Performance Enhancement of Distribution Power System by Optimal Sizing and Sitting of Distribution Statcom

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Abstract. In this paper, an approach for optimal sizing and sitting of D-STATCOM in radial distribution network is proposed with multi objective functions of power loss minimization, voltage stability, and voltage profile enhancement subjected to equality and inequality constraints. Voltage stability index is used to pre-determine the candidate bus for optimal sitting of D-STATCOM. Genetic algorithm is proposed to determine the optimal size and sit of D-STATCOM. The performance of the proposed method is tested on the two IEEE 33-bus and 69-bus radial distribution feeders. The test systems are analyzed with different loading and sizing condition of D-STATCOM. The simulation result shows that optimal sitting and sizing of D-STATCOM in the proposed networks effectively upgrade the performance of the system.

Keywords: D-STATCOM · Genetic algorithm · Loss minimization · Sitting · Sizing · Voltage profile · Voltage stability

1 Introduction

Power system networks are become very complex, dynamic, nonlinear, and are prone to various types of disturbances. The distribution system is part of a power system that distributes power to end users. It is the most extensive part of the electrical system as a result of being responsible for energy losses. Different studies indicated that 13% of the total power generated is wasted in the form of losses at the distribution network. The distribution system is constantly being faced with an ever-growing load demand; thus increasing load demand results in increasing system loading and reduced the voltage profile. The voltages at buses reduce if we moved away from substation, and under critical loading it may lead to voltage collapse. Thus to improve the voltage profile and to avoid voltage collapse reactive power compensation is required. Improving the overall efficiency of power delivery has forced the power utilities to reduce the losses at the distribution level [1].

Voltage instability problem occurs in a power system when a disturbance causes a progressive and uncontrollable decrease in acceptable voltage levels. A disturbance

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such as a fault or change in operating conditions leads to increased demand for reactive power. This increase in electric power demand makes the power system to operate close to their limit conditions, which indicates that the system is operating under heavy loading conditions. As a result, voltage stability becomes one of the major concerns and an appropriate solution must be found to avoid the voltage collapse in a operated system network [2].
The main causes of voltage instability problems are:

- High reactive power consumption at load center
- Generating stations located far from load center
- Difficulties in the transmission of reactive power under heavy loads
- Due to improper locations of FACTS controllers
- Poor coordination between multiple FACTS controllers

The voltage instability problem has the following effects:

- Loss of load in specific areas
- Tripping of distribution lines
- Voltage collapse in the system

Voltage stability can be improved using:

- Placement of FACTS controllers
- Co-ordination of multiple FACTS controllers
- Installation of synchronous condensers
- Placement of series and shunt capacitors/reactors

Series voltage regulator and shunt capacitor are the two convectional FACTS devices for enhancing voltages profile of the distribution system at an acceptable range but they have some operational limitations. Thus Series voltage regulators cannot generate reactive power and have a slow response due to their step by step operations. Shunt capacitors also cannot generate continuously variable reactive power and their natural oscillatory behavior when they are connected with the same circuits to inductive components [3]. In order to increase system performance in loss minimization, improvement of voltage profile and stability there should be an installation of highly advanced equipment; Such equipment's are capacitor banks, shunt and series reactors, Automatic Voltage Regulator (AVR) or recently developed Distribution Network Flexible AC Transmission (FACTS) such as Distribution Static Compensator (D-STATCOM), Unified Power Flow Conditioner (UPQC), and Static Synchronous Series Compensator (SSSC). D-STATCOM has unique features, such as low cost, compact size, less harmonic production, low power losses, and high regulatory capability as compared with other FACTS device [4].

D-STATCOM is one of a shunt FACTS device that can inject and absorb real or reactive power at the bus thereby removing the sag in bus voltages. It consists of a three phase inverter controlled by SCRs, MOSFETs or IGBTs, a D.C capacitor which provides the D.C voltage for the inverter, a link reactor which links the inverter output to the AC supply side, filter components to filter out the high frequency components due to the

PWM inverter. From the DC Side capacitor, a three phase voltage is generated by the inverter. This is synchronized with the AC supply. The link inductor links this voltage to the AC supply side. The magnitude of voltage sources used in D-STATCOM decides the direction and magnitude of reactive current flow at the point of connection. If a voltage magnitude is higher than the magnitude of the voltage source, it works as a reactor and absorbs the excess reactive power; otherwise, it will inject reactive power and works as a capacitor at point of connection [5].

2 Related Works

Recently, authors have been working on the optimal sizing and sitting of D-STATCOM for improving the performance of the distribution network with a different objective functions and system constraints [6].

