Impact of Various Load Models for Combined Assignment of DG Source and D-STATCOM Device in the Radial Distribution System

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Abstract

This research work is concentrated on swarm-based intelligence Particle Swarm Optimization algorithm for combined assignment of D-STATCOM device and Distributed Generation source in a radial distribution structure. This work intends to diminish total real power loss, total cost and voltage magnitude profile enhancement for different circumstances. Generally Constant Power load design analysis is carried out for a distribution scheme. However, it is observed that load models remarkably impact the optimum sizing and positioning of DG source and D-STATCOM device. In this paper, work has been carried out for constant power load, polynomial load, and load growth model under various load factor conditions from light load factor (0.6) to heavy load factor (1.6) for power system planning. The sizing and positioning of D-STATOM device and DG source are considered based on loss sensitivity factor computation and PSO algorithmic rule. The planned scheme is investigated on IEEE 69 node and IEEE 33 node

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radial distribution structures. Further, the simulated results obtained by this algorithm is compared with other available techniques.

Keywords: Distribute generators (DG), distributed static compensators (D-STATCOM), particle swarm optimization (PSO), load model, load variation.

List of Notations

$P_{\mathrm{Loss\ (mn)}}$ = Active power loss of the lines connected between nodes 'm' and 'n' (kW)
$Q_{\mathrm{Loss\ (mn)}}$ = Reactive power loss of the lines connected between nodes 'm' and 'n' (kVAr)
P_{n} = Real power requirement at node or bus 'n' (kW).
Q_{n} = Reactive power requirement at node or bus 'n' (kVAr)
V_{n} = Voltage at node 'n'
V_{m} = Voltage at node 'm'
R_{mn}, X_{mn} = Resistance and reactance of the distribution line between nodes m and n
nl = number of distribution lines or branches
nb = number of buses or nodes
P_{Loss} = Power loss after compensation
P_{cj} = DG source size (kW)
Q_{ck} = D-STATCOM device size (kVAr)
A_{p} = Energy cost ($/Kwh)
A_{c} = DSTATCOM device cost ($/kVAr)
A_{d} = DG source cost ($/ kW)
H = Total number of hours per annum
$V_{\mathrm{n,max}}$, $V_{\mathrm{n,min}}$ = Upper limit and Lower voltage limit of bus 'n'
P_{DGn} = Real power generated by DG source (kW)
$P_{\mathrm{DGn,min}}$, $P_{\mathrm{DGn,max}}$ = Upper and Lower real power rating limit on DG source (kW)
$Q_{\mathrm{stat,n}}$ = Reactive power rating of DSTATCOM device (kVAr)
$Q_{\mathrm{stat,nmin}}$, $Q_{\mathrm{stat,nmax}}$ = Upper & Lower reactive power rating limit on D-STATCOM device (kVAr)
P_{Sw}, Q_{Sw} = Total real and reactive power of the network (kW, kVAr)

1 Introduction

In distribution systems, losses will be around 10 to 13 percent of the total generated power. Total real power loss reduction is the preferred way to enhance the capability of the utility distribution structure. The power network is subjected to rapid changes due to the integration of RES, plugging of electric vehicles, energy storage devices. Since active power generation from DG source is uncontrolled, it leads to violation of bus voltages at peak time. Installing compensating devices would lower overall real power losses while improving the voltage magnitude profile [1].

Power losses can be reduced by properly sizing and positioning a DG source near the load. DSTATCOM is a compensating device located in the distribution scheme to compensate reactive power and correct power factor. DSTATCOM balances power quality issues in the distributions system like voltage imbalance, voltage sag, harmonic distortion, voltage swell and voltage fluctuation. To resolve the real power loss minimization problem, various approaches are used which differ in the selection of real power loss minimization tool box, problem conceptualization and techniques employed. Most often used techniques to reduce the total real power loss are (i) DG allocation, (ii) D-STATCOM allocation, (iii) Capacitor allocation and (iv) Re-configured Distribution Structure. For optimal benefits, a combination of above techniques are used. D-STATCOM and capacitor device will maintain reactive power supply to the distribution structure. With Capacitor alone, the losses would not reduce making it economically non-viable. The recent trend by many researchers is to install D-STATCOM device in distribution scheme for solving power quality issues [2].

Swarm behavior technique with simple mathematical equations is applied to resolve the simultaneous assignment and rating of DG source and compensating D-STATCOM device in the utility distribution structure to bring down total real power losses for constant power model [3]. The candidate bus for assignment of the D-STATCOM device and DG source in the distribution structure with various load factors is determined using loss sensitivity factor analysis. Bacterial Foraging Optimization Algorithm rule is implemented to achieve maximum benefits along with overall real power loss minimization and voltage magnitude profile betterment. In this research article, the convergence characteristics not discussed and needs further parameter tuning [4]. In this research work author proposes lightning phenomenon primarily depend on transition, space, projectile for best possible distribution of DG source and Distributed STATCOM device on the utility distribution network with various load factors. The algorithm attains reduced total active power loss, better voltage steadiness, but computational effectiveness of the methodology has not been mentioned [5].

The candidate node or bus position is determined using a direct load flow technique combined with a loss sensitivity factor approach. This scheme is simple and proper for coordinated positioning of DG source and compensating D-STATCOM device for real power loss minimization. The method used here is suitable for small system and viability of technique for huge network is not debated [6]. In this work [7] Evolutionary technique is realized for minimization of total real power loss, DG unresolved condition are designed and installed at optimum location. The benefits attained are decrease in total real power loss, annual operating expenses, and emission levels. This algorithm mainly tested on small test system and viability of technique for huge system not evaluated. The Loss Sensitivity Factor is calculated in this study to predetermine the location of the DG source. Four different algorithms for reconfiguration and DG source provision at the same time in a distribution system with varied load factors, Particle Swarm Optimization, Ant Bee Colony, Differential Evolutionary, and Genetic Algorithm rules are used. The algorithm is tested on large system to achieve reduction in loss and voltage deviation. The results obtained by all four algorithms yield identical results [8]. Integration of multiple DG source at potential location provides effective voltage profile improvement and a significant decrease in system losses from the Genetic Algorithm method [9]. A new hybrid algorithm addresses the optimization problem for the placement of DG source and DSTATCOM device, which converges with reasonable accuracy to the optimum solution [10].

