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Optimal Operation of Automated Distribution Networks Based-MRFO Algorithm

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ABSTRACT Nowadays, distribution utilities expend large investments on Distributed System Automation (DSA) based on smart secondary substations at load, capacitor, and distributed generator points with installed automatic sectionalizing switches on their branches. This article addresses the optimal control and operation of distribution systems that minimize the wasted energy and introducing quantitative and qualitative power services to meet consumers' satisfaction. Simultaneous allocations of Distributed Generators (DGs) and Capacitor Banks (CBs) are handled at peak loading condition. Then, the DSA is optimally activated for optimal Distribution Network Reconfiguration (DNR), optimal DGs commitment, and optimal CBs switching for losses minimization in coordination with different loading conditions. Practical daily load variation is applied to simulate the dynamic operation of automated distribution systems. For achieving these targets, the Manta Ray Foraging Optimization Algorithm (MRFOA) is adopted. MRFOA is an effective and simple structure optimizer that emulates three various individual manta rays foraging organizations. The capability of the MRFOA is applied to the IEEE 33-bus, 69-bus and practical distribution network of 84-bus due to the Taiwan Power Company (TPC). A comparison with recent techniques has been conducted to prove the effectiveness of MRFOA. The accomplished results demonstrate that the proposed MRFOA has great effectiveness and robustness among other optimization techniques.

INDEX TERMS Distributed generators, power losses minimization, switched capacitors, distribution reconfiguration, manta ray foraging algorithm.

NOMENCLATURE

N_{bn}	Whole number of the branches in the system
OFn	Objective function
CoV	Control variables
OT	Tie branches which are opened
N_T	Number of branches which could be opened to retain the radial structure of distribution system.
Qsc	Reactive output power from switching of the capacitors
N_C	Number of the current switched capacitors.
Pog	Dispatchable output power of DG
N_{dg}	Number of located DGs
Qsc^{min}	Minimum of reactive power resulting from switched capacitors
Qsc^{max}	Maximum of reactive power resulting from switched capacitors
Pog^{min}	Minimum of active power resulting from DG
Pog^{max}	Maximum of active power resulting from DG
V	Voltage magnitude
I_{bn}	Flow of the current in the branches
I_{bn}^{max}	Upper limit of the current flow in the branches

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Pd	Active load demand
Qd	Reactive load demand
PR_G & PR_Q	Penetration level which is acceptable from the DGs and CBs
M_b	Buses number of the system
QG_{sub}	Substation reactive power
PG_{sub}	Substation active power
M_{LC}	Number of designated load conditions
P_M	Number of populations of the manta rays
It_m	Maximum number of iterations
M_m	Individual of each manta ray (m)
M^*	New position of the manta ray position
M_B	Best position in the population
β & σ	Adaptive weight coefficients
S	Somersault coefficient
r_1, r_2, r_3 and r_4	Random uniformly distributed number in range [0, 1]

I. INTRODUCTION

The rapid power demand increase with limited generation and transmission expansion is a big challenge for numerous electrical grids. Therefore, the conventional distribution systems suffer from excessive losses, poor voltage regulation, continuous overloading, unreliability, and service insecurity [1], [2]. Commonly, the enhancement of distribution systems requires addition of active and reactive power resources and controlling these injected active and reactive power. Also, controlling the power flow through the system feeders is usually recommended techniques especially in case of modern active distribution systems. These can be accomplished using distributed generators (DGs), capacitor banks (CBs), distribution network reconfiguration (DNR). Non-automated distribution systems can't make use of these devices and sometimes have the opposite effect on distribution system performance [3], [4].

Distribution system planners and operators seek, always, to improve the performance of distribution systems using the CBs, DGs, and DNR in a separate manner or an optimal combination. Performance enhancement of the distribution system can greatly reduce the dissipated power and save millions of dollars per year. Also, reliable and secure power service can be achieved which is faced by consumers' satisfaction. In addition to this, sensitive devices to system voltage can maintain safe operation with voltage performance enhancement of the distribution systems which can increase the lifetime of these devices [5], [6].

Distribution system operators and planners' interests focused on improving distribution systems by optimizing the CBs, DGs and DNRs using the analytical techniques or meta-heuristic techniques [7]. Although the simplicity of the analytical techniques and its fast computation, different limitations are obstacles to apply the analytical techniques for the simultaneous achievement of multi-objectives. A shortage of analytical techniques can be overcome with meta-heuristic techniques and guarantee global optimal solution [8].

Several algorithms have been applied for optimal allocations and control of the CBs enhancement device on the distribution networks [9]–[11]. In similar manner, planners of distribution systems have great attention to optimal sizes and allocation of the DGs on the distribution networks, where a number of techniques have been introduced in literature [3], [12]–[14]. The interests of the distribution system researchers and planners did not stop there, but rather numerous techniques have been introduced for optimal control of DNR [15]–[17]. All of these researches are seek to give reliable service with satisfied power quality and minimum wasted energy with optimal allocation of the DGs, CBs, and DNR in a separate manner. To achieve this target, different meta-heuristic techniques have been applied in the previous literature for separate allocation and control of the DGs, CBs and DNR such as particle swarm optimization (PSO) [3], gravitational search algorithm [9], backtracking search optimizer [10], grasshopper optimization algorithm [11], stochastic fractal search algorithm [12], grey wolf optimizer [13], multi-objective chaotic differential evolution [14], non-dominated sorting genetic algorithm [15], selective firefly algorithm [16], feasibility-preserving evolutionary optimization [17].

Maximizing the benefits of CBs, DGs, DNR allocation, and control on the distribution systems, planners, and researchers of the distribution systems introduce the simultaneous allocation of these devices using different algorithms. Optimal DNR and CBs placement are presented in literature such as improved binary PSO [18], hybrid shuffled frog leaping algorithm in the fuzzy framework [19]. In addition to this, optimal DNR and DGs placement are manifested in literature based on various algorithms such as the dataset approach and water cycle algorithm [4], improved elitist–Jaya algorithm [7], and improved sine–cosine algorithm [20]. Furthermore, optimal DGs and CBs placement in distribution systems has been manifested in various articles using meta-heuristic techniques such as the water cycle algorithm [2], PSO [3], genetic algorithm [6], and enhanced grey wolf algorithm [21]. In [22], tabu search and PSO algorithms have been presented in a comparative manner for DNR with the allocation of different DG types to improve the voltage profile and minimize the losses, but the daily load variations have not been included.

In [23], a multi-objective ant lion optimizer was applied for DG planning integrated with energy storage. However, this study seeked for maximizing the voltage stability and the investment benefits, the installed locations were prespecified based on the loss sensitivity factor which is unsuitable for large scale systems and restricts the search space. In [24], an optimal methodology was introduced to maximize the profits of the distribution operator by promoting flexibility in the supply of energy on the market via the control of active and reactive power through the distribution of flexible loads and the controllable inverters of the connected solar DG units. In this analysis, load aggregators were designed to model and identify flexible loads, while the reactive power controllability of solar inverters was considered. On the other hand, the smart feature of the DNR capability related to smart grids and the reactive power support of the capacitors were neglected.

