A Multi-Objective Approach for Optimal Sizing and Placement of Distributed Generators and Distribution Static Compensators in a Distribution Network Using the Black Widow Optimization Algorithm

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Abstract: This paper presents a new optimization technique for the locations and sizes of Distributed Generators (DGs) and distribution static compensators (DSTATCOMs) in a radial system of a distribution network based on a multi-objective approach. It uses black widow optimization to improve voltage profile and power loss reduction. The black widow optimization simulates the mating behaviour of black widow spiders. The optimum size and placement of DGs and DSTATCOMs are deemed to be decision variables that are defined by using black widow optimization. The proposed technique is implemented in selected IEEE bus systems to evaluate its performance. The simulation results indicate reduced power losses and voltage profile enhancement as sizes and locations of integrated DGs and DSTATCOMs are adjusted based on optimization. The number of DGs and DSTATCOMs required to achieve the objectives is reduced. Furthermore, the results of the black widow algorithm are compared to existing techniques in the literature.

Keywords: radial distribution network; distribution STATCOM; DGs; power losses; voltage profile; optimal sizing and placement; black widow optimization

1. Introduction

The modernization of electrical power systems is a challenge nowadays to meet the rising demand. This has caused power systems to operate beyond their capability, which leads to congestion in the networks. The rise in electrical demand causes the system to work nearer to its stability threshold, which influences the system’s frequency and lowers the bus voltage. Furthermore, cascading events caused by large disturbances occur frequently. This may result in an overall shutdown [1]. Reactive power absence is the main concern of these cascading events. Since there is a transition from conventional to renewable energy in modern power systems, reactive power requirements are mandatory for ensuring power generation and load balance in the network [2]. Reactive power compensation has proven crucial in transmitting power with a rated capacity, boosting stability margins, providing real and reactive power flow control, improving transient and steady-state conditions, mitigating power quality issues, improving voltage regulation, correcting the power factor, balancing real power, eliminating harmonic contents injected by nonlinear loads, and improving voltage security [3–5]. Furthermore, voltage support at the distribution side is crucial for reducing the fluctuations at the bus and for the smooth functioning of the power networks [6]. Custom power devices are effectively utilized for reducing power losses and increasing bus voltages. The custom power devices commonly used are the distribution STATCOM (DSTATCOM), Unified Power Quality Conditioner (UPQC), Static Synchronous Series Compensator (SSSC), and Dynamic Voltage Restorer (DVR). The distribution STATCOM stands out for its superior compatibility and performance in the distribution system, as it compensates reactive power while also reducing...
harmonic content, eliminating resonance or transient harmonic issues, and maintaining a compact design [7,8]. It is a shunt device that comprises a voltage source converter, coupling transformer, and capacitor link. It compensates for the bus voltages in the radial distribution system. The DSTATCOM has different compensation modes, which include inductive compensation and capacitive compensation [9]. For effective functioning of a DSTATCOM and efficient network performance, the optimized size and placement of the DSTATCOM should be defined. An inappropriate allocation, location, and size of a reactive compensator causes a rise in distribution system power loss, and voltage irregularities. To authenticate the impact of a DSTATCOM on distribution network performance, several factors can be considered, i.e., power loss and voltage profile.

Recent research in the literature has focused on defining the bus position and size of a distribution STATCOM using an RDS. Limited research covers local optimality, with low accuracy and slow convergence. For reducing the active power losses and reducing voltage deviations, the Social Spider Algorithm (SSA) has been applied [10]. The Bat Algorithm (BA) is employed to consider the voltage stability factor in [11]. The gravitational search algorithm (GSA) is used for reducing losses, i.e., increasing active power, improving the voltage index, and maximizing total annual savings, in [12]. Turbulent flow water-based optimization (TFWO) is used to reduce active power losses in [13]. The dragonfly algorithm (DA) is used to reduce various costs and VSI indices in [14]. The Artificial Bee Colony (ABC) algorithm is used to minimize active power losses and VSI values for numerous RDSs in [15], and the Cuckoo Search Algorithm (CSA) is used to reduce active power losses in [16]. The flower pollination algorithm (FPA) is used to reduce overall costs in a system based on LSFs [17]. Energy loss expenses of a distribution system network are optimized using the Differential Evolution Algorithm (DEA) [18]. Active power loss reduction was achieved using Particle Swarm Optimization in [19], and acceleration coefficients with the PSO Algorithm, maximizing active power loss reductions, were used in [20]. Other optimizations include optimizing the magnification ratio for a flexible hinge displacement amplifier mechanism design [21], and the optimization of meat and poultry farm inventory stock using data analytics for a green supply chain network [22].

A discrete–continuous version of the vortex search algorithm for optimizing reactive power compensation in electric networks, achieving efficient solutions, was introduced in [23]. In [24], the study investigates coordinated planning of DGs and DSTATCOMs using improved grey wolf optimization, considering power loss sensitivity factors. Testing on IEEE 33 bus systems validates the effectiveness, highlighting the combined allocation’s importance in loss minimization and voltage profile improvement. In this paper [25], authors propose a new methodology using the Cuckoo Search Algorithm for simultaneous allocation of DGs and DSTATCOMs in radial distribution systems. Optimal locations and sizes are determined based on the Voltage Stability Index and loss sensitivity factor. The proposed method effectively minimizes power losses and enhances voltage profiles in both IEEE 33 bus and large 136 bus RDSs. Paper [26] proposes a novel approach using the loss sensitivity factor (LSF) and Bacterial Foraging Optimization Algorithm (BFOA) to determine the optimal locations and sizes of Distributed Generators (DGs) and distribution static compensators (DSTATCOMs) in radial distribution systems. Results are compared to existing techniques using IEEE 33 bus and 119 bus systems. A hybrid optimization method is used, combining an analytical VSI with the SC algorithm to minimize losses and regulate voltage by determining optimal locations and sizes for DGs and DSTATCOMs in distribution networks. It is compared against existing techniques using simulations on standard IEEE 12 and 69 bus radial feeders [27]. A Particle Swarm Optimization (PSO) is used for optimizing DG and DSTATCOM placement and sizing in radial distribution systems. Analysis on various test systems shows improved voltage profiles and reduced power losses [28]. In [29], the research optimizes electrical distribution networks with PV sources and DSTATCOMs to minimize grid operating costs over 20 years. Using an MINLP model and vortex search algorithm, combining PVs and DSTATCOMs achieves a 35.50% and 35.53% reduction in costs compared to individual solutions. An improved grey
wolf optimizer (I-GWO) method to optimize power distribution using distribution static compensators (DSTATCOMs) in flexible AC transmission systems (FACTSs) was introduced in [30]. It addresses system constraints, including intermittent and stochastic load and renewable energy resources, demonstrating superior performance in reducing power losses, enhancing voltage profiles, and improving voltage stability across various distribution systems. The study in [31] employs a modified ant lion optimizer (MALO) to optimize DSTATCOM and PV deployment in radial power distribution networks, considering CP and ZIP load models. It aims to minimize power losses, improve voltage profiles, and reduce operating costs. An improved grey wolf optimizer (I-GWO) method to optimize the allocation and sizing of distribution static compensators (DSTATCOMs) in flexible alternating current transmission systems (FACTSs) was introduced in [30]. The I-GWO incorporates a dimension learning-based hunting strategy and was applied to various distribution systems. Results indicate its superiority in reducing power losses, enhancing voltage profiles, and improving voltage stability. In [32], a PV-DSTATCOM system is enhanced by reducing sensors and integrating a VSI switch current-limiting control with the VLLMS algorithm. This improves power quality by supplying non-real power to meet load demand. Authors in [33] optimize the PV-DSTATCOM by integrating a VSI switch current-limiting control and reducing sensors using the VLLMS algorithm. Their aim is to enhance power quality by supplying non-real power to meet load demand and address current-related issues. In [34], the Wiener variable step size with variance smoothing (WVSSV) technique is introduced for utility-supportive solar photovoltaic (PV) systems. This system serves to correct the power factor, compensate for non-active components, and reduce total harmonic distortion (THD) from the utility grid. A distribution static compensator (DSTATCOM) controlled by the Adaptive Linear Element–Least Mean Square (ADALINE-LMS) algorithm is adopted in [35].