Seraj et al. presented an optimal location of STATCOM in the transmission network using the PSO method. This work states a single objective function which is RMS voltage deviation. The simulation result showed that there is a minimization in the voltage deviation of the system network. The effectiveness of the proposed control scheme has been verified experimentally using a laboratory prototype system [7]. Kumarasamy and Raghavan proposed a cost-effective solution for optimal placement and size of multiple Statcom units using particle swarm optimization. The objective function incorporates system parameters like voltage profile, system loss, reactive compensation, and system voltage stability. The proposed work shows a clear improvement in system performance in voltage deviation, size of Statcom, real power loss, and maximum load ability limit as compared with conventional methods [8]. Saket and Ifran proposed a method of optimal placement of Statcom for improving the system voltage stability using a genetic algorithm. The objective function considers the improvement of voltage stability and loss reduction. The result showed that a reduction in system loss, and cost of generation besides improving the voltage at the buses [9]. Yuvaraj et al. investigated an optimal location and size of D-STATCOM using harmony search algorithm for power loss minimization. The result showed that total annual cost and power loss reduction compared with an immune algorithm [6]. Gupta and Kumar presented an analytical approach for determining the optimal placement and size of D-STATCOM for radial distribution network with the aim of reducing loss, improving voltage profile and overall energy saving. Two different sensitivity methods were applied to determine the optimal location of D-STATCOM and its size was calculated using vibrational technique [10]. Devabalaji and Ravi proposed a novel approach to the optimal location and sizing of multiple DGs and D-STATCOMs in radial distribution system based on the combination of LSF and BFOA algorithm. This research considered a predetermined location for DGs and D-STATCOM using LSF; while the optimal size is determined using BFOA [11]. Gowtham and Lakshmi presented power loss reduction and voltage profile improvement of radial distribution networks using particle swarm optimization. First fuzzy logic approach is predetermined the optimal location and then PSO algorithm determined optimal size of D-STATCOM. The result showed that the reduction in power loss and system voltage profile is maintained within acceptable limits [12]. Atma et al. presented a modified power loss index method for optimal placement and size of D-STATCOM. An objective function of power loss reduction and improvement of voltage profile is considered. The result showed that the reduction in power loss as well as improvement in voltage profile and various aspects [13].

Tanmoy et al. proposed an approach for optimal placement of Statcom using a gravitational search algorithm. The proposed system reduces power loss, the installation cost of D-STATCOM, and improves system voltage profile [14]. Sanam et al. presented an optimal allocation of D-STATCOM and DG units in a radial distribution network using the exhaustive search algorithm with an objective function of power loss minimization and voltage profile improvement. The performance of the proposed method showed a great reduction in system power loss and improvement of voltage profile [15]. Mohammed and Srinivasula proposed an optimal placement of STATCOM using an artificial bee colony (ABC) algorithm. In this work, an objective function of minimizing power losses, installation cost, voltage deviation and fuel cost minimization of the network. The simulation result showed that the optimal placement of D-STATCOM by the ABC algorithm was effective [16]. Some of the limitations of reviewed literatures are convergence limitations of the optimization algorithm, unconstrained objective function, single objective fitness function, and either placement or sizing of D-STATCOM was done.

3 Genetic Algorithm

Genetic algorithm (GA) is one of the stochastic search algorithms based on the mechanics of natural genetics. It allows a population composed of many individuals to evolve under specified selection rules to a state that maximizes the fitness (minimizes the cost function). A solution variable for the problem is first represented using artificial chromosomes (strings). A string represents one search point in the solution space. After convergence, strings are decoded to the original solution variables and the final solutions are obtained [17, 18].

In the GA algorithm, the population has n chromosomes that represent candidate solution and its implementation steps are:

Step 1: (Initialization): Set the iteration counter $k = 1$ and generates randomly n chromosomes.
Step 2: (Fitness): Evaluate each chromosome in the initial population using the objective function. The fitness f(x) of each chromosome/individual x in the population.
Step 3: (Selection): Depending on individual chromosome fitness and using a given selection Scheme. The rank method is applied for the selection process. It first ranks the population and then every chromosome receives fitness from this ranking. Select two parent chromosomes from a population according to their Fitness (the better fitness, the bigger chance to get selected).
Step 4: (Elitism): Make a copy of selected parents.
Step 5: (Cross over): Cross over the selected parents to form a new child with a crossover probability. Two points cross over process is applied for crossover.
Step 6: (Mutation): Mutate new offspring at each locus (position in chromosome) with mutation probability. Interchanging Mutation process is applied for mutation.

Step 7: (New population): A new population is created with better fitness value.
Step 8: If the stopping criteria is satisfied go to step 10 else go to step 9.
Step 9: (Iteration updating): Update the iterations counter k = k + 1 and go to step 2.
Step 10: Stop, the optimized solution is the chromosome with the best fitness in the present Population (Table 1).

