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DSTATCOM Allocation in the Radial Distribution Networks with Different Stability İndices using Bat Algorithm

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Abstract

This present approach suggests a bio-inspired bat algorithm for optimal sizing of Distribution STATic COMpensator (DSTATCOM) to mitigate the total power loss of the system in the radial distribution systems (RDS). In the present approach, a new voltage stability factor (VSF) is utilized to identify the optimal placement for installation of DSTATCOM and the proposed VSF is compared with other stability indices. Bat algorithm (BA) is used to search the optimal size of DSTATCOM. The backward/forward sweep (BFS) algorithm is established for the power flow calculations. To verify the feasibility of the proposed work, it has been implemented on standard IEEE 33-bus RDS. The outcomes obtained using the proposed method shows that the optimal location of DSTATCOM in RDS adequately mitigates the loss at the same time enhances the bus voltages.

1. INTRODUCTION

In recent days, a major downfall is faced by the distribution power system. Previous literature study shows that losses in the distribution power sector are as high as 13 % [1]. To add to this misery, deregulation creates power quality issues like variations in voltage, distortion, imbalance, sag, voltage fluctuations and instability in the RDS. The aforementioned power quality problems lead to increase in power loss, response time is further reduced and also power flow limits are lessened [2, 3]. In consumer side, the power system network engineer should give good quality of power with less power loss.

Extensive research has been performed by researchers to mitigate the power loss in RDS. The necessity and significance of usage of highly advanced power equipment's such as series and shunt capacitor banks, reactors and Automatic Voltage Regulator (AVR) have been very well appreciated. Also, the importance of custom power devices like Distribution STATic COMpensator (DSTATCOM), Static Synchronous Series Compensator (SSSC) and Unified Power Quality Conditioner (UPQC) have been explained in detail [4-6]. The major importance of the aforesaid devices is the ability to reduce power losses. In comparison with the above devices, DSTATCOM is clearly the better device due to its manifold advantages like low loss and harmonic production, great controlling ability, compact size and minimal cost of the system [7]. In addition, it does not exhibit any resonance or transient harmonics problems.

The construction and basic principle of DSTATCOM also well-known as DFACTS (Distribution network Flexible AC Transmission Systems). It consists of three main components, (i) voltage source converter connected as shunt, (ii) coupling transformer and (iii) capacitor link. To control the power factor, load flows, DSTATCOM compensates the bus voltage in the RDS. DSTATCOM can provide fast and continuous inductive and capacitive mode compensation. This DFACTS device can also inject required level of leading or lagging compensating current, when it is linked with a specific load.

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Nomenclature

P_t	Real power load at bus t	nb	Total number of branches
Q_t	Reactive power load at bus *t*	P_{ss}	Power generation by Substation.
$P_{t,t+1}$	Real power flowing in the line between buses *t* and *t+1*	$R_{t,t+1}$	Resistance of the line section between buses *t* and *t+1*
$Q_{t,t+1}$	Reactive power flowing in the line between buses *t* and *t+1*	B T	Asset rate of return Hours per year
$P_{t+1,eff}$	Total effective real power supplied beyond the bus *t+1*	$P_{Loss}^{withDSTATCOM}$	Total power loss after installation of DSTATCOM
$Q_{t+1,eff}$	Total effective reactive power supplied beyond the bus *t+1*	$Q_{DSTATCOM}^{kVAr}$	Reactive power injecting to the network by DSTATCOM
$P_{Loss(t,t+1)}$	Power loss in the line section between buses *t* and *t+1* without DSTATCOM	K_p K_c	Energy cost of losses Time duration proportion
V_t	Voltage magnitude at bus *t*	$n_{DSTATCOM}$	Longevity of DSTATCOM
I_t	Equivalent current injected at node *t*	*TACS*	Total Annual Cost Saving
$J_{t,t+1}$	Branch current in the line section between buses t and *t+1*	$V_t^{\min}$	Minimum voltage limits of the buses
$J_{t,t+1,\max}$	Maximum branch current limit of line section between buses *t* and *t+1*	$V_t^{\max}$	Maximum voltage limits of the buses
		$X_{t,t+1}$	Reactance of the line section between buses *t* and *t+1*
α_t	The voltage angle at node *t*	α_{t+1}	The voltage angle at node *t+1*
$DSTATCOM_{\cos t,year}$	Annual cost of DSTATCOM	$DSTATCOM_{\cos t}$	Cost of investment in the year of allocation

Hence, this device needs to meet the total demand specified, for utility connection [8]. Another specialty of this device is that it can clean up the voltage of a utility bus from any unbalance and harmonic distortion [9]. Due to its increase in the power system load, DSTATCOM is anticipated to perform a significant role in the RDS. Optimum allocation of DSTATCOM maximizes the following constraints such as, power loss minimization, annual cost saving, load ability, compensation of reactive power, stability improvement and power quality improvement [10].

In literature, maximum optimization works have effectively been implemented to identify the location and sizing problem of compensating devices in the RDS. Even though, most of the researchers suffered from local optimality, low accuracy, slow convergence and require large CPU for optimization. To overcome the above said drawbacks, the present work introduces an efficient and nature inspired optimization approach called bat algorithm (BA) to resolve optimal DSTATCOM allocation problems in the RDS. A new-fashioned and promising BA has been implemented recently by Xin-She Yang [11].