The complexity of the optimization problem of simultaneous allocation and control of all enhancement devices (DGs, CBs, and DNR) at the same time make it rarely to find literatures that can solve this problem. Additionally, most of the previous literatures introduce the optimal operation of the distribution systems only at peak demand; however, they neglected practical load variation, that may conflict with practical distribution systems operating conditions. The target of this article is to fill this gap by introducing a Manta Ray Foraging Optimization Algorithm (MRFOA) for simultaneous allocation and control of DGs, CBs, and DNR. MRFOA was developed and proposed by Zhao and others [25], which has higher performance, lower computational cost, and solution accuracy. Several real-world designs were effectively inspected by MRFOA such as pressure vessel, rolling-element bearing, welded beam, multiple disc clutch brake [25], optimal power flow [26], and power and heat dispatch [27]. The main features of the proposed study are:

- The MRFOA is adopted for simultaneous DGs/CBs allocation considering the peak loading condition.
- For this target, the superiority of the proposed MRFOA is demonstrated by a comparison with other recent techniques; PSO, IMDE, TSA, EGA, GA, slime mould algorithm, and crow search optimizer.
- The proposed technique is employed with DSA for optimally coordination of the DNR, the DGs power output, and the operating capacitor step for losses minimization considering the loading variations.
- Practical daily load variation is applied to analyze the dynamic operation of automated distribution systems.
- For all load levels, the proposed MRFOA presents better convergence and performance compared to the recent TSA and ITSA
- Semi-automated distribution systems are optimized by deactivating the DNR while sufficiency of dispatching DGs outputs and the capacitors step to meet the hourly load variations.
- The feasibility of the suggested technique is illustrated by the Taiwan Power Company (TPC) with a nominal voltage of 11.4 kV for an existing practical system.

The rest of the paper is arranged as follows: The formulation of operation and control of the distribution systems is given in Section II. In Section III, MRFOA is presented for obtaining the optimal solution of this optimization issue. The simulation results are described in Section IV. The Finally, the paper conclusion is displayed in Section V.

II. PROBLEM FORMULATION

The main objective of the distribution systems planners and operators is to respond to the requirements of customers and assure efficient performance of distribution systems. In this problem, it is required to minimize the overall losses of power across the distribution network whilst handling the equality and inequality constraints. Thus, the objective function can be mathematically expressed as follows;

$$OFn = Min\left\{(\sum_{bn=1}^{N_{bn}} Loss_{bn}\right\} \tag{1}$$

This representation is mainly dedicated for detecting the optimal allocation and controlling of DGs, CBs, and DNR, while the loading conditions are denoted. In addition to that, the outputs of DGs and CBs could be dispatched to maximize the benefits of their allocation. Hence, the control variables (CoV) vector can be expressed as follows;

$$CoV=\{\underbrace{[OT_1, OT_2, \ldots, OT_{N_T}]}_{OpenTiebranches};\underbrace{[Pog_1, Pog_2, \ldots, Pog_{N_{dg}}]}_{DGsoutputpower}; \underbrace{[Qsc_1, Qsc_2, \ldots, Qsc_{N_C}]}_{OperatingstepofCBs}\} \tag{2}$$

N_T displays the number of branches which could be opened to retain the radial structure of distribution system, whereas Qsc describes the reactive output power from switching of the capacitors.

Concerning the system reliability and service quality, the relevant equality and inequality constraints of operation must be maintained as below;

$$1 \leq OT_k \leq N_T, k = 1, 2, \ldots, N_T \tag{3}$$

$$Qsc^{min} \leq Qsc_k \leq Qsc^{max}, k = 1, 2, \ldots, N_C \tag{4}$$

$$Pog^{min} \leq Pog_k \leq Pog^{max}, k = 1, 2, \ldots, N_{dg} \tag{5}$$

$$V_m^{min} \leq V_m \leq V_m^{max}, m = 1, 2, \ldots M_r \tag{6}$$

$$|I_{bn}| \leq I_{bn}^{max}, bn = 1, 2, \ldots, N_{bn} \tag{7}$$

$$\sum_{k=1}^{N_{dg}} Pog_k \leq PR_G \sum_{m=1}^{M_b} (Pd_m) \tag{8}$$

$$\sum_{k=1}^{N_C} Qsc_k \leq PR_Q \sum_{m=1}^{M_b} (Qd_m) \tag{9}$$

Both the terms (PR_G) and (PR_Q) refer to the penetration level which is acceptable from the DGs and CBs.

$$\left(PG_{Sub}+\sum_{k=1}^{N_{dg}} Pog_k\right)_{Lc} > \sum_{m=1}^{M_b} (Pd_m)_{Lc}, Lc=1, 2, \ldots, M_{Lc} \tag{10}$$

$$\left(QG_{Sub}+\sum_{k=1}^{N_C} Qsc_k\right)_{Lc} > \sum_{m=1}^{M_b} (Qd_m)_{Lc}, Lc=1, 2, \ldots, M_{Lc} \tag{11}$$

Equations (3-5) define the limitations of the control variables of the opened tie branches, DGs, and CBs. Equation (6) implies the voltage quality limitations for each loading condition, whereas (7) describes the safe loading of current across each branch. Moreover, (8) and (9) explain that, at any loading condition, the output power from both DGs and CBs should not exceed by 60% which is the acceptable penetration level as mentioned in [28]. Powering all loads in the electricity network, which are supplied from the substations, DGs and CBs, must be slightly more than the whole loads value as illustrated in (10) and (11). Another constraint is to maintain the active and reactive balance at each load condition according to (12) and (13).

$$PG_{Sub} + \sum_{i=1}^{N_{dg}} Pog_i - \sum_{bn=1}^{N_{bn}} Ploss_{bn} = \sum_{k=1}^{M_b} Pd_k \quad (12)$$

$$QG_{Sub} + \sum_{i=1}^{N_C} Qsw_i - \sum_{bn=1}^{N_{bn}} Qloss_{bn} = \sum_{k=1}^{M_b} Qd_k \quad (13)$$

Besides, a branch-bus incidence matrix is developed as depicted in (14) in order to maintain the radial network topology. operation [29], [30];

$$A_{ij} = \begin{cases} 0 & \text{when line i is not connected to bus k} \\ -1 & \text{when the line i passes into bus k} \\ 1 & \text{when the line i goes out from bus k} \end{cases} \quad (14)$$

III. MANTA RAY FORAGING OPTIMIZATION ALGORITHM FOR OPTIMAL OPERATION OF AUTOMATED DISTRIBUTION NETWORKS

Manta Ray Foraging Optimization Algorithm (MRFOA) is a novel optimizer [25] that simulates three intelligent foraging strategies of the manta rays which are chain foraging strategy, cyclone foraging strategy, and somersault foraging strategy. The chain foraging strategy illustrates that apart the manta rays forage in a small supportive way, meanwhile they are ordered in a line to pass the highest number of plankton into their gills. Moving to the cyclone foraging strategy, which is the second strategy, a myriad of manta rays is connected in a spiral way to produce a centralized spiraling peak that can force the water to move up towards the surface and pull out the plankton within their mouths. Finally, the third foraging strategy is the somersault, where the manta rays search for the position of plankton and swim on the way to them. In this technique, the manta rays describe the individuals in the search space that seek the position of plankton that represents minimum fitness. The MRFOA starts to initialize the stage after defining the number of populations of the manta rays and the maximum number of iterations, respectively. Therefore, the D-dimensional individuals are created initially within the defined bounds. The three strategies will be mathematically formulated as follows. In the chain foraging strategy, everyone is updated as follows;

$$M_m^* = \begin{cases} M_m + (M_B - M_m)(1+\sigma) & \text{if } m = 1 \\ M_m + r_1(M_{m-1} - M_m) + \sigma(M_B - M_m) & else \end{cases} \quad (15)$$

