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RESEARCH ARTICLE

Modified Gradient-Based Algorithm for Distributed Generation and Capacitors Integration in Radial Distribution Networks

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ABSTRACT With the use of cutting-edge demand management at the system or home level and powerful network reconfiguration tools, smart grids are expected to introduce advanced hardware and software resources to strengthen the operation of power systems. This article describes a Modified Gradient-Based Optimization (MGBO) algorithm for Distributed Generation (DG) and capacitors integration in distribution feeders. To increase the variety of the produced searching individuals, the suggested MGBO combines the basic Gradient Searching Method (GSM) and Local Escape Mechanism (LEM) with a binomial crossover strategy. This combined cross-over strategy upgrades the forthcoming searching individuals to be more random. The LEM assists in evading local optima, whereas the GSM guides the searching scan to promising regions and facilitates its convergence to the optimum solution. The suggested MGBO method is designed and implemented to improve the performance of radial distribution networks by reducing technical power losses while taking into account the peak loading. Its relevance is tested on a practical radial 59-bus Cairo distribution feeder in Egypt and a large-scale radial 135-bus distribution feeder. The proposed MGBO is compared with the original GBO, Manta ray foraging optimization (MRFO) and honey badger algorithm (HBA). The whole comparison of the suggested MGBO with the original GBO and the newly developed optimization algorithms demonstrates that the suggested MGBO derives the best performance in all of the cases studied. For the practical radial 59-bus Cairo distribution feeder in Egypt, the proposed MGBO shows great improvement of 18.40%, 20.17%, and 2.29% in robustness indicator of the standard deviation compared with GBO, MRFO, and HBA, respectively. For the large-scale radial 135-bus distribution feeder, the proposed MGBO shows great improvement of 46.92%, 62.94%, and 67.87% in robustness indicator of the standard deviation compared with GBO, MRFO, and HBA, respectively.

INDEX TERMS Gradient-based optimizer, distributed generation, capacitors, distribution systems, power losses minimization.

I. INTRODUCTION

Recent years have seen a significant increase in concern about distributed generation (DG) sources as an ongoing strategy for growing electric power networks and electrifying rural regions [1], [2], [3]. The depletion of conventional fossil fuels, the volatility of fuel prices, and the growing recognition of the significance of lowering environmental pollution are all contributing factors to its increasing demand [4], [5]. In order to meet the electrical and thermal energy requirements,

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participants in the European Union (EU) have vowed to use environmentally friendly energy sources at least 20% of the time [6]. A number of European nations, including Sweden, Finland, Denmark, and Germany use a variety of policies and financial plans to achieve substantial DG participation amounts in their current electricity networks [7].

Moreover, according to estimates, the power distribution infrastructure contributes to roughly 70% of the system's losses, which amount to about 13% of the total electricity produced [8]. In order to enhance the performance of power distribution feeders, several technologies are developing and emerging in optimal way. In [9], a mixed-integer nonlinear programming solver has been utilized and addressed for optimally coordinating the DGs, Distributed Thyristor-Controlled Series Compensators (D-TCSC), and Distributed Static VAR Compensators (D-SVC) to minimize the total power losses. In. [10], DGs have been integrated with static and mobile energy storage units in a multi-agent system for service restoration in distribution networks. In [11], a simulated annealing method has been combined with manta ray foraging technique for optimal controlling the operation of automatic voltage regulator (AVR) systems. In [12], a chaotic stochastic fractal searching variant has been adopted for optimal placement of DG units to minimize the network real power loss. In [13], automatic voltage regulators have been installed and operated in distribution networks based on local and remote control and applied for a real Egyptian distribution network with suitable verifications compared to ETAP software. Also, artificial bee colony and firefly algorithms have been utilized to minimize the power losses in [14] and [15], respectively, by searching for the optimal allocations of DGs in the system.

A DG comprises power producers that have less capacity than conventional centrally located power stations and are either built right into the distribution system or situated near consumption centers [16]. It frequently includes small-scale equipment for utilizing both non-renewable and renewable power supplies as an alternative to supplant the centrally controlled power production system [17]. It works for domestic, business, and industrial facilities alongside the capacity to produce electricity and heat [18].

Numerous traditional and optimization methods have been put forth by researchers at various stages of their work to find the precise degree and position of DG penetration while using the least amount of power possible, improving the voltage profile, and maximizing other advantages. Some of the population-based optimization techniques include ant-lion optimizer [19], equilibrium algorithm [20], ant colony algorithm [21], whale optimization technique [22], marine predator algorithm [23], honey badger optimization [24], and so on. The most effective capability of each Photovoltaic (PV) technology should be determined using the Jaya algorithm, according to Ref. [25], as this will increase voltage magnitudes and reduce loss at high penetration levels. Singh et al. [26], which included a voltage magnitude study, losses, and system cost, looked at the effects of DG implementation on the functioning of the distribution network. The method investigated the impact of spreading the DG over the bus where the burden is most important and various sizes of DG impact levels. We also looked at the voltage profile, actual power losses, and overall expense. In [27], a multi-objective framework for allocating solar and wind DGs incorporating capacitors and batteries has been adopted. In this study, GAMS environment software has been applied to maximize the economic index maximization, minimize the system losses, and maximize the voltage stability factor. However, it deals with only the maximization of the economic dimension while both the system losses, and voltage stability factor have been mathematically modeled as constraints regarding to a threshold level. In [28], the siting and sizing of simultaneous DGs and capacitors in distribution systems have been handled and solved using a bidirectional multi-objective coevolutionary algorithm. This technique has been designed for minimizing the power and energy losses, emissions, voltage deviations, and the investment costs of the installed devices while taking into consideration constant and voltage dependent behaviors of power system loadings. Bokhari et al. [29] used in-depth simulation of practical American power systems for studying the voltage quality under preserving voltage reduction and DG integration. According to the research, distributed networks with effective DG in place possessed improved voltage control, allowing utilities to use greater voltage reductions in times of need. It was also demonstrated that when DG penetration is high, the network power factor declines, necessitating a shift in the line drop compensation to take into consideration the elevated power consumption.

Additionally, for reactive power adjustment at carefully chosen places in the distribution systems that address the power quality problems, fixed or switchable capacitor devices are required with optimum sizing and positioning [30], [31]. Furthermore, it offers a wide range of technological and financial benefits, including a decrease in power loss, an increase in load-bus voltage, a better power factor, and a decrease in demands for reactive power from the supplier's perspective [32]. To address the steadily increasing energy demand as well as the technological and financial problems with distribution systems, effective and beneficial planning for reactive compensation of electricity is essential [33]. In [34], whale optimization algorithm has been adopted for capacitors allocation in power distribution networks for minimizing the line losses and the corresponding operating costs.

To satisfy the increased demand for energy and to better technical elements like power loss reduction, voltage profile development, etc., the integration of DGs, and capacitors in radial distribution systems has received little focus. Therefore, simultaneous allocation of both active and reactive power sources via DGs and capacitors is of great importance in distribution systems. In [35], a cuckoo search optimizer has been carried out for allocating shunt capacitors along with DGs to minimize the system losses and enhance the bus voltages. However, this study in [35] is applied to a small rural Indian network comprising 28 buses. In [36], a combined genetic algorithm (GA) with fuzzy concept has been presented in distribution systems for simultaneous allocation of DGs and capacitors. In [37], an intelligent salp swarm optimization has been performed for the same target and tested on IEEE 33 and 69 bus distribution networks. for optimal allocation of DGs and CBs. In [38], a strength Pareto evolutionary optimization has been executed for simultaneous placement of DGs and capacitors in radial distribution feeders and validated on two standard test systems of IEEE 33 and 69-buses. To decrease power loss and enhance the voltage profile of the distribution system, two novel optimizing algorithms—the Firefly Method and the Backtracking Searching technique—have been used to discover the most suitable sizing of DGs and capacitors and where they should be placed [39]. This study has been tested on standard IEEE 33 and 69-bus systems compared to GA, particle swarm algorithm and imperial competitive approach but these methods don't guarantee the achievement of global optimal solutions.

A. PROBLEM STATEMENT

Gradient-Based Optimization (GBO) [40] is a recently created population-based method that guides itself regarding the best solution by using the gradient-based approach proposed by Newton. Its two main components are the Local Escaping Mechanism (LEM) and the Gradient Search Method (GSM). It was effectively employed to multiple engineering problems, such as static var compensator operation in power systems [41], feature selection [42], [43], parameter identification of photovoltaic models [44], human activity recognition using smartphones [45], proton exchange membrane fuel cell parameter estimation [46], structural optimization [47] and economic dispatch [48].

Despite the GBO methods' age of roughly two years, the researchers developed multiple modifications (i.e., versions) that enabled it to become compatible for tackling various types of issues [49]. Despite the fact that GBO has demonstrated its ability to successfully tackle a variety of challenges. However, it appears that many metaheuristic algorithms are ineffective in dealing with all difficulties. As a result, it must be modified depending on the severity of the challenge.

B. PAPER CONTRIBUTIONS

This paper explains the Modified Gradient-Based Optimization (MGBO) method for DG and capacitor incorporation in distribution feeders. The proposed MGBO combines the fundamental Gradient searching Method (GSM) and Local Escape Mechanism (LEM) with a binomial crossover strategy to broaden the variation of the generated seeking people. The upcoming searchers will now be more erratic thanks to this merged crossover approach. The GSM directs the searching scan to promising areas and makes it easier for it to converge to the best answer, whereas the LEM aids in avoiding local optima. The proposed MGBO technique is intended to reduce technological power losses while accounting for peak demand in order to enhance the performance of radial distribution networks. Real radial 59-bus Cairo and large-scale radial 135-bus distribution feeders are used to demonstrate the applicability of the proposed MGBO. It is compared with the original GBO, Manta ray foraging optimization (MRFO) [50] and honey badger algorithm (HBA) [51]. The whole comparison of the suggested MGBO with the original GBO and the newly developed optimization algorithms demonstrates that the suggested MGBO derives the best performance in all of the cases studied. The following is a summary of the paper's major contributions:

- A new MGBO algorithm utilizing an integrated binomial crossover operation has been created for the simultaneous allocations of DGs and capacitors in power distribution networks.
- Great decreases in power losses are achieved via the presented MGBO algorithm for two practical 59-bus Cairo and large-scale radial 135-bus distribution feeders.
- The proposed MGBO algorithm is more effective and highly robust than the original GBO, MRFO, and HBA in minimizing the power losses for a both feeders under six different cases studied.

