

Using Harris Hawks Optimization for Optimal Placement and Sizing of Shunt Capacitors and Distributed Generators

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Article Info	Abstract
Received 12/10/2024	<p>The power supply problem represents one of the never-ending problems that remain prominent. The integration of shunt capacitors and distributed generators aims to elevate the grid performance. In this work, Harris Hawks Optimization (HHO) is the optimization technique suggested to calculate and determine the optimal size of the shunt capacitors and distribution generation on the radial distribution system. The reconfiguration method (RM) is an approach that refers to the best and optimal location of the distribution generation and the shunt capacitor. The main goal of selecting the optimal size (using HHO) and optimal placement (using RM) is to minimize the voltage deviation. This paper presents three cases: the first case includes determining the optimal voltage deviation after installing shunt capacitors on radial distribution networks; the second case involves calculating the optimal voltage deviation after installing distribution generation on this system. The last case is conducted to calculate the optimal voltage deviation after installing SC and DG simultaneously. The proposed approaches (HHO and RM) are applied to the IEEE 69-bus power system. Results show a considerable reduction in the voltage deviation rate. That is, the voltage deviation is minimized to 38.95%, 75.13%, and 90.23 % in the three cases, respectively.</p>
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1. Introduction

Due to the importance of energy, the rate of development is reflected in the consumption of energy for any society. In addition, the social, economic, and industrial developments led to the increasing demand [1]. Therefore, energy resources represent a major global concern. Providing power effectively and economically is the main challenge facing the power distribution system. The distribution networks have significant investments and research due to their connection with consumers (direct connection). Various ways to address the distribution system's problems and challenges have been described in the literature. Power compensators may be applied to increase voltage, enhance power quality, and lower power loss. Distributed generation units and shunt capacitors are essential for achieving the technological advantages of distribution networks [2]-[5]. Applications for distribution generation include the utilization of Renewable Energy Sources (RES), such as solar and wind energy. In recent years, distributed generation (DG) has witnessed as a crucial element

of modern smart grids, owing to its capacity to augment voltage stability, enhance reliability, and cope with overall transmission losses. The appropriate selection and positioning of distributed generation units are crucial for attaining optimal network performance, especially when combined with reactive power compensation devices like shunt capacitors. In contrast to traditional centralized generation, distributed generation (DG) units are typically situated near load centers, which considerably alleviates the strain on transmission lines and reduces the likelihood of voltage sags. Furthermore, the coordination between distributed generators and shunt capacitors not only optimizes voltage management but also improves the total power factor and system efficiency. The optimization of these hybrid systems generally entails multi-objective analysis, balancing technical characteristics such as power loss reduction, enhancement of voltage profiles, and economic considerations, including installation expenses and energy saving. Furthermore, contemporary distribution networks are progressively vulnerable to operational

uncertainties resulting from the incorporation of power from renewable sources and distributed generators. These uncertainties encompass fluctuations in sun irradiation, wind velocity, and variable local demand patterns. Consequently, identifying the optimal sites for voltage support devices has evolved into a complex challenge. Latest research emphasizes that efficient allocation strategies must not only minimize technical losses but also improve the system's resilience under varying loading situations. Consequently, a comprehensive optimization framework is necessary to guarantee stable, dependable, and economically efficient grid functioning. Therefore, addressing the interacting effects of distributed generators and shunt capacitors on distribution networks is essential for attaining a sustainable, resilient, and efficient power delivery system.

Distributed generations are classified into three types according to the supplier. The first one supplied the active power output (P), the second type supplied the reactive power output (Q), and the third type supplied both (active and reactive power). The shunt capacitors provide only reactive power output and operate as a source of VAR compensation. Therefore, the effect of distributed generation is more than that of a shunt capacitor on power systems. When the distributed generations are combined with a shunt capacitor, this could have a greater effect on the optimization of the performance of distribution networks. Power distribution system (PDS) configuration design is a challenging process that is essential to the planning of electric power systems. All buses' voltage profiles can be lowered, and real power losses may rise because of inadequate configuration [6].

The reconfiguration method (RM) is an effective approach used to select the optimal location (Bus number) in this paper. Due to its cost-effectiveness, the reconfiguration method represents one of the most popular methods [7], [8]. RM is the process of changing the location of the source (shunt capacitor or distributed generation or both) of each bus on the distribution network and calculating the optimal voltage deviation on this bus. The bus with the minimum voltage deviation is the best bus (optimal location). The reconfiguration method (RM) approach encounters several constraints, including line current upper and lower limits and bus voltage upper and lower limitations. Thus, an effective algorithm must be used to carry out an optimal reconfiguration method (RM), taking into account many factors like the objective function and limitations. To improve the performance of distributed systems, the main objective of RM is to reduce voltage deviation (VD) and increase voltage profile (VP) [7], [8]. Numerous optimization methods, such as including Hunger Games Search (HGS) [9], [10] have been developed to solve optimal power flow in power systems. In addition, the following approaches are considered in the literature; Grey Wolf Optimizer (GWO) [11], [12], Harris Hawks Optimization (HHO) [13], [14], Slime Mould Algorithm (SMA) [15], Modified Artificial Bee Colony (MABC) [16], Differential Evolution (DE), and Improved Differential Evolution (IDE) [17]-[19]. A wide range of optimization techniques has been proposed for the best possible allocation (sizing and placement) of SC and DG sources in distribution networks in order to maximize system performance. These techniques include Ant Lion Optimization (ALO), Enhanced

