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Optimal DG and Capacitor Allocation Along with Network Reconfiguration Using Grey Wolf Optimizer Algorithm

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ABSTRACT- This study introduces a multi-criteria optimization approach using the Grey Wolf Optimizer (GWO) algorithm to determine the optimal capacity, locations of DG units and capacitor banks, and network reconfiguration in distribution systems. The objective function incorporates six key performance metrics: real losses, imaginary losses, voltage variation, voltage stability index, section load ability, and current balancing index. The proposed GWO technique was evaluated on IEEE 33- and 69-bus systems and benchmarked against Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). Results demonstrate that GWO effectively optimizes the placement and sizing of DGs and capacitor banks under diverse conditions, enhancing system performance and reducing active power losses.

Keywords: Network Reconfiguration (NR), Grey Wolf Optimizer (GWO), Genetic Algorithm (GA), Particle Swarm Optimization (PSO)

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1. INTRODUCTION

When energy is transferred across long feeders to meet system demands, transmission and distribution losses grow. Large-scale distribution networks experience higher losses. As per [1], distribution system losses constitute 70% of total power losses. In contrast, the cost for power generation is directly proportional to power system losses. Much recent research has focused on resampling as a technique for decreasing losses in power networks. Evaluating that studying numerous structures to discover the best system configuration is an optimization structure. Consequently, the power system topology determination problem is handled by utilizing a range of optimization strategies [2-5]. In contrast, the higher reliability of the power system is due to the configuration change, which also reduces losses and improves the voltage profile [4-6]. Using distributed generation sources is another technique to reduce power system losses [7-8]. Installing distributed generation (DG) units near customers reduces power system losses, both overall and line losses [7-10]. Dispersed producing sources typically have a capacity of less than 10 megawatts [11-12]. As a result, the amount of electricity produced by distributed production sources is increasing daily [13]. Another way to reduce power system losses is to use capacitive banks to regulate the voltage [14-16]. To reduce losses, distributed generating sources and capacitors were installed simultaneously [17-18]. The Cuckoo search method served as the foundation for the distribution system reorganization in [19]. The projected method is validated by comparing IEEE 33, 69 bus systems. Ref [20] restructures the system to decrease losses and improve voltage stability using a forbidden search technique. Ref [21] investigates Ahwaz's distribution system, as well as the IEEE 33 and 69 systems, when performing restructuring using the learning algorithm. The principle of this reference is to decrease losses while boosting the voltage report.

The particle optimization technique was used to explain optimization problem. Within [22] An evolutionary differential technique was used to locate the capacitor and distributed generation sources. The goal function considers the expenses associated with minimizing both imaginary and real power losses in the network. Additionally, [23] has investigated how altering distribution system's structure might simultaneously locate scattered generation sources and capacitors. The Harmony Checker Algorithm is the method used to solve this problem. This study looks at network rearrangement in a distribution system while accounting for demand variability, as well as the instantaneous resolve of capacity and placement of distributed power sources & bank of capacitor. This is performed by using an objective task with six performance indices: section load ability, active power losses, reactive power losses, voltage fluctuations, voltage stability criterion and section balancing current criterion. A multi-objective Grey Wolf Optimization method is used to optimize network performance, and the suggested approach's effectiveness is proven on IEEE 33 also 69 bus systems.

The challenges described below are addressed in the section that follows: The second section covers the objective function, indices, and a problem summary. In the third section, the Grey Wolf Optimization (GWO) technique is to explain resolving the optimization issues. Simulation results are presented in section four. The GWO method's results were compared to genetic and particle swarm optimization methodologies, as well as cross-referenced with various sources. Finally, the final section provides conclusions.

2. PROBLEM FORMULATION

2.1 Normal or Body Text

This section seeks to convey the issue of finding the best position and dimensions of DG and capacitor bank based on network configurations.

