# Enhancement of Active Distribution Network Performance with Multiple Distributed Generators and DSTATCOMs using Reptile Search Algorithm

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***Abstract*** *– The integration of multiple DGs can introduce power quality issues and instability in the (DN) due to their intermittent and fluctuating nature. Distributed Static Compensators (DSTATCOMs) are devices that effectively manage and regulate both active and reactive powers, thereby maintaining the desired levels of reactive power in the DNs. This paper investigates the problem of determining the optimal number and placement of multiple DSTATCOMs within active DNs with multiple Distributed Generators (DGs) connected to them. To achieve the optimal sizing and allocation of multiple DSTATCOMs, a novel heuristic method called the reptile search algorithm (RSA) is introduced in this study. A combination of the RSA method and the loss sensitivity factor (LSF) are utilized to identify the optimal number, sizes, and locations of DSTATCOMs to enhance the performance of active DNs with different types of DGs and loads. The desired improvements include mitigating voltage deviation at nodes, minimizing system power losses, and alleviating overloading in feeders. The effectiveness of the algorithm is evaluated using an IEEE-33 bus DN, which is modified to incorporate different DGs and load types. To assess the efficiency of the proposed method, a modified particle swarm optimization (MPSO) algorithm is used for comparison. The results demonstrate that the RSA approach presented in this paper is robust in obtaining optimal solutions, offers fast and easy implementation, can be applied to large DNs, and outperforms the MPSO algorithm.*

***Keywords***: *DSTATCOM allocation and sizing, active distribution networks, RSA, MPSO, Active power losses*

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## 1. INTRODUCTION

Distribution networks (DNs) are traditionally configured to facilitate the one-way flow of energy from the transmission/generation systems to the end consumers. However, in active DNs, the energy can also be transmitted in the reverse direction from the consumers to the grids. This bidirectional power flow, attributed to Distributed Generators (DGs), introduces challenges related to the power quality of the DNs. The impact on power losses, whether decrease or increase, is predominantly contingent on factors such as network structure, configuration, DG type, capacity, and location. Furthermore, these dynamics influence the overall voltage profile of the system [1].

DSTATCOM, a component of distributed FACTS, serves as a shunt-connected apparatus for reactive power compensation, distinguishing itself among various compensation devices. Recently, DSTATCOM has gained prominence due to its operational flexibility and control capabilities within power systems. It effectively facilitates reactive power flow control, reduction of power losses, and regulation of voltage and current. Unlike series or shunt capacitors, DSTATCOM units operate without encountering operational challenges such as harmonics. DSTATCOM units offer several benefits, such as minimal harmonic distortion, low cost, high regulatory capability, and low power losses [2].

Recently, there has been significant scientific attention given to determining the optimal placement and capacity of renewable energy source (RES) based DGs to overcome the problems that were mentioned previously. The strategic placement of multiple DGs to simultaneously reduce the total active power losses (TACPL) and generation costs for both conventional generators and DGs was employed by [3]. The particle swarm optimization (PSO) method was implemented to attain the best locations and sizes of the RESs-based DGs (Solar, fuel cell, wind units) in the DNs. The main objective was to decrease the cost of DG units, the TACPLs, and Total Harmonic Distortion (THD) [4]. The ant lion optimizer was utilized to obtain the best sizes and settings of DGs in DNs while considering multiple objective functions such as reducing the cost of energy, TACPLs, and voltage drop and improving reliability [5]. A hybrid method based on Grey Wolf Optimizer method was introduced in [6] to place the REEs in the DNs. Another study utilized a hybrid optimization method based on combining the grasshopper optimization and cuckoo search algorithms to determine the best locations and capacities of DGs [7]. The optimal network reconfiguration and DG allocation were used to reduce TACPLs and enhance the stability of voltage using the adaptive modified whale optimization algorithm [8]. The quasi-oppositional grey wolf optimization technique with the Pareto concept were employed to optimally placement of DGs in the radial DNs to reduce the TACPLs and voltage drop [9]. The transient search optimizer (TSO) method was implemented to find the optimal DGs allocation to reduce the power losses and voltage deviation (VD) and enhance the stability of voltage [10]. Another study used the Whale Optimization technique (WOT) to obtain efficient DGs ratings and locations [11]. An analytical method to attain the best locations and rating of RESs based DGs in the DNs for minimizing the power flow limits, DG capacities, bus voltage limits and power loss using coot bird optimization method (CBOM) [12]. Although previous research laid the foundation for determining the best locations for DGs in the electrical DN, it was insufficient to solve the problems that arise from the presence of these DGs within the electrical DN.

Numerous research endeavors have leveraged DSTATCOM in distribution networks, reaping various advantages. Nevertheless, the size and placement of the DSTATCOM units are crucial factors that must be carefully considered to maximize the benefits from their installation. The optimal determination of distribution system tie switches, coupled with the optimal locations and sizes of DSTATCOM units, has been a key focus to achieve favorable operational conditions. To address the intricacies of this combinatorial nonlinear optimization problem, the Differential Evolution Algorithm (DEA) was employed [13] [14]. Additionally, the bio-inspired Cuckoo search method was used to obtain the best sizes of the DSTATCOM units in the radial DNs, while the loss sensitivity factor (LSF) was utilized to find the optimal locations [15]. Furthermore, the Ant-Lion optimization (ALO) method was applied in [16] to appropriately allocate the DSTATCOM. The objective was to increase the cost-benefit resulting from reducing the expense of purchasing power from the electrical power system, and the cost of DSTATCOM. The location strategy of DSTATCOM units within the radial DNs was accomplished using the black widow optimization technique [17]. The main objective was to reduce the TACPLs while considering different technical and economic factors such as annual cost savings and the voltage stability index (VSI). Furthermore, the modified capuchin search algorithm was introduced to address multiple issues related to optimal DSTATCOM allocations [18]. A multi-objective approach was employed to compensate the reactive power in radial DNs [19]. It focused on finding the optimal simultaneous allocation of DSTATCOMs and static capacitors by employing fuzzy decision making.

Other researchers have concurrently utilized DGs along with DSTATCOMs in the DNs to achieve both power loss minimization and power quality enhancement. In [20], an optimal placement strategy for multiple DG and DSTATCOM units in DN resulted in reduced line losses and improved power quality, as indicated by THD. Considering load models, ref. [21] utilized Genetic Algorithm (GA) to improve the total VD and minimize the TACPLs by integrating DGs with DSTATCOM units. The allocations of both DSTATCOM units and DGs were executed by implementing the LSF [22]. The bacterial foraging optimizer technique was introduced to ascertain the optimal size of DGs and DSTATCOM, considering different models of loads to minimize the VD, reduce TACPLs, improve VSI, and enhance the security of the DN [23]. Meanwhile, a novel Lightning Search Algorithm was applied to simultaneous allocate the DGs and DSTATCOM units in radial DNs to minimize TACPLs, Total VD, and maximize the value of VSI [24]. The whale optimization algorithm (WOA) was used to simultaneous allocate DGs and DSTATCOMs in the radial DNs [25]. The main goal of the algorithm was to reduce both the TACPLs of the system and the operating costs associated with DGs and DSTATCOMs. A planning strategy was introduced to optimally reconfigure the feeders, allocate and sizing the DSTATCOM in unbalance radial DNs [26]. The seagull optimization algorithm (SOA) was applied to address this mixed-integer nonlinear planning problem to achieve minimum TAC-

PLs. A hybrid technique based on Sine Cosine Algorithm (SCA) and Moth Flame Optimization (MFO) method was proposed for performing the exploitation and exploration phases in finding the best locations of the capacitors and DGs in DNs [27]. The TACPLs were applied as an objective function to integrate DGs and capacitors in DNs. The DSTATCOM and the PV DGs were integrated into the 33-bus and 69-bus DNs [28]. The modified homonuclear molecules optimizer technique is used to attain the optimal positions of them while minimizing the cost of devices' integrations, total voltage deviations (TVD), and TACPLs. The results demonstrated that the algorithm could reduce the TACPLs by 94.27% for IEEE 33-bus and 97.87% for IEEE 69-bus systems. The honey badger method was utilized to attain the optimal location and size of various types of DGs to reduce the TACPLs of the DNs [29]. The power LSF was used to order the buses for optimally installing the SCs and DGs in the radial DNs to accelerate conversion of the honey badger algorithm. Also, two types of DGs were applied in the IEEE 69-bus standard radial DN. The Slime Mould algorithm was used to locate the PVDGs and the distribution static Var compensators (DSVCs) to satisfy economic and technical objectives [30]. The selected objectives consisted of minimizing the TACPL, TVD, Total Reactive Power Loss (TRPL), Operating times of the overcurrent relays, and investment costs of both PVDGs and DSVCs. Previous studies did not consider the optimal number of DSTATCOMs, and the issue of relieving distribution systems by increasing DG penetration levels through optimal DSTATCOM allocation was not explored. Additionally, similar research did not investigate the impact of different load types and various DG types on DSTATCOM optimal allocation.