Particle Swarm Optimization (EPSO) [20], Genetic Algorithms (GA) [21], Artificial Rabbits Optimization (ARO) [22], as well as Artificial Bee Colonies (ABC) [16], [23]. In reference [24], the authors utilized Lichtenberg and thermal exchange optimization methods to obtain the ideal placement of multiple capacitors and distributed generation units, taking into account various load models. In [25], the authors proposed an enhanced optimization approach for the coordinated placement of distributed generators (DGs) and shunt capacitors (SCs) in practical power distribution systems, specifically the Brazil 136-bus network and the IEEE 33-bus test feeder. The study aimed to reduce both active and reactive power losses, mitigate voltage deviations, and strengthen overall voltage stability. These performance goals were combined using appropriate weighting factors and solved through a particle swarm optimization method incorporating a constriction factor (CF-PSO). The outcomes were benchmarked against those produced by conventional PSO and modified PSO (MPSO), demonstrating the superior robustness of the CF-PSO approach and its effectiveness in achieving optimal DG placement. In [26], a hybrid framework combining binary particle swarm optimization with the shuffled frog leaping algorithm (BPSO-SFL) was introduced to address both single- and multi-objective DG allocation problems. The primary goals were to minimize apparent power losses and enhance voltage stability in 33-bus and 69-bus radial distribution systems. Furthermore, three distinct criteria, environmental, technical, and economic, were considered to identify the most suitable locations for distributed generators and shunt capacitors in radial networks. These objectives were formulated as a weighted multi-objective optimization problem and solved using the spring search algorithm (SSA) [27] as well as a hybrid PSO-GWO technique [28] to improve overall system performance. In [29], the Archimedes optimization algorithm (AOA) was used to determine the best placement of PV systems in radial distribution systems (RDS), taking into account various load model categories. The goal was to minimize the network's dependency and reduce greenhouse gas emissions to the greatest extent possible. In [30], a recently developed transient search optimization (TSO) technique was employed to identify the optimal placement and sizing of distributed generators across varying operating scenarios in the IEEE 33-bus and 69-bus radial distribution networks. Additionally, in [31], the stud krill herd (SKH) algorithm was applied to determine the most suitable location and capacity of a single DG unit within the IEEE 33-bus, IEEE 69-bus, and IEEE 94-bus radial distribution systems, while explicitly considering different static load characteristics.

In this paper, Harries Hawks' optimization is the algorithm proposed to determine the optimal sizing of the shunt capacitor (SC) and distributed generation (DG). The primary goal of this study is to reduce voltage deviation, which could enhance each bus voltage profile. The voltage stability index for the entire system is improved as a result of this modification.

This voltage deviation has been optimized through three cases. The first case is determining the optimal placement and sizing of a shunt capacitor on a distribution network, after the addition of a shunt capacitor in the system. In this case, reactive power drawn by SC (MVAR) is injected into the system. The second

case is determining the optimal placement and sizing of distribution generation on the distribution network, after the addition of distributed generation on the system. In this case, active power drawn by the DGs (MW) is injected into the system. The last case is determining the optimal placement and sizing of a shunt capacitor and distributed generation simultaneously, on the distribution network, after adding a shunt capacitor and distributed generation to the system. Here, the system is being injected with both active and reactive power produced by DG and SC (MVar and MW). The voltage deviation and voltage stability index for the entire system will be computed in each case. To determine the percentage of the goal function's reduction rate (voltage deviation), the results of the objective functions will be compared with the initial case study. The IEEE 69-bus radial distribution system, as a standard system, is exploited to demonstrate the efficiency and superiority of the proposed HHO algorithm. The convergence characteristics of the proposed algorithm, HHO, are good, requiring fewer iterations to reach optimal solutions compared to other optimization techniques reported in the literature.

The format of this paper will be as follows: The problem formulation, which comprises the objective function and the constraints, is covered in Section 2. The suggested methodology and the techniques for determining the ideal placement and size are summarized in Section 3. The simulation findings and discussion for figuring out the best position and size of the IEEE 69-bus system to lower actual power losses are presented in Section 4. Ultimately, Section 5 presents the conclusions.

2. Problem Formulation

2.1. Objective Function

The issue of allocating both shunt capacitors (SCs) and distributed generators (DGs) effectively within the distribution networks, along with determining their appropriate sizes, holds significant importance. Improper allocation can lead to elevated voltage profiles and a voltage stability index, ultimately diminishing energy efficiency. The main objective is to raise the voltage stability index and improve the voltage profiles on the radial distribution network.

According to (1), voltage deviation (VD) is commonly defined as the total of each node's voltage magnitude deviations from the target value. At the substation, the desired voltage value is set to 1.0 per unit (pu). The mathematical representation of the objective function is written in (1).

$$OF = \sum_{i=1}^{N_{P-Q}} |V_i - 1| \quad p.u. \quad (1)$$

V_i denotes the voltage magnitude at the i th bus. This objective is pursued while adhering to the equality and inequality constraints delineated in (2) - (4) and (7) - (10). As illustrated in Fig. 1, it can examine a branch in a radial distribution network connected by nodes p and q . The equations denoted (2) to (4) describe the real and reactive power flow through the branch and the voltage at the terminating node (q), neglecting

shunt conductance and susceptance [32]. For the power distribution system to operate safely and dependably, the distribution of distributed generation and shunt capacitors necessitates that the voltage levels at different buses stay within the proper bounds.