Based on the aforementioned literature, allocation of DSTATCOM has an appreciable impact in RDS. Only a few researchers have worked on the research area of DSTATCOM allocation [12-16]. For DSTATCOM allocation, various methodologies have been implemented (i) Modal analysis (ii) Analytical method (iii) Optimization algorithms. The authors in [12] have implemented modal analysis and time-domain approach to found the finest location of DSTATCOM in the RDS for improvement of power quality. The authors in [13] used an analytical method to solve DSTATCOM allocation problem for mitigation the power loss and enhancing the voltage magnitudes of the system. For the optimal allocation of DSTATCOM, many researchers proposed various algorithms like Differential Evolution Algorithm [DEA] [14], Immune Algorithm [IA] [15], and Particle Swarm Optimization [PSO] [16] to improve the power loss minimization and voltage profile enhancement. In [14], authors utilized a DEA for optimum placement of DSTATCOM in the RDS by considering reconfiguration. In [15], IA is implemented for identifying the optimum placement and size of DSTATCOM with a multi objective. Further in [16], a popular stochastic based PSO is implemented for identifying the optimal allocation of DSTATCOM and DG for power loss mitigation and bus voltage improvement. Further, in [26-33] authors used different types of optimization techniques for optimal allocation of the DSTATCOM with different objective functions in the RDS.

Though the aforesaid methods exhibit good performance there are certain major drawbacks. Firstly, with respect to the analytical method, convoluted calculations, slower convergence and most importantly all authors have focused only on single load (medium). Also, in the previous published works no major research has been implemented with different load factors (light, medium and peak) in the RDS. Hence, to overcome the aforesaid limitation and other major drawbacks, in this research work, the authors make an attempt to propose a new optimization approach to find the optimal location, sizing of single and multiple DSTATCOMs for reduction of power losses in RDS with different load factors (light, medium, and peak). In addition in this paper an innovative way is presented to implement an integrated approach of VSF and recently developed nature inspired bat algorithm to identify the optimal location and sizing of single and multiple DSTATCOMs for power loss mitigation for different loading conditions also evaluated to verify the system performance which will helpful to the Distribution Network Operators (DNOs) to select the DSTATCOM size for a particular load level. To show the efficacy and prove the effectiveness of the present work, it has been tested on standard IEEE 33 test system. The obtained results are evaluated with other heuristic based algorithms using the present technique. The results show superiority in performance in comparison with other renowned algorithms with respect to power loss mitigation, bus voltage development and convergence time.

2. PROBLEM FORMULATION

2.1. Power flow analysis

Generally, radial distribution network has high resistance to reactance (R/X) ratio than transmission system. Therefore traditional power flow studies such as Gauss-Seidel, Newton- Raphson and Fast decoupled load flow studies are not appropriate for determining the line flows and voltages in the RDS. So, the proposed work Backward/Forward Sweep (BFS) algorithm is established for the power flow calculations [17]. A single line diagram of the RDS is depicted in Figure.1.

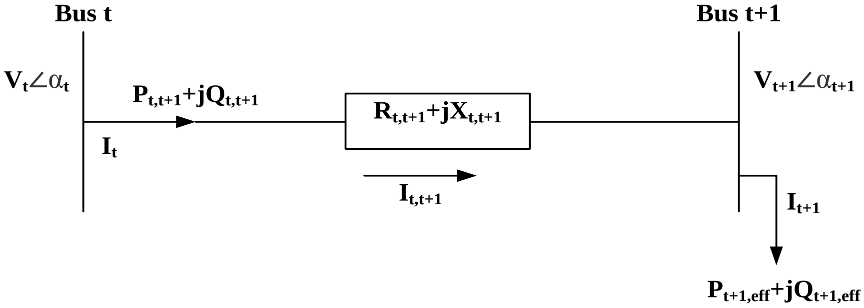

Figure 1. *Simple distribution system*

Consider two buses associated by a branch as a part in a RDS displayed in Figure. 1, where buses *t* and *t+1* are the sending and receiving end buses, correspondingly. As mentioned in Fig. 1, the real power $P_{t,t+1}$ and reactive power $Q_{t,t+1}$ flowing between buses *t* and *t+1* can be derived by applying the formulae given below:

$$P_{t,t+1} = P_{t+1,eff} + P_{Loss(t,t+1)} \tag{1}$$

$$Q_{t,t+1} = Q_{t+1,eff} + Q_{Loss(t,t+1)} \tag{2}$$

Where $P_{t+1,eff}$ and $Q_{t+1,eff}$ are the total effective real and reactive power supplied beyond the bus *t+1* respectively, $P_{Loss(t,t+1)}$ and $Q_{Loss(t,t+1)}$ are the active and reactive power losses between buses *t* and *t+1* respectively.

