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On the effect of optimal size and location of D-STATCOM in loss reduction of distribution system

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ABSTRACT

Reducing system loss and improving voltage profile and stability are proposed in this study using a D-STATCOM in distribution systems. Three indices have been considered in the problem formulations to achieve the aforementioned objectives. To implement the proposed method, a D-STATCOM is modeled in power flow calculations to compensate the reactive power and improve the system performance. The Particle Swarm Algorithm (PSO) and Backward-Forward power flow method are used to solve this optimization problem. Two IEEE standard systems, IEEE 33-bus and 69-bus systems, have been selected to implement the proposed method. The simulation results demonstrate that using D-STATCOM in the distribution systems can effectively reduce system loss and improve system voltage profile and stability.

1. Introduction

By increasing the cities' population, the distribution systems have been extended to supply the loads. This extension have results in using more and longer lines in the systems. When the system becomes large, more power is required to be flowed from the lines to supply the demands. Considering the lines' resistance, flowing current through the lines causes loss in the system. Hence, having a large system is accompanied with more loss. On the other hand, when a system is extended, the voltage drops when moving from the main bus to the ending ones. In addition, the voltage stability margin of the system is reduced in this condition. Hence, to reduce the system loss and maintain the voltage of buses and the stability margin in an acceptable range, some solutions must be considered. In doing so, many research has been conducted in literature. Some of these works have been assigned to distributed generation studies. Optimal placement and sizing of DG units is an attractive topic in distribution system studies. Since the installation of DGs in distribution systems may have some important impacts on the system, it is necessary to carefully study about the best location and size of these resources (Viral and Khatod, 2012). These problems have been solved by researchers to achieve different objectives using various methods including conventional algorithms (Tan et al., 2013) considering the analytical (Gözel and Hocaoglu, 2009) and numerical (Al Abri et al., 2013) methods, and evolutionary methods such as bacterial forging optimization (Devi and Geethanjali, 2014), particle warm optimization (Mistry and Roy, 2014), imperialist competition algorithm (ICA) (Soroudi and Ehsan, 2012) and genetic algorithm (GA). The genetic algorithm has been considered as an optimizer in Singh et al. (2007) and Singh et al. (2009) to find the optimal location and size of single and multiple DG units in distribution system.

Optimal allocation and sizing of DG units has been studied in Poornazaryan et al. (2016), to improve the system losses and voltage stability considering load variations. Improving voltage stability of the distribution system has been considered in Mohandas et al. (2015) by optimal location and sizing of real power DG units using a chaotic Artificial Bee Colony algorithm. In this study, the constant load model and voltage dependent load models including industrial, residential and commercial have been considered.

In Kefayat et al. (2015), a hybrid algorithm, composed of ant colony optimizer (ACO) and artificial bee colony optimizer (ABC), has been used for probabilistic optimal placement and sizing of distributed energy resources. Gas turbines, fuel cell and wind turbine have been considered to reduce power losses, total emission and energy cost. The GA and PSO algorithms have been implemented in Georgilakis and Hatziargyriou (2013) for optimal placement of DGs considering voltage stability and short circuit level in the distribution system. Devi and Geethanjali (2014) proposed a novel method for optimal placement of a photovoltaic (PV) system for loss reduction and voltage profile improvement in distribution systems. In this study, the PV system is considered as a source of active and reactive power considering hourly variation. Multi-objective placement of multiple distributed resources in distribution system has been studied using imperialist competitive algorithm in Ebrahimpourain and Kazemi (2014). Loss reduction and reduction in power purchased from the electricity market, loss reduction in peak load hours and therefore reduction in upgrade investment deferral as well as improving voltage profile are considered as the objectives in this study.

