlling the power flows in the network leads to reduce the flow of heavily loaded lines, increased system load ability, less system loss and improved security of the system. The increased interest in these devices is essentially due to recently development in high power electronics that has made these devices cost effective and increased loading of power systems, combined with deregulation of power industry. On account of considerable costs of FACTS devices, it is important to place them in optimal location.

As voltage stability is one of the important problems in the power system, FACTS devices attracts the power system engineers to solve this kind of problem. The project aims to improve voltage stability margin by incorporating SVC into power system.

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Haadi Saadat [2] discussed about the implementation of load flow studies using NR method. Allen J. Wood and Bruce F. Wollenberg, proposed the method of sensitivity analysis and sensitivity factor calculation.

K.R Padiyar [3] described the various FACTS controllers in power transmission and distribution. Narain G.Hingorani, Laszlo Gyugyi [4] discussed about understanding the FACTS devices prioritising SVC device and its modelling.

R. Mohan Mathur and Rajiv K.Varma [5] carried out a basic study of FACTS controllers along with the reactive power control in the electrical power transmission systems. Various methods of compensation techniques used in the power system were also studied.

In this paper, the optimal location of SVC, with specific characteristics is found. They are located optimally in order to maximize the security margin of the system in terms of branch loading and voltage levels. Optimal location of SVC in the given system is found using sensitivity analysis with the help of sensitivity factor values calculated for the load buses in the system. The bus with highest value of sensitivity factor with respect to both real and reactive power injections is considered as the most sensitive bus in the network and is the optimal location for the placement of SVC.

To enhance the voltage profile and to increase the transfer capability of the system a methodology is proposed which deals with finding the optimal location of SVC in the transmission network by calculating the sensitivity factor values using voltage sensitivity analysis.

## 2. Proposed Methodology

Now a day, sensitivity analysis is gaining more importance in practical power system operations. The power operator uses the sensitivity values to study and monitor the system behaviour and detect possible problems in the network.

Voltage sensitivity factor is related to voltage stability. Voltage instability is mainly associated with reactive power imbalance in a local network or a specified bus in a system which is called the weak bus. Voltage sensitivity analysis can detect the weak buses in the power system where the voltage is low. Therefore voltage sensitivity factor is used select the optimal locations of reactive power support.

### 2.1. Algorithm for Calculating Voltage Sensitivity Factor

Voltage sensitivity factor [6] is the variation of voltage stability index with respect to changes in real and reactive power injections at a bus. Sensitivity indices that relate the changes in the voltage stability index with respect to changes in injected active and reactive power at a load bus are derived from the voltage stability index formulation. Voltage stability index at a load bus identifies critical buses i.e. buses which are prone to voltage collapse in power system.

Step 1: Calculate the voltage stability index by using voltage equation. The voltage stability index is given by,

$$L_i = \frac{4[V_{oi}V_{Li}\cos\theta_i - V_{Li}^2\cos\theta_i^2]}{V_{oi}^2} \quad (1)$$

Where,

$$\theta_i = \theta_{oi} - \theta_{Li}\theta$$

Step 2: Calculate $\frac{\partial L_i}{\partial \theta_i}$ and $\frac{\partial L_i}{\partial V_{Li}}$ by differentiating equation (Equation 1) with respect to $\theta_i$ and $V_{Li}$ respectively as shown:

$$\frac{\partial L_i}{\partial \theta_i} = \frac{4[-V_{oi}V_{Li}\sin\theta_i + 2V_{Li}^2\cos\theta_i\sin\theta_i]}{V_{oi}^2} \quad (2)$$

$$\frac{\partial L_i}{\partial V_{Li}} = \frac{4(V_{oi}-2V_{Li})}{V_{oi}^2} \quad \text{(since cosine of } \theta_i \ll 1) \qquad (3)$$

Step 3: Obtain the values of elements.

$$\frac{\partial V_{Li}}{\partial P_i}, \frac{\partial \theta_{Li}}{\partial P_i}, \frac{\partial V_{Li}}{\partial Q_i}, \frac{\partial \theta_{Li}}{\partial Q_i}$$

From the inverse of load flow jacobian matrix.