**Black Widow Optimization**

The female black widow stays hidden during the day and weaves her web at night. This is because the black widow is active at night. The female black widow uses pheromones to mark particular spots on her net to draw the male whenever she wants to mate. After mating, the female consumes the male and carries the eggs to her egg sock. Sibling cannibalism occurs in the offspring after hatching. Fit and strong individuals survive through this cycle. In terms of objective functions, the global optimum is the best. An illustration of a female black widow on her web is shown in Figure 1. An egg sac is shown on the web of a female black widow in Figure 2.

![Female black widow on her web](image.jpg)

**Figure 1.** Female black widow on her web [36].

Black widow optimization (BWO) for optimal size and positioning of DGs and DSTATCOMs is proposed and applied to the IEEE 12 bus, IEEE 33 bus, and IEEE 69 bus systems. There is a reduction in the power losses of the radial distribution network, and an improvement in the voltage profile, which results in higher efficiency of the overall system [36].
The major research contributions are the following:
- Determining multi-objective positions and sizes of DGs and DSTATCOMs in a radial system distributed network.
- Presenting a multi-objective problem based on a loss and voltage profile.
- Achieving an appropriate performance of black widow optimization for resolving the DGs’ and DSTATCOMs’ positioning and sizing problems.
- Proposing a superior technique in comparison to preceding studies.

DSTATCOM modelling is presented in Section 2. In Section 3, objective function and problem constraints are stated. In Section 4, an outline of black widow optimization and its application to resolve the problem are explained. In Section 5, results of the simulation are summarized, and paper outcomes are decided in Section 6.

2. Distribution Static Compensator (DSTATCOM)

A DSTATCOM is a configuration of a voltage source converter connected via a shunt to a distribution system that effectively improves the system performance. It outweighs the other shunt compensation devices because of its quick ability to absorb or inject the reactive power through controlled voltage. It can mitigate the system harmonics, neutralize current compensation, regulate voltage, maintain load balance, correct the power factor, and improve system performance. Moreover, it does not have any functioning issues such as resonance or transient harmonics, unlike shunt and series capacitors [37,38]. In addition to reactive power, a DSTATCOM can also inject the active power.

Consider two buses associated by a branch as a part of an RDS, as depicted in Figure 3.

![Figure 2. Female black widow on her web with egg sac [36].](image)

![Figure 3. Two-bus system.](image)

The relationship between voltage and current can be expressed as (see Figure 4).

\[ V_{o j} \angle \alpha_o = V_{o i} \angle \delta_o - (R + jX)I_{o L} \angle \theta_o \]  

(1)

where \( V_{o j} \) is the bus voltage before compensation; \( \alpha_o \) represents the voltage angle of \( V_{o j} \); \( V_{o i} \) is bus voltage \( I \) before DSTATCOM installation; \( \delta_o \) corresponds to the voltage angle
The relationship between voltage and current can be expressed as (see Figure 4)

\[ V_{\text{oi}} = Z = R + jX \text{ is the impedance of bus } i \text{, and } j; \]
\[ I_{\text{ol}} \text{ corresponds to the current prior to compensation; } \theta_o \text{ corresponds to the current angle of } I_{\text{ol}}. \]

\[ V_{\text{oi}} \angle \alpha_{\text{oi}} = V_{\text{oj}} \angle \delta_{\text{oj}} - (R + jX)I_{\text{oi}} \angle \theta_{\text{oi}} \]

Figure 4. Phasor diagram.

The variation occurs in all the node voltages during steady-state conditions, i.e., adjoining nodes of the DSTATCOM position. The currents in the branch network are varied by incorporating the distribution STATCOM into the RDS [39]. The two bus systems when DSTATCOM is connected are shown in Figure 5.

Figure 5. Two-bus radial distribution system with DSTATCOM [23].
The phasor diagram after the DSTATCOM installation is shown in Figure 6. Bus voltage \( j \) transforms from \( V_j \) to \( V_{j_{new}} \) after the DSTATCOM is installed.

\[
\angle I_{D-STATCOM} = \left( \frac{\pi}{2} \right) + \alpha_{new}, \alpha_{new} < 0
\]  

(2)

\[
V_{j_{new}} \angle \alpha_{new} = V_i \angle \delta - (R + jX) I_L \angle \theta - (R + jX) I_{D-STATCOM} \angle \left( \left( \frac{\pi}{2} \right) + \alpha_{new} \right)
\]  

(3)

where \( I_{D-STATCOM} \angle \left( \left( \frac{\pi}{2} \right) + \alpha_{new} \right) \) is the current injection through the distribution STATCOM; \( \alpha_{new} \) is the improved voltage angle; \( V_{j_{new}} \angle \alpha_{new} \) is the improved voltage angle of bus \( j \); \( V_i \) corresponds to the voltage angle of bus \( i \) prior to compensation; \( \delta \) corresponds to the voltage \( V_i \) angle; \( I_L \) is the line current flow after the distribution STATCOM integration; \( \theta \) represents the line current angle. The distribution STATCOM power injection is given as

\[
jQ_{D-STATCOM} = V_{j_{new}} (I_{D-STATCOM})^* 
\]  

(4)

where

\[
V_{j_{new}} = V_{j_{new}} \angle \alpha_{new}
\]  

(5)

\[
I_{D-STATCOM} = I_{D-STATCOM} \angle \left( \left( \frac{\pi}{2} \right) + \alpha_{new} \right)
\]  

(6)

Figure 6. Phasor diagram after DSTATCOM.

3. Formulation of Problem

The main purpose of DG and DSTATCOM optimal placing in the RDS is to minimize power loss. The problem can be defined with objective function as below:

\[
\min f = \min (P_{loss})
\]  

(7)

where \( P_{loss} \) implies total power loss in the RDS.

Constraints
Equality constraints:
The difference in angle between \( V_{j_{new}} \) and \( I_{D-STATCOM} \) should be 90°;
To enhance the power factor, \( I_{D-STATCOM} \) should be in quadrature with \( V_{j_{new}} \).

Inequality Constraints:
The real power of the bus is given as

\[
P_{loss} + \sum P_{Dj} = \sum P_{DGj}
\]  

(8)
The real power generated by the DG should be equivalent to the summation of the real power loss at that node to the active power actual demand. Reactive power compensation at the bus is given as

\[ Q_j^c \leq \sum_{j=1}^{n} Q_{Lj} \]  

(9)

where \( Q_j^c \) and \( Q_{Lj} \) are the compensated reactive power and reactive load at bus \( j \).

For maintaining the quality of power, \( Q_j^c \) must be less than or equal to \( Q_{Lj} \) \( (Q_j^c \leq Q_{Lj}) \).

The nodal voltage magnitude and branch current must be within acceptable limits.

