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Optimal placement and sizing of battery energy storage systems for voltage stability enhancement in a 150 kV transmission system using discrete grey wolf optimization

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ABSTRACT

The increasing penetration of wind-based renewable energy introduces significant challenges to voltage stability and transmission system security due to the intermittent nature of wind generation. This study proposes a Discrete Grey Wolf Optimization (DGWO)-based framework for the optimal placement and sizing of battery energy storage systems (BESS) in the 150 kV South Sulawesi transmission system under high renewable-energy penetration conditions. The investigated network integrates large-scale wind generation from the Sidrap (275 MW) and Jeneponto (260 MW) wind farms. The proposed framework combines inverter-constrained BESS operation, adaptive reactive power control, wind curtailment management, and AC power flow analysis within a unified multi-objective optimization structure. The optimization identifies optimal BESS installations at Buses 1, 19, and 25 with reactive power capacities of 5.37 MVAr, 7.60 MVAr, and 39.19 MVAr, respectively. Simulation results under the worst-case operating condition demonstrate that the proposed approach improves the minimum bus voltage from 0.9400 pu to 0.9590 pu while maintaining all transmission line loadings within the thermal security limit of 250 MVA. The optimized solution requires only 15.51 MVAr of actual reactive power utilization and limits wind curtailment to 0.98%. In addition, most fitness improvement is achieved before iteration 60, indicating stable convergence and good computational efficiency. The results confirm that the proposed approach provides an efficient, technically feasible, and operationally realistic solution for voltage stability enhancement and secure operation of renewable-integrated transmission systems.

Keywords: discrete grey wolf optimization, battery energy storage systems, voltage stability, reactive power optimization, wind power integration, wind curtailment, transmission system optimization.

INTRODUCTION

Renewable energy, particularly wind power generation, has become one of the primary solutions for reducing dependence on fossil fuels and mitigating carbon emissions in modern power systems. However, the intermittent and stochastic nature of wind energy introduces significant power fluctuations that can adversely affect voltage stability and general system reliability. In high-voltage transmission networks, large-scale wind integration may lead to local undervoltage conditions, increased transmission losses, and redistribution of power flows approaching thermal limits of transmission lines [1, 2].

To address these challenges, the application of battery energy storage systems (BESS) has gained considerable attention. Beyond their conventional role as energy storage devices, BESS can provide fast and flexible reactive power support through dynamic reactive power injection. This capability enables BESS to effectively enhance voltage stability and mitigate fluctuations caused by renewable energy variability [3, 4]. However, the performance of BESS is inherently limited by inverter capacity, which introduces a nonlinear coupling between active and reactive power that must be explicitly considered in practical system modeling.

Despite these advantages, determining the optimal placement and sizing of BESS remains a challenging nonlinear and non-convex optimization problem involving multiple decision variables and operational constraints. Conventional optimization methods often struggle to achieve global optimality, particularly in large-scale systems with complex network interactions. As a result, metaheuristic algorithms such as particle swarm optimization (PSO), genetic algorithms (GA), and ant colony optimization (ACO) have been widely applied, although they may suffer from premature convergence and sensitivity to parameter settings [5].

Grey Wolf Optimization (GWO) has emerged as a promising alternative due to its strong balance between exploration and exploitation, enabling efficient navigation of complex search spaces [6]. Several studies have demonstrated the effectiveness of GWO in power system applications, including optimal reactive power planning and energy storage sizing [7, 8]. In addition, recent studies have explored the application of metaheuristic optimization for renewable-integrated transmission systems, highlighting the importance of coordinated voltage control, reactive power support, and operational flexibility under high renewable penetration conditions [9]. However, most existing studies treat reactive power compensation, energy storage operation, and renewable curtailment as separate problems, without fully capturing their coupled interactions under realistic operational constraints.

This study addresses these research gaps by proposing a Discrete Grey Wolf Optimization (DGWO) framework that integrates BESS placement, adaptive reactive power control, and wind curtailment into a unified optimization model under AC power flow constraints. In contrast to previous approaches, the proposed method explicitly considers:

- the nonlinear inverter constraint linking active and reactive power,
- adaptive reactive power control based on system voltage conditions, and
- the inclusion of wind curtailment as a controllable decision variable within the optimization process.

This integrated formulation is consistent with the system modeling and evaluation presented in the methodology and results sections, where the adaptive control mechanism ensures efficient reactive power utilization while the inverter capability constraint enforces realistic operational limits for BESS operation.

The main contributions of this study can be summarized as follows. First, a DGWO-based framework is developed for the optimal placement and sizing of BESS in a renewable-integrated 150 kV transmission system under high wind penetration conditions. Second, the proposed framework integrates inverter-constrained BESS operation, adaptive reactive power control, and wind curtailment strategy within a unified AC power flow optimization framework. Third, a multi-objective optimization function is formulated by simultaneously considering voltage deviation, transmission loading, reactive power utilization, and curtailment penalty under realistic operational constraints. Finally, the proposed framework is comprehensively evaluated on the South Sulawesi transmission system under worst-case operating conditions, demonstrating effective voltage stability enhancement with efficient reactive power utilization and minimal renewable curtailment.

The simulation results demonstrate that the proposed method successfully improves the voltage profile while maintaining transmission loading within thermal security limits and minimizing unnecessary reactive power utilization. Therefore, the proposed approach provides an optimization framework that is not only mathematically robust but also physically realistic and technically feasible for modern renewable-integrated power systems.

RELATED WORK

Various optimization techniques have been extensively developed to enhance power system performance, particularly for the optimal placement and sizing of reactive power compensation devices. Classical heuristic and metaheuristic methods, including PSO, GA, and ACO, have been widely applied in problems such as capacitor placement, Flexible AC Transmission System (FACTS) allocation, distributed generation planning, and energy storage deployment. These approaches are recognized for their ability to handle nonlinear and multi-objective optimization problems. However, several studies have reported inherent limitations, including premature convergence, sensitivity to initial parameter settings, and degraded performance when applied to large-scale or highly constrained systems.

Recent developments in renewable-integrated power systems have further increased the complexity of optimization problems due to the variability and uncertainty associated with renewable energy sources. Consequently, optimization frameworks are now required to simultaneously consider voltage stability, transmission security, renewable energy utilization, and operational flexibility under dynamic operating conditions. This has motivated the increasing adoption of advanced metaheuristic algorithms capable of solving nonlinear and non-convex optimization problems more effectively [10].

To overcome the limitations of conventional approaches, GWO has been introduced as a nature-inspired metaheuristic algorithm that mimics the social hierarchy and cooperative hunting strategy of grey wolves. One of the key strengths of GWO lies in its ability to maintain a dynamic balance between global exploration and local exploitation, enabling it to effectively avoid local optima while improving convergence stability [11]. Due to these advantages, GWO has been successfully applied in various power system optimization problems, including economic dispatch, optimal reactive power planning, transmission expansion planning, and energy storage placement [12].

