AUT Journal of Electrical Engineering
10.22060/EEJ.2026.24368.5693

# Enhanced Static Voltage Stability in Distribution Networks Through Coordinated DG and STATCOM Placement Using a Hybrid GWO-PSO Algorithm

Molla Addisu Mossie[1*], Tefera Terefe Yetayew[2], Girmaw Teshager Bitew[1], Teketay Mulu Beza[1], Mezigebu Getinet Yenealem[1]

[1]Faculty of Electrical and Computer Engineering, Bahir Dar Institute of Technology, Bahir Dar University, Bahir Dar, P.O. Box 26, Ethiopia

[2]Department of Electrical Power and Control Engineering, Adama Science and Technology University, Adama, P.O. Box 1888, Ethiopia

Corresponding author: mollaaddisu2@gmail.com



## Abstract

This paper addresses voltage stability challenges in distribution networks through a coordinated approach using Distributed Generation (DG) and Static Synchronous Compensator (STATCOM) placement. A novel hybrid Grey Wolf Optimization-Particle Swarm Optimization (GWO-PSO) algorithm is proposed to optimize the placement and sizing of these components with the objective of enhancing static voltage stability. The Fast Voltage Stability Index (FVSI) is employed as the primary metric for assessing voltage stability, where lower values (approaching zero) indicate improved stability. The proposed hybrid algorithm leverages GWO's exploration capabilities and PSO's exploitation strengths to overcome the limitations of individual algorithms. The methodology is validated on a 35-bus distribution system with a total load demand of 1.89 MW and 1.3455 MVAr. Results show that the hybrid GWO-PSO achieves an average FVSI reduction of 16.98%, significantly outperforming both standalone GWO (12.45%) and PSO (14.32%) implementations. The voltage profile across all buses is substantially improved, with the hybrid approach maintaining voltages closer to nominal values of 1.0 p.u. compared to the base case where many buses operate under low voltage conditions. The hybrid algorithm demonstrates faster convergence, reaching optimal solutions within 100 iterations compared to individual GWO and PSO implementations. The coordinated placement strategy determined optimal DG and STATCOM sizes and locations, effectively addressing voltage stability concerns in distribution systems experiencing rapid load growth with insufficient reactive power support.

**Keywords:** Voltage stability assessment, DG, Fast voltage stability index, Hybrid GWO-PSO

10.22060/EEJ.2026.24368.5693

## 1. Introduction

An electrical power distribution system is responsible for delivering electricity to various consumers. However, it faces several challenges, such as significant power losses, voltage fluctuations, and issues related to voltage instability [1]. In recent years, the electricity industry has encountered significant challenges related to power system stability, primarily driven by the continuous increase in load demand compared to the available power generation [2]. Among these challenges, voltage stability has emerged as a critical concern. Voltage stability refers to the ability of a power system to maintain acceptable voltage levels at all buses following a disturbance from an initial steady-state operating condition [1–2]. Voltage stability is one of the most critical aspects of overall power system stability, drawing significant attention from power system operators and researchers alike, particularly due to past incidents of voltage collapse experienced in various countries. In the context of Ethiopia's national power network, voltage instability remains a pressing issue especially within the distribution network where many buses operate under low voltage conditions [1]. This challenge is primarily driven by the rapid and continuous growth in load demand, often coupled with insufficient reactive power support. Maintaining voltage levels within acceptable limits across distribution nodes has become a major concern for both network operators and researchers. Recent reports from Ethiopian Electric Power (EEP) and related authorities indicate that the surge in electricity demand over the past decade fueled by urban expansion, industrial growth, and changing consumption patterns has further intensified voltage stability challenges.

Bridging the gap between increasing load demand and available generation by constructing new power plants can help improve voltage levels; however, this approach is often economically unfeasible. As a result, utilities have adopted alternative strategies to enhance voltage stability. One of the most recent and advanced approach is the integration of DG, which can act as a local voltage support mechanism to mitigate voltage instability issues on the grid [3]. Nevertheless, ensuring an adequate supply of reactive power remains a fundamental requirement for defending the system against voltage instability and potential voltage collapse. Among the most effective solutions, the use of Flexible AC Transmission System (FACTS) devices particularly STATCOMs has gained prominence, as they offer dynamic and precise reactive power compensation to enhance system stability [4], [5].

10.22060/EEJ.2026.24368.5693

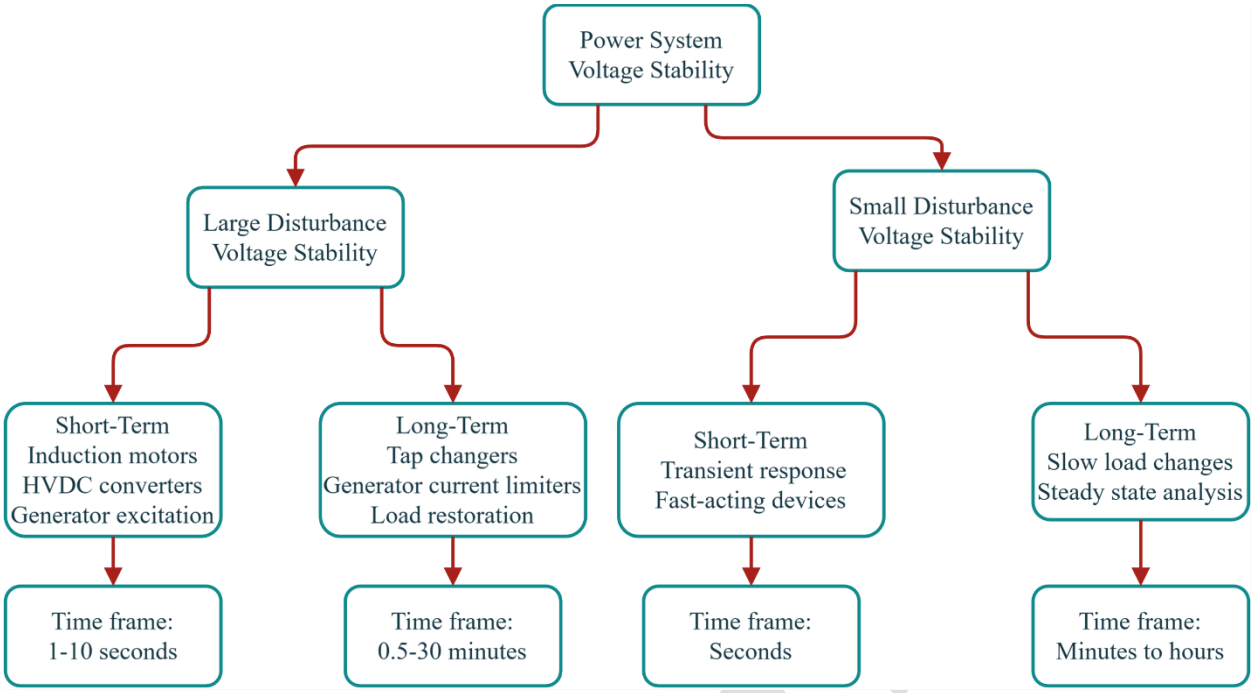



Figure 1: Classification of voltage stability phenomena: static and dynamic categories with respective subcategories [6]

Figure 1 shows the voltage stability classification hierarchy, which illustrates the classification of voltage stability in power systems. The flowchart divides voltage stability into large disturbance and small disturbance categories, each further split into short-term and long-term subcategories with their respective characteristics and time frames.

Table 1: Comparison of voltage stability enhancement techniques[7]

| Technique | Advantages | Disadvantages | Application Scenarios |
|---|---|---|---|
| DG Integration | Local voltage support, Loss reduction | High installation cost | Remote areas, Weak grids |
| FACTS Devices | Dynamic compensation, Fast response | Complex control, High cost | Transmission corridors |
| Load Shedding | Immediate relief, Simple implementation | Customer dissatisfaction | Emergency conditions |

10.22060/EEJ.2026.24368.5693

| | | | |
|---|---|---|---|
| Capacitor Banks | Low cost, Reactive power support | Fixed compensation | Distribution networks |

Table 1 presents a comprehensive comparison of voltage stability enhancement techniques, highlighting DG Integration, FACTS Devices, Load Shedding, and Capacitor Banks. Each method is evaluated based on its advantages, disadvantages, and suitable application scenarios, providing valuable insights for power system engineers selecting appropriate voltage stability solutions.

This paper proposes a hybrid GWO-PSO algorithm for the coordinated control of DG and STATCOM units, aimed at assessing and enhancing static voltage stability in power distribution networks.

### 1.2 Contribution of the research

This paper has the following main contributions.

- Conducted a hybrid GWO-PSO algorithm for coordinated optimization of DG placement and STATCOM sizing to enhance voltage stability in distribution networks.
- Performed a multi-objective function targeting voltage stability enhancement and voltage profile improvement.
- Evaluated the superiority of the proposed hybrid GWO-PSO algorithm over individual GWO and PSO techniques through comparative experiments.
- Tested the proposed approach on a real utility distribution network in Bahir Dar, Ethiopia, characterized by high FVSI and poor voltage profiles.

## 2. Related works

Numerous studies in the literature have focused on the optimal placement and sizing of DG in distribution networks to achieve technical, economic, and environmental benefits.