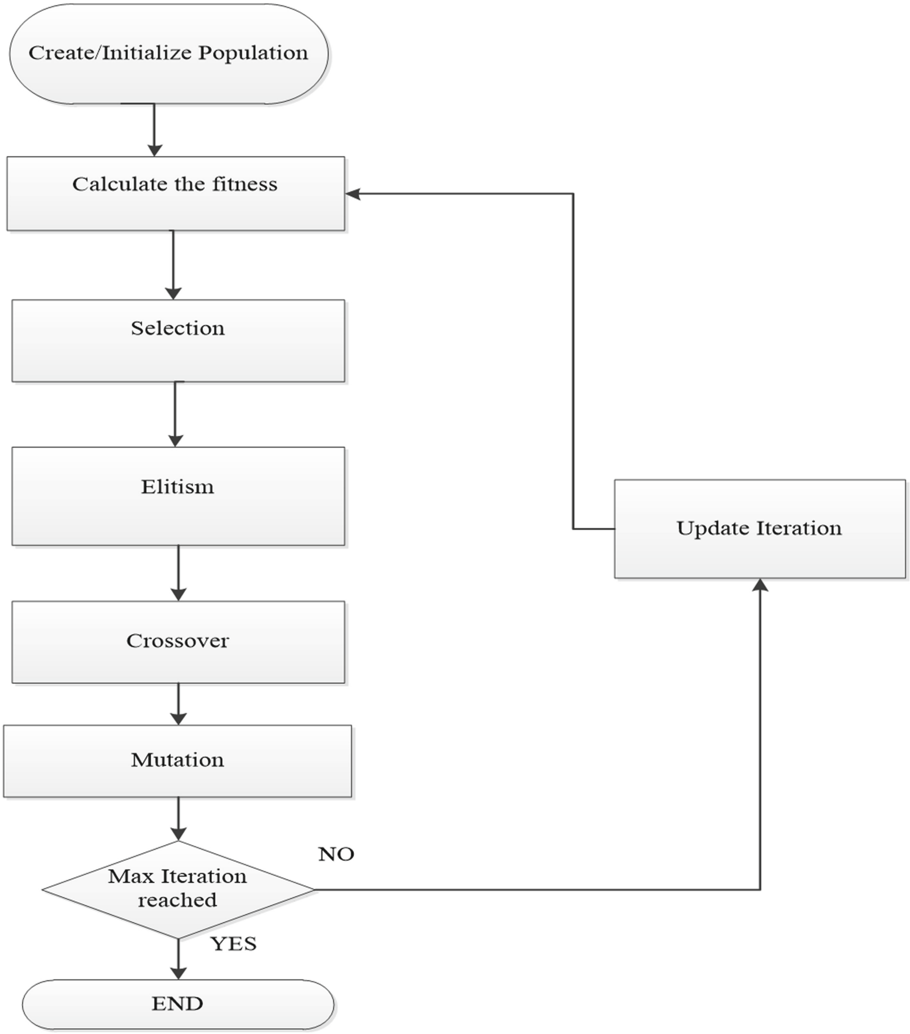

Fig. 1. Flow chart of genetic algorithm

Table 1. Input parameters of the GA algorithm

No	GA parameters	Values
1	Population size	40
2	Maximum iteration	30
3	Mutation probability	0.03
4	Cross-over probability	0.8

4 Problem Formulations

4.1 Power Flow Analysis

Newton rapson, Gauss seidel, and the two decoupled load flow solution techniques are unsuitable for solving load flow for radial distribution networks because of their high R/X ratio of branches. A direct load flow analysis is executed to find system voltage and loss at any bus by calculating load current, the formation of the BIBC matrix and forward sweep across a line [19, 20].

The single line diagram of a simple distribution system is shown in Fig. 2 and the load current at any bus t is given as:

$$I_t = \left(\frac{P_t + jQ_t}{V_t}\right)^* = \left(\frac{P_t - jQ_t}{V_t^*}\right) \tag{1}$$

Kirchhoff's current law used to calculate the branch current in the Line section between buses t and t + 1

$$J_{t,t+1} = I_{t+1} + I_{t+2} \tag{2}$$

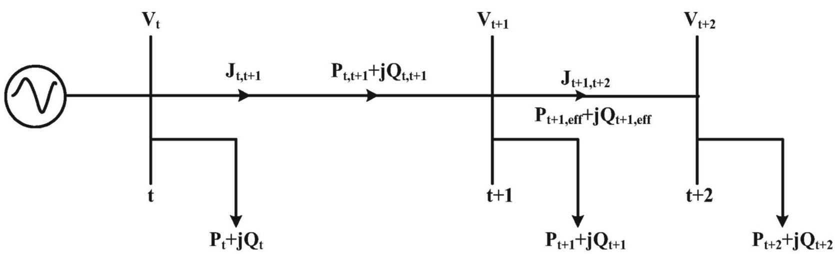

Fig. 2. Simple distribution system

The relationship between load current (I) and branch current (J) can found using simple KCL equations as follows where BIBC is bus injected to branch current matrix:

$$[J] = [BIBC][I] \tag{3}$$

The receiving end voltages can be calculated by forward sweeping method across the line by subtracting the line section drop from the sending end voltages of the line section:

$$V_{t+1} = V_t - J_{t,t+1}(R_{t,t+1} + jX_{t,t+1}) \quad (4)$$

The active and reactive power loss in the line section between t and t + 1, which is given as follows:

$$P_{Loss(t,t+1)} = \left(\frac{P_{t,t+1}^2 + Q_{t,t+1}^2}{\left|V_{t,t+1}\right|^2}\right) * R_{t,t+1} \quad (5)$$

$$Q_{Loss(t,t+1)} = \left(\frac{P_{t,t+1}^2 + Q_{t,t+1}^2}{\left|V_{t,t+1}\right|^2}\right) * X_{t,t+1} \quad (6)$$

The total active and reactive power loss of the distribution systems is found by adding each branch current line losses:

$$Q_{TLoss} = \sum_{t=1}^{nb} Q_{Loss(t,t+1)} \quad (7)$$

$$P_{TLoss} = \sum_{t=1}^{nb} P_{Loss(t,t+1)} \quad (8)$$

Percentage reduction in active power loss with D-STATCOM

$$\%\mathrm{P}_{Loss\,reduction} = \left(\frac{P_{loss}^{Base} - P_{loss}^{DSTATCOM}}{P_{loss}^{Base}}\right) * 100 \quad (9)$$

Percentage reduction in reactive power loss with D-STATCOM

$$\%Q_{Loss\,reduction} = \left(\frac{Q_{loss}^{Base} - Q_{loss}^{DSTATCOM}}{Q_{loss}^{Base}}\right) * 100 \quad (10)$$

4.2 Modeling of D-STATCOM

The steady state modeling of D-STATCOM which is installed at the radial distribution feeder bus is shown in Fig. 3 below. After integration of D-STATCOM at the candidate bus the voltage values where it is installed and at the neighboring buses changes. The new voltages are V'_n at the candidate bus and V'_m at the previous bus. Current changes to I'_m which is the summation of I_m and I_{DS}. Where I_{DS} is the current injected by D-STATCOM and is in quadrature with the voltage [20].