In the context of BESS, numerous studies have investigated optimal siting and sizing strategies to improve voltage stability, reduce power losses, enhance renewable energy integration, and increase system reliability. GWO-based approaches have demonstrated promising performance in determining optimal BESS locations and capacities in both distribution and microgrid systems [13]. Similarly, several recent studies have explored the application of BESS for voltage stability enhancement, frequency regulation, oscillation damping, and renewable fluctuation mitigation, highlighting the significant role of BESS as a flexible resource in modern power systems [14, 15].

Nevertheless, most existing studies primarily focus on either active power scheduling or static reactive power compensation without explicitly considering the nonlinear coupling between active and reactive power imposed by inverter operational limits. In practical BESS operation, the inverter apparent power capacity constrains the simultaneous provision of active and reactive power support. Therefore, neglecting this relationship may produce solutions that are mathematically optimal but physically unrealistic for real-world operation [16, 17].

Furthermore, previous studies often simplify renewable energy integration by assuming fixed operating conditions or neglecting renewable curtailment strategies. In practical transmission systems with high renewable penetration, wind curtailment may become necessary to maintain voltage stability and transmission security, particularly during critical operating conditions. However, only a limited number of studies have incorporated renewable curtailment as an integrated decision variable within BESS optimization frameworks [18, 19].

Another notable limitation observed in prior research is the absence of adaptive reactive power control mechanisms within the optimization process. Most existing approaches assume fixed reactive power injection or predefined operating conditions, which do not accurately represent the dynamic nature of voltage regulation in renewable-integrated power systems. Recent studies have emphasized that adaptive reactive power control is essential for improving voltage regulation efficiency while avoiding excessive reactive power utilization and overcompensation [20].

Based on these research gaps, this study proposes a Discrete Grey Wolf Optimization (DGWO) framework that integrates BESS placement, adaptive reactive power control, and wind curtailment into a unified AC power flow optimization model. Unlike previous approaches that mainly focus on static reactive compensation or simplified renewable integration, the proposed framework explicitly incorporates the nonlinear inverter capability constraint coupling active and reactive power support under realistic operational conditions. In addition, the framework implements an adaptive reactive power control mechanism to dynamically regulate reactive power injection according to real-time voltage conditions, thereby improving voltage regulation efficiency while preventing excessive compensation. Wind curtailment is also incorporated as a controllable optimization variable to maintain transmission security and renewable energy utilization under high wind penetration conditions. Each candidate solution is evaluated using AC power flow analysis to ensure technical feasibility and operational consistency. The study validates the effectiveness of the proposed framework on the 150 kV South Sulawesi transmission system under worst-case operating conditions, demonstrating stable convergence characteristics, improved voltage stability, efficient reactive power utilization, and secure transmission system operation with minimal renewable energy curtailment.

METHODOLOGY

Power system modeling

The system analyzed in this study is the 150 kV South Sulawesi transmission network [21, 22], consisting of 44 buses representing a regional interconnected power system with a combination of conventional and renewable generation units. The system includes coal-fired power plants, gas-fired generation, and hydropower plants, which serve as the primary sources for maintaining power balance.

To evaluate the impact of renewable energy integration, two wind power plants are incorporated into the system:

- Sidrap Wind Farm (275 MW) at Bus 8
- Jeneponto Wind Farm (260 MW) at Bus 32

Due to the intermittent nature of wind energy, additional support is required to maintain voltage stability. Therefore, Battery Energy Storage Systems (BESS) are integrated into the system as flexible resources capable of providing active and reactive power support.

BESS modeling as virtual STATCOM

In this study, BESS is modeled as a virtual STATCOM with the capability to simultaneously control active and reactive power within the inverter capacity limit [4, 23]. The operational constraint of BESS is defined based on the apparent power limit of Equation 1:

$$S_{BESS}^2 = P_{BESS}^2 + Q_{BESS}^2 \quad (1)$$

where: S_{BESS} represents the inverter capacity, while P_{BESS} and Q_{BESS} denote active and reactive power, respectively.

The active power output of the BESS is linked to wind curtailment and is expressed as Equation 2.

$$P_{BESS} = (1 - \alpha) \cdot P_{wind} \quad (2)$$

where: $\alpha \in [0,1]$ is the curtailment factor. As the inverter capacity is limited, an increase in active power reduces the available reactive power capability, which is constrained by Equation 3.

$$0 \leq Q_{BESS} \leq \sqrt{S_{BESS}^2 - P_{BESS}^2} \quad (3)$$

This formulation ensures that BESS operates realistically, capturing the trade-off between active and reactive power support.

Power flow analysis

The system operating condition is evaluated using AC power flow analysis based on the Newton–Raphson method [24–26]. The power flow equations are defined as Equation 4 and Equation 5.

$$P_i = \sum_{j=1}^{N} V_i V_j (G_{ij} \cos\, \theta_{ij} + B_{ij} \sin \quad (4)$$

$$Q_i = \sum_{j=1}^{N} V_i V_j (G_{ij} \sin\, \theta_{ij} - B_{ij} \cos \quad (5)$$

These nonlinear equations are solved iteratively to obtain bus voltages and line flows, which are then used to evaluate system performance at each optimization step.

Objective function formulation

The optimization problem is formulated as a multi-objective function that simultaneously considers voltage stability, transmission security, reactive power efficiency, renewable energy utilization, and voltage profile smoothness, as commonly adopted in multi-objective optimal power flow and reactive power optimization studies [27, 28]. The objective function is expressed in Equations 6–11.

$$J = w_1 f_V + w_2 f_S + w_3 f_Q + \\ + w_4 f_P + w_5 f_{smooth} \quad (6)$$

Components:

- Voltage deviation (Equation 7)

$$f_V = \sum (V_i - 1)^2 \quad (7)$$

- Line loading penalty (Equation 8)

$$f_S = \sum \max\,(0, S_i - S_{max})^2 \quad (8)$$

- Reactive power usage (Equation 9)

$$f_Q = \sum Q_k^2 \quad (9)$$

- Curtailment penalty (Equation 10)

$$f_P = (P_{wind} - P_{actual})^2 \tag{10}$$

- Voltage smoothness (Equation 11)

$$f_{smooth} = \sum | V_{i+1} - V_i | \tag{11}$$

The weighting coefficients $w_1 - w_5$ are selected empirically to balance system stability, operational security, and efficiency.

Adaptive reactive power control

To ensure realistic system operation, an adaptive reactive power control mechanism is embedded within the power flow calculation [29]. At each iteration, reactive power injection is adjusted based on voltage deviation as Equation 12.

$$Q_{req} = k(V_{ref} - V_{min}) \tag{12}$$

Reactive power is then distributed among BESS units while respecting inverter limits. This mechanism ensures that reactive power is injected only when necessary, avoiding overcompensation.

Discrete grey wolf optimization (DGWO)

DGWO is employed to solve the optimization problem by mimicking the leadership hierarchy and hunting mechanism of grey wolves [11, 30–32]. The population consists of candidate solutions categorized into alpha, beta, and delta wolves, representing the three best solutions.