The proposed algorithm in this paper tackles the combinatorial non-linear optimization problem of identifying the optimal number, location, and size for multiple DSTATCOM units in the DNs. This innovation is advantageous for distribution system operators seeking to enhance operational performance. The algorithm considers the presence of already allocated DGs and has the capability to remove DG penetration level restrictions. Furthermore, this work delves into the behavior of various load and DG types. The main contributions of this paper can be listed as:

- Propose a new methodological approach for achieving the best number, location, and sizing of DSTATCOMs in DNs.
- Determine the optimum location and sizing by the proposed Reptile Search Algorithm (RSA) and MPSO.
- Examine the impacts of various load types, DG types, and load factors on the optimal allocation and sizing of DSTATCOMs.
- The results of the RSA are compared with Modified PSO algorithms.

The structure of this paper is outlined as: The comprehensive review of modeling the DSTATCOM as a highly effective remedy in DNs is provided in section 2. Illustrating problem formulation and introducing the LSF as an indicator of potential bus locations for DSTATCOM placement are presented in section 3. Moreover, the proposed Reptile Search Algorithm (RSA) and MPSO method are introduced. The IEEE-33 bus radial DN is identified in section 4 as a test distribution system. Section 5 encompasses numerical analysis and simulation studies conducted using the proposed RSA and MPSO algorithms. Finally, the paper concludes with closing remarks in section 6.

## 2. DSTATCOM MODELING

The DSTATCOM functions as a variable current source (VCS) and is connected as a shunt element. It is able to absorb or inject reactive and active currents. To enhance the dynamic rating of the capacitive range, the DSTATCOM can be connected in parallel with a fixed capacitor. By incorporating energy storage apparatus on the DC side via DC/DC converter, the active power is temporarily interchanged with the grid, especially during events such as large voltage sags or momentary interruptions. The DSTATCOM can be composed of voltage source converter and energy storage, enabling injection of both reactive and active power. However, injecting active power for an extended duration is constrained by voltage regulation and the energy storage system's capacity limit. In the second model, the DSTATCOM is composed of a voltage source converter and small capacitor. In this configuration, only reactive power can be exchanged between the DSTATCOM and the AC system [31].

In an electric DN comprising two nodes labeled $j$ and $k$, a DSTATCOM unit is linked to bus k to regulate voltage. The installation of the DSTATCOM unit resulted in an increase in the voltage at node $k$ from $V_k$ to $V_k^n$. The amount of reactive power injected from the DSTATCOM denoted as QDSTATCOM, can be given by:

$$Q_{DSTATCOM} = Img\ (V_k^n . I_{DSTATCOM}{}^*) \tag{1}$$

$$V_k^n = V_k^n \angle\ \alpha_{new} \tag{2}$$

$$I_{DSTATCOM} = |I_{DSTATCOM}| \angle \left(\ \alpha_n + \frac{\pi}{2}\right) \tag{3}$$

where, $I_{DSTATCOM}$ represents the injected current from the DSTATCOM and $\alpha_{new}$ represents the voltage angle at node k after connecting DSTATCOM device.

## 3. DSTATCOM OPTIMAL SIZING AND ALLOCATION

The main objectives of the optimal locations and sizes of DSTATCOM units in the DN with DGs are to minimize the TACPLs and enhance the TVD in the system. These objectives are subject to constraints that ensure the system's feeder currents and voltage profile remain within specified bounds. The identifying of candidate buses for DSTATCOM units' allocation is accomplished by applying the LSF method, implemented through a MATLAB code. Subsequently, the optimal number, location, and size for multiple DSTATCOM units are obtained by applying the proposed RSA method, which is also implemented through a MATLAB code specifically designed for this purpose. The optimal solution is defined as the best among the candidate buses, where the TACPL is minimized, and the TVD is enhanced. The proposed algorithm can be divided into the following key stages.

- Stage 1, Using the LSF method for defined the DSTATCOM candidate buses.
- Stage 2, Using RSA and MPSO as optimization methods for calculating the best number of DSTATCOM units and their sizes.
- Stage 3, Comparing the values of the TACPLs and TVD of various combinations for defined the optimal DSTATCOM number.

### 3.1. DSTATCOM CANDIDATE BUSES BY USING LSF

The LSF method is employed to obtain the optimal locations of DSTATCOMs in the DN regarding power loss minimization. LSF has the ability to forecast the bus where the installation of DSTATCOM will result in the most significant reduction in power losses. Consequently, these critical locations serve as potential bus candidates for the allocation of DSTATCOM. To illustrate the LSF concept, let's examine a two-bus distribution system with a given impedance $R+jX$ connected between the two buses and a load of $P_e+jQ_e$ as shown in Fig. 1. The TACPLs through the line could be expressed as given in Eq. 4 [31].

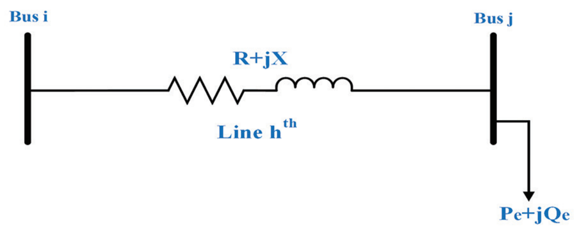


**Fig. 1.** Simple two-bus distribution system

$$P_{LL}(h) = \frac{[P_e^2(j) + Q_e^2(j)] * R(h)}{[V(j)]^2} \tag{4}$$

where, $P_{LL}(h)$ is the real power loss in distribution line hth, $V(j)$ is the value of voltage at bus jth, and $R(h)$ is the distribution line hth resistance. So, the LSF is calculated by:

$$LSF = \frac{\partial P_{LL}(j)}{\partial Q_e(j)} = \frac{[2 * Q_e(j)] * R(h)}{[V(j)]^2} \tag{5}$$

The LSF is computed using the Backward-Forward Distribution Load Flow technique [31]. Their values are arranged in descending sequence, and the respective buses indices are documented in the position vector, $Pp(i)$. Furthermore, the arranged components of ($\partial P_{LL}(j)/\partial Q_e(j)$) in $P_p(i)$ dictate the sequence of candidates for the optimal allocation of the DSTATCOMs. The normalized voltage magnitudes at the buses corresponding to $P_p(i)$ are computed by:

$$Norm\ V(i) = \frac{|V(i)|}{0.95} \tag{6}$$

where the division of $|V(i)|$ by 0.95 refers to the voltage acceptable tolerance of 5%. The $Norm(i)$ function assesses the requirement for reactive power compensation at the arranged buses. Therefore, for DSTATCOM placement, buses with $Norm\ V(i)$ greater than 1.01 are considered as DSTATCOM candidates. The process of identifying DSTATCOM candidates is outlined as follows:

Step 1: perform load flow analysis on the DN in the base case.

Step 2: LSF is calculated for each feeder in the DN.

Step 3: the values of the LSF are organized in descending sequence, and the associated buses are documented in the vector $Pp(i)$.

Step 4: for the corresponding feeders, the values of the normalized buses voltage are calculated.

Step 5: according to the $Norm(i)$, the reactive power compensation is established by selecting buses with a value less than 1.01 as candidates for installing DSTATCOM units. Conversely, buses with a Norm(i) exceeding 1.01, indicating that their voltage profile is within acceptable limits, do not require reactive power compensation.

### 3.2. DSTATCOM OPTIMAL SIZES DETERMINATION

In this paper, part of the proposed method involves obtaining the optimal sizes of DSTATCOMs. Mathematical formulation is employed to determine the sizing of DSTATCOM, posing it as an optimization problem. The objective function is optimized while adhering to specific equality and inequality constraints as illustrated below.