The current flow between buses *t* and *t+1* can be considered as

$$\mathrm{I}_{\mathrm{t,t+1}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}} - j\mathrm{Q}_{\mathrm{t,t+1}}}{\mathrm{V}_{\mathrm{t+1}} \angle -\alpha_{\mathrm{t+1}}} \right) \tag{3}$$

Also,

$$\mathrm{I}_{\mathrm{t,t+1}} = \left(\frac{\mathrm{V}_{\mathrm{t}} \angle \alpha_{\mathrm{t}} - \mathrm{V}_{\mathrm{t+1}} \angle \alpha_{\mathrm{t+1}}}{R_{t,t+1} + jX_{t,t+1}} \right) \tag{4}$$

Where V_t and V_{t+1} are the voltage magnitudes at nodes *t* and *t+1* respectively. α_{t} and $\alpha_{\mathrm{t+1}}$ are the voltage angles at nodes *t* and *t+1* respectively. $\mathrm{R}_{\mathrm{t,t+1}}$ and $\mathrm{X}_{\mathrm{t,t+1}}$ are the resistance and reactance of the line section between buses *t* and *t+1* correspondingly.

From equations (3) and (4), it can be found that

$$V_t^2 - V_t V_{t+1} \angle(\alpha_{t+1} - \alpha_t) = (\mathrm{P}_{\mathrm{t,t+1}} - j\mathrm{Q}_{\mathrm{t,t+1}})(R_{t,t+1} + jX_{t,t+1}) \tag{5}$$

By equating the real and imaginary parts on both sides in (5)

$$V_t V_{t+1} * \cos(\alpha_{t+1} - \alpha_t) = V_t^2 - (\mathrm{P}_{\mathrm{t,t+1}} R_{t,t+1} + Q_{t,t+1} X_{t,t+1}) \tag{6}$$

$$V_t V_{t+1} * \sin(\alpha_{t+1} - \alpha_t) = Q_{t,t+1} R_{t,t+1} - \mathrm{P}_{\mathrm{t,t+1}} X_{t,t+1} \tag{7}$$

After squaring and adding (6) and (7)

$$V_{t+1}^2 = V_t^2 - 2(\mathrm{P}_{\mathrm{t,t+1}} R_{t,t+1} + Q_{t,t+1} X_{t,t+1}) + (R_{t,t+1}^2 + X_{t,t+1}^2) \left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^2 + \mathrm{Q}_{\mathrm{t,t+1}}^2}{|\mathrm{V}_{\mathrm{t}}|^2} \right) \tag{8}$$

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

$$\mathrm{P}_{\mathrm{Loss(t,t+1)}} = I_{t,t+1}^2 * \mathrm{R}_{\mathrm{t,t+1}} \tag{9}$$

$$\mathrm{P}_{\mathrm{Loss(t,t+1)}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^2 + \mathrm{Q}_{\mathrm{t,t+1}}^2}{|\mathrm{V}_{\mathrm{t+1}}|^2} \right) * \mathrm{R}_{\mathrm{t,t+1}} \tag{10}$$

$$\mathrm{Q}_{\mathrm{Loss(t,t+1)}} = I_{t,t+1}^2 * \mathrm{X}_{\mathrm{t,t+1}} \tag{11}$$

$$\mathrm{Q}_{\mathrm{Loss(t,t+1)}} = \left(\frac{\mathrm{P}_{\mathrm{t,t+1}}^2 + \mathrm{Q}_{\mathrm{t,t+1}}^2}{|\mathrm{V}_{\mathrm{t+1}}|^2} \right) * \mathrm{X}_{\mathrm{t,t+1}} \tag{12}$$

The total real power loss (P_{TL}) and reactive power loss (Q_{TL}) of the RDS can be calculated by the addition of losses in all line sections, which is given by

$$\mathrm{P}_{\mathrm{TL}} = \sum_{\mathrm{t=1}}^{\mathrm{Nb}} \mathrm{P}_{\mathrm{Loss(t,t+1)}} \tag{13}$$

$$\mathrm{Q_{TL}} = \sum_{\mathrm{t=1}}^{\mathrm{Nb}} \mathrm{Q_{Loss(t,t+1)}} \tag{14}$$

Where *Nb* is a total number of branches.

2.2. Objective function

The primary purpose of DSTATCOM installation in the RDS is to mitigate the losses along with bus voltage improvement. The objective of the present approach has been framed as

$$Minimize(F) = Min(\mathrm{P_{TL}}) \tag{15}$$

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

2.2.1. Voltage magnitude limit

The voltage magnitude at each bus must be maintained within its permissible limits and is expressed as

$$V_t^{\min} \le |V_t| \le V_t^{\max} \tag{16}$$

Where $V_t^{\min}$ is the minimum voltage limit at the bus and $V_t^{\max}$ is the maximum voltage limit at the bus.

2.2.2. Power Balance constraint

Power balance constraint is equality constraints. It can be formulated as follows:

$$P_{SS} = P_{TL} + \sum P_{D(t)} - \sum P_{DSTATCOM(t)} \tag{17}$$

Where $P_{D(t)}$ is the power demand, $P_{D(t)}$ is the power demand at bus *t* and $P_{DSTATCOM(t)}$ is the power generation using DSTATCOM.

2.2.3. Reactive power compensation

Reactive power injected at each candidate bus must be within its permissible range.

$$Q_{DSTATCOM(t)}^{\min} \le Q_{DSTATCOM(t)} \le Q_{DSTATCOM(t)}^{\max} \qquad t = 1,2,\ldots\ldots.nb \tag{18}$$

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

2.3 Aggregate voltage deviation (AVD)

To achieve an improved voltage magnitude, the voltage deviation at each bus is made as small as possible. AVD is taken into account to specify the bus voltage enhancement [1]

$$AVD = \begin{Bmatrix} 0 \quad ,if \;\; 0.95 \le V_t \le 1.05 \\ \sum_{t=1}^{N} \left| V_{ref} - V_t \right|, \;\; else \end{Bmatrix} \tag{19}$$

Where N is a total number of buses, V_t is the voltage magnitude at bus *t* and V_{ref} is the reference voltage (i.e. 1.0 p. u).