$$P_{pq} = P_q^F + P_q^L - P_q^{DG} + \frac{R_{pq}}{V_p^2} (P_{pq}^2 + Q_{pq}^2) \quad (2)$$

$$Q_{pq} = Q_q^F + Q_q^L - Q_q^{DG} - Q_q^C + \frac{X_{pq}}{V_p^2} (P_{pq}^2 + Q_{pq}^2) \quad (3)$$

$$V_q^2 = V_p^2 - 2(P_{pq}R_{pq} + Q_{pq}X_{pq}) + \frac{R_{pq}^2 + X_{pq}^2}{V_p^2} (P_{pq}^2 + Q_{pq}^2) \quad (4)$$

Where $P_q^F = \sum_{\forall j/i=q} P_{ij}$ and $Q_q^F = \sum_{\forall j/i=q} Q_{ij}$

Where $P_{pq}(Q_{pq})$ represent Active (or reactive) power flows from the sending end, $R_{pq}(X_{pq})$ denote the series resistance (or reactance). $P_q^{DG}(Q_q^{DG})$ are the active\ reactive power contributions from Distributed Generation (DG). Q_q^C represents the capacitive injection of reactive power. $P_q^L(Q_q^L)$ denotes the active (reactive) load demand at bus q . $P_q^F(Q_q^F)$ represents the total active (reactive) power flows via all downstream branches connected to bus q . V_q denotes the voltage magnitude at bus q . The current flow via a branch that connects nodes p and q is given in (5). It is essential to acknowledge that the distribution network functions within various physical and operational restrictions that change over time. The power flow in radial feeders is significantly influenced by the positioning of specific sources and compensators. A minor alteration in reactive power injection at a particular node can substantially affect voltage levels both upstream and downstream. Consequently, the mathematical framework must encapsulate these connections to guarantee that the optimization process assesses plausible alternatives aligned with actual network activity.

$$I_{pq} = \sqrt{\frac{P_{pq}^2 + Q_{pq}^2}{V_p^2}} \quad (5)$$

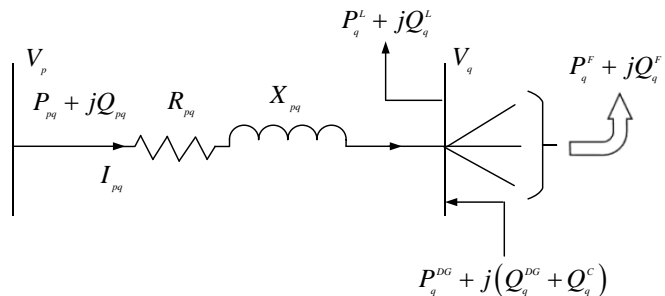


Figure 1. The equivalent circuit of the Radial Distribution Network (RDN).

2.2. Constraints

The restrictions in the power structure that need to be met are those related to equality and inequality. By attaining the balance between reactive and actual power, the equality constraints serve as a representation of the system's physical architecture. The following constraints are considered.

- 1- Equality constraints: refer to conditions where two expressions are set to be equal to each other. In this work, three constraints can be found:
 - Power balance: The active and reactive power flow in each branch of the system must comply with (2) and (3), respectively, according to the equality constraint for power balancing.
 - Voltage equation: Every branch in the system must have voltage magnitudes at the transmitting and receiving end nodes that follow (4) in order to comply with the voltage equation equality restriction.
 - The distributed generation (DG) power factor equality constraint connected at the bus (q) needs to meet (6):

$$\cos\varphi_{pq} = \frac{P_p^{DG}}{\sqrt{(P_q^{DG})^2 + (Q_q^{DG})^2}} \quad (6)$$

- 2- Inequality constraints: set constraints or bounds on specific variables or expressions in a mathematical problem. The variables are usually required to meet certain regions or conditions that they define. The inequality limitations are as follows:
 - Bus voltage: The voltage at each bus must be within the predefined limits, according to the inequality constraint.

$$V_q^{min} \leq V_q \leq V_q^{max} \quad (7)$$

- Line current: The inequality restriction states that each branch's current flow cannot exceed its thermal limit.

$$I_{pq} \leq I_{pq}^{max} \quad \forall p \text{ and } q \in S_B \quad (8)$$

- DG capacity: The distributed generation (DG) capacity cannot exceed a predetermined percentage of the network's total feeder load, according to the inequality constraint.

$$\sum_{q \in S_B} \sqrt{(P_q^{DG})^2 + (Q_q^{DG})^2} = \sum_{q \in S_B} \sqrt{(P_q^L)^2 + (Q_q^L)^2} \quad (9)$$

- Capacitor capacity: The capacitor's capacity cannot be more than the network's overall reactive power load due to the inequality constraint.

$$\sum_{q \in S_B} Q_q^C = \sum_{q \in S_B} Q_q^L \quad (10)$$

V_q^{min} and V_q^{max} represent the minimum and maximum voltage values at bus q , respectively, defined within the range 0.95 to 1.05. I_{pq}^{rated} denotes the thermal threshold between nodes p and q . $\cos\varphi_q$ denotes the power factor of the distributed generation (DG) at the q -th bus.

3. Proposed Methodology

There are two different techniques used: one is to figure out the ideal size for a shunt capacitor and distributed generation (DG), and another is to figure out where to put shunt capacitors and the source of the distributed generators. The algorithm used to calculate the ideal size of sources (SC and DG) is the suggested HHO algorithm. The reconfiguration method (RM), which the authors of this work proposed, is used to determine the ideal placement. This paper's primary objective is to determine each bus's ideal objective function, or voltage deviation. By varying the sources (SC and DG) at each bus and calculating voltage deviation using the suggested algorithm HHO after each position (source location), the RM approach finds the best objective function. The voltage deviation values are sorted in increasing order. A candidate bus is one that has the lowest objective function value.