In addition to DGs studies, some other techniques have been used in literature to improve the system indices including shunt capacitor, D-STATCOM, and simultaneous capacitor and DG placement. Optimal size and location of shunt capacitors has been determined in Gnanasekaran et al. (2016) to minimize the costs associated to the energy loss and reactive compensation of distribution system using a new Shark Smell Optimization algorithm. In Raju et al. (2012), a direct search algorithm has

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been proposed to find optimal locations and optimal sizes of fixed and switched capacitors. Energy saving using D-STATCOM placement in radial distribution system has been studied in Gupta and Kumar (2015), where the problem includes voltage profile and overall energy saving objectives. In Gupta and Kumar (2016), optimal placement of D-STATCOM using sensitivity approaches in mesh distribution system with time variant load models under load growth has been analyzed. An efficient hybrid method for solving the optimal sitting and sizing problem of DG and shunt capacitor banks simultaneously, has been employed in Devi and Geethanjali (2014) using imperialist competitive algorithm and genetic algorithm. Intersect mutation differential evolution (IMDE) algorithm has been used in Khodabakhshian and Andishgar (2016) to optimally locate and determine the size of DGs and shunt capacitors in distribution system.

In the present study, a method is proposed for optimal placement and sizing of D-STATCOM in distribution system to reduce losses and improve voltage profile and stability. The method is implemented using PSO algorithm and Backward-Forward power flow method on two IEEE systems. The results show that the proposed method can improve the problem objectives appropriately. The paper is organized as follows:

In section II, the D-STATCOM model, as a shunt reactive power compensator, is presented. Problem formulation comes in section III, where the objectives and constraints of the problem are discussed. Backward-Forward algorithm is given in section IV. The implemented PSO algorithm is briefly described in section V. The paper moves on with simulation results in section VI and conclusions in section VII.

2. D-STATCOM model

One of the most practical reactive power compensator devices that is used in distribution systems is D-STATCOM (Distribution STATic COMpensator). This device is mainly used to inject the reactive power to the system. This device can also generate active power, but the small capacity of its energy storage limits the continuous active power generation. A D-STATCOM includes an energy storage (mainly a capacitor) that is connected to the system by a converter. A simple model of a D-STATCOM can be seen in Fig. 1.

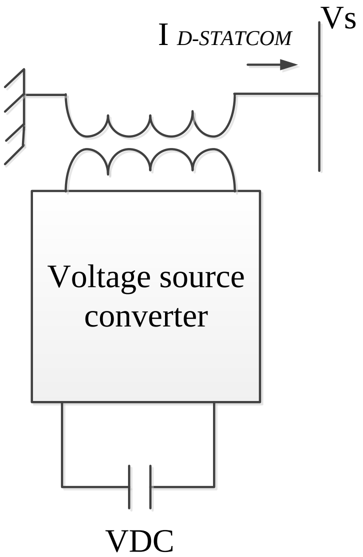

Fig. 1: D-STATCOM model.

Considering a simple two-bus system, the reactive compensation capability of a D-STATCOM can be discussed. The single line diagram (SLD) of a two-bus system is shown in Fig. 2. In this figure, the voltage of buses and the line between two buses are shown. Since the reactive power can change the voltage's angle at buses, the phasor diagram analysis can be helpful which is illustrated in Fig. 3. By analysis according to phasor diagram, Eq. 1 can be driven:

$$V_{oj}\angle\alpha_o = V_{oi}\angle\delta_o - (R + jX)I_{oL}\angle\theta_o \quad (1)$$

where, V_{oj} and V_{oi} are the voltage of bus j and bus i before D-STATCOM installation, α_o and δ_o are the angle of voltage V_{oj}, and V_{oi}, $Z=R+jX$ is the impedance of the line between bus i and bus j, I_{oL} is the current flow in the line before compensation and θ_o is the angle of current I_{oL}.

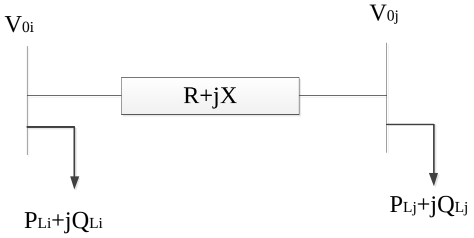

Fig. 2: Single line diagram of a two-bus system.