2.4 Voltage Stability Factor

There are many indices utilized to identify the best location of the compensating devices (DG, capacitor, DSTATCOM, etc.,) in the RDS [18-22]. Because optimum location of compensating devices maximizes the load ability, minimizes the power loss, enhances the stability and power quality along with reactive power compensation. In this paper, a new Voltage Stability Factor (VSF) is utilized in order to determine the bus which has more chances to DSTATCOM installation. The VSF at each bus is determined using Eq. (20). VSF for any bus *'t + 1'* is selected as

$$VSF_{(t+1)} = (2V_{t+1} - V_t) \tag{20}$$

The buses of lower VSF and lesser bus voltage values have more chances of being known as appropriate placement for DSTATCOM in the RDS. The approximation of these optimum buses primarily uses to mitigate the search space meaningfully for the optimization approach. The optimal size of DSTATCOM at the optimum buses are identified by using BA.

3. BAT ALGORITHM

3.1 Overview of bat algorithm

Nowadays, nature inspired algorithms play a major role in distribution system optimization. Xin-Sha Yang developed a nature inspired algorithm known as bat algorithm in the year of 2010 [11]. Echolocation behavior is the main tool of bat algorithm. Bats are alluring animals, these are only the mammals having wings and innovative echolocation ability to find their prey. Generally it radiates a sound signal named echolocation to sense the objects nearby them and identify their technique even in the night times.

Based on the BA idealization rules, the step by step execution of BA for the proposed DSTATCOM allocation work is described in the following steps and the implementation flowchart for bat algorithm is shown in Fig. 2.

The input parameters used in implementation of Bat algorithm listed out in Table 1 [34].

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

3.2 Steps for implementation of proposed work by using BA

In this section, BA is defined for resolving the optimal allocation of DSTATCOMs in RDS.

Step 1: Read the input data

In the first step, read all input bus and line data and run the BFS for uncompensated system, calculate base case real and reactive power losses, AVD, bus voltages and also calculate the Voltage Stability Factor (VSF) to identify the optimal placement of DSTATCOM.

Step 2: *P*arameters initialization

In step 2, the algorithm parameters should be initialized, for example size of the population (POP), maximum number of iterations (itermax), pulse rate, loudness and dimensions. In addition to that, the problem parameters like number of DSTATCOMs to be used, DSTATCOM size limits, limitation of bus voltages, system line and bus data limits are to be given.