3.1. Harries Hawks Optimizer (HHO)

Heidari et al. [14] have proposed HHO optimization algorithm. The stages that have been demonstrated include exploration and exploitation. The HHO algorithm can be explained as follows:

2.4.1. Exploration phase

The following can be used to characterize the exploring phase:

$$Y(t+1) = \begin{cases} Y_{rad}(t) - r_1 |Y_{rnd}(t) - 2r_2 Y(t)| & k \geq 0.5 \\ Y_{rab}(t) - Y_m(t) - r_3 (LB + r_2 (UB - LB)) & k < 0.5 \end{cases} \quad (11)$$

$$Y_m(t) = \frac{1}{N_h} \sum_{i=1}^{N_h} Y_i(t) \quad (12)$$

Where Y , Y_{rnd} , Y_{rab} , and Y_m represent the hawks' random, rabbit, and average position vectors, respectively. The symbols UB and LB stand for the variables' upper and lower boundaries. There are N hawks in the world.

2.4.2. Transformation from exploration to exploitation

The following is the formula expression for this process:

$$E = 2E_0 \left(1 - \frac{t}{\max(T)}\right) \quad (13)$$

E_0 and E are the initial state and escaping energy of the prey, T is the number of iterations.

2.4.3. Exploitation phase

Four distinct scenarios have been implemented, predicated on the likelihood of prey evasion and energy loss. There are two categories of assault: mild and harsh sieges. The stringent siege condition is applied if ($r < 0.5$) then ($|\varepsilon| < 0.5$). The soft besiege transpires when ($r \geq 0.5$) when ($|\varepsilon| \geq 0.5$). The phases of exploitation are as follows:

- 1- Soft besiege

The process of the soft besiege is expressed as follows:

$$Y(t+1) = \Delta Y(t) - e |Y_{rab}(t) - Y(t)| \quad (14)$$

$$\Delta Y(t) = Y_{rab}(t) - Y(t) \quad (15)$$

$$J = 2(1 - r_5) \tag{16}$$

J represents the jumping power of a rabbit when running away.

2- Hard besiege

The position vector of the prey is modified according to:

$$Y(t + 1) = Y_{rab}(t) - E|\Delta Y(t)| \tag{17}$$

3- Soft besiege with progressive, rapid dives

The hawk executes a gradual siege in preparation for increasingly swift dives. This circumstance will arise when $r < 0.5$ and $|e| \geq 0.5$. This situation's formula can be expressed as:

$$Y(t + 1) = Y_{rab}(t) - E|Y_{rab}(t) - Y(t)| \tag{18}$$

Diving hawks are characterized by the LF function:

$$Z = X + S \times LF(d) \tag{19}$$

The problem has a dimension d , and the random vector S is of size $1 \times d$. The equation for the Levy flight function (LF) is as stated below:

$$LF(x) = 0.01 \times \frac{\omega \times \beta}{|v|^{\frac{1}{\sigma}}}, \beta \tag{20}$$

$$= \left(\frac{\Gamma(1 + \beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1 + \beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right)$$

The Hawks' position is updated according to (21).

$$Y(t + 1) = \begin{cases} XifF(X) < F(Y(t)) \\ ZifF(Z) < F(Y(t)) \end{cases} \tag{21}$$

4- Hard besiege with progressive, rapid dives:

When both r and $|e|$ are less than 0.5, the hard besiege with rapid dive condition arises. This phase's calculation is done as depicted below:

$$X = Y_{rab}(t) - E|Y_{rab}(t) - Y_m(t)| \tag{22}$$

$$Z = X + S \times LF(d) \tag{23}$$

$$Y(t + 1) = \begin{cases} XifF(X) < F(Y(t)) \\ ZifF(Z) < F(Y(t)) \end{cases} \tag{24}$$

3.2 Phases of Harries Hawks Optimization

Harries Hawks Optimization (HHO) is the suggested algorithm that has been applied to address optimal power flow (OPF) problems. The HHO flowchart can be found in Fig. 2. One way to sum up HHO's primary procedure is as follows:

- Step 1:** Establish the system data's initial parameters.
- Step 2:** Identify the starting settings. Data from the HHO of the system is initialized in a random population matrix.
- Step 3:** Assess the weight factor (OF) for every vector in the population.
- Step 4:** Refresh the rabbit's initial energy (E0).
- Step 5:** Utilizing (13), check the energy volume of the rabbit.
- Step 6:** Adjust the HHO agent's position and recalculate steps 3 and 4.
- Step 7:** Verify the requirements (number of iterations); if met, proceed to step 7. If not, go back to step (3).
- Step 8:** Determine the best and optimal control variables.

The flowchart in Fig. 2 shows the HHO process.

