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DSTATCOM allocation in distribution networks considering load variations using bat algorithm

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Voltage Stability Index (VSI);
Distribution Network Operators (DNOs);
Curve Fitting Technique (CFT)

Abstract This paper proposes a new method of scheduling for optimal placement and sizing of Distribution STATic COMpensator in the radial distribution networks to minimize the power loss. In the proposed method Voltage Stability Index is used to search the optimal placement for installation of DSTATCOM. Optimal size of DSTATCOM is found by using bat algorithm. The feeder loads are varied by linearly from light load to peak load with a step size of 1%. In each load step, the optimal placement and sizing for DSTATCOM are calculated. By using the Curve Fitting Technique, the optimal sizing for DSTATCOM per load level is formulated in the form of generalized equation. The proposed approach will help the Distribution Network Operators to select the DSTATCOM size according to the load changes. To check the feasibility of the proposed method, system has been tested on two standard buses such as IEEE 33 and 69 bus radial distribution systems.

1. Introduction

In recent years, the distribution networks have attained much attention by the researchers because it plays a vital role in power system quality and planning. To introduce deregulation in power system, it causes the power quality problems such as voltage fluctuation, voltage sag and voltage instability in the distribution system. These power quality problems lead to power loss increase, slower response time and decrease in power flow limits [1,2]. From the literature it is observed that 13% of total generated power is wasted as a loss in the distribution side [3]. From the consumer point of view, the power loss reduction is one of the major important issues to improve the overall efficiency of the power delivery.

To resolve this issue completely, it requires to use highly advanced equipments for power loss reduction in the distribution network. Such equipments are capacitor banks, shunt and series reactors, automatic voltage regulator (AVR) or recently developed Distribution network Flexible AC Transmission (DFACTS) such as Distribution Static compensator (DSTATCOM), Unified Power Flow Conditioner (UPQC), and Static Synchronous Series Compensator (SSSC) [8]. Compared with other reactive power compensation devices, DSTATCOM has many features such as low power losses, less harmonic

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Nomenclature

P_t	real power load at bus t
Q_t	reactive power load at bus t
$P_{t,t+1}$	real power flowing in the line between buses t and $t+1$
$Q_{t,t+1}$	reactive power flowing in the line between buses t and $t+1$
$P_{t+1,eff}$	total effective real power supplied beyond the bus $t+1$
$Q_{t+1,eff}$	total effective reactive power supplied beyond the bus $t+1$
$P_{Loss(t,t+1)}$	power loss in the line section between buses t and $t+1$ without DSTATCOM
V_t	voltage magnitude at bus t
I_t	equivalent current injected at node t
$J_{t,t+1}$	branch current in the line section between buses t and $t+1$
$J_{t,t+1,max}$	maximum branch current limit of line section between buses t and $t+1$
$\text{DSTATCOM}_{cost,year}$	annual cost of DSTATCOM
nb	total number of branches
η	load coefficient
$R_{t,t+1}$	resistance of the line section between buses t and $t+1$
B	asset rate of return
T	hours per year
$P_{Loss}^{with\ DSTATCOM}$	total power loss after installation of DSTATCOM
$Q_{DSTATCOM}^{kVAr}$	reactive power injecting to the network by DSTATCOM
K_p	energy cost of losses
K_c	time duration proportion
$n_{DSTATCOM}$	longevity of DSTATCOM
TACS	Total Annual Cost Saving
V_t^{min}	minimum voltage limits of the buses
V_t^{max}	maximum voltage limits of the buses
$X_{t,t+1}$	reactance of the line section between buses t and $t+1$
DSTATCOM_{cost}	cost of investment in the year of allocation

production, high regulatory capability, low cost and compact size [7]. In addition, the DSTATCOM does not have any operational problems such as resonance or transient harmonics unlike shunt or series capacitors [7].

DSTATCOM is a shunt connected Voltage Source Converter (VSC) which has been used in distribution networks to compensate the bus voltage so as to provide improved power factor and reactive power control. DSTATCOM has the capability of providing quick and continuous capacitive and inductive mode compensation. DSTATCOM can inject sufficient amount of leading or lagging compensating current when it is associated with a specific load so that the total demand meets the specification for utility connection [4]. Simultaneously, it can clean up the voltage from any unbalance and harmonic distortion [5]. DSTATCOM is predicted to play significant role in the radial distribution systems due to the increasing power system load. Optimum allocation of DSTATCOM maximizes the load ability, power loss minimization, stability enhancement, reactive power compensation and power quality enhancement such as voltage regulation, voltage balancing a flicker suppression system [6].

Based on the literature review, determination of the optimal location and sizing of DSTATCOM has a considerable impact on radial distribution system. Only a few researchers worked under the area of DSTATCOM allocation. To find the optimal location of the DSTATCOM, various researchers have implemented various optimization algorithms such as differential evolution [7], immune algorithm [8], and particle swarm optimization algorithm [9]. In Ref. [7], a differential evolution algorithm is presented for optimal DSTATCOM allocation in radial distribution system with reconfiguration consideration. In [8], an immune algorithm approach for determining the optimal location and size of DSTATCOM with an objective function of power and energy losses reduction was investigated. Then in [9] particle swarm optimization algorithm is used for determining the optimal location and sizing of DSTATCOM and DG with an objective function of power loss minimization and voltage profile improvement. So many research work has been carried out on optimal allocation of STATCOM in transmission systems using different optimization techniques such as particle swarm optimization (PSO) and genetic algorithm (GA) [10–12].

Recently, a new meta-heuristic optimization technique, known as bat algorithm has been developed by Yang in the year of 2010 [13]. It is one of the latest nature inspired algorithms, used to solve complex and multiobjective optimization problems in various fields as well as power system applications. The authors in [14] presented the application of bat algorithm to find optimal placement and size of the Distributed Energy Resources (DERs) with load variation for minimizing the power loss and voltage profile improvement. Then in Ref. [15] bat search algorithm is used to achieve optimal power flow for generation reallocation with Unified Power Flow Controller (UPFC). The authors in Ref. [16], found optimal spot pricing in electricity market with inelastic load by implementing bat algorithm. The authors designed conventional power system stabilizer for small signal stability [17] and also optimal design of power system stabilizers in multimachine environment is achieved [18] by applying bat algorithm.

From the above literature it can be observed that authors obtained encouraging results in finding the DSTATCOM placement in radial distribution networks. However, these methods consist of several drawbacks with respect to computational time in solving DSTATCOM and all the authors have focused only on three load levels (light, medium and peak) and the load variation has not been considered in radial distribution system. For each and every change in load steps affects variation the optimal size of DSTATCOM, it will cause uncertainty in the distribution system for minimization of power loss. In addition to that authors implemented only single

DSTATCOM in the distribution networks for minimization of power loss and failed to consider multiple DSTATCOMs in the radial distribution networks.