Maximum loads can be characterized as the composite ZIP model with diverse parameters reflecting configuration [11]. The author proposes a Whale Optimization technique to decrease total active power losses, total expenses, and voltage profile improvement by placing D-STATCOM device and multiple DG source using loss sensitivity factors under various load conditions [12]. The Gravitational Search Optimization Algorithm is projected to achieve the meticulous allotment of Distributed STATCOM device and DG source alone and combined assignment in distribution network for total real power loss diminution and total yearly energy saving [13]. Immune technique for reducing overall real power loss and improving current and voltage contours in a radial distribution scheme was presented by the author [14]. The author proposes a Harmonic Search Algorithm rule for optimum assignment of DSTATCOM device with total system real power loss minimization as objective [15]. In this paper [16], the author proposes Bio-inspired Bat procedure for D-STATCOM device distribution with load demand variation to diminish real power loss. In this research work [17] author proposes provision of distributed generation in radial supply network built on novel voltage stability index (VSI) during load progress scenario, cost of energy losses and DSTATCOM device is estimated.

The author considered DG distribution in a radial distribution network with diverse objective functions [18]. Assessment of various load models CI, CZ, ZIP, and load growth are considered for D-STATCOM device assignment in radial delivery structure under reconfigured network topology in [19]. In this research work author suggest a various functional performance parameter based rating and site finding of DG reserve in distribution schemes along with diverse load models. It revealed that load representations can considerably impact the best position and rating of DG reserves in distribution structure [20]. Optimization methodology should be utilized for restructuring of the power utilities, permitting for the optimum allotment of the DG sources [21, 22]. Under varying load scenarios on the distribution network, the author developed a Genetic Algorithm to reduce overall real power loss, ideal location, and rating of DG sources and Distributed STATCOM device. This approach is computationally simple, but convergence characteristics is not discussed [23]. Root tree algorithm is recommended to achieve maximum benefits along with total real power loss diminution and voltage magnitude profile magnification. In the projected technique computational efficiency and feasibility for large system not highlighted [24]. Effect of load designs on ideal position and rating of DG source is analyzed in [25].

The methodology for optimum assignment of Distributed STATCOM device in mesh topology utilizing sensitivity methods is suggested. The novelty of the work in this paper are best Distributed STATCOM device position established on the voltage sensitivity index (VSI) in mesh topology, optimum Distributed STATCOM device rating computation for weather dependent loads with load change situation, assessment of Distributed STATCOM device employment and capacity finding with the present sensitivity approach, effect of best possible D-STATCOM device assignment on voltage stability gap boosting, energy loss diminution and total energy saving cost [26]. Author suggested a Flower Pollination Algorithm for installing DG source and DSTATCOM device using loss sensitivity and tested on various IEEE test structures to diminish real power losses and cost [27]. Population based algorithm is proposed to resolve the multi objective function for DG source estimation in distribution network [28, 29]. Improved cat swarm optimization technique employed for D-STATCOM device location in stabilized radial distribution structure with a motive of enhancing voltage magnitude profile and reduction of losses [30].

The authors recommend utilising a hybrid lightning search algorithm-simple technique to identify the appropriate size of the DG and DSTATCOM device [31]. The author proposes an optimization technique supported on a bio-inspired cuckoo search algorithm [32] for evaluating the DSTATCOM device's capacity. The author recommends installing and sizing D-STATCOM devices in the distribution scheme to reduce yearly operating expenditure associated to energy losses [33]. The author presented a generalised optimization framework for locating and capacity of D-STATCOM devices in radial and mesh topologies in power and distribution structures [34]. The exact mathematical optimization point [35] was used to tackle the problem of optimal STATCOM siting and sizing with radial and mesh structures. Several PSO acceleration coefficients are proposed for optimal integration of a variety of renewable DG solar PV and Distributed STATCOM devices in this study. Finally, according to the author, basic PSO converges faster than other approaches [36].

It is found from the literature review that, mainly the work is carried out on optimizing position and size of either DG source or D-STATCOM device. However, few researchers have carried out work on simultaneous techniques with basic objective function as loss minimization, voltage profile improvement, sizing and location. Also the research on simultaneous technique in literature focused on constant power model. It is found that load designs can considerably alter the rating and position designing of DG source and D-STATCOM device.

The novelty of the work presented in this paper is to realize actual distribution structure conditions to evaluate the position and capacity of single DG source and single DSTATCOM device individual placement. Also simultaneous arrangement of DG source and DSTATCOM device, considering the effect of different load models under various loading scenarios are explored. In addition to this work, reduction of cost of total real power losses, the overall operating expenses of DG source and DSTATCOM device concurrently considered for all load models and scenarios.

In this work, PSO algorithm is selected to evaluate the rating and location of DG source and DSTATCOM devices to minimize overall active power losses, total expenditure, and enhancement of voltage magnitude profile in the radial topology. This algorithm is selected because of simplicity and it is data tested. Also, efficiency is high for multi objective problem as compared to swarm intelligence algorithms. In addition to this diversity of the problem is effectively solved [36, 37].

The structure of the current research work is presented as follows: Section 2 presents loss computation, determination of loss sensitivity factors for identifying candidate buses. Section 3 describes objective function formulation for minimizing power loss, cost of additional devices. Section 4 details different load models considered and Section 5 presents the PSO algorithm and methodology. Section 6 presents the simulation results and analysis of IEEE 33 node and IEEE 69 node standard systems, and obtained simulated results are correlated with various methods discussed in the literature. Section 7 concludes the overall simulated results obtained using the current PSO technique.

2 Loss Sensitivity Factor for Choice of Candidate Buses

The voltage at node or bus ‘n’ as seen from the electrical equivalent circuit of a radial topology illustrated in Figure 1 is,

$$V_n = V_m - (R_{mn} + X_{mn}) \tag{1}$$

Where $n = m + 1$.

Backward/Forward Sweep power flow algorithm rule is utilized to compute the uncompensated voltage magnitude and phase angle, active and reactive power loss of the radial topology. The real and reactive power losses of the network are computed by the succeeding Equations (2) and (3):

$$\mathrm{P}_{\mathrm{Loss(mn)}} = \frac{(\mathrm{P}^2_{\mathrm{mn}} + \mathrm{Q}^2_{\mathrm{mn}})\mathrm{R}_{\mathrm{mn}}}{(\mathrm{V}_{\mathrm{n}})^2} \tag{2}$$

$$\mathrm{Q}_{\mathrm{Loss(mn)}} = \frac{\mathrm{P}^2_{\mathrm{mn}} + \mathrm{Q}^2_{\mathrm{mn}})\mathrm{X}_{\mathrm{mn}}}{(\mathrm{V}_{\mathrm{n}})^2} \tag{3}$$

The total real (P_{TL}) and reactive power (Q_{TL}) losses of the network scheme are obtained by summing all the line power losses stated by

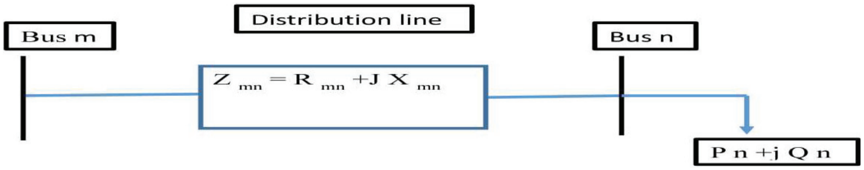

Figure 1 Electrical equivalent circuit of a radial topology.

