OPTIMAL D-STATCOM PLACEMENT METHODS IN RADIAL DISTRIBUTION SYSTEM USING SENSITIVITY APPROACHES

S. GANESH[1*], R. KANIMOZHI[2]
[1, 2] Department of Electrical & Electronics Engineering
Anna University- BIT campus, Trichy, Tamil Nadu, India
[1]gauti.ganeshs@gmail.com, [2]kanimozhi_17@yahoo.com

S. DEVARAJ[3]
[3] Department of Electrical & Electronics Engineering
Anna University- BIT campus, Trichy, Tamil Nadu, India
[3]devaraj8796@gmail.com

Abstract: *The major challenge in the radial distribution network is the reactive power demand, which the system fails to meet up leading to high power loss, low voltage drop and low power factor. In order to compensate this reactive power demand, D-STATCOM installation at the candidate buses is the optimal solution. In this paper, five different sensitivity methods are analysed to examine the weak bus for optimal allocation of D-STATCOM with a fixed size of 500 kVAr. Also, in this paper multi objective has been achieved by the placement of D-STATCOM in the distribution system. The presented approach has been tested and validated on a 69-bus system and a real time 31-bus system under different loading conditions. The effectiveness of the proposed approach is the exact identification of the prior candidate buses. The results show the robustness of the proposed methodology to solve the distribution network problems.*

Key words: *Distribution system, sensitivity approaches, D-STATCOM, real power loss, voltage profile, power factor*

1. Introduction

Distribution systems are featured by its high R/X ratios and they essentially found to be weak in nature when compared to other stiff grids. Hence the distribution system is susceptible to voltage dips, fluctuations, flickers and so on. In the present scenario, the small distribution generations are more viable option for power generation in case of distribution system problems like voltage instability and overloading conditions. The distribution generation is provided with the help of FACTS device Distribution Static Compensator (D-STATCOM) to the grid planners and engineers and are found to be the greatest choice regarding corrective compensation for the power system available today [1]. The D-STATCOM overcomes the disadvantages of electromechanical controlled power system networks. They are used as parallel static VAR compensators in the distribution network [2]. However, in a radial distribution system the presence of unbalanced and non-linear loads causes the distortions and unbalance in the system quantities leading to a greater burden of the distribution feeder. A D-STATCOM can be used at the buses to prevent the drawing of unbalanced and distorted currents from the network [3]. In the power system planning the main function is to serve the distributed loads without any interruptions, taking into account of the reliability, stability and high quality of electric power in the market. This could be favored by injecting distribution static compensators at the collapsed buses. The desired effect of D-STATCOM on system performance can be increased by obtaining its best location and size in the network [4]. A scheme based on improved active and reactive current component theory can provide better performance of this D-STATCOM in an effective manner in 3-phase three wire systems, 3-phase four wire systems and delta connected load systems [5]. There are several algorithms presented in the optimal sizing and placement of the D-STATCOM in the distribution network. One such among them is the immune algorithm which mainly focuses on the sake of improvement on current and voltage profile and on power loss reduction [6]. Similarly a harmony search algorithm for optimal placement and sizing of D-STATCOM helps on the total power loss reduction [7]. Hence placement and sizing of D-STATCOM in the distribution system is needed to reduce the power loss with voltage and power factor improvement [8]. Thus, it is indeed a necessity of these distribution compensating devices to be optimally placed in the distribution network resulting in the greatest improvement of voltage profile, loss reduction and enhancement of sensitivity index and increase in the system security level [9].

The novelty of this work is implementing an integrated approach of various sensitivity factors for determining the optimal location of D-STATCOM and placement of fixed size of a D-STATCOM for the sake of minimizing power loss, voltage profile and power factor improvements. The previous work done by researchers in this area had been focused on one or two sensitivity indices for weak bus identification, but in this paper five different sensitivity approaches has been prepared which provides the most candidate bus as weak bus in the radial distribution system. The proposed methods have been tested on a 69-bus and a real time 31-bus test system where the presence of different load levels and the respective results are tabulated.

2. Problem Formulation

2.1 Load Flow

For improved efficiency and accuracy, the direct load flow approach is developed for the load flow analysis in a radial distribution system. The relationship between the current injections at the buses and the branch currents are represented as Bus Injection to Branch Current (BIBC) matrix. The relationship between the branch currents and the bus voltages are given as the Branch Current to Bus Voltage (BCBV) matrix. The two matrices are combined to form a direct approach for solving load flow problem [10]. The load flow helps to find the power loss and voltage in the distribution system. The voltage at bus 'i+1' is given by

$$V_{i+1} = V_i - J_i * (R_i + jX)_i \quad (1)$$

The branch current at each line can be specified as follows:

$$J = [BIBC]*[I] \quad (2)$$

$$\mathrm{I}_i = \left(\frac{P_i + jQ_i)}{V_i^K} \right)^* \quad (3)$$

Where P_i and Q_i are the real and reactive power through bus 'i'. The real and reactive power losses between buses 'i' and 'i+1' is calculated by using the following equation:

$$P_{Loss}(i, i+1) = R_i * \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) \quad (4)$$

$$Q_{Loss}(i, i+1) = X_i * \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) \quad (5)$$