The authors in the present work focused to develop a fast and effective optimization technique to determine the optimal location and size of the single and multiple DSTATCOMs for power loss minimization in the radial distribution system. The location of DSTATCOM has been calculated by using Voltage Stability Index. Sizing of DSTATCOM has been calculated by using bio inspired bat algorithm. In this paper, the feeder loads are linearly changed from 0.5 (light) to 1.6 (peak) with a step size of 0.01. For each step change in load, the optimal location and sizing of DSTATCOM is evaluated. Curve Fitting Technique is used to find the optimal size of DSTATCOM at each load level which is formulated in the form of simple quadrature equation. The proposed work is more helpful for the DNOs to select size of DSTATCOM based on load steps. The feasibility and effectiveness of the proposed method have been tested with two standard IEEE buses such as 33-bus and 69-bus test systems and obtained simulation results are compared with other heuristic based algorithms.

2. Problem formulation

2.1. Power flow analysis

The traditional load flow studies such as Newton–Raphson, Gauss-Seidal and Fast Decoupled load flow methods are not suitable for finding the voltages and line flows in the radial distribution systems because of high resistance to reactance ratio (R/X). A Direct Approach for Distribution System Load Flow Solution has been used in [19]. The single line diagram of simple distribution system is shown in Fig. 1.

From Fig. 1, the equivalent injected current at node t is given as

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

Kirchhoff's current law is applied to calculate the branch current in the line section between buses t and $t+1$, and it is given as

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

By using of Bus Injected to Branch Current matrix (BIBC), the Eq. (2) is derived into matrix format

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

Kirchhoff's voltage law was applied to calculate the voltage at buses $t+1$, which is given as

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

The real and reactive power loss in the line section between buses t and $t+1$ can be calculated as

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

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

The total power loss P_{TLoss} of the distribution systems is calculated by addition of losses in all line sections, which is given by

$$P_{\mathrm{TLoss}} = \sum_{t=1}^{nb} P_{(\mathrm{Loss},t,t+1)} \tag{7}$$

2.2. Objective function

The objective of DSTATCOM placement in the radial distribution system is to minimize the total power losses while satisfying the equality and inequality constraints. The mathematical formulation of the objective function (F) is given by

$$\mathrm{Minimize}(F) = Min(P_{\mathrm{TLoss}}) \tag{8}$$

The considered equality and inequality constraints in the present problem are as follows:

2.2.1. Voltage deviation limit

$$V_t^{\min} \leqslant |V_t| \leqslant V_t^{\max}$$

2.2.2. Power balance constraints

$$P_{\mathrm{TLoss}} + \sum P_{D(t)} = \sum P_{\mathrm{DSTATCOM}(t)}$$

where $P_{D(t)}$ is the power demand at bus t and $P_{\mathrm{DSTATCOM}(t)}$ is the power generation using DSTATCOM.

2.2.3. Reactive power compensation

$$Q_{\mathrm{DSTATCOM}(t)}^{\min} \leqslant Q_{\mathrm{DSTATCOM}(t)} \leqslant Q_{\mathrm{DSTATCOM}(t)}^{\max} \quad t = 1, 2, \ldots, nb$$

where $Q_{\mathrm{DSTATCOM}(t)}^{\min}$ is the minimum reactive power limits of compensated bus t and $Q_{\mathrm{DSTATCOM}(t)}^{\max}$ is the maximum reactive power limits of compensated bus t.

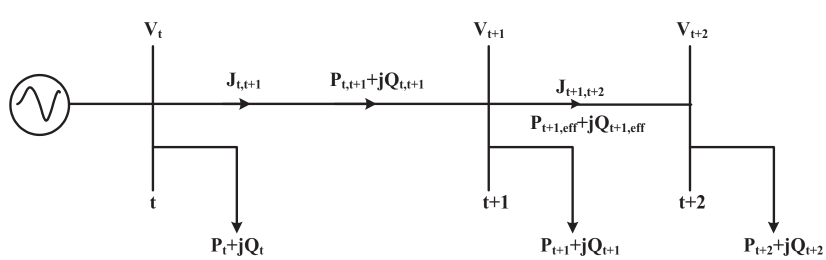

Fig. 1 Simple distribution system.

2.3. Cost of DSTATCOM

The investment cost of DSTATCOM per year [26] can be calculated by using Eq. (9) as follows:

$$\text{DSTATCOM}_{\text{cost},year} = \text{DSTATCOM}_{\text{cost}} \times \frac{(1+B)^{n_{\text{DSTATCOM}}} \times B}{(1+B)^{n_{\text{DSTATCOM}}} - 1} \quad (9)$$

2.4. Total Annual Cost Saving (TACS)

Total Annual Cost Saving (TACS) of DSTATCOM is the difference between total energy loss cost before installation and total energy loss cost and annual DSTATCOM after installation is given by Eq. (10) as follows:

$$\text{TACS} = K_{\text{p}}(T \times P_{\text{TLoss}}) - K_{\text{p}}(T \times P_{\text{TLoss}}^{\text{with DSTATCOM}}) - (K_{\text{c}} \times \text{DSTATCOM}_{\text{cost},year}) \quad (10)$$

2.5. Voltage Stability Index

There are many indices used to check the power system security level. In this section a new steady state Voltage Stability Index is used in order to identify the node which has more chances to voltage collapse [20,29]. The voltage stability at each node is calculated using Eq. 12. The node which has the low value of VSI has more chance to install DSTATCOM. Hence the VSI should be maximized to prevent the possibilities of voltage collapse.

$$\text{VSI}(t+1) = |V_{\text{t}}|^4 - 4\left[P_{\text{t+1,eff}} * X_{\text{t}} - Q_{\text{t+1,eff}} * R_{\text{t}}\right]^2 - 4\left[P_{\text{t+1,eff}} * R_{\text{t}} + Q_{\text{t+1}} * X_{\text{t}}\right]|V_{\text{t}}|^2 \quad (11)$$

3. Bat algorithm

3.1. Overview of bat algorithm

In recent years, nature inspired algorithms are the most powerful algorithms for tough power system optimization problems. Based on the echolocation behavior of natural bats in locating their foods, a new nature inspired meta-heuristic algorithm called "Bat Algorithm" has been proposed by Yang [13]. Bats are interesting animals, which are only the mammals having wings and advanced echolocation capability to find their prey. Generally it radiates a sound signal called echolocation to detect the objects surrounding them and find their way even in full darkness.

Bat algorithms can be developed by idealizing some of the characteristics of bats. The approximated or idealized three rules are given as follows:

1. Each bat utilizes echolocation characteristic to sense distance, and they also 'know' the difference between food/prey and background obstacles in some magical way using echolocation property.
2. Each bat flies randomly with velocity v_i position x_i, with a frequency f_{min} varying wavelength λ and loudness A_0 to seek for prey. It has an ability to regulate the frequency (or wavelength) of emitted pulse and regulate the rate of pulse emission r in the range of $[0,1]$ relying on the proximity of its aim.
3. Even though the loudness can vary in different ways we assume that the loudness varies from a large positive A_0 to a minimum constant value A_{min}.

3.1.1. Initialization of population

Initially the population, that is number of virtual bats for bat algorithm is generated randomly. The number of virtual bats should be anywhere between 10 and 40 and after getting the initial fitness of the population for given function the values are updated based on loudness, movement and pulse rate.