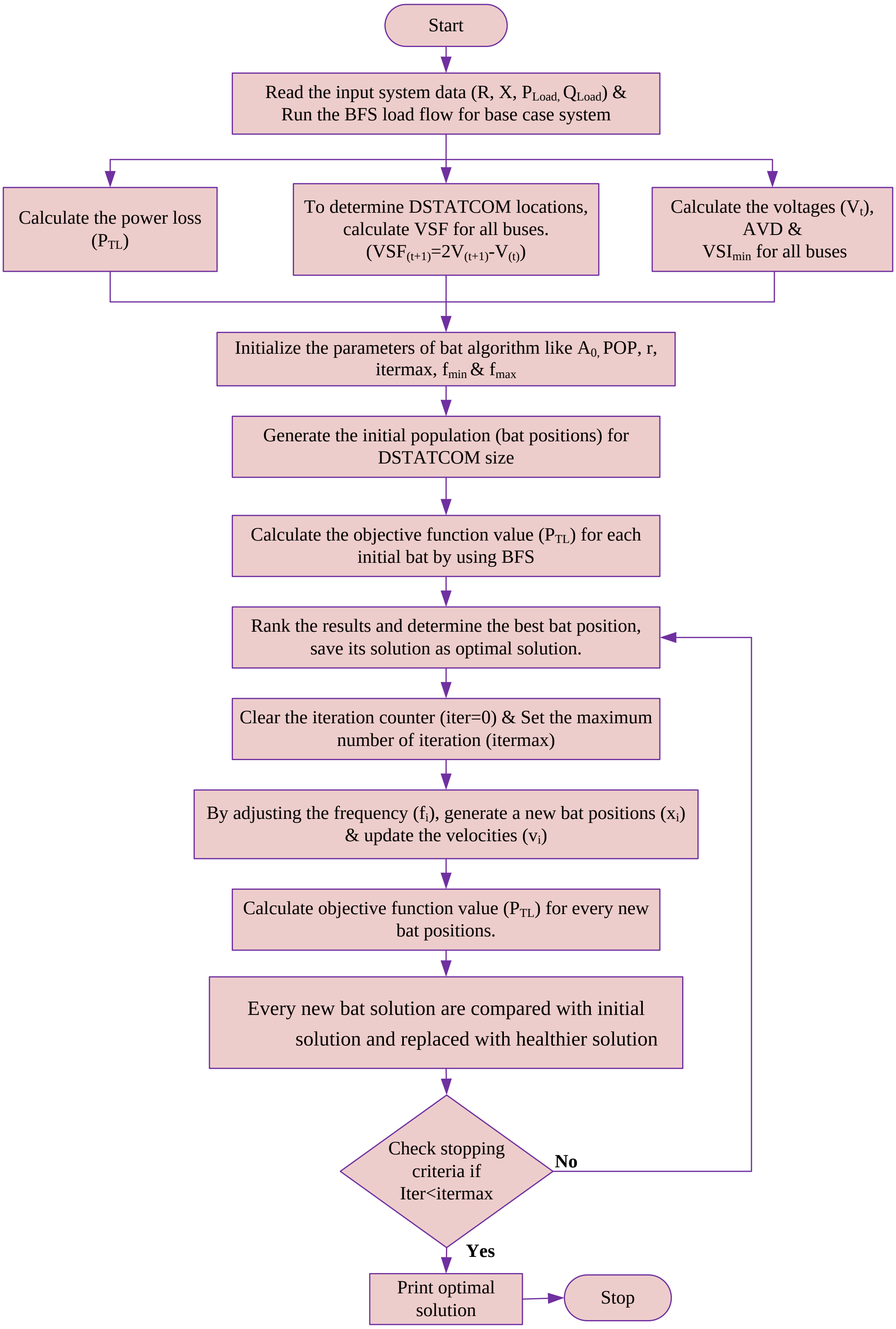

Figure 2. *Flowchart for implementation of BA.*

Step 3: Random generation of DSTATCOM sizes

$$DSTSIZE=\begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{d-1}^1 & x_d^1 \\ x_1^2 & x_2^2 & \cdots & x_{d-1}^2 & x_d^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{pop-1} & x_2^{pop-1} & \cdots & x_{d-1}^{pop-1} & x_d^{pop-1} \\ x_1^{pop} & x_2^{pop} & \cdots & x_{d-1}^{pop-1} & x_d^{pop-1} \end{bmatrix} \tag{21}$$

$$x_i^j = x_{\min,i} + (x_{\max,i} - x_{\min,i}) * rand\,() \tag{22}$$

where d is the number of decision variables, x_i^j represents DSTATCOM sizes, i.e., j^th^ population of i^th^ DSTATCOM size, which is produced arbitrarily in between the limits as $x_{\max,i}$ and $x_{\min,i}$ are the i^th^ DSTATCOM size limits, and rand() is a random number in between 0 and 1.

$$\text{Solution} = [\text{DSTSIZE}] \tag{23}$$

In BA, "*Solution*" signifies a group of bats, where bat is one location in search space. Bat is a solution that contains DSTATCOM sizes.

Step 4: Evaluation of fitness function

Run the Backward/Forward Sweep Load Flow for compensated system and calculate the real and reactive power losses and voltages of the system and corresponding objective function value for each initial bat. Note down the best solution.

Step 5: Start evolution procedure of BA. Assign frequency for each bat randomly

$$f_i = f_{\min} + (f_{\max} - f_{\min})\beta \tag{24}$$

Where $\beta \in [0,1]$ is a random vector drawn from a uniform distribution.

Initially each bat is randomly assigned a frequency which is drawn uniformly from $[f_{\min}, f_{\max}]$

Step 6: Generation bat positions randomly (Sizes of DSTATCOM)

The following equations can be used to find new sizing of DSTATCOM

$$sizeV_i^t = V_i^{t-1} + (DSTsize_i^t - bestsize_*) f_i \tag{25}$$

$$DSTSIZE_i^t = DSTSIZE_i^{t-1} + sizeV_i^t \tag{26}$$

Step 7: Evaluation of fitness (Objective function)

In this step, the objective function value for every new bats has been determined with help of BFS.

Step 8: Every new bat solution are compared with initial solution and replaced with healthier solution

Step 9: Stopping condition.

If the approach is attained maximum no of iterations, computation is stopped. Else, Step 5 to Step 8 is repeated.

Step 10: Display the best values of the objective function.

4. NUMERICAL RESULTS AND DISCUSSION

To prove the efficacy and superiority of present approach, it has been implemented on standard IEEE 33 RDS that works at 12.66 kV [23, 24]. Total annual cost saving (TACS) of DSTATCOM has been calculated from [15]. The modelling of STATCOM for RDS has been taken from the existing literature [15]. To prove the superiority of the proposed method, simulations have been carried out by considering various load factors such as light (0.5), medium (1.0), and peak (1.6). The codes were developed for both the bat algorithm and BFOA using MATLAB environment to identify the size of DSTATCOM. The MATLAB codes are executed for the same conditions to compute the objective function values.

4.1 IEEE 33-bus test system

This is the medium level test case consists of 33 buses and 32 branches. The necessary data are taken from [25]. The line voltage, real and reactive power loads of the RDS are 12.66 kV, 3.72 MW and 2.3 MVAr, correspondingly. The initial active and reactive power losses of the uncompensated RDS are 202.67 kW and 135.24 kVAr, correspondingly. The one line diagram of IEEE 33-bus RDS is presented in figure 3.