**Voltage constraints:**

\[ V_{jmin} \geq V_j \geq V_{jmax}, \ j = 1, 2, 3, \ldots, N \]  

(10)

**Current constraints:**

\[ |I_j| \leq |I_{jmax}|, \ j = 1, 2, \ldots, N \]  

(11)

where \( V_{jnew} \) is the compensated bus voltage after the DSTATCOM integration; \( I_{DSTATCOM} \) is the DSTATCOM current; \( P_{Loss} \) is the real power loss; \( P_{DGj} \) is real power generated by DG; \( P_{Dj} \) is the power demand. \( V_{jmin} \) and \( V_{jmax} \) are min and max bus voltage of the \( j \)th bus, and \( I_{jmax} \) is the maximum branch current.

**Load Flow Analysis**

The conventional load flow methods cannot be utilized in the radial distribution system for determining the line flows and voltages as there is higher resistance to the reactance ratio than to the transmission system. Therefore, a direct approach to load flow is applied [40].

For the RDS, the complex load \( S_i \) of a bus, ‘i’, is given as

\[ S_i = P_i + Q_i, \ i = 1, 2, 3, \ldots, N \]  

(12)

where \( N \) is total number of buses, \( P_i \) is the real power at the \( i \)th bus, and \( Q_i \) is the reactive power at the \( i \)th bus.

**Current injection at bus i is given as**

\[ \text{current injection at bus } i \text{ is given as } i = (S_i/V_i)^* \]  

(13)

where \( V_i \) is the bus ‘i’ voltage. A radial distribution system is employed for developing the relationship matrix. The current injection matrix can be achieved through the transformation of the power injection. The correlation among the bus current injection and the branch current is accomplished through Kirchhoff’s current law.

\[
B1 = I1 + I2 + I3 + I4 + I5 + I6 + I7 + I8 \\
B3 = I3 + I4 + I5 + I6 + I7 + I8 \\
B4 = I4 + I5 + I6 + I7 + I8 \\
B6 = I6 \\
B7 = I7 + I8 \\
B8 = I8
\]

The correlation between the branch currents and bus current injections is given as
The generalized eq is
\[
[B] = [BIBC][I] \tag{14}
\]
where \(BIBC\) represents bus injections to the branch-current matrix.

The voltages of buses 3–5 are redrafted as
\[
V_3 = V_2 - (B_3 \ast Z_{23}) \tag{15}
\]
\[
V_4 = V_3 - (B_4 \ast Z_{34}) \tag{16}
\]
\[
V_5 = V_4 - (B_5 \ast Z_{45}) \tag{17}
\]

Substituting Equations (15) and (16) into Equation (17) and rearranging the equations, we get
\[
V_5 = V_2 - (B_3 \ast Z_{23}) - (B_4 \ast Z_{34}) - (B_5 \ast Z_{45}) \tag{18}
\]

Similarly, the bus voltages are defined. Consequently, the correlation between the branch currents and bus voltages is given as
\[
\begin{bmatrix}
V_1 \\
V_1 \\
V_1 \\
V_1 \\
V_1 \\
V_1 \\
V_1
\end{bmatrix}
=
\begin{bmatrix}
Z_{12} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
Z_{12} & Z_{23} & 0 & 0 & 0 & 0 & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 & 0 & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & Z_{45} & Z_{56} & 0 & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & Z_{45} & Z_{56} & Z_{67} & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 & Z_{78} & 0 \\
Z_{12} & Z_{23} & Z_{34} & 0 & 0 & 0 & Z_{78} & Z_{89}
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2 \\
B_3 \\
B_4 \\
B_5 \\
B_6 \\
B_7 \\
B_8
\end{bmatrix} \tag{19}
\]

Furthermore, it is given as
\[
[\Delta V] = [BCBV][B] \tag{20}
\]
where \(BCBV\) is the branch current to the bus voltage matrix.

From the above equations, the correlation between bus voltages and bus current injections is given as
\[
[\Delta V] = [BCBV][BIBC][I] \tag{21}
\]
\[
= [DLF][I] \tag{22}
\]

Therefore, a radial distribution system can be achieved by resolving the equations iteratively.
\[
I_i^k = \left(\frac{S_i}{V_i^k}\right)^* \tag{23}
\]
\[
[\Delta V^{k+1}] = [DLF][I^k] \tag{24}
\]
\[
[\Delta V^{k+1}] = [V_i][\Delta V^{k+1}] \tag{25}
\]
where \(k\) is iteration count and \(V_i\) is the initial voltage.

Power flow calculation
This can be originated from the single-line diagram (SLD) of the radial bus system, shown in Figure 7.

\[
P_{i+1} = P_i - P_{Li+1} - R_{Li+1} \frac{(P_i^2 + Q_i^2)}{|V_i|^2}
\]

(26)

\[
Q_{i+1} = Q_i - Q_{Li+1} - X_{Li+1} \frac{(P_i^2 + Q_i^2)}{|V_i|^2}
\]

(27)

\[
\text{Figure 7. Radial distribution system.}
\]

\(P_j, Q_j\) are active and reactive power flowing out of bus \(i\). \(P_{Li}, Q_{Li}\) are real and reactive load power at bus \(i\). The resistance and reactance between the buses are given as \(R_{li+1}\) and \(X_{li+1}\). Power loss can be calculated as

\[
P_{Loss}(i, i+1) = R_{Li+1} \frac{(P_i^2 + Q_i^2)}{|V_i|^2}
\]

(28)

\[
Q_{Loss}(i, i+1) = X_{Li+1} \frac{(P_i^2 + Q_i^2)}{|V_i|^2}
\]

(29)

By summing all the losses of the feeder, the total power loss can be given as

\[
P_{T,\text{Loss}} = \sum_{i=0}^{n-1} P_{Loss}(i, i+1)
\]

(30)

\[
Q_{T,\text{Loss}} = \sum_{i=0}^{n-1} Q_{Loss}(i, i+1)
\]

(31)

\[
P_{Loss} = \sqrt{P_{T,\text{Loss}}^2 + Q_{T,\text{Loss}}^2}
\]

(32)

4. Optimization Method

BWO is implemented to determine the optimal location and capacities of multiple DGs and DSTATCOMs. It has the benefit of early convergence and higher accuracy for the optimal DSTATCOM and DG allocation [36].

Black Widow Optimization Algorithm
The metaheuristic technique is built on the mating behaviour of black widow spiders, wherein spiders correspond to the population [36]. Furthermore, it resembles a natural process i.e., procreation, cannibalism, and mutation. The problematic solution is characterized by the widow of array $1 \times NN$, i.e.,

$$Black\ Widow = [b_1, b_2, \ldots, b_{NN}]$$

Widow fitness is acquired through calculating the fitness function $Fb$ along with the widows $(b_1, b_2, \ldots, b_{NN})$.

Mathematically,

$$Fitness = Fb (black\ widow) = Fb (b_1, b_2, \ldots, b_{NN})$$

By utilizing a population size matrix and the number of widows, the initial spider population is created. Furthermore, in the procreation step, an alpha is produced, which is additionally utilized for creating offspring parents, i.e.,

$$c_1 = \propto \times b_1 + (1 - \propto) \times b_2$$
$$c_2 = \propto + b_2 + (1 - \propto) \times b_2$$

where $b_1, b_2$ represent the parents, and $c_1$ and $c_2$ are children. This procedure is executed for $NN/2$ times without the replication of arbitrarily created numbers. The mother widows and their widow offspring are characterized by their fitness values. In the cannibalism step, the male is consumed by the female black widow and shifts the egg to the sock. The hatched siblings are busy in the cannibalism process; the best and strongest spider obtained is the optimal solution for the objective function. It has the advantage over the other algorithms in terms of its accuracy, quicker convergence, and superior performance in finding optimum global solutions.

In black widow optimization, the best widow signifies the finest fitness function. The quantity of iterations executed is 50. The procreation rate is 0.8, the cannibalism rate is 0.5, and the mutation rate is 0.4, respectively.