3.1.2. Movement of virtual bats

In bat algorithm we have to define the rules for updating the position x_i and velocities v_i of the virtual bats. These are given by

$$f_i = f_{\text{min}} + (f_{\text{max}} - f_{\text{min}})\beta \quad (12)$$

$$v_{\text{i}}^{\text{t}} = v_{\text{i}}^{\text{t}-1} + \left(x_{\text{i}}^{\text{t}-1} - x^*\right)f_{\text{i}} \quad (13)$$

$$x_{\text{i}}^{\text{t}} = x_{\text{i}}^{\text{t}-1} + v_{\text{i}}^{\text{t}} \quad (14)$$

where $\beta \in [0,1]$ is a random vector drawn from a uniform distribution, and here x^* is the current global best location (solution) among all the n bats. Locally generated new solution for all bats using random walk is given by (15)

$$x_{\text{new}} = x_{\text{old}} + \varepsilon A^{\text{t}} \quad (15)$$

where ε is the random number in the range $[0,1]$, while $A^{\text{t}} = (A_{\text{i}}^{\text{t}})$ is the average loudness of all the bats at this time step.

3.1.3. Loudness and pulse emission

Based on the iteration the loudness A_{i} and the rate of pulse emission r_{i} are updated as a bat reaches to its prey and the pulse emission increases while the loudness decreases, i.e., the equation for convergence can be taken as

$$A_{\text{i}}^{\text{t}+1} = \alpha A_{\text{i}}^{\text{t}} \quad (16)$$

$$R_{\text{i}}^{\text{t}+1} = r_{\text{i}}^{0}[1 - \exp(-\gamma t)] \quad (17)$$

where α and γ are constant values.

For any value of $0 < \alpha < 1$ and $\gamma > 0$ we have

$$A_i^t \to 0, \quad r_i^t \to r_i^0 \text{ as } t \to \infty$$

The initial value of loudness A_0 can typically be in the range of $[0,1]$, while the initial value of emission rate r_i can be in the range of $[0,1]$.

Table 1 Input parameter of bat algorithm.

S.no.	Parameters	Quantity
1.	Population size	20
2.	Number of generations	50
3.	Loudness	0.5
4.	Pulse rate	0.5

The selected parameters for bat algorithm are given in Table 1. Based on above approximation and idealization the step by step implementation of bat algorithm for the optimization process can be described in the following steps and the flowchart is shown in Fig. 2.

- Step 1: First, read the system input data (bus data and load data).
- Step 2: Run the base case distribution load flow and determine the real and reactive power losses, voltages and Voltage Stability Index (VSI).
- Step 3: Identify the candidate buses for placement of DSTATCOM using VSI.
- Step 4: Set the lower and upper bounds for the constraints, bat algorithm control parameters (pulse frequency, pulse rates and loudness) and maximum number of iteration.
- Step 5: Generate the initial bat population randomly in the feasible area. Each bat indicates an encouraging optimal size (kVAr) for the DSTATCOM devices in the distribution network.
- Step 6: Evaluate the fitness function. In this step, the expected value of the active and reactive power losses and the voltage deviation of the objective function can be calculated by using Direct Load Flow method for each solution or bat.
- Step 7: Choose the best bat in the population (minimum power loss value).
- Step 8: Update the bat population.
- Step 9: Now run the load flow and determine the active power loss and reactive power loss with the updated population.
- Step 10: Check the termination criterion. The termination criterion can be the maximum number of iterations to update the Bat Algorithm population or a specific value which the objective function should reach to minimum value. If it is satisfied then finish the algorithm otherwise return to step no 5.
- Step 11: Display the optimal solutions.

These steps will be followed in order to minimize the objective function.

4. Results and discussion

In the power systems by static characteristic studies the load models can be classified into following three types:

i. Constant power model.
ii. Constant current model.
iii. Constant impedance model.

In this paper constant power load model has been considered for modeling the behavior of loads of the power system networks [21,22]. The Objective Function parameter settings for optimization are shown in Table 2 [27,28]. The parameters are common for both (IEEE 33 and 69 buses) test systems. The proposed method has been programmed and implemented using MATLAB environment to run distribution system load flow, calculate real and reactive power losses and to identify the optimal location and size of DSTATCOM.

The load variation between no-load to full-load can be calculated as follows:

$$P_{t,new} + jQ_{t,new} = \eta(P_t + jQ_t) \quad \eta = 0.5, 0.51, 0.52, \ldots, 1.6 \tag{18}$$

To show the effectiveness and performance of proposed method, it has been tested on standard IEEE 33-bus and 69-bus systems that work at 12.66 kV and have radial structure [23,24].

4.1. IEEE 33-bus test system

This is a medium scale radial distribution system with 33 buses and 32 branches. The line and bus data are taken from [25]. The line voltage, and real and reactive power loads of the radial distribution networks are 12.66 kV, 3.72 MW and 2.3 MVAr, respectively. The single line diagram of IEEE 33-bus radial distribution system is shown in Fig. 3.

In IEEE 33 and 69 bus test systems, three different cases have been considered to analyze the effectiveness of the proposed method:

- Case (i) System without DSTATCOM.
- Case (ii) System with single DSTATCOM.
- Case (iii) System with multiple DSTATCOM.

For all cases of 33- bus and 69-bus test systems, the feeder loads are linearly changed from light load to peak load (50–160%) with step size of 1% and the optimization procedure is followed for the entire period.

4.1.1. Case (i): System without DSTATCOM

The initial active and reactive power losses before DSTATCOM placed are 202.67 kW and 135.24 kVAr, respectively. The power losses and voltage profile of the 33-bus test system without DSTATCOM are shown in Figs. 4 and 5 respectively.

Based on the Curve Fitting Technique the total real and reactive power losses of the IEEE 33-bus system (without DSTATCOM) can be formulated as generalized equations and it is given by

$$P_{loss}\ (\text{kW}) = (50.86 \times \eta^3) + (123.6 \times \eta^2) + (37.09 \times \eta) - 8.954 \tag{19}$$

$$Q_{loss}\ (\text{kVAr}) = (34.56 \times \eta^3) + (81.4 \times \eta^2) + (25.33 \times \eta) - 6.12 \tag{20}$$

4.1.2. Case (ii): System with single DSTATCOM

In this case, a single DSTATCOM has been optimally placed at 30th bus. Table 3, shows the comparison of real and reactive power losses, locations, optimal size (kVAr) and the total annual cost saving for existing and proposed methods. In the proposed method, the real and reactive power losses have been reduced to 143.97 kW (i.e. percentage of reduction is 28.97%) and 96.47 kVAr (i.e. percentage of reduction is 28.67%) after installing the DSTATCOM. In the proposed method, total power losses reduction is high compared to existing Immune Algorithm based method. The cost of total energy lost before compensation (without DSTATCOM) is 106,529 ($), which can be calculated based on the data in Table 2, resulting from