Power loss is directly proportional to the square of the reactive power on the bus. The total real power losses can be computed as follows:

$$P_{T,Loss} = \sum_{i=1}^{n} P_{Loss}(i, i+1) \quad (6)$$

The D-STATCOM is generally used for absorbing or injecting the reactive power in the distribution system. It helps to improve the power factor in the system. The power factor at each bus can be represented as

$$P.F = \frac{P_i}{\sqrt{\left(P_i^2 + Q_i^2\right)}} \quad (7)$$

2.2 Objective Function

The main objectives of the proposed approach is to minimize the real power losses, maximizes the voltage profile and power factor using D-STATCOM installation, which is given by,

$$\mathrm{F(x)} = Min.\left(\frac{P_{T,Loss}^{DSTATCOM}}{P_{T,Loss}} \right) + \max.\left(\frac{n}{\sum_{i=1}^{n} V_i(x)} \right) + \max.\left(P.F\right) \quad (8)$$

Subjected to the following constraints,

$$V_i^{\min} \le V_i \le V_i^{\max} \quad (9)$$

$$\sum_{i=i}^{\mathrm{n}} \mathrm{P}_{\mathrm{i}}^{\mathrm{DSTATCOM}} \le \sum_{i=i}^{\mathrm{n}} \mathrm{P}_{\mathrm{i}} + \mathrm{P}_{\mathrm{i,Loss}} \quad (10)$$

3. D-STATCOM

D-STATCOM is an ac electrical regulating FACTS device used in the distribution networks which consist of a DC voltage source, self commutated converter and a step up transformer that can either absorb or deliver the reactive power in the distribution network. D-STATCOM is connected near the load at the distribution system. The D-STATCOM controller is help to drive the inverter hence the phase angle between the line voltage and the inverter voltage is dynamically adjusted, so that the D-STATCOM generates or absorbs the desired VAR at the point of connection [11]. The phase of the output voltage (V_i) of the thyristor based converter is controlled in the same way as the distribution system voltage (V_s). Hence, it is able to control its bus voltage and the power factor.

If the output voltage of D-STATCOM V_i is equal to system voltage V_s, exchange of reactive power between D-STATCOM and grid will be zero and D-STATCOM operates in standby mode. If the output voltage of the D-STATCOM Vi is greater than system voltage V_s, the current flows through the transfer reactance from D-STATCOM to the system causing D-STATCOM to generate a capacitive reactive power. Finally, if the output voltage V_i is lower than system voltage V_s, the current flows from the system to the D-STATCOM causing D-STATCOM to absorb an inductive reactive power [6]. Fig. 1 shows the installation of D-STATCOM at bus 'i+1'.

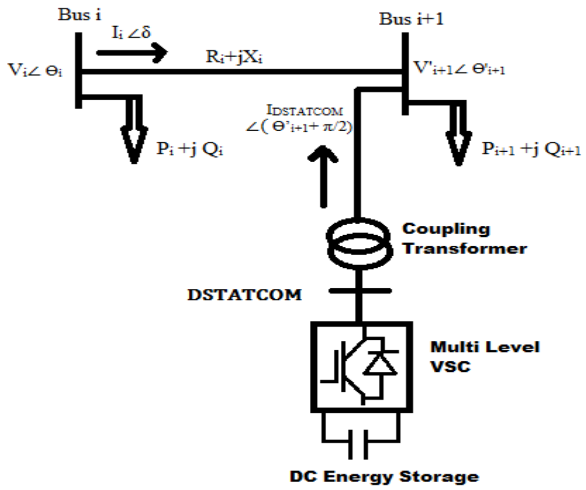

Fig.1 Single line diagram of 2 buses with D-STATCOM

Let us consider a two bus system where the buses are 'i' and 'i+1' and the resistance and reactance between buses are R_i and X_i. The current flowing through the line is $I_i \angle\delta$. The voltages at bus 'i' and 'i+1' are the V_i and V_{i+1} respectively. The voltage on the bus 'i+1' after the installation of D-STATCOM be V'_{i+1}.