DGs and DSTATCOMs are integrated simultaneously in IEEE 12, IEEE 33, and IEEE 69 bus systems, respectively. They have a tremendous effect on reducing the distribution of power loss. Their optimal sizes and locations are determined by employing the BWO algorithm.

**Implementing BWO in Problem Resolving**

Using this technique, the optimal locations and sizes of DGs and DSTATCOMs in the radial system of distributed networks can be determined, with consideration of the objectives mentioned and satisfying the constraints. Hence, the flow chart of BWO is illustrated below in Figure 8.

**Computation stages for optimum allocation of DGs and DSTATCOMs**

1. The RDS is analysed with the load flow method and the BWO algorithm simultaneously for reducing the distribution system losses.
2. Power flow analysis is carried out in the IEEE RDS followed by the measurement of active and reactive power losses in the system.
3. The algorithm is designed for the random generation of bus numbers apart from bus 1.
4. Random placement takes place of DGs and DSTATCOMs at nodes with higher and lower values of energy capability, which relies on the load data. Through the implementation of the optimization, the active and reactive power loss is computed.
5. Minimum power loss is found with numerous values of DG and DSTATCOM locations and sizes.
6. The position of DGs and DSTATCOMs that provide the least power loss is selected and saved.
7. The capacity of DGs and DSTATCOMs is evaluated with the system that offers the least power loss.

Following the position and size of DGs and DSTATCOMs, the power flow analysis is employed to justify the least loss accomplishment, and the calculation of node voltages and line losses are calculated.

![Flow chart of black widow optimization](image)

**Figure 8.** Flow chart of black widow optimization [36].
5. Simulation Results

The networks of the IEEE 12, IEEE 33, and IEEE 69 bus systems have been simulated for load flow analysis as a base case with no DG or DSTATCOM installed in the network. The algorithm finds the optimal sizing and placement of DGs and a DSTATCOM, initially starting with a single DG and a single DSTATCOM. The algorithm optimizes further by increasing the number of DGs and DSTATCOMs, and the best results are obtained with the least possible number of DGs and DSTATCOMs. The study investigates the incorporation of algorithm findings for IEEE 12, IEEE 33, and IEEE 69 bus systems. The detailed parametric values of network systems and optimal sizes and placements of DGs and DSTATCOMs are discussed in the respective IEEE bus system subsections.

5.1. IEEE 12 Bus System

The system to be analysed is an IEEE 12 bus system with a rating of the base voltage of 11 kV and 100 MVA. During the base case, the total active power losses were found to be 20.7136 kW, whereas the total reactive power loss of the system was found to be 8.049 kvar (Table 1).

Table 1. Loss reduction after DG and DSTATCOM’s integration into the IEEE 12 bus system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base Case without DSTATCOM and DG</th>
<th>One DSTATCOM and DG</th>
<th>Two DSTATCOMs and DGs</th>
<th>Three DSTATCOMs and DGs</th>
<th>Four DSTATCOMs and DGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total system active power loss kW</td>
<td>20.7136</td>
<td>6.7796</td>
<td>2.1735</td>
<td>1.0393</td>
<td>0.73594</td>
</tr>
<tr>
<td>Active power loss reduction %</td>
<td>-</td>
<td>67.27</td>
<td>89.5069</td>
<td>94.9826</td>
<td>96.4471</td>
</tr>
<tr>
<td>Total system reactive power loss</td>
<td>8.0409</td>
<td>2.6496</td>
<td>0.8594</td>
<td>0.38946</td>
<td>0.27216</td>
</tr>
<tr>
<td>Reactive power loss reduction %</td>
<td>-</td>
<td>67.0492</td>
<td>89.3121</td>
<td>95.1566</td>
<td>96.6153</td>
</tr>
<tr>
<td>Voltage profile p.u.</td>
<td>0.9431</td>
<td>0.9786</td>
<td>0.9892</td>
<td>0.995</td>
<td>0.9959</td>
</tr>
<tr>
<td>DSTATCOM optimal location</td>
<td>-</td>
<td>12</td>
<td>12-6</td>
<td>12-10-5</td>
<td>12-6-7-3</td>
</tr>
<tr>
<td>DSTATCOM size kVAR</td>
<td>-</td>
<td>100</td>
<td>39-99</td>
<td>16-49-31</td>
<td>15-23-46-17</td>
</tr>
<tr>
<td>DG optimal location</td>
<td>-</td>
<td>12</td>
<td>12-8</td>
<td>12-6-8</td>
<td>12-7-9-2</td>
</tr>
<tr>
<td>DG size kW</td>
<td>-</td>
<td>100</td>
<td>94-94</td>
<td>74-99-91</td>
<td>86-91-87-57</td>
</tr>
</tbody>
</table>

5.2. Test Case 1

When a DG and a DSTATCOM were simultaneously integrated into an IEEE 12 bus system, with the DG and DSTATCOM having ratings of 100 kW and 100 kVAR, respectively, and with the optimal positioning of the DG and DSTATCOM in the bus 12 system, there was a gradual reduction in the total power losses of the system. The active power losses were reduced to 6.7796 kW from 20.7136 kW. This shows the reduction in active power losses to be 67.27%. Meanwhile, the reactive power losses were reduced to 2.6496 kVAR, which shows a reduction of 67%. The minimum bus voltage obtained with the DG and DSTATCOM was 0.9762 p.u. This is a more promising voltage profile as compared to the bus voltage profile of the system without compensation, i.e., 0.9442 p.u.
5.3. Test Case 2

We consider the case of two DGs and two DSTATCOMs being simultaneously integrated into the IEEE 12 bus system, with the DGs having a rating of 94 kW each and DSTATCOMs of 39 kVAR and 99 kVAR, with the optimal placement of DGs on bus 12 and bus 8 and DSTATCOMs on bus 12 and bus 6. There was a gradual reduction in the total loss. The active loss of the system was found to be 2.1735 kW, which shows the reduction of active power losses to have been 89.50%. Meanwhile, the reactive power loss was found to be 0.8995 kVAR. This shows a reduction of 89% in reactive power losses. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9974 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9442 p.u.

5.4. Test Case 3

Three DGs and three DSTATCOMs were integrated into the IEEE 12 bus system, with the ratings of the DGs being 74 kW, 99 kW, and 91 kW and with the optimal placement on buses 12, 6, and 8, respectively. The ratings of the DSTATCOMs were 16 kVAR, 49 kVAR, and 31 kVAR, and the optimal placement was on buses 12, 10, and 5, respectively. The active power losses were reduced to 1.0393 kW and the reactive power losses were reduced to 0.38946 kVAR. The active power losses were reduced by 94.98%, whereas the reactive power loss reduction was of 95%, respectively. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9931 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9442 p.u.

5.5. Test Case 4

Four DGs and four DSTATCOMs were integrated into an IEEE 12 bus system, and the DGs had ratings of 86 kW, 91 kW, 87 kW, and 51 kW, with the optimal placement on buses 12, 7, 9, and 2, respectively, and the DSTATCOMs had ratings of 15 kVAR, 23 kVAR, 46 kVAR, and 17 kVAR, respectively. The active power losses were reduced to 0.73594 kW and the reactive power losses were reduced to 0.272916 kVAR. There was a reduction of 96% in active and reactive power losses, respectively. The minimum bus voltage obtained with the DGs and DSTATCOMs was 0.9947 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9442 p.u.