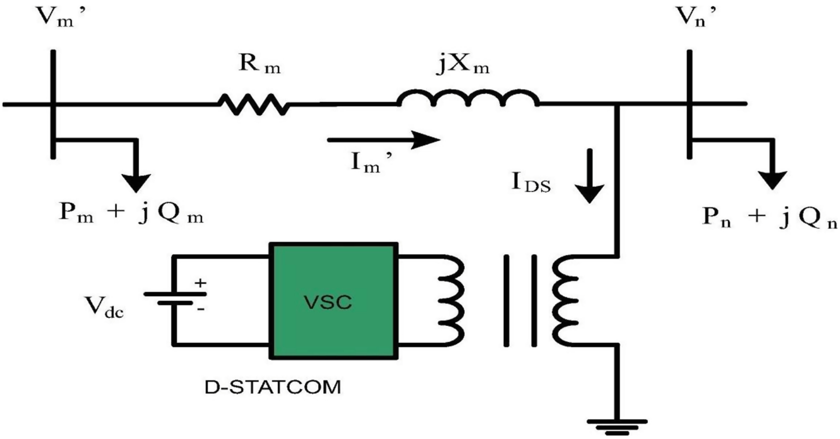

Fig. 3. Single line diagram of two-bus distribution system with D-STATCOM integration

Therefore, the expression for new voltage after installing D-STATCOM is given as

$$V_n' \angle \theta_n = V_m' \angle \theta_m' - (R_m + jX_m)(I_m \angle \delta + I_{DS} \angle (\frac{\pi}{2} + \theta_n')) \tag{11}$$

Here θ_n', θ_m' and δ are the phase angles of V_n', V_m' and I_m respectively.

By separating real and imaginary parts of Eq. (11) and manipulating the equations we get

$$t = \frac{-B \pm \sqrt{D}}{2A} \tag{12}$$

Where

$$t = \sin \theta' \tag{13}$$

$$A = (h_1 h_3 - h_2 h_4)^2 + (h_1 h_4 + h_2 h_3)^2 \tag{14}$$

$$B = 2(h_1 h_3 - h_2 h_4) + (V_n^{'})(h_4) \tag{15}$$

$$C = (V_n^{'} \cdot R_m)^2 - (h_1 h_4 + h_2 h_3)^2 \tag{16}$$

$$D = B^2 - 4AC \tag{17}$$

Where

$$h1 = \text{Real}(V_m' \angle \theta_m') - \text{Real}(Z_m I_m \angle \delta) \tag{18}$$

$$h2 = \text{Imag}(V_m^{'} \angle \theta_m^{'}) - \text{Imag}(Z_m I_m \angle \delta) \tag{19}$$

$$h3 = -X_m \tag{20}$$

$$h4 = -R_m \tag{21}$$

Now there are two roots of t to determine the correct value of roots, the boundary conditions are examined as:

$$V_n' = V_n \Rightarrow I_{DS} = 0 \text{ And } \theta_n' = \theta_n \tag{22}$$

Results show that $t = \frac{-B \pm \sqrt{D}}{2A}$ it is the desired root of the Eq. (12).

D-STATCOM current angle and magnitude is:

$$\angle I_{DS} = \frac{\pi}{2} + x_2 = \frac{\pi}{2} + \sin^{-1} t \tag{23}$$

$$|I_{DS}| = x_1 = \frac{V_n' \cos\theta_n - h_1}{-h4 \sin\theta_n' - h3 \cos\theta_n'} \tag{24}$$

Finally, the reactive power injected is:

$$jQ_{DS} = (V_n' \angle \theta_n').(I_{DS} \angle (\frac{\pi}{2} + \theta_n'))^* \tag{25}$$

Where * denotes the complex conjugate.

4.3 Objective Function

The objective of D-STATCOM allocation in the radial distribution system is to minimize the total active power losses, enhancement of voltage profile and voltage stability index while satisfying the equality and inequality constraints.

Loss Minimization

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

$$F_1 = \sum_{i=1}^{NBr} R_i \times I_i^2 \tag{26}$$

Where F_1 is the first objective function associated with the system power loss minimization

I_i is the current of line i

R_i is the resistance of i^{th} line

NBr is the number of system branches.

Voltage Profile Improvement

The second objective function is improving the voltage profile of the network:

$$F_2 = \sum_{i=1}^{NBus} (1 - V_i)^2 \tag{27}$$

Where

V_i is the voltage of the i^{th} bus
NBus is the number of the system bus.

Voltage Stability Improvement
A new steady state bus based voltage stability index method is used to identify the node, which has more chance to voltage collapse. The stability index at each node is calculated using Eq. (28). The node which has the low value of VSI is the weakest node and the voltage collapse phenomenon will start from that node. VSI is calculated from the load flow for all the buses of the given system and the values are arranged in ascending order. The VSIs choose the sequence in which the buses are to be considered for D-STATCOM placement. Therefore to avoid the possibilities of voltage collapse, the VSI of nodes should be maximized [11, 21] (Fig. 4).