When, a D-STATCM is installed in a bus, bus voltages are changed, especially for the neighboring bus of D-STATCOM location. After installation of D-STATCOM is the system, the current flow through the line is varied and consequently the voltages are varied. Considering a D-STATCOM installed in bus 'j', the bus voltages are changed as follows:

$$\angle I_{D-STATCOM} = (\pi/2) + \alpha_{new}; \alpha_{new} < 0 \quad (2)$$

$$V_{jnew}\angle\alpha_{new} = V_i\angle\delta - (R + jX)I_L\angle\theta$$
$$-(R + jX)I_{D-STATCOM}\angle((\pi/2) + \alpha_{new}) \quad (3)$$

where, $I_{D-STATCOM}\angle((\pi/2) + \alpha_{new})$is the current injected by D-STATCOM, V_{newj} and V_i are the voltages of bus i and bus j after D-STATCOM installation in bus 'j',α_{new} and δ are the angles of voltage V_{newj} and V_i, I_L is the current flow in line after compensation and $\theta$is the angle of current I_L.

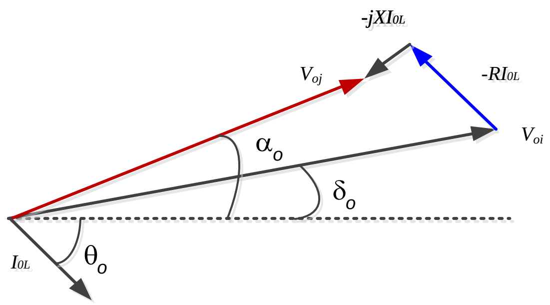

Fig. 3: Phasor diagram of a two-bus system.

The modified phasor diagram after D-STATCOM installation is shown in Fig. 4. The injected reactive power by D-STATCOM to the system can be calculated using (4):

$$jQ_{D-STATCOM} = V_{jnew}(I_{D-STATCOM})^* \quad (4)$$

where

$$V_{jnew} = V_{jnew}\angle\alpha_{new}$$
$$I_{D-STATCOM} = I_{D-STATCOM}\angle((\pi/2) + \alpha_{new}) \quad (5)$$

3. Problem formulation

Different objectives can be considered in an optimization problem. In this study, three terms are considered in objective function and the optimizer is run to optimize all terms. Loss reduction, voltage profile and voltage stability improvement are considered as the objectives of this study. Each term is formulated separately and finally the objective function includes all terms considering weighting coefficients for each one. The first term in the object function is system loss which is formulated in the following sub-section.

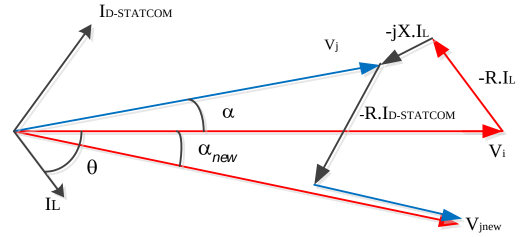

Fig. 4: Phasor diagram of a two-bus system after D-STATCOM installation.

3.1. Loss reduction

The total losses in distribution system can be calculated as follows:

$$f_1 = \sum_{i=1}^{NBr} R_i |I_i^2| \quad (6)$$

where, f_1 is the first term of objective function associated with the system losses, I_i is current of line *i*, R_i is the resistance of i^{th} line, and *NBr* is the number of system branches.

3.2. Voltage profile improvement

Since it was discussed in the previous section, D-STATCOM can compensate reactive power and improve the voltage profile. The objective function for improving voltage profile is:

$$f_2 = \sum_{i=1}^{NBus} (V_{nom} - V_i)^2 \quad (7)$$

where, f_2 is the objective function for voltage profile improvement, V_{nom} is the nominal voltage of the system which is equal to 1 p.u, V_i is the voltage of the i^{th} bus, and *NBus* is the number of system buses.

3.3. Voltage stability improvement

One of an important issues in the system is voltage stability. In fact, voltage stability is the ability of the system to maintain the voltages of all buses in an acceptable range. In weak systems, the reactive power demanded by loads cannot be sufficiently satisfied and this problem may result in system instability and voltage collapse. Several indices have been introduced in literature as voltage stability measures. Some of them are associated with buses and the others are related to the lines. In this paper, we have used a bus-based voltage stability index proposed in Chakravorty and Das (2001).