#### 3.2.1. Objective function

The objective function (OF) is nonlinear, aiming to minimize the TACPs and enhance the TVD in the DN. It can be expressed as follows:

$$TACPL = \sum_{h=1}^{N_f} P_{LL}(h) \tag{7}$$

$$TVD = \sum_{j=1}^{n} (V_{ref} - V_j)^2 \tag{8}$$

$$OF = \min(\omega_1 TACPL + \omega_2 TVD) \tag{9}$$

where, $N_f$ and $n$ are the total number of feeders and nodes, respectively. $V_{ref}$ and $V_j$ are the reference and node voltage magnitude. $\omega_1$ and $\omega_2$ are the weighted factors where the summation these factors should be equal one. In this paper, many combinations of the weighted factors are evaluated by applying them to the IEEE 33-bus test system to reach the best one. Finally, the best one is used to obtain the OF. For this analysis, the power losses have the higher weight (0.63) since it is important for distribution system. The total voltage deviations receive a weight of 0.37.

#### 3.2.2. Constraints

The objective function is bound by multiple operational constraints, encompassing voltage limitations, feeder current restrictions, constraints on reactive power compensation, power balance constraints, and limits on both active and DSTATCOM sizes. These constraints can be articulated by:

1. - Feeder current limits

The primary feeders within the DNs are capable of providing a maximum magnitude of current, defined by:

$$\left|I_{fi}\right| \leq I_{fi}^{max}\ ;\ \ i = 1,2,\ldots\ldots,N_f \tag{10}$$

where, $I_{fi}^{max}$ represents the maximum current in feeder ith and $I_{fi}$ represent the flow current in feeder $i^{th}$.

2. - Bus voltage constraints

$$V_{j\,min} \leq V_j \leq V_{j\,max} \quad ,j = 1,2,\ldots\ldots,n \tag{11}$$

where, $V_{jmax}$ and $V_{jmin}$ represent the upper and lower voltage limits at busbar $j^{th}$, respectively.

3. - Generator reactive power limits

$$Q_G \leq Q_G^{max} \tag{12}$$

where, $Q_G$ and $Q_G^{max}$ are the current value and maximum permissible value of generator reactive power.

4. - DSTATCOM size

$$Q_{DSTATCOM}^{min} \leq Q_{DSTATCOM} \leq Q_{DSTATCOM}^{max} \tag{13}$$

where, $Q_{DSTATCOM}^{max}$ and $Q_{DSTATCOM}^{min}$ represent the upper and lower limits of injected reactive power from DSTATCOM.

5. - Slack bus active power limit

$$P_S \leq P_S^{max} \tag{14}$$

where, $P_S$ and $P_S^{max}$ are the current and maximum permissible active power generated at the slack bus, respectively.

6. - Power balance constraints

Maintaining a balance among power generation, power demand, and power loss, is of utmost importance in DNs to uphold system stability and reliability.

$$P_{LOSS} = \sum_{j=1}^{n} P_{Gj} - \sum_{j=1}^{n} P_{Dj} \tag{15}$$

$$Q_{LOSS} = \sum_{j=1}^{n} Q_{Gj} - \sum_{j=1}^{n} Q_{Dj} \tag{16}$$

The succeeding section outlines the optimization methods that are employed to determine the optimal size of DSTATCOMs. The main problem is to obtain the best locations and sizes of DSTATCOM units. The subsequent section outlines the principles and implementation strategies of the proposed MPSO and RSA.

#### 3.2.3. The proposed optimization algorithms

1. - Modified particle swarm optimization Algorithm (MPSO)

The PSO operates on the premise that every particle in the population represents a potential solution to the problem. It relies on the concept of parallel search within a group of particles. These particles, working collectively, converge towards the optimal value by leveraging their current velocity and positions [32]. The fundamental rules for updating the position and velocity are outlined as follows [32-33]:

$$V_i^{t+1} = wV_i^t + A_1R_1 \times (P_i^t - X_i^t) + A_2rR_2 \times (G^t - X_i^t) \tag{17}$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{18}$$

where $V_i^t$ and $V_i^{t+1}$ are the velocity of particle ith at iteration $t$ and $t$+1, respectively. $P_i^t$ and $P_i^{t+1}$ represent the position of particle ith at iteration $t$ and $t$+1, respectively. $R1$ and $R2$ are random numbers between 0, and 1, and $w$ is the weighed inertia coefficient. $A1$ and $A2$ are accelerating factors.

When the PSO method is dealing with a large search space, its convergence speed tends to slow down, resulting in suboptimal solutions. Additionally, when dealing with large and complex datasets, the algorithm may produce unsatisfactory results in terms of accuracy. In order to overcome these constraints and improve both convergence speed and accuracy of the PSO, several variants of the PSO have been proposed [32]. This paper utilizes various variants of the PSO algorithm, PSO with time-varying acceleration coefficient (PSO-TVAC) and damped inertial weight (PSO-DIW) to conduct a comparative analysis. TVAC and DIW values in the PSO algorithm are updated by applying Eqs. (19)-(22) [34].

$$\alpha_1 = \left(\alpha_{1f} - \alpha_{1i}\right)\frac{iter}{Max_{iter}} + \alpha_{1i} \tag{19}$$

$$\alpha_2 = \left(\alpha_{2f} - \alpha_{2i}\right)\frac{iter}{Max_{iter}} + \alpha_{2i} \tag{20}$$

$$w = (w_{max} - w_{min})\frac{t_m - t}{t_m} + w_{min} \tag{21}$$

$$w = w \times w_{damp} \tag{22}$$

where $\alpha_{1f}$ and $\alpha_{1i}$ represent the final and initial values, respectively, of the first acceleration coefficients. $\alpha_{2f}$ and $\alpha_{2i}$ represent the final and initial values, respectively, of the second acceleration coefficients. $w_{min}$, $w_{max}$ and $w_d$ represent the lower, upper, and damped values, respectively, of the weighed inertia.

In this research, Eqs. 19-21 are employed to dynamically adjust the acceleration and weighted coefficients in the PSO-TVAC variant. However, Eq. 22 is specifically used to adjust the coefficients in the PSO-DIW variant. The flowchart in Fig. 2 illustrates the different PSO variants, including the traditional PSO algorithm, employed to optimize sizes of the DSTATCOM units.

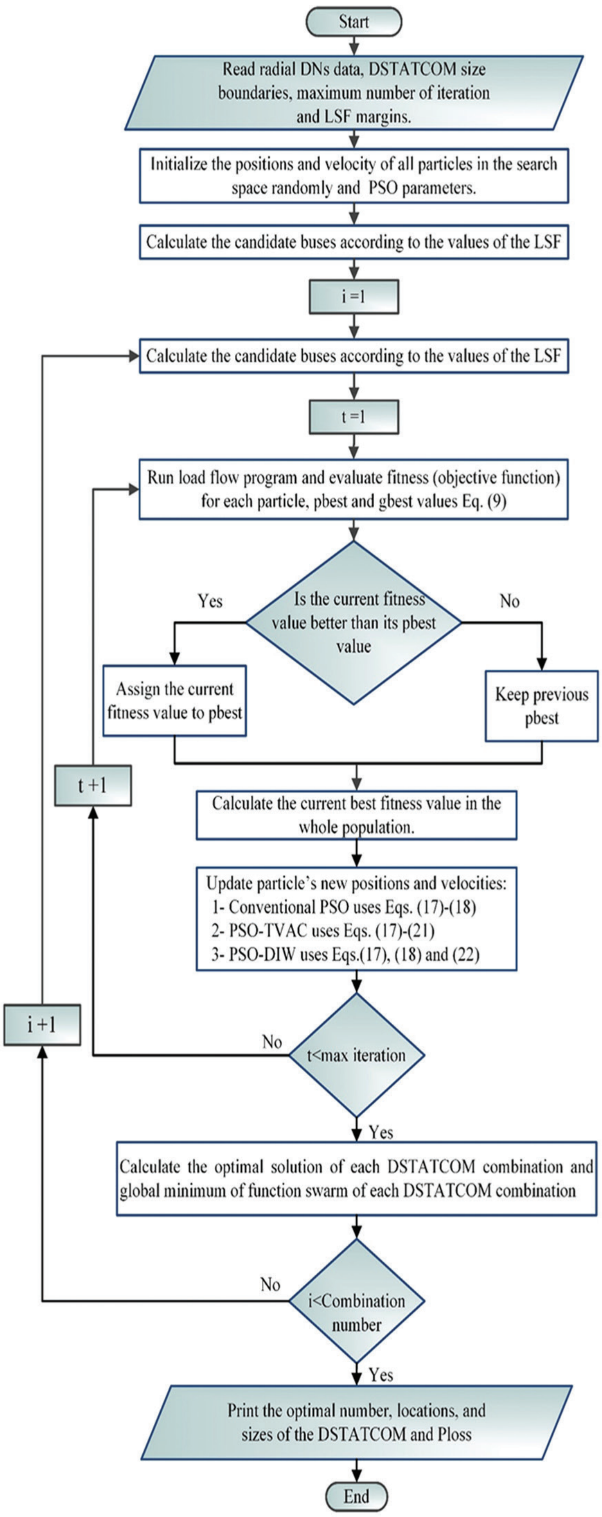


**Fig. 2.** Proposed MPSO algorithm flowchart for DSTATCOM optimal sizing

2- Reptile search algorithm (RSA)