At the bus 'i+1', the injected voltage is represented by [6],

$$V_{i+1}^{'} = V_{i+1}^{'} \angle(\theta^{'}_{i+1}) \quad (11)$$

The current injection at bus 'i+1' is denoted as,

$$I^{DSTATCOM} = I^{DSTATCOM} \angle(\theta^{'}_{i+1} + \pi / 2) \quad (12)$$

The amount of reactive power is injected at 'i+1' bus,

$$Q^{DSTATCOM} = (\frac{V_i^2}{X_i}) - (\frac{V_i V_j}{X_i})\cos\delta \tag{13}$$

4. Sensitivity Approaches

Power distribution systems are becoming large and complex, leading to higher system losses and poor voltage regulation. D-STATCOM installation in the distribution system would be one of the optimal solutions. The weak bus is identified through various indices for the D-STATCOM placement and are as follows,

4.1 Loss Sensitivity Factor

The loss sensitivity factor prefers the order in which buses are selected for compensation and the normalised voltage decides whether the buses need reactive power compensation or not. The real power loss and the corresponding loss sensitivity factor of each bus are calculated. The highest priority buses are identified by arranging the index values in descending order [12]. Considering a radial distribution line with a load and the impedance of r + jx and P[i] + Q[i] respectively connected between 'i' and 'j'.

$$\mathrm{P_{Loss}}[i] = \frac{\left(P^2[i] + Q^2[i]\right) * r(k)}{V[i]^2} \tag{14}$$

$$\mathrm{Q_{Loss}}[i] = \frac{\left(P^2[i] + Q^2[i]\right) * x(k)}{V[i]^2} \tag{15}$$

Where P[i] and Q[i] are the total effective active and reactive power supplied beyond the bus 'i'. The parameters r(k) and x(k) are the resistance and reactance of the branch 'k' respectively. Now the loss sensitivity factor is evaluated by the following equation.

$$\frac{\partial P_{Loss}[i]}{\partial Q[i]} = \frac{\left(2 * Q[i]\right) * r(k)}{V[i]^2} \tag{16}$$

After calculating loss sensitivity factor at each bus, the normalized voltage magnitudes are calculated for all the buses can be determined as [13],

$$Norm(i) = \frac{V(i)}{0.95} \tag{17}$$

Finally, those buses having higher loss sensitivity factor values and normalized voltage below 1.01 are selected as candidate bus. The weakest bus is the one which has maximum loss sensitivity factor value. Loss sensitivity factor is the rate of change of real power loss with respect to effective reactive power.

4.2 Voltage Sensitivity Index

The voltage sensitivity index is used to find the distance between the current operating point to the marginally stable point of operation in the power system. Here, the weakest bus has to be found using voltage sensitivity index. This index is the numerical solution to find how close the system is to collapse or to initiate the remedial actions to prevent the voltage collapse in the system. The voltage collapse starts at the most sensitive bus and then spread out to other sensitive buses. The voltage sensitivity index of all the buses of the distribution network is computed at unity power factor. Considering the 'i^{th}' bus in the radial distribution system, the voltage sensitivity index can be calculated as follows [14],

$$VSI(i) = \sqrt{\frac{\sum_{i=1}^{n}(1 - V_i)^2}{n}} \tag{18}$$

Where 'n' is the total number of buses. The values of the voltage sensitivity index of all the buses are calculated and are arranged in ascending order. The bus with minimum value of the voltage sensitivity index is identified as the most sensitive bus. In comparison, the most sensitive bus will be the bus with least value of voltage stability index and the corresponding locations of D-STATCOM allocation have been identified.

4.3 Index Vector Method

The index vector method is formulated by running the distribution load flow and calculating reactive component of current in the branches and reactive power load concentration at each bus of the considered test system. The index vector method value of each bus is calculated with respect to reactive load of each bus. Based on the index values obtained at each bus a sequence of weak buses to be compensated are identified and on sorting these index values in descending order the priority of the weaker buses is determined [15]. The index vector for bus n is calculated as,

$$Index(i) = \frac{1}{V_i^2} + \frac{I_q(k)}{I_P(K)} + \frac{Q_{eff}(i)}{Total(Q)} \tag{19}$$

Where V_i is the voltage of the i^{th} bus, I_p (k) and I_q (k) are the real and a reactive component of current in the k^{th} branch, Q_{eff} (i) is the effective reactive power demand at the i^{th} bus and total (Q) is the total reactive power demand of the given distribution system. After calculating index vector's values at all the buses, the magnitudes of normalized voltage are determined for all the buses by using equation (17). Then, those buses having higher index vector and normalized voltage below1.01 are selected as candidate bus [16].

4.4 Power Loss Index

The power loss index is used to determine the candidate buses for D-STATCOM installation. First, the load flow is performed for test systems and the total real power losses of the system are derived. And also, the reactive power injection is made in all the phases except at source bus and further new real power losses are computed. Then the reduction in real power loss is calculated and its associated real power loss index is calculated [17].

$$PLI(i) = \frac{Lr(i) - Lr(\min)}{Lr(\max) - Lr(\min)} \quad \text{n= 1, 2, ---n bus} \tag{20}$$

Where Lr (i) is the loss reduction in bus [i], Lr (min) and Lr (max) are the minimum and maximum power loss reduction. Power loss reduction is calculated by compensating the reactive power flow into the bus, considering one bus at a time. These values are normalized based on a scale of 1 to 0, with one being the highest loss and zero being the lowest loss. The power loss index of all the buses are arranged in descending order and the bus with the highest value of the power loss index is identified to be the weakest bus with maximum power loss. The weaker buses with considerable effect on the active power loss reduction are best candidate buses for the D-STATCOM placement that gives the highest net profit satisfying the system constraints.