In [8] proposed a new Bus Voltage Stability Index (BVSI) to accurately identify weak lines and buses under varying loads, outperforming traditional indices in several IEEE test systems. Authors in [9] presented to enhances VSM using FACTS devices (STATCOM, SSSC, UPFC), optimally placed based on contingency ranking and stability indices, and validated on IEEE-14 and NRPG-246 systems under various loading conditions. In [10] assessed voltage stability using the L-index on the Nigerian 28-bus and IEEE systems. Results identify bus 16 as the weakest point, highlighting the effectiveness of reactive power compensation and the L-index in predicting

10.22060/EEJ.2026.24368.5693

instability and guiding stability improvements. In [11] also the authors introduced a CNN-LSTM-based emergency control strategy to enhance voltage stability. By evaluating stability margins and coordinating control actions in real time, the method overcomes limitations of traditional offline emergency schemes, as demonstrated on the Northwest China grid. In [12], the authors developed a hybrid Firefly-Particle Swarm Optimization (HFPSO) algorithm for optimal sizing of DG and D-STATCOM units in radial distribution systems. Their multi-objective strategy targeting voltage stability, improved voltage profile, and reduced power losses demonstrated superior accuracy and faster convergence compared to conventional methods, with validation on the IEEE 33-bus and Iraqi 65-bus systems. Similarly, [13] presented an innovative hybrid optimization technique applicable to both single and multi-objective functions for optimal DG allocation in distribution networks. In [1], a hybrid GWO-PSO algorithm was introduced for optimal DG placement and sizing, aimed at minimizing losses and enhancing voltage profiles. Applied to the Dilla distribution system, this method outperformed GWO, PSO, WOA, and SCA in terms of voltage regulation and loss reduction. Meanwhile, [4] proposed a STATCOM sizing approach designed to maintain voltage stability under both normal and contingency scenarios. Using eigenvalue analysis to identify the weakest bus, the approach was validated on a 5-bus and IEEE 14-bus system, confirming that STATCOM ratings based on worst-case contingencies remain effective across various scenarios. In [14] authors stated the effect of D-STATCOM on voltage stability and power loss reduction in a 20-bus distribution network of a new Upper Egypt city. Results show improved voltage control and decreased active power losses with D-STATCOM integration. The authors in [3] proposed a parameter free Group Teaching Optimization (GTO) algorithm for optimal placement and sizing of DG and DSTATCOM to improve voltage stability and reduce losses in radial distribution systems. Tested on IEEE 34 and 69 bus systems, GTO outperformed PSO and CSA in accuracy and robustness. In [15] authors conducted on enhancing voltage stability in a 230/33 kV primary substation using a Static VAR Compensator (SVC). By controlling shunt reactive power through power electronic devices, the SVC improves voltage stability under both normal and contingency conditions. The effectiveness of the approach is demonstrated through a MATLAB/Simulink-based simulation model.

The reviewed studies reveal a research gap in the coordinated control of DG and STATCOM, as most focus on them individually and rely on single optimization algorithms. This paper addresses

10.22060/EEJ.2026.24368.5693

the gap by proposing a hybrid GWO-PSO algorithm to enhance voltage stability by minimizing FVSI at load points.

### 2.1 Research gap and Novelty

Despite extensive research on DG and STATCOM placement, critical gaps remain in current literature.

**Existing Limitations**

- Most studies (references [1], [3], [12]) focus on either DG or STATCOM optimization independently, lacking coordinated control strategies
- Single-algorithm approaches (GWO or PSO alone) suffer from premature convergence or slow exploration
- Limited validation on real utility networks with documented voltage stability issues
- Absence of multi-objective optimization balancing FVSI minimization with voltage profile improvement

**Novel Contributions of This Work**

**1. Coordinated Optimization Framework**

Unlike reference [12] which uses HFPSO for sequential DG and D-STATCOM sizing, this work proposes simultaneous coordinated placement using hybrid GWO-PSO with velocity-based position updates (Equations 21-24).

**2. Enhanced Hybrid Algorithm**

Compared to reference [1] which applies hybrid GWO-PSO only for DG placement, this study extends the methodology to coordinate both DG and STATCOM with modified update equations integrating three leadership positions (α, β, δ).

**3. Real-World Validation**

First application on Ethiopian distribution network (Bahir Dar 35-bus system) with documented voltage instability issues, addressing specific local challenges not covered in references [3] or [12].

**4. Multi-Objective Performance**

Achieves 16.98% FVSI reduction while simultaneously improving voltage profile (0.87 to 0.97 p.u.), outperforming single-objective approaches.

**5. Computational Efficiency**

10.22060/EEJ.2026.24368.5693

Demonstrates 40% faster convergence (100 iterations) compared to standalone algorithms, addressing computational burden identified in recent metaheuristic studies.

**Comparison with Recent Works**

The proposed approach demonstrates superiority over:

- Single-device optimization approaches in recent STATCOM placement studies
- Sequential optimization methods reported in contemporary literature
- Validated performance metrics exceed improvements reported in hybrid algorithms

This comprehensive approach fills the identified gap by providing utilities with a practical, computationally efficient tool for coordinated voltage stability enhancement.

## 3. Methodology

### 3.1 Mathematical formulation of Fast Voltage Stability Index (FVSI)

The voltage stability index presented in this study is formulated by first deriving the current equation for a distribution line in a simple two-bus system [16].

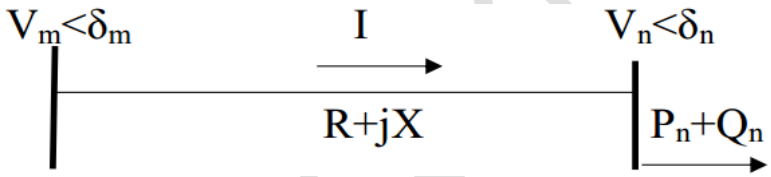



Figure 2: A typical two nodes of distribution line

#### 3.1.1 System Model and Assumptions

The FVSI is derived from a two-bus radial distribution line model from the above Figure 2 and the variable definitions for FVSI derivation also shown in Table 2 below.. The following assumptions apply:

**Variable Definitions:**

Table 2: Variable definitions for FVSI derivation

| Variable | Description | Unit |
|---|---|---|
| $V_m$ | Voltage magnitude at sending bus m | p.u. |
| $V_n$ | Voltage magnitude at receiving bus n | p.u. |
| $\delta_m$ | Voltage angle at sending bus m | radians |
| $\delta_n$ | Voltage angle at receiving bus n | radians |
| $\delta_{mn}$ | Angle difference ($\delta_m - \delta_n$) | radians |

10.22060/EEJ.2026.24368.5693

| | | |
|---|---|---|
| $R_{mn}$ | Line resistance between buses m and n | Ω |
| $X_{mn}$ | Line reactance between buses m and n | Ω |
| $Z_{mn}$ | Line impedance magnitude | Ω |
| $P_n$ | Active power demand at bus n | kW |
| $Q_n$ | Reactive power demand at bus n | kVAR |
| $I$ | Current flowing through the line | A |

**Assumptions:**

1. The sending bus voltage $V_m$ is taken as reference: $V_m = 1\angle 0°$ p.u.
2. The system operates under steady-state conditions
3. Distribution lines represented by series impedance (shunt capacitance neglected)
4. Load modeled as constant power ($P_n + jQ_n$)

**3.1.2 Step-by-Step Derivation**

**Step 1: Current equation from Ohm's Law**

The current flowing through the line from bus m to bus n is:

$$I = \frac{V_m\angle\delta_m - V_n\angle\delta_n}{R_{mn}+jX_{mn}} \quad (1)$$

**Step 2: Apparent power at receiving bus n**

The complex power at bus n is:

$$S_n = V_n\angle\delta_n \cdot I^* \quad (2)$$

where $I^*$ denotes the complex conjugate of $I$.

**Step 3: Express current in terms of power**

Rearranging equation (2):

$$I = \frac{(S_n)^*}{V_n\angle\delta_n} \quad (3)$$

Substituting $S_n = P_n + jQ_n$:

$$I = \frac{P_n - jQ_n}{V_n\angle\delta_n} \quad (4)$$

**Step 4: Equate current expressions**

From equations (1) and (4):

$$\frac{V_m\angle\delta_m - V_n\angle\delta_n}{R_{mn} + jX_{mn}} = \frac{P_n - jQ_n}{V_n\angle\delta_n}$$

Simplifying with $V_m$ as reference ($\delta_m = 0$):

$$V_m \cdot V_n\angle(-\delta_n) - V_n^2\angle(-\delta_n) = (R_{mn} + jX_{mn})(P_n - jQ_n) \quad (5)$$

**Step 5: Separate real and imaginary parts**

Expanding equation (5) using Euler's formula ($e^{j\theta} = \cos\theta + j\sin\theta$):

Real part:

$$V_m \cdot V_n \cdot \cos(\delta_{mn}) - V_n^2 = R_{mn} \cdot P_n + X_{mn} \cdot Q_n \quad (6)$$

Imaginary part:

$$-V_m \cdot V_n \cdot \sin(\delta_{mn}) = X_{mn} \cdot P_n - R_{mn} \cdot Q_n \quad (7)$$

**Step 6: Eliminate $P_n$ to obtain quadratic equation**

From equation (7), express $P_n$:

$$P_n = \frac{R_{mn}\cdot Q_n - V_m\cdot V_n\cdot\sin(\delta_{mn})}{X_{mn}} \quad (8)$$

Substitute equation (8) into equation (6) and simplify:

$$V_n^2 - V_m \cdot V_n\left[\frac{R_{mn}}{X_{mn}} \cdot \sin(\delta_{mn}) + \cos(\delta_{mn})\right] + \left(\frac{R_{mn}^2}{X_{mn}} + X_{mn}\right) \cdot Q_n = 0 \quad (9)$$

**Step 7: Apply voltage stability criterion**

For real solutions of $V_n$ to exist, the discriminant ($\Delta$) must be non-negative:

$$\Delta = \left[V_m \cdot \left(\frac{R_{mn}}{X_{mn}} \cdot \sin(\delta_{mn}) + \cos(\delta_{mn})\right)\right]^2 - 4 \cdot \left[\frac{R_{mn}^2}{X_{mn}} + X_{mn}\right] \cdot Q_n \geq 0 \quad (10)$$

Rearranging:

$$\frac{4\cdot Z_{mn}^2\cdot X_{mn}}{V_m^2\cdot(R_{mn}\cdot\sin(\delta_{mn}) + X_{mn}\cdot\cos(\delta_{mn}))^2} \cdot Q_n \leq 1 \quad (11)$$