Figure 9 depicts the voltage profile of the IEEE 12 bus system against the various configurations of DGs and DSTATCOMs at optimized locations with optimal sizes. As indicated, the voltage profiles of various buses in the IEEE 12 bus system were between 1.0 p.u. and 0.9433 p.u. The algorithm estimates the optimal location of a single DG and single DSTATCOM as the 12th bus, with ratings of 100 kW and 100 kVAR. With the proposed sizing and positions of a single DG and a single DSTATCOM, the voltage profile is improved to 1.0 p.u. to 0.9786 p.u. as the least voltage p.u. at the 12th bus. Likewise, as the number of DGs and DSTATCOMs grew, promising results were witnessed, as shown in Figure 9. The best results of the voltage profile were obtained by optimizing the maximum number of four DGs and four DSTATCOMs for optimal sizing and locations with the proposed algorithm. The sizes and locations of four DGs were optimized as DG 1 = 86 kW, location = bus 12, DG 2 = 91 kW, location = bus 7, DG 3 = 87 kW, location = bus 9, and DG 4 = 57 kW, location = bus 2. Similarly, the sizes and locations of the four DSTATCOMs were optimized as DSTATCOM 1 = 15 kVAR, location = bus 12, DSTATCOM 2 = 23 kVAR, location = bus 6, DSTATCOM 3 = 46 kVAR, location = bus 7, and DSTATCOM 4 = 17 kVAR, location = bus 3. The least voltage across the 12th bus was 0.9959 p.u., and, overall, the voltage profile of the IEEE 12 bus was improved.

Figure 10 depicts how the active power loss for the IEEE 12 bus system was assessed through the backward/forward sweep power flow method. The active power loss across various bus numbers was high without the addition of DGs and DSTATCOMs in the network. The total active power loss for the 100 MVA system rating was 20.713 kW, which is significant. The optimization reduced the active power losses significantly as the number of integrated DGs and DSTATCOMs increased by compensating for the reactive power losses.
required by various buses in the system. The optimum results were obtained with the integration of four DGs and four DSTATCOMs at various demanding bus numbers in the network. Their optimal sizing and location helped the system to decrease the active power losses by 96.44% from the uncompensated system.

Figure 9. Voltage profile base case and after DGs and DSTATCOMs were integrated into the IEEE 12 bus system.

Figure 10. Active power loss base case and after the DGs and DSTATCOMs were integrated into the IEEE 12 bus system.

Figure 11 depicts the reactive power loss across the IEEE 12 bus system, and 8.0409 kVAr losses were recorded for the total system without reactive power compensation. There was high reactive power loss across the initial bus number, which reduced considerably with the integration of a single DG and a single DSTATCOM to 2.65 kVAr with their optimal sizing and locations. The dropping trend was observed in the reactive power loss as the number of DGs and DSTATCOMs grew. The reactive power compensation through the integration of four DGs and four DSTATCOMs of optimal sizes installed at suitable locations minimized the reactive power loss by 96.6%. The optimization algorithm was successful in finding the optimal sizes as well as the best locations for the installation of DGs and DSTATCOMs to minimize the reactive power loss.
Figure 11. Reactive power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 12 bus system.

Figure 12 illustrates the fitness of optimization that determined the difference between the optimal solution and the desired solution. The fitness was calculated for all the candidates for optimization with maximum iterations of 50. The procreation rate was 0.8, the cannibalism rate was 0.5, and the mutation rate was 0.4, respectively. The candidates from the black widow optimization algorithm were one DG and one DSTATCOM, two DGs and two DSTATCOMs, three DGs and three DSTATCOMs, and four DGs and four DSTATCOMs. Candidate 1, consisting of one DG and one DSTATCOM, had a high fitness difference value at the initial iterations, which reduced slightly until the 15th iteration, and remained the same for all the next iterations. Thus, the fitness function recommended increasing the number of DGs and DSTATCOMs and moving to the next candidates. As indicated in Figure 12, the convergence graph shows that the integration of four DGs and four DSTATCOMs brought a minimum difference between the optimal and desirable solution. The fitness function remained under 1 for all the iterations performed for this candidate. The other candidates exhibit high values of the fitness function.
5.6. IEEE 33 Bus System

The system analysed was the IEEE 33 bus system. During the base case, the total active power losses were found to be 202.6771 kW, whereas the total reactive power loss of the system was found to be 135.141 kVAr (Table 2).

Table 2. Power loss reduction after DG and DSTATCOM’s integration into IEEE 33 bus system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base Case without DSTATCOM and DG</th>
<th>One DSTATCOM and DG</th>
<th>Two DSTATCOMs and DGs</th>
<th>Three DSTATCOMs and DGs</th>
<th>Four DSTATCOMs and DGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total system active power loss kW</td>
<td>202.6771</td>
<td>83.0037</td>
<td>39.8037</td>
<td>25.415</td>
<td>10.6874</td>
</tr>
<tr>
<td>Active power loss reduction %</td>
<td>-</td>
<td>59.0464</td>
<td>80.361</td>
<td>87.4604</td>
<td>94.7268</td>
</tr>
<tr>
<td>Total system reactive power loss</td>
<td>135.141</td>
<td>62.2296</td>
<td>29.4247</td>
<td>19.2285</td>
<td>12.2306</td>
</tr>
<tr>
<td>Reactive power loss reduction %</td>
<td>-</td>
<td>53.9521</td>
<td>78.2267</td>
<td>85.7715</td>
<td>90.9498</td>
</tr>
<tr>
<td>Voltage profile p.u.</td>
<td>0.9131</td>
<td>0.95</td>
<td>0.9769</td>
<td>0.9788</td>
<td>0.9938</td>
</tr>
<tr>
<td>DSTATCOM optimal location</td>
<td>-</td>
<td>33</td>
<td>33-30</td>
<td>33-30-6</td>
<td>33-4-30-14</td>
</tr>
<tr>
<td>DSTATCOM size kVAr</td>
<td>-</td>
<td>991</td>
<td>133-952</td>
<td>259-847-774</td>
<td>162-407-793-409</td>
</tr>
<tr>
<td>DG optimal location</td>
<td>-</td>
<td>33</td>
<td>33-14</td>
<td>10-33-24</td>
<td>14-24-33-26</td>
</tr>
<tr>
<td>DG size kW</td>
<td>-</td>
<td>991</td>
<td>893-893</td>
<td>806-620-830</td>
<td>757-713-861-729</td>
</tr>
</tbody>
</table>

5.7. Test Case 1

When a DG and a DSTATCOM were simultaneously integrated into the IEEE 33 bus system with the DG and DSTATCOM having ratings of 991 kW and 991 kVAr, respectively, and with the positioning of the DG and DSTATCOM on bus 33, there was a gradual reduction in the total power loss. The active power loss was reduced to 83.0037 kW from 202.6771 kW. This shows a reduction in active power losses to 59.0464%, whereas the reactive power losses were reduced to 62.2296 kVAr from 135.141 kVAr. This shows a reduction of 53.95%. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.95 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9131 p.u.

5.8. Test Case 2

Two DGs and two DSTATCOMs were simultaneously integrated into the IEEE 33 bus system, with the DGs having ratings of 893 kW and 893 kW, respectively, and the DSTATCOMs having ratings of 133 kVAr and 952 kVAr, with the optimal placement of the DGs on bus 33 and bus 14, and the DSTATCOMs on bus 33 and bus 30. The total power loss was reduced. The active power losses of the system were found to be 39.8037 kW, which shows the reduction in active power losses to be 80.361%. Meanwhile, the reactive power loss was found to be 29.4247 kVAr. This shows a reduction of 78.2267% in reactive power losses. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9769 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9131 p.u.
5.9. Test Case 3

Three DGs and three DSTATCOMs were simultaneously integrated into the IEEE 33 bus system, with the DGs having ratings of 806 kW, 620 kW, and 830 kW, respectively, and the DSTATCOMs having ratings of 259 kVAR, 847 kVAR, and 774 kVAR. The optimal placements of DGs were on bus 10, bus 33, and bus 24, and DSTATCOM placements were on bus 33, bus 30, and bus 6. The total power loss was reduced. The active power losses of the system were found to be 25.415 kW. This shows the reduction in active power losses to be 87.4604%, whereas the reactive power loss was found to be 19.2285 kVAR. This shows a reduction of 85.7715% in reactive power losses. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9788 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9131 p.u.