Equations (4) and (5),

$$\mathrm{P_{TL}} = \sum_{\mathrm{m=1}}^{\mathrm{nl}} \mathrm{P_{Loss}(mn)} \tag{4}$$

$$\mathrm{Q_{TL}} = \sum_{\mathrm{m=1}}^{\mathrm{nl}} \mathrm{Q_{Loss}(mn)} \tag{5}$$

The Loss Sensitivity Factor is a critical factor in determining candidate nodes or buses for DG source and D-STATCOM device deployment [5]. The normalised voltages can then be obtained by solving Equations (6) and (7) as shown below. If the uncompensated bus voltages are less than 1.01, the nodes are designated as candidate nodes for the deployment of the Distributed STATCOM device and DG source. The Loss Sensitivity factors is attained by partially differentiating Equations (2) and (3)

$$\frac{\partial \mathrm{P_{Loss(mn)}}}{\partial \mathrm{P_n}} = \frac{2\mathrm{P_n} * \mathrm{R_{mn}}}{(\mathrm{V_n})^2} \tag{6}$$

$$\frac{\partial \mathrm{Q_{Loss(mn)}}}{\partial \mathrm{Q_n}} = \frac{2\mathrm{Q_n} * \mathrm{X_{mn}}}{(\mathrm{V_n})^2} \tag{7}$$

3 Problem Formulation

The motive of present research work is to minimize the total real power loss, total cost, and enhancement of voltage magnitude profile by simultaneous sizing and locating of DG source and Distributed STATCOM device stated by Equation (8) subjected to security limitations mentioned below. The cost factors utilized are stated in Table 1 [26].

$$\mathrm{Cost} = \mathrm{A_p} * \mathrm{P_{Loss}} * \mathrm{H} + \mathrm{A_d} * \sum_{\mathrm{j=1}}^{\mathrm{m}} \mathrm{P_{cj}} + \mathrm{A_c} * \sum_{\mathrm{k=1}}^{\mathrm{n}} \mathrm{Q_{ck}} \tag{8}$$

Table 1 Cost factors

Energy cost (Ap)	0.06 $/kwh
DSTATCOM cost for every kVAr (Ac)	50 $/kVAr
DG cost for every kW (Ad)	1 $/kW

Equality Constraints

Total real power generation of the structure is equated to the real power requirement and real power losses.

$$\mathrm{P_{Sw}} + \sum_{\mathrm{b=1}}^{\mathrm{nb}} \mathrm{P_{DG}(b)} = \sum_{\mathrm{i=1}}^{\mathrm{nb}} \mathrm{Pn(i)} + \sum_{\mathrm{j=1}}^{\mathrm{nl}} \mathrm{P_{Loss(mn)}(j)} \tag{9}$$

The structure total reactive power generation is equated to reactive power requirement plus reactive power losses

$$\mathrm{Q_{Sw}} + \sum_{\mathrm{a=1}}^{\mathrm{nb}} \mathrm{Q_{stat}(a)} = \sum_{\mathrm{i=1}}^{\mathrm{nb}} \mathrm{Qn(i)} + \sum_{\mathrm{j=1}}^{\mathrm{nl}} \mathrm{Q_{Loss(mn)}(j)} \tag{10}$$

Inequality Constraints

The various inequality constraints are:

(i) Voltage constraints:
The magnitude of node voltages must be between the $\mathrm{V_{min}}$ and $\mathrm{V_{max}}$ at all buses.

$$\mathrm{V_{n,min}} \leq |\mathrm{V_n}| \leq \mathrm{V_{n,max}} \quad n = 1 \ldots nb \tag{11}$$

(ii) Reactive power constraints:
DSTATCOM reactive power injected $\mathrm{Q_{stat}(a)}$ should not exceed the overall reactive power requirement $\mathrm{Qn(i)}$

$$\sum_{\mathrm{a=1}}^{\mathrm{nb}} \mathrm{Q_{stat}(a)} \leq \sum_{\mathrm{i=1}}^{\mathrm{nb}} \mathrm{Qn(i)} \tag{12}$$

(iii) DG rating constraints:

$$\mathrm{P_{DGn,min}} \leq \mathrm{P_{DG,n}} \leq \mathrm{P_{DGn,max}} \quad \mathrm{n = 1 \ldots nb} \tag{13}$$

(iv) D-STATCOM rating constraints:

$$\mathrm{Q_{stat,nmin}} \leq \mathrm{Q_{stat.n}} \leq \mathrm{Q_{stat,nmax}} \quad \mathrm{n = 1 \ldots nb} \tag{14}$$

4 Load Model

For the static load model, the actual and reactive powers are:

$$\mathrm{P} = \mathrm{P_o}\left(\frac{\mathrm{V}}{\mathrm{V_o}}\right)^{\mathrm{n_p}} \tag{15}$$

$$\mathrm{Q} = \mathrm{Q_o}\left(\frac{\mathrm{V}}{\mathrm{V_o}}\right)^{\mathrm{n_q}} \tag{16}$$

Where, $\mathrm{P_o}$ and $\mathrm{Q_o}$ are the real and reactive powers at bus set voltage $\mathrm{V_o}$. V indicates bus load voltage, $\mathrm{n_p}$ and $\mathrm{n_q}$ are the load exponents.

The following are the values assigned for load exponents:

$\mathrm{n_p}$ and $\mathrm{n_q}$ = '0' value assigned for the "Constant Power load model".
$\mathrm{n_p}$ and $\mathrm{n_q}$ = '1' value assigned for the "Constant Current load model".
$\mathrm{n_p}$ and $\mathrm{n_q}$ = '2' value assigned for the "Constant Impedance load model"[19].