Step 4: Calculate the first sensitivity factor which is the change in $L_i$ with respect to the injected real power $P_i$ in i<sup>th</sup> bus given by:

$$\frac{\partial L_i}{\partial P_i} = \frac{\partial L_i}{\partial V_{Li}} \times \frac{\partial V_{Li}}{\partial P_i} + \frac{\partial L_i}{\partial \theta_{Li}} \times \frac{\partial \theta_{Li}}{\partial P_i} \qquad (4)$$

Step 5: Express the above equation in a matrix as below:

$$\frac{\partial L_i}{\partial P_i} = \begin{bmatrix} \frac{\partial L_i}{\partial V_{Li}} & \frac{\partial L_i}{\partial \theta_{Li}} \end{bmatrix} \begin{bmatrix} \frac{\partial V_{Li}}{\partial P_i} \\ \frac{\partial \theta_{Li}}{\partial P_i} \end{bmatrix} \qquad (5)$$

Step 6: Calculate the second sensitivity factor which is the change in $L_i$ with respect to the injected reactive power $Q_i$ in the i<sup>th</sup> bus given by:

$$\frac{\partial L_i}{\partial Q_i} = \frac{\partial L_i}{\partial V_{Li}} \times \frac{\partial V_{Li}}{\partial Q_i} + \frac{\partial L_i}{\partial \theta_{Li}} \times \frac{\partial \theta_{Li}}{\partial Q_i} \qquad (6)$$

Step 7: Express the (equation. 6) in a matrix as below:

$$\frac{\partial L_i}{\partial Q_i} = \begin{bmatrix} \frac{\partial L_i}{\partial V_{Li}} & \frac{\partial L_i}{\partial \theta_{Li}} \end{bmatrix} \begin{bmatrix} \frac{\partial V_{Li}}{\partial Q_i} \\ \frac{\partial \theta_{Li}}{\partial Q_i} \end{bmatrix} \qquad (7)$$

Step 8: Equations (5) and (7) give the voltage sensitivity factor values with respect to the injected real and reactive power at the i<sup>th</sup> bus respectively.

### 2.2. Algorithm and Flowchart for the Proposed Scheme

The proposed scheme is to enhance the voltage profile of the uncompensated system by providing compensation using SVC controller. To achieve this effectively optimal locations for placing the SVC have to be found. Therefore for finding the optimal locations of VAR support sensitivity analysis is carried out as discussed earlier. The step by step procedure is as follows.

Step 1: Create the PSAT model of the given system and input the given line data and bus data in the respective blocks of the PSAT model.

Step 2: Run the power flow program using NR method and save the load flow results for the normal system.

Step 3: From the load flow results, check whether the system is compensated i.e., voltage magnitude of all the buses are within limits. If it is not compensated go to next step otherwise print the load flow results.

Step 4: Run the matlab coding for sensitivity analysis by providing line data and bus data of the given system as inputs and save the sensitivity factor values for all the load buses.

Step 5: Find the bus with the highest value of sensitivity factor with respect to both real and reactive power injections and declare that bus as the most sensitive bus in the network.

Step 6: Therefore the most sensitive bus is considered to be the optimal location for placing the SVC. Model the SVC block and connect it to the most sensitive bus in the network in parallel in the PSAT model.

Step 7: Run the power flow program using NR method for the new model with SVC and save the load flow results.