II. DGs AND CAPACITORS INTEGRATION IN RADIAL DISTRIBUTION NETWORKS

In radial distribution networks, the minimization of the overall technical losses over the distribution lines is usually shown as the main objective function for the optimization model of the allocations of both DGs and capacitors. This objective function can be created by effectively establishing the sizes and placements of the DGs and capacitors while meeting different equality and inequality constraints. The following is a representation of the goal function:

$$Objective = \sum_{k=1}^{N_L} Losses_k = \sum_{k=1 k=ij}^{N_L} G_{ij}\left(V_i^2 + V_j^2 - V_i V_j \cos\theta_{ij}\right) \quad (1)$$

where $Losses_k$ refers to the active power losses in every line (k) in the distribution system; N_L is the number of the distribution lines in the whole system; G_{ij} indicates the mutual conductance between bus i and j; V_i and V_j are the voltage magnitudes, respectively, at buses i and j; θ_{ij} represents the phase angle difference demand power between buses i and j.

A. INEQUALITY CONSTRAINTS RELATED TO THE CONTROL VARIABLES

There are two different kinds of control variables for that issue. Dealing with the capacitors' reactive power sources comes first. The selected buses and capacities to insert capacitors, as in Eqs. (2) and (3), are constrained in this respect.

Taking into consideration their practical form, integer variables are used to represent the potential positions for the capacitors, and discrete variables are used to indicate their sizes.

$$N_{Nodes} \geq CAP_{Bus,j} \geq 1, \quad j = 1, 2, \ldots..N_{CAP} \tag{2}$$
$$CAP_{max} \geq CAP_{Size,j} \geq 0, \quad j = 1, 2, \ldots..N_{CAP} \tag{3}$$

where, CAP_{Bus} alludes to potential places where capacitors could be placed while the number of distribution buses is N_{Nodes} and the number of mounted capacitors is N_{CAP}. The amount of the installed capacitors is indicated by CAP_{Size}, and their utmost size is indicated by CAP_{max}.

At second, there are limits on the buses and capacities that can be used to place DGs, as shown in Eqs. (4) and (5). While the power that will be output from the DGs is depicted by continuous variables, the potential sites for the DGs are integer variables.

$$N_{DGen} \geq DGen_{Bus,i} \geq 1, \quad i = 1, 2, \ldots..N_{DGen} \tag{4}$$
$$DGen_{max} \geq DGen_{Size,i} \geq 0, \quad i = 1, 2, \ldots..N_{DGen} \tag{5}$$

where, $DGen_{Bus}$ alludes to potential sites for installing DGs while their number is symbolized by N_{DGen}. $DGen_{Size}$ and $DGen_{ma_x}$ indicate, respectively, the rated capacity of each DG (i) and its maximum limit.

B. INEQUALITY CONSTRAINTS RELATED TO THE CONTROL VARIABLES

On the other side, diverse inequality constraints must be maintained in terms of the nodes operating voltages, the current flow through the distribution lines and the penetration limit of installing DGs as described in Eqs. (6)-(8), respectively.

$$V_k^{min} \leq V_k \leq V_k^{max} \quad k = 1, 2, ..N_{Nodes} \tag{6}$$
$$|I_k| \leq I_k^{max} \quad k = 1, 2, .N_L \tag{7}$$
$$\sum_{i=1}^{N_{DGen}} DGen_i \leq KP \sum_{j=1}^{N_{Nodes}} (PD_j) \tag{8}$$

where V_k is the voltage magnitude at every distribution node (k); I and I_{max} refer to the current flow through the lines and the regarding thermal limit. PD_j is the active power demand at node (j) while KP represents the penetration percentage that is acceptable for DGs insertion in the system which is usually considered 60% [52], [53].

C. EQUALITY CONSTRAINTS

Additionally, load flow balance limitations in terms of active and reactive power must be achieved as inequality constraints as described in Eqs. (9) and (10), respectively [54].

$$P_{Sub} + \sum_{k=1}^{N_{DGen}} DGen_k > \sum_{j=1}^{N_{Nodes}} PD_j \tag{9}$$
$$Q_{Sub} + \sum_{k=1}^{N_{CAP}} CAP_k > \sum_{j=1}^{N_{Nodes}} QD_j \tag{10}$$

where P_{Sub} and Q_{Sub} addresses, respectively, the supplied active and reactive power from the substation. QD_j is the reactive power demand at node (j).

III. MATHEMATICAL MODEL OF ADVANCED MGBO ALGORITHM

A GBO addresses complex optimization problems by combining population-based and gradient-based methods. The searching agent's orientation is guided through Newton's method which examines the problem space using the GBO algorithm [40]. An improved designed MGBO method is demonstrated by combining the crossover strategy with the basic GBO to further increase the variety of the produced searching agents. The combined crossover strategy results in more randomly generated population in the following iteration while preserving the basic GSM and LEM in the suggested GBO.

A. INITIALIZATION STAGE

The GBO technique begins with a generated set of initial searching solutions and progresses each regarding position along a gradient-determined path as follows:

$$Z_j = Lower + (Upper - Lower) \times rand(1, Dim) j = 1 : NS \tag{11}$$

B. GSM STAGE

The GSM employs a gradient-based method to improve scanning universe exploration and accelerate the convergence of the best choice. To alter the findings after each iteration, the GBO method uses the following mathematical equation:

$$Z_j(t+1) = r_1 \left(r_2 Z1_j(t) + (1 - z_2) Z2_j(t)\right) + (1 - r_1) Z3_j(t) j = 1 : NS; t = 1 : t_{Max} \tag{12}$$

where r_1 and r_2 refer to two random values inside boundary [0 1]; t *and* t_{Max} indicate the current and maximum iteration; *Zj(t+1)* and *Zj(t)* represent newer and previous vectors linked to the solution position (j); *Z1j(t)*, *Z2j(t)* and *Z3j(t)* demonstrate three new assessed solutions as follows:

$$Z1_j(t) = Z_j(t) + \sigma_1 \times rand \times \left(Z_{Best} + Z_j(t)\right) - GSM \quad j = 1 : NS; t = 1 : t_{Max} \tag{13}$$
$$Z2_j(t) = Z_{Best} + \sigma_1 \times rand \times (Z_{R1} + Z_{R2}) - GSM \quad j = 1 : NS; t = 1 : t_{Max} \tag{14}$$
$$Z3_j(t) = Z1_j(t) - \sigma_2 \left(Z2_j(t) - Z1_j(t)\right) \quad j = 1 : NS; t = 1 : t_{Max} \tag{15}$$
$$GSM = \sigma_1 \times randn \left(\frac{2 \times Z_j(t) \times \Delta Z}{\varepsilon + yp_j - yq_j}\right) j = 1 : NS \tag{16}$$

where σ_1 refers to key parameter that varies based on the sine function; σ_2 indicates a randomized parameter; *randn* and *rand* represent, accordingly, a generated integer number and a uniformly distributed generated number inside boundary [0 1]; Z_{Best} is the finest searching solution that gives the minimum objective score; Z_{R1} and Z_{R2} illustrate two randomly selected and different solutions.

C. LEM STAGE

The LEM helps the program avoid local optima. After each iteration, the GBO method modifies the findings using the accompanying mathematical model:

$$Z_j(t+1) = \begin{cases} Z_j(t+1) + \phi_1 \left(I_1 Z_{Best} - I_2 X_{k,It}\right) + \\ \sigma_1 \phi_2 \left(I_3 Z2_j(t) - Z1_j(t)\right) + I_2 \left(Z_{R1} - Z_{R2}\right) \; if \; r_3 < 0.5 \\ Z_j(t+1) + \phi_1 \left(I_1 Z_{Best} - I_2 X_{k,It}\right) + \; if \; r_4 < \Pr \\ \sigma_1 \phi_2 \left(I_3 Z2_j(t) - Z1_j(t)\right) + \dfrac{I_2 \left(Z_{R1} - Z_{R2}\right)}{2} \; Else \end{cases} \tag{17}$$

where Pr is the probable chance that the LEM step will be activated; r_3 and r_4 indicate randomized values inside bound [0 1]; ϕ_1 and ϕ_2 denote two randomized values created using a uniformly distribution function within the set [-1; 1]; I_1, I_2, and I_3 are three randomized number produced through the following equations:

$$I_1 = 2 \times r_5 \times M - (M-1) \tag{18}$$

$$I_2 = r_5 \times M - (M-1) \tag{19}$$

$$I_3 = r_5 \times M - (M-1) \tag{20}$$

$$M = \begin{cases} 0 & H1 > 1/2 \\ 1 & Else \end{cases} \tag{21}$$

where $H1$ indicates a number created at random inside [0; 1] set.

$$Z_j(t) = \begin{cases} Z_{R3} & if \; H2 < 1/2 \\ Lower_j + rand \left(Upper_j - Lower_j\right) & Else \end{cases} \tag{22}$$

where Z_{R3} is an arbitrarily chosen searching individual and $H2$ a number created at random inside [0; 1] set.

D. CROSSOVER STRATEGY INCORPORATION

In order to improve the diversification of the produced searching solutions, an improved evolutionary MGBO method is presented in this article by integrating the crossover strategy with the basic GBO. Based on a crossing chance in each iteration, the crossover strategy is turned on for every searching individual. By swapping the elements of the existing search individual and a randomized one, the crossover strategy produces a new solution vector as follows:

$$Z_j(t+1) = \begin{cases} Z_{SR} & if \; IR < 1/4 \\ Z_j(t) & Else \end{cases} \quad j = 1 : NS \tag{23}$$

where $Zj(t)$ and Z_{SR} stand for the present searching solution and a randomly chosen one from the GBO population. IRaddresses typically an arbitrary number selected from the [0 1] region. This involves applying a binomial crossover strategy to each of the control factors. The major phases of the suggested MGBO are shown in Figure 1.

TABLE 1. Case studies under investigation.

Case Study No.	Type of allocated devices			System under study	No. of search agents	No. of iterations
	DGs only	Capacitors only	DGs and Capacitors			
1	✓	-	-	Practical radial 59-bus Cairo distribution feeder in Egypt	30	60
2	-	✓	-			
3	-	-	✓			
4	✓	-	-	Large scale radial 135-bus distribution feeder	50	150
5	-	✓	-			
6	-	-	✓			

IV. SIMULATION RESULTS

The suggested MGBO's relevance is tested on two distribution power networks. The first one is the practical radial 59-bus Cairo distribution feeder in Egypt [55] while the second one is the large scale radial 135-bus distribution feeder [56]. The proposed MGBO is applied compared to the basic GBO considering the peak nominal loading. The maximum possible number of DGs or capacitors is considered to be while their maximum rates are considered of 5000 kW and 3600 kVAr. The capacitors are considered as integer variables with 300 kVAr step. The proposed MGBO is applied compared to the basic GBO, Manta ray foraging optimization (MRFO) [50] and honey badger algorithm (HBA) [51], [57]. These algorithms are applied with settings of 30 and 50 search agents and 60 and 150 iterations, for radial 59-bus Cairo and 135-bus distribution feeders, respectively. A summary of six case studies is displayed in Table 1 which are investigated based on the type of the allocated devices to be inserted. In this table, the settings of the compared techniques are tabulated as well.