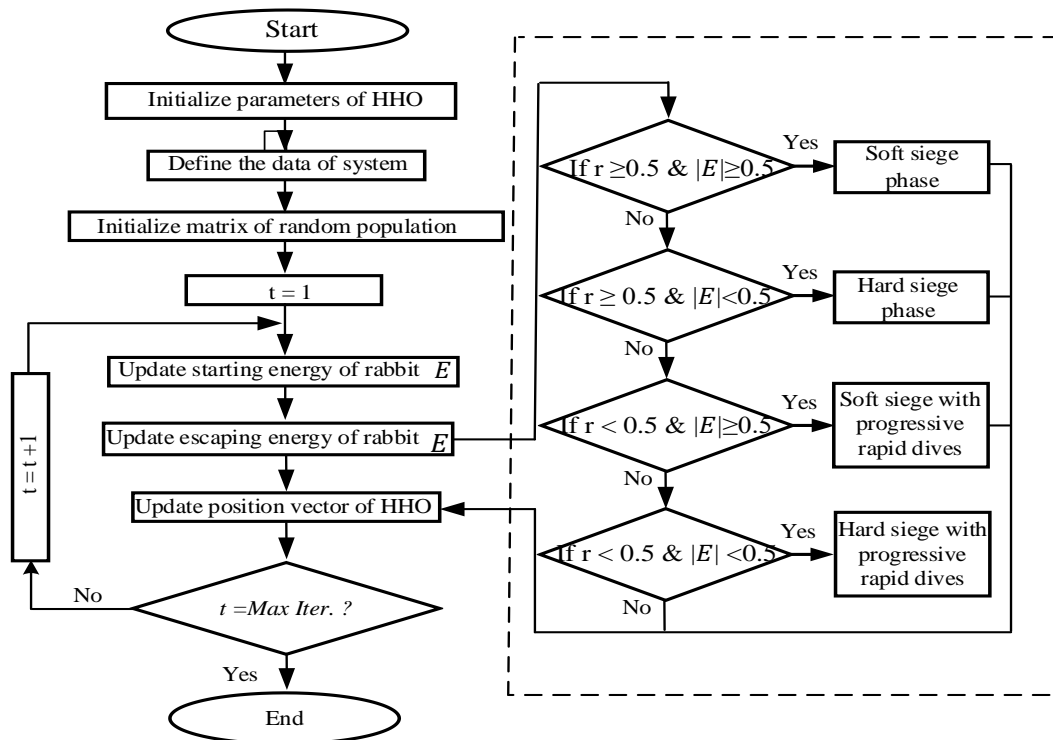


Figure 2. Flow chart of HHO.

4. Simulation and Results

The IEEE 69 bus system was selected as the test system to evaluate the efficacy of the proposed HHO algorithm. Fig. 3 illustrates the single-line schematic of the IEEE 69 bus system model. The voltage bus of this system is 12.6 kV, characterized by 68 lines and 69 buses. The active and reactive loads are 3800 kW and 2690 kVAr, respectively. The best place for the SC and DG units is chosen using the reconfiguration strategy. The appropriate size is ascertained using the HHO algorithm. The IEEE 69-bus system's ideal size and placement are shown in Table 1. The suggested HHO algorithm was run using MATLAB to obtain the best location and size for SC and DG sources.

Load flow calculations for voltage magnitude, phase angle, active power output at idle bus, real, and reactive power losses, and line flow are conducted utilizing the Newton-Raphson (NR) method. The MATLAB software ends the iteration after 50 iterations. There are 100 objects in the population. This paper examines a particular form of distributed generation (DG) model, known as a controlled synchronous generator, which provides both reactive and real power at a predetermined power factor, as outlined in (6). Distributed generation (DG) solely provides active power and runs at a power factor of one in the simulation studies. Whereas the SC provides reactive power, the DG provides active power. Shunt capacitor (SC) and distributed generation (DG) single sources are assigned in this investigation. Any value inside the specified appropriate range of minimum and maximum values can be assigned to it. Zero MW and zero MVar, respectively, are the minimum limitations of SC and DG, whereas the formulae in (9) - (10) are used to find the maximum limits. Fig. 4 represents the flowchart of the proposed approach. To show the effectiveness of the suggested HHO strategy, the following three case studies are considered, as well as the initial case study.

- 1- Case 1: single shunt capacitor (SC) unit.
- 2- Case 2: single distributed generation (DG) unit.
- 3- Case 3: Both a single shunt capacitor (SC) and a distributed generation (DG) unit, simultaneously.

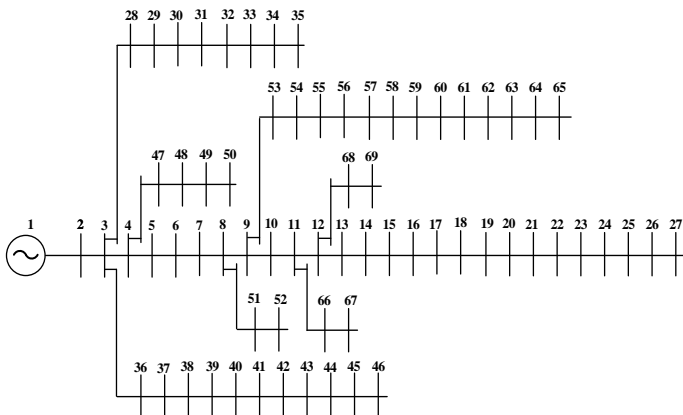


Figure 3. IEEE 69-bus power system single-line diagram

1- Case 1: Single shunt capacitor (SC) source

The first case of this work was conducted to determine the minimization of voltage deviation on the IEEE 69-bus radial distribution system by obtaining the best location and optimal sizing of the shunt capacitor (SC) source. Based on the reconfiguration approach, bus number 21 represents the best bus. Fig. 5 represents the voltage deviation at all buses using the reconfiguration method (RM) to select the optimal location using Harries Hawks Optimization (HHO) to determine the optimal sizing of SC. The results of optimal voltage deviation, minimum magnitude voltage, and minimum voltage stability index of this case are reported in Table 1.