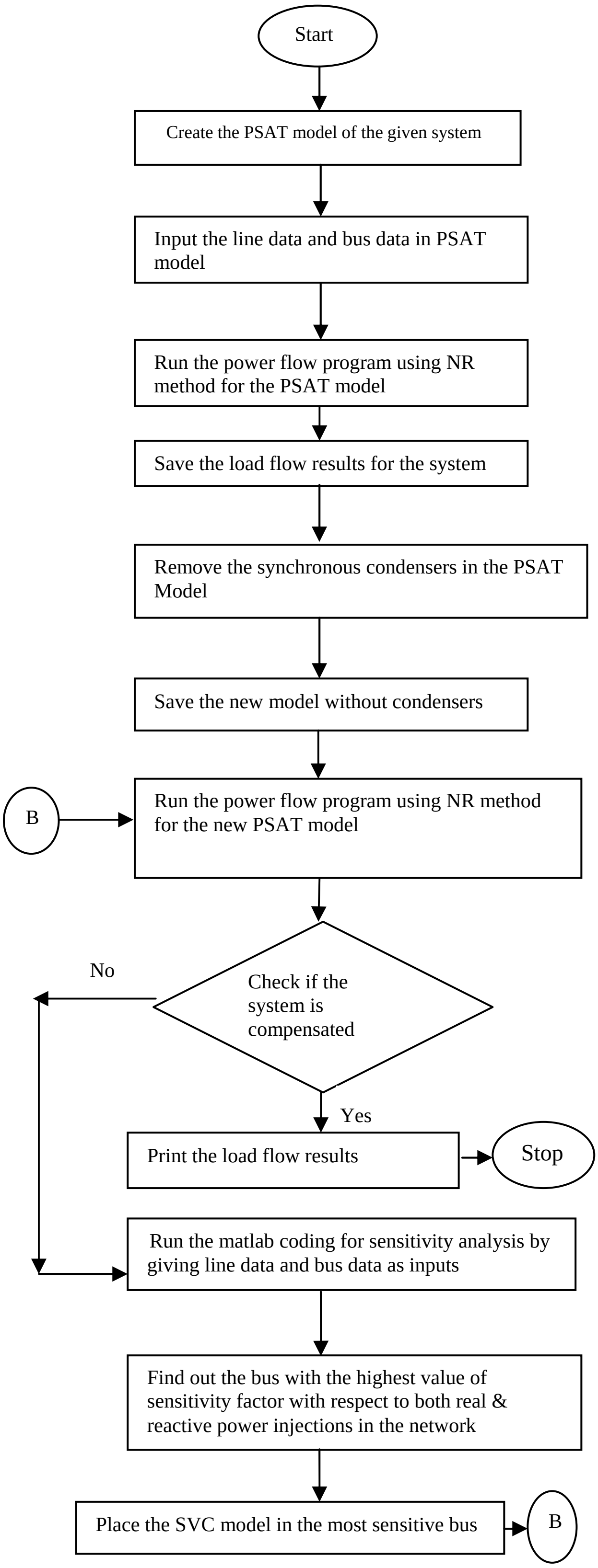

Figure 1. Flowchart for the Proposed Scheme

Step 8: Compare the load flow results of the system which is uncompensated and with SVC. Check whether the system is compensated and the voltage profile of the system is enhanced. If it is so print the results otherwise repeat step 4 and find the next most sensitive bus in the network and repeat the steps from 6 to 8. The flowchart of the proposed methodology is given in Figure 1.

Therefore by calculating the voltage sensitivity factor values for all the load buses, the bus with the highest value of sensitivity factor with respect to both real and reactive power injections is considered to be the most sensitive bus in the system.

## 3. Test System and Results

The proposed scheme is implemented in a standard IEEE 14 bus and IEEE 39 bus network and the results are discussed. The single line diagram of standard IEEE 14 bus network is shown in Figure 2.

A standard IEEE 14 bus network is considered and assumptions are made to obtain various ill conditions (i.e., voltage collapse). In the assumed network sensitivity analysis is done to find the optimal location of FACTS controllers.