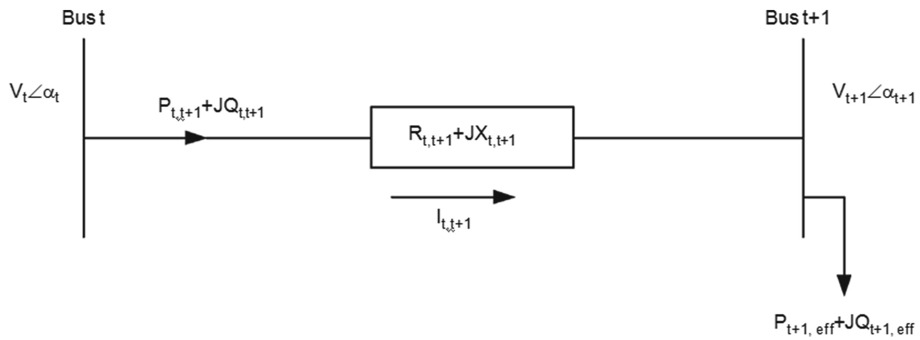

Fig. 4. Two-bus distribution system for VSI analysis

$$VSI(t+1) = |V_t|^4 - 4\left[P_{t+1,eff} \times X_t - Q_{t+1,eff} \times R_t\right]^2 - 4\left[P_{t+1,eff} \times R_t + Q_{t+1} \times X_t\right]|V_t|^2 \tag{28}$$

$$F_3 = \min(VSI(t+1)) \tag{29}$$

Where VSI (t + 1) is the voltage stability index at bus t + 1, t and t + 1 are the sending and receiving bus number. $P_{t+1, eff,}$ and $Q_{t+1, eff}$ are active and reactive power demands at bus t + 1, respectively, V_t is the voltage of the sending bus, $R_{t, t+1}$, $X_{t, t+1}$ are the resistance and reactance of branch between bus t, and t + 1 (Table 2).

The mathematical formulation of the general objective function (F) is given by

$$Minimize\,(F) = min\,(w_1 * F_1 + w_2 * F_2 + w_3 * \frac{1}{F_3}) \tag{30}$$

Where

$$\sum\nolimits_{n=1}^{3} wn = 1 \tag{31}$$

Table 2. Weighting value representation

No	Objective functions	Weighting value
1	Power loss (w_1)	0.4
2	Voltage profile (w_2)	0.3
3	Voltage stability index (w_3)	0.3

4.4 System Constraint

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

$$V_m^{\min} \leq |V_m| \leq V_m^{\max}$$

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

$$Q_m^{\min} \leq |Q_m| \leq Q_m^{\max}$$

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

$$|S_{ij} \leq S_{ij}\max|$$

4.5 Methodology for the Proposed Optimization Algorithm

The proposed optimization algorithm is implemented using the following steps:

1. Read line and load data for test network of radial distribution feeders.
2. Set the lower and upper bounds of system constraints, genetic algorithm control parameters (population size, mutation probability, and cross-over probability) and maximum iteration.
3. Generate an initial random population.
4. Run the base case load flow algorithm and compute voltage profile at each bus, the real and reactive power loss of lines.
5. Developing bus based voltage stability index method for selecting candidate buses for sitting D-STATCOM.
6. Apply all steps for genetic optimization algorithm from Fig. 1 steps from (1–10), and optimized the fitness function using Eq. 30.
7. Select an optimal solution (Optimal sizing and sitting).
8. Display optimal solutions.

5 Result and Discussion

The performance of the proposed work is tested on the two IEEE-33 and IEEE-69 bus system in Matlab simulation software. The optimal sizing and sitting of D-STATCOM for test systems are considered under different test cases and loading conditions.

5.1 IEEE 33-Bus Test System

This is a medium scale radial distribution feeder with 33 buses and 32 branches. The single line diagram for the test system is shown in Fig. 5 below with bus voltage = 12.66 kV, base MVA = 100 MVA, total active power load 3.715 MW, and reactive power load 2.3 MVAr. The optimal sizing and sitting of D-STATCOM for the test system are considered with different system constraints and cases. The line and load data of the test system are taken from [22].

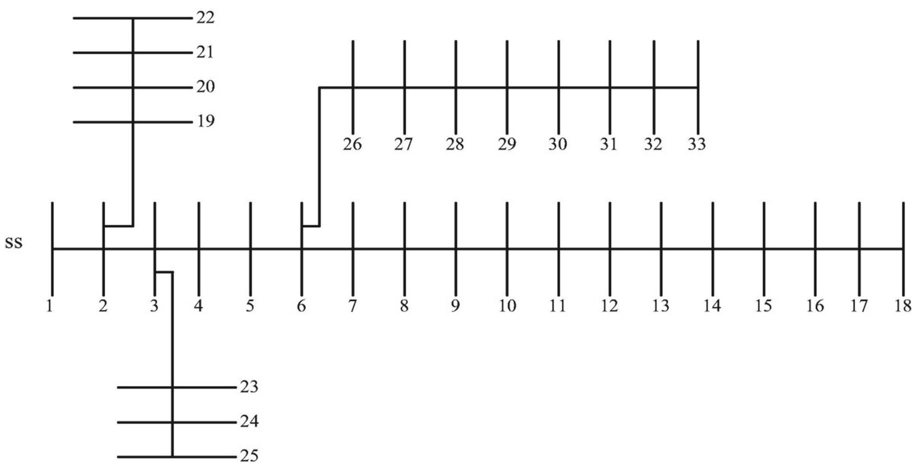

Fig. 5. Single line diagram for IEEE 33-bus radial distribution network

Case 1: System with D-STACOM the reactive power injected by D-STACOM is constrained with the maximum value of 1000 kVAr and the bus voltage is in range of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

In Table 3 it shows that comparison of reactive and real power losses, voltage profile, voltage stability index, location, optimal size (kVAr) for the proposed method. In case 1, the real and reactive power losses have been reduced to 145.88 kW (percentage of reduction is 28.02%), 97.43 kVAr (percentage of reduction is 27.9065%), minimum voltage with a compensating device improves to 0.9230 p.u, and minimum VSI increases to 0.7258 p.u after installing the D-STATCOM. The optimal size of D-STACOM is 1000 kVAr and sits in bus 30 of the test network.