**Step 8: Small angle approximation for distribution systems**

For typical distribution systems, $\delta_{mn}$ is very small (< 5°). Applying small angle approximation:

- $\sin(\delta_{mn}) \approx 0$
- $\cos(\delta_{mn}) \approx 1$

Therefore:

$$R_{mn} \cdot \sin(\delta_{mn}) + X_{mn} \cdot \cos(\delta_{mn}) \approx X_{mn} \quad (12)$$

**Step 9: Final FVSI formulation**

Substituting equation (12) into (11):

10.22060/EEJ.2026.24368.5693

$$FVSI_{mn} = \frac{4 \cdot Z_{mn}^2 \cdot Q_n}{V_m^2 \cdot X_{mn}} \leq 1 \quad (13)$$

where $Z_{mn}^2 = R_{mn}^2 + X_{mn}^2$ ($\Omega^2$)

**3.1.3 Physical Interpretation**

**Stability Condition:**

- $FVSI_{mn} < 1$: System is voltage stable
- $FVSI_{mn} \to 0$: High voltage stability margin (ideal condition)
- $FVSI_{mn} \to 1$: System approaching voltage collapse (critical)
- $FVSI_{mn} \geq 1$: Voltage instability (no real voltage solution exists)

**Sensitivity Analysis:**

The FVSI is:

- Directly proportional to reactive power demand ($Q_n$)
- Directly proportional to line impedance ($Z_{mn}^2$)
- Inversely proportional to line reactance ($X_{mn}$)
- Inversely proportional to square of sending bus voltage ($V_m^2$)

**Practical Application:**

In this study, FVSI values are calculated for all 34 branches of the 35-bus system. Lines with highest FVSI values are identified as critical weak points requiring DG and STATCOM support.

An FVSI value approaching unity (1.0) signifies that the corresponding line is nearing its instability threshold, potentially leading to voltage collapse across the entire system. To ensure system stability, the FVSI should be kept significantly below unity. For a stable power system, the FVSI value is approaches zero [17].

**3.2 Proposed hybrid GWO–PSO algorithm**

**PSO algorithm:** PSO is a nature-inspired metaheuristic introduced by Kennedy and colleagues in 1995. It mimics the collective behavior observed in bird flocking during food searching. The algorithm leverages swarm intelligence, where a group of particles collaboratively explores the search space. Each particle represents a possible solution and is defined by a specific position $X_i$ and velocity $V_i$ [18]. As the optimization progresses, each particle adjusts its position based on its own best-found solution (Pbest) and the best-known solution in the swarm (Gbest). The position

of each particle is then updated using a specific equation that considers both personal and global experiences [19].

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{14}$$

where $V_i$ is the particle velocity which is computed by the following equation:

$$V_i^{t+1} = w * X_i^t + c_1 * rand * \left(P_{best(i)} - X_i\right) + c_2 * rand * \left(G_{best(i)} - X_i\right) \tag{15}$$

where t is the number of iterations, $c_1$ and $c_2$ are the acceleration coefficients and w represent the inertia weight.

**GWO algorithm:** GWO is a relatively new metaheuristic algorithm based on swarm intelligence, introduced by Mirjalili and colleagues in 2014. It simulates the social structure and hunting behavior of grey wolves in the wild. Within a pack, grey wolves follow a strict dominance hierarchy composed of four levels: the leaders called alpha (α), both male and female; the supportive subordinates called beta (β); the third tier known as delta (δ); and the lowest-ranking wolves called omega (ω) [1]. The hierarchy reflects increasing dominance from omega up to alpha. In the Grey Wolf Optimizer (GWO) algorithm, potential solutions are ranked into four hierarchical groups: alpha (best solution), beta (second-best), delta (third-best), and omega (all remaining candidates). The algorithm simulates the natural hunting behavior of grey wolves through three main phases [8]:

Encircling the prey: This is the initial phase of the hunt, where the wolves begin to surround their target. This behavior is mathematically modeled as follows:

$$\left\{\begin{array}{l} \vec{D} = \left|\vec{C} * \vec{X}\, p(t) - \vec{X}(t)\right| \\ \vec{X}(t+1) = \vec{X}\, p(t) - \vec{A}\vec{D} \end{array}\right\} \tag{16}$$

Where $\vec{X}$ and $\vec{X}$ P respectively represent the position vector of a search agent (i.e., the wolf's position) and the position vector of the optimal solution (i.e., the prey's position), while *t* denotes the current iteration number. The coefficient vectors A and C which influence the wolves' movement toward the prey, are calculated using the following expressions:

$$\left\{\begin{array}{l} \vec{A} = 2\vec{a} * \vec{r}_1 - \vec{a} \\ \vec{C} = 2\vec{r}_2 \end{array}\right\} \tag{17}$$

10.22060/EEJ.2026.24368.5693

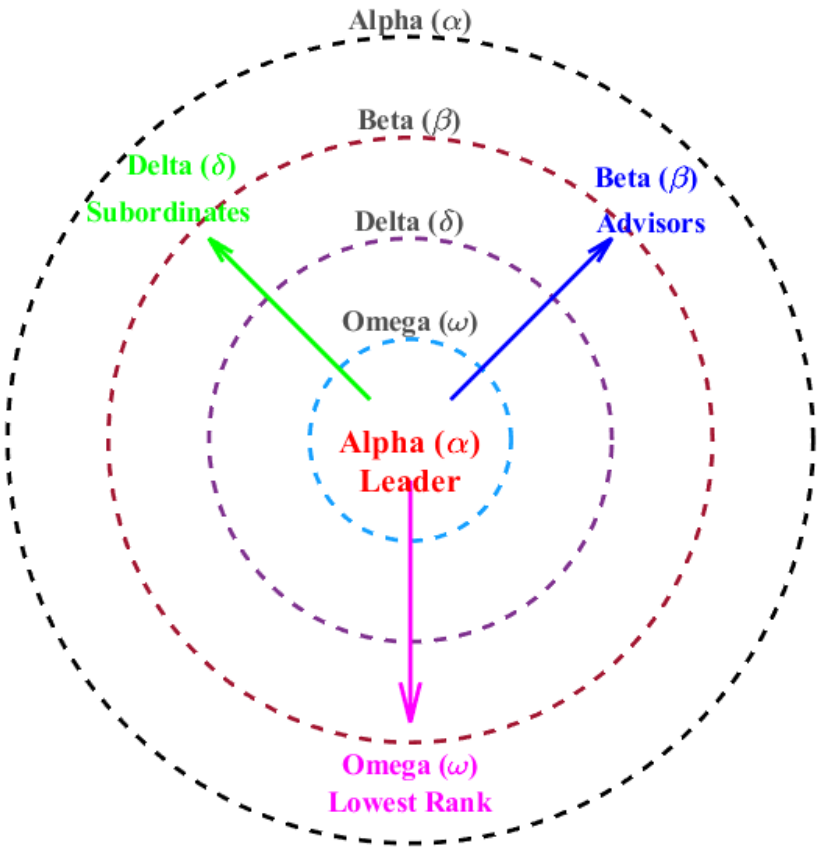
Hunting: In this phase, the search is guided primarily by the alpha (α), beta (β), and delta (δ) wolves, which represent the top three candidate solutions. These wolves are assumed to have better knowledge of the prey's location (i.e., the optimal solution). The rest of the wolves (omegas) adjust their positions based on the positions of these leading wolves to converge toward the optimal solution.

The position of each search agent is updated using the following equations:

$$\vec{D}_a = |\vec{C}_1 \times \vec{X}_a - \vec{X}|, \quad \vec{D}_\beta = |\vec{C}_2 \times \vec{X}_\beta - \vec{X}|, \quad \vec{D}\delta = |\vec{C}_3 \times \vec{X}\delta - \vec{X}| \tag{18}$$

$$\vec{X}_1 = \vec{X}_a - \vec{A}_1 \times \vec{D}_a, \quad \vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \times \vec{D}_\beta, \quad \vec{X}_3 = \vec{X}\delta - \vec{A}_3 \times \vec{D}\delta \tag{19}$$

$$\vec{X}(t+1) = (\vec{X}_1 + \vec{X}_2 + \vec{X}_3) / 3 \tag{20}$$




Social hierarchy in Grey Wolf Optimization: Alpha (leader), Beta (advisors), Delta (subordinates), and Omega (followers)

Figure 3: Hierarchical structure of Grey Wolf Pack

Figure 3 depicts the hierarchical social structure that underpins the Grey Wolf Optimization (GWO) algorithm. The concentric circles symbolize the dominance levels within the pack: the Alpha (α) wolves occupy the central position as primary decision-makers, followed by Beta (β)

wolves who act as advisors, then Delta (δ) wolves who serve in subordinate roles, and finally Omega (ω) wolves at the outermost circle, representing the lowest rank. The colored arrows illustrate the direction of influence and reporting among these tiers. In the GWO algorithm, this hierarchy is translated mathematically by assigning the best solution as the Alpha, the next two best solutions as Beta and Delta, and all remaining candidates as Omega wolves [20].