4.5 Voltage Stability Index

The voltage stability indicates the closeness to voltage collapse for a given loading condition. Voltage stability is the consequence on the ability of the power system to maintain or to restore the equilibrium between load demand and the load supply. A system becomes unstable if a bus in the system experiences a decrease in voltage magnitude once the reactive power injection increases. Also, the voltage stability can be considered as load stability because the driving force for voltage instability is increase in load.

The buses with the minimum stability index are called weak buses and should be reinforced by injecting reactive power through the optimal allocation of D-STATCOM. The concept of voltage stability index has been introduced that indicates the strength of the system based on the voltage level maintained on it [18]. The voltage stability index can be denoted as,

$$VSI_{(m)} = \left|V_{(m-1)}\right|^4 - 4*\left\{P_{eff\,(m)} * X1_{(k)} - Q_{eff\,(m)} * R1_{(k)}\right\}^2 - 4*\{P_{eff\,(m)} * R1_{(k)} + Q_{eff\,(m)} * X1_{(k)}\}*\left|V_{(m-1)}\right|^2 \quad (21)$$

Where $R1_{(K)}$ and $X1_{(k)}$ are the resistance and reactance of k^{th} branch, $V_{(m-1)}$ is the voltage magnitude at bus (m-1), $P_{eff(m)}$ and $Q_{eff(m)}$ are the real and reactive power demand fed through bus m. After calculation of the voltage stability index at all buses, the overall voltage stability of the system can be determined. The voltage stability index of all the buses are arranged in ascending order in order to find the list of weak buses. The bus which has the lowest voltage stability index is the weakest among all buses. The weakest bus is identified for further D-STATCOM allocation.

5. Simulation and Results

The proposed approach is tested on a 69-bus and a real time 31-bus test system and encouraged results were obtained. For these test systems, the substation voltage is considered as 1 p.u. In this work, five different sensitivity approaches are considered to identify the location of D-STATCOM and size of a D-STATCOM is fixed by 500 kVAr. There are three different load levels (minimum, nominal and heavy load) are discussed in the simulation to analyse the performance of the proposed methods. The results of the proposed methodology are implemented using MATLAB (R2010a) with the system configuration of a core 2 deo, 3 GB RAM, 2-GHz. Before compensation, the results of a 69-bus and a real time 31-bus system are debited in the Table 1.

Table 1 Test systems results before compensation

Parameters	69-bus system	Real time 31-bus system
Base Voltage (KV)	12.66	11
Real Power (kW)	3802.19	9790
Reactive Power (kVAr)	2694.06	4744
Base Loss (kW)	225	775.99
Minimum bus voltage (p.u)	0.9092	0.9041

MATLAB simulink environment is used for D-STATCOM modeling. In modeling, the D-STATCOM is in voltage control mode and its reference voltage is set to V_{ref} =1.0 p.u. When the D-STATCOM operating point changes from fully capacitive (+500kVAr) to fully inductive (-500kVAr) the D-STATCOM voltage various between 1-0.05=0.95 and 1+0.05=1.05. The parameters of the D-STATCOM setting are represented in Table 2.

Table 2 Parameters of D-STATCOM setting

Parameters	setting
Source	11 kV, 50 Hz, 3-phase
Inverter	IGBT, 6-pulse, 3-arm
PI Controller	K_p=0.6, K_i=50, sample time = $10*10^{-6}$ s C_{dc}=10000uF
Transformer	3-winding, 50 Hz

5.1 Weak bus identification using the loss sensitivity factor

The optimal D-STATCOM placement using the loss sensitivity factor method is applied on test systems. The buses with higher loss are identified as the weak buses in Fig. 2.

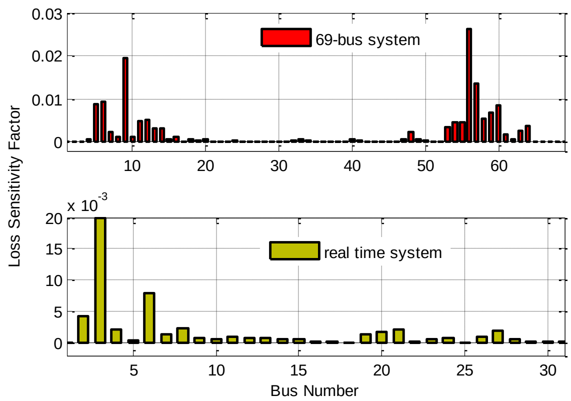

Fig. 2. Loss sensitivity factor for the test systems

Once the loss sensitivity factor values are calculated, the normalized voltage profile has been determined for these test systems by dividing base case voltage magnitude by a constant 0.95 as shown in Fig. 3. The normalized voltage decides whether the buses need reactive compensation or not.