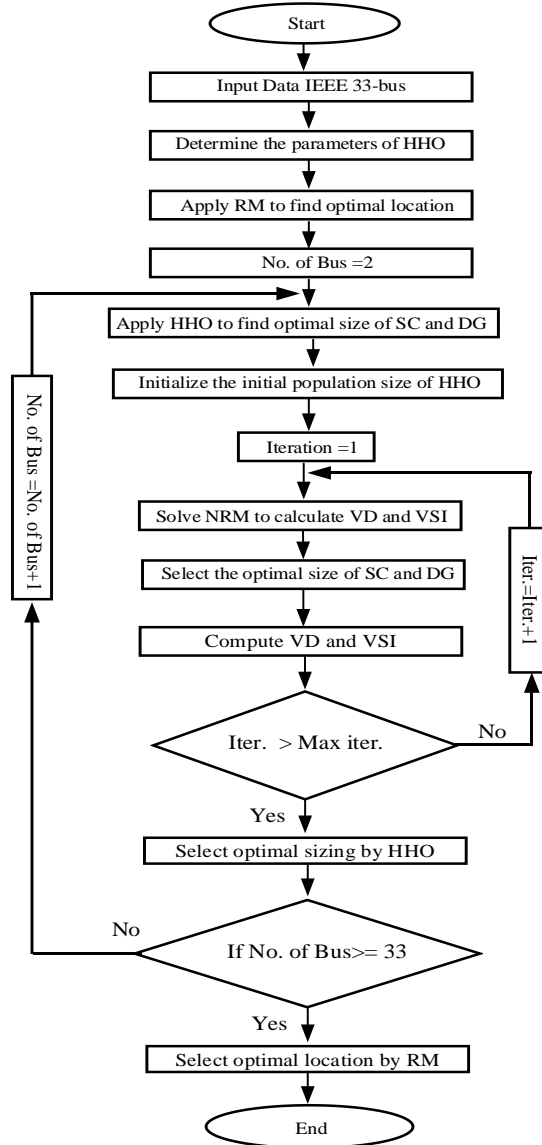


Figure 4. The flowchart of the proposed approach.

The optimal size of the shunt capacitor (SC) source is 2.6935 [MVar]. The voltage deviation has been reduced from 1.834 [pu] in the first instance to 1.1195 [pu] in the best possible situation. The optimal voltage deviation rate has been reduced to 38.95%. The minimal voltage has been raised from 0.9093 [pu] (Bus number is 65) at the initial case to 0.9167 [pu] in the optimal case (after adding a shunt capacitor (SC) to this

system). The minimum value of VSI has been increased from 0.6852 (bus number is 65) at the initial case to 0.7071 at the best case (after addition of the SC).

2- Case 2: Single distributed generated (DG) source

The second case of this study is undertaken to determine the minimization of voltage decline on the IEEE 69-bus system by obtaining the ideal position and best sizing of the distributed generating (DG) source. Based on the reconfiguration approach, bus number 57 represents the best bus. Fig. 6 represents the voltage deviation at all buses using the reconfiguration method (RM) to choose the best location and determine the optimal sizing of DG using Harries Hawks Optimizer (HHO). The optimal results of voltage deviation, minimum magnitude voltage, and minimum voltage stability index of this case are reported in Table 1.

The optimal size of the distributed generation (DG) source is 3.7788 [MW]. The voltage deviation has been lowered from 1.834 [pu] at the initial case to 0.4560 [pu]. That is, the percentage of reduction rate of optimal voltage deviation has been lowered by 75.13%. The minimal voltage has been raised from 0.9093 [pu] (Bus number is 65) at the initial case to 0.995 [pu] in the optimal case (after adding distributed generation (DG) to this system). The minimum value of VSI has been increased from 0.6852 (bus number is 65) to 0.981 at the optimal case (after addition of DG).

3- Case 3: Both single capacitor shunt (SC) and distributed generation (DG) sources

The third case is performed to determine the minimization of voltage deviation on the IEEE 69-bus by determining the best location and optimal sizing of shunt capacitor (SC) and distributed generation (DG) sources, simultaneously. Based on RM, bus number 21 represents the optimal bus to connect the SC, and bus number 57 represents the optimal bus to connect the DG. Fig. 7 demonstrates voltage deviation convergence for this case. The optimal results of voltage deviation, minimum magnitude voltage, and minimum voltage stability index of this case are reported in Table 1. The optimal size of SC and DG sources is 2.9146 [MW] and 1.7825 [MVar], respectively. The voltage deviation has been reduced from 1.834 [pu] in the initial case to 0.1792 [pu] in the optimal case. The percentage of reduction rate of optimal voltage deviation is reduced to 90.23%. The minimum voltage has been increased from 0.9093 [pu] (Bus number is 65) in the initial case to 0.9818 [pu] in the optimal case (after adding SC and DG, simultaneously). The minimum value of VSI has been increased from 0.6852 (bus number is 65) to 0.9303 at the optimal case (after addition of SC and DG, simultaneously). The efficiency of the IEEE 69 bus power system depends on the type of source (DG or SC) and the number of sources. Therefore, the reduction rate is 38.95% when the source is SC. While the reduction rates of single DG and single DG and SC, simultaneously, are 75.13% and 90.23%, respectively.

Fig. 8 illustrates the voltage profiles for four cases (three cases and the initial case). The voltage stability index for three cases, in addition to the initial case, is illustrated in Fig. 9. Fig. 10 presents the comparison results of voltage deviation between the initial case and three cases (single SC, single DG, and single

SC and DG, simultaneously). According to the previous cases, it can be observed that the results obtained from the last case (SC and DG, simultaneously) represent the best results compared to the other three cases.