Case 2: System with D-STACOM the reactive power injected by D-STACOM is constrained with the maximum value of 2000 kVAr and the bus voltage is in range of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

In Table 3 it shows that comparison of reactive and real power losses, voltage profile, voltage stability index, locations, optimal size (kVAr) for proposed method. In case 2, the real and reactive power losses have been reduced to 143.62 kW (percentage of reduction is 29.14%), 96.30 kVAr (percentage of reduction is 28.74%), minimum voltage with compensating device improves to 0.9251 p.u, and minimum VSI increases to 0.7325 p.u after installing the D-STATCOM. The optimal size of D-STATCOM is 1232 kVAr and sits in bus 30 of the tested network.

Table 3. Performance evaluation of IEEE-33 bus system

No	Parameters	Base case	Case-1	Case-2	PSO [22]
1	Active power loss	202.68 kW	145.88 kW	143.62 kW	148.8 kW
2	Reactive power loss	135.14 kVAr	97.43 kVAr	96.3070 kVAr	…………..
3	Minimum VSI	0.6950 p.u	0.7258 p.u	0.7325 p.u	0.74 p.u
4	Minimum voltage	0.9131 p.u	0.9230 p.u	0.9251 p.u	………….
5	D-STATCOM location	…………..	30	30	30
6	D-STATCOM size	…………..	1000 kVAr	1232 kVAr	887 kVAr
7	Active power loss %	……………..	28.0219%	29.14%	26.00%
8	Reactive power loss %	……………	27.9065%	28.74%	………..

Case 3: System with D-STACOM considering different loading conditions with the maximum size of 1000 kVAr and the bus voltage of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

The proposed system is tested under different loading conditions 90%, 95%, 105%, and 110% of the normal loading conditions. From Table 4 it shows that as system loading increases system performance decrease and the installation of D-STATCOM improves its performance. Therefore distribution network operators can easily select the size of D-STATCOM as the load changes for the efficient operation of the network.

From the simulation result, it is shown that the comparative performance analysis of the proposed methods with a GA optimization algorithm for case 1 and case 2 in Power loss, voltage profile, and stability index. The proposed method shows an improvement as compared with PSO tested results. For the existing PSO method, the real power losses have been reduced to 148.8 kW (percentage of reduction is 26.00%), and minimum VSI

Table 4. IEEE 33-bus loading condition

No	Loading (%)	Ploss base case (kW)	Sitting (bus)	Sizing (kVAr)	Ploss with D-STATCOM (kW)	Reduction (%)
1	90%	161.6419	29	984	117.52	27.29%
2	95%	181.4935	30	1000	130.13	28.30%
3	105%	225.2272	30	962.25	163.77	27.28%
4	110%	249.1815	29	1000	184.30	26.03%