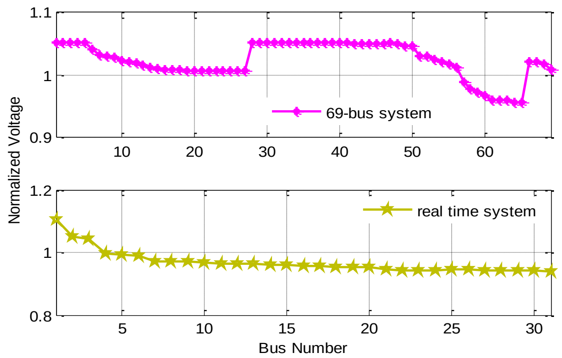

Fig. 3. Normalized voltage for the test systems

Finally top five buses having higher loss sensitivity factor values and normalized voltage below 1.01 are selected as candidate bus in Table 3.

Table 3 Candidate buses and their index values

	69-bus system		Real time system	
No.	Bus No.	Index value	Bus No.	Index value
1.	57	0.9896	6	0.9897
2.	60	0.9681	8	0.9702
3.	59	0.9734	21	0.9471
4.	58	0.9779	4	0.9860
5.	64	0.9576	27	0.9437

It is observed from Table 3, the weakest bus in a 69-bus system and a real time 31-bus system are ‘57’and ‘6’ respectively for D-STATCOM placement using loss sensitivity factor. The highest values of loss sensitivity factor indicate that the buses suffer from maximum power loss.

5.2 Weak bus identification using the voltage sensitivity index

Considering the test systems, the identification of weak buses for placement of D-STATCOM is achieved using the voltage sensitivity index. The voltage sensitivity index values at each bus for the test systems are plotted in Fig. 4. The high sensitivity buses are identified as the weakest buses from the graph.

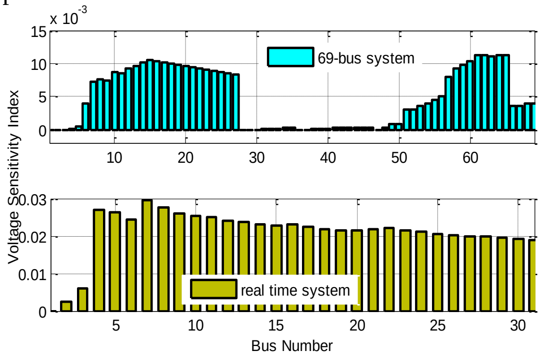

Fig. 4. Voltage sensitivity index for the test systems

5.3 Weak bus identification using the index vector method

The candidate bus for the optimal placement of D-STATCOM is implemented through which the sequence of buses requiring the compensation is obtained from the graph in Fig.5.

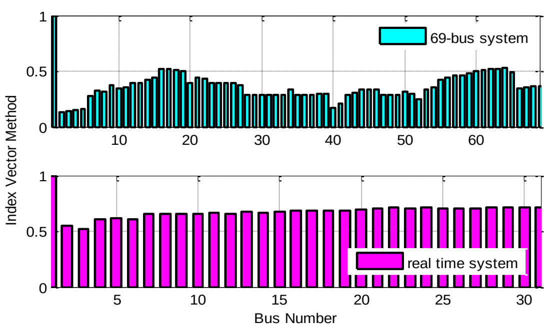

Fig. 5. Index vector method for the test systems

The index vector method values are further examined with the values of the normalized voltage profile for the test systems. The normalized voltage profile has been determined for the system, based on higher index vector values and normalized voltage values at the buses are less than 1.01. These buses are considered as candidate buses for D-STATCOM placements and it is tabulated in Table 4.

Table 4 Candidate buses and their index values

	69-bus system		Real time system	
No.	Bus No.	Index value	Bus No.	Index value
1.	61	0.9576	28	0.9511
2.	63	0.9596	16	0.9541
3.	17	1.0085	15	0.9556
4.	16	1.0094	9	0.9747
5.	64	0.9604	8	0.9814

The highest values of index vector method indicate the candidate buses for compensation. It is observed from that the weakest buses for a 69-bus system and a real time 31-bus system are “61 and 28” respectively.

5.4 Weak bus identification using the power loss index

The Power loss index for identification of candidate buses for the optimal placement of D-STATCOM is depicted along with the bus number as shown in Fig. 6.