The target function's goal is to decrease losses also voltage variations while also improving the voltage stability criterion and system current balance. As a result, the objective function developed here is a combination of power losses, voltage stability criterion, voltage deviation criterion, sectional currents, line limitations, and optimization problem restrictions.

2.1.1. Power Loss Calculation

There are two approaches for reducing distribution system real power losses: lowering line resistance and lowering current. Modifications to the system's topology may affect network section resistance. The active loss criterion is explained as the reduction in network power loss

$$P_{LI} = \frac{P_L^a}{P_L^b} \quad (1)$$

Similarly, the reactive power loss catalog is stated as a decrease in reactive network power loss.

$$Q_{LI} = \frac{Q_L^a}{Q_L^b} \quad (2)$$

The purpose function with loss in power is expressed as:

$$\min OF_1 = X_1 P_{LI} + Y_1 Q_{LI} \quad (3)$$

$X_1 \& Y_1$ values are taken as 0.8 and 0.2 respectively.

2.1.2. Voltage Deviation Criterion

One security metric is bus voltage, and power quality is critical to the system's functionality. The electrical system operates poorly when the voltage is adjusted. *Equation (4)* describes the voltage variations in network buses.

$$VI = \sum_{k=1}^{N_b} \frac{V_b - V_k}{V_b} \quad (4)$$

2.1.3. Voltage Stability Criterion

The voltage stability criterion is increased to establish a proper stability buffer for each bus. The voltage balance profile in a bus is derived using *equation (5)* in accordance with [30].

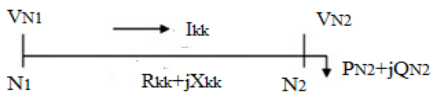

Fig.1. Simple branch of the network

The voltage stability criterion in a bus can be calculated using the following formula:

$$V_{SI,N2} = |V_{N2}|^4 - 4(P_{N2}X_{kk} - Q_{N2}R_{kk}) + 4(P_{N2}R_{kk} + Q_{N2}X_{kk})|V_{N1}|^2 \quad (5)$$

The purpose function with voltage difference criterion and voltage permanence criterion can be represented as:

$$\min OF_2 = X_2 VI + Y_2 \frac{1}{V_{SI}} \quad (6)$$

The values of $X_2 \& Y_2$ are taken as 0.5 and 0.5, respectively.

2.1.4. Section balancing currents criterion

The occurrence of active and reactive producing units adjacent to the loads affects the current flow in various network segments. The flow balance criterion gives critical knowledge regarding the level of system variation following rectification. Lowering this criterion improves the network's ability to withstand increasing demands. The criterion is defined using *equation (7)*.

$$SBCI = \frac{\sum_{s=1}^{Ns} \left| \frac{I_{sb} - I_{sa}}{max(I_{sa}, I_{sb})} \right|}{Ns} \quad (7)$$

The objective function with section load criterion and section balancing currents criterion is expressed as:

$$\min OF_3 = X_3 \times SLI + Y_2 \times SBCI \quad (8)$$

The values of $X_3 \& Y_3$ are taken as 0.5 and 0.5 respectively.

2.1.5. Limits and Constraints

The optimization problem's constraints include the highest real as well as reactive power delivered by DG units and capacitors, as well as the voltage limit and temperature constraint of network lines, as indicated in *equations (9-12)*.

Bus Voltage maximum value is written as:

$$0.9 \leq V_k \leq 1.1 \, ; \; k = 1,2 \ldots \ldots . NB \quad (9)$$

Section current limit is written as:

$$|I_{k,k+1}| \leq |I_{k,k+1,max}| \, ; k = 1,2, \ldots Ns \quad (10)$$

The distributed generation units are supposed to be restricted to generating active electricity. *Equation (11)* calculates the sources' power production capacity. Each bank of capacitor has a 50 kV capacity, and because it has 20 capacitors, the reactive bank of capacitor may generate electricity at 21 different levels. The DG and Capacitor bank constraints can be written as:

$$P_{DG}^{min} \leq P_{DG}^{k} \leq P_{DG}^{max} \quad (11)$$

$$Q_{C}^{min} \leq Q_{C}^{k} \leq Q_{C}^{max} \quad (12)$$

The power balance constraints or equality constraints are written as:

$$P_{G,NB} + \sum_{k=1}^{N_{DG}} P_{k,NB}^{DG} = P_{Load,NB} + P_{L,NB} \quad (13)$$

$$Q_{G,NB} + \sum_{k=1}^{N_{C}} Q_{k,NB}^{C} = Q_{Load,NB} + Q_{L,NB} \quad (14)$$

2.1.6. Multi Objective Function

Equation (15) shows that the suggested multi-objective function is divided into three sections. The f_1 function was used to indicate uniform criterions of active as well as reactive power losses; the f_2 function is used to indicate voltage deviation criterions and improvements in voltage stability; and the f_3 function was used to indicate criterions of line current limit and current adjustment in each system section. These operations are weighted and combined with the objective function, causing the optimization problem.

$$OF = X_T \times OF_1 + Y_T \times OF_2 + Z_T \times OF_3 \quad (15)$$

The values of $X_T, Y_T \& Z_T$ are taken as 0.4, 0.3 and 0.3 respectively.

3. GREY WOLF OPTIMIZER ALGORITHM

The appropriate placement of Distributed Generators also bank of Capacitors in power distribution system can be easily handled utilizing optimization algorithms like the Grey Wolf Optimizer (GWO). Here's a full explanation on how to handle this problem with GWO:

Phase I: Problem Formulation Objectives

- Minimize Power Loss: Is to Reducing power losses in distribution system.
- Enhance Voltage Profile: Ensure that voltage levels on all buses are within acceptable standards.
- Reduce costs, including the installation and operation of DGs and capacitor banks.

Constraints:

Power Balance: Ensuring power supply meets the demand.
Voltage Limits: Voltage levels must remain within specified limits.
Thermal Limits: Current through the network components must not exceed their thermal ratings.
DG Capacity: Limits on the capacity of DGs and capacitor banks.

Phase II: Grey Wolf Optimizer (GWO) Algorithm

GWO is nature-encouraged optimization algorithm based on grey wolves' social design and hunting behaviour. The algorithm mimics the natural leadership stratification and hunting process of grey wolves, which include:

Alpha (α): The leader or the most effective solution.
Beta (β): The 2nd-finest answer.
Delta (δ): The 3rd-gratest solution.
Omega (ω): The other solutions,

Implementation Steps

Initialize the Population: Generate an initial population of wolves (possible solutions), which represents different configurations of DG and capacitor bank placements.

Evaluate Fitness: Calculate the fitness for each wolf based on objectives (power loss, voltage profile, and costs).

Update Positions: The placement of the wolves are updated location on the positions of α, β, and δ wolves using the below equations:

$$\vec{D}_\alpha = |\vec{C}_1 * \vec{X}_\alpha - \vec{X}| \quad (16)$$

$$\vec{D}_\beta = |\vec{C}_2 * \vec{X}_\beta - \vec{X}| \quad (17)$$

$$\vec{D}_\delta = |\vec{C}_3 * \vec{X}_\delta - \vec{X}| \quad (18)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 * \vec{D}_\alpha \quad (19)$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 * \vec{D}_\beta \quad (20)$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 * \vec{D}_\delta \quad (21)$$

$$\vec{A} = 2 * \vec{a} * \vec{rv}_1 - \vec{a} \quad (22)$$

$$\vec{C} = 2 * \vec{rv}_2 \quad (23)$$

Iterate: Repeat the evaluation and status update stages until a stopping criterion is reached (like a maximum no. of iterations or a convergence threshold). Select Optimal Solution: The position of the α wolf represents the most efficient solution for the establishing of DGs and capacitor banks.