A. PRACTICAL RADIAL 59-BUS CAIRO DISTRIBUTION FEEDER IN EGYPT

This feeder is a practical electrical distribution system that lies in Cairo governorate in Egypt with rated voltage of 22 kV. It has 59 distribution node and its single line configuration is displayed in Fig. 2 [55]. System reactive and apparent power demands are 21.448 MVAr and 50.348 MVA, respectively, for the peak nominal loading.

1) CASE STUDY NO. 1

In this case, active power sources are only considered where DGs are to be optimally installed. To determine the proper positioning and sizing of the DGs, the proposed MGBO is compared to the original GBO, MRFO, and HBA to reduce overall power losses. Table 2 tabulates the DGs' location and power ratings and the converging features of the suggested MGBO, the initial GBO, the MRFO, and the HBA for this case study are also shown in Fig. 3.

As shown, the suggested MGBO determines that 64.902 kW has the best performance with the least amount of power losses. The second-placed HBA experiences power losses of 65.076 kW, while the third-placed MRFO O, and

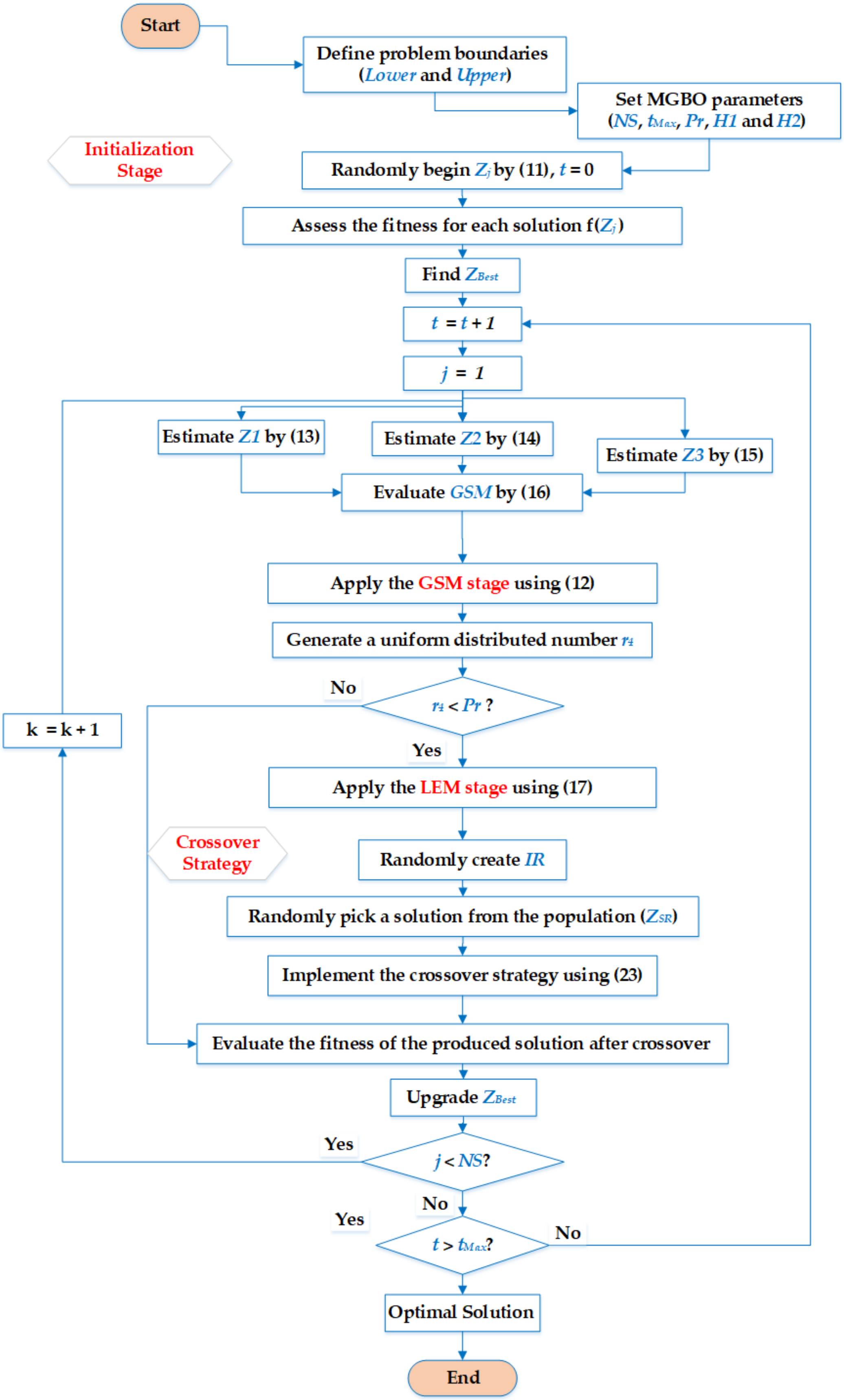

FIGURE 1. Key stages of the innovative proposed MGBO.

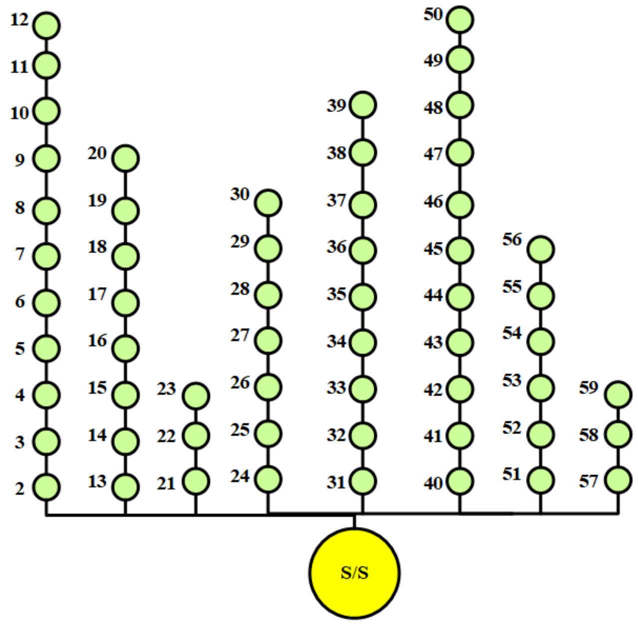

FIGURE 2. Practical radial 59-bus cairo distribution feeder in egypt [58].

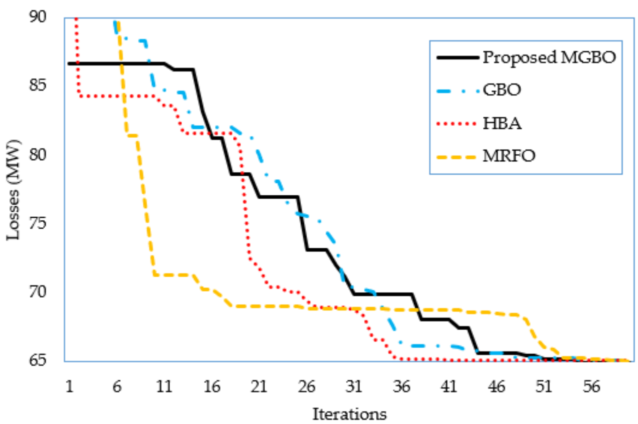

FIGURE 3. Convergence characteristics of MGBO, GBO, MRFO and HBA for the cairo distribution feeder under case study No. 1.

HBA for case stuexperiences losses of 64.997 kW. The original GBO ultimately records power losses of 65.082 kW.

To further assess the effectiveness of the proposed approach compared to existing works, the obtained results of the MGBO technique are contrasted to other approaches from the existing literature of PSO [59] and the binary PSO [59] as depicted in Table 3. As shown, the proposed approach shows higher superiority over PSO () [59] and the binary PSO [59]. The proposed MGBO declares great improvement of 36 % and 47.1 % compared to PSO [59] and the binary PSO [59], respectively.

In contrast to the initial case, Fig. 4 depicts the voltage profile for the proposed MGBO, GBO, MRFO, and HBA. Compared to the initial situation, all of the employed optimization techniques increase the voltage magnitudes at all distribution nodes in this case.

TABLE 2. Allocations of DGs for Cairo distribution feeder under case study No. 1.

Items	Initial Case	Proposed MGBO	GBO	HBA	MRFO
Installed buses	-	45	8	50	50
	-	8	50	8	35
	-	29	44	29	45
	-	35	37	37	8
	-	50	29	45	29
Rate (kW)	-	3877	5000	3525	3471
	-	5000	3802	5000	4413
	-	5000	4020	4962	4125
	-	4263	3920	3917	4990
	-	3961	5000	4303	4919
Losses	218.9067	**64.90198943**	65.08183661	65.07587022	64.99725956

TABLE 3. Comparisons of the MGBO technique and other approaches from the existing literature under case study No. 1.

Items	Losses	Improvement %
Proposed MGBO	**64.90198943**	-
PSO [59]	101.39	35.99%
Binary PSO [59]	122.75	47.13%
Initial Case	218.9067	70.35%

Moreover, Fig. 5 displays the statistical comparisons of the obtained power losses over 30 different separate runs of the proposed MGBO, original GBO, MRFO, and HBA for case study No. 1. As shown, in comparison to all compared methods, the proposed MGBO demonstrates the least best, mean and worst obtained losses of 64.9, 66.71 and 72.64 kW, respectively. Additionally, the proposed MGBO derives great improvement in robustness indicator of the standard deviation (STD), where it achieves the smallest standard deviation of loss with 1.90 KW compared with 2.23, 4.19, and 2.82 for original GBO, HBA, and MRFO, respectively.

2) CASE STUDY NO. 2

In this case, reactive power sources are only considered where capacitors are to be optimally located and sized. To reduce overall power losses, the proposed MGBO, the original GBO, MRFO, and HBA are performed, and Table 4 tabulates the related capacitors' location and power ratings. For this case study, the converging features of the initial GBO, the suggested MGBO, the MRFO, and the HBA are also shown in Fig. 6.