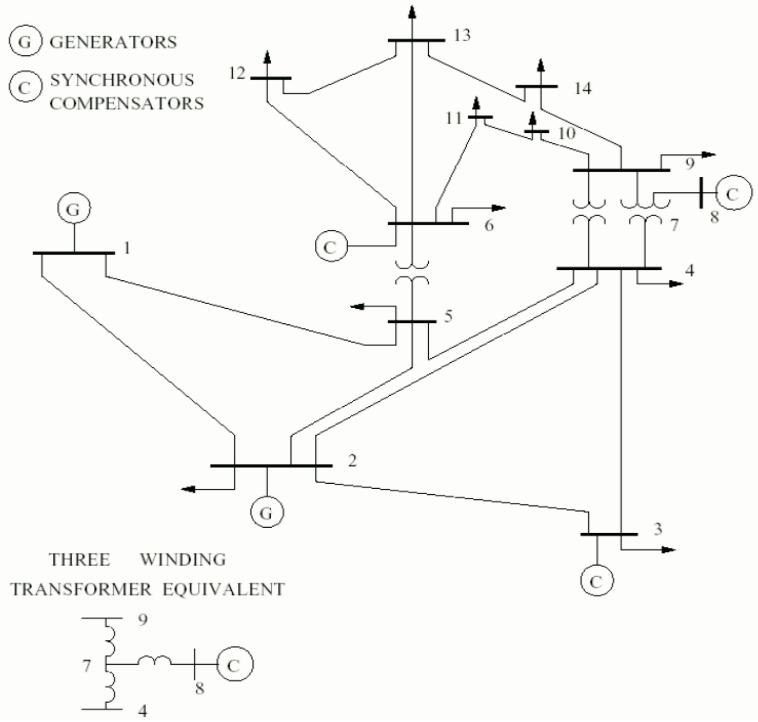

Figure 2. IEEE 14 Bus Network

Considering the standard IEEE – 14 bus network [7] as our test case, load flow analysis by NR method is done for the network model in PSAT software. By analyzing the voltage magnitude from the results (Table 2) it is found that the system is stable. In the next step, the condensers located in bus 6 and bus 8 in the system are removed as shown in Figure 3. By analyzing the voltage magnitude (Vm) from load flow results it varies in the range from 0.89654 (p.u) to 1.05 (p.u). Sensitivity analysis is done using matlab coding and sensitivity factor values for the load buses are calculated as discussed and tabulated in Table 1.

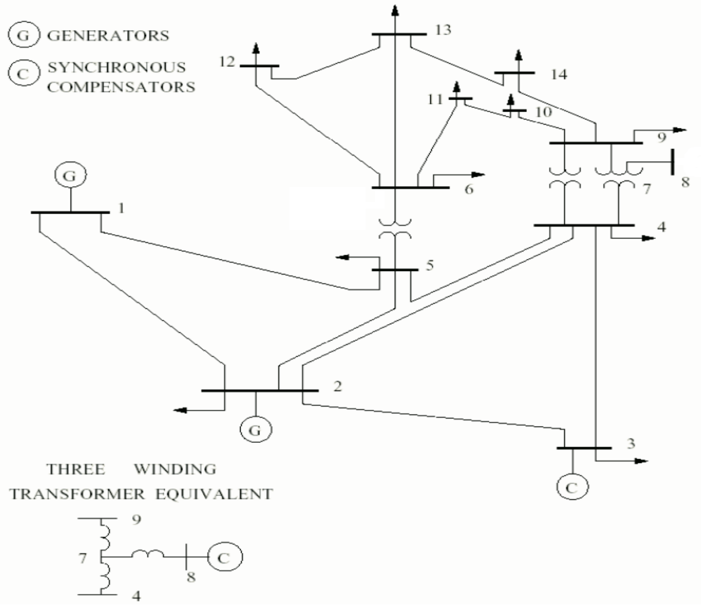

Figure 3. Modified 14 Bus Network

Table 1. Sensitivity Values for IEEE 14 Bus Network

| Bus no | Normal system | | Without condensers | |
|---|---|---|---|---|
| | $\frac{\partial L_i}{\partial P_i}$ | $\frac{\partial L_i}{\partial Q_i}$ | $\frac{\partial L_i}{\partial P_i}$ | $\frac{\partial L_i}{\partial Q_i}$ |
| 4 | 0.7489 | 0.0506 | 0.1032 | 0.4384 |
| 5 | 0.4987 | 0.2744 | 0.6394 | 0.0997 |
| 7 | 0.0969 | 0.3260 | 0.5720 | 0.4297 |
| 9 | 1.0138 | 0.5484 | **1.0841** | **1.2079** |
| 10 | 0.4698 | 0.6737 | 0.4688 | 0.8839 |
| 11 | 1.1782 | 0.7934 | 0.8412 | 1.5371 |
| 12 | 1.7732 | 0.2660 | 0.7494 | 0.6300 |
| 13 | 2.2847 | 0.1753 | 1.6339 | 0.5208 |
| 14 | 2.6178 | 0.2020 | 1.0699 | 0.8377 |