A weight coefficient (σ) is characterized in Eq (16) which is varied at each iteration as follows;

$$\sigma = 2.r_1.\sqrt{|log(r_1)|} \quad (16)$$

In the second strategy (cyclone foraging), the iterations are equally divided into two halves. The first half concentrates on improving the exploration of MRFOA and everyone is updated as follows;

$$M_m^* = \begin{cases} M_R + (M_R - M_m)(r_1 + \beta) & \text{if } m = 1 \\ M_R + r_1(M_{m-1} - M_m) + \beta(M_R - M_m) & else \end{cases} \quad (17)$$

where M_R reflects a created individual in a random way in specific limits as follow;

$$M_R = M^{\min} + r_1.(M^{\max} - M^{\min}) \quad (18)$$

The adaptive weight coefficient (β) is varied depending on the following equation;

$$\beta = 2e^{r_2\left(\frac{It_m - It + 1}{It_m}\right)}.sin(2\pi r_2) \quad (19)$$

Moving to the second half of the iterations which concentrates on improving the MRFOA exploitation. Therefore, everyone is updated as according to the following equation;

$$M_m^* = \begin{cases} M_B + (M_B - M_m)(r_1 + \beta) & \text{if } m = 1 \\ M_B + r_1(M_{m-1} - M_m) + \beta(M_B - M_m) & else \end{cases} \quad (20)$$

In the Somersault foraging (the third strategy), everyone is updated near the best extracted position as depicted in (21);

$$M_m^* = M_m + S(r_3 M_B - r_4 M_m) \quad (21)$$

The somersault coefficient (S) controls the manta rays somersault domain and has a value of ($S = 2$).

To employ it for the optimized operation of the automated distribution networks, the control variables described in (2) is considered with the tie branches to be opened, the operating step of switched capacitors, and the DG output power. In addition to that, the fitness function of the overall power losses (1) is evaluated through Load flow routine using Newton Raphson method. The inequality constraints of the control variables (3)-(5) are maintained inherently by checking their feasibility in each iteration. On the other side, the radiality of the network of (14) and the inequality constraints (6)-(11) are examined in each iteration and the fitness takes infinity if there is violation. The equality limits of (12) and (13) is guaranteed due to Load Flow routine.

The pseudo code of the proposed MRFOA is discussed through Fig. 1 to illustrate in detail how the coding scheme is working.

IV. SIMULATION RESULTS

A. TEST SYSTEMS

In this section, the developed MRFOA is tested on both 33-bus and 69-bus distribution systems. For both systems, optimal allocation and control of the three elements DGs, CBs, and DNR are executed with different operational cases.

The 12.66 kV IEEE 33-bus distribution system contains 33-node, which are divided into 32 sectionalizing lines

```
Initialize the P_M and It_m
Randomly initialize the positions of manta rays (M), It = 1
If It < It_m
Evaluate the fitness for each individual and Extract MB
Update σ using Eq. (16)
Update β using Eq. (19)
Apply the chain foraging strategy via Eq. (15)
If It > MIt / 2
Apply the cyclone foraging strategy via Eq. (17)
Else
Apply the cyclone foraging strategy via Eq. (20) based on the iteration number
End If
Check their feasibility and set the violated variable to the nearest bound
Evaluate the fitness for each individual and Extract MB
Apply the somersault strategy via Eq. (21)
Check their feasibility and set the violated variable to the nearest bound
End If
```

FIGURE 1. Pseudo code of the developed MRFOA.

(from L1 to L32) and 5 opened lines (from L33 to L37). The total active and reactive demand of the system are 3715 kW and 2300 kVAr, respectively [31]. It is assumed, in this article, that all branches can be switched on or off. The system's initial power loss (without DGs, CBs, and initial configuration) is 202.69 kW taking into consideration a minimum voltage of 0.9108 p.u. at bus 18.

The second test system is called the radial 12.66 kV IEEE 69-bus distribution system. This system load is 3.8 MW active load and 2.69 MVAr reactive load which consists of a 69-bus with 68 sectionalizing lines (L#1 – L#68) and 5 open lines (L#69 - L#73) [30]. The system initial power loss, without DGs, CBs, and initial configuration, is 224.95 kW with minimum voltage of 0.909 p.u.

For all tested systems, the maximum number of DGs and CBs to be installed is taken as 3, respectively, whereas the CBs are assumed to be discrete handling with a step of 300 kVAr. The maximum size of the DGs is 3 MW with a maximum penetration of 60% of load demand. MatlabR2017b is used to perform the simulations on a system with 8 GB of RAM and Intel(R) Core (TM) i7-7200U CPU (2.5 GHz).

The proposed MRFO algorithm has four control parameters. The first two are σ and β coefficients while the other two are the number of individuals and the maximum number of the iterations. σ and β coefficients are adaptive factors which are automatically varied in a random way as described in Eqs. 16 and 19.

Consequently, they are built-in adaptive values that does not affect on the MRFO performance. On the other side, the number of individuals and the maximum number of the iterations are considered 50 and 200, respectively which are the same as taken in TSA [1] in order to make fair comparison.

B. CASE STUDIES

As listed above, the connection of CBs and DGs within distribution systems should be optimally allocated as changing their location with daily load variation is impossible. Three cases are executed for each system as follow:

- **Case 1:** The optimal allocations of the DGs and CBs using the proposed MRFOA at the peak load. The attained results are compared with other techniques presented in the literatures to examine the effectiveness and robustness of the proposed MRFOA. To compare the obtained results in this study with the others, the location and the rated power of the DGs and CBs are settled at the peak load demand with the same objective function in the literatures, which is losses minimization.
- **Case 2:** Optimal DSA by controlling DGs, CBs, and DNR simultaneously with daily load variation. The optimal control of the dispatchable DGs, the connected switched CBs, and the tie switches of DNR is introduced. A practical daily load curve is applied to analyze the dynamic operation of the automated distribution system. The higher cost of fully automated switches used in DNR and lifetime effect due to continuous switching with daily load variation may limit the continuous DNR with load variation.
- **Case 3:** Semi-automation of the distribution network with dispatching the capacitors step and DGs outputs while deactivating the DNR. This case introduces an optimal control of the DGs and CBs without DNR.

C. SIMULATION RESULTS FOT THE 33-BUS TEST SYSTEM

1) CASE 1: OPTIMAL ALLOCATION OF CBs AND DGs

The proposed MRFOA is applied for optimal sizing and siting of DGs and CBs considering the initial configuration. The verification of the proposed MRFOA is executed by comparison with other techniques such as; Analytical [32], PSO [33], BFOA [34], IMDE [35], WCA [2], TSA [36], binary GA [37], and EGA [6]. Fig. 2 shows the 33-bus system with the optimal allocation of the DGs and CBs which obtained by the proposed MRFOA.