The position of each wolf is updated based on these leaders of Equation 13.

$$X^{new} = \frac{X_1 + X_2 + X_3}{3} \tag{13}$$

where each component is calculated using Equation 14, Equation 15, and Equation 16.

$$X_1 = X_\alpha - A_1 \cdot | C_1 X_\alpha - X | \tag{14}$$

$$X_2 = X_\beta - A_2 \cdot | C_2 X_\beta - X | \tag{15}$$

$$X_3 = X_\delta - A_3 \cdot | C_3 X_\delta - X | \tag{16}$$

The coefficient vectors are defined as Equation 17.

$$A = 2ar_1 - a, C = 2r_2 \tag{17}$$

where: α decreases linearly from 2 to 0 to balance exploration and exploitation.

Since BESS locations are discrete variables, the updated positions are rounded as Equation 18.

$$X_{bus} = \text{round}(X_{bus}) \tag{18}$$

The overall optimization framework integrates the DGWO algorithm with AC power flow analysis and adaptive reactive power control within a closed-loop optimization structure. The optimization procedure is summarized as follows in Algorithm 1.

Each candidate solution is evaluated under realistic operating conditions while satisfying voltage, transmission loading, inverter capability, and reactive power constraints.

Integrated optimization framework

The proposed optimization framework integrates the DGWO algorithm with AC power flow analysis, adaptive reactive power control, and wind curtailment within a unified closed-loop

```
1. Initialize DGWO parameters:
  - Population size
  - Maximum iterations
  - Control parameter (a)
2. Generate initial wolf population:
  - BESS locations (discrete bus indices)
  - Reactive power capacities
  - Wind curtailment factors
3. Evaluate fitness of each candidate solution:
  - Perform AC power flow analysis
  - Compute objective function value
4. Identify alpha, beta, and delta wolves
5. While iteration < MaxIter
    For each wolf:
      a. Update wolf position using DGWO equations
      b. Apply variable boundary constraints
      c. Update BESS placement and capacity
      d. Apply wind curtailment:
         P_actual = (1 − α) P_wind
      e. Perform AC power flow calculation
      f. Apply adaptive reactive power control
      g. Evaluate objective function
    End
    Update alpha, beta, and delta wolves
  End
6. Return optimal solution:
  - Optimal BESS locations
  - Reactive power capacities
  - Curtailment factor
  - Minimum objective function value
```

Algorithm 1. DGWO-based optimization framework optimization structure. The overall optimization process is performed iteratively to ensure that each candidate solution satisfies both technical and operational constraints under realistic system conditions.

The optimization procedure can be summarized as follows:

- Initialize the DGWO population, including BESS locations, reactive power capacities, and wind curtailment factors.
- Perform AC power flow analysis for each candidate solution.
- Apply adaptive reactive power control based on voltage deviation conditions.
- Evaluate the multi-objective fitness function.
- Update wolf positions using DGWO equations.
- Repeat the process until the convergence criterion is satisfied.

This integrated framework enables simultaneous evaluation of voltage stability, transmission loading, reactive power utilization, and renewable energy integration within each optimization iteration. Consequently, the obtained solutions are not only mathematically optimal but also technically feasible for practical power system operation.

The total workflow of the proposed DGWO-based optimization framework is illustrated in Figure 1. The flowchart summarizes the interaction between BESS modeling, adaptive reactive power control, wind curtailment strategy, and AC power flow analysis within the iterative optimization loop.

As shown in Figure 1, the optimization process begins with the initialization of candidate solutions, followed by iterative evaluation through AC power flow simulation and adaptive control mechanisms. During each iteration, the DGWO search mechanism updates the candidate solutions, while the system continuously evaluates operational constraints. The optimization process continues until convergence is achieved, resulting in the optimal configuration of BESS placement, reactive power capacity, and wind curtailment settings.

RESULTS AND DISCUSSION

Convergence characteristics of the DGWO algorithm

The convergence behavior of the proposed DGWO algorithm is presented in Figure 2 through the evolution of the objective function value during the optimization process. At the initial stage, the algorithm demonstrates a rapid decrease in fitness value, dropping from approximately 19.9 to 19.6 within the first few iterations. This rapid improvement indicates a strong global exploration capability in identifying promising regions of the search space efficiently. Such behavior is attributed to the large control parameter at the early iterations, which allows the wolves to explore the solution space broadly and avoid premature convergence to local optima [12, 31].

As the optimization progresses, the rate of fitness reduction becomes more gradual, particularly between iterations 10 and 50. This phase represents the transition from exploration to exploitation, where the DGWO algorithm begins refining candidate solutions around the best-performing wolves, namely Alpha, Beta, and Delta. The relatively stable convergence trend during this interval indicates that the algorithm maintains solution diversity while simultaneously improving solution quality. This convergence behavior confirms the effectiveness of the proposed multi-objective formulation in guiding the optimization process toward solutions that simultaneously satisfy voltage stability enhancement, transmission security, reactive power efficiency, and renewable energy utilization objectives [26–28].

A noticeable improvement in fitness value is observed again around iterations 50 and 60, where the objective function decreases from approximately 19.51 to 19.22. This behavior suggests that the algorithm successfully escapes potential local optima and continues searching for a better global solution. Such step-like convergence characteristics are commonly observed in population-based metaheuristic algorithms, where improvements occur whenever superior candidate solutions are discovered during the search process. Similar convergence characteristics have also been reported in previous studies employing population-based optimization algorithms such as PSO and conventional GWO for power system applications [6, 8, 9]. However, the DGWO-based approach demonstrates a more stable convergence trend and reduced oscillatory behavior, indicating an improved exploration–exploitation balance during the optimization process.

After iteration 60, the convergence curve gradually approaches a stable plateau, eventually reaching a final fitness value of approximately 19.17 at iteration 100. The absence of significant oscillations at later iterations demonstrates the