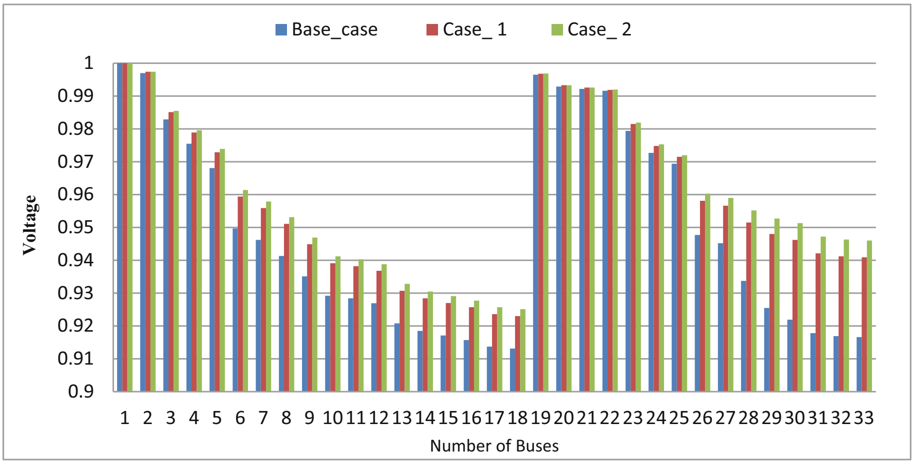

Fig. 6. Voltage profile for IEEE-33 bus

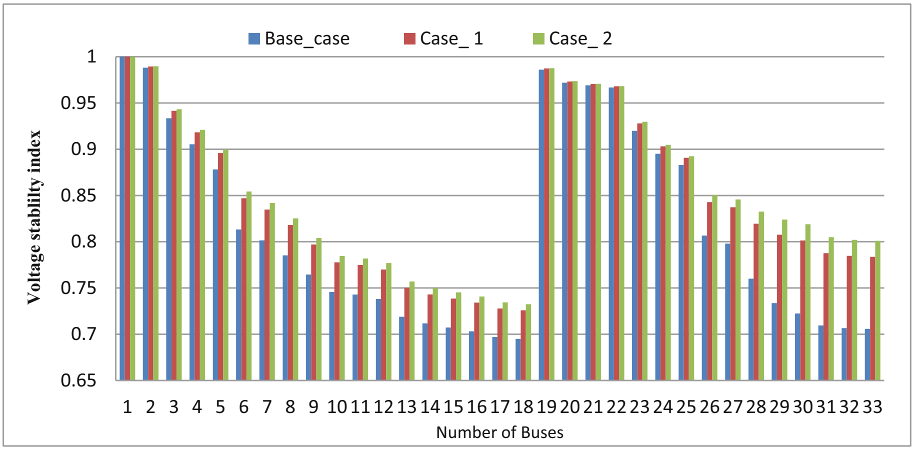

Fig. 7. Voltage stability index for IEEE-33 bus

increases to 0.74 p.u after installing the D-STATCOM. The optimal size of D-STATCOM is 887 kVAr and sits in bus 30 of the radial distribution network [22]. From Figs. 6 and 7 it shows a comparative voltage profile and voltage stability index for the base case, case 1, and case 2 of the test network respectively. It has shown clearly that as the size of D-STATCOM increases there is an improvement in system voltage profile magnitude and bus voltage stability index.

5.2 IEEE 69-Bus Test System

This is a large-scale radial distribution feeder with 69 buses and 68 branches. The single line diagram for the test system showed in Fig. 8 below with bus voltage = 12.66 kV, base MVA = 100 MVA, total active power load 3.8 MW, and reactive power load 2.69 MVAr. The optimal sizing and placement of D-STATCOM for the test system are considered under different system constraints. The line and load data are taken from [22].

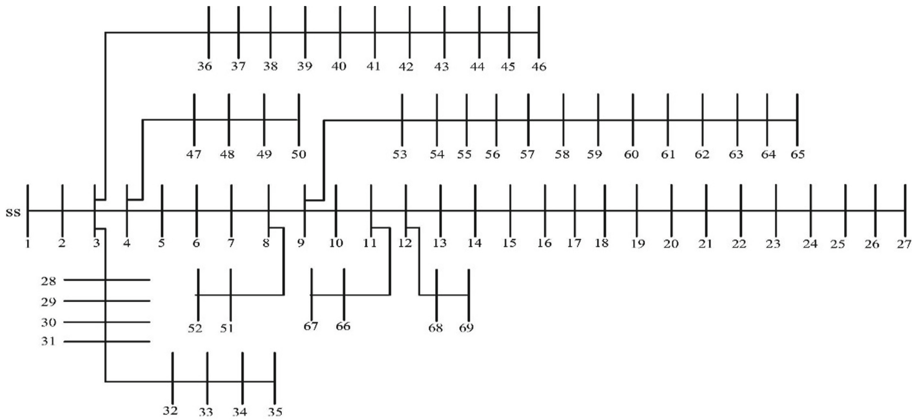

Fig. 8. Single line diagram for IEEE 69-bus radial distribution network

Case 1: System with D-STACOM the reactive power injected by D-STACOM is constrained with the maximum value of 1000 kVAr and the bus voltage is in range of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

In Table 5 it shows that comparison of reactive and real power losses, voltage profile, voltage stability index, location, optimal size (kVAr) for the proposed method. In case 1, the real and reactive power losses have been reduced to 156.7897 kW (percentage of reduction is 30.3035%), 72.8594 kVAr (percentage of reduction is 28.6720%), minimum voltage with compensating device improves to 0.9259 p.u, and minimum VSI increases to 0.7349 p.u after installing the D-STATCOM. The optimal size of D-STATCOM is 1000 kVAr and sits in bus 62 of the test network.

Case 2: System with D-STACOM the reactive power injected by D-STACOM is constrained with the maximum value of 2000 kVAr and the bus voltage is in range of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

In Table 5 it shows that comparison of real and reactive power losses, voltage profile, Voltage stability index, location, optimal size (kVAr) for proposed methods. In case 2, the real and reactive power losses have been reduced to 152.2115 kW (percentage of reduction is 32.3386%), 70.6490 kVAr (percentage of reduction is 30.8360%), minimum voltage with compensating device improves to 0.9293 p.u, and minimum VSI increases to 0.7459 p.u after installing the DSTATCOM. The optimal size of DSTATCOM is 1258.6 kVAr and sits in the bus 61 of the test network.

Table 5. Performance evaluation of IEEE-69 bus system

No	Parameters	Base case	Case-1	Case-2	PSO [22]
1	Active power loss	224.96 kW	156.7897 kW	152.2115 kW	158.8 kW
2	Reactive power loss	102.1470 kVAr	72.8594 kVAr	70.6490 kVAr	…………
3	Minimum VSI	0.6828 p.u	0.7349 p.u	0.7459 p.u	0.734 p.u
4	Minimum voltage	0.9090 p.u	0.9259 p.u	0.9293 p.u	…………
5	D-STATCOM location	…………..	62	61	63
6	D-STATCOM size	…………..	1000 kVAr	1258.6 kVAr	947 kVAr
7	Active power loss %	……………..	30.3035%	32.3386%	29%
8	Reactive power loss %	……………	28.6720%	30.8360%	……….

Case 3: System with D-STACOM considering different loading conditions with the maximum size of 1000 kVAr and the bus voltage of $0.91 < V_m < 1.05$ with maximum power transfer capability of $S_{max} = 100$ MVA.

The proposed system is tested under different loading conditions 90%, 95%, 105%, and 110% of the normal loading conditions. From Table 6 it shows that as system loading increases system performance decrease and the installation of D-STATCOM improves its performances. Therefore distribution network operators can easily select the size of D-STATCOM as the load changes for the efficient operation of the network.