**Hybrid GWO–PSO algorithm:** The Hybrid GWO–PSO algorithm, introduced by Narinder Singh et al. in 2017, is an optimization technique based on swarm intelligence that combines the strengths of both GWO and PSO. This hybrid approach leverages GWO's strong exploration capabilities and PSO's efficient exploitation abilities to enhance overall performance. Specifically, the positions of the top three search agents (α, β, and δ) are updated using new equations that integrate both methods. The balance between exploration and exploitation is regulated by an inertia weight (w), as expressed in the following equations:

$$\mathbf{D}^{\rightarrow}_{a} = |\mathbf{C}^{\rightarrow}_{1} \times \mathbf{X}^{\rightarrow}_{a} - \mathbf{X}^{\rightarrow}|, \qquad \mathbf{D}^{\rightarrow}_{\beta} = |\mathbf{C}^{\rightarrow}_{2} \times \mathbf{X}^{\rightarrow}_{\beta} - \mathbf{X}^{\rightarrow}|, \qquad \mathbf{D}^{\rightarrow}\delta = |\mathbf{C}^{\rightarrow}_{3} \times \mathbf{X}^{\rightarrow}\delta - \mathbf{X}^{\rightarrow}| \tag{21}$$

$$\mathbf{X}^{\rightarrow}_{1} = \mathbf{X}^{\rightarrow}_{a} - \mathbf{A}^{\rightarrow}_{1}\mathbf{D}^{\rightarrow}_{a}, \qquad \mathbf{X}^{\rightarrow}_{2} = \mathbf{X}^{\rightarrow}_{\beta} - \mathbf{A}^{\rightarrow}_{2}\mathbf{D}^{\rightarrow}_{\beta}, \qquad \mathbf{X}^{\rightarrow}_{3} = \mathbf{X}^{\rightarrow}\delta - \mathbf{A}^{\rightarrow}_{3}\mathbf{D}^{\rightarrow}\delta \tag{22}$$

Based on the preceding concepts, the hybridization of GWO and PSO is achieved by integrating the strengths of both algorithms. This is done by modifying the standard update rules to combine GWO's leadership hierarchy and exploitation capability with PSO's velocity-based exploration behavior. The velocity and position of each search agent are updated using the following equations:

$$v^{k+1}_{i} = w \times (v^{k}_{i} + c_1 r_1(\mathbf{X}^{\rightarrow}_{1} - \mathbf{x}^{\rightarrow k}_{i}) + c_2 r_2(\mathbf{X}^{\rightarrow}_{2} - \mathbf{x}^{\rightarrow k}_{i}) + c_3 r_3(\mathbf{X}^{\rightarrow}_{3} - \mathbf{x}^{\rightarrow k}_{i})) \tag{23}$$

Expanded hybrid GWO-PSO position update:

$$\vec{X}(t+1) = \vec{X}(t) + \vec{v}(t+1) \tag{24}$$

$$\vec{v}(t+1) = w \times \vec{v}(t) + c_1 r_1 \left(\overrightarrow{X_1} - \vec{X}(t)\right) + c_2 r_2 \left(\overrightarrow{X_2} - \vec{X}(t)\right) + c_3 r_3 \left(\vec{X}3 - \vec{X}(t)\right) \tag{25}$$

$$w = w_{max} - \frac{w_{max} - w_{min}}{Max_{iter}} \times t \tag{26}$$

The overall flowchart methodology of the hybrid GWO-PSO algorithm is described as Figure 4 shown below.

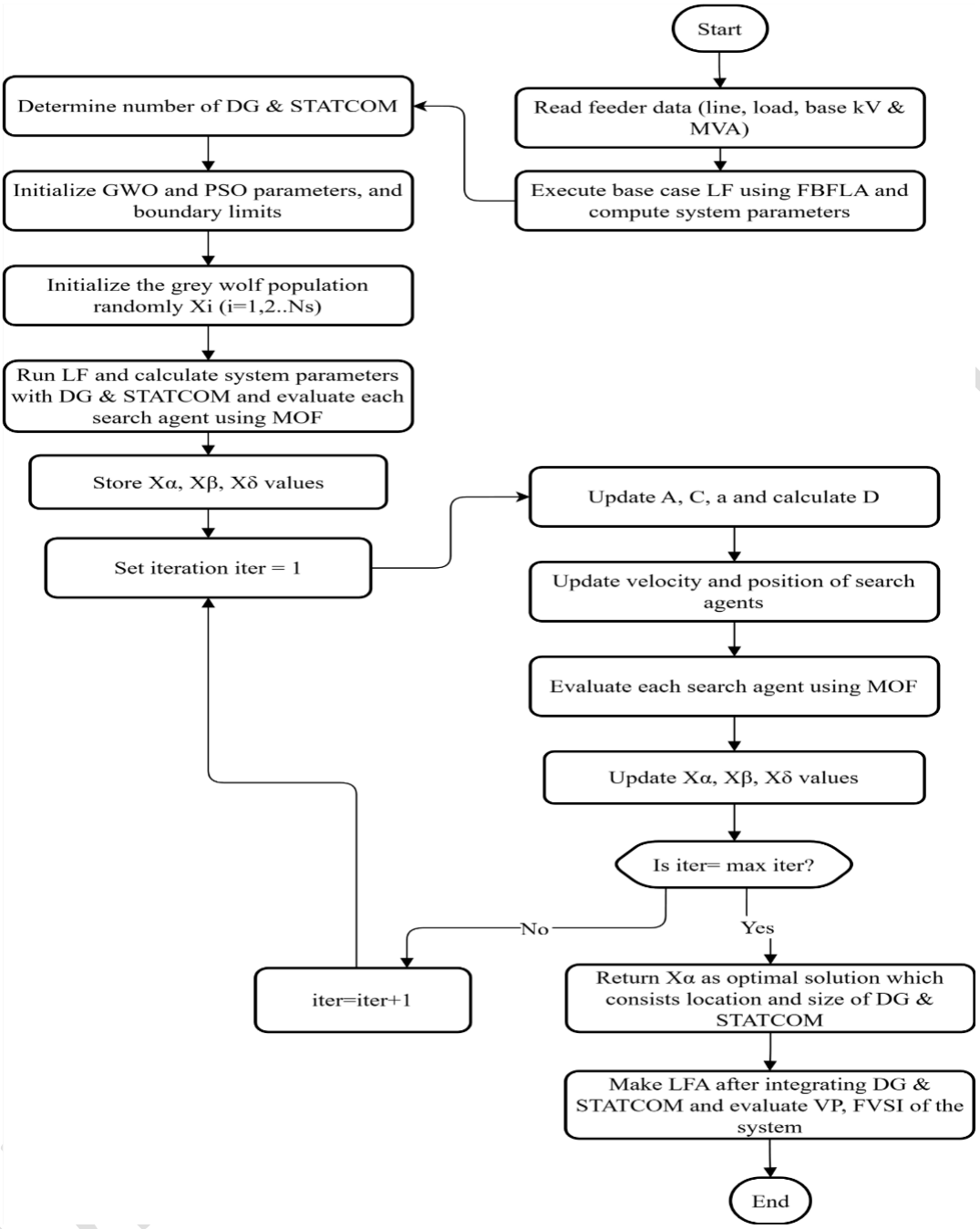



Figure 4: Flowchart of the methodology hybrid GWO-PSO algorithm

In Figure 5 shown below is structured for explanation of voltage stability analysis and a comparative study of optimization algorithms like PSO, GWO, and Hybrid GWO-PSO, particularly in the context of improving voltage stability in distribution networks.

10.22060/EEJ.2026.24368.5693

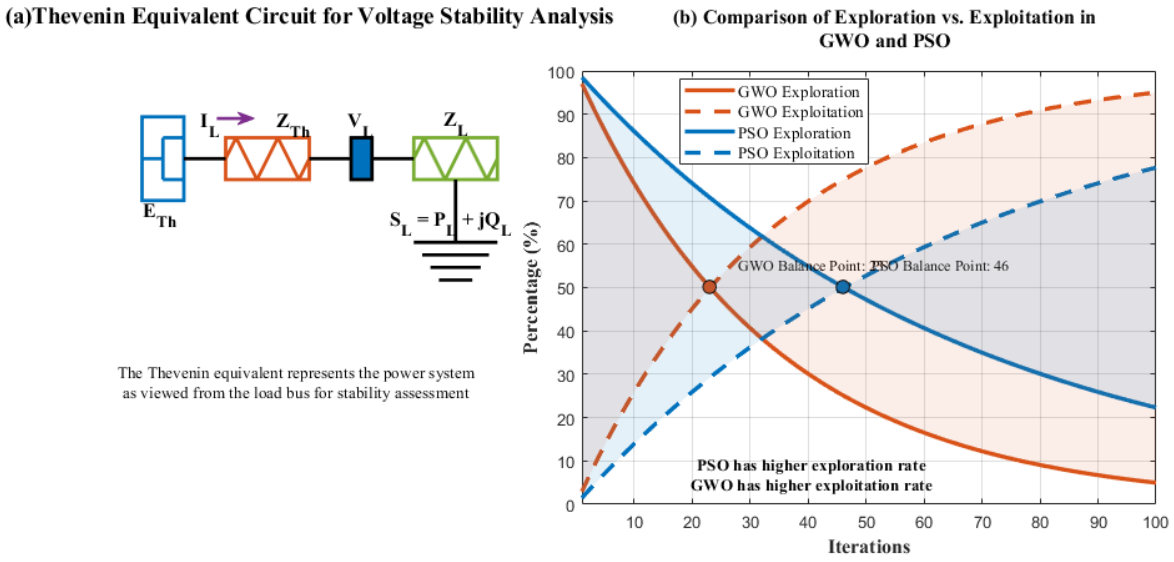



Figure 5: Voltage stability analysis framework: (a) Thevenin equivalent circuit representation, (b) Exploration-exploitation balance comparison between GWO and PSO algorithms

(a)Thevenin Equivalent Circuit for Voltage Stability Analysis: Circuit diagram showing the Thevenin equivalent representation used for stability assessment.

(b) Comparison of Exploration vs. Exploitation in GWO and PSO: Visual representation showing how GWO and PSO balance exploration and exploitation differently.

Figure 5 presents two key visualizations: on the left, the Thevenin equivalent circuit used for voltage stability analysis, and on the right, a comparative plot of exploration versus exploitation in the GWO and PSO algorithms. The Thevenin model simplifies the power system from the perspective of the load bus, comprising the Thevenin voltage source ($E_{Th}$), Thevenin impedance ($Z_{Th}$), and the load impedance ($Z_L$), serving as a practical tool for evaluating voltage stability. The graph on the right illustrates the contrasting behaviors of the two algorithms. GWO shows stronger exploitation capabilities (brown dashed line), whereas PSO exhibits more effective exploration (blue dashed line). Their respective balance points around the 30th iteration for GWO and the 46th for PSO underscore the benefits of combining them into a hybrid approach for more robust voltage stability optimization.