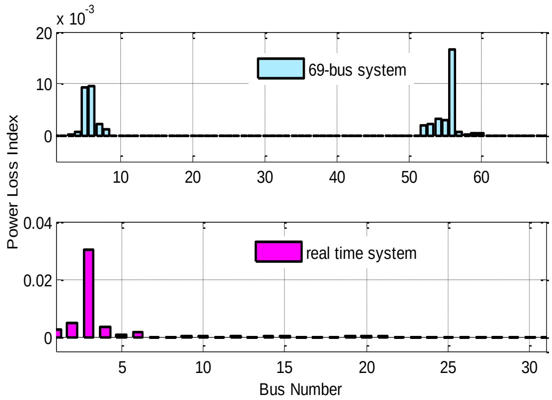

Fig. 6. Power loss Index for the test systems

5.5 Weak bus identification using the voltage stability index

The lowest values of voltage stability index the buses that suffer from the stability problem. These buses should provide optimum solution for D-STATCOM placement according to the index. The voltage stability index for the test systems are shown in Fig. 7.

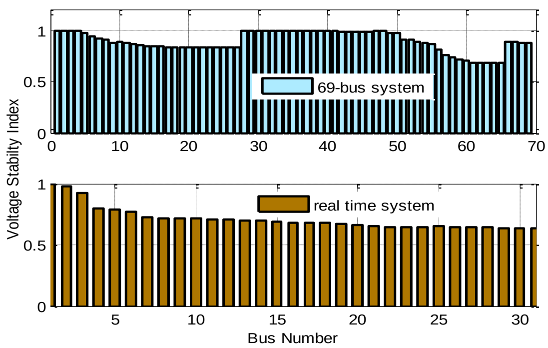

Fig. 7. Voltage stability index for the test systems

Table 5 Results of test systems

	Method	Item	Load level		
			Minimum	**Nominal**	**Heavy**
69-bus system	**Before compensation**	$P_{T,Loss}$ (kW)	51.61	225	433.31
		V_{min} (p.u)	0.9567	0.9092	0.8735
		Power Factor	0.9409	0.8115	0.6794
	Loss Sensitivity Factor	Dstatcom placed at Bus No.	57	57	57
		$P_{T,Loss}$ (kW)	41.15	173.00	352.93
		% Loss Reduced	20.2	23.1	18.7
		V_{min} (p.u)	0.9617	0.9147	0.8735
		Power Factor	0.9787	0.8688	0.7323
	Voltage sensitivity index	Dstatcom placed at Bus No.	63	63	63
		$P_{T,Loss}$ (kW)	39.57	180.30	361.33
		% Loss Reduced	23.3	19.8	16.6
		V_{min} (p.u)	0.9709	0.9194	0.8837
		Power Factor	0.9854	0.8786	0.7452
	Index Vector Method	Dstatcom placed at Bus No.	61	61	61
		$P_{T,Loss}$ (kW)	38.04	179.42	363.31
		% Loss Reduced	26.3	20.2	16.1
		V_{min} (p.u)	0.9692	0.9232	0.8837
		Power Factor	0.9602	0.8394	0.7056
	Power Loss Index	Dstatcom placed at Bus No.	56	56	56
		$P_{T,Loss}$ (kW)	43.94	189.86	381.6
		% Loss Reduced	17.4	15.7	12
		V_{min} (p.u)	0.9615	0.9204	0.8769
		Power Factor	0.9602	0.8394	0.7056
	Voltage Stability Index	Dstatcom placed at Bus No.	64	64	64
		$P_{T,Loss}$ (kW)	37.54	165.78	325.84
		% Loss Reduced	**27.3**	**26.3**	**24.8**
		V_{min} (p.u)	**0.9658**	**0.9375**	**0.9019**
		Power Factor	**0.9662**	**0.8958**	**0.7119**
Real time 31-bus system	**Before compensation**	$P_{T,Loss}$ (kW)	174.44	775.4	1988.5
		V_{min} (p.u)	0.9500	0.9041	0.8297
		Power Factor	0.9659	0.8984	0.8064
	Loss Sensitivity Factor	Dstatcom placed at Bus No.	6	6	6
		$P_{T,Loss}$ (kW)	158.22	731.25	1899.6
		% Loss Reduced	9.3	5.69	4.5
		V_{min} (p.u)	0.9542	0.9088	0.8350
		Power Factor	0.9956	0.9494	0.8714
	Voltage sensitivity index	Dstatcom placed at Bus No.	8	8	8
		$P_{T,Loss}$ (kW)	162.58	745.15	1927.9
		% Loss Reduced	6.8	3.9	3.0
		V_{min} (p.u)	0.9528	0.9073	0.8330
		Power Factor	0.9919	0.9221	0.8339
	Index Vector Method	Dstatcom placed at Bus No.	28	28	28
		$P_{T,Loss}$ (kW)	159.68	735.42	1906.6
		% Loss Reduced	8.4	5.15	4.1
		V_{min} (p.u)	0.9559	0.9106	0.8370
		Power Factor	0.9965	0.9505	0.8688
	Power Loss Index	Dstatcom placed at Bus No.	23	23	23
		$P_{T,Loss}$ (kW)	159.75	735.30	1834.2
		% Loss Reduced	8.4	5.2	7.8
		V_{min} (p.u)	0.9585	0.9088	0.8405
		Power Factor	0.9993	0.9795	0.9129
	Voltage Stability Index	Dstatcom placed at Bus No.	30	30	30
		$P_{T,Loss}$ (kW)	150.72	702.40	1835.3
		% Loss Reduced	**13.5**	**9.4**	**7.7**
		V_{min} (p.u)	**0.9611**	**0.9163**	**0.8435**
		Power Factor	**0.9949**	**0.9978**	**0.9246**