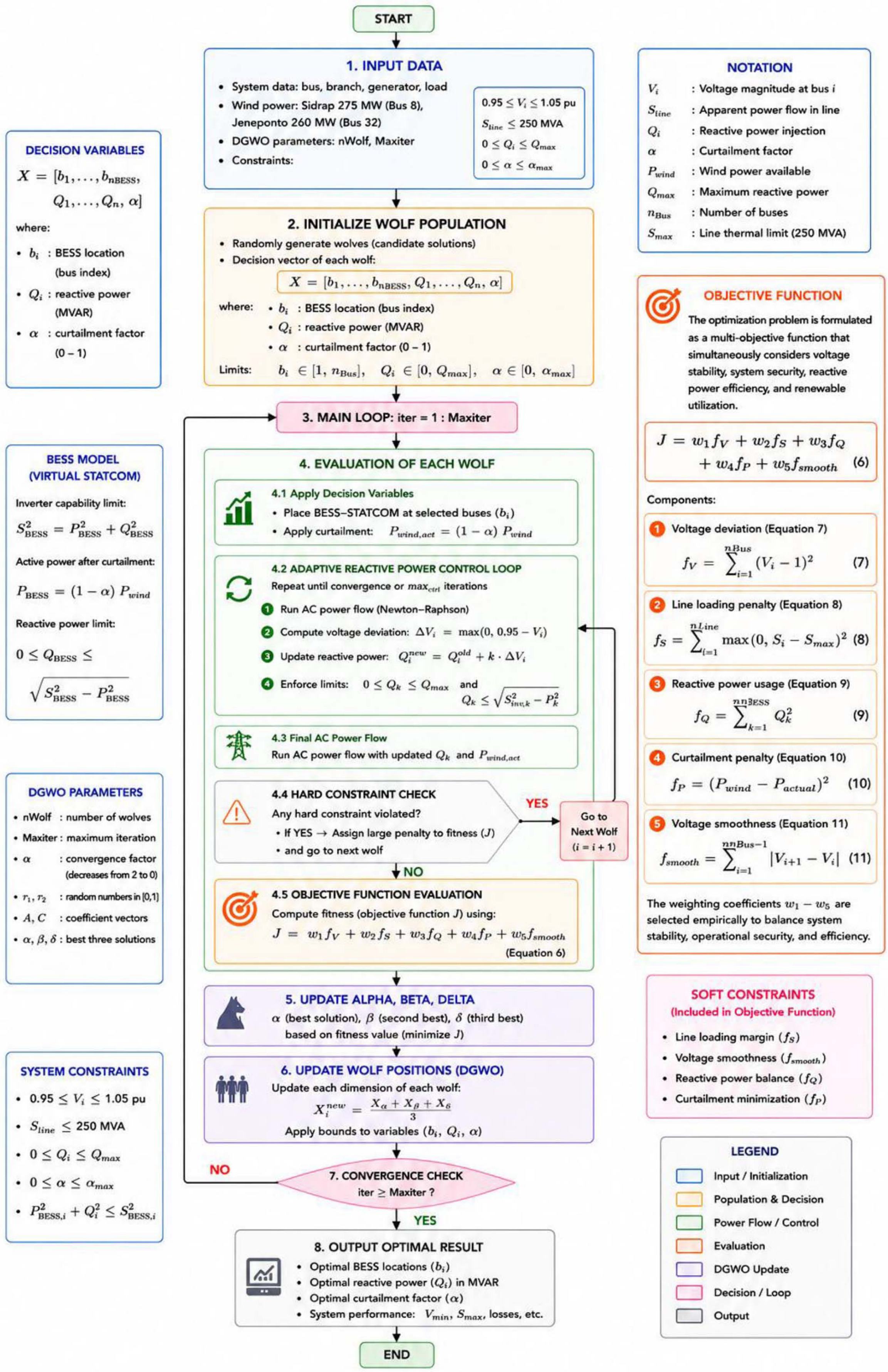

Figure 1. Proposed DGWO-based integrated optimization framework for optimal BESS placement, incorporating adaptive reactive power control, wind curtailment, and AC power flow evaluation

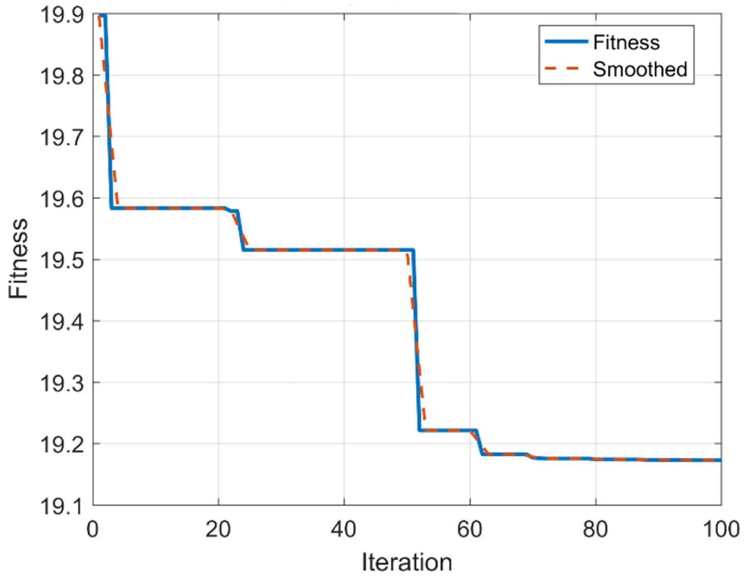

Figure 2. Evolution of the objective function value during the DGWO optimization process

stability and robustness of the proposed DGWO approach. Moreover, the very small improvement observed after iteration 70 indicates that the algorithm has effectively converged toward a near-optimal solution.

From a computational perspective, most of the fitness improvement is achieved before iteration 60, indicating that the optimization framework provides good convergence speed and computational efficiency for solving complex nonlinear optimization problems in power systems. This characteristic is particularly important for large-scale renewable-integrated transmission systems, where optimization algorithms must provide stable and computationally feasible solutions under multiple operational constraints.

The obtained results confirm that the proposed DGWO algorithm efficiently maintains an effective balance between global exploration and local exploitation while avoiding premature convergence and maintaining solution stability. These characteristics demonstrate the suitability of the proposed method for solving complex multi-objective optimization problems in renewable-integrated power systems under realistic operational constraints. Based on this stable convergence behavior, the obtained optimal solution is further evaluated in terms of voltage profile enhancement, transmission line loading, and reactive power distribution.

System voltage profile

The comparison of voltage profiles before and after optimization demonstrates a substantial improvement in system voltage stability, particularly in the minimum voltage magnitude, as illustrated in Figure 3. Simulation results indicate that the minimum bus voltage increases from 0.9400 pu under the base condition to approximately 0.9590 pu after the implementation of the proposed DGWO method.

This improvement of approximately 2.02% confirms that the proposed optimization framework effectively mitigates undervoltage conditions while maintaining all bus voltages within the acceptable operational range of 0.95–1.05 pu. Importantly, no overvoltage condition is observed after optimization, indicating that the reactive power compensation is performed in a controlled and balanced manner. These results demonstrate that the DGWO-based strategy effectively enhances voltage stability while simultaneously satisfying system operational constraints [1, 9].

From a physical perspective, the voltage enhancement is primarily achieved through the strategic placement of BESS units at buses with high voltage sensitivity. Unlike conventional compensation approaches that rely mainly on increasing reactive power capacity, the proposed DGWO method focuses on identifying the most effective locations for reactive power support. Consequently, the improvement in voltage profile is strongly influenced by optimal

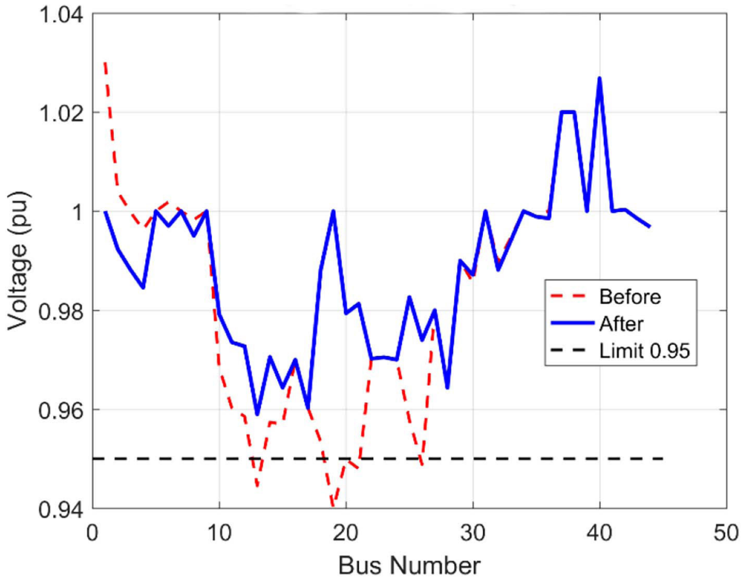

Figure 3. Comparison of voltage profiles before and after DGWO optimization

placement strategy rather than by excessive reactive power injection. Similar observations have been reported in previous studies, where optimal BESS placement provided more effective voltage support than simply increasing reactive power capacity [13, 15].