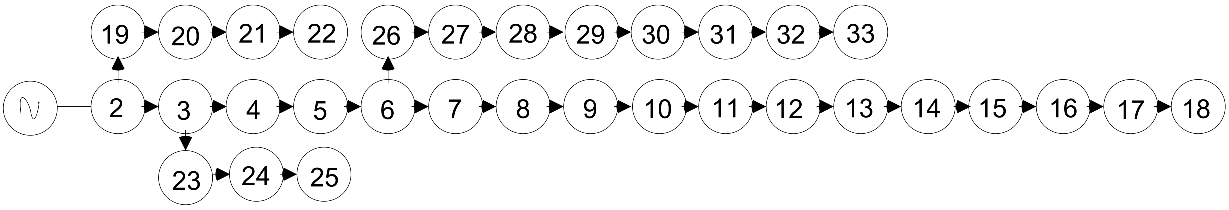

Figure 3. *One line diagram of IEEE 33-bus system.*

4.1.1 Validation of VSF

To validate the VSF, it has been compared with other voltage stability indices available in the literature such as Voltage stability Index (VSI) [20], Power stability Index (PSI) [21] and Loss Sensitivity Factor (LSF) [22] with respect to power loss, minimum voltage levels, Total AVD and total annual cost saving are tabularized in Table 2. It can be observed from Table 2 that the presented VSF can identify the candidate buses accurately to place the DSTATCOM. VSF is also helpful to identify the total voltage stability level of the system. In comparison with other stability indices like VSI, PSI, and LSF less data is required for VSF to find the optimal location of DSTATCOM in RDS. In conjunction with voltage, other system data such as load data and line data are also required in case of other indices. Hence, other stability index needs more complex calculation than VSF. Compared to other voltage stability index and power stability index, developed VSF has appeared as simpler and an efficient tool to find the optimal location of DSTATCOM in terms of power loss reduction, bus voltage development and total annual cost saving.

Table 2 *Results of 33-bus system with different stability indices*

Point of comparison	Uncompensated	Compensated (with utilizing)			
		VSI [20]	PSI [21]	LSF [22]	VSF
Optimal Location	-------	11	31	29	30
Optimal Size (kVAr)	-------	1050	1150	1400	1250
Power Loss (kW)	202.67	172.80	150.20	145.57	143.38
% Reduction in P_{loss}	-------	14.73	25.88	28.16	29.25
$V_{\min}$ (p.u)	0.9131	0.7266	0.9243	0.9246	0.9260
Total AVD	1.5194	0.7600	0.8212	0.8837	0.8194
Total annual cost saving ($)	-------	10,135	21,480	22,585	24,545

To analyze the efficiency of the present approach using IEEE 33-bus test system, two scenarios have been considered:

Scenario (i): System with single DSTATCOM

In this scenario, a single DSTATCOM has been optimally placed at the 30th bus. To achieve minimum power losses, the sizing of DSTATCOM is calculated using bat algorithm. Table 3, demonstrations the comparison of active and reactive power losses, location, optimal kVAr, total AVD and the total annual cost saving for IA and present method.

Table 3 *Results of 33-bus system (With single DSTATCOM)*

	Without Compensation	With Single DSTATCOM	
		IA [15]	Present Method
Optimal size (kVAr)	-------	962.49	1250
Location	-------	12	30
P_{loss} (kW)	202.67	171.79	143.38
% Reduction in P_{loss}	-------	15.24	29.25
Q_{loss} (kVAr)	135.24	115.26	96.17
% Reduction in Q_{loss}	-------	14.78	28.89
$V_{\min}$ (p.u)	0.9131	0.9258	0.9260
$VSI_{\min}$ (p.u)	0.6890	0.7266	0.7272
Total AVD	1.5194	0.8465	0.8194
Total annual cost saving ($)	-------	11,120	24,545
Computation time (s)	-------	-------	6.5

Table 4 *Results for 33-bus system under various types of Load Factor (With single DSTATCOM).*

With Single DSTATCOM	Load Factor					
	Light Load (0.5)		Medium Load (1.0)		Peak Load (1.6)	
	Base case	Proposed method	Base case	Proposed method	Base case	Proposed method
Optimal size (kVAr) & Location	-------	580(30)	-------	1250(30)	-------	1980(30)
P_{loss} (kW)	47.06	33.89	202.66	143.38	575.33	394.63
% Reduction in P_{loss}	-------	28	-------	29.25	-------	31.4
Q_{loss} (kVAr)	31.37	22.54	135.23	96.17	384.53	264.43
% Reduction in Q_{loss}	-------	28.15	-------	28.89	-------	31.23
$V_{\min}$ (p.u)	0.9583	0.9730	0.9131	0.9264	0.8527	0.8860
$VSI_{\min}$ (p.u)	0.8402	0.8632	0.6890	0.7272	0.5192	0.5823
Total AVD	0	0	1.5194	0.8194	2.6735	1.9698

In the present approach, the active and reactive power losses have been mitigated to 143.38 kW and 96.17 kVAr after installing DSTATCOM in the RDS. The loss reduction is high in case of proposed method when compare to IA method. The total AVD is reduced from 1.5194 to 0.8194, which ensures the voltage profile improvement in the RDS. This ensures that the present BA based approach is more accurate than the IA based approach.

Scenario (ii): System with multiple DSTATCOM

In this scenario, three DSTATCOMs are optimally placed at the 11th, 24th and 30th buses and the optimal size of these locations can be calculated by using the proposed bat algorithm. In order to show the performance of the present approach, the authors have executed the objective function with the help of two algorithms namely BFOA and proposed Bat algorithm. Since there is no research work published on RDS with multiple DSTATCOMs, the authors have implemented the same objective function with BFOA and compared the results with the proposed bat algorithm.