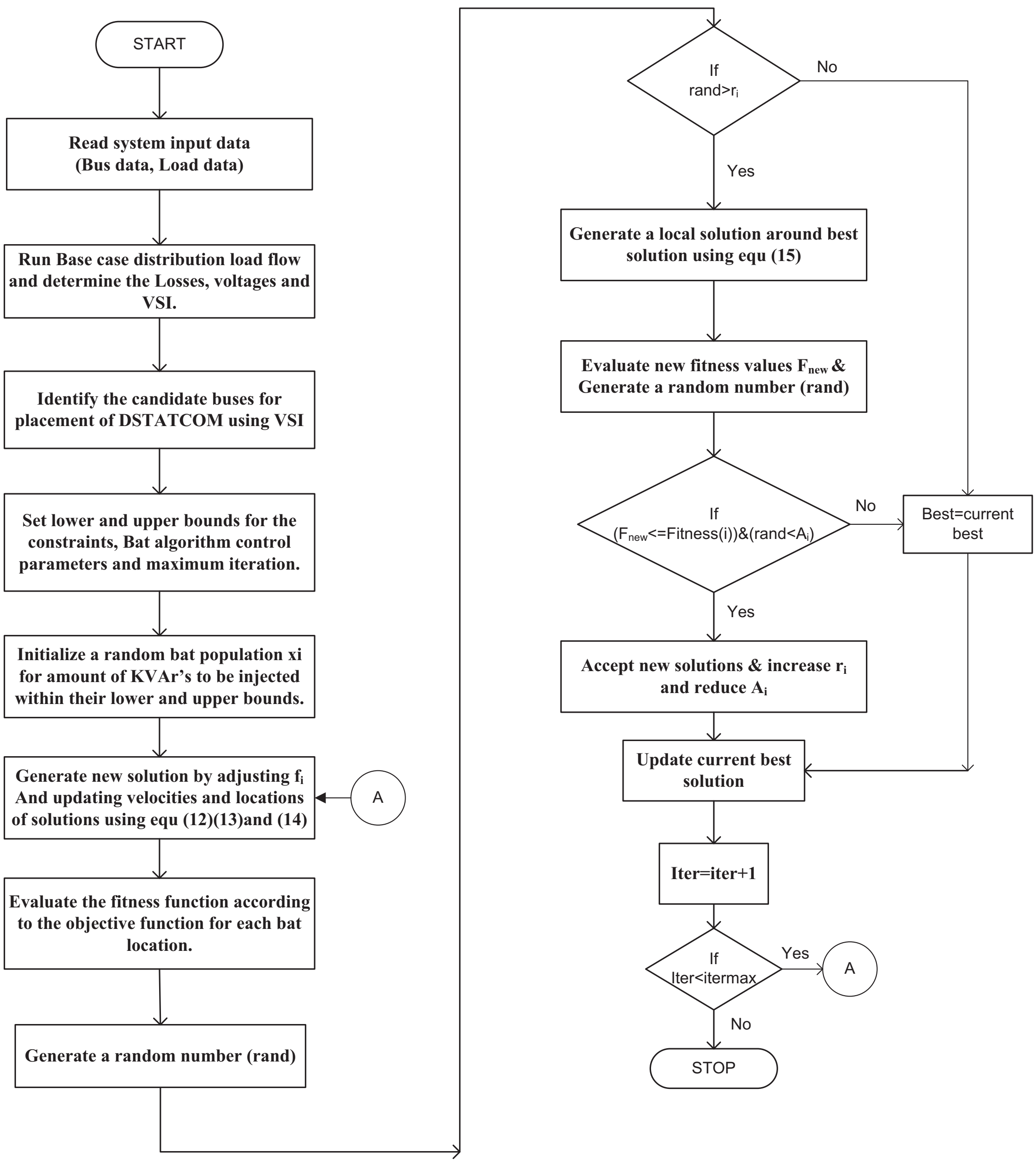

Fig. 2 Flowchart of the proposed method.

Table 2 Objective function parameter settings for optimization.

$DSTATCOM_{cost}$ ($/kVAr)	$n_{DSTATCOM}$ (year)	B	K_p ($/kW h)	K_c	T
50	30	0.1	0.06	1	8760

the network power losses. After performing the optimization process in this system, the total annual cost saving is 24,768 ($),which is the highest total annual cost saving compared to immune algorithm (11,120 $). The total annual cost saving is calculated from the difference between total energy loss cost before installation and total energy loss cost (75,667 $) and annual cost of DSTATCOM (6100 $) after installation which can be calculated by using bat optimization algorithm. The CPU time needed by the proposed method is 7.2 s. This shows that the proposed bat algorithm based optimization is more effective than the Immune algorithm based optimization. Table 4, shows the optimal size, location, real and reactive power losses of proposed method under three different load factors.

4.1.3. Case (iii): System with multiple DSTATCOM

In this case, the two DSTATCOMs are optimally placed in 10th and 30th buses and the optimal size of these locations can be calculated by using bat algorithm. In order to show the effectiveness of proposed method, the authors have implemented the objective function with the help of two algorithms

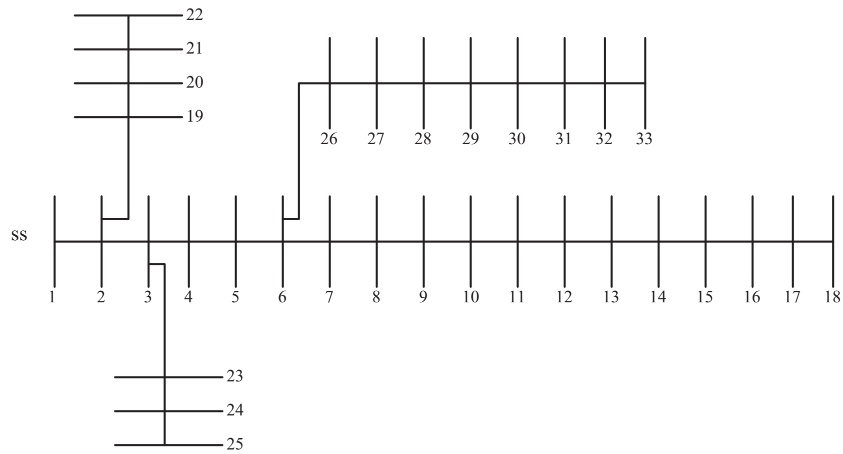

Fig. 3 Single line diagram of IEEE 33-bus system.

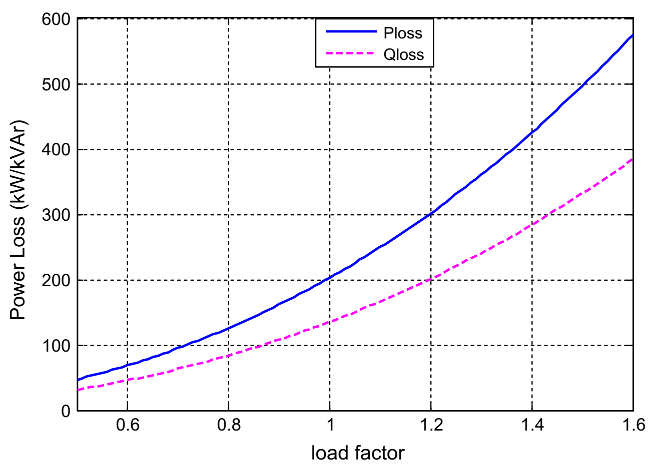

Fig. 4 Real and reactive power losses of the 33-buses without DSTATCOM.