Initialize the population of wolves (solutions) X Initialize the parameters a, A, and C Evaluate fitness of every wolf in population while stopping criterion not met:

Update the placements of α, β, and δ for each wolf in the population: Update coefficients A and C Update the position of the wolf Evaluate the placement of each wolf upgraded α, β, and δ if necessary, Return the position of the α wolf as the optimal solution.

Phase III: Practical Considerations

Network Configuration: The algorithm must consider the specific configuration of power distribution network, containing the topology and load distribution.
Load Flow Analysis: Conduct a load flow study to determine the power loss and voltage profile for each potential solution.
Scalability: Ensure the algorithm can handle large and complex networks by optimizing the computational efficiency.

4. SIMULATION RESULTS

This paper approaches an optimization problem using a Grey Wolf Optimizer algorithm. The system's performance was

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evaluated in order to select the best configuration for the system, as well as locate distributed generation sources and bank of capacitors to optimise various network metrics such as line capacity, voltage stability, current equilibrium, real & reactive power loss reduction, and voltage variation. The performance and efficacy of the suggested approach are assessed by running it on the IEEE 33 and IEEE 69 bus distribution systems [34].

Case A: IEEE 33 bus system

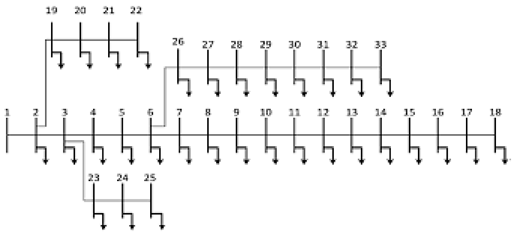

Fig.2(a). Single line representation of IEEE 33

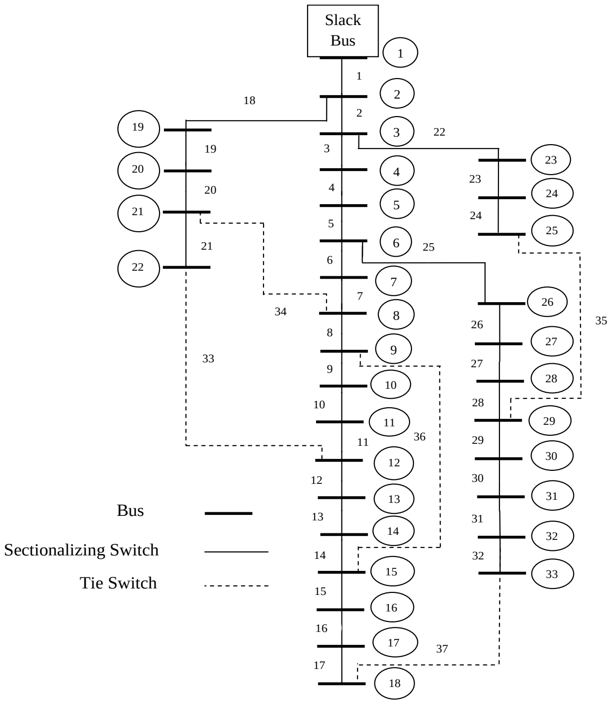

Fig.2(b). IEEE 33 bus system with sensationalizing switches

Table 1. IEEE 33 bus system base values

Active Power Loss (kW)	211
Reactive Power Loss (kVAR)	143
Voltage Deviation	1.8
Voltage Stability Margin	0.67
Maximum Line Loadability (A)	4.61
Maximum Line current (A)	4.62

The IEEE 33-bus distribution scheme has 37 branches, 32 sectionalizing switches, five tie switches. [34] displays load as well as line data for this network. *Figure 2* depicts a network diagram. Furthermore, depending on load flow, the actual and reactive power losses for the first scenario are 210.679 kW and 143.14 kVAR, respectively. The total active and reactive power of the network's loads is 3.715 MW and 2.3 MVAr, respectively. *Table 1* gives the indices for the system's fundamental state.