From both Table 4 and Fig. 6, according to the recommended MGBO, 189.826 kW has the most powerful performance and the fewest power losses. Power losses for the HBA in second place are 189.864 kW, and for the MRFO in third place, they are 189.87 kW. In the end, the initial GBO registers power losses of 189.899 kW. In contrast to the

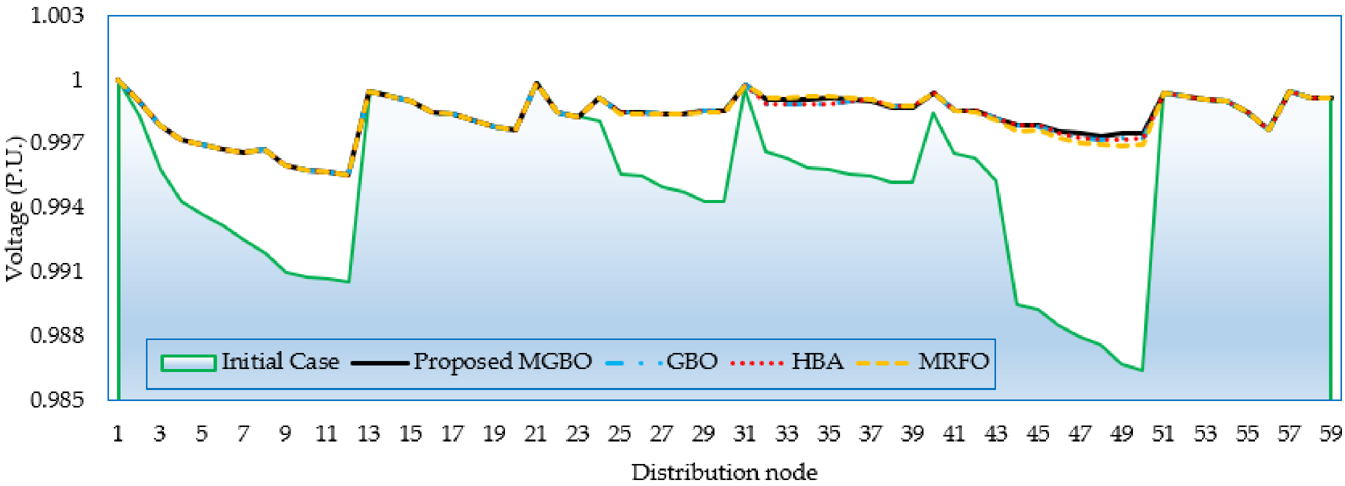

FIGURE 4. Voltage profile for Cairo distribution feeder under case No. 1 versus the outcomes of MGBO, GBO, MRFO, and HBA.

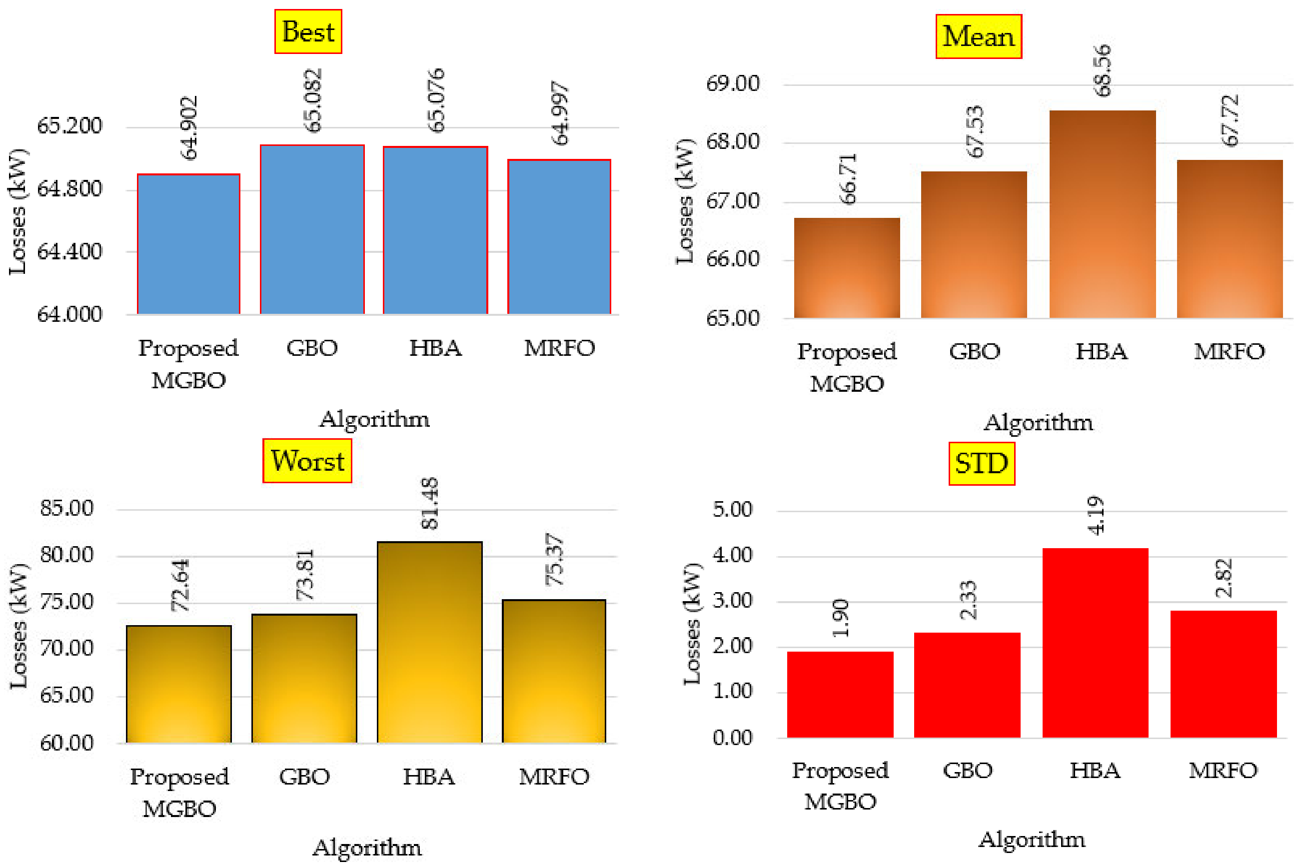

FIGURE 5. Statistical comparisons of the outcomes of MGBO, GBO, MRFO, and HBA for case study No. 1.

initial case, Fig. 7 depicts the voltage profile for the proposed MGBO, GBO, MRFO, and HBA. Compared to the initial situation, all the employed optimization techniques increase the voltage magnitudes at all distribution nodes.

Fig. 8 displays the statistical comparisons of the obtained power losses over 30 different separate runs of the proposed MGBO, original GBO, MRFO, and HBA for case study No. 2. As shown, the proposed MGBO derives great improvement in robustness indicator of the standard deviation (STD), where the proposed MGBO achieve standard deviation of loss with 0.27 KW compared with 0.37, 0.60, and 0.25 for original GBO, HBA, and MRFO, respectively. It is also noticed that

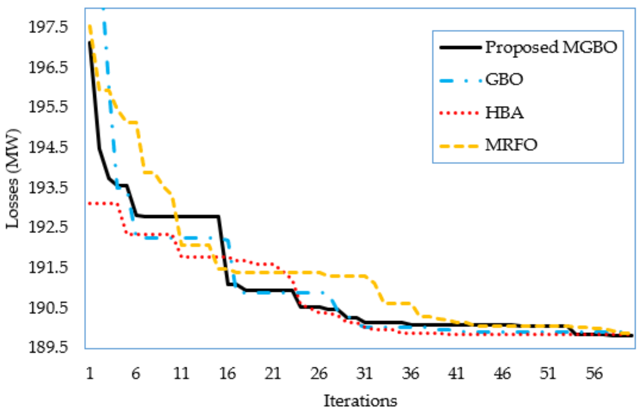

FIGURE 6. Convergence characteristics of MGBO, GBO, MRFO and HBA for the cairo distribution feeder under case study No. 2.

TABLE 4. Allocations of capacitors for Cairo distribution feeder under case study No. 2.

Items	Initial Case	Proposed MGBO	GBO	HBA	MRFO
Installed buses	-	35	29	35	17
	-	17	48	56	48
	-	48	7	7	7
	-	7	55	29	35
	-	29	35	47	29
Rate (kVAr)	-	1800	2100	1800	1500
	-	1800	2700	1200	3000
	-	3000	3000	3000	2700
	-	3300	1800	2400	1800
	-	2400	1800	3300	2400
Losses	218.9067	**189.8265433**	189.8994	189.8646	189.8703

in comparison to the original GBO, the proposed MGBO demonstrates high improving for the best, mean and worst values of the obtained losses. Additionally, the proposed MGBO declares superior performance for achieving the least value of the best objective of 189.83 kW. Also, the MRFO achieves comparable outcomes with the MGBO under this case in finding the least mean of 190.11 kW and standard deviations of 0.25 and 0.27, respectively.

3) CASE STUDY NO. 3

In this case, simultaneous active and reactive power sources via installing DGs and capacitors are considered for minimizing the overall power losses. For this target, Table 5 tabulates the locations and power ratings of both capacitors and DGs based on the initial GBO, the suggested MGBO, the MRFO, and the HBA. The corresponding converging features for this case are also shown in Fig. 9. As shown, the suggested MGBO has the capability to achieve the minimum power losses of 39.960 kW where the HBA, MRFO and the original GBO experiences power losses of 40.544, 40.373 and 40.443 kW, respectively.

Fig. 10 shows the voltage profile for the suggested MGBO, GBO, MRFO, and HBA in comparison to the initial instance. All of the utilized optimization methods raise the voltage magnitudes at all distribution nodes in comparison to the initial state.

Moreover, Fig. 11 displays the statistical comparisons of the obtained power losses over 30 different separate runs of the proposed MGBO, original GBO, MRFO, and HBA. As shown, in comparison to the original GBO, the proposed MGBO demonstrates high improving percentage of the obtained losses of 1.19%, 1.02%, and 1.44%, for the best value of GBO, MRFO, and HBA, respectively. Besides, the mean values obtained from the proposed MGBO refer to the high improving percentage of the obtained losses of 3.10%, 2.52%, and 4.96%, for the GBO, MRFO, and HBA, respectively. In the line with these improvements, the proposed MGBO manifest high enhancements in the worst values, where it achieves improving the percentage of the obtained losses of 5.32%, 11.44%, and 3.40%, for the GBO, MRFO, and HBA, respectively. It is worthy noticed that the proposed MGBO derives great improvement of 18.40%, 20.17%, and 2.29% in robustness indicator of the standard deviation (STD) compared with GBO, MRFO, and HBA, respectively.

B. LARGE SCALE RADIAL 135-BUS DISTRIBUTION FEEDER

The second system is another practical distribution feeder which has 135 nodes and eight distribution feeders where its configuration is depicted in Fig. 12, and its standard voltage is 13.686 kV [56]. System reactive and active power demands are 7.9 MVAr and 18.3 MW, respectively, for the peak nominal loading.

1) CASE STUDY NO. 4

For this case, the proposed MGBO, original GBO, MRFO, and HBA are applied to size and site DGs to reduce overall power losses. Table 6 tabulates their obtained locations and power ratings of the DGs while their related converging features are shown in Fig. 13.