The results further reveal that although the installed reactive power capacity of BESS is relatively large, the actual reactive power injected into the system remains considerably lower. The AC power flow analysis indicates that only 15.51 MVAr of reactive power is required to maintain acceptable voltage conditions throughout the transmission network. This behavior is directly associated with the adaptive reactive power control mechanism incorporated into the proposed framework, where reactive power injection is continuously adjusted according to real-time voltage deviation conditions. As a result, reactive power is supplied only when required, thereby preventing unnecessary compensation and improving general operational efficiency [20].

In addition, the inverter capability constraint incorporated into the proposed BESS model ensures that the energy storage system operates within realistic physical and operational limits. Accordingly, an increase in active power delivery reduces the available reactive power support capability, reflecting the practical characteristics of inverter-based energy storage systems [3, 4, 30]. This coordinated interaction between active power support, reactive power injection, and voltage regulation contributes significantly to the stability improvement achieved by the proposed optimization framework.

Another important observation is that the improved voltage profile is achieved without introducing unstable voltage oscillations or excessive voltage deviation among buses. This indicates that the proposed adaptive reactive power control mechanism effectively maintains smooth voltage regulation across the transmission network, even under high renewable penetration conditions. Such behavior is particularly important for renewable-integrated transmission systems, where voltage fluctuations may become more severe due to the intermittent characteristics of wind generation [2, 22].

Collectively, the proposed DGWO method effectively enhances the voltage profile while maintaining efficient reactive power utilization and respecting system operational constraints. The simulation results demonstrate that the proposed optimization framework is capable of improving voltage stability without introducing excessive reactive power injection or operational violations. Furthermore, the improved voltage profile subsequently influences the redistribution of power flow within the transmission network, which is analyzed further in the following section.

Transmission loading analysis

The evaluation of transmission line loading after the implementation of the proposed DGWO method indicates that no thermal limit violations occur within the system, as illustrated in Figure 4. The simulation results show that the maximum transmission line loading increases from 195.00 MVA under the base condition to approximately 247.32 MVA after optimization. Although a significant increase in line loading is observed, the value remains below the predefined thermal limit of 250 MVA, indicating that all transmission lines continue to operate within safe operational boundaries.

The increase in transmission loading is primarily caused by the redistribution of power flow resulting from the improved voltage profile and reactive power support provided by the optimally placed BESS units. In interconnected power systems, reactive power injection influences bus voltage magnitudes and phase angle differences, which subsequently alters the active and reactive power flow distribution throughout the transmission network. Consequently, certain transmission corridors experience higher loading levels after optimization [24, 25]. This observation is consistent with previous studies on renewable-integrated transmission systems, where voltage support mechanisms were found to significantly influence transmission power flow redistribution and network utilization patterns.

Despite this redistribution effect, the absence of overload conditions demonstrates that the developed optimization framework effectively maintains transmission system security while simultaneously improving voltage stability. No critical bottleneck conditions are observed, and the loading increase remains physically reasonable and operationally acceptable. This result indicates that the optimization process does not simply maximize voltage improvement without considering network security constraints. Instead, the proposed method effectively coordinates voltage regulation and transmission loading management within a unified optimization structure.

Moreover, the obtained results confirm the effectiveness of the transmission loading penalty component incorporated within the proposed multi-objective function. The penalty mechanism effectively restricts candidate solutions that exceed thermal constraints, thereby guiding the optimization process toward solutions that simultaneously satisfy voltage stability and transmission security requirements. This demonstrates that the proposed optimization scheme is capable of balancing multiple operational objectives under realistic AC power flow conditions.

Another important observation is that the transmission loading increase remains concentrated on several major transmission corridors with relatively high power transfer capability, while weaker lines remain within moderate loading conditions. This indicates that the optimization process naturally redistributes power flow toward stronger transmission paths, thereby improving the global operational efficiency of the network without introducing critical stress conditions on vulnerable transmission lines.

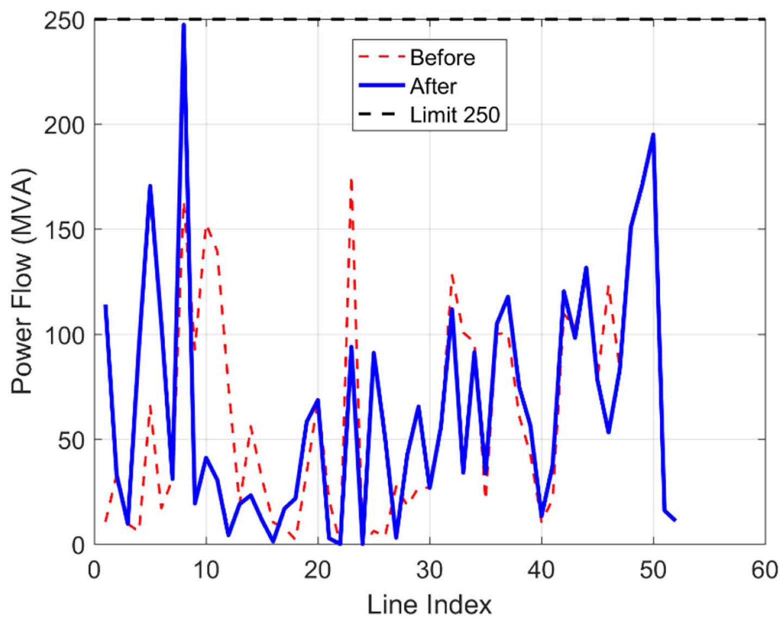

Figure 4. Transmission line loading before and after DGWO optimization

From a practical perspective, the results demonstrate that the proposed DGWO method is capable of achieving a balanced trade-off between voltage profile enhancement and transmission line utilization. Although several transmission lines operate closer to their thermal limits after optimization, the system remains within acceptable operational margins, confirming that the obtained solution is both technically feasible and operationally reliable for realistic power system applications. Furthermore, the coordinated interaction between voltage improvement, reactive power support, and transmission loading regulation confirms the effectiveness of the proposed integrated optimization framework for renewable-integrated transmission systems.