Table 5 *Results of 33-bus system (With Multiple DSTATCOMs)*

	Without Compensation	With Multiple DSTATCOMs	
		BFOA	Present Method
Optimal size (kVAr) & Location	-------	570(11) 580(24) 1080(30)	440(11) 520(24) 1000(30)
Total kVAr	-------	2230	1960
P_{loss} (kW)	202.67	134.33	132.08
% Reduction in P_{loss}	-------	33.71	34.84
Q_{loss} (kVAr)	135.24	90.02	88.30
% Reduction in Q_{loss}	-------	33.43	34.7
$V_{\min}$ (p.u)	0.9131	0.9382	0.9361
$VSI_{\min}$ (p.u)	0.6890	0.7723	0.7602
Total AVD	1.5194	0.6208	0.5800
Total annual cost saving ($)	-------	24,100	26,715
Computation time (s)	-------	10.68	9.62

The loss values, optimal kVAr, minimum bus voltage, total AVD and total annual cost saving of two DSTATCOMs is obtained by BFOA and proposed algorithm are presented in Table 5. Table 5 concludes that the presented BA based approach owns more system power loss reduction and higher total annual cost saving compared with other method with lesser computation time. This ensures that the presented algorithm is more efficient than BFOA.

In addition, the performance of the 33 bus test system with different load factors (Light, Medium, Peak) before and after placement of single and multiple DSTATCOMs in the RDS are shown in Table 4 & 6. The tables represent a noteworthy improvement in the power loss mitigation is nearly equal even when the load rises from light to peak load levels. Also, the bus voltage has been gradually enhanced for all load factors. This demonstrates that the present method is very effective in determining the optimal kVAr and site of DSTATCOMs for the networks with different load conditions. Thus, the solution of proposed method with various load factors to distribution network will be useful for DNOs to select the DSTATCOM size for a particular load level.

Table 6 *Results for 33-bus System under various types of Load Factor (With Multiple DSTATCOMs).*

With Multiple DSTATCOMs	Load Factor					
	Light Load (0.5)		Medium Load(1.0)		Peak Load(1.6)	
	Base case	Proposed method	Base case	Proposed method	Base case	Proposed method
Optimal size (kVAr) & Location	-------	220(11) 250(24) 510(30)	-------	440(11) 520(24) 1000(30)	-------	740(11) 830(24) 1620(30)
Total kVAr	-------	980	-------	1960	-------	3190
P_{loss} (kW)	47.06	31.06	202.66	132.08	575.33	360.25
% Reduction in P_{loss}	-------	34	-------	34.84	-------	37.38
Q_{loss} (kVAr)	31.37	20.68	135.23	88.3	384.53	240.23
% Reduction in Q_{loss}	-------	34.08	-------	34.7	-------	37.52
$V_{\min}$ (p.u)	0.9583	0.9710	0.9131	0.9361	0.8527	0.9020
$VSI_{\min}$ (p.u)	0.8402	0.8868	0.6890	0.7602	0.5192	0.6492
Total AVD	0	0	1.5194	0.5800	2.6735	1.6218

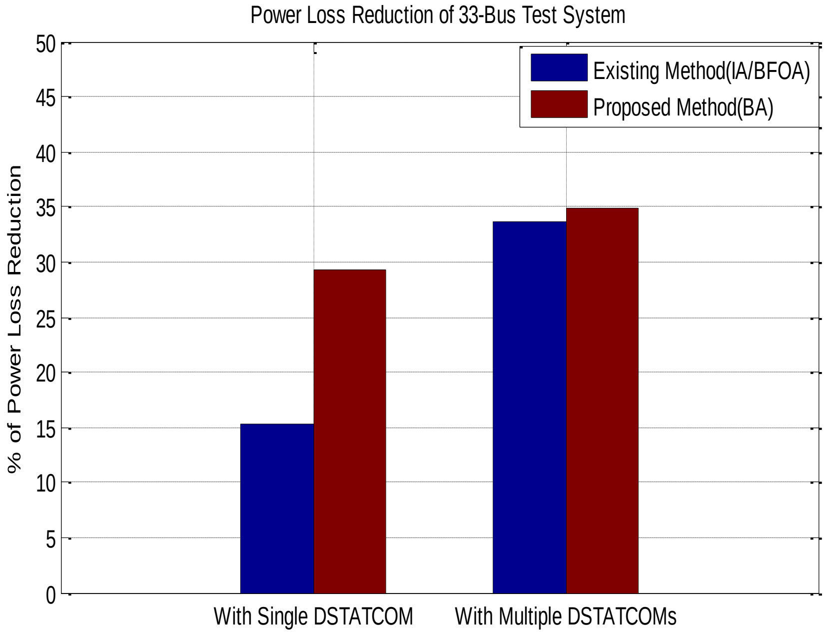

Figure 4. *Comparison of IA/BFOA and present methods for power loss mitigation in a 33 bus test system*