This index is calculated for all buses and its value can vary between zero and unity. Zero associated to voltage instability and unity is the best condition from the viewpoint of voltage stability. For evaluation, this index is calculated in all buses and the bus with the lowest value is the weakest and most appropriate bus for installing the D-STATCOM. Considering a two-bus system, shown in Fig. 5, the Voltage stability index (VSI) is given in (8) as follows:

$$VSI(n_2) = |V_{mi}|^4 - 4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}]|V_{mi}|^2 \\ -4[P_{ni}(ni)R_{ni} + Q_{ni}(ni)X_{ni}]^2 \quad (8)$$

where, *VSI* (n_2) is the voltage stability index at bus n_2, *mi* and *ni* are the sending and receiving bus number, P_{ni} and Q_{ni} are active and reactive power demands at bus *ni*, respectively, V_{mi} is the voltage of the sending bus, R_{ni}, X_{ni} are the resistance and reactance of branch *ni.*

Since the bus with the smallest value of *VSI* is the weakest bus, it determines the stability margin of the system. Hence its *VSI* is considered in the objective function.

$$f_3 = \min(VSI_i); i = 1, \dots, Nb \quad (9)$$

Considering the aforementioned three objectives, the final objective function of this study is as follows:

$$\min\{f\} = w_1 \times f_1 + w_2 \times f_2 + w_3 \times \frac{1}{f_3} \quad (10)$$

where, w_1, w_2, w_3 are weighting coefficients that are determined considering the importance of the three objectives. The summation of these weighing coefficient must be equal to 1.

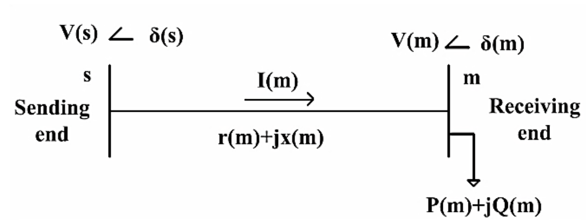

Fig. 5: Two-bus system for VSI analysis.

3.4. Constraints

The reactive power injected by D-STATCOM to the system is limited by a lower and upper bounds as given in following:

$$Q_{\min} \leq Q_{D-STATCOM} \leq Q_{\max} \quad (11)$$

The system voltage in all buses should be in an acceptable range:

$$V_{\min} \leq V_i \leq V_{\max} \quad (12)$$

V_i is the voltage of i^{th} bus and *i* varies from 1 to the number of system buses.

The power flow through the lines is limited by the thermal capacity of lines:

$$S_{ij} \leq S_{ij\max} \quad (13)$$

where, S_{ijmax} is the maximum capacity of the line between bus *i* and bus *j*.

4. Backward-forward power flow method

Considering high R/X ratio in distribution systems, power flow methods such as Newton-Raphson and fast decoupled may not converge if they used for power flow calculations in distribution systems. Due to this issue, a power flow method which is capable of converging fast is required in distribution system studies. The Backward-Forward power flow method is one of these methods consisting mainly of two, backward and forward, steps and it can converge fast. When the algorithm is run, these steps are executed in a loop until the convergence criteria is satisfied (Nanda et al., 2000; Shirmohammadi et al., 1988). These steps are briefly explained in following.

In the first step, the distribution system should be layered considering the branches between one bus and the next buses. When the layering is completed, the branches are numbered according to the layering that was carried out in the first step. After determining the numbering, the two main steps are run as follows.

4.1. Backward sweep

The power flow is calculated in the backward sweep step using the following formula. This calculation is carried out by moving from the ending buses to the main bus (slack).

$$S_n = S_i + \sum_{m \in M} S_m + Loss_n \quad (14)$$

where, S_n is the power flowing through the nth branch, i is the last bus of the n^{th} branch, S_i is the power of the load connected to the i^{th} node, M is sum of the branches which are connected to the nth branch in ith node, S_m is Power of the M^{th} branch and $Loss_n$ is N^{th} branch loss (which is considered zero in the first iteration).