Table 1 gives the results for the optimal allocation of the DGs and CBs on the 33-bus test system using the proposed MRFOA and compare them with other previous techniques in the literature for varied single, double and triple CBs and DGs. In the case of single CB/DG, the power losses are reduced from 202.69 kW to 52.9583 kW. Compared with PSO [33], GA [37] that lead to power losses of 59.7 kW and 48.31 kW, the proposed MRFOA leads to the highest reduction. But the GA in [37], more sizes of DG and CB are needed. By running the load flow with these values, the losses are 51.7849 but the installed DGs are 2510 kW which are higher than the penetration limit of 60% of the total load of 2229 kW. Additionally, with allowing two DGs/CBs, the total power losses after optimal allocation and

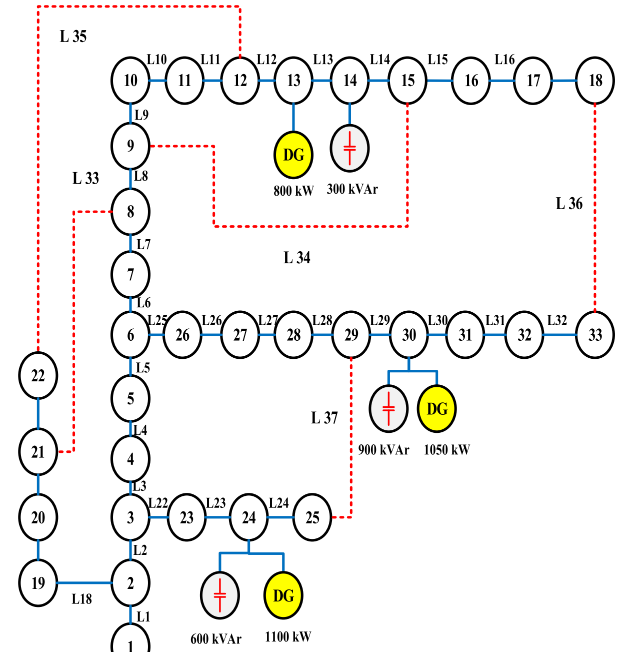

FIGURE 2. Modified 33-node system with allocated DGs and CBs.

TABLE 1. Optimal allocations of DGs and CBs at nominal loading condition.

Limited number of DGs/CBs		CBs size in kVAr (bus)	DGs size in kW (bus)	kW Losses
	Initial			202.69
Ndg=Nc=1	PSO [33]	1457(30)	2511(6)	59.7
	Binary GA [37]	1200(30)	2510(6)	48.31 (Reported)
	Proposed MRFOA	1200(30)	2229(6)	52.9583
Ndg=Nc=2	Analytical [32]	400(33), 500(32)	447(18), 559(17),	84.28
	IMDE [35]	254.8(16), 932.3(30)	1080(10), 896.4(31)	32.08
	Proposed MRFOA	600(30), 900(9)	841(13), 1144(30)	29.0809
Ndg=Nc=3	BFOA [34]	163(18), 338(33), 541(30)	542(17), 160(18), 895(33)	41.41
	WCA [2]	465(23), 565(30), 535(14)	973(25), 1040(29), 536(11)	24.68
	TSA [36]	1060(30), 246(11), 566(24)	766(24), 917(30), 976(12)	15.0
	EGA [6]	388.75(25), 334.77(14), 1189.91(30)	1094.96(24), 767.74(14), 964.22(30)	12.7
	Proposed MRFOA	300(14), 600(24), 900(30)	803(13), 1073(24), 1040(30)	12.572

initial system losses are manifested in this table. The power losses can be reduced from 202.69 kW to 29.9089 kW with 85.244% reduction which is the lowest losses among other techniques by applying the proposed technique. The losses reduction using the Analytical [32], IMDE [35], are, respectively, 58.42%, 84.17%.

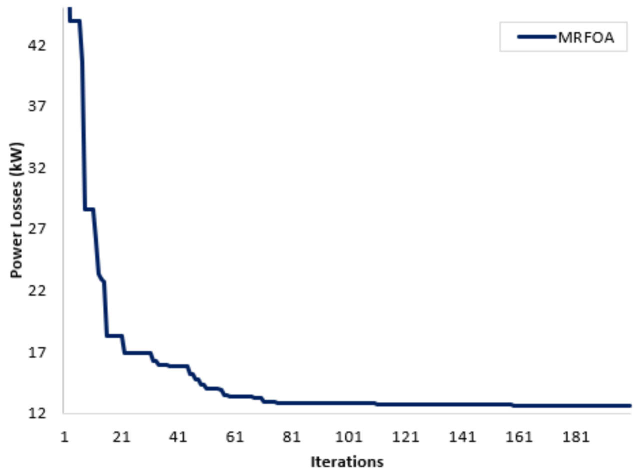

FIGURE 3. Convergence rate of the MRFOA for case 1.

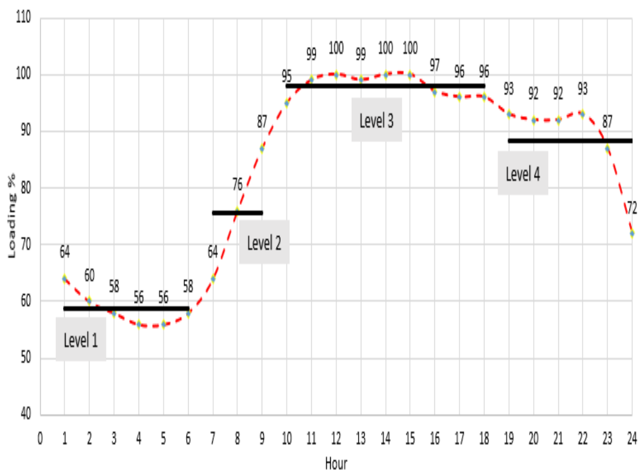

FIGURE 4. Percentage of hourly loading.

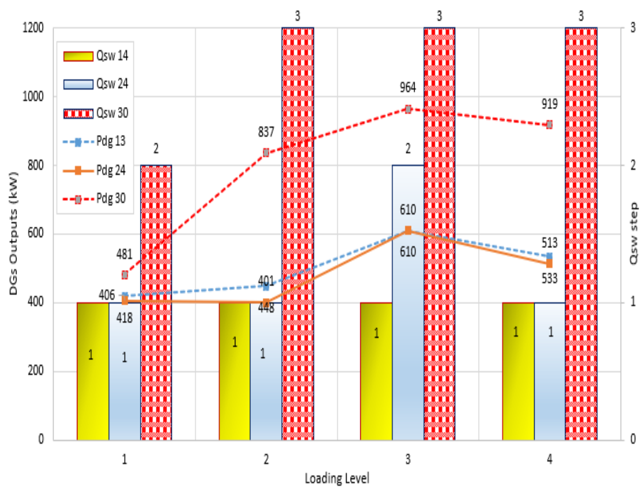

FIGURE 5. MRFOA for DGs dispatching and optimal CBs steps and at each load level.

Additionally, with allowing three DGs/CBs, the total power losses after optimal allocation and initial system losses are manifested in this table. The power losses can be reduced