In addition, the obtained results of the MGBO technique are contrasted to Mixed-Integer Linear Programming [60] as depicted in Table 7. As shown, the proposed approach shows higher superiority over Mixed-Integer Linear Programming [60] with great improvement of 28.02 %.

According to the recommended MGBO, which is illustrated, 122.174 kW has the most efficient performance and the fewest power losses. Power losses for the second-placed HBA are 123.800 kW, while losses for the third-placed MRFO are 122.033 kW. Power losses totaling 122.290 kW are eventually recorded by the initial GBO.

Fig. 14 shows the voltage profile for the suggested MGBO, GBO, MRFO, and HBA in comparison to the initial instance. All of the utilized optimization methods raise the voltage magnitudes at all distribution nodes in comparison to the initial state.

2) CASE STUDY NO. 5

For this case, the proposed MGBO, original GBO, MRFO, and HBA are applied to size and site capacitors and Table 8

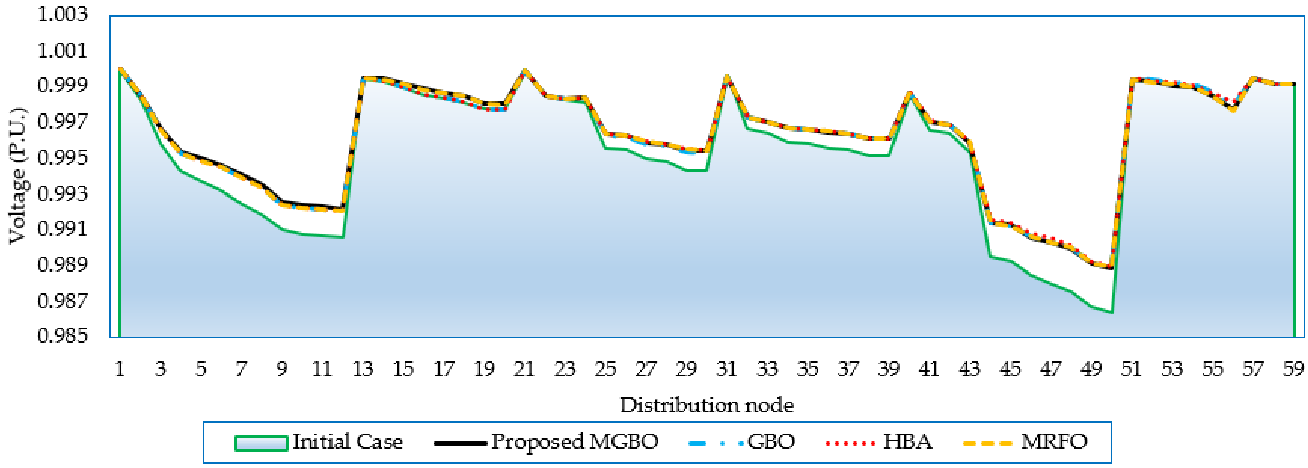

FIGURE 7. Voltage profile for cairo distribution feeder under case No. 2 versus the outcomes of MGBO, GBO, MRFO, and HBA.

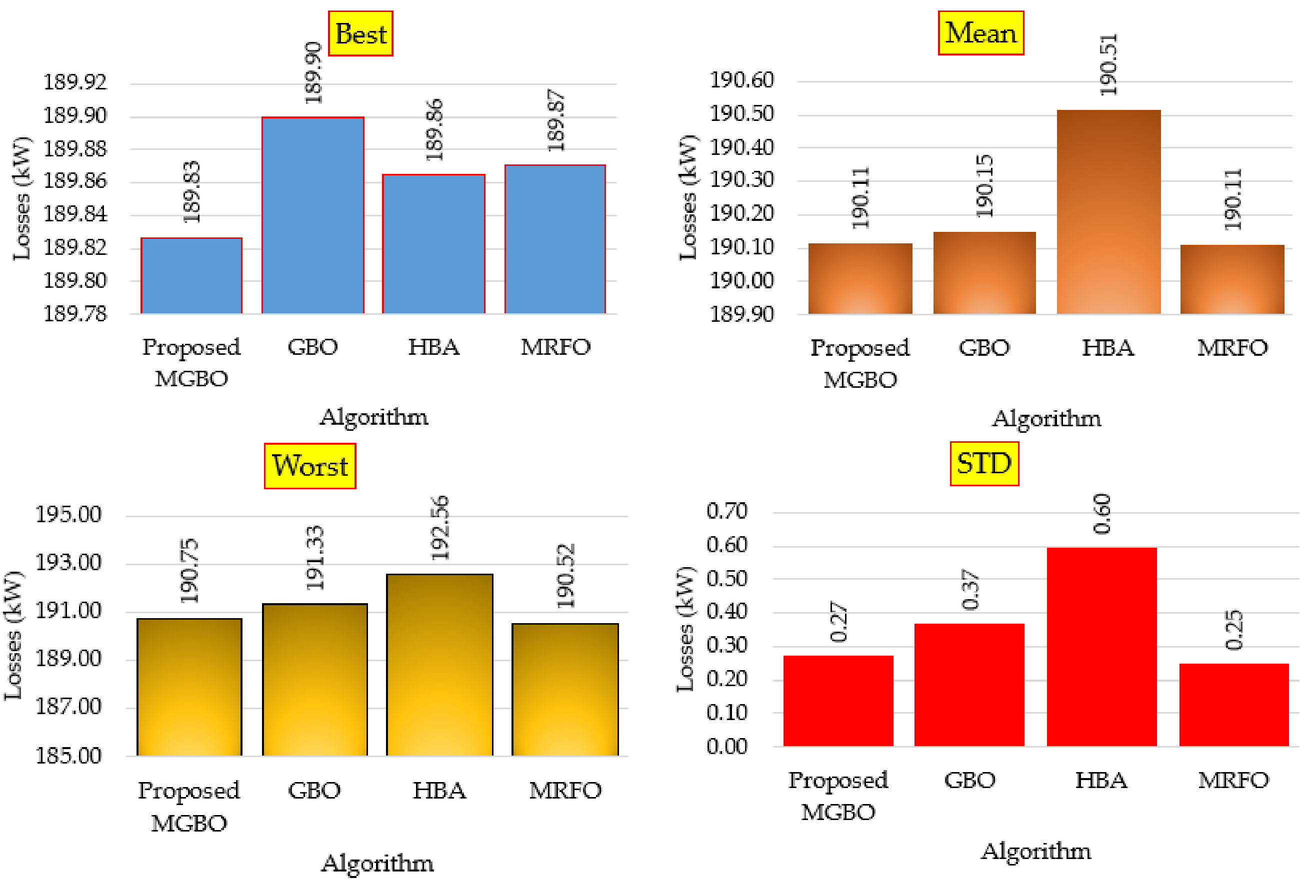

FIGURE 8. Statistical comparisons of the outcomes of MGBO, GBO, MRFO, and HBA for case study No. 2.

tabulates their acquired capacitors' location and power ratings. As shown, the suggested MGBO obtains the least power losses of 275.220 kW while HBA, MRFO and the original GBO experience power losses of 275.980, 275.280 and 275.290 kW, respectively.

Also, the converging features of the initial GBO, the suggested MGBO, the MRFO, and the HBA for the 135-bus distribution feeder under case study No. 5 are also shown in Fig. 15. As shown, the proposed MGBO declares high capability in evolving the best solution as it

TABLE 5. Allocations of capacitors and DGs for cairo distribution feeder under case study No. 3.

Items		Initial Case	Proposed MGBO	GBO	HBA	MRFO
Capacitors	Installed buses	-	28	29	27	8
		-	36	14	37	27
		-	48	10	8	35
		-	52	48	48	45
		-	11	4	7	47
	Rate (kVAr)	-	2700	1500	3300	3000
		-	2100	2400	1800	3000
		-	3300	1500	1500	1800
		-	2100	3000	2700	1500
		-	1800	1500	600	2400
DGs	Installed buses	-	50	50	49	8
		-	44	8	8	49
		-	29	35	37	29
		-	35	44	44	37
		-	8	29	29	44
	Rate (kVAr)	-	2989	4582	4707	4862
		-	4886	4996	5000	4491
		-	5000	4179	2921	4525
		-	4483	3660	3451	3197
		-	4717	4995	5000	2773
Losses		218.9067	**39.95974636**	40.44334	40.54361	40.37314

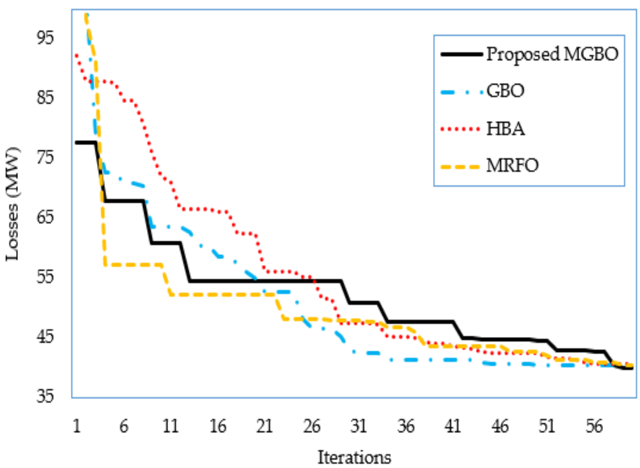

FIGURE 9. Convergence characteristics of MGBO, GBO, MRFO and HBA for the cairo distribution feeder under case study No. 3.

TABLE 6. Allocations of DGs for 135-bus distribution feeder under case study No. 4.

Items	Initial Case	Proposed MGBO	GBO	HBA	MRFO
Installed buses	-	32	106	52	90
	-	106	49	82	49
	-	52	32	14	106
	-	90	14	29	14
	-	11	90	106	32
Rate (kVAr)	-	1906	2774	2207	1971
	-	2767	2230	1297	2125
	-	2141	1982	2203	2801
	-	1932	2061	2064	2144
	-	2241	1935	2841	1946
Losses	320.35	**122.174**	122.290	123.800	122.033

TABLE 7. Comparisons of the MGBO technique and other approaches from the existing literature under case study No. 4.

Items	Losses	Improvement %
Proposed MGBO	**122.174**	-
Mixed-Integer Linear Programming [60]	169.74	28.02%
Initial Case	320.35	61.86%

outperforms the others from the iteration 63 until the end of iterations.

Fig. 16 shows the voltage profile for the suggested MGBO, GBO, MRFO, and HBA in comparison to the initial instance. Every optimization method used raises the voltage magnitudes at every distribution point in comparison to the initial state. To further assess the effectiveness of the proposed approach compared to existing works, the obtained results of the MGBO technique are contrasted to other approaches from the existing literature of hybrid method, genetic algorithm and PSO as depicted in Table 9. As shown, the proposed approach shows higher superiority over hybrid method [61], genetic algorithm. [62] and PSO [62]. The proposed MGBO declares great improvement of 12.2 %, 9.07 % and 8.95 %, respectively.