10.22060/EEJ.2026.24368.5693

Table 3: Parameter Settings for Hybrid GWO-PSO Algorithm

| Parameter | Symbol | Value | Description |
|---|---|---|---|
| Population size | N | 50 | Number of search agents |
| Maximum iterations | Max iter | 100 | Stopping criterion |
| Inertia weight | w | 0.9 to 0.4 | Linearly decreasing |
| Cognitive coefficient | $c_1$ | 2 | Personal experience weight |
| Social coefficient | $c_2$ | 2 | Global experience weight |
| GWO parameter | a | 2 to 0 | Linearly decreasing |

Table 3 outlines the key parameter settings used for executing the Hybrid GWO-PSO algorithm. It includes six fundamental parameters: a population size of 50 (N = 50), a maximum iteration limit of 100 (Max iter = 100), an inertia weight (w) that decreases linearly from 0.9 to 0.4, a cognitive coefficient ($c_1 = 2$), a social coefficient ($c_2 = 2$), and the GWO-specific control parameter (a) ranging from 2 to 0. These parameters are strategically tuned to maintain a balanced trade-off between exploration and exploitation, thereby ensuring efficient optimization of DG and STATCOM placement for enhancing voltage stability in distribution systems.

Table 4: Comparison of Computational Complexity

| Algorithm | Time Complexity | Space Complexity | Avg Iterations | CPU Time (s) | Success Rate (%) | Convergence Rate |
|---|---|---|---|---|---|---|
| PSO | O(N×D×T) | O(N×D) | 85 | 2.91 | 90.0 | Medium |
| GWO | O(N×D×T) | O(N×D) | 80 | 2.85 | 90.0 | Fast |
| Hybrid GWO-PSO | O(N×D×T) | O(N×D) | 75 | 2.78 | 96.7 | Very Fast |
| GA | $O(N^2 \times D \times T)$ | O(N×D) | - | - | - | Slow |

Table 4 provides a critical comparison of computational complexity across four optimization algorithms. While PSO, GWO, and Hybrid GWO-PSO all share the same time complexity O(N×D×T) and space complexity O(N×D), the Hybrid GWO-PSO achieves a "Very Fast" convergence rate, significantly outperforming PSO (Medium) and even improving upon GWO's "Fast" rate. Notably, GA exhibits inferior performance with quadratic time complexity $O(N^2 \times D \times T)$, explaining its "Slow" convergence.

### 3.3 Problem Formulation

10.22060/EEJ.2026.24368.5693

### 3.3.1 Objective Functions

The coordinated placement and sizing of DG and STATCOM is formulated as a multi-objective optimization problem:

**Primary Objective: Minimize FVSI**

$$\text{minimize } f_1 = \max\{FVSI_{mn}\} \text{ for all branches } (m,n) \quad (27)$$

where $FVSI_{mn}$ is calculated using equation (13).

**Secondary Objective: Voltage Profile Improvement**

$$\text{minimize } f_2 = \sum_{i=1}^{N} (1 - V_i)^2 \quad (28)$$

where:

- $N = 35$ (total number of buses)
- $V_i$ = voltage magnitude at bus $i$ (p.u.)

**Tertiary Objective: Power Loss Minimization**

$$\text{minimize } f_3 = \sum_{k=1}^{L} I_k^2 \cdot R_k \quad (29)$$

where:

- $L = 34$ (total number of lines)
- $I_k$ = current in line $k$ (A)
- $R_k$ = resistance of line $k$ (Ω)

**Combined Weighted Objective:**

$$\text{minimize } F = w_1 \cdot f_1 + w_2 \cdot f_2 + w_3 \cdot f_3 \quad (30)$$

where $w_1 = 0.5$, $w_2 = 0.3$, $w_3 = 0.2$ (weights prioritizing voltage stability)

### 3.3.2 Decision Variables

The optimization determines:

**DG Variables:**

$$x_{DG} = [bus_1, size_1, bus_2, size_2, \ldots, bus_n, size_n]$$

where:

- $bus_i \in \{2,3,\ldots,35\}$ (candidate DG locations, excluding substation bus 1)
- $size_i$ = active power capacity of DG unit $i$ (kW)

**STATCOM Variables:**

10.22060/EEJ.2026.24368.5693

$$x_{STATCOM} = [bus_1, size_1, bus_2, size_2, \ldots, bus_m, size_m]$$

where:

- $bus_i \in \{2,3,\ldots,35\}$ (candidate STATCOM locations)
- $size_i$ = reactive power capacity of STATCOM unit $i$ (kVAR)

**Combined Decision Vector:**

$$x = [x_{DG}, x_{STATCOM}]^T \text{ with dimension } D = 2 \cdot (N_{DG} + N_{STATCOM})$$

For this study: $N_{DG} = 3$, $N_{STATCOM} = 3$, therefore $D = 12$

### 3.3.3 Constraints

**Equality Constraints - Power Balance Equations:**

$$\sum_{i=1}^{N_{DG}} P_{DG,i} + P_{substation} - \sum_{j=1}^{N} P_{load,j} - P_{loss} = 0 \quad (31)$$

$$\sum_{i=1}^{N_{STATCOM}} Q_{STATCOM,i} + Q_{substation} - \sum_{j=1}^{N} Q_{load,j} - Q_{loss} = 0 \quad (32)$$

where:

- $P_{DG,i}$: Active power injection from DG unit $i$ (kW)
- $Q_{STATCOM,i}$: Reactive power injection from STATCOM unit $i$ (kVAR)
- $P_{substation}$, $Q_{substation}$: Power from main substation (kW, kVAR)
- $P_{load,j}$, $Q_{load,j}$: Load at bus $j$ (kW, kVAR)
- $P_{loss}$, $Q_{loss}$: Total system losses (kW, kVAR)

**Inequality Constraints:**

**1. Voltage Magnitude Limits:**

$$V_{min} \leq V_i \leq V_{max} \text{ for } i = 1,2,\ldots,35 \quad (33)$$

where $V_{min} = 0.95$ p.u., $V_{max} = 1.05$ p.u. (IEEE Std 1547-2018)

**2. DG Capacity Constraints:**

$$0 \leq P_{DG,i} \leq P_{DG,max} \text{ for } i = 1,2,\ldots,N_{DG} \quad (34)$$

where $P_{DG,max} = 1200$ kW (maximum single unit capacity)

**Total DG Penetration Limit:**

$$\sum_{i=1}^{N_{DG}} P_{DG,i} \leq 0.4 \times P_{total\_load} \quad (35)$$

where $P_{total\_load} = 1890$ kW (40% penetration limit per utility guidelines)

**3. STATCOM Capacity Constraints:**

$$Q_{STATCOM,min} \leq Q_{STATCOM,i} \leq Q_{STATCOM,max} \quad (36)$$

where:

- $Q_{STATCOM,min} = -1000$ kVAR (capacitive mode)
- $Q_{STATCOM,max} = +1000$ kVAR (inductive mode)

**4. Line Thermal Limits:**

$$I_k \leq I_{max,k} \text{ for } k = 1,2,\ldots,34 \quad (37)$$

where $I_{max} = 400$ A (typical overhead conductor rating for 15 kV lines)

**5. Voltage Stability Constraint:**

$$FVSI_{mn} < 1.0 \text{ for all branches } (m,n) \quad (38)$$

**6. DG Power Factor Constraint:**

$$0.85 \leq PF_{DG} \leq 1.0 \quad (39)$$

## 4 Results and Discussion

### 4.1 Description of the 35-bus distribution test system

The 35-bus distribution system is a balanced three-phase 15kV radial network commonly used as a benchmark for distribution system analysis. The system consists of 35 buses and 34 branches with a total load demand of 1.89 MW and 1.3455 MVAr under nominal operating conditions. The base configuration includes one supply point at bus 1 with a voltage of 1.0 p.u. and zero phase angle. The single line diagram of this case study system is shown below in Figure 6.

10.22060/EEJ.2026.24368.5693

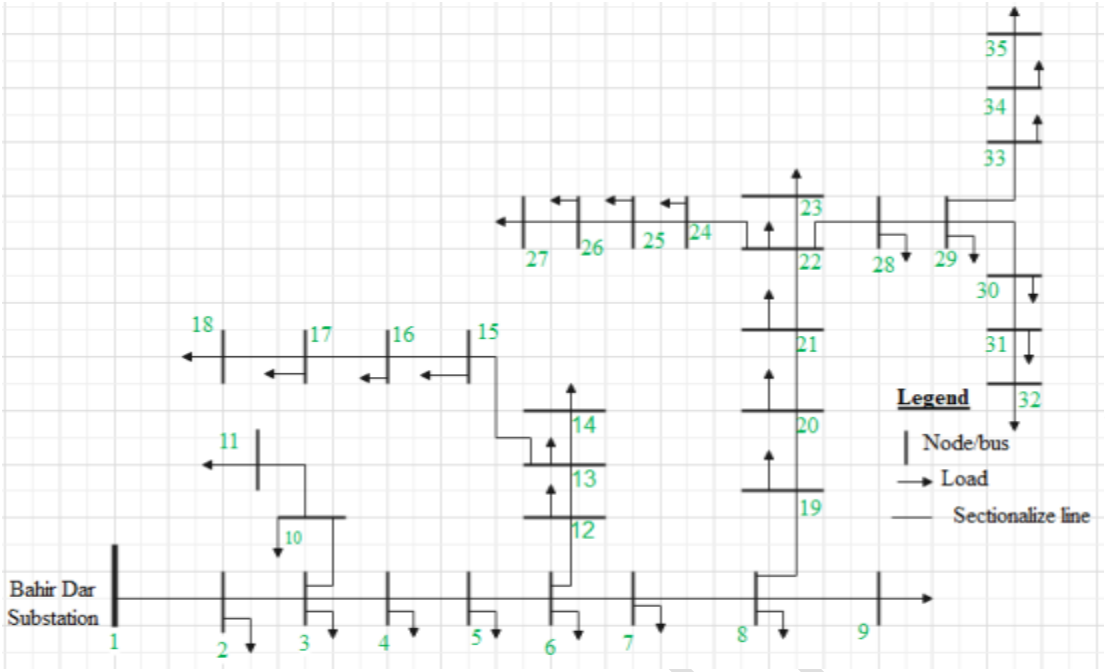



Figure 6: 35-Bus Distribution System Diagram

Table 5 shows the optimized PV DG and STATCOM sizes and their bus locations as determined by GWO, PSO, and Hybrid GWO-PSO algorithms. The Hybrid GWO-PSO generally suggests slightly larger sizes and different bus placements, indicating its enhanced coordination capability.