The RSA is a metaheuristic method that derives its inspiration from the natural behaviors of crocodiles. It incorporates elements such as the hunting behavior, enveloping mechanism, and social dynamics observed in crocodiles. By employing a swarm-based approach, the RSA algorithm leverages these principles to effectively guide its search process [35]. The RSA initialization formula is employed to generate the initial solution in a random manner, ensuring it falls within the solution domain. The solution domain encompasses the entire range of potential solutions for the given optimization problem [35].

$$L_{ij} = L_v + r_1 .(U_v - L_v) \tag{23}$$

where $L_{ij}$ is the value of the jth dimension of the ith crocodile. $L_v$ and $U_v$ minimum and maximum boundary values of the search domain, respectively. $r_1$ is random number in range 0 and 1, and n is the size of populations. The mathematical modeling of the RSA is expressed in the following subsections.

- Enveloping Mechanism

The RSA incorporates the concept of enveloping to explore the search space in a manner that prioritizes promising regions while avoiding less favorable ones. This approach enables the algorithm to effectively navigate complex optimization landscapes. In the global search phase, crocodiles engage in extensive and wide-ranging walks, which can be quantified through iterations. The mathematical models capturing this mechanism are described in references [35, 36].

$$\boldsymbol{L_{ij}(t+1)} = \begin{cases} \boldsymbol{L^t_{j,best} \cdot \left(-\vartheta^t_{ij} \times \beta \times \left(\frac{L^t_{j,best} - L^t_{ij}}{L^t_{j,best} + \varepsilon}\right) \times r_1\right)} & \boldsymbol{t \le \frac{T_m}{4}} \\ \boldsymbol{L^t_{j,best} \times L^t_{j,rand} \times 2r_2 \left(\frac{T_m - 1}{T_m}\right) \times r_1} & \boldsymbol{\frac{T_m}{4} \le t \le \frac{2T_m}{4}} \end{cases} \tag{24}$$

where $t$ and $T_{max}$ are the current and maximum number of iterations, respectively. $\vartheta_{ij}^{t}$ denotes the hunting operator value for ith solution at jth location during the tth iteration. $L^t_{j,best}$ represents the optimum solution at jth location during the tth iteration. The hunting operator is determined by the following expression[44]:

$$\vartheta^t_{ij} = L^t_{j,best} \times \left(\sigma + \frac{L^t_{ij} - Avr\left(L^t_{ij}\right)}{L^t_{j,best} \times (U_v - L_v) + \varepsilon}\right) \tag{25}$$

where $r_2$ represents a random number ranging from -1 to 1, $\sigma$ is a constant to controls the accuracy of the exploration, $\varepsilon$ is a minimum number that guarantees the denominator does not reach zero, and $Avr$ refers to the average value.

- Hunting Mechanism

The hunting mechanism within the RSA is analogous to the enveloping mechanism and comprises two distinct phases: hunting coordination and cooperation. These phases are designed to explore the search domain and facilitate the identification of the best possible solution while capturing the prey.

The specific definition of these phases is based on the number of iterations. Hunting coordination is applied for iterations in range 0.5 $T_{max} < t \le 0.75\ T_{max}$, whereas hunting cooperation is employed in range 0.75 $T_{max} < t \le T_{max}$.

The hunting mechanism is mathematically represented by the following equations as described in references [33, 34].

$$
L_{ij}(t+1) = \begin{cases} L^t_{j,best} \times P_{ij} \times r_1 & \frac{T_m}{2} < t \leq \frac{3T_m}{4} \\ L^t_{j,best} - \vartheta^t_{ij} \times \varepsilon - \left( \frac{L^t_{j,best} - L^t_{ij}}{L^t_{j,best} + \varepsilon} \right) \times r_1 & \frac{3T_m}{4} < t \leq T_m \end{cases} \quad (26)
$$

- Modified Reptile Search Algorithm (MRSA)

The RSA algorithm, despite its effectiveness, is subject to certain limitations, including the trapping of local minima, high computational complexity, and slow convergence speed. To overcome these challenges, several modifications have been proposed for the original RSA. One particular adjustment involves incorporating a sine operator into the high walking phase of the previous RSA algorithm. This modification draws inspiration from the SCA [37]. By introducing the sine operator, the algorithm becomes capable of avoiding local minimum trapping and enhancing global exploration. The sin operator is inserted into Eq. 24 and is modified as follows.

$$
L_{ij}(t+1) = \begin{cases} L^t_{j,best} + \left( r_2 \times \sin(r) \times \left| r_3 \times L^t_{j,best} - L^t_{ij} \right| \right) & t \leq \frac{T_m}{3} \\ L^t_{j,best} \times L^t_{j,rand} \times 2r_2 \left( \frac{T_m - 1}{T_m} \right) \times r_1 & \frac{T_m}{4} \leq t \leq \frac{2T_m}{4} \end{cases} \quad (27)
$$

In the given context, the variables $r_2$ and $r_3$ represent randomly selected numbers within the range of [0, 1]. The adoption of the chaotic inverse learning strategy by all individuals results in increased computing-related to costs and hampers algorithm convergence. To tackle this problem, the paper introduces the linear decreasing population strategy. As the iteration continues, there is a gradual decrease in the number of individuals utilizing the chaotic backward learning strategy. The precise mathematical formula for implementing this strategy is described by:

$$
P = r_1 \times \left( \frac{(P_{min} - P_{max}) \times t}{T_m} + P_{max} \right) \quad (28)
$$

where $P_{max}$ and $P_{min}$ represent the maximum and minimum number of populations, respectively. $P$ represents the number of chaotic backward learning strategy populations.

In this research the RSA technique is implemented, aiming to calculate the optimal size of the DSTATCOM. A detailed depiction of the proposed RSA can be observed in Fig. 3, showcasing the flowchart of the MRSA.

## 4. DSTATCOM OPTIMAL NUMBER DETERMINATION

To identify the optimal number of DSTATCOMs, the solution with the minimum objective function is sought. Consequently, all conceivable combinations of DSTATCOM units at candidate buses are compared based on their respective objective function values. The algorithm proposed in this study calculates the minimum TACPLs and enhance the TVD in the DN and determines the optimal sizes of DSTATCOMs at each potential location. These values are saved for comparison, making it easier to identify the combination that results in the lowest power loss. This combination represents the optimal number, locations, and sizes of DSTATCOMs.