Reactive power distribution

The optimized reactive power distribution obtained using the proposed DGWO method demonstrates that reactive power support is not uniformly allocated across the network but instead concentrated at specific buses with high voltage sensitivity, as shown in Figure 5. The optimization process identified Buses 1, 19, and 25 as the optimal installation locations for BESS Units 1, 2, and 3, with installed reactive power capacities of 5.37 MVAr, 7.60 MVAr, and 39.19 MVAr, respectively. The significantly larger capacity assigned to Bus 25 indicates that this location exhibits the highest voltage sensitivity and therefore contributes most strongly to voltage stability enhancement within the South Sulawesi transmission system. However, Figure 5 shows that the actual reactive power injections required under the final operating condition are only approximately 4.4 MVAr, 5.0 MVAr, and 6.1 MVAr for BESS Units 1, 2, and 3, respectively. This difference between installed capacity and actual utilization demonstrates the effectiveness of the adaptive reactive power control mechanism, which injects only the amount of reactive power required to maintain system voltage within acceptable limits. These results confirm that voltage stability improvement is achieved primarily through strategic BESS placement and bus sensitivity characteristics rather than through excessive reactive power compensation, thereby improving operational efficiency and ensuring realistic utilization of inverter-based BESS resources.

The AC power flow simulation reveals that the total reactive power actually utilized is only 15.51 MVAr, which is substantially lower than the total installed reactive power capability. The simulation data reveal that the proposed framework does not continuously utilize the full reactive power capacity, but instead injects reactive power only according to actual system requirements. Similar observations have been reported in previous studies on adaptive reactive power compensation, where efficient voltage regulation was achieved using relatively low reactive power

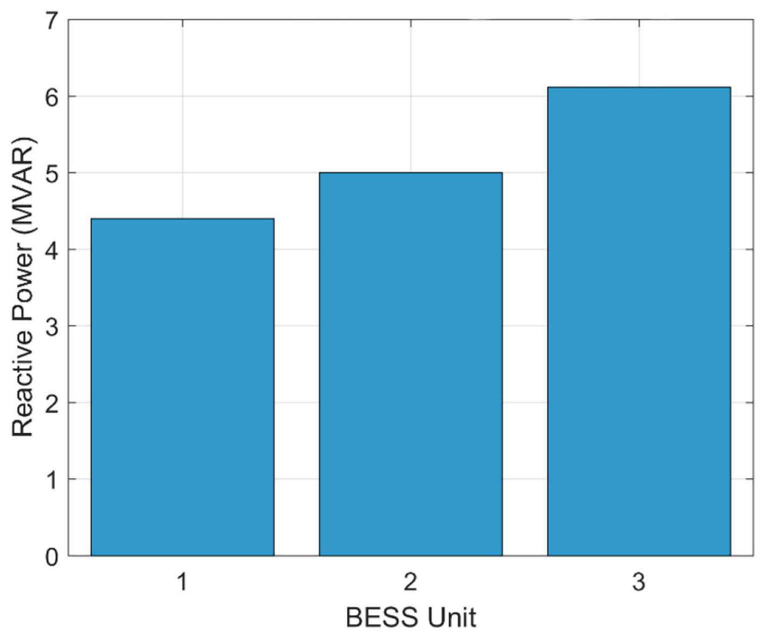

Figure 5. Actual reactive power injection of BESS units after DGWO optimization

support through optimal device placement and coordinated control strategies [13].

This discrepancy between installed capacity and actual reactive power injection is primarily attributed to the adaptive reactive power control mechanism integrated into the proposed methodology. In this approach, reactive power support is dynamically adjusted based on voltage deviation conditions during each optimization iteration. Consequently, reactive power is supplied only when necessary to maintain acceptable voltage levels, thereby improving operational efficiency and preventing excessive compensation. This adaptive behavior also contributes to maintaining stable voltage regulation under varying operating conditions associated with renewable energy fluctuations.

Furthermore, the inverter capability constraint incorporated within the BESS model also contributes to limiting reactive power injection. Since the BESS units simultaneously provide active and reactive power support, the available reactive power capability decreases as active power output increases. This constraint ensures that the BESS units operate within realistic physical limits and accurately represent practical inverter-based energy storage behavior [3, 4]. Therefore, the obtained reactive power allocation reflects not only optimization performance but also the physical feasibility of the proposed framework.

The non-uniform reactive power allocation further indicates that voltage sensitivity varies considerably among buses in the transmission network. In particular, Bus 25 exhibits the largest reactive power capacity contribution, suggesting that this location has the strongest impact on improving system voltage stability. Such behavior confirms that the effectiveness of reactive compensation is determined primarily by optimal placement rather than by excessive reactive power magnitude. This finding is consistent with recent studies emphasizing that strategic placement of inverter-based support devices is more effective than simply increasing reactive power capacity [15, 19].

From a system operation perspective, the obtained results are consistent with the concept of a minimum reactive power injection strategy, where system stability is achieved using the minimum required reactive power support. This strategy is highly beneficial because it reduces the possibility of overcompensation, minimizes unnecessary reactive power circulation, and prevents potential overvoltage conditions. In addition, lower reactive power utilization contributes to reducing converter stress and improving the operational efficiency of inverter-based energy storage systems [29].

In general, the proposed DGWO framework produces an efficient and technically feasible reactive power distribution while maintaining voltage stability and respecting inverter operational constraints. These results confirm that the proposed method is capable of achieving effective voltage support with relatively low reactive power utilization, demonstrating the importance of strategic BESS placement and adaptive reactive power control in renewable-integrated transmission systems.

Overall performance analysis

The obtained optimization results demonstrate that the developed framework significantly enhances power system performance through an adaptive, efficient, and operationally realistic optimization strategy. The proposed method successfully improves voltage stability, maintains transmission system security, minimizes unnecessary reactive power utilization, and supports renewable energy integration under realistic AC power flow constraints.

First, substantial voltage profile improvement is achieved without requiring excessive reactive power injection. Although the installed reactive power capacities of the BESS units reach 5.37 MVAr, 7.60 MVAr, and 39.19 MVAr at Buses 1, 19, and 25, respectively, the actual reactive power utilized during system operation is only 15.51 MVAr. Meanwhile, the minimum bus voltage successfully increases from 0.9400 pu to approximately 0.9590 pu. These findings indicate that the optimization algorithm effectively identifies buses with high voltage sensitivity, allowing reactive power support to be allocated at the most influential locations. Consequently, voltage stability enhancement is achieved primarily through optimal placement strategy rather than excessive reactive power magnitude. Similar observations have been reported in previous studies, where strategic placement of reactive support devices provided more effective voltage regulation than approaches relying solely on large reactive power capacities [13, 15].

Second, the obtained wind curtailment level remains relatively low at approximately 0.98%, indicating that most wind energy generation can still be utilized effectively. This result confirms the effectiveness of integrating wind curtailment as a controllable decision variable within the optimization framework. By simultaneously considering voltage stability, transmission loading, reactive power utilization, and renewable energy integration, the DGWO-based strategy maintains a balanced trade-off between system security and renewable energy utilization under high wind penetration conditions.