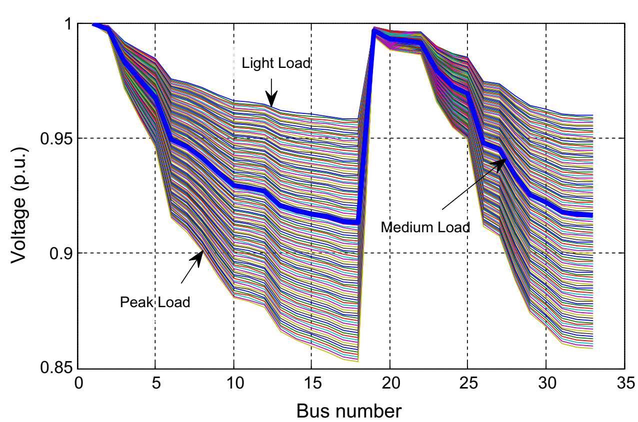

Fig. 5 Voltage profile of the 33-buses under different load variations without DSTATCOM.

such as BFOA (Bacterial Foraging Optimization Algorithm) and proposed Bat algorithm. Since radial distribution system with multiple DSTATCOM is not available in the literature, the authors have implemented same objective function with BFOA and compared the results with proposed bat algorithm.

Table 3 Performance analysis of the proposed method after installation of single DSTATCOM on 33-bus system.

	Base case	Immune algorithm [12]	Proposed method
Optimal size (kVAr)	–	962.49	**1150**
Location	–	12	**30**
P_{loss} (kW)	202.67	171.79	**143.97**
% Reduction in P_{loss}	–	15.24	**28.97**
Q_{loss} (kVAr)	135.24	115.26	**96.47**
% Reduction in Q_{loss}	–	14.78	**28.67**
V_{min}	0.9131	0.9258	**0.9244**
VSI_{min}	0.6890	0.7266	**0.7242**
Total annual cost saving ($)	–	11,120	**24,768**
Computation time (s)	–	–	**7.2**

The bold values define the significance of proposed method over other methods in terms of power loss minimization and TACS.

The real and reactive power losses, voltage profile and optimal sizing for DSTATCOM of the 33-buses with multiple DSTATCOM under different loading conditions are shown in Figs. 6–8, respectively. By comparing Fig. 4, with Fig. 6, it can be noted that the real and reactive power losses have been decreased for all load levels. Similarly by comparing the Fig. 5, with Fig. 7, it can be noted that implementation of DSTATCOM in the radial distribution system has improved the voltage profile effectively. The minimum bus voltage obtained with the proposed bat algorithm is 0.9356 p.u which is better when compared to 0.9131 p.u obtained without DSTATCOM installation. The results presented in Table 5 indicate that the bat algorithm shows better performance than BFOA in terms of real and reactive power loss reduction and total annual cost saving.

The performances of the classical methods on 33-bus test system are also statistically compared and are shown in Fig. 9. From Tables 3 and 5 and Fig. 9, it is clear that the performance of the proposed bat algorithm is better compared to other existing methods in terms of quality of solutions.

Based on the Curve Fitting Technique, the total real and reactive power losses of the IEEE 33-bus system (with DSTATCOM) can be formulated as generalized equations and it is given by

Table 4 Results for 33-bus system under different types of load factor.

Cases		Load factor		
		Light load (0.5)	Medium load (1.0)	Peak load (1.6)
Case (i) Single DSTATCOM	Optimal size (kVAr) & Location	520(30)	1150(30)	1950(30)
	P_{loss} (kW)	34.3328	143.9625	395.6335
	Q_{loss} (kVAr)	22.9424	96.4659	265.7290
	V_{min} (p.u)	0.9630	0.9244	0.8740
	VSI_{min} (p.u)	0.8572	0.7242	0.5740
Case (ii) Multiple DSTATCOM	Optimal size (kVAr) & Location	190(10)	450(10)	780(10)
		465(30)	995(30)	1650(30)
	Total kVAr	655	1550	2430
	P_{loss} (kW)	32.592	146.73	371.1263
	Q_{loss} (kVAr)	21.6963	68.43	247.8005
	V_{min} (p.u)	0.9671	0.9299	0.891
	VSI_{min} (p.u)	0.8717	0.7418	0.6206

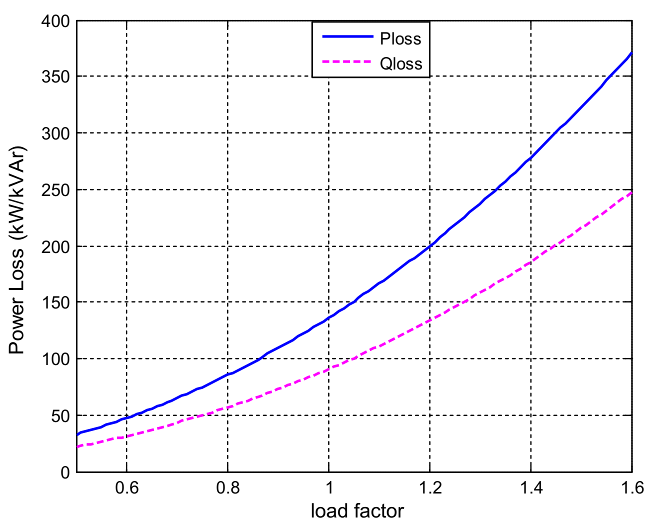

Fig. 6 Real and reactive power losses of the 33-buses with multiple DSTATCOMs.

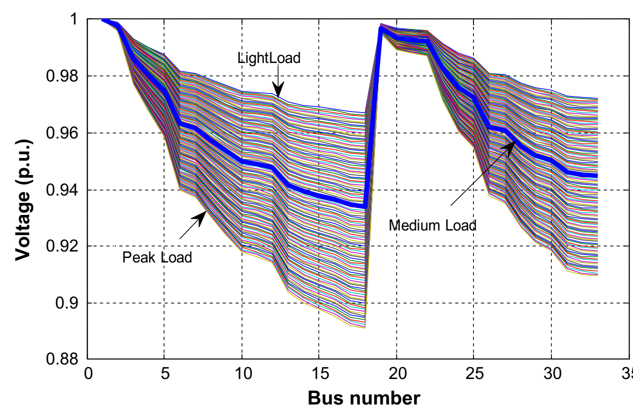

Fig. 7 Voltage profile of the 33-buses under different load variations with multiple DSTATCOMs.

$$P_{loss}\ (kW) = (168.9 \times \eta^2) - (49.03 \times \eta) + 16.04 \quad (21)$$

$$Q_{loss}\ (kVAr) = (113 \times \eta^2) - (33.35 \times \eta) + 10.89 \quad (22)$$

Optimal size of the DSTATCOM for 10th and 30th location with different load changes is given by

$$Q_{optimal}^{10th\ Loc}\ (kVAr) = (33.35 \times \eta^2) + (466.4 \times \eta) - 50.35 \quad (23)$$

$$Q_{optimal}^{30th\ Loc}\ (kVAr) = (28.6 \times \eta^2) + (1015 \times \eta) - 48.97 \quad (24)$$

In order to predict the superiority of the bat algorithm, the convergence characteristic of bat algorithm for 33 bus test system is compared with other existing immune algorithm and it is shown in Fig. 17. From the figure, it is very clear that the bat algorithm takes only 12 iterations to converge the best solution. In addition to that bat algorithm shows a stable and quick convergence with a global searching ability to find the optimal DSTATCOM sizes.