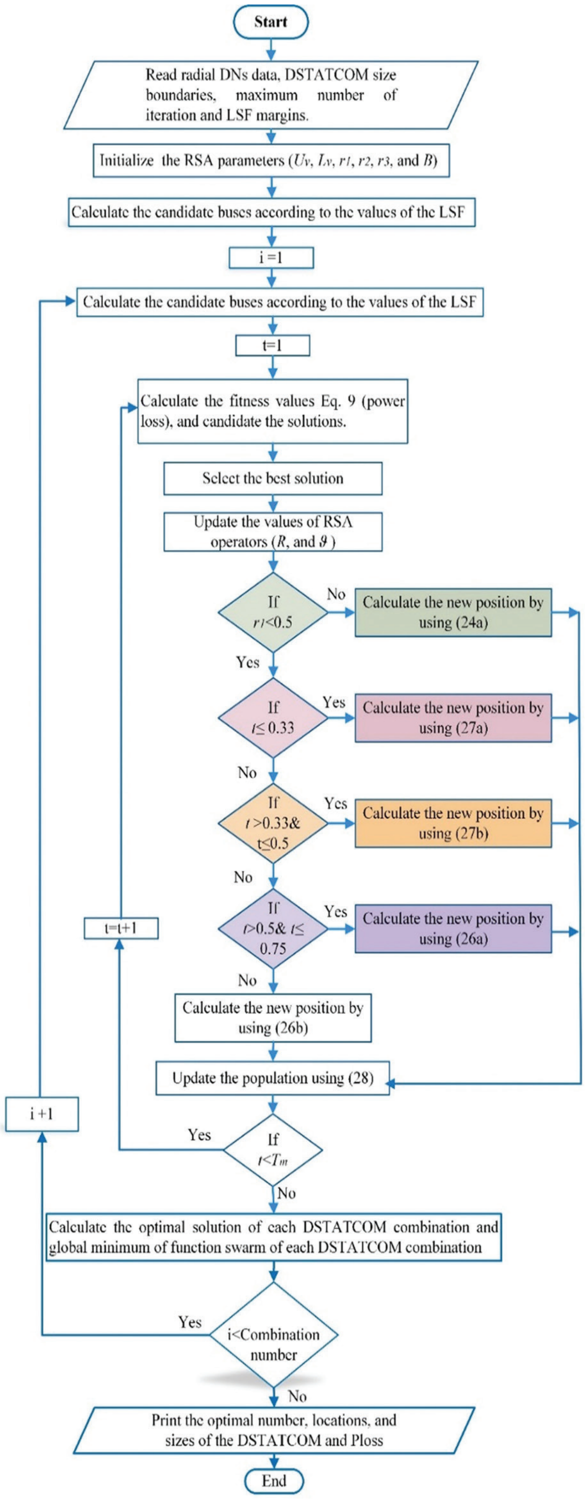


**Fig. 3.** Flowchart of the MRSA method

## 5. TEST SYSTEM: IEEE-33 BUS SYSTEM.

It comprises 33 buses and 32 feeders, with base voltage value of 12.66 kV and 100 MVA for apparent power. The total power consumed by the system is 2300 kVAR for reactive power and 3715 kW for real power. In the base scenario, the TACPLs are 210.9 kW and 135.03 kVAR for reactive power. Bus 1 serves as the power feeder linked to the transmission network, while the other buses can potentially accommodate DSTATCOM [21]. The maximum permissible value of $Q_G^{max}$ and $P_S^{max}$ are 2.5 MVAR and 4 MW, rspectively. The single-line diagram of the system is depicted in Fig. 4. The line and bus data in IEEE-33 bus distribution network in light loading are shown in Table A1 in the appendix.

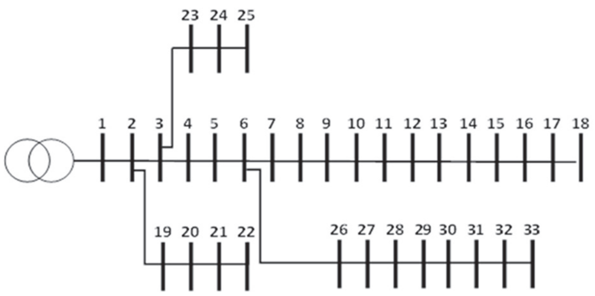


**Fig. 4.** Single line diagram of IEEE-33 bus radial DN

The permissible range for DSTATCOM sizes is set between 0.1 MVAR and 10 MVAR. The maximum allowable voltage deviation at the buses is limited to 10%. Branches 1 to 5 are designed to carry a maximum current of 400 A, while branches 6 to 7 and branches 25 to 27 have a constraint of 300 A. The current carrying capacity for all other branches, including tie lines, is set at 200 A.

## 6. SIMULATION RESULTS AND DISCUSSION

To perform load flow analysis and compute power loss for the optimal placement of multiple DSTATCOM units, a custom-coded program is introduced utilizing the MATLAB software. Both LSF and the proposed optimization algorithms (MPSO and RSA) are implemented to an IEEE-33 bus DN. This showcases the efficacy of the proposed algorithm in improving system performance. The simulation results prioritize TVD enhancement and TACPLs minimization while adhering to specified constraints. The influence of various DG models and various load types on the optimal placement of DSTATCOM units is also examined.

A population size of 50 particles is chosen for the proposed MPSO and RSA algorithms, and the maximum number of iteration criterion is defined as 250 iterations. The parameters of the MPSO and the MRSA algorithms are illustrated in Table 1.

**Table 1.** MPSO and MRSA algorithms parameters

| Parameter | Value |
|---|---|
| **MPSO** | |
| Max. No. of iterations | 250 |
| Population size | 50 |
| Inertia weight ($w$) | 0.7 |
| Cognitive parameter ($c1$) | 1.5 |
| Social parameter ($c2$) | 1.5 |
| **RSA** | |
| Max. No. of iterations | 250 |
| Population size | 50 |
| Dimensions | 6 |
| $\alpha$ | 0.1 |
| $\beta$ | 0.05 |

Assuming an extension to the IEEE 33-bus radial DN with a new community installed at buses 24, 25, and 30, the system's topology is taken into account. The objective is to investigate the influence of three factors: varying load factors (LFs), load types, and DG types on the optimal placement of multiple DSTATCOM units in the DN. To streamline the exploration of various combinations of these factors and reduce the number of scenarios, the simulations are organized into three stages as outlined below:

Stage 1: Simulating various load types and selecting the worst case.

Stage 2: Simulating various DG types and selecting the worst case.

Stage 3: Simulating various LF.

Upon completion of each stage, the least favorable type is selected, and the following factors are systematically varied. This approach aims to facilitate a comprehensive assessment of the effectiveness of DSTATCOM units in addressing various operational scenarios within active distribution systems.

### 6.1. STAGE #1 LOAD TYPE IMPACT ON OPTIMAL LOCATION AND SIZING OF DSTATCOM.

During the first stage, a modification in the load type for the load center of modified configuration at buses 24, 25, and 30 is performed in the IEEE 33-bus radial DN, while the other buses are constant power load type. Additionally, the characteristics of DSTATCOM units, encompassing the optimal number, locations, and sizes, are compared across these load types. Furthermore, the study explored the influence of load types on voltage profiles and power losses. In this stage, the intention is to keep all other variables constant, enabling a focused examination of the impact of load types. Accordingly, the LF is set to unity, and no DG is integrated into the test radial DN. Four distinct cases are chosen, each representing one of the four load types: residential load (RL), commercial load (CL), industrial load (IL), and constant power load (CPL). These four cases can be illustrated in the following subsections.

#### 6.1.1. Case# 1: CPL type (unity load factor (LF))

Before installing the DSTATCOM units, the TACPLs is 210.9 kW, and the bus with the minimum voltage value is 0.903 p.u at bus 18 while no overloaded feeders. In the LSF computation, the values for test system branches are determined, leading to the identification of potential candidate buses. The top five candidate buses are ranked as follows: 6, 28, 8, 29, and 30.

The main objective is to improve the performance of the IEEE 33-bus radial DN. After implementing the proposed MPSO algorithm, the TACPL is decreased from 210.9 kW to 143.27 kW, resulting in a significant reduction of 32.1%. The best number of DSTATCOM units is determined to be four, allocated at buses 6, 8, 29, and 30, with sizes of 0.53743, 0.44425, 0.37655, and 0.43043 MVAR, respectively. Furthermore, the MRSA algorithm has the ability to decrease the TACPL to 132.27 kW leading to a substantial decrease of 37.31% in case of installing four DSTATCOM units at the same buses.

The comprehensive voltage profile, both before and after DSTATCOM allocation, is detailed in Fig. 5. Consequently, the system's voltage profile is improved. The MPSO algorithm can improve the minimum voltage to 0.925 p.u, while the MRSA algorithm produced a slightly higher values of 0.929 p.u. These values satisfy the criteria for acceptable voltage limits. The proposed MPSO and MRSA algorithms exhibit effectiveness in balancing feeder loadings, which is evident in the reduction of the TACPL in the test system.