Third, although the redistribution of power flow resulting from voltage improvement causes an increase in transmission line loading, the maximum loading remains within the allowable thermal limit. The maximum line loading reaches approximately 247.32 MVA, which remains below the specified thermal constraint of 250 MVA. This behavior demonstrates that the proposed method not only improves voltage conditions but also maintains transmission system security and operational reliability. In addition, the transmission loading penalty incorporated into the objective function effectively prevents the optimization process from producing infeasible operating conditions.

Furthermore, all operational constraints incorporated into the optimization problem, including voltage limits, inverter capability constraints, reactive power limits, and transmission thermal capacities, are successfully satisfied throughout the optimization process. This confirms that the obtained solution is not only mathematically optimal but also technically feasible and physically realistic for practical implementation in renewable-integrated transmission systems. In particular, the inverter-constrained BESS model ensures that reactive power allocation remains consistent with the actual operating characteristics of inverter-based energy storage systems.

From a broader optimization perspective, the obtained results validate the effectiveness of the proposed multi-objective formulation in balancing several critical performance indices simultaneously, including voltage stability enhancement, reactive power efficiency, transmission security, and renewable energy utilization. The adaptive reactive power control mechanism further contributes to operational efficiency by ensuring that reactive power is injected only when required by the actual system conditions, thereby minimizing unnecessary reactive power circulation and preventing excessive compensation.

Compared with previous studies employing PSO, GA, and conventional GWO-based optimization approaches for voltage stability enhancement and reactive power planning, the optimization framework demonstrates improved operational realism through the simultaneous consideration of inverter capability constraints, adaptive reactive power control, renewable curtailment management, and AC power flow feasibility [6, 8, 9]. In addition, most fitness improvement is achieved before iteration 60, indicating good convergence speed and stable optimization performance for complex renewable-integrated transmission system applications.

Collectively, the obtained results demonstrate that the proposed DGWO-based optimization framework provides a reliable, efficient, and technically feasible solution for improving voltage stability while maintaining secure transmission system operation under high renewable energy penetration conditions. The coordinated interaction among adaptive reactive power control, inverter-constrained BESS operation, renewable curtailment management, and transmission security evaluation confirms the suitability of the proposed framework for solving complex multi-objective optimization problems in modern renewable-integrated power systems.

CONCLUSIONS

This study proposed a DGWO-based framework for the optimal placement and sizing of BESS in a renewable-integrated 150 kV transmission system under high wind penetration conditions. The proposed framework integrated inverter-constrained BESS operation, adaptive reactive power control, wind curtailment strategy, and AC power flow analysis within a unified multi-objective optimization structure. The obtained results demonstrated that the proposed approach successfully improved voltage stability, maintained transmission system security, minimized reactive power utilization, and reduced renewable energy curtailment under realistic operational constraints.

The simulation results demonstrated that the proposed approach significantly improved the system voltage profile while maintaining transmission system security. The minimum bus voltage increased from 0.9400 pu to approximately 0.9590 pu after optimization, while all transmission line loadings remained within the allowable thermal limit of 250 MVA. The optimal BESS installations were obtained at Buses 1, 19, and 25 with reactive power capacities of 5.37 MVAr, 7.60 MVAr, and 39.19 MVAr, respectively. Despite the relatively large installed reactive power capacities, the actual reactive power utilized during operation was only 15.51 MVAr, indicating efficient reactive power allocation through the proposed adaptive control mechanism. In addition, the obtained solution maintained a low wind curtailment level of approximately 0.98%, confirming effective renewable energy utilization under worst-case operating conditions.

The obtained results further confirmed that voltage stability enhancement was achieved primarily through strategic BESS placement rather than excessive reactive power injection. The adaptive reactive power control mechanism successfully ensured that reactive power was injected only when required by the actual system conditions, thereby improving operational efficiency and preventing unnecessary compensation. Furthermore, the inverter capability constraint incorporated into the proposed framework ensured that the obtained solutions remained physically realistic and technically feasible for practical implementation in modern inverter-based renewable energy systems.

From a broader optimization perspective, the developed optimization framework demonstrated strong capability in solving complex, nonlinear, and multi-objective optimization problems associated with renewable-integrated transmission systems. The coordinated interaction among voltage regulation, transmission loading management, reactive power optimization, inverter-constrained operation, and renewable energy utilization confirmed the effectiveness of the proposed integrated optimization strategy under high renewable penetration conditions. In addition, most fitness improvement was achieved before iteration 60, indicating stable convergence characteristics and good computational efficiency for large-scale renewable-integrated power system optimization problems.

Compared with conventional optimization approaches, the DGWO-based approach provided a more balanced and operationally realistic solution by explicitly considering the nonlinear coupling between active and reactive power capability, adaptive reactive power control behavior, renewable curtailment management, and AC power flow feasibility within a unified optimization structure. These characteristics confirmed the suitability of the proposed method for improving voltage stability while maintaining secure and efficient transmission system operation under high renewable penetration conditions.

Future research may focus on extending the proposed DGWO framework to multi-period and uncertainty-based optimization problems that consider dynamic renewable energy fluctuations and time-varying load conditions. Further investigation involving dynamic stability analysis, contingency assessment, and hybrid metaheuristic optimization techniques may also improve the robustness and scalability of the proposed framework for large-scale renewable-integrated transmission systems. In addition, the incorporation of real-time operational data and practical inverter control strategies may provide deeper insights into the real-world implementation of adaptive BESS-based voltage support in modern power systems.

REFERENCES

1. Malik F.H., Khan M.A., Rahman T., Ehtisham M., Faheem M., Haider Z.M., et al. A Comprehensive review on voltage stability in wind-integrated power systems. Energies. 2024; 17: 644. https://doi.org/10.3390/en17030644
2. Mastoi M.S., Zhuang S., Haris M., Hassan M., Ali A. Large-scale wind power grid integration challenges and their solution: A detailed review. Environmental Science and Pollution Research. 2023; 30: 103424–103462. https://doi.org/10.1007/s11356-023-29653-9
3. Bhutto J.K., Kumar A., Kamangar S., Arabi A.I.A., Hakami H., Mushtaque N. Coordinated hybrid VAR compensation strategy with grid-forming BESS and solar PV for enhanced stability in inverter-dominated power systems. Sustainability. 2025; 17: 10820. https://doi.org/10.3390/su172310820
4. Banda J.K., Araújo L.S., D'Arco S., Moen T.E., Tedeschi E. A reactive power boosting strategy for BESS-STATCOMs. IEEE Journal of Emerging and Selected Topics in Industrial Electronics. 2025; 6: 1258–1270. https://doi.org/10.1109/jestie.2025.3545888
5. Priyadarshi R., Kumar R. Evolution of swarm intelligence: A systematic review of particle swarm and ant colony optimization approaches in modern research. Archives of Computational Methods in Engineering. 2025; 32: 3609–3650. https://doi.org/10.1007/s11831-025-10247-2
6. Nadimi-Shahraki M.H., Taghian S., Mirjalili S. An improved grey wolf optimizer for solving engineering problems. Expert Systems with Applications. 2020; 166: 113917. https://doi.org/10.1016/j.eswa.2020.113917