4.1 Polynomial Load Model

$$P = P_0\left[a_p\left(\frac{V}{V_0}\right)^2 + b_p\left(\frac{V}{V_0}\right)^2 + C_p\right] \tag{17}$$

$$Q = Q_0\left[a_q\left(\frac{V}{V_0}\right)^2 + b_q\left(\frac{V}{V_0}\right)^2 + C_q\right] \tag{18}$$

Where, value 1 is provided to the sum of the polynomial load coefficients for P and Q load. Therefore, $a_p + b_p + c_p = 1$ and $a_q + b_q + c_q = 1$. Assuming each load type constitutes 1/3rd of the total load, the simulation parameters considered are $a_p = a_q = 0.33$; $b_p = b_q = 0.33$; $c_p = c_q = 0.33$. At specified voltage V_o, P_o and Q_o represent active and reactive power.

4.2 Load Growth Model

"Load growth" is reflected for planning of distribution network [19].

$$\text{Load demand} = \text{Load demand} * (1 + \mathrm{R})^{\wedge}\mathrm{T} \tag{19}$$

$$\mathrm{R} = \text{annual load growth rate } (7\%) \tag{20}$$

$$\mathrm{T} = \text{period } (5 \text{ years}) \tag{21}$$

5 PSO Algorithm

PSO was invented in 1995 by Kennedy and Eberhart. “Particle swarm optimization (PSO) is a meta-heuristic optimization technique inspired by bird flocking’s social behaviour. A population (swarm) of potential solutions is used to solve the PSO (particles). Each particle in search space adjusts its “flying” based on its own flying experience (personal best position) and that of other particles (global best position) [11]”.

$$\mathrm{X = L + rand * (U - L)} \tag{22}$$

$$\mathrm{w = w_{max} - \frac{[(w_{max} - w_{min}) * current\ generation\ number]}{Maximum\ generation\ number}} \tag{23}$$

$$\mathrm{v_i^{KH} = [wv_i^k + c_1r_1(p_{best} - x_i^k) + c_2r_2(g_{best} - x_i^k)]}$$

$$\mathrm{v_i^{KH} = [wv_i^k + c_1r_1(p_{best} - x_i^k) + c_2r_2(g_{best} - x_i^k)]} \tag{24}$$

Improved particle swarm optimization (IPSO)

$$\mathrm{v_i^{K+1} = c * [wv_i^k + c_1r_1(p_{best} - x_i^k) + c_2r_2(g_{best} - x_i^k)]} \tag{25}$$

$$\mathrm{X_i^{k+1} = X_i^k + V_i^{k+1}} \tag{26}$$

$$\mathrm{c = \frac{2}{(2 - \emptyset - \emptyset 1)}} \tag{27}$$

$$\emptyset 1 = \sqrt{(\emptyset^2 - 4\emptyset)} \tag{28}$$

c is the constriction coefficient and value can be calculated from acceleration coefficients limits $\emptyset$ and $\emptyset 1$. Here $\emptyset$ parameter is varied between limits $\emptyset_{\mathrm{min}}$ and $\emptyset_{\mathrm{max}}$.

The steps involved in implementing PSO for combined assignment of the DG source and DSTATCOM device in the distribution network are presented.

Step 1: Provide the input values: base MVA, base kV, line data, bus data for the load flow software.

Step 2: For distribution power flow analysis, compute actual and reactive power losses, as well as voltage magnitude at all buses, using the Backward/Forward sweep algorithm (Base case).

Step 3: Compute loss sensitivity factors using Equations (6) and (7). Then identify candidate nodes or buses for assignment of D-STATCOM device and DG source at the same time.

Step 4: Assign the population size, c1, c2, the maximum number of iterations, search dimensions.

Step 5: Set minimum limits, step size, maximum limits for the capacity of DG source and DSTATCOM device.

Step 6: Set the number of candidate buses to find the best location for the DG source and D-STATCOM device.

Step 7: Assign lower and upper bound for candidate buses, DG source, D-STATCOM device capacity.

Step 8: Obtain initial population randomly within search space between the limits U and L using Equation (22).

Step 9: Evaluate the objective function corresponding to particles and find particle velocities.

Step 10: Every particle moves at a velocity to the optimum point. The velocity of every particle is presumed to be zero. Set number k for iteration. Find the following two significant parameters in the k^{th} iteration.

(i) Obtain the best historical value of $\mathrm{P}_{\mathrm{best}}$ that was found in the previous iteration by particle.

(ii) Find the historical best value of $\mathrm{G}_{\mathrm{best}}$ that was found by each of the particles in all previous iteration.

(iii) Find i^{th} particle V_{i} velocities in the k^{th} iteration using Equation (24).

Step 11: Find the location of i^{th} particle in k^{th} iteration by Equation (26).

Step 12: If every particle position converges to the identical values, then the method is converged. If convergence is not reached, step 10 is repeated by updating the $\mathrm{k} = \mathrm{k} + 1$ iteration number by calculating the new $\mathrm{P}_{\mathrm{best}}$, i, and $\mathrm{G}_{\mathrm{best}}$ Values. The iterative process continues till all the particles converge to an optimum result.

6 Simulation Results and Analysis

In this research work, distinctive scenarios are reflected to appraise the performance of the projected method. Various load models are considered to illustrate the real time distribution for power structure planning. The simultaneous assignment of DG source and D-STATCOM compensating devices to decrease real power losses and better voltage magnitude profile has

Table 2 Parametric quantity utilized in PSO algorithm

Number of population	20
Acceleration constant ‘c1’	0.9
Acceleration constant ‘c2’	0.9
Search dimensions	4
Inertia constant w_{max}	0.8
Inertia constant w_{min}	0.1
$Ø_{max}$	0.42
$Ø_{min}$	0.41

been achieved by applying the PSO algorithm. All situations are encoded in MATLAB and simulations are executed on IEEE 33 node and IEEE 69 node test radial distribution structure. The suggested method is tested at different loading conditions: Light load factor (0.6), Nominal load factor (1.0), and Heavy load factor (1.6). Parameters utilized in PSO algorithm are presented in Table 2.

Scenario 1: Distribution network excluding DG source and D-STATCOM device
Scenario 2: Distribution network with DG source installation
Scenario 3: Distribution network with D-STATCOM device installation
Scenario 4: Distribution structure with simultaneous location of DG source and D-STATCOM device installation.

The projected technique is initially examined on IEEE 33 node radial test structure. The system has a overall real power requirement of 3715 kW and a reactive power requirement of 2300 kVAr. Backward Forward Sweep Procedure is performed to select the candidate nodes or buses. The power flow analysis is executed with the value $S_{base} = 1$ MVA and $V_{base} = 12.66$ kV. The distribution line and load demand information are referred from [2]. PSO algorithm is simulated for sizing and placement of D-STATCOM device and DG source from the determination of candidate nodes or buses.

6.1 IEEE 33 Bus Network

The single line diagram for IEEE 33 node radial topology is illustrated in Figure 2.