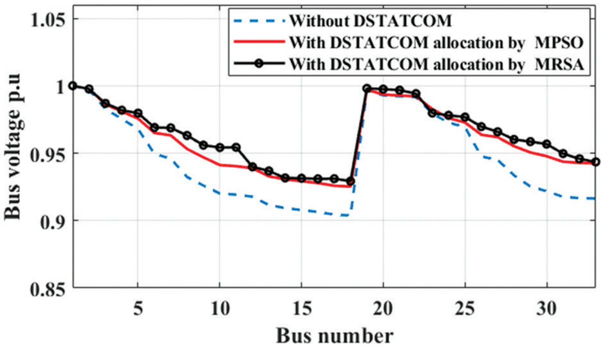


**Fig. 5.** Bus voltage for DSTATCOM installation in case#1 of CPL type

#### 6.1.2. Case# 2: Industrial load type

The radial DN of IEEE 33-bus configuration is equipped with an IL type, which is installed to the new load center of modified configuration. This load type is connected to buses 24, 25, and 30, and there is no DG installed to the test system. The TACPLs in the system before allocating DSTATCOM units is 188.5 kW. The bus with minimum voltage value is 0.906 p.u at bus 18 while no overloaded feeders.

In the LSF computation, the values for test system branches are determined, leading to the identification of potential candidate buses. The candidate buses are ranked as follows: 6, 8, 28, 29 and 9. After applying the proposed optimization algorithms (MPSO and MRSA). It is observed that the TAPLs were decreased to 142.38 kW, reflecting a 24.47% reduction in the TACPL using the proposed MPSO algorithm. The optimal number of DSTATCOM units is determined to be four, strategically placed at buses 6, 9, 28, and 29, with sizes of 0.39862, 0.32428, 0.34033, and 0.3864 MVAR, respectively. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 134.54 kW leading to a substantial decrease of 28.31% in case of installing four DSTATCOM units at the same buses.

As a result of the allocation of DSTATCOM units, the system voltage profile has improved. The bus with the lowest voltage level is now bus 18, which has a voltage of 0.924 p.u in case of using the proposed MPSO algorithm while the proposed MRSA algorithm can produce a slightly higher value of 0.932 p.u . The complete voltage profile, both before and after DSTATCOM allocation, is provided in Fig. 6.

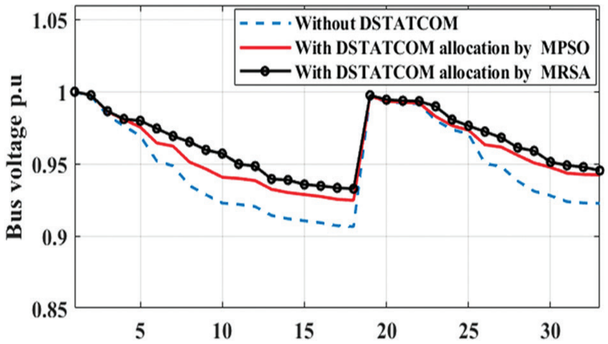


**Fig. 6.** Bus voltage for DSTATCOM installation in case#2 of IL type

#### 6.1.3. Case# 3: Residential load type

In this scenario, the IEEE 33-bus radial DN incorporates a RL type, which is installed to buses 24, 25, and 30 and there is no DG installed to the test system. The proposed optimization algorithms (MPSO and MRSA) for optimal DSTATCOM allocation are employed to identify the worst load type. Prior to the allocation of DSTATCOM units, the TACPL in the test system is recorded at 191.87 kW. The bus with the minimum voltage value is 0.906 p.u at bus 18 while no overloaded feeders.

After implementing the proposed MPSO algorithm for DSTATCOM allocation, it is observed that the TACPLs decreased to 141.43 kW, resulting in a significant reduction of 26.29% in the TACPL. The optimal number of DSTATCOM units is attained to be four, strategically placed at buses 6, 9, 28, and 29. The respective sizes of these units are 0.44275, 0.43531, 0.4203, and 0.2623 MVAR. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 139.34 kW leading to a substantial decrease of 27.38% in case of installing four DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the minimum voltage level is bus 18, with 0.927 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.937 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation, can be illustrated in Fig.7.

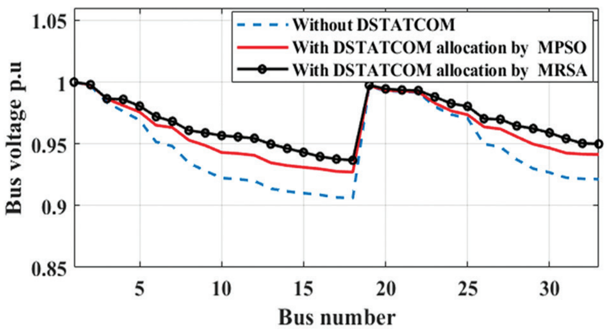


**Fig. 7.** Bus voltage for DSTATCOM installation in case#3 of RL type

#### 6.1.4. Case# 4: system with commercial load

In this scenario, the IEEE 33-bus radial DN incorporates a CL type, which is installed to buses 24, 25, and 30 and there is no DG installed to the test system. Prior to DSTATCOM allocation, the power loss was 192.34 kW. The bus with the minimum voltage value is 0.906 p.u at bus 18 while no overloaded feeders.

Following implementing the proposed MPSO algorithm for optimal DSTATCOM allocation, the five candidate buses are sequenced as 6, 28, 8, 29, and 30. The TACPLs were decreased to 137.94 kW, representing a 28.28% reduction in the TACPL. The optimal configuration includes five DSTATCOM units placed at buses 6, 8, 28, 29, and 30, with sizes of 0.28306, 0.39505, 0.244, 0.4114, and 0.4254 MVAR, respectively. Furthermore, the proposed RSA algorithm has the ability to decrease the TACPL to 132.46 kW leading to a substantial decrease of 31.13% in case of installing five DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.926 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.935 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation, can be illustrated in Fig.8.

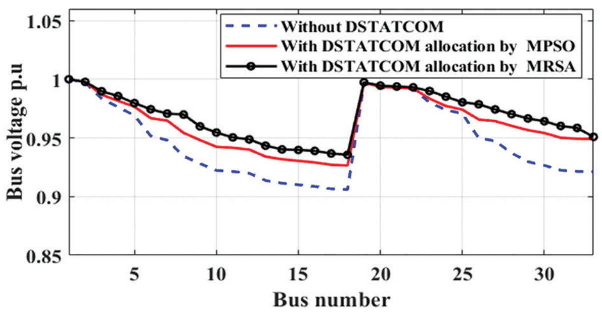


**Fig. 8.** Bus voltage for DSTATCOM installation in case#4 of CL type

The proposed optimization algorithms (MPSO and MRSA) demonstrate their effectiveness in balancing feeder loadings, leading to a decrease in the TACPL in the system. Additionally, Fig. 9 illustrates the values of the TACPL in the aforementioned cases.

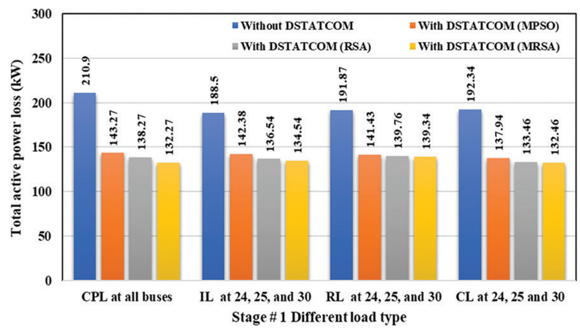


**Fig. 9.** TACPLs comparison before& after DSTATCOM with different load types

### 6.2. STAGE TWO: DG TYPE IMPACT ON OPTIMAL LOCATION AND SIZING OF DSTATCOMS

In the previous stage, the CPL type emerged as the worst load type. Consequently, this load type remains constant, while the second variable, DG type, is subjected to variation.

In the subsequent stage, changes are made to the DG type connected to the modified configuration at buses 24, 25, and 30 in the IEEE 33-bus radial DN. All other buses maintained a CPL type at ULF. Furthermore, the analysis includes a comparison of different aspects of DSTATCOM units, such as the optimal sizes, locations, and number with respect to these types of loads. The examination also covers the evaluation of the impact of DG types on TACPLs and voltage profiles. Three specific cases, representing DG types 1, 3, and 4, have been chosen. These cases are further elaborated in the following cases.

#### 6.2.1. Case# 1: DG type 1 and CPL

In this scenario, the IEEE 33-bus radial DN features a CPL across all buses and DG type 1, which exclusively supplies only active power (at p.f=1). The DGs with capacities of 0.25 MW, 1 MW, and 0.5 MW, are installed to the modified configuration at buses 24, 25, and 30, respectively.