7. Jamal R., Men B., Khan N.H. A novel nature inspired meta-heuristic optimization approach of GWO optimizer for optimal reactive power dispatch problems. IEEE Access. 2020; 8: 202596–202610. https://doi.org/10.1109/access.2020.3031640
8. Varan M., Erduman A., Menevşeoğlu F. A grey wolf optimization algorithm-based optimal reactive power dispatch with wind-integrated power systems. Energies. 2023; 16: 5021. https://doi.org/10.3390/en16135021
9. Adegoke S.A., Sun Y., Wang Z., Oladipo S. A mini review on optimal reactive power dispatch incorporating renewable energy sources and flexible alternating current transmission system. Electrical Engineering. 2024; 106: 3961–3982. https://doi.org/10.1007/s00202-023-02199-2
10. Minh C.L.T., Le X.C., Huynh N.N., Doan A.T., Viet D.T., Duong M.Q. Optimal power flow solutions to power systems with wind energy using a highly effective meta-heuristic algorithm. International Journal of Renewable Energy Development. 2023; 12: 467–477. https://doi.org/10.14710/ijred.2023.51375
11. Mirjalili S., Mirjalili S.M., Lewis A. Grey wolf optimizer. Advances in Engineering Software. 2014; 69: 46–61. https://doi.org/10.1016/j.advengsoft.2013.12.007
12. Laouafi F. Improved grey wolf optimizer for optimal reactive power dispatch with integration of wind and solar energy. Electrical Engineering & Electromechanics. 2025; 23–30. https://doi.org/10.20998/2074-272x.2025.1.04
13. Zhang D., Shafiullah G., Das C.K., Wong K.W. Optimal allocation of battery energy storage systems to improve system reliability and voltage and frequency stability in weak grids. Applied Energy. 2024; 377: 124541. https://doi.org/10.1016/j.apenergy.2024.124541
14. Zhu Y., Liu C., Sun K., Shi D., Wang Z. Optimization of battery energy storage to improve power system oscillation damping. IEEE Transactions on Sustainable Energy. 2018; 10: 1015–1024. https://doi.org/10.1109/tste.2018.2858262
15. Parajuli A., Gurung S., Chapagain K. Optimal placement and sizing of battery energy storage systems for improvement of system frequency stability. Electricity. 2024; 5: 662–683. https://doi.org/10.3390/electricity5030033
16. Wang Z., Zhang L., Li G. The active power and reactive power dispatch plan of DFIG based wind farm considering wind power curtailment. International Journal of Computational Intelligence Systems. 2015; 8: 553. https://doi.org/10.1080/18756891.2015.1036222
17. Ma X., Chen L., Dong X., Li Y. Multi-objective reactive power optimization strategy of power system considering large-scale renewable integration. Frontiers in Energy Research. 2023; 11. https://doi.org/10.3389/fenrg.2023.1213154
18. Santos S.F., Gough M., Fitiwi D.Z., Silva A.F.P., Shafie-khah M., Catalào J.P.S. Influence of battery energy storage systems on transmission grid operation with a significant share of variable renewable energy sources. IEEE Systems Journal. 2021; 16: 1508–1519. https://doi.org/10.1109/jsyst.2021.3055118
19. Xu G., Cheng H., Fang S., Ma Z., Zeng P., Yao L. Optimal size and location of battery energy storage systems for reducing the wind power curtailments. Electric Power Components and Systems. 2018; 46: 342–352. Available from: https://doi.org/10.1080/15325008.2018.1445141
20. Hu J., Zhang Z., Zeng Z., Tang Z., Kong W., Li H. An adaptive strategy for reactive power optimization control of offshore wind farms under power system fluctuations. Electronics. 2026; 15: 327. https://doi.org/10.3390/electronics15020327
21. Tumiran, Putranto L.M., Irnawan R., Sarjiya, Priyanto A., Isnandar S., Savitri I. Transmission expansion planning for the optimization of renewable energy integration in the Sulawesi electricity system. Sustainability. 2021; 13: 10477. https://doi.org/10.3390/su131810477
22. Krismanto A.U., Sulistiawati I.B., Limpraptono F.Y., Priyadi A., Setiadi H., Abdillah M. Impact of large-scale wind power penetration on dynamic voltage stability of interconnected power system: An Indonesia case study. International Journal of Intelligent Engineering and Systems. 2021; 14. https://doi.org/10.22266/ijies2021.0831.23
23. Li G., Chen Y., Luo A., Wang H. An enhancing grid stiffness control strategy of STATCOM/BESS for damping sub-synchronous resonance in wind farm connected to weak grid. IEEE Transactions on Industrial Informatics. 2020; 16: 5835–5845. https://doi.org/10.1109/TII.2019.2960863
24. Kulworawanichpong T. Simplified Newton–Raphson power-flow solution method. International Journal of Electrical Power & Energy Systems. 2010; 32: 551–558. https://doi.org/10.1016/j.ijepes.2009.11.011
25. Bayat M., Koushki M.M., Ghadimi A.A., Tostado-Véliz M., Jurado F. Comprehensive enhanced Newton Raphson approach for power flow analysis in droop-controlled islanded AC microgrids. International Journal of Electrical Power & Energy Systems. 2022; 108493. https://doi.org/10.1016/j.ijepes.2022.108493
26. Ilyas M.A., Abbas G., Alquthami T., Awais M., Rasheed M.B. Multi-objective optimal power flow with integration of renewable energy sources using fuzzy membership function. IEEE Access. 2020; 8: 143185–143200. https://doi.org/10.1109/

ACCESS.2020.3014046
27. Álvarez O., Carrión D., Jaramillo M. Optimal reactive power dispatch planning considering voltage deviation minimization in power systems. Energies. 2025; 18: 2982. https://doi.org/10.3390/en18112982
28. Shaheen M.A.M., Hasanien H.M., Alsaleh I., Alassaf A., Zhang M., Alateeq A. Optimal power flow in power systems with renewable energy resources uncertainty including geothermal power plants. Ain Shams Engineering Journal. 2025; 16: 103784. https://doi.org/10.1016/j.asej.2025.103784
29. Trinh P.H., Chung I.Y. Integrated active and reactive power control methods for distributed energy resources in distribution systems for enhancing hosting capacity. Energies. 2024; 17: 1642. https://doi.org/10.3390/en17071642
30. Faris H., Aljarah I., Al-Betar M.A., Mirjalili S. Grey wolf optimizer: a review of recent variants and applications. Neural Computing and Applications. 2018; 30: 413–435. https://doi.org/10.1007/s00521-017-3272-5
31. Sharma S., Bhattacharjee S., Bhattacharya A. Grey wolf optimisation for optimal sizing of battery energy storage device to minimise operation cost of microgrid. IET Generation, Transmission & Distribution. 2016; 10. https://doi.org/10.1049/iet-gtd.2015.0429
32. Aeggegn D.B., Nyakoe G.N., Wekesa C. Optimal sizing of grid connected multi-microgrid system using grey wolf optimization. Results in Engineering. 2024; 23: 102421. https://doi.org/10.1016/j.rineng.2024.102421