Fig. 17 displays the statistical comparisons of the obtained power losses over 30 different separate runs of the proposed MGBO, original GBO, MRFO, and HBA for case study

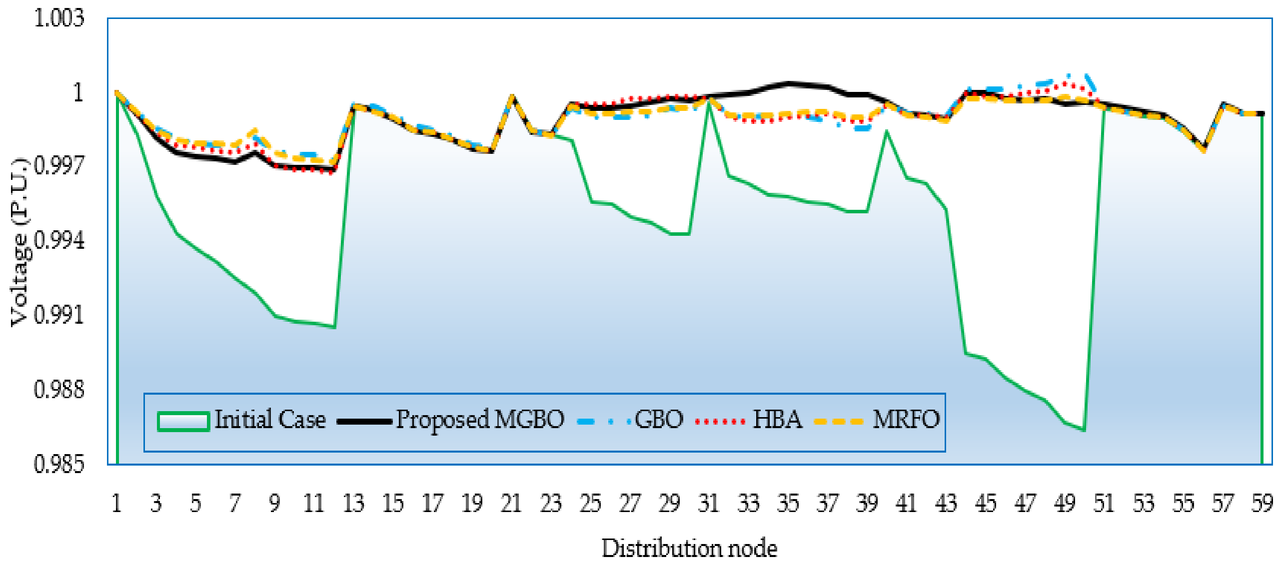

FIGURE 10. Voltage profile for cairo distribution feeder under case No. 3 versus the outcomes of MGBO, GBO, MRFO, and HBA.

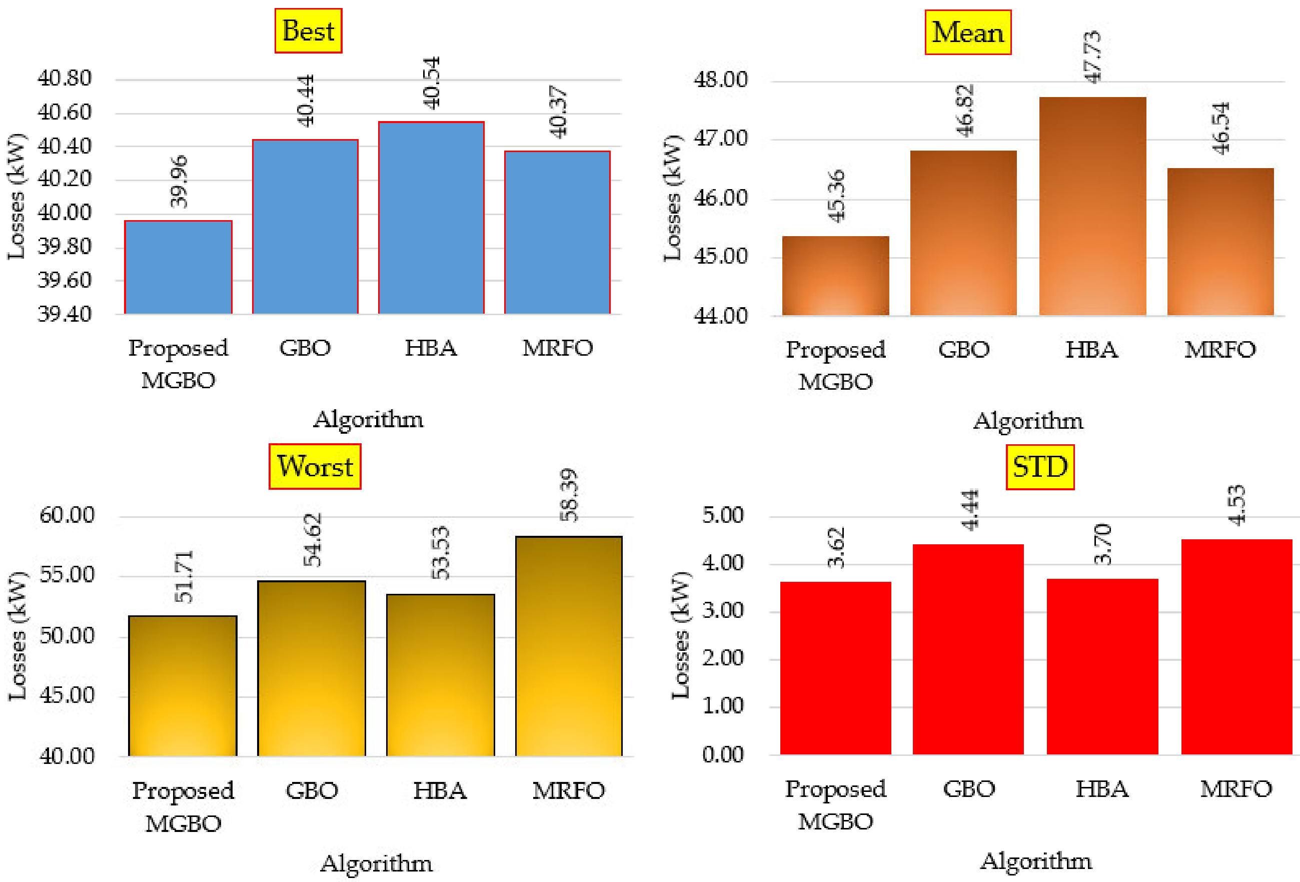

FIGURE 11. Statistical comparisons of the outcomes of MGBO, GBO, MRFO, and HBA for case study No. 3.

No. 5. The proposed MGBO derives great improvement in robustness indicator of the standard deviation (STD), where the proposed MGBO achieves standard deviation of loss with 0.44 compared with 1.58, 3.15, and 0.8 for original GBO, HBA, and MRFO, respectively. It is also noticed that in comparison to the other applied algorithms, the proposed

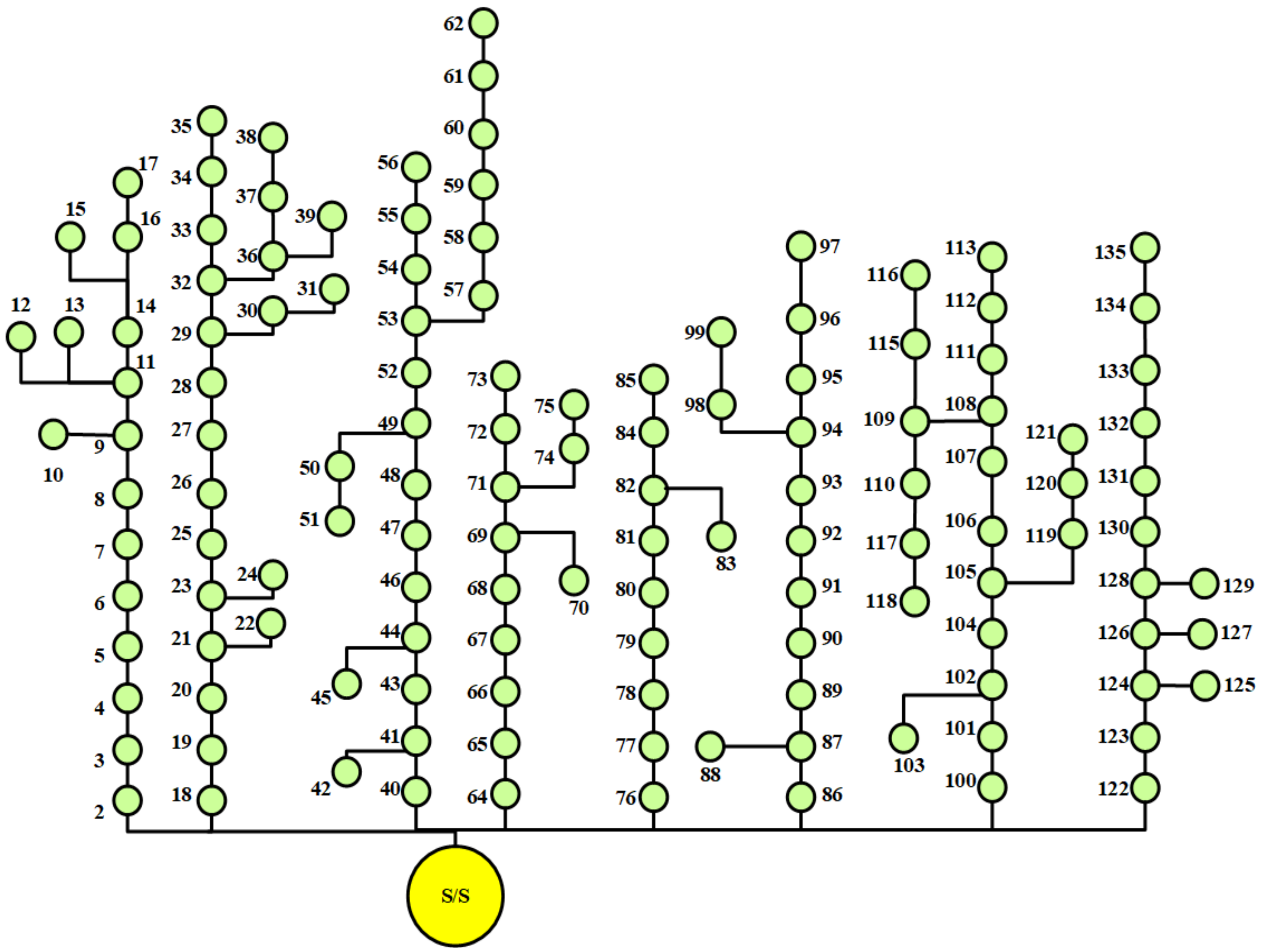

FIGURE 12. Large scale radial 135-bus distribution feeder.