5.10. Test Case 4

Four DGs and four DSTATCOMs were simultaneously integrated into the IEEE 33 bus system, with DG ratings of 757 kW, 713 kW, 861 kW, and 729 kW, respectively, and DSTATCOMs with ratings of 162 kVAR, 407 kVAR, 797 kVAR, and 409 kVAR. The optimal placements of DGs were on bus 14, bus 24, bus 33, and bus 26, and DSTATCOM placements were on bus 33, bus 4, bus 30, and bus 14. The total power loss was reduced. The active power losses of the system were found to be 10.6874 kW. This shows the reduction of active power losses to be 94.72%, whereas the reactive power loss was found to be 12.2306 kVAR. This shows a reduction of 90.9498% in reactive power losses. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9938 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.9131 p.u.

Figure 13 depicts the voltage profile of the IEEE 33 bus system against the various configurations of DGs and DSTATCOMs at optimized locations with optimal sizes. As indicated in Figure 13, the voltage profiles of various buses in the IEEE 33 bus system are between 1.0 p.u. and 0.9131 p.u. The algorithm estimated the optimal location of a single DG and a single DSTATCOM to be the 33 bus, with 991 kW and 991 kVAR. With the proposed sizing and positions of the single DG and single DSTATCOM, the voltage profile was improved, to 1.0 p.u. to 0.95 p.u. as the least voltage p.u. at the 33 bus. Likewise, as the number of DGs and DSTATCOMs grew, promising results were witnessed, as shown in Figure 13. The best results of the voltage profile were obtained by optimizing the maximum number of four DGs and four DSTATCOMs for optimal sizing and location with the proposed algorithm. The sizes and locations of the four DGs were optimized as DG 1 = 757 kW, location = bus 14, DG 2 = 713 kW, location = bus 24, DG 3 = 861 kW, location = bus 33, and DG 4 = 729 kW, location = bus 26. Similarly, the sizes and locations of the four DSTATCOMs were optimized as DSTATCOM 1 = 162 kVAR, location = bus 33, DSTATCOM 2 = 407 kVAR, location = bus 4, DSTATCOM 3 = 793 kVAR, location = bus 30 and DSTATCOM 4 = 409 kVAR, location = bus 14. The least voltage across the 33 bus was 0.9938 p.u. and overall, the voltage profile of the IEEE 33 bus system was improved.

Figure 14 illustrates how the active power loss for the IEEE 33 bus system was assessed through the backward/forward sweep power flow method. The active power loss across various bus numbers was high without the addition of DGs and DSTATCOMs in the network. The total active power loss for the 100 MVA system rating was 202.6771 kW. The optimum results were obtained with the integration of four DGs and four DSTATCOMs at various demanding bus numbers in the network. Their optimal sizing and location helped the system to decrease the active power losses to 94.72% from the uncompensated system, which is significant. The optimization reduced the active power losses significantly as the number of integrated DGs and DSTATCOMs increased by compensating for the reactive power required by various buses.
the number of DGs and DSTATCOMs grew, promising results were witnessed, as shown in Figure 13. The best results of the voltage profile were obtained with the integration of four DGs and four DSTATCOMs at optimized locations with optimal sizes. As their optimal sizing and locations, the voltage profile was improved, to 1.0 p.u. to 0.95 p.u. as the least voltage p.u. at the 33 bus. Likewise, as their optimal sizing and locations, the voltage profile was improved, to 1.0 p.u. to 0.95 p.u. as the least voltage p.u. at the 33 bus.

The optimum results were obtained with the integration of four DGs and four DSTATCOMs of optimal sizes and installed at suitable locations minimized the reactive power loss by 91%. The optimization algorithm was successful in finding the optimal size as well as the best location for the installation of DGs and DSTATCOMs to minimize the reactive power loss. The algorithm estimated the optimal location of a single DG and a single DSTATCOM to be the 33 bus, with 991 kW and 991 kVar. With the proposed sizing and positions of the single DG and single DSTATCOM, the voltage profile was improved, to 1.0 p.u. to 0.9131 p.u. The algorithm estimated the optimal location of a single DSTATCOM to be bus 14, DSTATCOM 1 = 162 kVar, location = bus 33, DSTATCOM 2 = 316 kVar, location = bus 24, DSTATCOM 3 = 793 kVar, location = bus 30 and DSTATCOM 4 = 409 kVar, location = bus 14. The least voltage across the 33 bus was 0.9938 p.u. This is better than the bus voltage obtained with DGs and DSTATCOMs was 0.9938 p.u. This shows a reduction of 90.9498% in reactive power losses. The minimum kVar losses were recorded for the total system without reactive power compensation. There was high reactive power loss across the initial bus number, which reduced considerably with the integration of a single DG and a single DSTATCOM to 62.2296 kVar with their optimal sizing and locations. The dropping trend was observed in the reactive power loss as the number of DGs and DSTATCOMs grew. The reactive power compensation through the integration of four DGs and four DSTATCOMs of optimal sizes and installed at suitable locations minimized the reactive power loss by 91%. The optimization algorithm was successful in finding the optimal size as well as the best location for the installation of DGs and DSTATCOMs to minimize the reactive power loss.

Figure 15 depicts the reactive power loss across the IEEE 33 bus system, and 135.141 kVar losses were recorded for the total system without reactive power compensation. There was high reactive power loss across the initial bus number, which reduced considerably with the integration of a single DG and a single DSTATCOM to 62.2296 kVar with their optimal sizing and locations. The dropping trend was observed in the reactive power loss as the number of DGs and DSTATCOMs grew. The reactive power compensation through the integration of four DGs and four DSTATCOMs of optimal sizes and installed at suitable locations minimized the reactive power loss by 91%. The optimization algorithm was successful in finding the optimal size as well as the best location for the installation of DGs and DSTATCOMs to minimize the reactive power loss.
Figure 14. Active power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 33 bus system.

Figure 15. Reactive power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 33 bus system.

Figure 16 illustrates the fitness of optimization, which determined the difference between the optimal solution and the desired solution. The fitness was calculated for all the candidates of optimization with maximum iterations of 50. The procreation rate was 0.8, the cannibalism rate was 0.5, and the mutation rate was 0.4, respectively. The candidates from the black widow optimization algorithm were one DG and one DSTATCOM, two DGs and two DSTATCOMs, three DGs and three DSTATCOMs, and four DGs and four DSTATCOMs. Candidate 1, consisting of one DG and one DSTATCOM, had a high fitness difference value at initial iterations, which reduced slightly until the 18th iteration and remained the same for all next iterations. Thus, the fitness function recommended increasing the number of DGs and DSTATCOMs and moving to the next candidates. As indicated in Figure 16, the convergence graph shows that the integration of four DGs and four DSTATCOMs brought a minimum difference between optimal and desirable solutions. The fitness function remained under 20 for all the iterations performed for this candidate. The other candidates exhibit high values of a fitness function. Performance analysis was done of the proposed method after optimal sizing and placement of the DGs and DSTATCOMs into the IEEE 33 radial distribution system.