Table 6. IEEE 69-bus loading conditions

No	Loading (%)	Ploss base case (kW)	Sitting (bus)	Sizing (kVAr)	Ploss with D-STATCOM (kW)	Active power loss reduction (%)
1	90%	178.9130	61	1000	122.9430	31.28%
2	95%	201.1623	63	966.37	140.7865	30.01%
3	105%	250.3566	61	1000	175.130	30.04%
4	110%	277.4018	64	1000	199.9365	27.93%

From the simulation result, it is shown that the comparative performance analysis of the proposed method with a GA optimization algorithm for case 1 and case 2 in Power loss, voltage profile, and stability index. For the existing PSO method, the real power losses have been reduced to 158.8 kW (percentage of reduction is 29.00%), and minimum VSI increases to 0.734 p.u after installing the D-STATCOM. The optimal size of D-STATCOM is 947 kVAr and sits in bus 30 of the radial distribution network [22]. From Figs. 9 and 10 shows a comparative voltage profile and voltage stability index for the base case, case 1, and case 2 of the test network respectively. It has shown clearly that as the size of D-STATCOM increases there is an improvement in system voltage profile and voltage stability index.

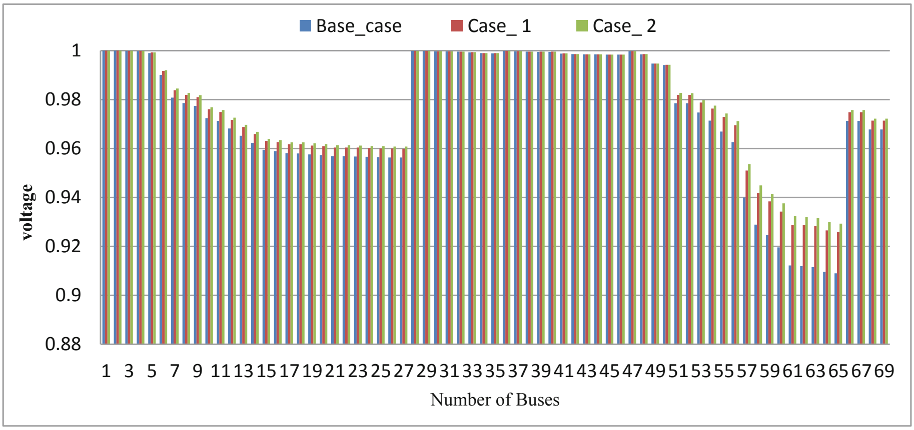

Fig. 9. Voltage profile for IEEE-69 bus

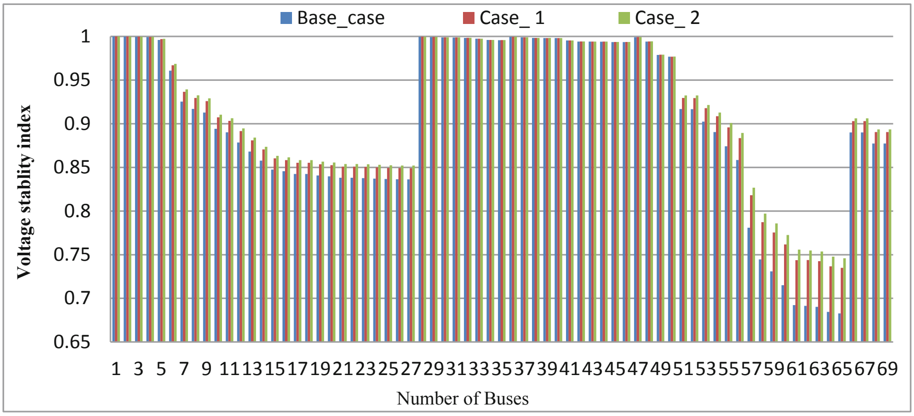

Fig. 10. Voltage stability index for IEEE-69 bus

6 Conclusion

A combined method of VSI and GA is proposed for optimal sitting and sizing of D-STATCOM with a multi-objective function of minimizing power loss, enhancing the voltage profile, and stability of the system. The bus-based voltage stability index method is used to predetermine the candidate bus for optimal sitting, and GA algorithm selects for optimal sitting and sizing of D-STATCOM. The proposed method is tested on IEEE 33-bus and 69-bus radial distribution system with different cases. It is necessary to place the D-STATCOM at optimal location with optimal size to ensure the maximum benefits of the system from its integration. The great improvement in system voltage profile, loss minimization, and enhancement of VSI is shown after installation of D-STATCOM at the candidate bus. The simulation result shows that the proposed method gives better results when compared with the existing Pso method.

Nomenclature

ABC	Artificial Bee Colony
AVR	Automatic Voltage Regulator
BFOA	Bacterial Foraging Optimization algorithm
BIBC	Bus Injected to Branch Current
DC	Direct current
DG	Distribution Generator
D-STATCOM	Distribution Static synchronous compensator
ESA	Exhaustive Search algorithm
FACTS	Flexible AC Transmission System
GA	Genetic Algorithm
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilovolt
kVA	Kilovolt Ampere

kVAr	Kilo volt ampere reactive
KVL	Kirchhoff's Voltage Law
kW	Kilowatt
LSF	Loss sensitivity factor
MVA	Mega volt ampere
MVAr	Mega volt ampere reactive
MW	Megawatt
PSO	Particle Swarm Optimization
p.u	Per unit
R	Resistance
RDS	Radial distribution system
SSSC	Static synchronous series compensator
UPQC	Unified power quality control
VSC	Voltage source converter
VSI	Voltage stability index
X	Reactance

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