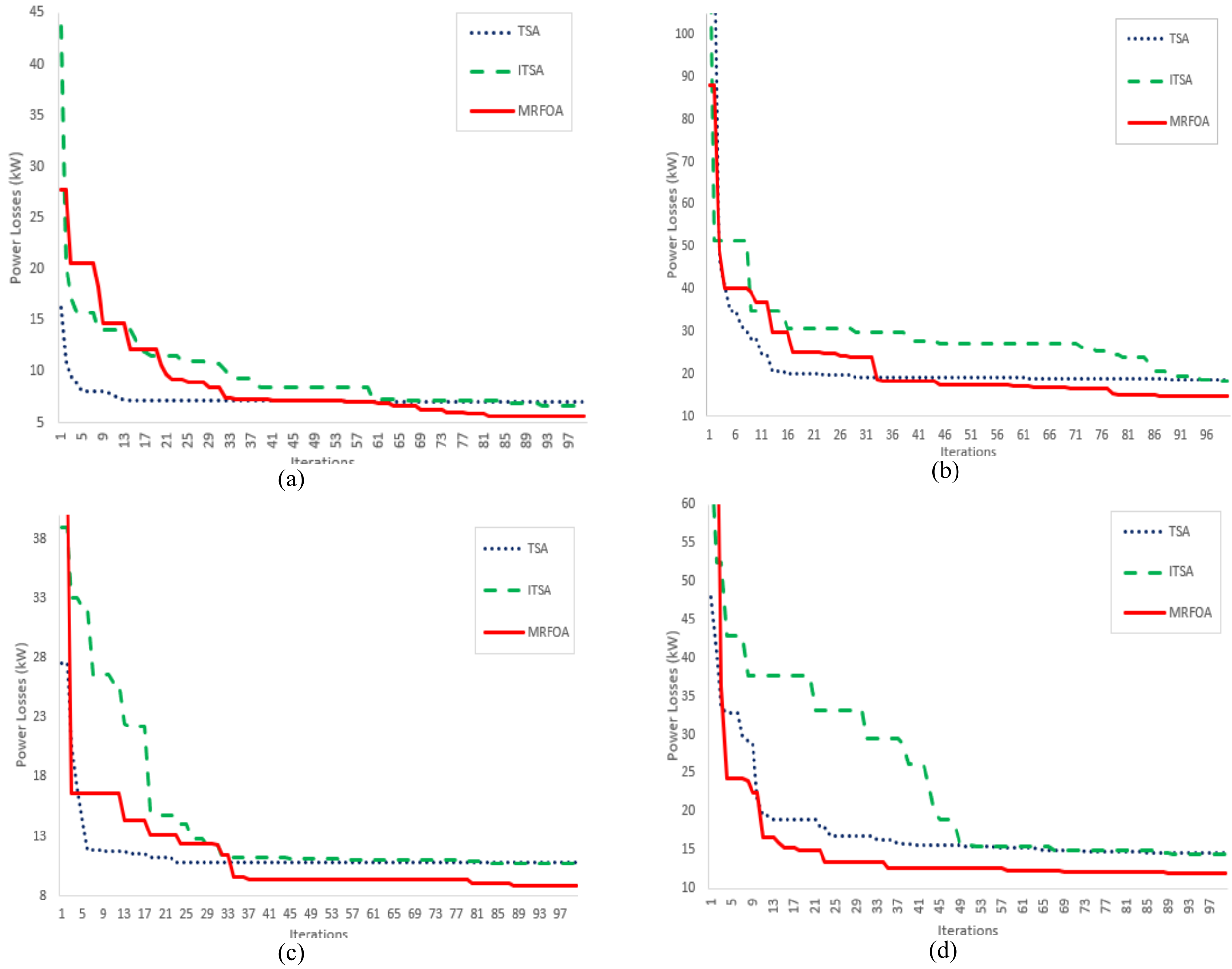

FIGURE 6. Convergence rates of MRFOA, TSA and ITSA for case 2 on the 33-bus distribution system.

from 202.69 kW to 12.572 kW with 93.80% reduction which is the lowest losses compared with other. The losses reduction using the BFOA, IMDE, WCA, TSA and EGA are, respectively, 79.57%, 84.17%, 87.82%, 92.60% and 93.73%.

Convergence characteristics of MRFOA for optimal allocation of DGs and CBs on this system are shown in Fig. 3, which clarify the effectiveness of the proposed technique for searching the optimal solution.

2) CASE 2: SIMULTANEOUS ALLOCATION OF DGs, CBs, AND DNR

Practically, the distribution system loads are changed continuously, and therefore the connected DGs, CBs, and reconfiguration of the distribution system are optimally automated for losses minimization and voltage improvement. In Case 2, the daily load variation is considered where the daily load profile is divided into minimum numbers of load levels, as shown in Fig. 4 [38]. Thus, the optimal tie line of DNR at each level is tabulated in Table 2. Dispatching of DGs and optimal switching of the CBs are displayed in Fig. 5.

TABLE 2. Optimal tie line at each load level of the 33-bus system developed by MRFOA.

Loading Level	1	2	3	4
Optimal tie lines	7, 8, 6, 32, 34	7, 8, 9, 17, 25	7, 8, 9, 17, 27	7, 8, 9, 17, 27

A comparison between initial, optimal allocation, and fully automated system with simultaneous control of DGs, CBs, and DNR is introduced in Table 3. *Scenario-1* represents the initial system performance. *Scenario-2* represents the system performance with the allocated of DGs and CBs in Fig. 2. *Scenario-3* represents the system with simultaneous control of DGs, CBs, and DNR as described in Fig. 5 and Table 2. The proposed MRFOA can control the DGs, CBs, and tie switching simultaneously and achieve minimum dissipated daily energy. The daily dissipated energy is reduced from 3402.8 kWh to 265.919 kWh with a reduction ratio of 92.18%. Added to that, it also achieves great reduction

TABLE 3. Corresponding results of optimal control of DGs, CBs and DNR at each load level of the 33-bus system.

Loading Level		1	2	3	4
Initial system (Scenario-1)	Losses	65.5036	111.722	194.011	154.7548
	Min-V (bus)	0.949 (18)	0.9334 (18)	0.9125 (18)	0.9219 (18)
	Max-V (bus)	1 (1)	1(1)	1 (1)	1 (1)
	Energy losses per day = 3402.8 kWh				
CBs and DGs without DNR (Scenario-2)	Losses	31.17	16.05	11.949	11.457
	Min-V (bus)	0.997 (22)	0.996 (22)	0.992 (8)	0.995 (22)
	Max-V (bus)	1.0296 (33)	1.0166 (30)	1.0016 (24)	1.0073 (30)
	Energy losses per day = 411.495 kWh				
CBs and DGs with DNR (Scenario-3)	Losses	5.611	8.8734	14.84	12.012
	Min-V (bus)	0.993 (8)	0.991 (8)	0.9873 (18)	0.989 (8)
	Max-V (bus)	1 (1)	1 (1)	1(1)	1 (1)
	Energy losses per day = 265.919 kWh				

TABLE 4. Statistical analysis of optimal operation of the DGs, CBs, and DNR at each load level of the 33-bus system.

Loading	Level 1			Level 2		
Index	TSA [36]	ITSA [1]	MRFOA	TSA [36]	ITSA [1]	MRFOA
Min	7.0723	6.6229	5.6112	10.7879	10.7331	8.8734
Max	28.7835	10.898	8.4721	15.9733	14.7109	13.5255
Average	9.9764	7.7454	6.3852	13.0396	12.2192	10.0012
Std	6.6463	1.3025	0.8531	1.5461	1.1867	1.4657
Loading	Level 3			Level 4		
Min	18.5342	18.3358	14.8400	14.7001	14.5103	12.0111
Max	50.0707	27.2523	18.6601	39.7786	26.5889	13.6348
Average	25.8633	21.415	16.5246	21.2055	17.164	12.6690
Std	9.1926	2.47	1.2145	8.0781	3.477	0.6499

compared to *Scenario-2,* which reduces the energy losses to 411.495 kWh. Moreover, the optimal control of the DGs, CBs, and tie switching simultaneously using the proposed MRFOA improves successfully the minimum and maximum voltages which are close to the preferred standard value (1 p.u.) at all loading levels. This capability of the proposed MRFOA in searching for optimal solution is clearly appeared in Table 4. This table shows the statistical analysis of the proposed MRFOA for the optimal operation of the DGs, CBs, and tie switching simultaneously with 10 independent runs in comparison with the recent algorithm of tunicate swarm optimizer (TSA). For all load levels, the best solution is obtained by the proposed MRFOA as presented in Table 4, where a dramatic decrease in the standard deviation obtained by the proposed MRFOA than the TSA [36] and ITSA [1] is achieved. Fig. 6 demonstrates the convergence rates of the proposed MRFOA compared to TSA and ITSA [1]. This figure shows the improvement of convergence rates of MRFOA in providing higher efficacy to override the premature convergence and developing its obtained solution.