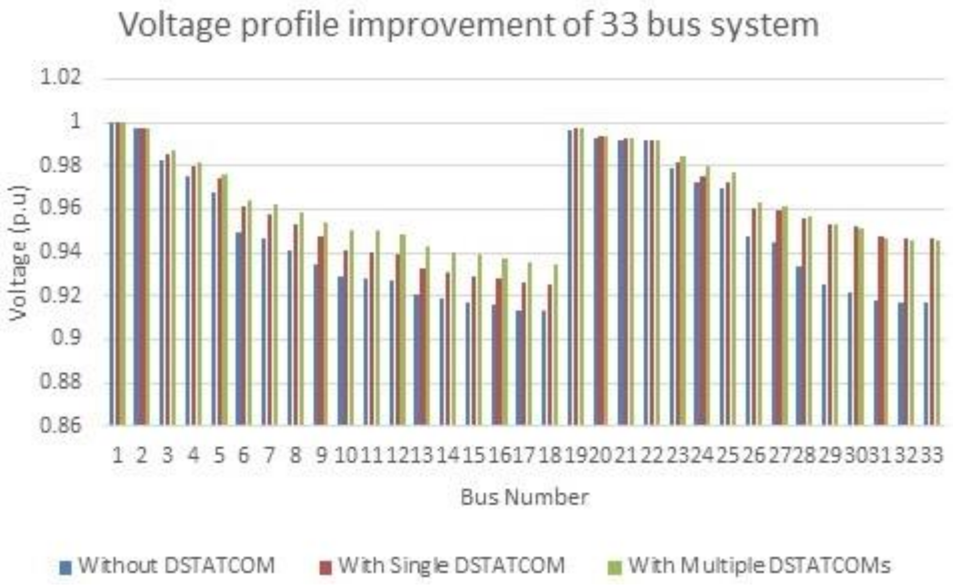

Figure 5. *Voltage profile improvement of 33 bus system with and without DSTATCOM*

Figure 4 displays the active power loss mitigation of IM/BFOA and the proposed method for single and multiple DSTATCOMs in 33 IEEE bus RDS. The present approach shows more mitigation in power loss as compared to the other methods. The voltage magnitude improvement of 33 bus system without DSTATCOM and with single and multiple DSTATCOMs are given in Fig. 5. It is clear from Fig. 5 that there is a development in magnitude of voltage with optimal placement of single and multiple DSTATCOMs in the RDS. From the above words, it can be decided that the optimal placement of DSTATCOM in the RDS will mitigate the power loss and improve the bus voltage of the RDS.

In order to predict the supremacy of BA, the convergence characteristics of the BA for 33 bus test system is compared with IA as displayed in Fig. 6. From the figure, it is very clear that the bat algorithm takes only 12 iterations to settle for the optimal solution. Additionally, bat algorithm demonstrations a steady and rapid convergence with a universal searching capability to find the optimum DSTATCOM sizes.

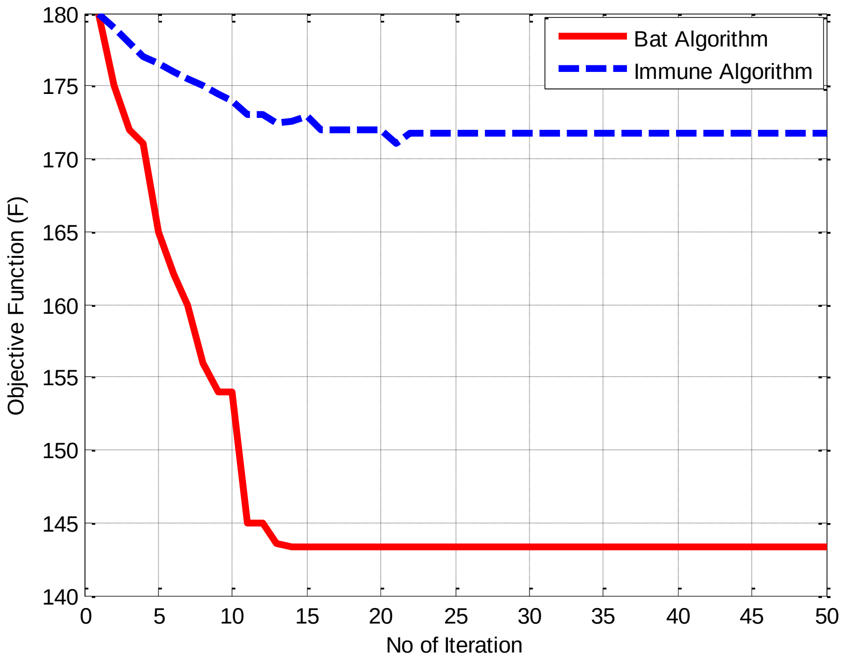

Figure 6. *Comparison of convergence characteristic for the 33 bus RDS*

5. CONCLUSION

A new BA based approach has been presented in this work in order to allocate the optimum placement and sizing of DSTATCOMs in the RDS. The appropriate location of DSTATCOM is more important to guarantee that network power loss is mitigated and bus voltage is maximized. In this present work, a new VSF is used to determine the optimal location of the DSTATCOM. Compared with other stability indices, VSF gives better locations in terms of minimum power losses, maximum TACS with good bus magnitudes in the RDS. The proposed method is implemented on 33-bus RDS, and the results are verified with other heuristic methods. The results presented in the article indicate that the implementation of the DSTATCOM in the RDS is capable to decrease the total power loss and enhancing the voltage magnitudes of the RDS. Hence by using this methodology it can be suggest that the operational efficacy of the RDS improves considerably and it is efficient technique to implement in all the RDS to achieve better performance.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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