5.6 Comparison of results after D-STATCOM placement

To verify the success of the proposed methods, an optimal solution is made from three different types of load levels. Table 5 shows the real power loss, minimum voltage profile, power factor and optimal location of D-STATCOM using different sensitivity techniques with fixed size of 500 kVAr D-STATCOM. For 69-bus system, it is pointed out from Table 4 that the optimal power loss reduction is achieved by D-STATCOM placement at bus number ‘64’ using the voltage sensitivity index. At minimum, nominal and heavy load, the power loss before compensation is reduced by 27.3 %, 26.3 % and 24.8 % after compensation with 500 kVar D-STATCOM placement, whereas the minimum voltage profile is improved from 0.9567, 0.9092 and 0.8735 p.u to 0.9658, 0.9375 and 0.9019 p.u. In addition, the power factor enhances from 0.9409, 0.8115 and 0.6794 to 0.9662, 0.8958 and 0.7119. For 69-bus system at nominal load, after compensation the voltage profile at each bus and the real power loss at each branch are shown in Fig. 8 and 9 respectively.

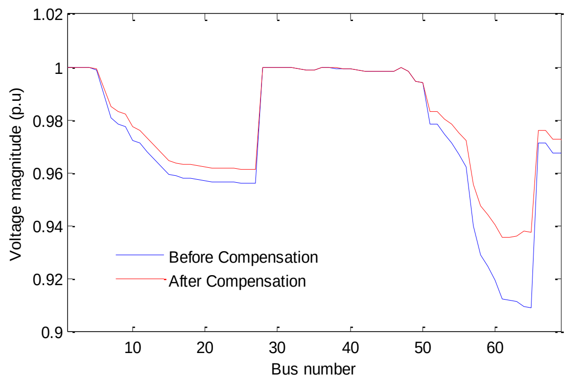

Fig. 8. Voltage profile at each bus for a 69-bus system

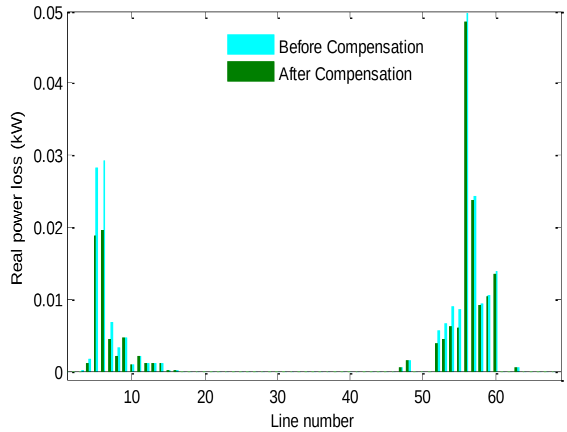

Fig. 9. Real power loss at each branch for a 69-bus system

Similar to 69-bus system, the real time 31-bus system is also simulated using all sensitivity methods at different load levels and its results are presented in Table 5. The optimal location of D-STATCOM placement at bus number “30” is identified using the voltage sensitivity index. In this regard, the total power loss (kW) at minimum, nominal and heavy load is reduced from 174.44, 775.4 and 1988.5 to 150.72, 702.40 and 1835.3 respectively. And also, the minimum voltage profile is enhanced from 0.9500, 0.9041and 0.8297 p.u to 0.9611, 0.9163 and 0.8435 p.u. Moreover, the power factor before compensation is increased by 30.7 %, 54.8 % and 71.8 % after compensation using the voltage sensitivity index. Based on the results obtained with different sensitivity methods, the comparison of results corresponding to optimum solutions obtained for installation of D-STATCOM have been provided for both 69-bus and real time 31-bus test systems. This has been proposed to compare the pros and cons of sensitivity based approaches for optimal D-STATCOM location.

6. Conclusion

In this paper, the weak buses are identified for D-STATCOM placement using various sensitivity methods. The benefit of the proposed approach is proved by using two test systems at three different load levels viz., minimum, nominal, heavy. The result shows that the D-STATCOM installation methods are more effective in reducing power loss, improving the voltage profile and power factor. For the test systems, the computational results proved that performance of the voltage stability index is better than other sensitivity approach in terms of quality solutions. The identified weak buses are “64 and 30” for a 69-bus and a real time 31-bus test system using the voltage stability index. In this regard, at nominal load the loss reductions are attained as 26.3 % and 9.4 %. Besides, the minimum voltage profile is enhanced from 0.9092 p.u and 0.9041 p.u to 0.9375 p.u and 0.9163 p.u for 69-bus and real time 31-bus system respectively. The power factor is also boosted by 9.4 % and 54.8 % for the test systems. Thus, these test results are effective in finding the weak buses in the distribution system and the necessary D-STATCOM placement.