This scenario does not include any capacitor banks or distributed producing sources. The voltage stability limit for this system is considered insufficient at 0.67, which puts strain on the buses. As a result, network losses can be reduced by restructuring the network and using distributed production sources and capacitive banks to reduce bus stress.

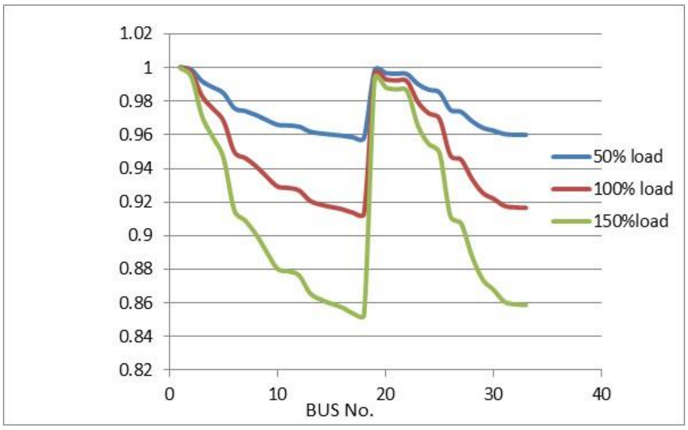

Fig.4. Voltage deviations at different loading conditions before optimal placement of DG, capacitor bank and network configuration

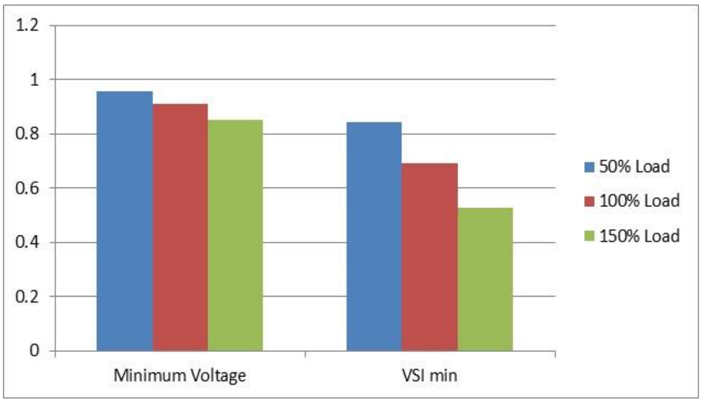

Fig.5. Minimum voltage and voltage stability criterion at different loading conditions before optimal placement of DG, capacitor bank and network configuration

Figure 5 shows the six target function indices in the basic scenario and after installing DG and capacitors and reconfiguring the network using the GWO algorithm. The indices are comprised of reactive loss, active loss, voltage difference, voltage constancy, section load ability, and estimation current criterion between sections. The six measures are compared before as well as after the GWO method & optimization technique, with real and imaginary power losses set to 210.679 kW & 143.14 kVAR, correspondingly. A significant reduction in both real and imaginary power loss is realized. Voltage variation is decreased, and voltage constancy is improved. Furthermore, section load ability, balancing current criterion are greatly decreased. *Fig. 4 and 5* depicts the voltage deviations,

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minimum voltage and voltage stability criterion at different loading conditions before optimal placement of DG, Capacitor bank and Network Configuration respectively. *Fig. 6 & 7* depicts voltage deviations, minimum voltage and also voltage stability criterion at different loading conditions after optimal placement of DG, Capacitor bank and Network Configuration respectively.