The objective is to improve the performance of the IEEE 33-bus radial DN by incorporating DSTATCOM, facilitating a comparative analysis of the three previously mentioned DG types. Consequently, the proposed algorithms (MPSO and MRSA) for optimal DSTATCOM allocation and sizing are tested using the least favorable DG type.

Before installing the DSTATCOM, the TACPL for the IEEE 33-bus radial DN is 135 kW. The bus with the minimum voltage value is 0.917 p.u at bus 18 while no overloaded feeders. The level of DG penetration in this particular scenario is at 45.45%. The goal is to improve system performance using DSTATCOM, considering five candidate buses in the order of 28, 8, 29, 30, and 9.

After allocating and sizing the DSTATCOM using the proposed MPSO algorithm, the TACPL is reduced to 73.08 kW, marking a 45.87% reduction. The optimal configuration involves installing five DSTATCOM units at buses 8, 9, 28, 29, and 30, with respective sizes of 0.33135, 0.45581, 0.4342, 0.3075, and 0.2708 MVAR. Consequently, the DG penetration level increases to 46.17% with the integration of DSTATCOM. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 72.56 kW leading to a substantial decrease of 46.25% in case of installing five DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.945 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.955 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation are illustrated in Fig.10.

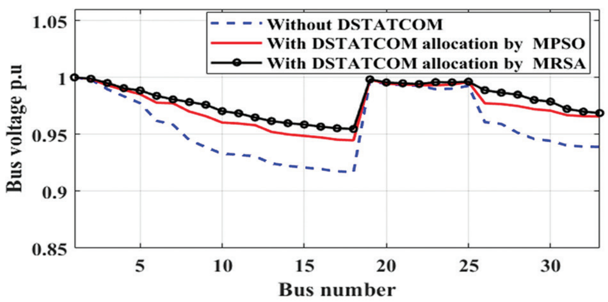


**Fig. 10.** Bus voltage for DSTATCOM installation in case#1 of DG type 1

#### 6.2.2. Case# 2: DG type 3 and CPL

In this scenario, DG units with capacities of 0.25 MVA, 1 MVA, and 0.5 MVA are installed at buses 24, 25, and 30, respectively. These DG units supply both reactive and active power at p.f equal 0.8, as determined through preliminary sensitivity analysis. The initial TACPL before installing the DSTATCOM units is 110.6 kW, with bus 18 exhibiting the lowest level voltage at 0.919 p.u while no overloaded feeders. The selected level of the DG penetration is 36.55%. Five candidate buses ordered as 8, 28, 29, 9, and 13 undergo a

By applying the proposed MPSO algorithm, the TACPL is reduced to 78.87 kW, marking a 28.69% decrease. The optimal configuration involves four DSTATCOM units installed at buses 8, 13, 28, and 29, with respective sizes of 0.28646, 0.4872, 0.2556, and 0.4863 MVAR. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 78.61 kW leading to a substantial decrease of 28.93% in case of installing four DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.949 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.957p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation are illustrated in Fig.11.

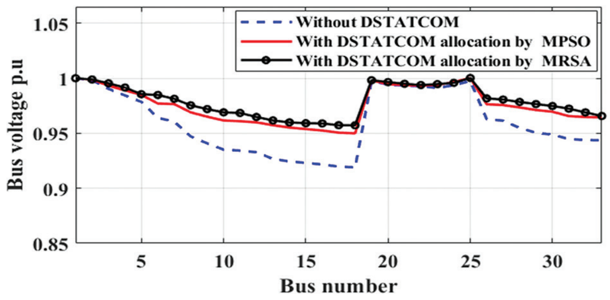


**Fig.11.** Bus voltage for DSTATCOM installation in case#2 of DG type 3

#### 6.2.3. Case# 3: DG type 4 and CPL

The DG units are installed at buses 24, 25, and 30, supplying active power and consuming reactive power at p.f equal 0.8. Their capacities are 0.25 MVA, 1 MVA, and 0.5 MVA, respectively. The initial TACPL, prior to installing the DSTATCOM units, is 206.4 kW, with bus 18 having the lowest level voltage of 0.909 p.u., while no overloaded feeders. The current level of DG penetration in this scenario is 35.71%. The five candidate buses are ranked in the following order: 6, 28, 29, 8, and 30. By applying the proposed MPSO algorithm, the TACPL is reduced to 98.91 kW, marking a 52.08% decrease. The optimal DSTATCOM configuration involves installing five units at buses 6, 8, 28, 29, and 30, with sizes of 0.38721, 0.51646, 0.33417, 0.48635, and 0.52263 MVAR, respectively. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 97.85 kW leading to a substantial decrease of 52.59% in case of installing five DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.937 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.943 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation are illustrated in Fig.12.

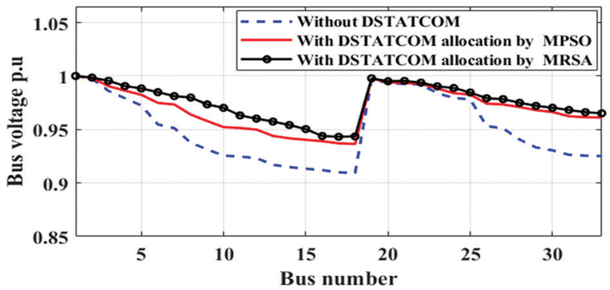


**Fig. 12.** Bus voltage for DSTATCOM installation in case#3 of DG type 4

The proposed optimization algorithms (MPSO and MRSA) demonstrate their effectiveness in balancing feeder loadings, leading to a decrease in the TACPL in the system for different DG types. Additionally, Figure 14 illustrates the changes in TACPL in the aforementioned cases.

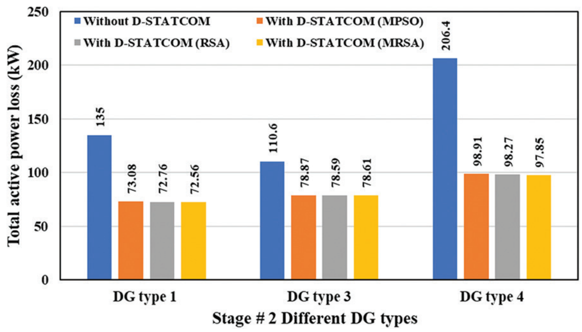


**Fig. 13.** TACPLs comparison before & after DSTATCOM with different DG types

### 6.3. STAGE THREE: LOAD FACTOR IMPACT ON OPTIMAL LOCATION AND SIZING OF DSTATCOMS

The most challenging DG and load types identified in the previous stages are the DG type 4 and CPL type, respectively. Consequently, these DG and load types will be kept constant in this stage, while the final variable, the LF, will be systematically altered. This variation is essential to assess the proposed algorithm's efficacy in optimizing the allocation and sizing the multiple DSTATCOM units under different LFs. Additionally, the study will investigate the influence of load factors on TACPL and voltage profiles. This stage serves as a crucial verification of the algorithm's effectiveness in this study, as it is anticipated that a heavily loaded system may negatively impact overall system performance. Two load levels LFs (0.6 and 1.2), are chosen to represent different LFs at distinct times. The outcomes of these two cases are discussed in the following sections.

#### 6.3.1. Case# 1: DG type 4 and CPL at lightly loaded.

In this particular scenario, DG units with capacities of 0.25 MVA, 1 MVA, and 0.5 MVA are installed at buses 24, 25, and 30, respectively. These DG units supply active power while consuming reactive power at p.f equal 0.8. The system is operating with a light load, characterized by a LF of 0.6. Prior to installing the DSTATCOM, the TACPL value is 84.716 kW. Among the buses, bus 18 has the lowest voltage level at 0.95 p.u., while no overloaded feeders. The current level of DG penetration in this scenario is 60.51%. The five candidate buses are ranked in the following order: 13, 10, 14, 12, and 17.

By applying the proposed MPSO algorithm, the TACPL is reduced to 65.48 kW, reflecting a significant 22.71% reduction. The optimal configuration involves installing two DSTATCOM units at buses 10 and 14, with sizes of 0.57558 and 0.13375 MVAR, respectively. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 63.34 kW leading to a substantial decrease of 25.23% in case of installing two DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.97 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.98 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation are illustrated in Fig.14.