Economical comparison between DSTATCOM and capacitor on 33-bus test system is given in Table 9. From Table 9, it is observed that the total cost saving by the proposed DSTATCOM placement is high than the capacitor placement for the same optimal candidate location, kVAr size and power losses. It shows that the optimal DSTATCOM placement gives better performance than capacitor placement in the radial distribution systems.

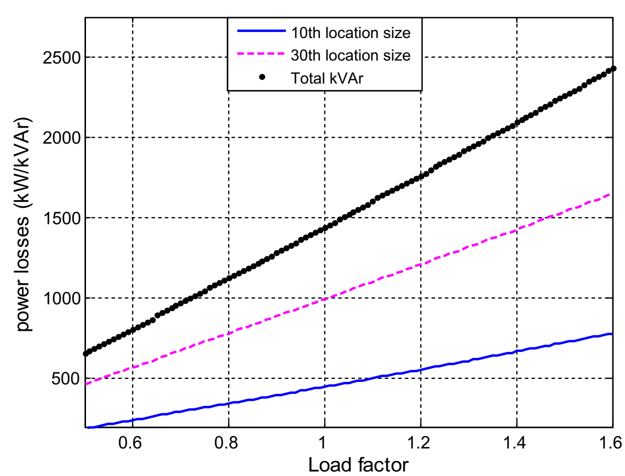

Fig. 8 Optimal sizing for DSTATCOM under different load variations of 33-bus system.

Table 5 Performance analysis of the proposed method after installation of multiple DSTATCOM on 33-bus system.

	Base case	BFOA	Proposed method
Optimal size (kVAr) & Location	–	600(10) 1200(30)	**450(10)** **995(30)**
Total kVAr	–	1800	**1445**
P_{loss} (kW)	202.67	137.5	**136.05**
% Reduction in P_{loss}	–	32.15	**32.87**
Q_{loss} (kVAr)	135.24	92.01	**90.63**
% Reduction in Q_{loss}	–	31.96	**33.20**
V_{min} (p.u)	0.9131	0.9392	**0.9356**
VSI_{min} (p.u)	0.6890	0.7720	**0.7548**
Total annual cost saving ($)	–	24713.35	**27356.97**
Computation time (s)	–	11.06	**9.85**

The bold values define the significance of proposed method over other methods in terms of power loss minimization and TACS.

4.2. IEEE 69-bus test system

This is a large scale test system which consists of 69 buses and 68 branches with a total real and reactive load of 3.80 MW and 2.69 MVAr respectively. The line and bus data are taken from [25]. The single line diagram of IEEE 69-bus radial distribution system is shown in Fig. 10.

4.2.1. Case (i): System without DSTATCOM

The initial active and reactive power losses without using any DSTATCOM in the radial networks are 225 kW and 102.2 kVAr, respectively. The active and reactive power losses and voltage profile of the 69-bus test system without DSTATCOM are shown in Figs. 11 and 12 respectively.

By using CFT the total real and reactive power losses of the IEEE 69-bus system (without DSTATCOM) can be approximated as simple equations as follows:

$$P_{loss}\,(\text{kW}) = (72.87\times\eta^3) + (105.7\times\eta^2) + (61.13\times\eta) - 14.88 \quad (25)$$

$$Q_{loss}\,(\text{kVAr}) = (31.08\times\eta^3) + (51.42\times\eta^2) + (25.94\times\eta) - 6.313 \quad (26)$$

4.2.2. Case (ii): System with single DSTATCOM

In this system, the 61st bus is selected for optimal DSTATCOM installation and the optimal size of this locations can be calculated by using bat algorithm. The real and reactive power losses in the proposed method have been reduced more than those obtained by the other method as seen in Table 6. And also the total annual cost saving for the proposed method is higher than that of immune algorithm based optimization method. The proposed bat optimization method achieved the higher power loss reduction and total net saving of the DSTATCOM. Table 7, shows the optimal size, location, real and reactive power losses of proposed 69-bus radial distribution network under three different load factors.

4.2.3. Case (iii): System with multiple DSTATCOM

In this test case, two DSTATCOMs are optimally placed and sized at 15th and 61st buses. In order to show the effectiveness of proposed method, its performance results are compared with BFOA, run on the same basis. The real and reactive power losses, voltage profile and optimal sizing for DSTATCOM of the 69-buses with multiple DSTATCOM under different loading condition are shown in Figs. 13–15, respectively. By comparing Fig. 11, with Fig. 13, it is observed that the real and reactive power losses have been reduced for all load levels.

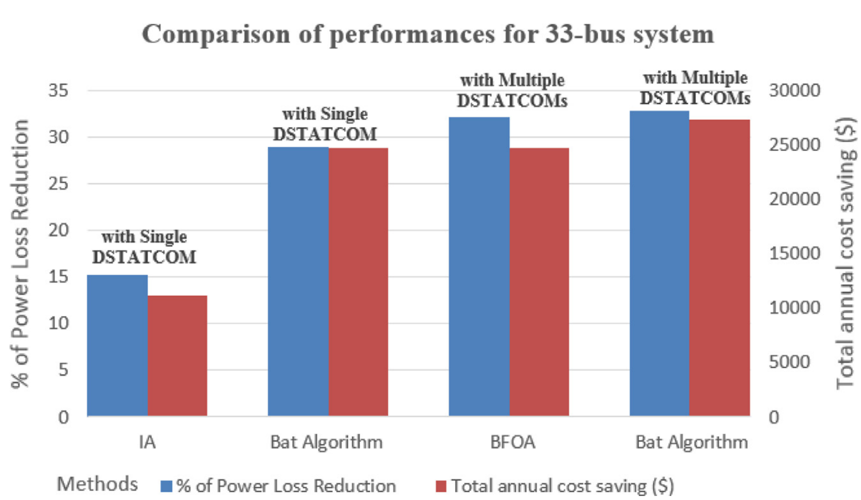

Fig. 9 Comparison of performances for 33-bus test system.

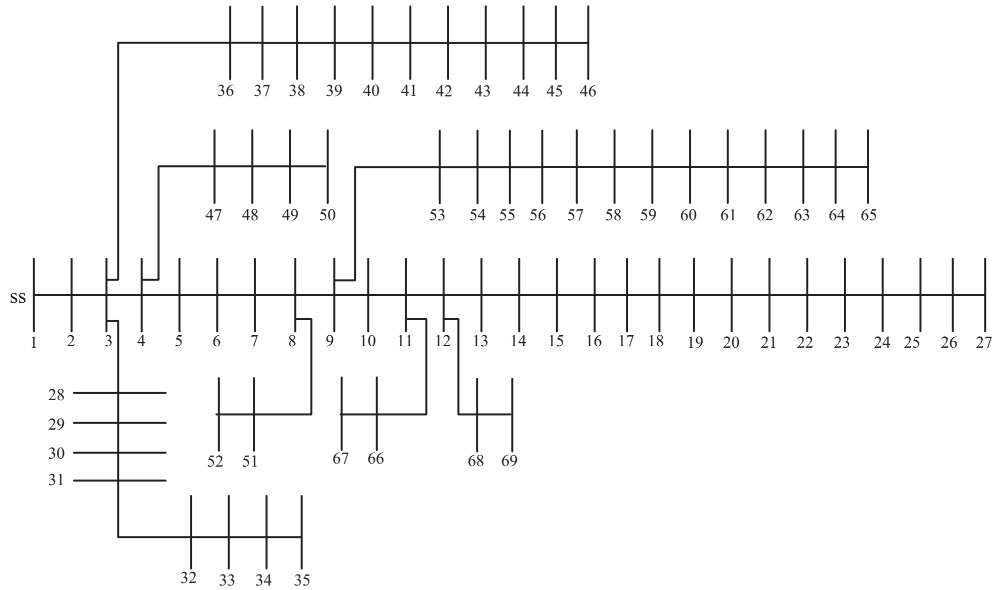

Fig. 10 Single line diagram of IEEE 69-bus system.