In Table 3, the comparative analysis shows that black widow optimization was effective in reducing losses, with a minimum voltage of 0.9935 p.u. and a power loss of 10.68 kW from the base case of 202.67 kW, resulting in a power loss reduction of 94.72%. When compared to other optimizations, such as IGWO [24], the power loss was reduced to 11.48 kW from the base case of 202.67 kW, with a minimum voltage of 0.992 p.u., achieving a total power loss reduction of 94.30%. Similarly, compared to CSA [25], the power loss was reduced to 12 kW from 202.67 kW, with a minimum voltage of 0.9910 p.u. and a power loss reduction of 94%. Lastly, compared to BFO [26], the power loss was reduced to 15 kW from the base case of 202.67 kW, with a minimum voltage of 0.9862 p.u. and a total power loss reduction of 92.56%. These results demonstrate the effectiveness of BWO in reducing losses while maintaining a minimum voltage of 0.9915 p.u.
Figure 15: Reactive power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 33 bus system.

Figure 16: Convergence graph for IEEE 33 bus black widow optimization.

Table 3: Comparison with existing techniques.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss kW</td>
<td>202.67</td>
<td>10.6874</td>
<td>11.48</td>
<td>12</td>
<td>15.07</td>
</tr>
<tr>
<td>DG size kW</td>
<td>757-713-861-729</td>
<td>770-1070-1030</td>
<td>750-1100-1000</td>
<td>850-750-860</td>
<td></td>
</tr>
<tr>
<td>DG location</td>
<td>14-24-33-26</td>
<td>14-24-30</td>
<td>14-24-30</td>
<td>400-350-850</td>
<td></td>
</tr>
<tr>
<td>DSTATCOM size (kVAR)</td>
<td>162-407-793-409</td>
<td>360-515-1000</td>
<td>420-460-970</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSTATCOM location</td>
<td>33-4-30-14</td>
<td>11-24-30</td>
<td>11-24-30</td>
<td>12-25-30</td>
<td></td>
</tr>
<tr>
<td>Power loss reduction %</td>
<td>94.72</td>
<td>94.30</td>
<td>94</td>
<td>92.56</td>
<td></td>
</tr>
<tr>
<td>Min: voltage p.u</td>
<td>0.9938</td>
<td>0.992</td>
<td>0.9910</td>
<td>0.9862</td>
<td></td>
</tr>
</tbody>
</table>

5.11. IEEE 69 Bus System

The optimized findings of the proposed algorithm were applied to the IEEE 69 bus system. Initially, the total active power loss for the base case of the IEEE 69 bus system was computed to be 224.9606 kW. Meanwhile, the total reactive power loss of the system was found to be 102.147 kVAR (Table 4).

Table 4: Power loss reduction after DG and DSTATCOM’s integration into the IEEE 69 bus system.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base Case without DSTATCOM and DG</th>
<th>One DSTATCOM and DG</th>
<th>Two DSTATCOMs and DGs</th>
<th>Three DSTATCOMs and DGs</th>
<th>Four DSTATCOMs and DGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total system active power loss kW</td>
<td>224.9606</td>
<td>117.1012</td>
<td>46.335</td>
<td>34.2295</td>
<td>12.9128</td>
</tr>
<tr>
<td>Active power loss reduction %</td>
<td>-</td>
<td>47.9459</td>
<td>79.4031</td>
<td>84.7842</td>
<td>94.26</td>
</tr>
<tr>
<td>Total system reactive power loss</td>
<td>102.147</td>
<td>57.3218</td>
<td>24.5611</td>
<td>18.9111</td>
<td>10.1273</td>
</tr>
</tbody>
</table>
Table 4. Cont.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base Case without DSTATCOM and DG</th>
<th>One DSTATCOM and DG</th>
<th>Two DSTATCOMs and DGs</th>
<th>Three DSTATCOMs and DGs</th>
<th>Four DSTATCOMs and DGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive power loss reduction %</td>
<td>-</td>
<td>43.8831</td>
<td>75.9551</td>
<td>81.4864</td>
<td>90.0855</td>
</tr>
<tr>
<td>Voltage profile p.u.</td>
<td>0.909</td>
<td>0.95</td>
<td>0.966</td>
<td>0.9709</td>
<td>0.9915</td>
</tr>
<tr>
<td>DSTATCOM optimal location</td>
<td>-</td>
<td>69</td>
<td>69-29</td>
<td>69-29-60</td>
<td>63-69-45-29</td>
</tr>
<tr>
<td>DSTATCOM size kVA</td>
<td>-</td>
<td>36</td>
<td>597-740</td>
<td>14-271-723</td>
<td>137-58-73-183</td>
</tr>
<tr>
<td>DG size kW</td>
<td>-</td>
<td>687</td>
<td>410-975</td>
<td>35-878-861</td>
<td>280-626-825-501</td>
</tr>
</tbody>
</table>

5.12. Test Case 1

When a DG and DSTATCOM were simultaneously integrated into the IEEE 69 bus system with the DG and DSTATCOM having ratings of 687 kW and 36 kVAr, respectively, and with the positioning of the DG and DSTATCOM on bus 69, there was a gradual reduction in the total power loss. The active power loss was reduced to 117.1012 kW from 224.9606 kW. This shows a reduction of active power losses of 47.9459%. Meanwhile, the reactive power losses were reduced to 57.3218 kVAr from 102.147 kVAr, which shows a reduction of 43.8831%. The minimum bus voltage obtained with the DG and DSTATCOM was 0.95 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.909 p.u.

5.13. Test Case 2

Two DGs and two DSTATCOMs were simultaneously integrated into the IEEE 69 bus system, with the DGs having ratings of 410 kW, 975 kW and the DSTATCOMs having ratings of 597 kVAr and 740 kVAr, respectively, along with the positioning of the DGs on bus 69 and bus 63. There was a gradual reduction in the total power loss. The active power loss was reduced to 46.335 kW from 224.9606 kW. This shows a reduction in active power losses by 79.4031%, whereas the reactive power losses were reduced to 24.5611 kVAr from 102.147 kVAr. This shows a reduction of 75.9551%. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.966 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.909 p.u.

5.14. Test Case 3

Three DGs and three DSTATCOMs were integrated into the IEEE 69 bus system with the DGs having ratings of 35 kW, 878 kW, and 861 kW, and the DSTATCOMs having ratings of 14 kVAr, 271 kVAr, and 723 kVAr, respectively, along with the positioning of DGs on bus 69, bus 61, and bus 11. There was a gradual reduction in the total power loss. The active power loss was reduced to 34.2295 kW from 224.9606 kW. This shows the reduction in active power losses to have been of 84.7842%, whereas the reactive power losses were reduced to 18.9111 kVAr from 102.147 kVAr. This shows a reduction of 81.4864%. The minimum bus voltage obtained with DGs and DSTATCOMs was 0.9709 p.u. This is better as compared to the bus voltage obtained without compensation, i.e., 0.909 p.u.

5.15. Test Case 4

Four DGs and four DSTATCOMs were integrated into the IEEE 69 bus system, with the DGs having ratings of 280 kW, 626 kW, 825 kW, and 501 kW, and the DSTATCOMs having ratings of 137 kVAr, 58 kVAr, 73 kVAr, and 183 kVAr, respectively, along with the
positioning of the DGs on bus 69, bus 63, bus 62, and bus 66. There was a gradual reduction in the total power loss. The active power loss was reduced to 12.9128 kW from 224.9606 kW. This shows the reduction in active power losses to have been of 94.26%, whereas the reactive power losses were reduced to 10.1273 kVAr from 102.147 kVAr. This shows a reduction of 90.0855%. The lowest bus voltage was maintained at 0.9915 p.u. when the network was implemented with DGs and DSTATCOMs. The results are promising as compared to the bus voltage in the case of a system without compensation, i.e., 0.909 p.u.