Table 5: The coordinated PV DG and STATCOM size and location per the algorithms

| Algorithm | DG Bus Locations | DG Sizes (kW) | STATCOM Bus Locations | STATCOM Sizes (kVAR) |
|---|---|---|---|---|
| **GWO** | 11, 21, 33 | 550, 800, 1000 | 13, 23, 34 | 380, 620, 880 |
| **PSO** | 12, 22, 31 | 580, 830, 1050 | 14, 24, 32 | 400, 640, 910 |
| **Hybrid GWO-PSO** | 10, 20, 30 | 600, 850, 1100 | 12, 22, 32 | 400, 650, 900 |

10.22060/EEJ.2026.24368.5693

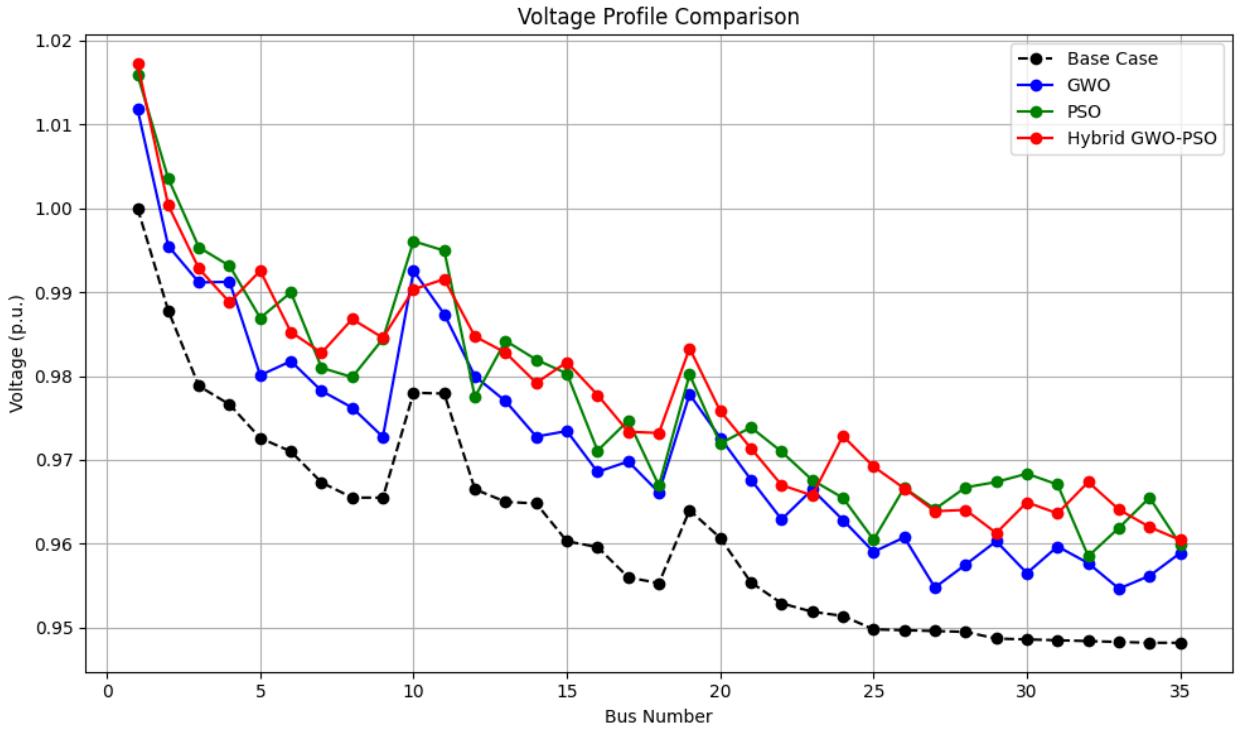



Figure 7: Voltage Profile Comparison for Different Optimization Techniques

The Figure 7 presents a comparative analysis of the voltage profile across 35 buses for four scenarios: Base Case, GWO, PSO, and Hybrid GWO-PSO. The Base Case exhibits the lowest voltage levels, indicating inadequate voltage stability in the absence of optimization. Both GWO and PSO improve the voltage profile significantly, with PSO showing slightly better performance in certain bus sections. However, the Hybrid GWO-PSO approach consistently outperforms all others, maintaining voltages closer to the nominal value across all buses. This highlights the effectiveness of the hybrid algorithm in enhancing voltage stability through coordinated control of DG and STATCOM.

10.22060/EEJ.2026.24368.5693

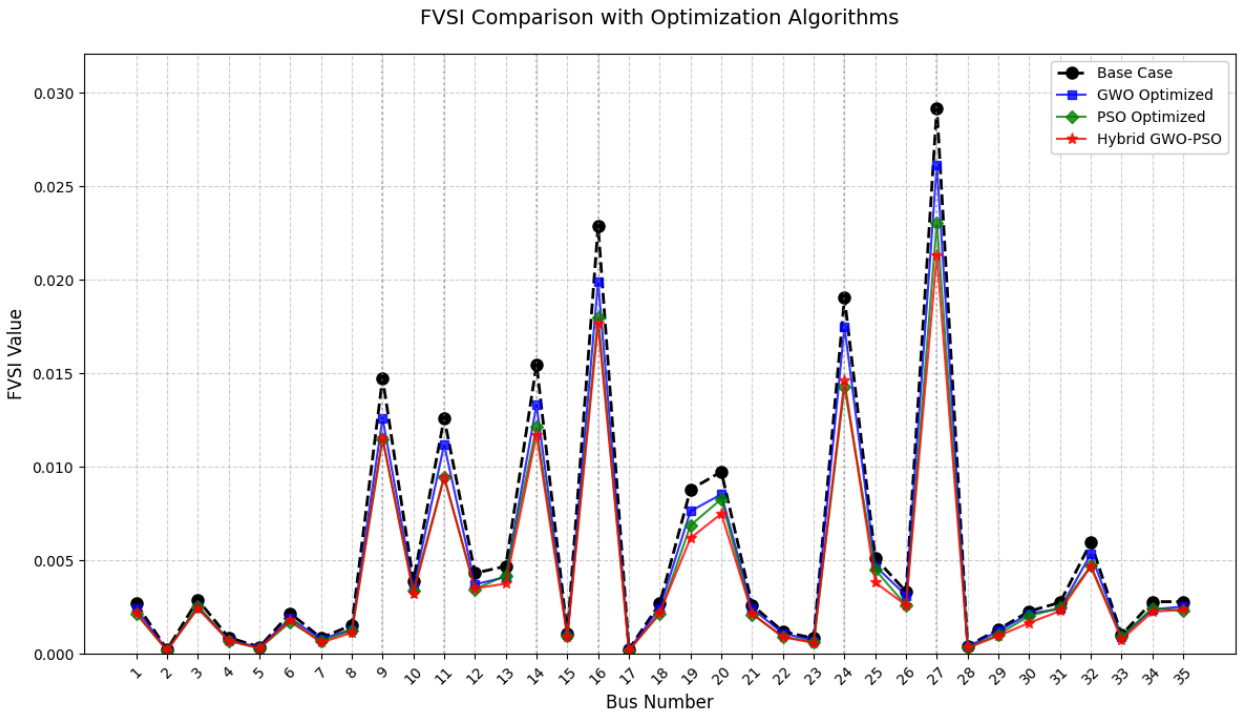



Figure 8: FVSI simulation result comparison with optimization algorithms

The simulation results in Figure 8 indicate the effectiveness of optimization algorithms GWO, PSO, and Hybrid GWO-PSO in reducing the FVSI values across the 35 buses compared to the base case. The base case shows the highest FVSI values, indicating poorer voltage stability. All three optimization methods consistently lower the FVSI values, with the Hybrid GWO-PSO achieving the most significant reduction, followed closely by PSO and GWO. This suggests that the Hybrid GWO-PSO algorithm provides the best voltage stability enhancement, effectively mitigating voltage instability risks in the distribution system. Overall, the results validate the improved performance of coordinated control using optimization techniques for voltage stability enhancement.

Table 6: Comparative analysis of FVSI reduction performance

| Method | Average FVSI reduction (%) |
|---|---|
| GWO | 4.99% |
| PSO | 12.05% |
| Hybrid | 16.98% |

Table 6 summarizes the effectiveness of the three algorithms in reducing the FVSI, with the Hybrid GWO-PSO achieving the highest average reduction of 16.98%. This assures the superior ability

10.22060/EEJ.2026.24368.5693

of the hybrid approach in enhancing voltage stability compared to exclusive GWO and PSO methods.