PSO algorithm is applied for sizing and assignment of D-STATCOM device and DG source established on candidate nodes or buses. The numerical values obtained for IEEE 33 test system using PSO for four scenarios under

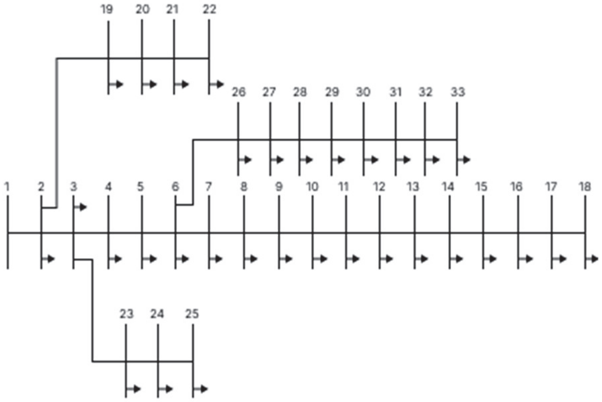

Figure 2 IEEE 33 node test system radial topology.

different load factors for the constant power, polynomial, and load growth model are furnished in Table 3.

It is observed from the Table 3 results, for combined placement of DG source and DSTATCOM device during a nominal load condition, rating and position of the DG source requirement are 150(33), 100(33), 900(33) kW, and DSTATCOM device is 50(18), 50(28), 50(18) kVAr for constant, polynomial, load growth model respectively. During light load conditions, the size and location of the DG source requirement are 50(33), 50(33), 50(33) kW, and DSTATCOM device is 50(29), 50(18), 50(18) kVAr for constant, polynomial, and load growth model respectively. During heavy load conditions, the size and location of DG source estimated are 3600(33), 3600(33), 2950(33) kW, and DSTATCOM device is 50(18), 50(18), 50(18) kVAr for a constant, polynomial and loads growth model respectively.

The losses estimated for the polynomial load model are 2.7, 7.7, 10.2 during light load factor, nominal load factor, and heavy load factor situation. Similarly, losses estimated for the constant power model are 3.1, 86, 74 under light load factor, nominal load factor, and heavy load factor situation.

The minimal voltage magnitude (p.u) improved to 0.9543(18), 0.9226(18), 0.9009(6) (polynomial load model) from 0.9509(18), 0.921(18), 0.9014(18) (constant power model) during light load factor, nominal load factor and heavy load factor situation.

The percentage net saving estimated for the polynomial load model is 87.87,92.70, 95.10 during light load factor, nominal load factor and heavy load factor situation. similarly, percentage savings calculated for the constant

Table 3 Assessment of IEEE 33 bus test system for various load models with diverse factors

		Constant Power Model			Load Growth Model			Polynomial Load Model		
Cases	Parametric Quantity	Light Load Factor	Nominal Load Factor	Heavy Load Factor	Light Load Factor	Nominal Load Factor	Heavy Load Factor	Light Load Factor	Nominal Load Factor	Heavy Load Factor
Scenario-1	PLoss(kW)	68.7	202.7	575.3	95.3	426.3	1300	62.3	173.3	445.8
Without DG and	Vmin(pu)	0.9495 (18)	0.9131 (18)	0.8528 (18)	0.9405 (18)	0.8735 (18)	0.7772 (18)	0.9522 (18)	0.9202 (33)	0.872 (18)
DSTATCOM	Cost($/year)	36124* 10ˆ4	106530	3.02*10ˆ5	50068	224060	683500	3274488	91086	234312
	%Net saving	–	–	–	–	–	–	–	–	–
Scenario-2	PLoss (Kw)	3.1	89	84	43	55	59.6	2.8	7.7	11.1
DG placement	Vmin(pu)	0.9507 (18)	0.9174 (18)	0.9014 (18)	0.942 (18)	0.9009 (18)	0.9005 (18)	0.9526 (18)	0.9202 (18)	0.9009 (18)
	%Loss reduction	95.4	56.09	83.39	54.87	87.04	95.41	95.5	95.5	97.51
	DG size(Kw)	50	150	3600	50	3900	3200	50	150	3600
	DG bus	33	33	33	33	33	6	33	33	33
	Cost($/year)	1679.36	46928	47750.4	22650	32808	34525	1469.1	4197.1	9434
	%Net saving	95.35	55.08	84.19	54.75	85.35	94.94	95.51	95.39	95.97
Scenario-3	PLoss (Kw)	3.1	107	252	43	260	54.6	2.9	9.3	20.4
DSTATCOM placement	Vmin(pu)	0.9505 (18)	0.9189 (33)	0.8602 (18)	0.9419 (18)	0.9000 (33)	0.7944 (18)	0.9524 (18)	0.9222 (18)	0.8728 (18)
	%Loss reduction	95.4	47.21	56.1	54.87	39.05	95.8	95.3	94.63	95.42
	DSTATCOM size(kVAr)	50	50	50	50	1350	50	50	50	5
	DSTATCOM bus	33	18	33	33	18	33	33	18	33
	Cost($/year)	4129.36	56241	134951	25100	2041.56	31197	4024.24	7388	13222
	% Net saving	88.56	47.20	55.31	49.86	8.8	95.43	87.71	91.88	94.37
Scenario-4	PLoss (Kw)	3.1	86	74	41	48	20.6	2.7	7.7	10.2
Simultaneous Placement of	Vmin(pu)	0.9509 (18)	0.921 (18)	0.9014 (18)	0.9424 (18)	0.9099 (4)	0.9021 (6)	0.9543 (18)	0.922 (18)	0.9009 (6)
DG and DSTATCOM	%Loss reduction	95.4	57.57	87.13	56.9	88.74	98.41	95.66	95.55	97.71
	DG size(Kw)	50	150	3600	50	900	2950	50	100	3600
	DG bus	33	33	33	33	33	33	33	33	33
	DSTATCOM size(kVAr)	50	50	50	50	50	50	50	50	50
	DSTATCOM bus	29	18	18	18	18	18	18	28	18
	Cost($/year)	4179.36	47851	44994	24099	31628	16277	3969.12	6647	11461
	%Net saving	88.43	55.08	85.10	51.86	85.88	97.61	87.87	92.70	95.10

power model is 8.43, 55.08, 85.10 under light load factor, nominal load factor and heavy load factor situation.

The network voltage magnitude profile of the IEEE 33 node radial topology for four scenarios under heavy load conditions for the constant power, polynomial and load growth model are demonstrated in Figures 3, 4, and 5 respectively.