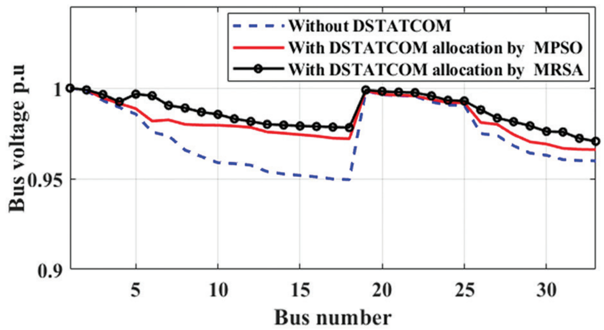


**Fig. 14.** Bus voltage for DSTATCOM installation in case#1 of LF=0.6

#### 6.3.2. Case# 2: DG type 4 and CPL at heavily loaded

The DG units remain consistent with the previous case, but the system is under heavy load with LF of 1.2. The initial TACPL before installing the DSTATCOMs units is 299.81 kW, and bus 18 registers the minimum level voltage at 0.888 p.u, while no overloaded feeders. The current level of DG penetration in this scenario is 29.43%, The five candidate buses are ranked in the following order: 6, 28, 29, 8, and 30, chosen to enhance system performance.

By applying the proposed MPSO algorithm, the TACPL is reduced to 155.29 kW, reflecting a significant 48.2% reduction. The optimal configuration involves installing five DSTATCOM units at buses 6, 28, 29, 8, and 30, with respective sizes of 0.36844, 0.51691, 0.3574, 0.49, and 0.505 MVAR. Furthermore, the proposed MRSA algorithm has the ability to decrease the TACPL to 141.88kW leading to a substantial decrease of 52.67% in case of installing five DSTATCOM units at the same buses.

The system voltage profile is enhanced as a consequence of the DSTATCOM allocation. The bus with the lowest voltage level is bus 18, with 0.915 p.u. voltage magnitude using the proposed MPSO. While the proposed MRSA algorithm can achieve the minimum bus voltage level of 0.926 p.u. A comprehensive voltage profile, both before and after the DSTATCOM allocation are illustrated in Fig.15.

Figure 16 visually depicts the variations in TACPLs across the discussed cases.

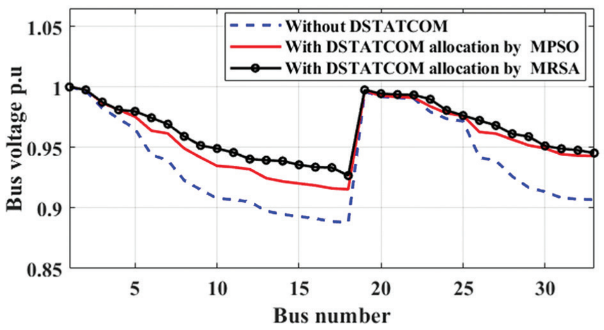


**Fig. 15.** Bus voltage for DSTATCOM installation in case#1 of LF=1.2

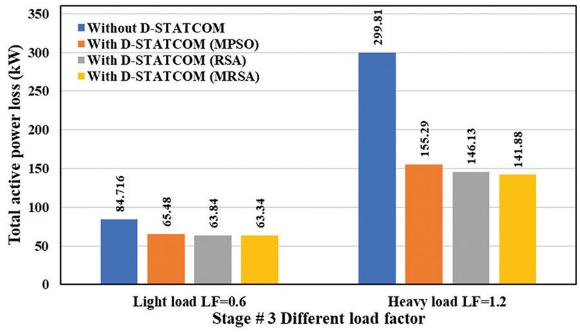


**Fig.16.** TACPLs comparison before & after DSTATCOM at different LF

## 7. CONCLUSION

This paper presents the optimal allocation of DSTATCOM units in IEEE-33 bus radial DN with DG, utilizing the LSF and a proposed MPSO and the MRSA methods. The primary objective is to enhance the distribution system's performance by enhancing the voltage profile, reducing TACPL, and maximizing DG penetration to meet consumer load requirements. The simulations were conducted using MATLAB, where the DSTATCOM units model underwent testing and verification. A comparative analysis was performed by assessing the TACPL and voltage profile of the tested radial DN with and without the DSTATCOM.

The optimal determination of the number, size, and location of the multiple DSTATCOM units holds significant importance in the DNs. The study concludes that, among various load types and DG types, CPL type and DG type 4 exhibit unfavorable characteristics in terms of power loss and voltage profile, especially in heavily loaded systems as illustrated below:

- The MRSA obtained the optimum location and size of the DSTATCOM in the DN to minimuze the TACPLs for the different load types. It reduced the TACPLs by 37.31%, 28.31%, 27.38%, and 27.38% for load types CPL, IL, RL, and CL, respectively. While the minimum bus voltage level was improved to 0.929 p.u., 0.932 p.u., 0.937 p.u., and 0.935 p.u. for load types CPL, IL, RL, and CL, respectively.
- For different types of DGs, the TACPLs were reduced by 46.25%, 28.93%, and 52.59% for DG type 1, type 3, and type 4, respectively. While the minimum bus voltage level was improved to 0.955 p.u., 0.957 p.u., and 0.943 p.u. for for DG type 1, type 3, and type 4, respectively.

These findings highlight the effectiveness of the proposed algorithm in addressing challenges posed by the worst load type (CPL) and DG type 4. Furthermore, the algorithm proves its utility in handling different combinations of DG types connected to DNs under varying LFs. The results emphasize the practical benefits of the proposed algorithm for DN operators, offering an efficient approach to allocate DSTATCOM units and optimize system parameters across various operating scenarios in distribution networks. Additionally, the results demonstrated that the MRSA approach was applicable to large DNs, offered fast and easy implementation, was robust in obtaining optimal results, and outperforms the MPSO algorithm.

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## APPENDIX

**Table A1** Line and bus data in IEEE-33 bus distribution network

| Bus Send | Bus Receive | $R(\Omega)$ | $X(\Omega)$ | $P_{Recieve}$ (kW) | $Q_{Recieve}$ (kVAR) |
|---|---|---|---|---|---|
| 1 | 2 | 0.0922 | 0.0470 | 100 | 60 |
| 2 | 3 | 0.4930 | 0.2511 | 90 | 40 |
| 3 | 4 | 0.3660 | 0.1864 | 120 | 80 |
| 4 | 5 | 0.3811 | 0.1941 | 60 | 30 |
| 5 | 6 | 0.8190 | 0.7070 | 60 | 20 |
| 6 | 7 | 0.1872 | 0.6188 | 200 | 100 |
| 7 | 8 | 0.7114 | 0.2351 | 200 | 100 |
| 8 | 9 | 1.0300 | 0.7400 | 60 | 20 |
| 9 | 10 | 1.0440 | 0.7400 | 60 | 20 |
| 10 | 11 | 0.1966 | 0.0650 | 45 | 30 |
| 11 | 12 | 0.3744 | 0.1238 | 60 | 35 |
| 12 | 13 | 1.4680 | 1.1550 | 60 | 35 |
| 13 | 14 | 0.5416 | 0.7129 | 120 | 80 |
| 14 | 15 | 0.5910 | 0.5260 | 60 | 10 |
| 15 | 16 | 0.7463 | 0.5450 | 60 | 20 |
| 16 | 17 | 1.2890 | 1.7210 | 60 | 20 |
| 17 | 18 | 0.7320 | 0.5740 | 90 | 40 |
| 2 | 19 | 0.1640 | 0.1565 | 90 | 40 |
| 19 | 20 | 1.5042 | 1.3554 | 90 | 40 |
| 20 | 21 | 0.4095 | 0.4784 | 90 | 40 |
| 21 | 22 | 0.7089 | 0.9373 | 90 | 40 |
| 3 | 23 | 0.4512 | 0.3083 | 90 | 50 |
| 23 | 24 | 0.8980 | 0.7091 | 420 | 200 |
| 24 | 25 | 0.8960 | 0.7011 | 420 | 200 |
| 6 | 26 | 0.2030 | 0.1034 | 60 | 25 |
| 26 | 27 | 0.2842 | 0.1447 | 60 | 25 |
| 27 | 28 | 1.0590 | 0.9337 | 60 | 20 |
| 28 | 29 | 0.8042 | 0.7006 | 120 | 70 |
| 29 | 30 | 0.5075 | 0.2585 | 200 | 600 |
| 30 | 31 | 0.9744 | 0.9630 | 150 | 70 |
| 31 | 32 | 0.3105 | 0.3619 | 210 | 100 |
| 32 | 33 | 0.3410 | 0.5302 | 60 | 40 |