Based on table results the sensitivity factor which is the change in $L_i$ with respect to the injected real power $P_i$, the highest value is at bus 13, if compensated at this bus real power only will be compensated. This can be achieved by using distributed generators. Similarly on table results the sensitivity factor which is the change in $L_i$ with respect to the injected reactive power $Q_i$, the highest value is at bus 11, if compensated at this bus reactive power only will be compensated. This can be achieved by using capacitor banks. Here SVC is used which can be used to compensate both the parameters. Based on which it is found that the most sensitive bus in the network model is bus 9 since bus 9 have the higher value of sensitivity factor with respect to both real and reactive power injections compared to all other load buses. Therefore by placing SVC in that bus it is found that the voltages in all the buses in the network got compensated which is given in Table 2. From the Table 2, comparing the voltage magnitude of the system without condenser and of the system with SVC at bus 9 from the load flow results it is clear that the voltage profile of the system has improved and the system is compensated. The proposed scheme is implemented on a standard IEEE 14 bus network using PSAT software and the load flow results obtained verify that the system is compensated by placing the SVC in the optimal location found by sensitivity factor analysis.

Table 2. Load Flow Results

| Bus no | Normal system | | Without condenser | | With SVC | |
|---|---|---|---|---|---|---|
| | $V_m$ (p.u) | $V_a$ (rad) | $V_m$ (p.u) | $V_a$ (rad) | $V_m$ (p.u) | $V_a$ (rad) |
| 1 | 1.05 | 0.000 | 1.05 | 0.0000 | 1.05 | 0.000 |
| 2 | 1.05 | 0.002 | 1.05 | 0.0021 | 1.05 | 0.050 |
| 3 | 1.01 | - 0.140 | 0.96 | -0.1377 | 1.00 | -0.02 |
| 4 | 1.01 | - 0.108 | 0.97 | -0.1024 | 1.03 | 0.062 |
| 5 | 1.02 | - 0.089 | 0.98 | -0.0826 | 1.03 | 0.057 |
| 6 | 1.05 | - 0.192 | 0.93 | -0.1961 | 0.98 | 0.108 |
| 7 | 1.02 | - 0.165 | 0.93 | -0.1699 | 1.04 | 0.208 |
| 8 | 1.05 | - 0.165 | 0.93 | -0.1699 | 1.04 | 0.208 |
| 9 | 1.00 | - 0.195 | 0.92 | -0.2077 | 1.05 | 0.284 |
| 10 | 1.00 | - 0.200 | 0.91 | -0.2122 | 1.03 | 0.249 |
| 11 | 1.02 | - 0.198 | 0.92 | -0.2072 | 1.00 | 0.179 |
| 12 | 1.03 | - 0.212 | 0.91 | -0.2202 | 0.96 | 0.105 |
| 13 | 1.02 | - 0.216 | 0.91 | -0.2270 | 0.97 | 0.117 |
| 14 | 0.99 | - 0.223 | 0.89 | -0.2393 | 0.99 | 0.195 |