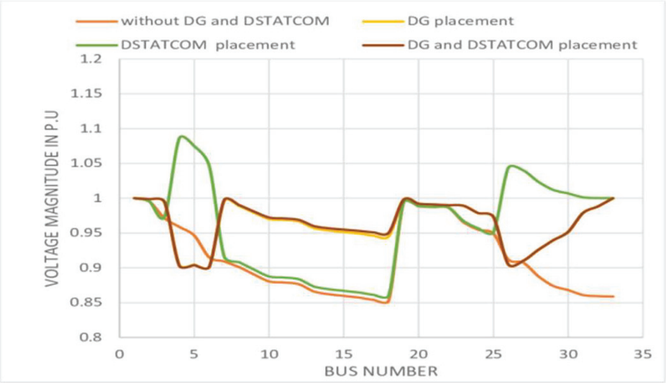

Figure 3 IEEE 33 test system distribution network voltage magnitude profile for constant power load model under heavy load condition.

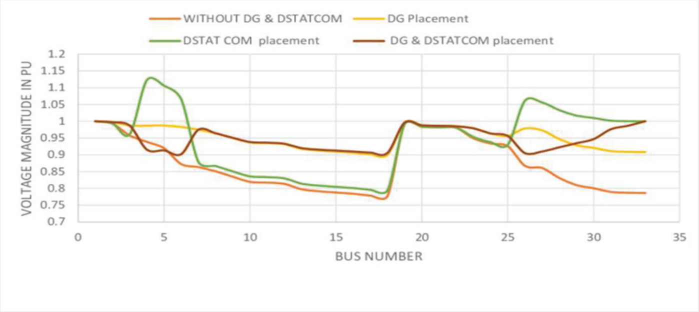

Figure 4 IEEE 33 test system utility distribution scheme voltage magnitude profile for polynomial load model under heavy load condition.

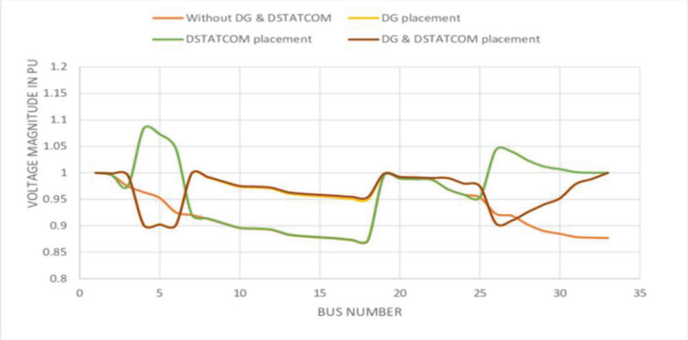

Figure 5 IEEE 33 test system radial distribution network voltage profile for load growth model under heavy load condition.

6.2 IEEE 69 Bus Network

The single line diagram for IEEE 69 node radial distribution network is represented in Figure 6. The proposed method is examined on IEEE 69 node test system. The test system has a overall real power requirement of 3.8 MW and reactive power requirement of 2.7 MVAr. The power flow analysis is performed with the value S_base = 1 MVA and V_base = 12.66 kV. The distribution line and load data information are considered from [2]. PSO algorithm is applied for sizing and assignment of DG source and DSTATCOM device from the determination of candidate nodes or buses.

The numerical values obtained for the IEEE 69 test system using PSO for four scenarios under different load factors for the constant power, polynomial, and load growth model furnished in Table 4.

The results of Table 4 shows that, for combined placement of DG source and DSTATCOM device for the IEEE 69 node test scheme, during nominal load situation, size and location of DG source requirement are 450(65), 100(65), 100(65) kW, and DSTATCOM device is 100(21), 100(21), 100(21) kVAr for constant, polynomial, and load growth model respectively. Similarly, for light load conditions, the size and location of the DG source are 100(65), 200(65), 200(65) kW, and the DSTATCOM device is 100(61), 100(61), 100(61) kVAr for a constant, polynomial, and load growth model respectively. During heavy load conditions, the size and location of the

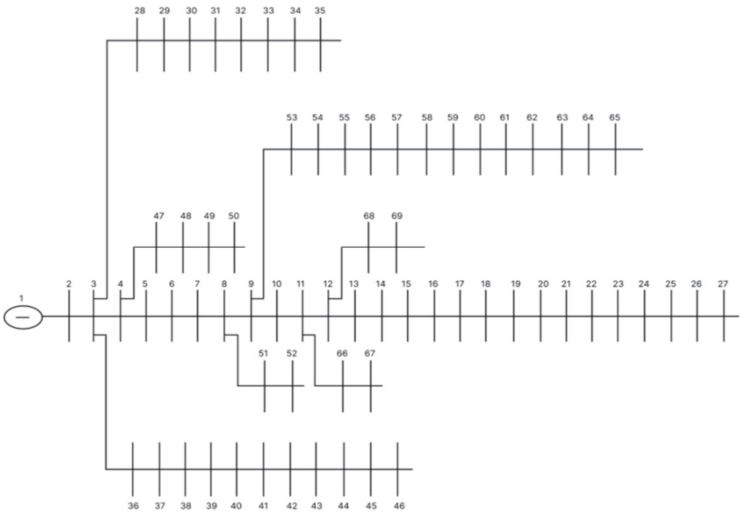

Figure 6 IEEE 69 node radial distribution structure.

Table 4 Assessment of IEEE 69 node test scheme for various load models with diverse factors