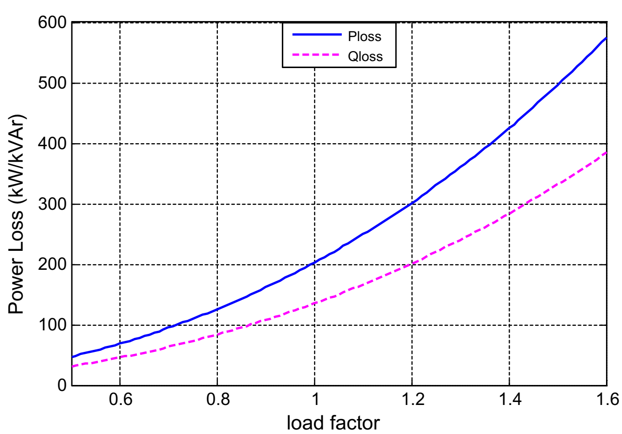

Fig. 11 Real and reactive power losses of the 69-bus without DSTATCOM.

Similarly by comparing the Fig. 12, with that of Fig. 15, it is observed that the application of DSTATCOM in the distribution system has improved the voltage profile greatly. The minimum bus voltage obtained with the proposed method is 0.9278 p.u which is better when compared to 0.9090 p.u obtained without DSTATCOM installation.

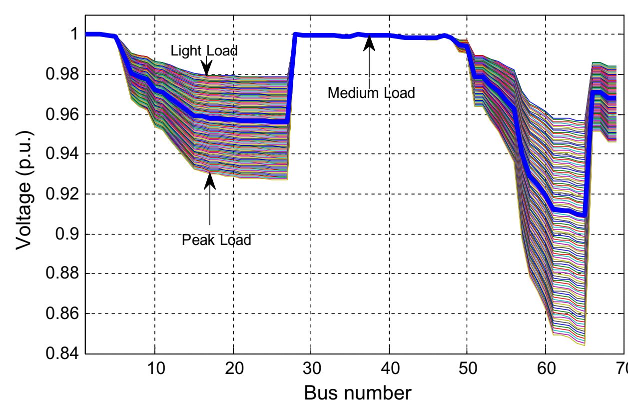

Fig. 12 Voltage profile of the 69-buses under different load variations without DSTATCOM.

Table 8, shows the optimal size and location of the DSTATCOM, minimum bus voltage, real and reactive power losses and total annual cost saving ($) of two DSTATCOMs

Table 6 Performance analysis of the proposed method after installation of single DSTATCOM on 69-bus system.

	Base case	Immune algorithm [12]	Proposed method
Optimal size	–	1704.42	**1150**
Location	–	61	**61**
P_{loss} (kW)	225	157.5	**153.36**
% Reduction in P_{loss}	–	30	**31.9**
Q_{loss} (kVAr)	102.2	72.4	**71.26**
% Reduction in Q_{loss}	–	29.2	**30.27**
V_{min} (p.u)	0.9090	0.9353	**0.9278**
VSI_{min}	0.6822	0.7561	**0.7356**
Total annual cost saving ($)	–	26,438	**31,573**
Computation time (s)	–	–	**8.5**

The bold values define the significance of proposed method over other methods in terms of power loss minimization and TACS.

Table 7 Results for 69-bus system under different types of load factor.

Cases		Load factor		
		Light load (0.5)	Medium load (1.0)	Peak load (1.6)
Case (i) Single DSTATCOM	Optimal size (kVAr) & Location	550(61)	1150(61)	2050(61)
	P_{loss} (kW)	36.0527	153.36	425.6970
	Q_{loss} (kVAr)	16.8401	71.26	196.4285
	V_{min}	0.9649	0.9278	0.8812
	VSI_{min}	0.8647	0.7356	0.5912
Case (ii) Multiple DSTATCOM	Optimal size (kVAr) & Location	135(15)	330(15)	570(15)
		575(61)	1220(61)	2030(61)
	Total kVAr	710	1550	2600
	P_{loss} (kW)	34.5931	146.73	409.3748
	Q_{loss} (kVAr)	16.2212	68.43	189.5954
	V_{min}	0.9657	0.9299	0.8829
	VSI_{min}	0.8674	0.7418	0.5960

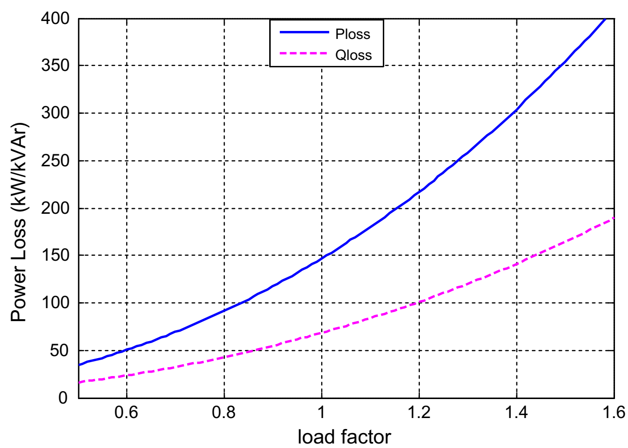

Fig. 13 Real and reactive power losses of the 69-buses with multiple DSTATCOMs.

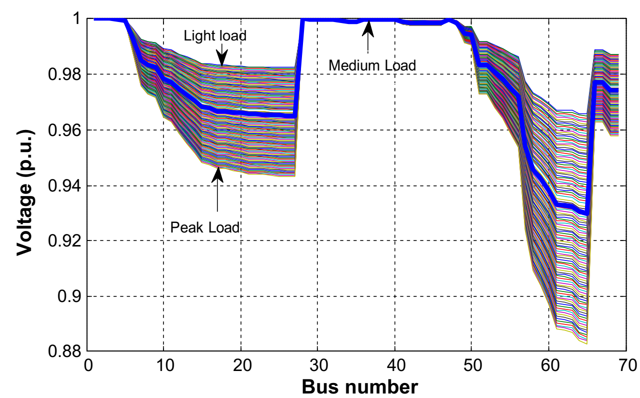

Fig. 14 Voltage profile of the 69-buses under different load variations with multiple DSTATCOMs.

obtained by BFOA and proposed bat algorithm. The real and reactive power losses are reduced to 146.73 kW and 68.43 kVAr by installing DSTATCOM in the radial distribution network. Total annual cost saving of the proposed method is 32923.72 ($). It is observed that the real and reactive power loss reduction and total annual cost saving ($) obtained from proposed method are significantly high compared to BFOA method. The CPU time needed by the proposed method is 10.6 s. This shows that the proposed method is more effective than BFOA method.