4.2. Forward sweep

In this step, by moving from branches which connected to the slack bus to the ending branches, the branch current in sending bus of the n^{th} branch (j) and the voltage in the receiving bus of n^{th} branch (i) is calculated using Eqs. 15 and 16. Calculation of branches losses can be done by using Eq. 17.

$$J_n = \left(\frac{S_n}{V^j}\right)^* \quad (15)$$

$$V^i = V^j - Z_n \times J_n \quad (16)$$

$$Loss_n = \left(V^j - V^i\right) \times J_n^* \quad (17)$$

4.3. Voltage deviation calculation

The algorithm stop criteria is determined by two parameters including iteration number and the maximum allowed voltage deviation. The voltage deviation is calculated in each iteration by $\Delta V^{i^{(k)}} = \left|V^{i^{(k)}}\right| - \left|V^{i^{(k-1)}}\right|$, where, k is iteration number.

The calculation continues until ΔV^i becomes smaller than convergence criterion or the iteration number is reached.

5. Particle swarm optimization

PSO is a heuristic algorithm which is based on population search. This algorithm was developed in 1995 (Kennedy, 2011). In this algorithm, a swarm is a population and it is generated randomly. This population includes some individuals (particles). Each particle is a solution for the optimization problem. These particle move in different positions with different velocities in the search space to find the best position. The position and velocity of the particles determines the convergence speed of the algorithm. In each iteration the algorithm parameters, i.e. position and velocities are updated according to the following formula:

$$v_{id}^{k+1} = w v_{id}^{k} + c_1 r_1 (pbest_i^{k} - y_{id}^{k}) - c_2 r_2 (gbest^{k} - y_{id}^{k}) \quad (18)$$

$$y_{id}^{k+1} = y_{id}^{k} + v_{id}^{k+1} \quad (19)$$

where, w is the weighting coefficients, c_1,c_2 are acceleration coefficients, r_1, r_2 are random numbers between 0 and 1 which can change the speed and accuracy of the algorithm , $pbest_i^k$ is the best position that has been found by the i^{th} particle until the k^{th} *iteration*, $gbest^k$ is the best position that has been found by all particles.

6. Simulation results

6.1. Case study

Two Standard IEEE distribution systems, 33-bus and 69- bus, have been chosen to implement the proposed method. The single phase diagram of these systems are shown in Figs. 6 and 7, respectively. The data of these systems are given in Appendix A, Table A1 and Table A2.

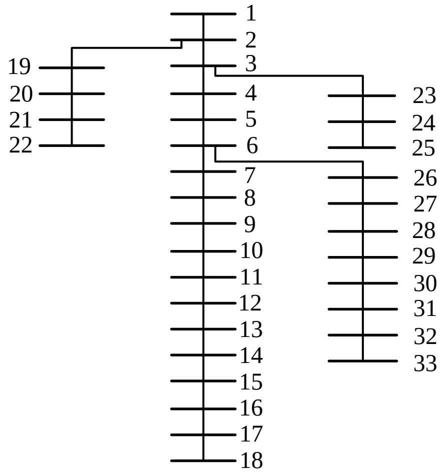

Fig. 6: Single line diagram of IEEE 33-bus distribution system.

6.2. Results of IEEE 33-bus distribution system

In this part, the impact of D-STATCOM sizing and placement on the system loss, voltage profile and voltage stability is analyzed. The maximum size of a D-STATCOM is limited due to budget and technical issues. In this study, it is assumed that the maximum size of D-STATCOM is equal to 1000 kVAr and the optimizer finds the best size and location to satisfy the objective function.

The results including the optimum size and location of D-STATCOM and the values for the problem's objectives are given in Table 1.

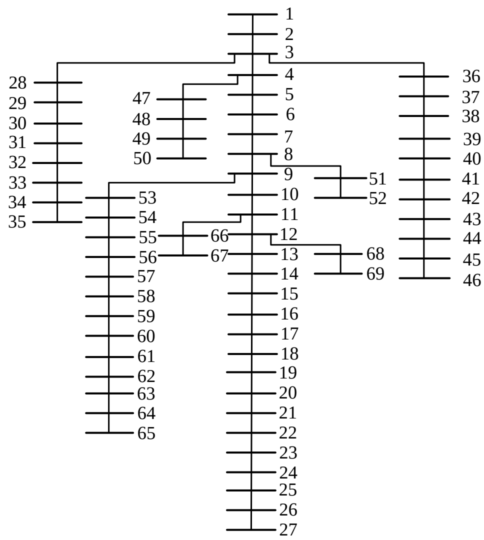

Fig. 7: Single line diagram of IEEE 69-bus distribution system.