Fig. 7 demonstrates the voltage profile with simultaneous control of DGs, CBs, and DNR at four load levels. It is clearly observed that the proposed technique improves the system voltage, where the minimum voltage at load levels 1, 2, 3 and 4 is increased from 0.9493 p.u., 0.9334 p.u., 0.9125 p.u., and 0.9219 p.u., to 0.9931 p.u., 0.991 p.u., 0.9873 p.u., and 0.989 p.u., respectively.

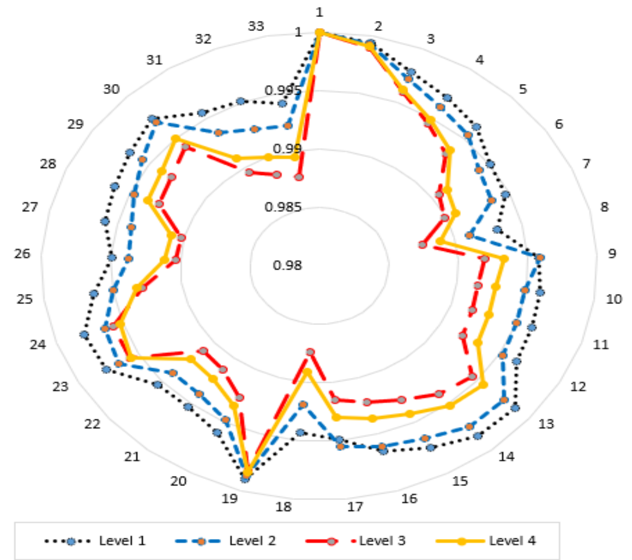

FIGURE 7. Voltage profile with simultaneous control of DGs, CBs, and DNR at each load level of the 33-bus system.

3) CASE 3: OPTIMAL SIMULTANEOUS ALLOCATION OF DGs, CBs

Case 3 introduces a semi-automated distribution system with optimal control of DGs and CBs while deactivating DNR and take into consideration the hourly load variations. DGs dispatching and the optimal switching of the CBs for each hour are depicted in Fig. 8. The related losses and minimum voltage are described in Fig. 9 for the three stated scenarios. The dissipated energy is calculated in this case to be 3419.2033, 423.8099, and 284.32 kWh for the three scenarios, respectively. As shown, the proposed MRFOA can optimally control the DGs and CBs per hour to achieve the minimum dissipated daily energy. The minimum voltages are greatly increased in *Scenarios-2* and *3* compared to *Scenario-1*.

D. SIMULATION RESULTS FOT THE 69-BUS TEST SYSTEM

1) CASE 1: OPTIMAL ALLOCATION OF CBs AND DGs

The proposed technique is applied for optimal sizing and siting of the DGs and CBs with initial system configuration. The verification of the proposed MRFOA is executed by a comparison with other techniques; PSO [33], IMDE [35], TSA [36], EGA [6], GA [39], Binary genetic algorithm (BGA) [41], PSO [1], Slime Mould Algorithm (SMA) [1], Crow Search Optimizer (CSO) [40], Improved TSA (ITSA) [1], and MOEA/D [5]. In this system, the CBs are assumed to be discrete handling with a step of 300 kVAr. Furthermore, the maximum size of the DGs is 3 MW with a maximum penetration of 60% of maximum load demand. Fig. 10 shows the 69-bus system with the optimal allocation of the DGs and CBs using the proposed MRFOA.

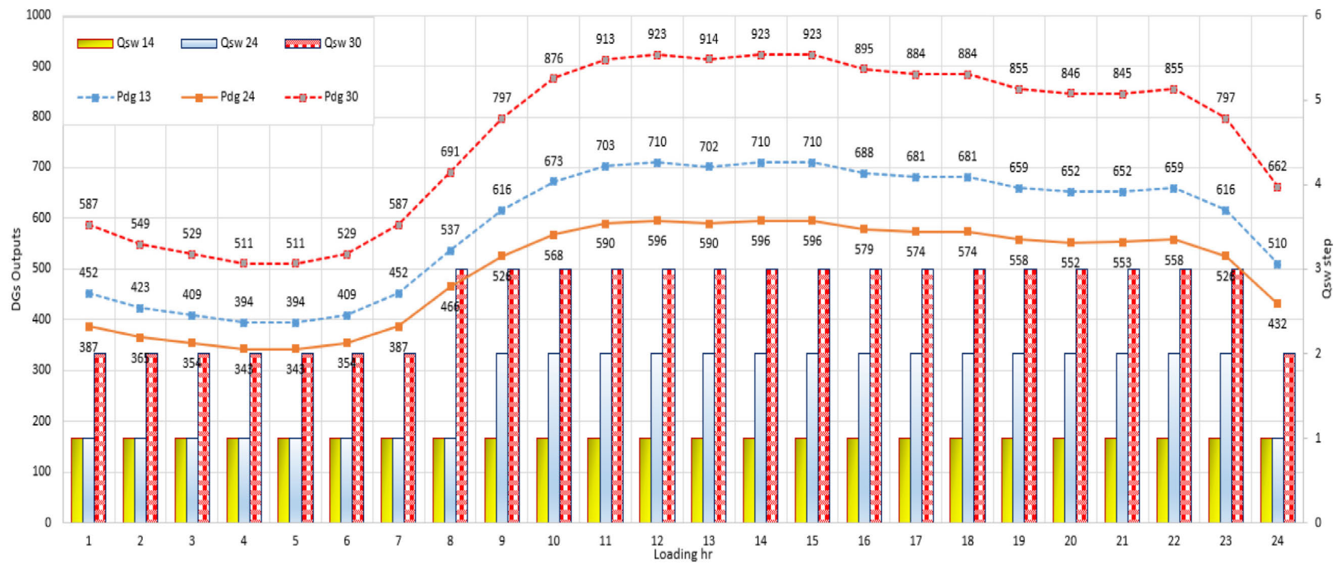

FIGURE 8. Output of DGs and optimal switching of CBs at each load level of the 33-bus system with initial system configuration.

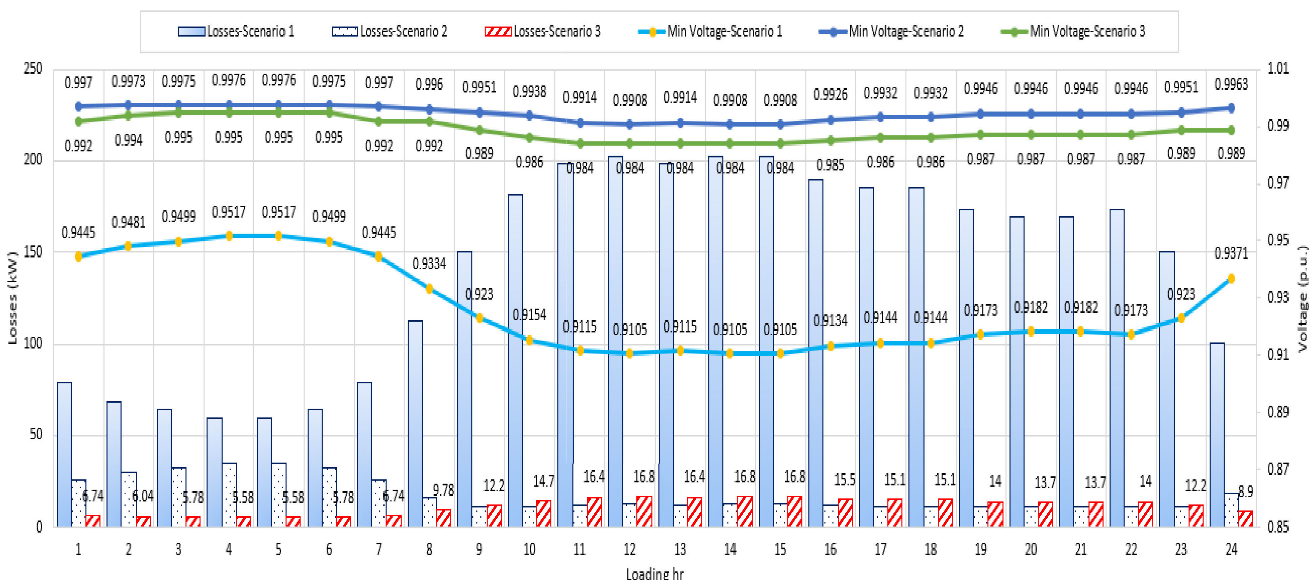

FIGURE 9. Voltage profile and hourly losses of the 33-bus system for various control scenarios.