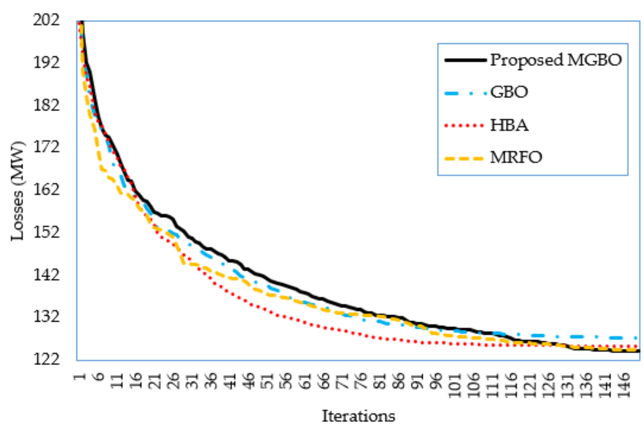

FIGURE 13. Average convergence curves of MGBO, GBO, MRFO and HBA for 135-bus distribution feeder under case study No. 4.

TABLE 8. Allocations of capacitors for 135-bus distribution feeder under case study No. 5.

Items	Initial Case	Proposed MGBO	GBO	HBA	MRFO
Installed buses	-	11	106	90	106
	-	106	48	52	48
	-	49	28	106	11
	-	133	11	11	32
	-	28	133	28	133
Rate (kVAr)	-	900	1500	900	1500
	-	1500	1200	900	1200
	-	900	1200	1500	900
	-	900	1200	1200	900
	-	1200	900	1200	900
Losses	320.350	**275.220**	275.290	275.980	275.280

MGBO demonstrates the least power losses for the best, mean and worst values of 275.22, 275.67 and 276.67 kW, respectively.

3) CASE STUDY NO. 6

For this case, DGs and capacitors are optimally allocated using the proposed MGBO, original GBO, MRFO, and HBA.

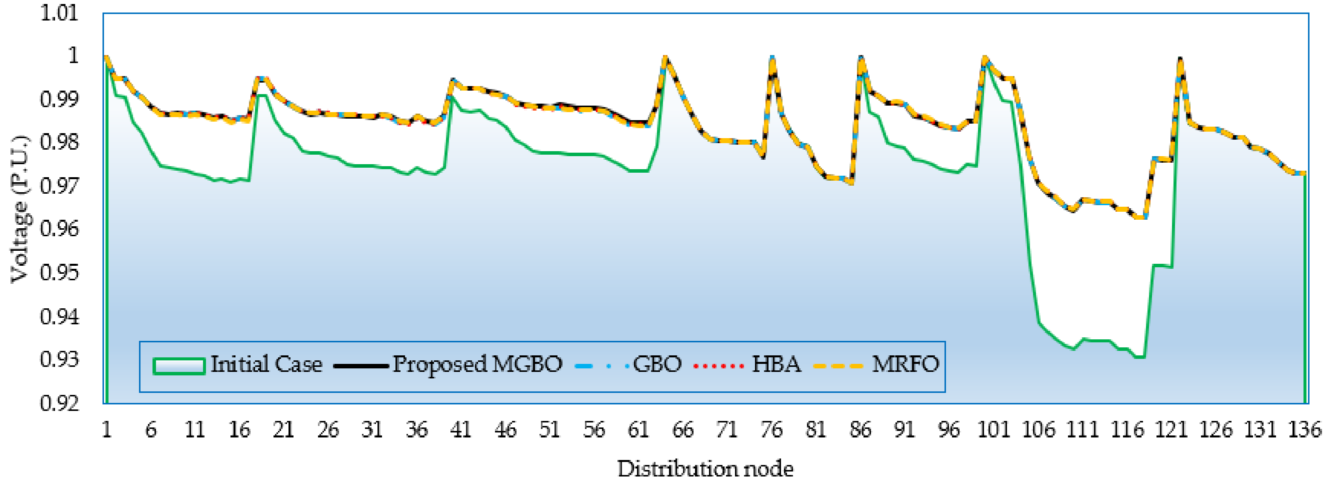

FIGURE 14. Voltage profile for 135-bus distribution feeder under case No. 4 versus the outcomes of MGBO, GBO, MRFO, and HBA.

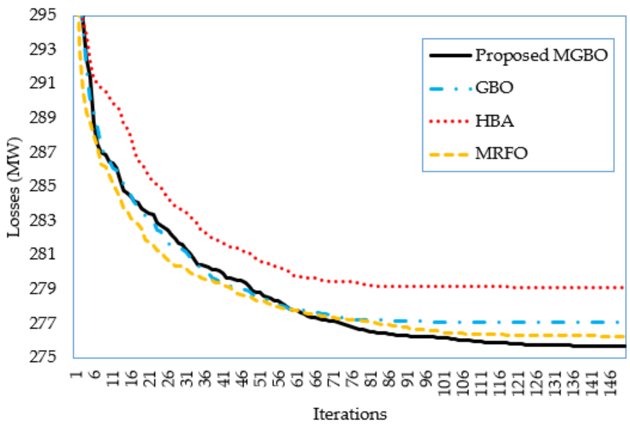

FIGURE 15. Average convergence curves of MGBO, GBO, MRFO and HBA for 135-bus distribution feeder under case study No. 5.

TABLE 9. Comparisons of the MGBO technique and other approaches from the existing literature under case study No. 5.

Items	Losses	Improvement %
Proposed MGBO	**275.220**	-
Hybrid method [61]	313.53	12.22%
Genetic Algorithm [62]	302.67	9.07%
PSO [62]	302.28	8.95%
Initial Case	320.350	14.09%

In this regard, Table 10 tabulates their allocated locations and power ratings of both capacitors and DGs whereas the regarding converging features are displayed in Fig. 18. From Table 10, the proposed MGBO selects the buses 28, 90, 53, 106 and 11 to install capacitors with power ratings of 600, 900, 900, 1200 and 600 kVar, respectively. At the same time,

TABLE 10. Allocations of capacitors and DGs for 135-bus distribution feeder under case study No. 6.

Items		Initial Case	Proposed MGBO	GBO	HBA	MRFO
Capacitors	Installed buses	-	28	29	111	29
		-	90	49	57	90
		-	53	133	132	106
		-	106	14	86	78
		-	11	106	28	57
	Rate (kVAr)	-	600	1200	900	600
		-	900	900	900	900
		-	900	900	600	1200
		-	1200	900	2700	600
		-	600	1200	900	900
DGs	Installed buses	-	11	84	57	52
		-	106	111	106	84
		-	133	53	9	11
		-	52	14	29	29
		-	32	32	90	106
	Rate (kVAr)	-	2087	1272	1995	2273
		-	2593	2488	2684	1252
		-	1647	1829	2549	2276
		-	2179	2258	1837	2032
		-	1840	1992	1835	2849
Losses		320.350	**91.900**	93.67425	96.45473	92.22379

the proposed MGBO selects the buses 11, 106, 133, 52 and 32 to install DGs with power ratings of 2087, 2593, 1647, 2179 and 1840 kW, respectively. From Fig. 18, the suggested MGBO determines that 91.900 kW has the best performance with the least amount of power losses. The HBA, MRFO and the original GBO acquire power losses of 96.455, 92.224 and 93.674 kW, respectively.

Furthermore, Fig. 19 displays the statistical comparisons of the obtained power losses over 30 different separate runs of the proposed MGBO, original GBO, MRFO, and HBA for case study No. 6.

As shown, the proposed MGBO demonstrates high improving percentage of the obtained losses of 1.89%, 0.35%, and 4.72%, for the best value of GBO, MRFO, and HBA, respectively. Besides, the mean values obtained from the proposed MGBO refer to the high improving percentage of

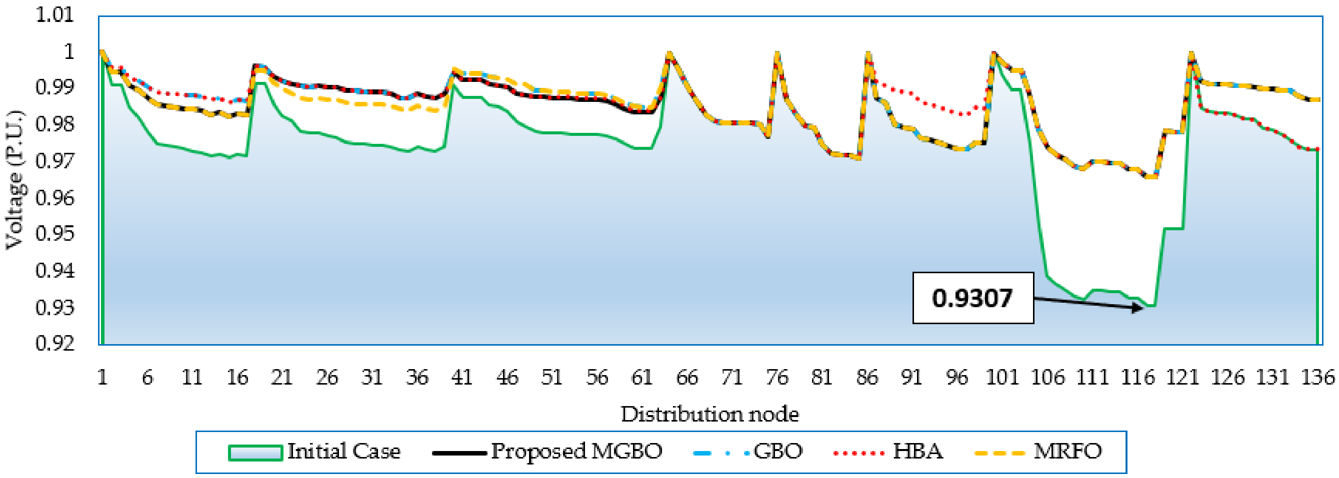

FIGURE 16. Voltage profile for 135-bus distribution feeder under case No. 5 versus the outcomes of MGBO, GBO, MRFO, and HBA.