Table 1
The results of the proposed method for IEEE 33-bus system.

With D-STATCOM	Base Case	Parameters
887	-	D-STATCOM size (kVAr)
30	-	D-STATCOM Location
0.593	-	f1
0.68	-	f2
0.73	-	f3
0.65	-	ftotal
148.4	202.7	Loss (kW)
0.74	0.695	Min (VSI)

In Table 1; f_1, f_2, f_3 are the normalized values for the three objectives of the problem, and f_{total} is the normalized objective function, loss is the total loss of the system and Min (VSI) is the minimum value of VSI which is related to the weakest bus, from the voltage stability viewpoint.

The results show that after determining the optimal size and location of D-STATCOM in the system, the objectives of the problem, i.e., system losses, voltage profile and voltage stability are improved. The loss of system is reduced about 50 kW which is in a good range. In addition, the voltage stability of the weakest bus increases from 0.695 to 0.74. The voltage profile and voltage stability for all system buses are depicted in Figs. 8 and 9, respectively. It can be seen that the voltage of bus 30 and neighboring buses improves more than the other buses. The voltage stability index also shown a similar behavior in the system. Therefore, the system loadability increases when the VSI of the weakest bus increases due to reactive power compensation.

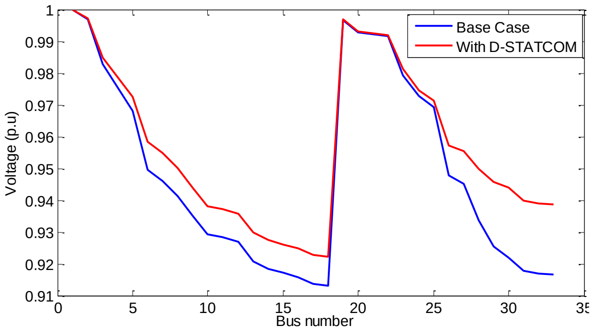

Fig. 8: Voltage profile of the system before and after compensation.

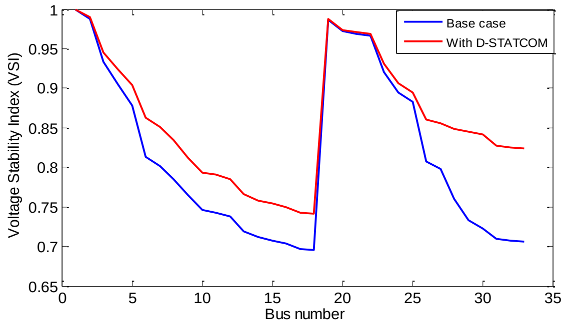

Fig. 9: Voltage stability index for all buses.

6.3. Results of IEEE 69-bus distribution system

The proposed method is also implemented on IEEE 69-bus test system. The optimal size, location, loss, minimum VSI, and the normalized terms of objective function are given in Table 2.

Table 2
The results of the proposed method for IEEE 33-bus system.

With D-STATCOM	Base Case	Parameters
947	-	D-STATCOM size (kVAr)
63	-	D-STATCOM Location
0.53	-	f1
0.72	-	f2
0.81	-	f3
0.64	-	ftotal
158.8	225	Loss (kW)
0.734	0.68	Min (VSI)

The results of simulation, shown in Table 2, demonstrate a good performance of the proposed method in improving the problem objectives. The system loss is decrease from 225 to 158.8 and the voltage stability margin increases from 0.68 to 0.734. Voltage profile and voltage stability index for all buses are shown in Figs. 10 and 11, respectively.

Fig. 10 demonstrates the improvement of voltage of buses. A D-STATCOM is installed in bus 63 and the voltages of that bus and other buses are improved.