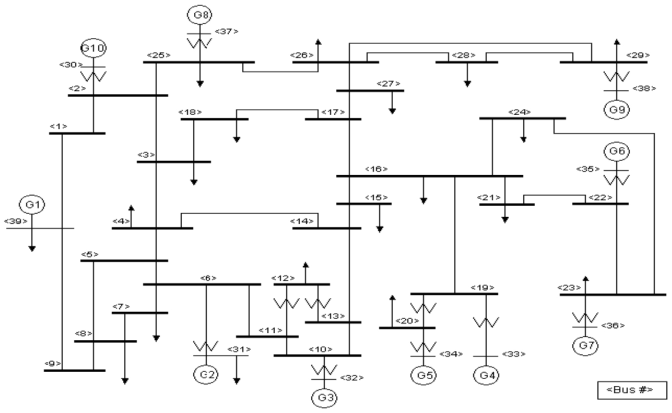

Figure 4. IEEE 39 Bus Network

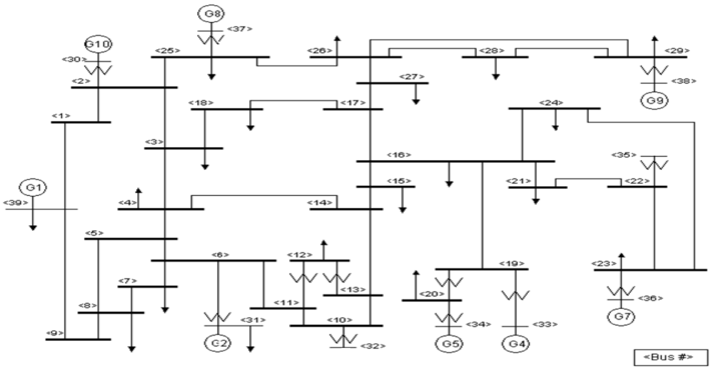

Figure 5. Modified 39 Bus Network after Removing Generators G3 and G6

Considering the standard IEEE 39 bus [8] as shown in Figure 4 networks as our test cases, load flow analysis by NR method is done for the network models in PSAT software. By analyzing the voltage magnitude from the results (Table 4) it is found that the systems are compensated. In the next step, two generators in the IEEE 39 bus system are removed as shown in Figure 5 and analyzing the voltage magnitude (Vm) from load flow results it varies in the range from 0.878 p.u to 1.00 p.u. for IEEE 39 bus network. Sensitivity analysis is done using matlab coding and sensitivity factor values for the load buses are calculated as tabulated in Table 3I for 39 bus networks.

Table 3. Sensitivity Values for IEEE 39 Bus Network

| Bus no | Normal system | | Without 2 generators | |
|---|---|---|---|---|
| 15 | 0.2706 | 0.0702 | 0.3662 | 0.0296 |
| 16 | 0.0725 | 0.0371 | 0.4385 | 0.0644 |
| 17 | 0.1590 | 0.0565 | 0.0555 | 0.0440 |
| 18 | 0.3153 | 0.0786 | 0.0800 | 0.0669 |
| 19 | 0.4580 | 0.0339 | 0.2673 | 0.0333 |
| 20 | 0.1346 | 0.0426 | 0.5403 | 0.0360 |
| 21 | 0.2141 | 0.0544 | 0.2297 | 0.0654 |
| 22 | 0.1134 | 0.0373 | 0.3062 | 0.0416 |
| 23 | 0.1203 | 0.0453 | 0.1337 | 0.0416 |
| 24 | 0.0948 | 0.0525 | 0.2399 | 0.0673 |
| 25 | 0.0369 | 0.0447 | 0.0034 | 0.0417 |
| 26 | 0.0137 | 0.0742 | 0.0087 | 0.0738 |
| 27 | 0.0403 | 0.0818 | 0.4346 | 0.0422 |
| 28 | 0.5221 | 0.1068 | 0.2549 | 0.1047 |
| 29 | 0.1219 | 0.0564 | 0.0917 | 0.0573 |