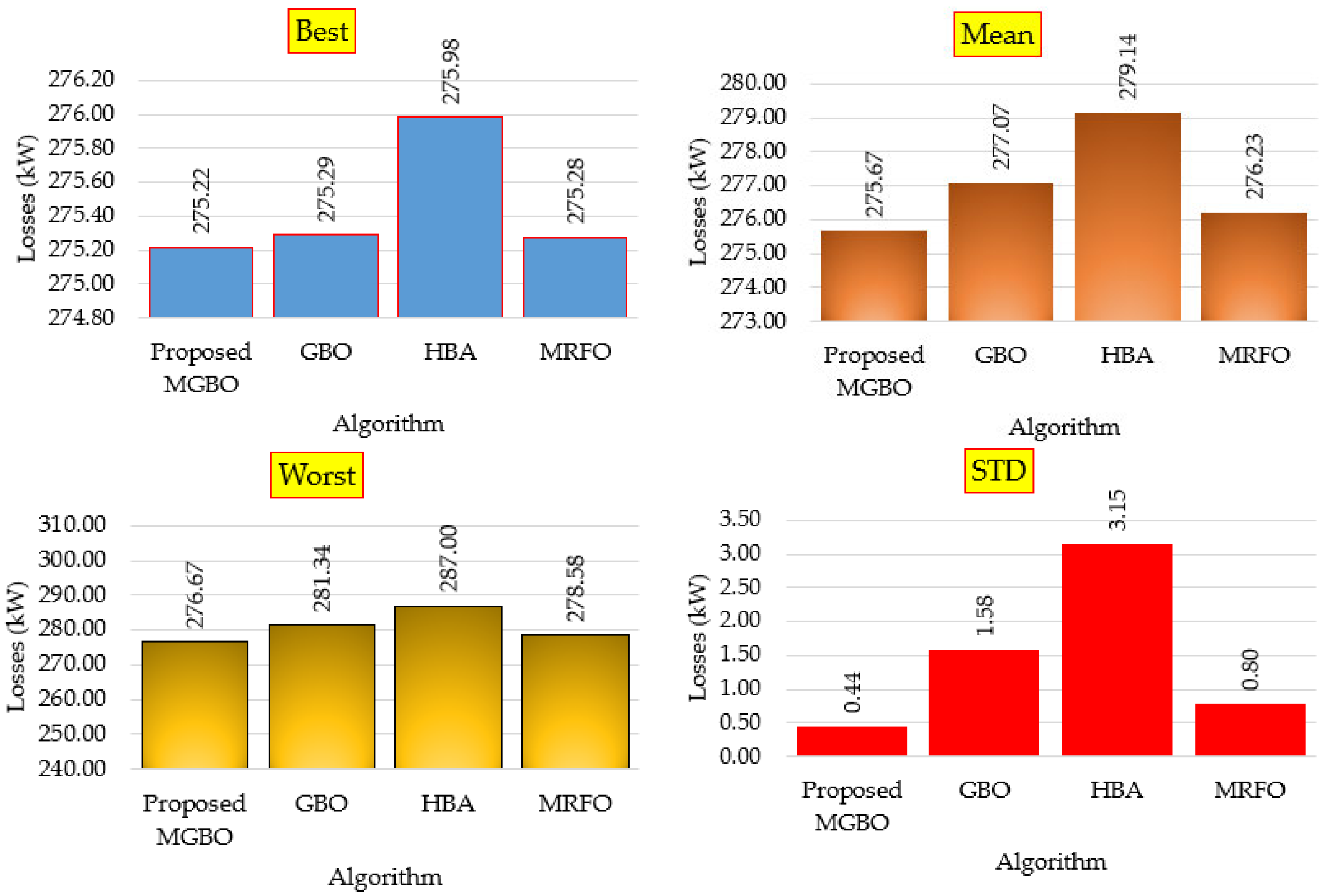

FIGURE 17. Statistical comparisons of the outcomes of MGBO, GBO, MRFO, and HBA for case study No. 5.

the obtained losses of 2.49%, 1.40%, and 9.69%, for the GBO, MRFO, and HBA, respectively.

In the line with these improvements, the proposed MGBO manifest high enhancements in the worst values where it achieves improving percentage of the obtained losses of 6.25%, 18.39%, and 16.89%, for the GBO, MRFO, and HBA, respectively. It is worthy noticed that the proposed MGBO derives great improvement of 46.92%, 62.94%, and 67.87% in robustness indicator of the standard deviation (STD) compared with GBO, MRFO, and HBA, respectively.

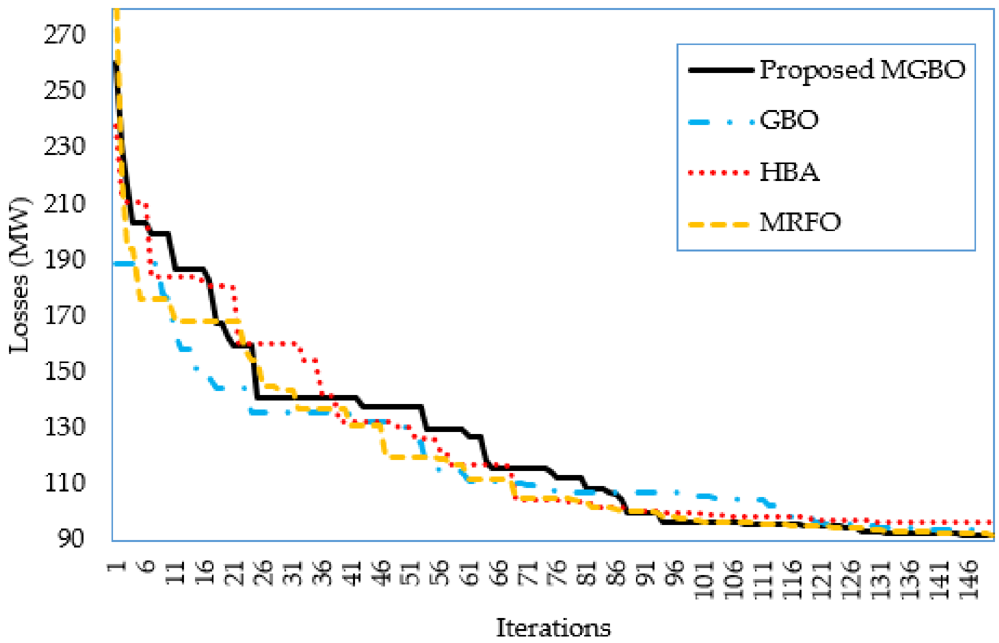

FIGURE 18. Convergence characteristics of MGBO, GBO, MRFO and HBA for 135-bus distribution feeder under case study No. 6.

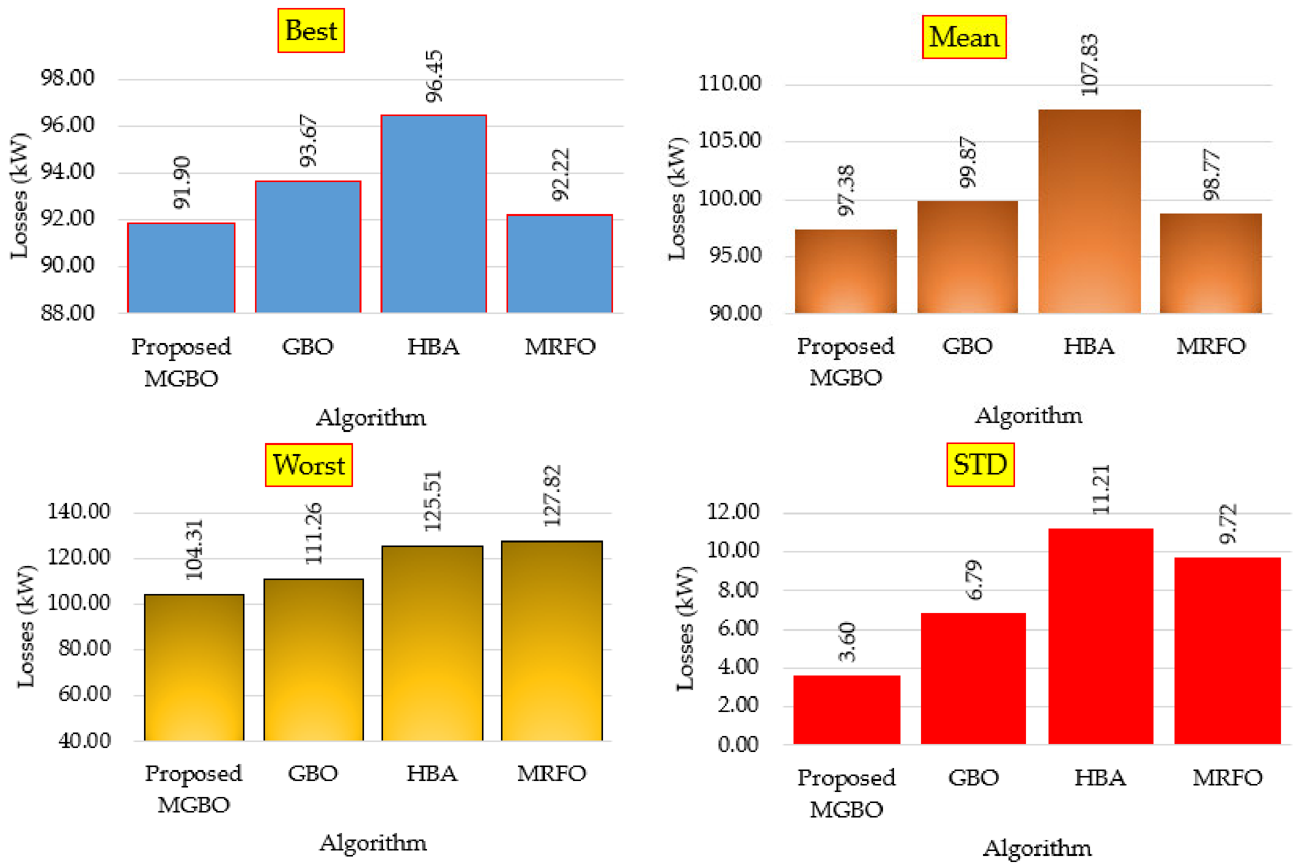

FIGURE 19. Statistical comparisons of the outcomes of MGBO, GBO, MRFO, and HBA for case study No. 6.

V. CONCLUSION

In this study, a modified version of Gradient-Based Optimization (MGBO) algorithm is presented to improve the performance of radial distribution networks by reducing technical power losses while taking into account the peak loading. The basic Gradient Searching Method (GSM) and Local

Escape Mechanism (LEM) with a binomial crossover strategy are emerged with the original GBO. The suggested MGBO method is designed and tested on a practical radial 59-bus Cairo distribution feeder in Egypt and a large-scale radial 135-bus distribution feeder. The suggested MGBO is compared with the original GBO and new developed optimization algorithms which are MRFO, and HBA. The results proved that the suggested MGBO algorithm overwhelmed the original GBO and the newly developed optimization algorithms in the best, mean, worst, and standard deviation values. Besides, the simulation results characterize the superiority of the suggested MGBO compared to the original GBO, MRFO, and HBA for solving the radial distribution networks issue.

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