		Constant Power Model			Load Growth Model			Polynomial Load Model		
Cases	Parametric Quantity	Light Load Factor	Nominal Load Factor	Heavy Load Factor	Light Load Factor	Nominal Load Factor	Heavy Load Factor	Light Load Factor	Nominal Load Factor	Heavy Load Factor
Scenario-1	PLOSS (kW)	80.4	224.9	622.4	161.4	470.1	1297	161.4	470.1	1297
Without DG and	Vmin (pu)	0.9447 (65)	0.908 (65)	0.8534 (65)	0.9225 (65)	0.8713 (65)	0.7953 (65)	0.9225 (65)	0.8713 (65)	0.7953 (65)
DSTATCOM	Cost ($/year)	423000	118207	327000	84830	247000	682100	84830	247000	682100
	%Net saving	–	–	–	–	–	–	–	–	–
Scenario-2	PLoss (Kw)	10.4	34.1	103.8	22.2	76.8	224.6	22.2	76.8	224.6
DG	Vmin (pu)	0.9724	1.0	0.9326	0.9619	0.9724	0.907	0.9619	0.9724	0.9073
placement	%Loss reduction	87.06	84.48	83.33	86.24	83.66	82.68	86.24	83.66	82.68
	DG size(Kw)	100	450	900	250	800	1150	250	800	1150
	DG bus	65	65	65	65	65	65	65	65	65
	Cost ($/year)	5580	18380	55481	11900	41147	119210	11900	41147	119210
	%Net saving	98.68	84.4	83.03	98.68	83.34	82.52	98.68	83.34	82.52
Scenario-3	PLoss (Kw)	10.8	51.8	84.1	28.8	63.5	175.6	28.8	63.5	175.6
DSTATCOM	Vmin(pu)	0.9722	1.0	0.924	0.9621	0.9722	0.891	0.9621	0.9722	0.8914
placement	%Loss reduction	85.56	76.96	86.48	82.1	86.4	86.46	82.1	86.4	86.46
	DSTATCOM size (kVAr)	100	1050	100	550	100	100	550	100	100
	Cost ($/year)	10700	79751	149000	42612	138370	197270	42612	138370	197270
	%Net saving	97.47	32.43	54.43	97.47	43.97	71.07	97.47	43.97	71.07
Scenario-4	PLoss (Kw)	7.1	30.7	94.2	21.6	69.5	189.9	21.6	69.5	189.9
Simultaneous	Vmin (pu)	0.9722	1.0	0.9358	0.9619	0.9722	0.9164	0.9619	0.9722	0.9164
Placement of	%Loss reduction	91.11	86.3	84.86	86.6	85.2	85.35	86.6	85.2	85.35
DG and	DG size(Kw)	100	450	900	200	100	150	200	100	150
DSTATCOM	DG bus	65	65	65	65	65	65	65	65	65
	DSTATCOM size (kVAr)	100	100	100	100	100	200	100	100	200
	DSTATCOM bus	61	21	21	61	21	21	61	21	21
	Cost ($/year)	8830	21600	55400	16577	42340	110960	16577	42340	110960
	%Net saving	97.91	81.72	83.05	91	82.85	83.73	91	82.85	83.73

DG source are 900(65), 150(33), 150(65) kW, and DSTATCOM device is 100(21), 200(21), 200(21) kVAr for a constant, polynomial and loads growth model respectively.

The losses estimated for the polynomial load model are 21.6, 69.5, 189.9 during light load factor, nominal load factor, and heavy load factor situation. Similarly, losses estimated for the constant power model are 7.1, 30.7, 94.2 under light load factor, nominal load factor, and heavy load factor situation.

The lowest voltage magnitude (pu) estimated for the polynomial load model is 0.9619, 0.9722, 0.9164 during light load factor, nominal load factor, and heavy load factor situation. Similarly, the lowest voltage magnitude (pu)

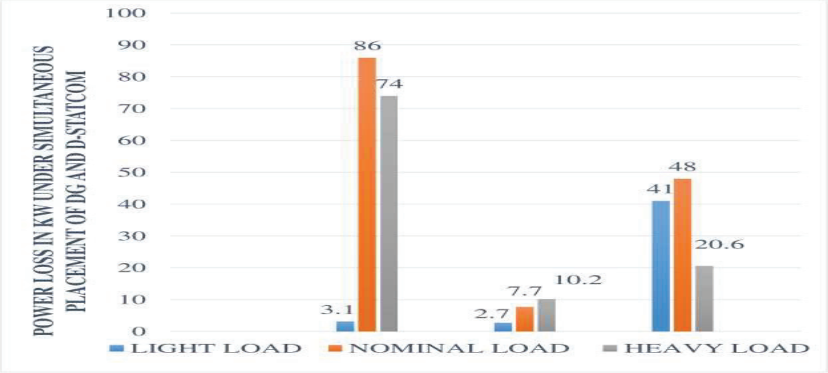

Figure 7 IEEE 33 node test system radial distribution network power loss under various load models.

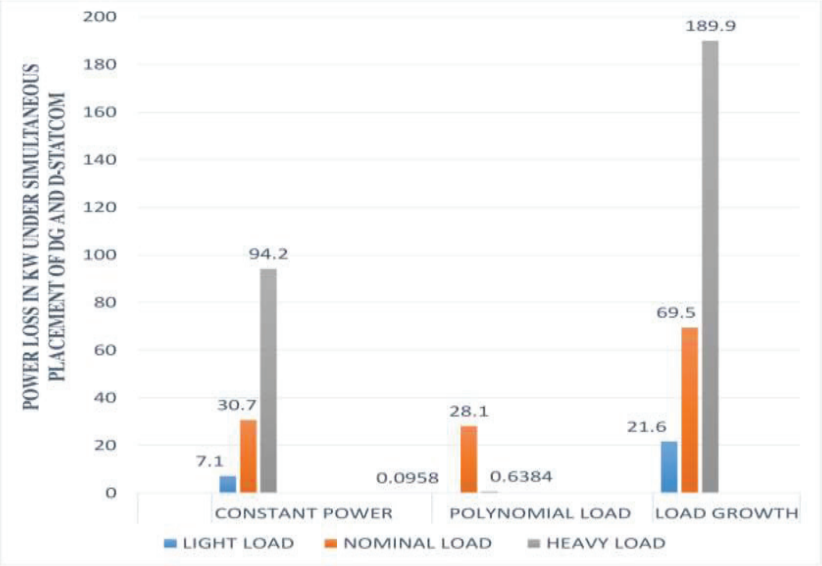

Figure 8 IEEE 69 node test system radial distribution network power loss under various load models.

estimated for the constant power model are 0.9722, 1, 0.9358 under light load factor, nominal load factor, and heavy load factor situation.

The distribution power loss estimated for IEEE 33 node radial test scheme and IEEE 69 node radial test scheme under various load models are demonstrated in Figures 7 and 8 respectively.

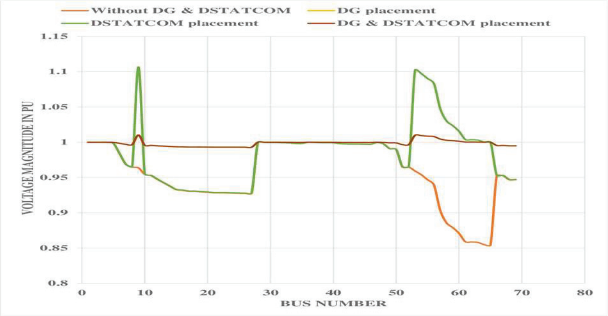

Figure 9 IEEE 69 test system radial distribution network voltage magnitude profile for constant power load model under heavy load condition.