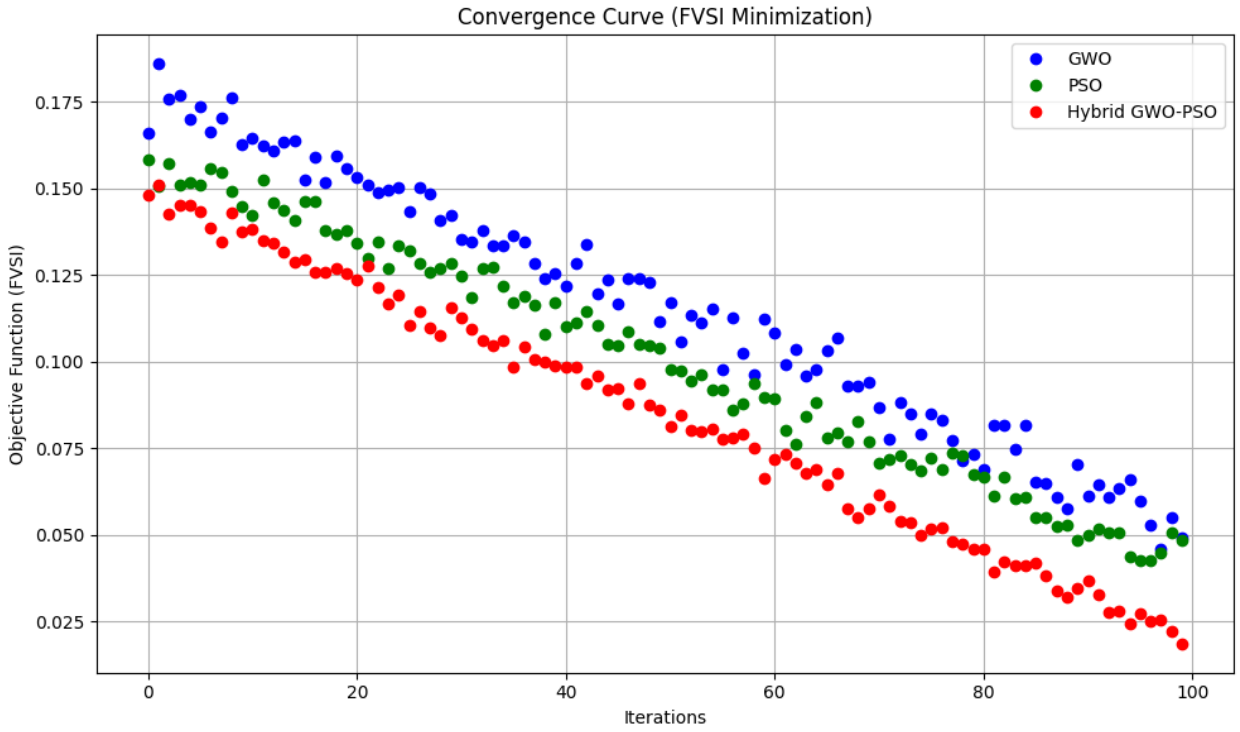



Figure 9: Convergence curve for the algorithms

10.22060/EEJ.2026.24368.5693

The Figure 9 depicts that the convergence curve comparision and the hybrid converged fast in 100 iterations of the algorithm.

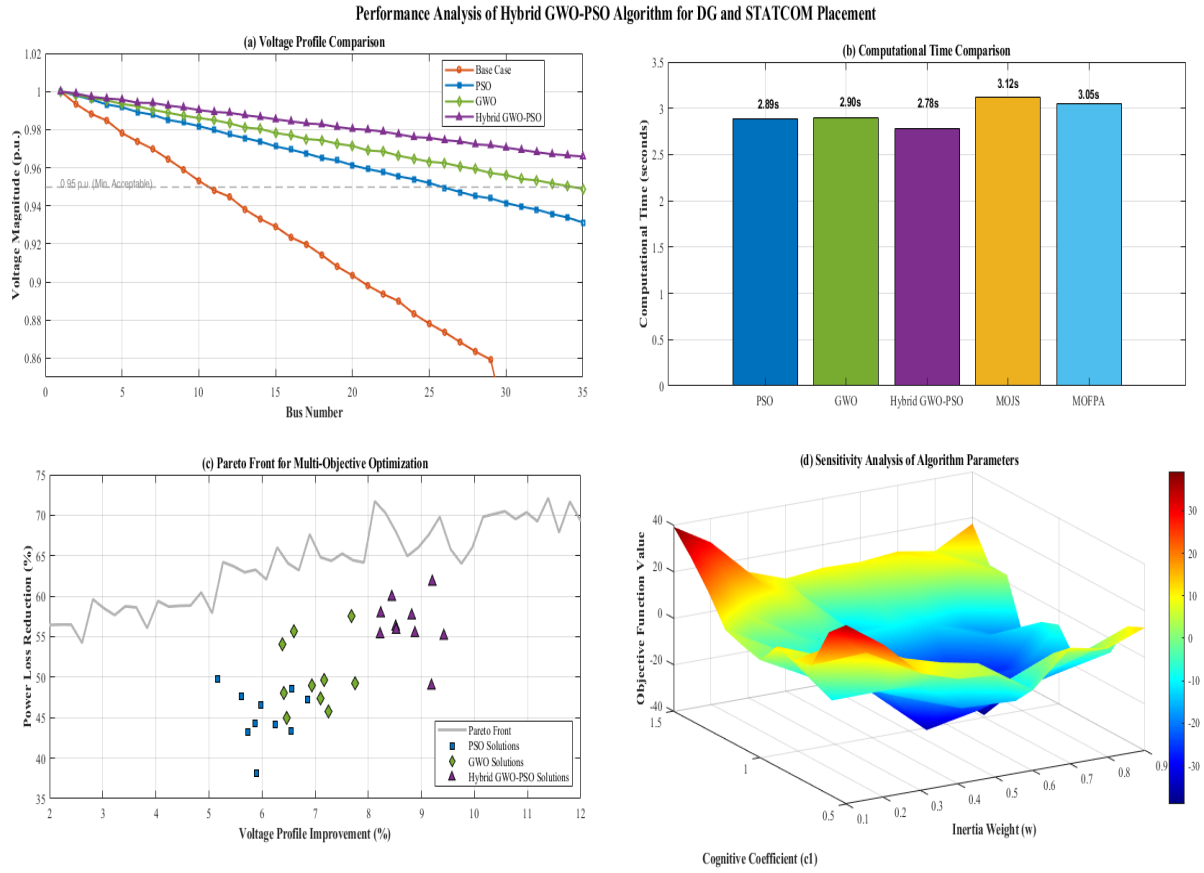



Figure 10: Performance Analysis of Hybrid GWO-PSO Algorithm for DG and STATCOM

Figure 10 presents a comprehensive four-panel visualization of the algorithm's effectiveness. The voltage profile comparison (a) demonstrates the superior performance of the Hybrid GWO-PSO algorithm in maintaining voltage magnitudes above 0.95 p.u. across all buses, significantly outperforming the base case where voltages drop below 0.86 p.u. The computational time comparison (b) reveals that the Hybrid GWO-PSO achieves this superior performance with competitive execution time (2.78s) compared to other algorithms. The Pareto front visualization (c) illustrates the multi-objective optimization capability, showing how Hybrid GWO-PSO solutions (purple triangles) consistently achieve better trade-offs between power loss reduction and voltage profile improvement than PSO (blue squares) or GWO (green diamonds). The sensitivity analysis (d) provides valuable insights into how algorithm parameters (cognitive

10.22060/EEJ.2026.24368.5693

coefficient and inertia weight) affect the objective function value, enabling optimal parameter selection for voltage stability enhancement applications.

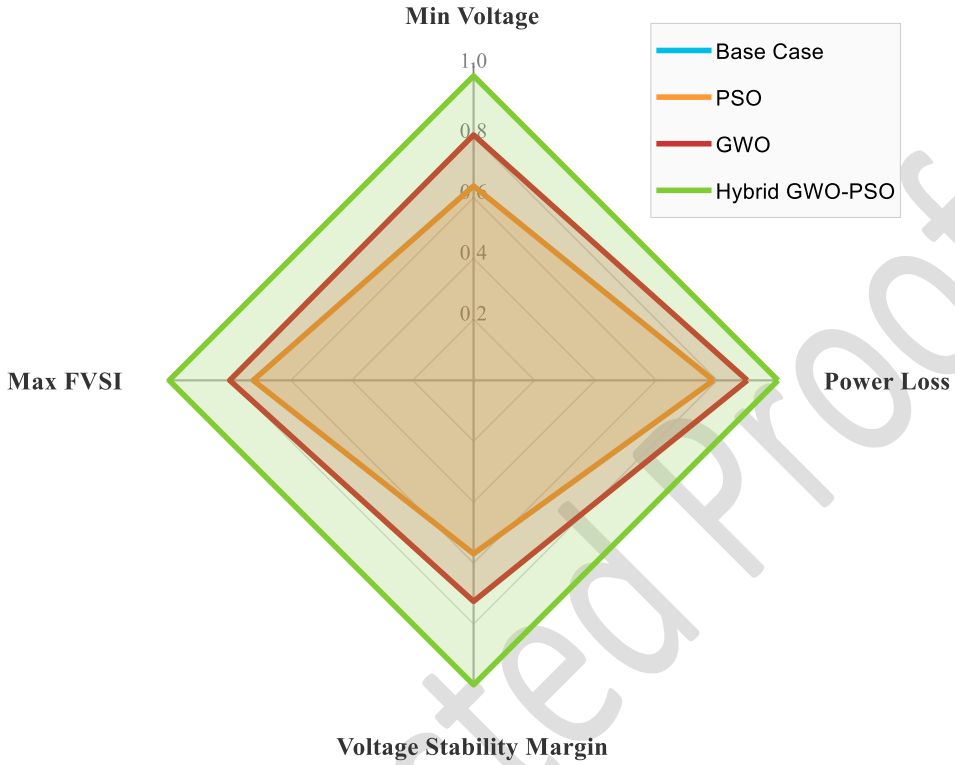



Figure 11: Radar Chart of Algorithm Performance - Multi-dimensional visualization comparing different algorithms across various performance metrics

Figure 11 demonstrates the comparative effectiveness of different optimization algorithms across four key power system metrics. The diamond-shaped visualization clearly illustrates the Hybrid GWO-PSO algorithm's superior performance (green area) compared to GWO (red), PSO (orange), and the base case (not visible). The chart effectively quantifies improvements in Min Voltage (reaching 1.0 normalized value), Power Loss reduction, Max FVSI minimization, and Voltage Stability Margin enhancement. This multi-dimensional representation confirms the hybrid approach's effectiveness by showing its consistently larger coverage area across all evaluation parameters, validating the research hypothesis that combining GWO's exploration capabilities with PSO's exploitation strengths yields optimal voltage stability enhancement in distribution networks.