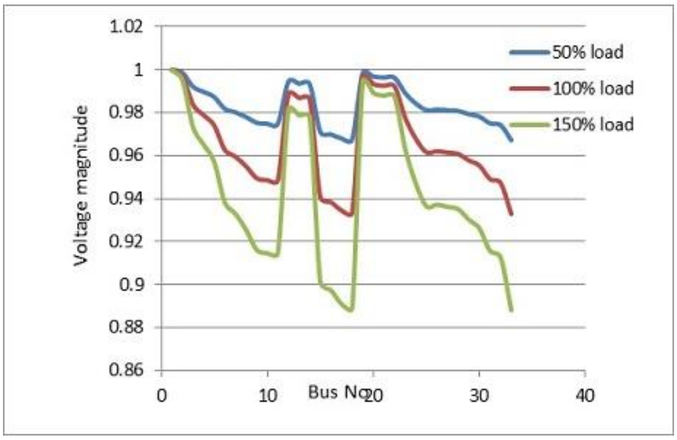

Fig.6. Voltage deviations at different loading conditions after optimal placement of DG, capacitor bank and network configuration

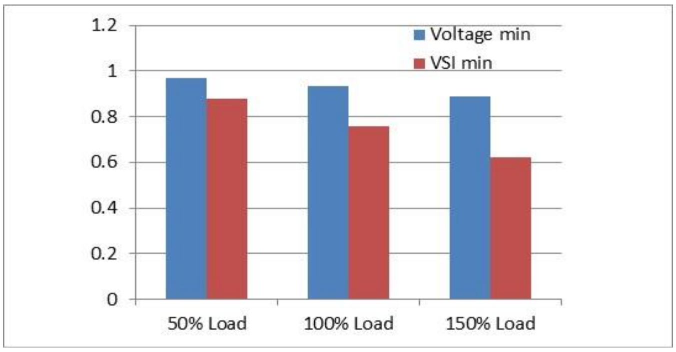

Fig.7. Minimum voltage and voltage stability criterion at different loading conditions after optimal placement of DG, capacitor bank and network configuration

Table 2 shows the simulation results obtained after applying multiple optimization strategies to simultaneously place the DG and bank of capacitors in 33-bus system and rearrange the network. After using the GWO algorithm, the open switches that make up the final 33 bus structure are 7, 10, 13, 27, and 32. Looking at the results, it is clear that, when contrasted to the GA and PSO strategies, the proposed GWO strategy is better suited to handling the optimization problem.

The GWO technique produces lower active and reactive losses than the GA and PSO algorithms. The suggested GWO method yields a voltage stability criterion that is greater than the voltage deviation criterion achieved via the use of GA and PSO approaches, but the voltage deviation criterion produced through these methods is roughly equal. In contrast to the values provided by the GA and PSO approaches, the GWO methodology experienced lower values for Section load ability and balancing current criterion of sections.

Table 2. Performance Comparison table (IEEE 33 bus)

	GA	PSO	GWO
Open Switches	5,7,8,11,12	5,8,9,25, 31	7,10,13,27,32
DG (finest Sizing (MW) & placement)	1.155 @ bus 18 1.500 @ bus 29	1.500 @ bus 13 1.254 @ bus 29	0.426 @ bus 32 1.202 @ bus 29
Capacitor (finest Capacity (MVar) and location	0.650 @ bus 6 1.000 @ bus 18	0.700 @ bus 16 0.900 @ bus 30	0.713 @ bus 18 0.65 @ bus 27
Real power losses (kW) (P loss)	27.82	24.51	22.03
Imaginary power losses (kVar) (Q loss)	26.51	23.32	20.22
Voltage Deviations Criterion (VI)	0.008	0.005	0.004
Voltage stability criterion (VSC)	0.9	0.91	0.93
Section Balancing Current Criterion (SBCI)	0.3	0.28	0.26

Case B: IEEE 69 bus system

Figure 8 shows the IEEE 69 bus test system. *Figure 8(a)* depicts a single line diagram, whereas *Figure 8(b)* depicts a test system with sectionalizing and tie line switches, respectively.