Acknowledgments

This work was supported by Technical Education Quality Improvement Programme II (TEQIP II).

References

[1] Singh, B., Adya, A., Mittal, A.P., Gupta, J.R.P.: *Power Quality Enhancement with D-STATCOM for Small Isolated Alternator feeding Distribution System.* In: International Conference on Power Electronics and Drives Systems, Vol. 2, 2005, pp. 274 – 279

[2] Tavakoli Binaa, M., Eskandari M.D., M, Panahlou.: *Design and installation of a ±250 kVAr D-STATCOM for a distribution substation*. In: Electric Power Systems Research, Vol. 73, 2005, pp. 383–39

[3] Shivkumar, I., Arindam, G., Avinash, J.: *Inverter topologies for D-STATCOM applications—a simulation stud.* In: Electric Power Systems Research, Vol. 75, 2005, pp. 161–170

[4] Jazebi, S., Hosseinian, S.H., Vahidi, B.: *D-STATCOM allocation in distribution networks considering reconfiguration using differential evolution algorithm*. In: Energy Conversion and Management, Vol. 52, 2011, pp. 2777–2783

[5] Tejas, Z., Bhalja, B.R., Naimish, Z.: *Load compensation using D-STATCOM in three-phase, three-wire distribution system under various source voltage and delta connected load conditions.* In: Electrical Power and Energy Systems, Vol. 41, 2012, pp. 34–43

[6] Seyed, A.T., Seyed, A.A.: *Optimal location and sizing of D-STATCOM in distribution systems by immune algorithm.* In: Electrical Power and Energy Systems, Vol. 60, 2014, pp. 34–44

[7] Yuvaraja, T., Devabalaji, K.R., Ravi, K.: *Optimal placement and sizing of D-STATCOM using Harmony Search algorithm*, In: Energy Procedia. Vol. 79, 2015, pp. 759 – 765

[8] Devi . S., Geethanjali, M.: *Optimal location and sizing determination of Distributed Generation and D-STATCOM using Particle Swarm Optimization algorithm*. In: Electrical Power and Energy Systems, Vol. 62, 2014, pp. 562–570

[9] Devabalaji, K.R., Ravi, K.: *Optimal size and siting of multiple DG and D-STATCOM in radial distribution system using Bacterial Foraging Optimization Algorithm*. In: Ain Shams Engineering Journal, Vol.7, 2016, pp. 959–971

[10] Mohamed Imran, A., Kowsalya, M and Kothari, D.P.: *A novel integration technique for optimal network reconfiguration and distributed generation placement in power distribution networks*. In: Int. J Electr. Power Energy Sys., Vol 63, 2014, pp. 461–472

[11] Rajanna, B.V., Rami Reddy, CH., Harinadha Reddy, K.: *Design, Modeling & Simulation of DSTATCOM for Distribution Lines for Power Quality Improvement*. In: Journal of Electrical Engineering., pp: 1-6

[12] Usha Reddy, V., Gowri Manohar, T., Dinakara Prasad Reddy, P.: *Capacitor placement for loss reduction in radial distribution networks: a two stage approach*. In: Journal of Electrical Engineering., pp: 1-6

[13] Kamisett, P., Maheswarapu, S.: *Optimal capacitor placement in radial distribution systems using differential evolution*. In: Journal of Electrical Engineering., pp: 1-6

[14] Murthy, V.V.S.N., Kumar, A.: *Comparison of optimal DG allocation methods in radial distribution systems based on sensitivity approaches*. In: Electrical Power and Energy Systems, Vol. 53, 2013, pp. 450–467

[15] Murty, V.V.S.N., Kumar, A.: *Comparison of optimal capacitor placement methods in radial distribution system with load growth and ZIP load model.* In: Front. Energy, Vol. 7, No. 2, 2013, pp. 197–213

[16] Dixit, M., Kundu, P., Hitesh R, Jariwala.: *Optimal placement and sizing of DG in distribution system using artificial bee colony algorithm*. In: IEEE 6th International Conference on Power Systems (ICPS), 2016, pp. 1-6

[17] Abdelaziz, A.Y., Ali, E.S., Abd Elazim, S.M.: *Optimal sizing and locations of capacitors in radial distribution systems via flower pollination optimization algorithm and power loss index*. In: Engineering Science and Technology, an International Journal, Vol. 19, 2016, pp. 610–618

[18] Poornazaryan, B., Karimyan P., Gharehpetian, G.B., Abedi, M.: *Optimal allocation and sizing of DG units considering voltage losses and load variations.* In: Int. J Electr. Power Energy Sys., Vol. 79, 2016, pp.42–52