Table 5 illustrates the results for optimal allocation of the DGs and CBs on the 69-bus test system using the proposed MRFOA with respect to other reported techniques. In this table, the results for the optimal allocation of the DGs and CBs by using the proposed MRFOA are compared with previous techniques in the literature for varied single, double and triple CBs and DGs. In the case of single CB/DG, the power losses are reduced from 224.95 kW to 23.4877 kW. It is compared with PSO [33], that leads to power losses of 25.9 kW which is higher than the obtained with MRFOA. Additionally, with allowing two DGs/CBs, the total power losses with optimal allocation and initial system losses are manifested in this table. The power losses are reduced to 12.4467 kW with 94.47 % reduction which is higher than that is obtained by IMDE [35].

Additionally, with allowing penetration of three DGs/CBs, the total power losses after optimal allocation and initial system losses are manifested in this table. The power losses are sharply decreased 4.351 kW with reduction of 98.06%, which is the lowest losses among other techniques. The losses achieved by using the GA [39], TSA [36], PSO [1], SMA [1], CSO [40] and ITSA [1] are, respectively, 29.748 kW, 6.9 kW, 10.6515 kW, 9.0053 kW, 7.5488 kW and 6.8012 kW

TABLE 5. Simultaneous allocations of DGs and CBs at nominal loading condition for the 69-bus system.

		CBs size in kVAr (bus)	DGs size in kW (bus)	kW Losses
	Initial			224.95
N_{dg}=N_c=1	PSO [33]	1401.3(61)	1566(61)	25.9
	Proposed MRFOA	**1200(61),**	**1836(61)**	**23.4877**
N_{dg}=N_c=2	IMDE [35]	109(63), 1192(61)	1738(62), 479(24)	13.83
	Proposed MRFOA	**1200(61)**	**523(17), 1744(61)**	**12.4467**
N_{dg}=N_c=3	GA [39]	500(7), 500(12), 500(50), 500(61)	500(58), 500(61), 500(65)	29.748
	TSA [36]	299(21), 605(53), 1148(61)	452(9), 555(16), 1500(61)	6.9
	PSO [1]	1222(6), 344(66), 235(69)	799(66), 1689(61)	10.6515
	SMA [1]	708(2), 623(13), 1091(61)	497(16), 112(30), 1625(61)	9.0053
	CSO [40]	1367(61), 311(67), 323(68)	535(17), 1728(61), 299(67)	7.5488
	ITSA [1]	288(9), 292(23), 1149(61)	291(10), 491(15), 1500(61)	6.8012
	Proposed MRFOA	**300(11), 300(18), 1200(61)**	**528(11), 345(21), 1674(61)**	**4.351**

TABLE 6. Optimal tie line of the 33-bus system at each load level via MRFOA.

Loading Level	1	2	3	4
Optimal tie lines	9, 12, 13, 18, 56	10, 13, 17, 26, 72	9, 12, 13, 26, 55	9, 12, 14, 26, 56

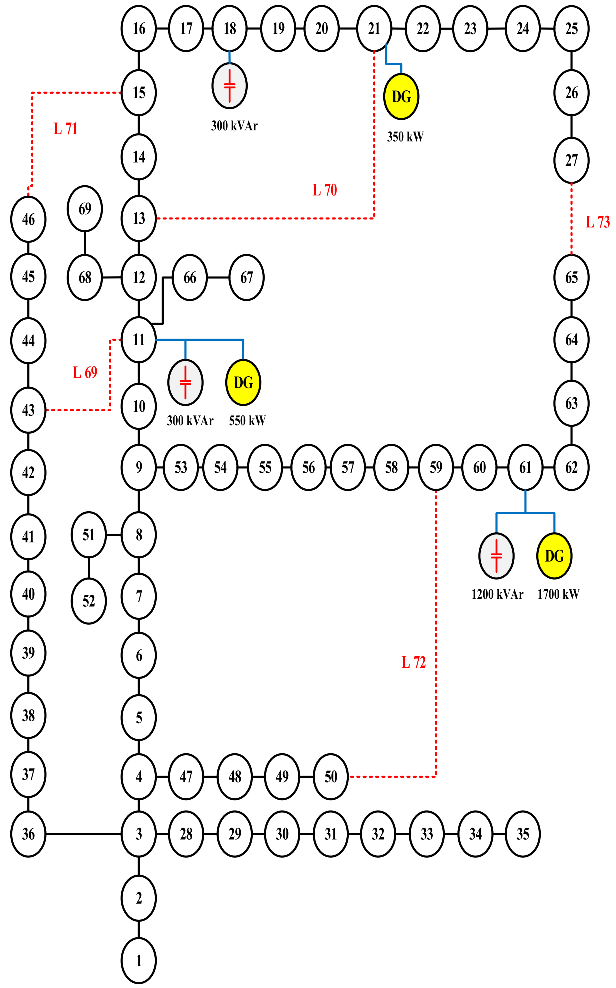

FIGURE 10. Modified 69 node system with optimal allocated DGs and CBs.

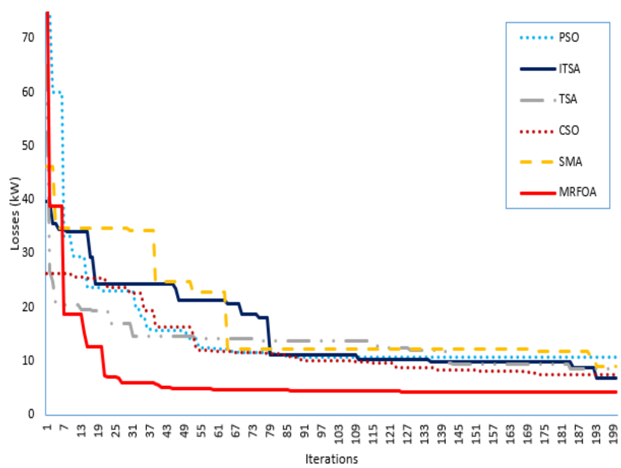

FIGURE 11. Convergence rates of several algorithms for optimal allocation of DGs and CBs on the 69-bus distribution system.

In addition to that, Fig. 11 shows the improvement of convergence rates of MRFOA for optimal allocation of DGs and CBs compared to PSO, SMA, CSO, ITSA. As shown, the proposed MRFOA provides higher efficacy to override the premature convergence and developing its obtained solution.