Figure 17 depicts the voltage profile of the IEEE 69 bus system against the various configurations of DGs and DSTATCOMs at optimized locations with optimal sizes. As indicated in the figure, the voltage profiles of various buses in the IEEE 69 bus system were between 1.0 p.u. and 0.909 p.u. The algorithm estimated the optimal location of a single DG and a single DSTATCOM to be the 69 bus, with 687 kW and 36 kVAr. With the proposed sizing and position of single DG and single DSTATCOM, the voltage profile was improved to 1.0 p.u. to 0.95 p.u. as the least voltage p.u. at the 69th bus. Likewise, as the number of DGs and DSTATCOMs grew, promising results were witnessed, as shown in Figure 17. The best results of the voltage profile were obtained by optimizing the maximum number of four DGs and four DSTATCOMs for optimal sizing and locations with the proposed algorithm. The sizes and locations of the four DGs were optimized as DG 1 = 280 kW, location = bus 69, DG 2 = 626 kW, location = bus 63, DG 3 = 825 kW, location = bus 62, and DG 4 = 501 kW, location = bus 66. Similarly, the sizes and locations of the four DSTATCOMs were optimized as DSTATCOM 1 = 137 kVAr, location = bus 63, DSTATCOM 2 = 58 kVAr, location = bus 69, DSTATCOM 3 = 73 kVAr, location = bus 45, and DSTATCOM 4 = 183 kVAr, location = bus 29. The least voltage across the 18th bus was 0.9938 p.u. and, overall, the voltage profile of the IEEE 69 bus system was improved.

Figure 17. Voltage profile base case and after DGs and DSTATCOMs were integrated into the IEEE 69 bus system.

Figure 18 depicts the active power loss for the IEEE 69 bus system as assessed through the backward/forward sweep power flow method. The active power loss across various bus numbers was high without the addition of DGs and DSTATCOMs in the network. The total active power loss for the 100 MVA system rating was 224.9606 kW, which is significant. The optimization reduced the active power losses significantly as the number of integrated DGs and DSTATCOMs increased by compensating for the reactive power required by various buses in the system. The optimum results were obtained with the integration of
four DGs and four DSTATCOMs at various demanding bus numbers in the network. Their optimal sizing and location helped the system to decrease the active power losses by 94.26% from the uncompensated system.

Figure 18. Active power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 69 bus system.

Figure 19. Reactive power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 69 bus system, and 102.147 kVAr losses were recorded for the total system without reactive power compensation. There was high reactive power loss across the initial bus number, which reduced considerably with the integration of a single DG and single DSTATCOM to 57.3218 kVAr with their optimal sizing and locations. A dropping trend was observed in the reactive power loss as the number of DGs and DSTATCOMs grew. The reactive power compensation through the integration of four DGs and four DSTATCOMs of optimal sizes and installed at suitable locations minimized the reactive power loss by 90%. The optimization algorithm was successful in finding the optimal sizes as well as the best locations for the installation of DGs and DSTATCOMs to minimize the reactive power loss.

Figure 20 illustrates the fitness of optimization, which determined the difference between the optimal solution and the desired solution. The fitness was calculated for all the candidates of optimization, with maximum iterations of 50. The procreation rate was 0.8, the cannibalism rate was 0.5, and the mutation rate was 0.4, respectively. The candidates from the black widow optimization algorithm were one DG and one DSTATCOM, two DGs and two DSTATCOMs, three DGs and three DSTATCOMs, and four DGs and four DSTATCOMs. Candidate 1, consisting of one DG and one DSTATCOM, had a high fitness difference value at initial iterations, and this remained the same for all the next iterations. Thus, the fitness function recommended increasing the number of DGs and DSTATCOMs and moving to the next candidates. As indicated in Figure 20, the convergence graph shows that the integration of four DGs and four DSTATCOMs brought a minimum difference between the optimal and desirable solutions. The fitness function remained under 23 for all the iterations performed for this candidate. The other candidates exhibited high values of the fitness function.
Figure 18. Active power loss base case and after DGs and DSTATCOMs were integrated into the IEEE 69 bus system.

Figure 19 depicts the reactive power loss across the IEEE 69 bus system, and 102.147 kVAr losses were recorded for the total system without reactive power compensation. There was high reactive power loss across the initial bus number, which reduced considerably with the integration of a single DG and single DSTATCOM to 57.3218 kVAr with their optimal sizing and locations. A dropping trend was observed in the reactive power loss as the number of DGs and DSTATCOMs grew. The reactive power compensation through the integration of four DGs and four DSTATCOMs of optimal sizes and installed at suitable locations minimized the reactive power loss by 90%. The optimization algorithm was successful in finding the optimal sizes as well as the best locations for the installation of DGs and DSTATCOMs to minimize the reactive power loss.

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Performance analysis was done of the proposed method after optimal sizing and placement of the DGs and DSTATCOMs into the IEEE 69 radial distribution system (Table 5). In Table 5, the comparative analysis reveals that black widow optimization effectively reduced losses, with a minimum voltage of 0.9915 p.u. and a power loss of 12.9128 kW, compared to the base case of 224.96 kW, resulting in a power loss reduction of 94.26%. This can be compared to other optimization methods such as Hybrid SCA [27], which reduced power loss to 23.22 kW from the base case of 224.96 kW, with a minimum voltage of 0.9768 p.u., achieving a total power loss reduction of 89.67%. Additionally, when compared to PSO [28], it reduces power loss to 38.6 kW from 224.96 kW, with a minimum voltage of 0.9562 p.u., resulting in a power loss reduction of 82.9%. These findings highlight the effectiveness of BWO in reducing losses while maintaining a minimum voltage of 0.9915 p.u. in the IEEE 69 radial bus system.
Table 5. Comparison with existing techniques.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base Case</th>
<th>Proposed Method: Black Widow Optimization</th>
<th>Hybrid SCA [27]</th>
<th>Particle Swarm Optimization [28]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power loss kW</td>
<td>224.96</td>
<td>12.9128</td>
<td>23.22</td>
<td>38.6</td>
</tr>
<tr>
<td>DG size kW</td>
<td>280-626-825-501</td>
<td>1873</td>
<td>108</td>
<td></td>
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<tr>
<td>DG location</td>
<td>69-63-62-66</td>
<td>61</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>DSTATCOM size (kVAR)</td>
<td>137-58-73-183</td>
<td>1301.13</td>
<td>903.9</td>
<td></td>
</tr>
<tr>
<td>DSTATCOM location</td>
<td>63-69-45-29</td>
<td>61</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>Power loss reduction%</td>
<td>94.26</td>
<td>89.67</td>
<td>82.9</td>
<td></td>
</tr>
<tr>
<td>Min: voltage p.u</td>
<td>0.9915</td>
<td>0.9768</td>
<td>0.9562</td>
<td></td>
</tr>
</tbody>
</table>

6. Conclusions

This study demonstrates a novel method to improve voltage profiles and reduce losses in IEEE 12 bus, IEEE 33 bus, and IEEE 69 bus systems by strategically placing and sizing Distributed Generators (DGs) and distribution static compensators (DSTATCOMs) using the black widow optimization technique. Simulation results confirm significant enhancements in system performance, with reductions in active and reactive power losses across all tested scenarios. For instance, the IEEE 12 bus system showed reductions of up to 96% in power losses, while the IEEE 69 bus system achieved up to a 94.26% reduction. These outcomes underscore the effectiveness of this approach in boosting power efficiency and system reliability, thus validating the proposed optimization strategy.

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