Table 4. Load Flow Results

| Bus no | Normal system | | Without 2 generators | | With SVC | |
|---|---|---|---|---|---|---|
| | $V_m$ (p.u) | $V_a$ (rad) | $V_m$ (p.u) | $V_a$ (rad) | $V_m$ (p.u) | $V_a$ (rad) |
| 1 | 1.000 | 0.000 | 1.000 | 0.0000 | 1.000 | 0.000 |
| 2 | 1.011 | -0.050 | 0.978 | -0.4168 | 0.986 | -0.409 |
| 3 | 0.983 | -0.134 | 0.933 | -0.6063 | 0.951 | -0.593 |
| 4 | 0.949 | -0.191 | 0.897 | -0.7323 | 0.932 | -0.712 |
| 5 | 0.948 | -0.193 | 0.899 | -0.7304 | 0.936 | -0.710 |
| 6 | 0.950 | -0.187 | 0.903 | -0.7309 | 0.940 | -0.711 |
| 7 | 0.940 | -0.218 | 0.887 | -0.7368 | 0.923 | -0.716 |
| 8 | 0.940 | -0.221 | 0.885 | -0.7264 | 0.920 | -0.707 |
| 9 | 0.985 | -0.138 | 0.937 | -0.4072 | 0.953 | -0.404 |
| 10 | 0.958 | -0.125 | 0.901 | -0.7328 | 0.954 | -0.714 |
| 11 | 0.954 | -0.146 | 0.900 | -0.7322 | 0.953 | -0.713 |
| 12 | 0.935 | -0.141 | 0.879 | -0.7340 | 1.000 | -0.716 |
| 13 | 0.956 | -0.134 | 0.910 | -0.7334 | 0.955 | -0.715 |
| 14 | 0.956 | -0.155 | 0.905 | -0.7349 | 0.947 | -0.715 |
| 15 | 0.965 | -0.139 | 0.923 | -0.7417 | 0.947 | -0.722 |
| 16 | 0.985 | -0.102 | 0.947 | -0.7115 | 0.963 | -0.693 |
| 17 | 0.987 | -0.116 | 0.945 | -0.6710 | 0.960 | -0.654 |
| 18 | 0.984 | -0.131 | 0.938 | -0.6555 | 0.955 | -0.640 |
| 19 | 0.989 | -9e-05 | 0.976 | -0.6067 | 0.981 | -0.589 |
| 20 | 0.986 | -0.017 | 0.979 | -0.6246 | 0.982 | -0.607 |
| 21 | 0.993 | -0.057 | 0.950 | -0.7250 | 0.964 | -0.706 |
| 22 | 1.020 | 0.023 | 0.971 | -0.6978 | 0.982 | -0.679 |
| 23 | 1.019 | 0.022 | 0.983 | -0.6797 | 0.992 | -0.661 |
| 24 | 0.993 | -0.100 | 0.957 | -0.7242 | 0.972 | -0.705 |
| 25 | 1.021 | -0.031 | 0.985 | -0.4271 | 0.992 | -0.417 |
| 26 | 1.012 | -0.068 | 0.976 | -0.5422 | 0.985 | -0.529 |
| 27 | 0.994 | -0.112 | 0.952 | -0.6243 | 0.965 | -0.609 |
| 28 | 1.016 | -0.002 | 0.998 | -0.4747 | 1.002 | -0.462 |
| 29 | 1.019 | 0.049 | 1.006 | -0.4225 | 1.009 | -0.410 |
| 30 | 1.048 | -0.008 | 1.048 | -0.3726 | 1.048 | -0.365 |
| 31 | 0.982 | -0.168 | 0.982 | -0.7109 | 0.982 | -0.692 |
| 32 | 0.983 | 0.014 | 0.901 | -0.7328 | 0.954 | -0.714 |
| 33 | 0.997 | 0.091 | 0.997 | -0.5154 | 0.997 | -0.498 |
| 34 | 1.012 | 0.073 | 1.012 | -0.5339 | 1.012 | -0.516 |
| 35 | 1.049 | 0.113 | 0.971 | -0.6978 | 0.982 | -0.679 |
| 36 | 1.064 | 0.162 | 1.064 | -0.5351 | 1.064 | -0.518 |
| 37 | 1.028 | 0.088 | 1.028 | -0.3043 | 1.028 | -0.295 |
| 38 | 1.027 | 0.172 | 1.027 | -0.2979 | 1.027 | -0.286 |
| 39 | 1.000 | -0.082 | 1.000 | -0.2128 | 1.000 | -0.213 |

It is found that the most sensitive bus in the IEEE 14 bus network is bus nine since bus nine have the highest value of sensitivity factor with respect to both real and reactive power injections compared to all other load buses, similarly for IEEE 39 bus network the most sensitive bus is found to be bus 12. Therefore by placing SVC in the respective buses it is found that the voltages in all the buses in the networks got compensated which is given in Table 4. From the table, comparing the voltage magnitude of the systems without condenser and of the systems with SVC from the load flow results it is clear that the voltage profiles of the systems have improved and the systems are compensated.

## 4. Conclusion

In this paper sensitivity factor based optimal location of SVC is found where the best location is inferred considering the losses, investment in the FACTS controllers and also the voltage improvement values. The proposed method is an effective and practical method for the allocation of FACTS controllers.

In the considered test case bus 9 is found to be most sensitive with respect to both real and reactive power injections by trial and error method and sensitivity analysis method. Therefore bus 9 is considered as the optimal location for the placement of SVC. Thus the optimal location for placing the FACTS devices (SVC) in the network model is found by sensitivity factor analysis.

It is clearly evident from the result that effective placement of FACTS devices in proper locations can significantly improve system performance. This approach could be a new technique for the installation of FACTS devices in the transmission system.

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