By using Curve Fitting Technique, the optimal power losses of the IEEE 69-bus system (with DSTATCOM) can be written as follows:

$$P_{loss}\ (\text{kW}) = (29.22 \times \eta^3) + (103.2 \times \eta^2) + (18.44 \times \eta) - 4.2 \quad (27)$$

$$Q_{loss}\ (\text{kVAr}) = (12.5 \times \eta^3) + (49.82 \times \eta^2) + (7.88 \times \eta) - 1.78 \quad (28)$$

Also by using CFT, the optimal size of the DSTATCOM for 15th and 61st location with different load changes can be written as follows:

$$Q_{optimal}^{15th\ Loc}\ (\text{kVAr}) = (14.96 \times \eta^2) + (361.4 \times \eta) - 48.79 \quad (29)$$

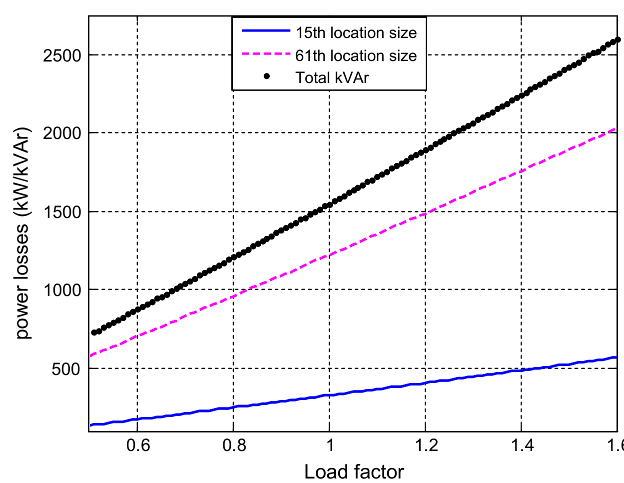

Fig. 15 Optimal sizing for DSTATCOM under different load variations of 69-bus system.

$$Q_{optimal}^{61st\ Loc}\ (\text{kVAr}) = (51.28 \times \eta^2) + (1251 \times \eta) - 44.5 \quad (30)$$

The performances of the classical methods on 69-bus test system are statistically compared and are shown in Fig. 16. From Tables 6, 8 and 9, it is clear that the performance of the proposed bat algorithm is more accurate compared to other existing methods in terms of quality of solutions.

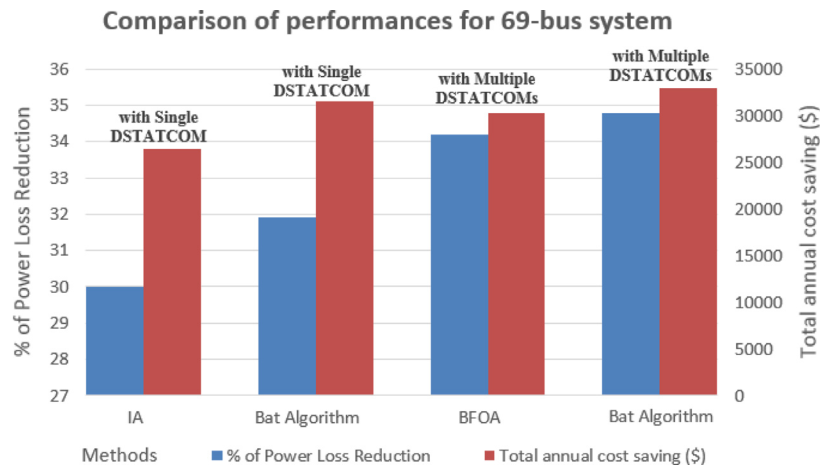

Fig. 16 Comparison of performances for 69-bus test system.

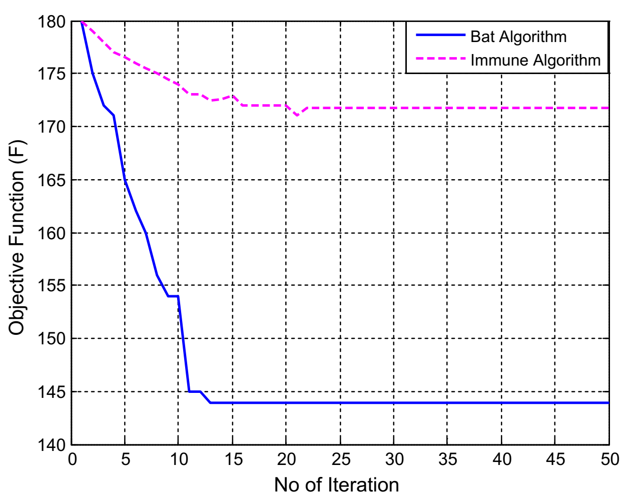

Fig. 17 Comparison of convergence characteristic of objective function for 33-bus system.

Table 8 Performance analysis of the proposed method after installation of multiple DSTATCOM on 69-bus system.

	Base case	BFOA	Proposed method
Optimal size (kVAr) & Location	–	480(15) 1430(61)	**330(15)** **1220(61)**
Total kVAr	–	1910	**1550**
P_{loss} (kW)	225	148.07	**146.73**
% Reduction in P_{loss}	–	34.19	**34.78**
Q_{loss} (kVAr)	102.2	68.76	**68.43**
% Reduction in Q_{loss}	–	32.72	**33.04**
V_{min} (p.u)	0.9090	0.9332	**0.9299**
VSI_{min} (p.u)	0.6822	0.7512	**0.7418**
Total annual cost saving ($)	–	30311.41	**32923.72**
Computation time (s)	–	12.83	**10.6**

The bold values define the significance of proposed method over other methods in terms of power loss minimization and TACS.

Table 9 Economical comparison between DSTATCOM and capacitors on 33-bus test system.

	Capacitor	DSTATCOM
Optimal size (kVAr)	1150	1150
Location	30	30
P_{loss} (kW)	143.97	143.97
V_{min}	0.9244	0.9244
VSI_{min}	0.7242	0.7242
Total annual cost saving ($)	24,482	**24,768**

The bold values define the significance of proposed method over other methods in terms of power loss minimization and TACS.

5. Conclusion

This paper proposes a new long term scheduling for optimal placement and sizing of DSTATCOM in radial distribution network using nature inspired bat algorithm for obtaining minimization of power loss. Suitable location of DSTATCOM is also important to ensure that network power loss is minimum. In this proposed method VSI is used to find the optimal location and bat algorithm is used to find the optimal size of DSTATCOM. The equation obtained from CFT is very useful for the DNOs to select the optimal size of the DSTATCOM according to the load changes. This long term scheduling gives maximal benefits for DNOs because of optimal operation procedure over the scheduling period. The proposed method is applied to 33-bus and 69-bus radial distribution systems and the results are compared with other heuristic methods. The simulation results show that the implementation of the DSTATCOM in the radial distribution network has decreased the total power loss. Future work can be carried out considering the installation and maintenance costs of both DSTATCOM and Distributed Generation (DG) for higher bus and real time radial distribution systems.

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