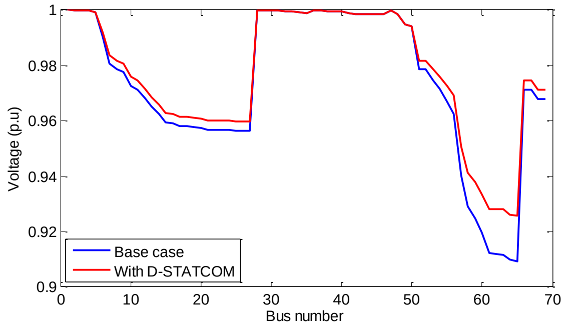

Fig. 10: Voltage profile of the system before and after compensation.

Fig. 11 shows the impact of reactive power compensation on the voltage stability of system. The voltage stability index of the weakest bus (bus 65) increases from 0.68 to 0.734, and this index for neighboring buses also improves more than the remote buses.

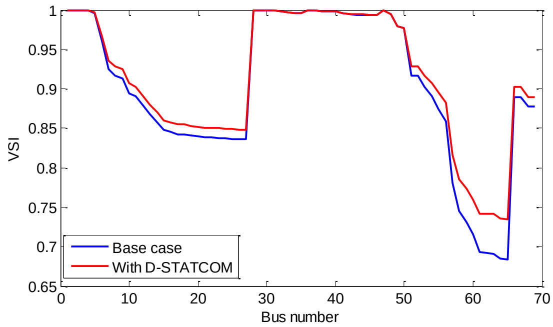

Fig. 11: Voltage stability index for all buses.

7. Conclusion

Distribution systems are always encountered some problems such as voltage drop, voltage instability and high losses; hence, a solution must be considered to improve these problems. In this paper, an optimal sizing and placement of a D-STATCOM was proposed to improve the aforementioned problems. The problem was formulated considering three indices for the three objectives and the PSO algorithm and Backward/Forward power flow method were used for optimization. The method was implemented on two IEEE standard test systems. The simulation results showed that installing an optimal-sized D-STATCOM in the optimal location can significantly improves voltage stability and voltage profile of the system. Furthermore, it can reduce the system losses about 30 % which is a considerable value and it helps to save money.

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Appendix A: Data of IEEE 33-bus and IEEE 69-bus systems

Table A1
IEEE 33-bus system data.

Reactive power (kVAr)	Active power (kW)	Bus number	Reactive power (kVAr)	Active power (kW)	Bus number
200	420	25	0	0	1
25	60	26	60	100	2
25	60	27	40	90	3
20	60	28	80	120	4
70	120	29	30	60	5
600	200	30	20	60	6
70	150	31	100	200	7
100	210	32	100	200	8
40	60	33	20	60	9
			20	60	10
			30	45	11
			35	60	12
			35	60	13
			80	120	14
			10	60	15
			20	60	16
			20	60	17
			40	90	18
			40	90	19
			40	90	20
			40	90	21
			40	90	22
			50	90	23
			200	420	24

Table A2
EEE 69-bus system data.

Reactive power (kVAr)	Active power (kW)	Bus number	Reactive power (kVAr)	Active power (kW)	Bus number
18.55	26	36	0	0	1
18.55	26	37	0	0	2
0	0	38	0	0	3
17	24	39	0	0	4
17	24	40	0	0	5
1	1.2	41	2.2	2.6	6
0	0	42	30	40.4	7
4.3	6	43	54	75	8
0	0	44	22	30	9
26.3	39.22	45	19	28	10
26.3	39.22	46	104	145	11
0	0	47	104	145	12
56.4	79	48	5	8	13
274.5	384.7	49	5.5	8	14
274.5	384.7	50	0	0	15
28.3	40.5	51	30	45.5	16
2.7	3.6	52	35	60	17
3.5	4.35	53	35	60	18
19	26.4	54	0	0	19
17.2	24	55	0.6	1	20
0	0	56	81	114	21
0	0	57	3.5	5	22
0	0	58	0	0	23
72	100	59	20	28	24
0	0	60	0	0	25
888	1244	61	10	14	26
23	32	62	10	14	27
0	0	63	18.6	26	28
162	227	64	18.6	26	29
42	59	65	0	0	30
13	18	66	0	0	31
13	18	67	0	0	32
20	28	68	10	14	33
20	28	69	14	19.5	34
			4	6	35