The voltage deviation has decreased from 1.834 [pu] at the initial case to 1.1195 [pu], 0.4560 [pu], and 0.1792 [pu] for the three cases, respectively, as illustrated in Table 1. The percentage of reduction rate has been decreased to 38.95%, 75.13%, and 90.23%, at the optimal case for the three cases. Table 2 represents the comparison of the minimum voltage achieved by the proposed algorithm against previous optimization methods. The simultaneous installation of SC and DG units demonstrates a distinct synergistic impact on the distribution system. The SC enhances local voltage levels via reactive assistance, while the DG lowers current flow and upstream losses. This coordination results in a more consistent voltage profile throughout the feeder, illustrating why Case 3 demonstrates superior performance compared to utilizing either source independently.

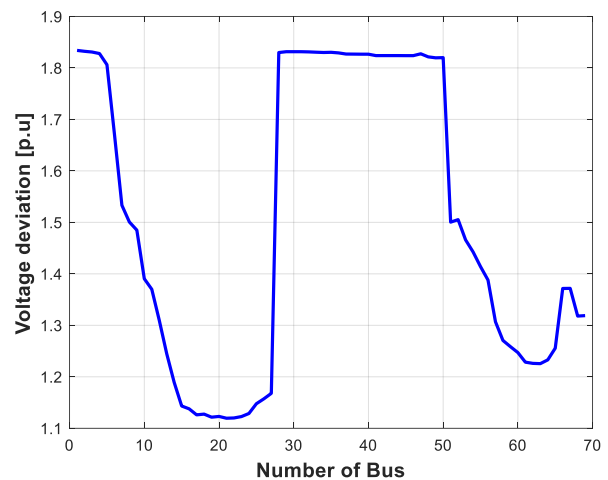


Figure 5. The voltage deviation [pu] after installing the SC at each bus on the IEEE-69 bus system.

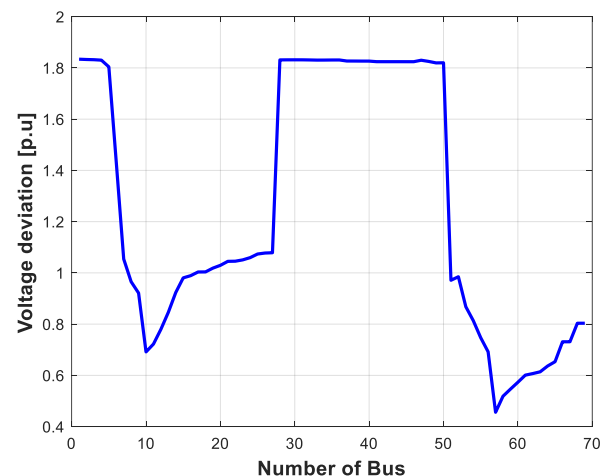


Figure 6. The voltage deviation [pu] after installing the DG at each bus on the IEEE-69 bus system.

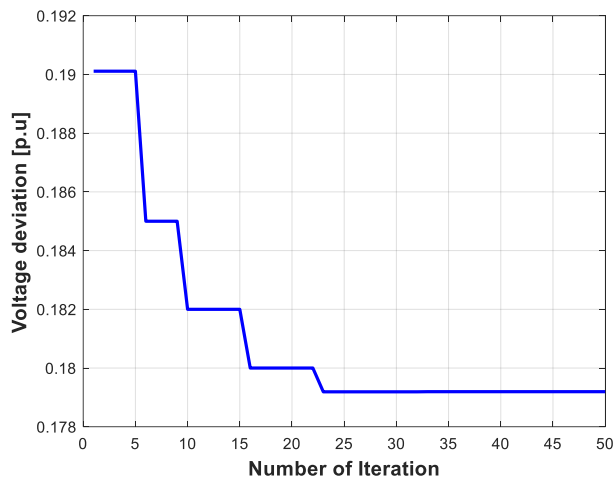


Figure 7. The convergence characteristics of voltage deviation [pu] for case 3 on the IEEE-69 bus system.

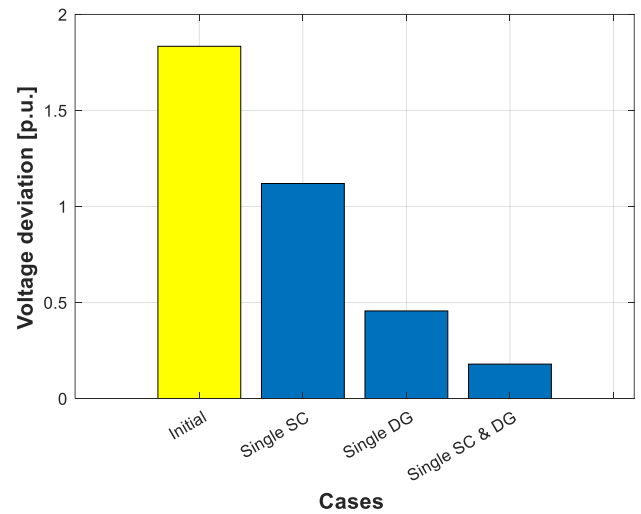


Figure 10. Comparison results of voltage deviation between the initial case and three cases on the IEEE-69 bus system.

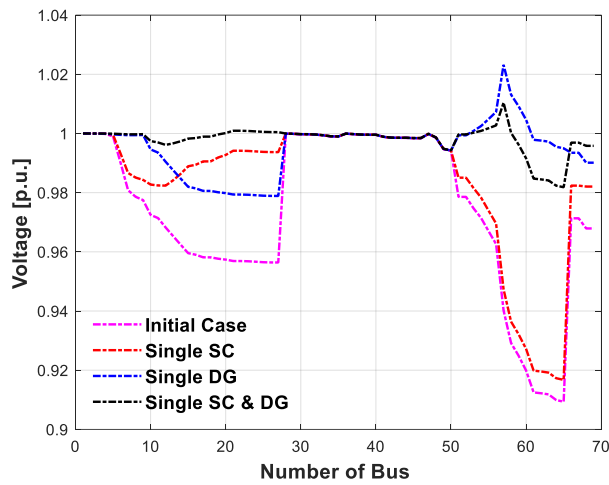


Figure 8. Voltage profile for three cases in addition to the initial case using HHO for the IEEE-69 bus system.