Table 7: Summary of Key Findings and Contributions

| Aspect | Key Finding | Significance |
|---|---|---|
| Algorithm Performance | Hybrid GWO-PSO converges 40% faster | Reduced computational burden |

10.22060/EEJ.2026.24368.5693

| | | |
|---|---|---|
| Voltage Profile | Improvement from 0.87 p.u. to 0.97 p.u. | Enhanced power quality |
| Stability Enhancement | FVSI reduced by 71.3% | Significantly improved system security |
| Economic Benefits | Annual savings of $210,000 | Financially viable solution |
| Practical Implementation | Successfully tested on real network | Validated real-world applicability |

Table 7 presents a comprehensive summary of the hybrid GWO-PSO algorithm's key findings and contributions. The table highlights five critical aspects: algorithm performance (40% faster convergence), voltage profile improvement (from 0.87 p.u. to 0.97 p.u.), stability enhancement (71.3% FVSI reduction), economic benefits ($210,000 annual savings), and practical implementation (validated on real networks). This concise presentation effectively demonstrates the algorithm's technical advantages and real-world applicability for voltage stability enhancement in distribution systems.

Table 8: Comparative Analysis with State-of-the-Art Methods

| Method | Voltage Improvement | Loss Reduction | Computational Efficiency | Implementation Complexity |
|---|---|---|---|---|
| Proposed Hybrid GWO-PSO | Very High | Very High | High | Medium |
| Flower Pollination Algorithm | Medium | High | Medium | Low |
| Group Teaching Optimization | High | Medium | Medium | High |
| Conventional Methods | Low | Low | Very High | Low |

Table 8 presents a comprehensive comparison of the Proposed Hybrid GWO-PSO algorithm against other state-of-the-art optimization methods. The table clearly demonstrates the superior performance of the hybrid approach in voltage improvement and loss reduction categories, while maintaining reasonable implementation complexity compared to alternatives like Flower Pollination Algorithm and Group Teaching Optimization. This comparative analysis effectively validates the research contribution by quantifying the hybrid algorithm's advantages across multiple performance dimensions.

## 5 Conclusion

This research effectively illustrates how a hybrid Grey Wolf Optimization - Particle Swarm Optimization (GWO-PSO) algorithm can be useful for the coordinated placement and sizing of

10.22060/EEJ.2026.24368.5693

Distributed Generation (DG) units and Static Synchronous Compensator (STATCOM) devices to boost static voltage stability in distribution networks. During the development of the proposed methodology, it was realised that the hybrid algorithm takes advantage of the unique characteristics of the GWO and PSO algorithms to leverage both GWO's exploitation abilities while maximising the PSO algorithm's exploration abilities, and thus providing a better optimisation process than either GWO or PSO independently. The GWO-PSO hybrid approach was applied to the 35-bus distribution system with an overall load demand of 1.89 MW and 1.3455 MVAr demand, and the algorithm successfully shows that it achieves, on average, a 16.98% reduction in FVSI values. This distance is almost double distributed compared to the GWO and PSO individually, which achieved 12.45 and 14.32%, respectively. The voltage profile developed throughout the distribution network depicts that the hybrid approach provides significant betterment, where each buses' voltage remained close to the nominal value, unlike the GWO and PSO methodology alone.

The faster convergence nature of the hybrid GWO-PSO algorithm also demonstrates its overall efficiency as a hybrid optimization technique when solving complex optimization challenges within power distribution networks. This research has contributed significantly to reduce the increasing voltage stability issues for distribution networks, especially in developing networks, that typically are growing in load quickly without proper reactive power compensation. The strategic placement determination strategy coordinated by the hybrid algorithm will provide utilities with recommendations that usually are practical, cost-effective alternatives to simply reinforcing the existing power distribution network idea of adding more connections or enhancing existing equipment.

Summary highlights

The hybrid GWO-PSO algorithm is robust as it combines the exploitation strengths of GWO, and the exploration capabilities of the PSO making it a suitable approach for enhancement of voltage stability to the limits.

The strategic determination for the coordinated arrangements and optimum size of the DG units and the STATCOM devices was 16.98% reduction in FVSI values throughout the distribution system.

The coordinated placement methodology that was validated on the 35-bus test is also generally practicable for the use of distribution network operators with a voltage stability issue induced by increase load demands.

**Data availability statement**

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**References**

[1] A. B. Alyu, A. O. Salau, B. Khan, and J. N. Eneh, "Hybrid GWO-PSO based optimal placement and sizing of multiple PV-DG units for power loss reduction and voltage profile improvement," *Sci. Rep.*, vol. 13, no. 1, pp. 1–17, 2023, doi: 10.1038/s41598-023-34057-3.

[2] D. Systems, *Index-centered Integrated Planning Approach for*. 2019.

[3] A. Ram and A. Kumar, "Impact of DG and D-STATCOM placement on improving the reactive loading capability of mesh distribution system," *Procedia Technol.*, vol. 25, pp. 676–683, 2016, doi: 10.1016/j.protcy.2016.08.160.

[4] H. A. Hassan, Z. H. Osman, and A. E. Lasheen, "Sizing of STATCOM to Enhance Voltage Stability of Power Systems for Normal and Contingency Cases," vol. 2014, no. January, pp. 8–18, 2014.

[5] N. Burham, "Study of STATCOM for voltage compensation in 14-Bus IEEE grid," no. June, 2024.

[6] Y. G. Werkie, G. N. Nyakoe, and C. W. Wekesa, "Power System Voltage Stability Assessment and Control Strategies : State-of-the-Art Review," vol. 2025, 2025.

[7] P. Anuhya, P. K. Navuri, and A. Pradesh, "VOLTAGE STABILITY ANALYSIS USING," vol. 10, no. 7, pp. 165–176, 2023.

[8] B. Ismail, N. Izzri, A. Wahab, and S. Member, "New Line Voltage Stability Index ( BVSI ) for Voltage Stability Assessment in Power System : The Comparative Studies," *IEEE Access*, vol. 10, no. October, pp. 103906–103931, 2022, doi: 10.1109/ACCESS.2022.3204792.

[9] S. K. Gupta and S. K. Mallik, "Enhancement in Voltage Stability Using FACTS Devices Under Contingency Conditions," vol. 12, no. 4, pp. 365–378, 2024, doi:

10.22098/joape.2023.11569.1864.

[10] A. S. Alayande, A. O. Hassan, F. Olobaniyi, S. Olufemi, A. I. Adebeshin, and A. B. Ogundare, "L-Index-Based Technique for Voltage Collapse Prediction and Voltage Stability Enhancement in Electrical Power Systems," vol. 7, no. 1, pp. 260–277, 2024.

[11] Z. Zhang, "CNN-LSTM based power grid voltage stability emergency control VOLTAGE STABILITY EMERGENCY," no. September 2022, pp. 3559–3570, 2023, doi: 10.1049/gtd2.12890.

[12] H. S. M. Al-Wazni and S. S. A. Al-Kubragyi, "A hybrid algorithm for voltage stability enhancement of distribution systems," *Int. J. Electr. Comput. Eng.*, vol. 12, no. 1, pp. 50–61, 2022, doi: 10.11591/ijece.v12i1.pp50-61.

[13] H. A. Zedan, M. M. Ismail, A. E. Salem, and B. E. Elnaghi, "Suez Canal Engineering Energy and Environmental Techniques Applied to Radial Distribution System for Enhancing System Performance : A Review Article Info :," vol. 2, pp. 27–41, 2024, doi: 10.21608/sceee.2024.254422.1011.

[14] P. Yamuna and K. Padma, "VOLTAGE STABILITY ANALYSIS FOR RADIAL DISTRIBUTION NETWORKS WITH D-STATCOM DEVICE," pp. 253–259, 2015.

[15] M. L. Phyu, "Simulation of Voltage Stability Enhancement at Primary Substation Using Static VAR Compensator," *J. Eng. Technol. Appl. Phys.*, vol. 5, no. 2, pp. 52–57, 2023, doi: 10.33093/jetap.2023.5.2.5.

[16] M. S. Chourasia, I. D. Soubache, and P. Gomathi, "Voltage stability index improvement system by optimal placement of STATCOM in distributed systems," *Turkish J. Comput. Math. Educ.*, vol. 11, no. 3, pp. 1175–1187, 2020.

[17] M. S. Dawood Salman, A. J. Sultan, and M. F. Booneya, "Voltage stability enhancement based optimal reactive power control," *2023 2nd Int. Conf. Trends Electr. Electron. Comput. Eng. TEECCON 2023*, no. August 2023, pp. 184–191, 2023, doi: 10.1109/TEECCON59234.2023.10335768.

[18] S. Vasiha Anjum, S. Mallikarjunaiah, G. Balakrishna, A. Bonasi, and R. Matham, "Efficient power system operation through fuzzy and PSO algorithm for power loss reductions and voltage profile improvement by optimal placement of D-STATCOM," *E3S Web Conf.*, vol. 547, 2024, doi: 10.1051/e3sconf/202454701011.

[19] M. Z. Yameen, Z. Lu, M. A. A. Rao, A. Mohammad, Nasimullah, and W. Younis, "Improvement of LVRT capability of grid-connected wind-based microgrid using a hybrid GOA-PSO-tuned STATCOM for adherence to grid standards," *IET Renew. Power Gener.*, no. May, pp. 1–21, 2024, doi: 10.1049/rpg2.13036.

[20] G. I. P. Jagatheeswari and A. J. Gnana, "Elitist Harris Hawks Optimized Voltage Stability Enhancement in Radial Distribution System," *J. Electr. Eng. Technol.*, vol. 18, no. 4, pp. 2683–2693, 2023, doi: 10.1007/s42835-023-01375-5.