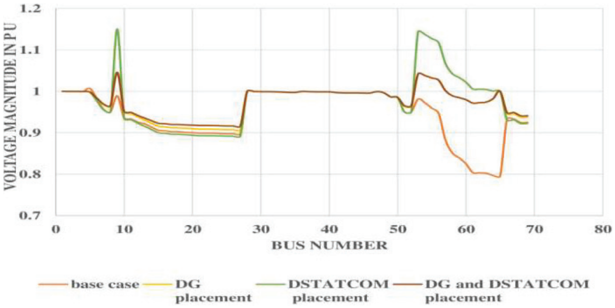

Figure 10 IEEE 69 test system radial distribution network voltage magnitude profile for load growth model under heavy load condition.

The network voltage magnitude profile of the IEEE 69 test system radial distribution structure for four scenarios under heavy load conditions for the constant power, polynomial, and load growth model are portrayed in Figures 9, 10, and 11 respectively.

The results obtained from the present work are compared with those accessible in literature and are presented in Tables 5 and 6 for IEEE 69 node and IEEE 33 node radial system.

In the present work, with simultaneous assignment of D-STATCOM device and DG source in IEEE 69 node radial distribution scheme, it is observed from Table 5 that to attain a voltage profile of 1 p.u the DG source size and DSTATCOM device size requirement is drastically reduced as compared to the results accorded in the literature. Also, it is observed that, with simultaneous positioning of DSTATCOM device and DG source in IEEE 69 radial topology, losses are relatively reduced for optimized DG

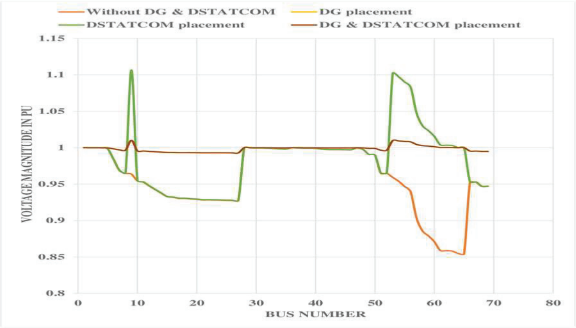

Figure 11 IEEE 69 test system radial distribution network voltage magnitude profile for polynomial load model under heavy load condition.

Table 5 Comparison of simulated results for IEEE 69 radial distribution test scheme for constant power model under nominal load condition

Scenario	Parameter	Proposed Method	Aadesh Kumar [13] GSA	Yuvaraj [1] CSA	Vittal Bhat [27] FPA
Without DG and DSTATCOM placement	Ploss(kW)	224.9	186.63	225	224.9
	Vmin(pu)	0.908	–	0.9090	0.908
	Cost $/year	118207.4	–	–	118207.4
DG placement	Ploss(kW)	34.1	63.13	83.21	–
	Vmin(pu)	1	–	0.9679	–
	Cost($/year)	18380	–	9696.3	–
	DGsize (Location)(kW)	450(65)	1870(60)	1873(61)	–
DSTATCOM placement	Ploss(kW)	51.8	123.21	152.07	–
	Vmin(pu)	1	–	0.9285	–
	Cost($/year)	79751	–	6611.8	–
DG & DSTATCOM placement	Ploss(kW)	30.7	8.46	24.15	32.24
	Vmin(pu)	1	–	0.9715	0.956
	Cost($/year)	21600	–	14596.6	19900
	DG size (kW) DG bus	450(65)	1870(60)	1750(61)	450(65)
	DSTATCOM(kVAr) DSTATCOM bus	100(21)	1320(60)	1150(61)	50(24)

source rating of 450 kW at bus number 65 and D-STATCOM device rating of 100 kVAr at bus number 21.

In the present work, with combined assignment of D-STATCOM device and DG source in IEEE 69 node radial distribution scheme, it is observed

Table 6 Comparison of simulated results for IEEE 33 node test scheme for constant power model under nominal load condition

Scenario	Parameters	Proposed	Aadesh Kumar [13] GSA	Devabalaji & Ravi [4] BFOA	Vittal Bhat [27] FPA
Without DG and DSTATCOM placement	Ploss (kW)	202.7	210.9	210.98	202.7
	Vmin (pu)	0.9131	0.9037	0.9037	0.913
	Cost $/year	106530	–	–	106525
DG placement	Ploss (kW)	89	111.03	111.17	–
	Vmin (pu)	0.9174(18)	–	–	–
	Cost($/year)	46928	–	–	–
	DGsize (Location)(kW)	150(33)	2570(6)	2690(6)	–
DSTATCOM placement	Ploss (kW)	107	141.63	(IA) 171.81	–
	Vmin (pu)	0.9189(33)	–	–	–
	Cost($/year)	56241	–	–	-
	DSTATCOM Size(kVAr) (Location)	50(18)	1250(30)	1490(12)	–
Simultaneous DG & DSTATCOM placement	Ploss (kW)	86	51.18	70.87	85.97
	Vmin (pu)	0.921	–	–	0.9205
	Total cost($/year)	47851	–	–	47840
	DG size (KW) (location)	150(33)	2570(6)	1090(30)	150(33)
	DSTATCOM Size(kVAr) (location)	50(18)	1240(30)	1230(10)	50(18)

from Table 6 that to attain a voltage profile of 0.921 pu the DG source size and DSTATCOM device size requirement is drastically reduced as compared to the results accorded in the available literature. Also, it is observed that, with simultaneous positioning of DG source and D-STATCOM device in IEEE 33 node radial topology losses are relatively reduced for optimized DG source rating of 150 kW at bus number 33 and DSTATCOM device rating of 50 kVAr at bus number 18.

7 Conclusion

In this research work, a PSO-based optimization technique is applied for simultaneous placing of D-STATCOM device and DG source allocation to minimize the overall real power losses, total cost, and voltage magnitude profile improvement for diverse load models under nominal, light load & heavy load situations and the results are presented. The impact of various load models is investigated to realize actual load conditions for the sizing and positioning of Distributed Generation source and D-STATCOM device. The simulation results for a nominal load condition shows that the size of the DG source requirement changes for different models, however, the location remains the same. It is also observed from the result that, the size requirement of the DSTATCOM device is the same for various load models, however, the location changes for the nominal load. The simulation results for light load conditions show that size and location of DG source will not change for load models considered, however, for DSTATCOM device size remains the same, and location changes. In the simulation results for heavy load conditions, it is observed that the size requirement of DG source changes, and the location remains the same.

Also, it is observed that when load demand grows, power loss increases. The required DSTATCOM device rating (KVAr) also increases and change in the location is essential to reach the load growth demand for larger systems. The size of the DG requirement also increases and the location remains same for various load factors considered. The simulated results are compared with the available techniques and validated.

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