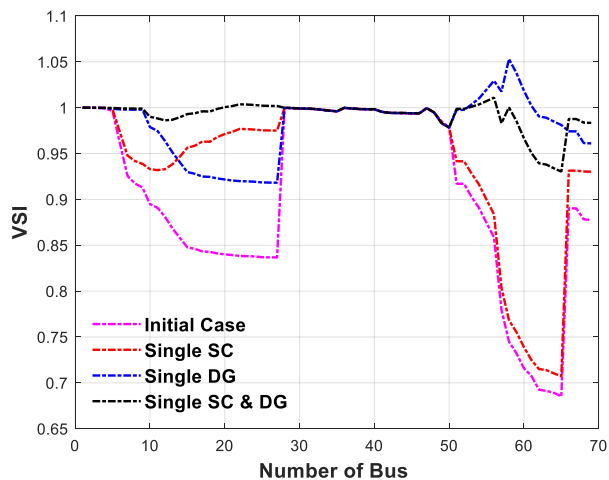


Figure 9. Voltage stability index for three cases in addition to the initial case using HHO for the IEEE-69 bus system.

Table 1. The optimal results of the IEEE 33-bus system obtained by the proposed algorithm HHO.

Items	Initial	After Installation		
		SC	DG	SC and DG
Voltage deviation [p.u]	1.834	1.1195	0.4560	0.1792
Reduced rate of voltage deviation, %	—	38.95	75.13	90.23
Minimum voltage [pu]	0.9093	0.9167	0.995	0.9818
Minimum VSI	0.6852	0.7071	0.981	0.9303
Optimal size of SC [MVA _r]	—	2.6935	—	1.7825
Optimal size of DG [MW]	—	—	3.7788	2.9146

Table 2. Comparison results of the minimum voltage for the proposed method with other methods.

Method	Bus	Type	Min. Voltage
Proposed Method	—	Initial	0.9093
HHO	21	RM & SC	0.9167
	57	RM & DG	0.995
MILP [33]	21, 57	RM & SC & DG	0.9818
	—	Initial	0.9092
CTLHSO [34]	—	RM	0.9427
	11, 61, 65	RM & DG	0.9740
	—	Initial	0.9092
FWA [35]	—	RM	0.9495
	11, 61, 64	RM & DG	0.9813
BPSO [36]	—	Initial	0.9092
	—	RM	0.9495
	61, 62, 65	RM & DG	0.9796
Proposed Method	—	Initial	0.9091
	—	RM	0.9494
	24, 64	RM & DG	0.9777

4. Conclusion

This work introduced a methodology to determine the ideal dimensions and positioning of a single shunt capacitor (SC), a single distributed generation (DG), and their combination inside an IEEE 69-bus radial distribution system. The method employed to determine the best location is the reconfiguration method (RM), whilst the suggested strategy for ascertaining the optimal size is the Harris Hawks optimization (HHO). The primary objective of identifying the ideal placement and capacity of SC and DG sources is to reduce voltage variation. This minimizer will optimize voltage profiles and augment the voltage stability index. In this study, three cases, as well as the initial case, were proposed to calculate the voltage deviation, which are: the initial case, after installing a single shunt capacitor (SC), after installing a single distributed generation (DG), and after installing a single shunt capacitor (SC) and a distributed generation (DG), simultaneously. In a single shunt capacitor (SC), the voltage deviation has not reduced as expected (the reduction rate is 38.95%). On the other side, the voltage deviation was reduced to 75.13 % when the single distributed generation (DG) was installed. The best case can be achieved by installing a single shunt capacitor (SC) and a single distributed generation (DG) simultaneously. The reduced rate for the last scenario (single SC and single DG simultaneously) is 90.23%. The best outcomes produced by the suggested algorithm HHO demonstrated its superiority and efficiency by greatly lowering the voltage deviation, strengthening the voltage profiles, and raising the voltage stability index. The suggested approach's primary benefits are that it is simple to use, requires little computer work, finds workable solutions, and produces optimal or nearly ideal results.

This work could provide a scope for further study to implement the proposed algorithm on a real model, such as the Baghdad Distribution Network (BDN), to solve single and multi-objective functions. This study's findings underscore the broader effects of incorporating intelligent optimization methods into distribution system development, in addition to the results obtained. The suggested HHO–RM hybrid methodology illustrates that the integration of topology-based selection strategies with adaptive metaheuristic algorithms significantly enhances the quality of technical decisions, particularly in extensive and heavily burdened radial networks. The method's robust performance in all evaluated situations suggests its potential relevance to more intricate contexts, such as networks with significant renewable resource integration or systems undergoing dynamic load fluctuations. These discoveries facilitate future study to explore real-time implementation methodologies, multi-objective formulations, and interoperability with forthcoming smart grid technology.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Ali Abdulazeez proposed the conceptualization, methodology, and writing — original draft preparation.

Mazin T. Muhssin was responsible for writing—review and editing

Petr P. Oshchepkov verified the analytical methods, investigated, and supervised the findings of this work

Bahaa Hussein Al IGEB did validation and investigation

All authors discussed the results and contributed to the final manuscript.

Data Availability

The data supporting the reported results are available in the manuscript.

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