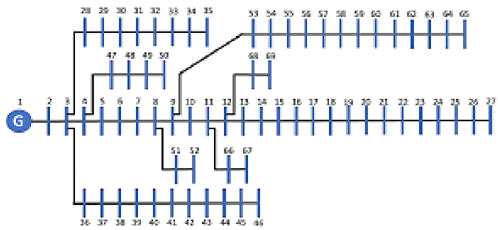

Fig.8(a). Single line representation of IEEE 69 bus system

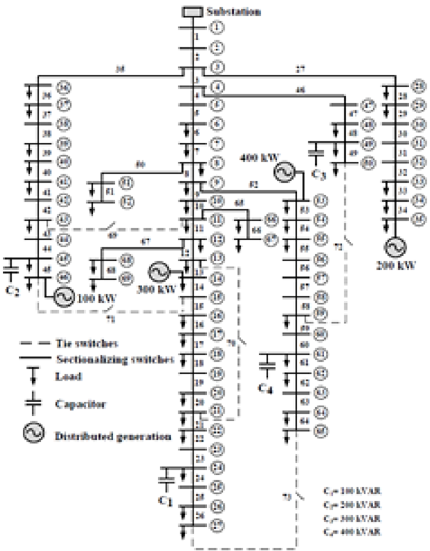

Fig.8(b). IEEE 69 bus system under sensationalizing and tie switches

Table 3 shows a performance comparison. In the base situation, switches 69, 70, 71, 72, and 73 are activated. In this basic situation, the power dissipated and minimum voltage are 225kW and 0.9092 p.u, respectively.

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After applying GWO algorithm for appropriate placement and sizing of DGs and capacitor banks considering network configuration are: three DGs with 0.614 MW, 1.82 MW and 0.6 MW are located at 37, 61 and 22 respectively; three capacitor banks with ratings 0.29 MVAR, 0.926 MVAR & 0.3 MVAR located at 25, 62 and 28 respectively.

After applying GA algorithm for optimal placing and sizing of DGs and bank of Capacitors considering network configuration are: three DGs with 0.4 MW, 0.4 MW and 0.4 MW are located at 58, 61 and 65 respectively; three capacitor banks with ratings 0.5 MVAR, 0.47 MVAR and 0.7 MVAR located at 7, 13 and 61 respectively.

After applying PSO algorithm for optimal location and sizing of DGs and Capacitor banks considering network configuration are: three DGs with 0.35 MW, 0.62 MW also 1.164 MW are located at 11, 18 and 62 respectively; three capacitor banks with ratings 0.2 MVAR, 0.4 MVAR and 0.47 MVAR located at 21, 62 and 64 respectively.

Table 3. Performance comparison table (IEEE 69 bus)

	GA	PSO	GWO
Open Switches	20, 37, 43, 57, 60	13, 17, 47, 49, 69	9,70, 17, 26, 54
DG (optimal sizing (MW) and placement)	0.4@bus 58 0.4@bus 61 0.4@bus 65	0.35@bus 11 0.62@bus 18 1.164@bus 62	0.614@bus 37 1.82@bus 61 0.6@bus 22
Capacitor (optimal sizing (MVar) and placement	0.5@bus 7 0.47@bus 13 0.7@bus 61	0.2@bus 21 0.4@bus 62 0.47@bus 64	0.29@bus 25 0.926@bus 62 0.3@bus 28
Real power losses (kW) (Ploss)	34.27	32.21	10.45
Imaginary power losses (kVar) (Qloss)	32.25	30.09	9.55
Voltage Deviations Criterion (VI)	0.01	0.007	0.002
Voltage stability criterion (VSC)	0.92	0.94	0.96
Section Balancing Current Criterion (SBCI)	0.32	0.29	0.27

5. CONCLUSION

In this analysis, the Grey Wolf Optimizer (GWO) method for determining optimal capacity, DG unit and capacitor bank locations, and network reassembly in distribution network is effectively applied. The proposed solution is created and implemented in the MATLAB/Simulink environment for IEEE 33 and IEEE 69 bus systems. The performance is compared to GA and PSO with respect to performance indicators; the findings prove that the proposed method achieved the objectives more effectively than GA and PSO algorithms.

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