2) CASE 2: SIMULTANEOUS ALLOCATION OF DGs, CBs, AND DNR

MRFOA is tested on the 69-bus system with the daily load levels given in Fig. 4. The optimal tie lines at each level are tabulated in Table 6, whilst the simultaneous switching of CBs and dispatching of DGs are depicted in Fig. 12. Moreover, Fig. 13 demonstrates the convergence rates of MRFOA for each loading level. This convergence clarifies the great evolution over the iterations to improve the optimal solution. A comparison between the three previous scenarios is conducted in Table 7.

As Tabulated in Table 7, the proposed MRFOA can optimally control the DGs, CBs, and tie switching simultaneously. The daily dissipated energy is reduced from 3765.933 kWh to 91.1373 kWh with 97.58% reduction. Besides, it achieves a great reduction compared to *Scenario-2* which reduces the energy losses to 351.6279 kWh.

TABLE 7. Corresponding results of optimal control of DGs, CBs, and DNR of the 69-bus system at each load level.

Loading Level		1	2	3	4
Initial system (Scenario-1)	Losses	72.002	123.25	215.19	171.24
	Min-V (bus)	0.949 (65)	0.933 (65)	0.911 (65)	0.921 (65)
	Max-V (bus)	1 (1)	1 (1)	1 (1)	1 (1)
	Energy losses per day = 3765.933 kWh				
CBs and DGs without DNR (Scenario-2)	Losses	37.172	15.745	4.4173	6.9339
	Min-V (bus)	0.9967 (50)	0.9957 (50)	0.9944 (50)	0.995 (50)
	Max-V (bus)	1.0342 (61)	1.0208 (61)	1.0027 (61)	1.0107 (61)
	Energy losses per day = 351.6279 kWh				
CBs and DGs with DNR (Scenario-3)	Losses	2.2128	3.2365	4.822	4.1255
	Min-V (bus)	0.9973 (27)	0.9956 (50)	0.9919 (27)	0.9953 (27)
	Max-V (bus)	1 (1)	1 (1)	1 (1)	1 (1)
	Energy losses per day = 91.1373 kWh				

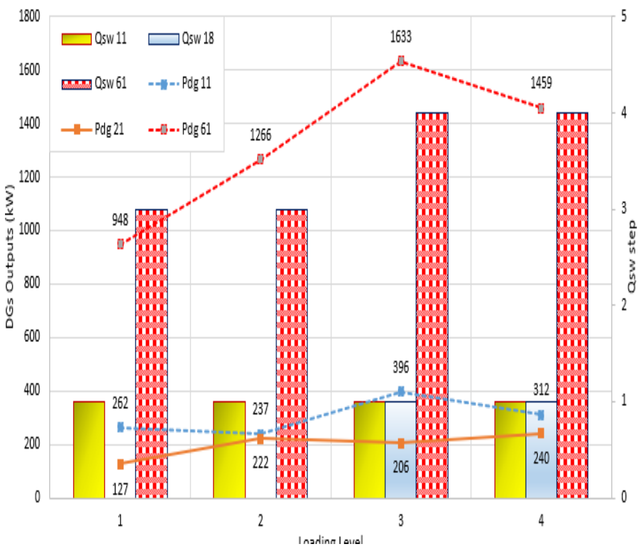

FIGURE 12. Dispatching of DGs and optimal switching of CBs of the 69-bus system at each load level using the MRFOA.

Additionally, the optimally control the DGs, CBs, and tie switching simultaneously using the proposed MRFOA successfully improves the minimum and maximum voltages to be close to the preferred at 1 p.u. approximately at all loading levels. Table 8 reflects the statistical analysis of the proposed MRFOA compared to TSA for optimal operation of the DGs, CBs, and tie switching simultaneously with 10 independent runs. For all load levels, the proposed MRFOA obtains the best solution where a dramatic decrease in the standard deviation of the MRFOA is clearly demonstrated with respect to TSA [36]. Fig. 14 illustrates the voltage profile of the system for the considered four load levels with simultaneous control of DGs, CBs, and DNR. It is greatly improved where the minimum voltage at load levels 1-4 is increased from 0. 949 p.u., 0. 933 p.u., 0. 911 p.u., 0.921 p.u., to 0. 9973 p.u., 0.9956 p.u., 0. 9919 p.u., and 0.9953 p.u., respectively.

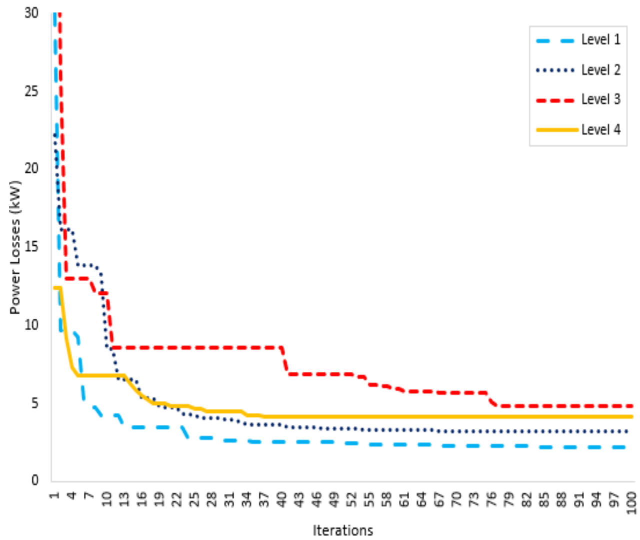

FIGURE 13. MRFOA convergence rates at each level of the 69-bus system.

TABLE 8. Statistical analysis of optimal operation of the DGs, CBs, and DNR of the 69-bus system at each load level.

Loading	Level 1		Level 2	
Index	TSA [36]	MRFOA	TSA [36]	MRFOA
Min	4.64487	2.21282	7.84853	3.23648
Max	27.60530	2.60777	29.78091	3.55405
Average	8.10048	2.35072	11.16118	3.30853
Std	7.03395	0.11025	6.64094	0.09645
Loading	Level 3		Level 4	
Min	13.61507	4.82224	10.65868	4.12551
Max	31.10509	7.52144	14.94947	4.49514
Average	16.43452	5.32579	12.26569	4.24579
Std	5.23589	0.79275	1.45768	0.12323

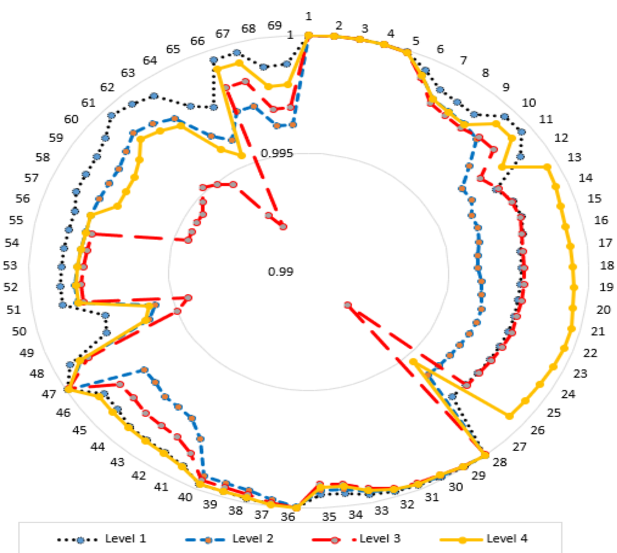

FIGURE 14. Voltage profile at each load level with control of DGs, CBs, and DNR.

3) CASE 3: OPTIMAL SIMULTANEOUS ALLOCATION OF DGs, CBs

In this case, with deactivating DNR considering hourly load variations, the DGs dispatching, and optimal switching of the

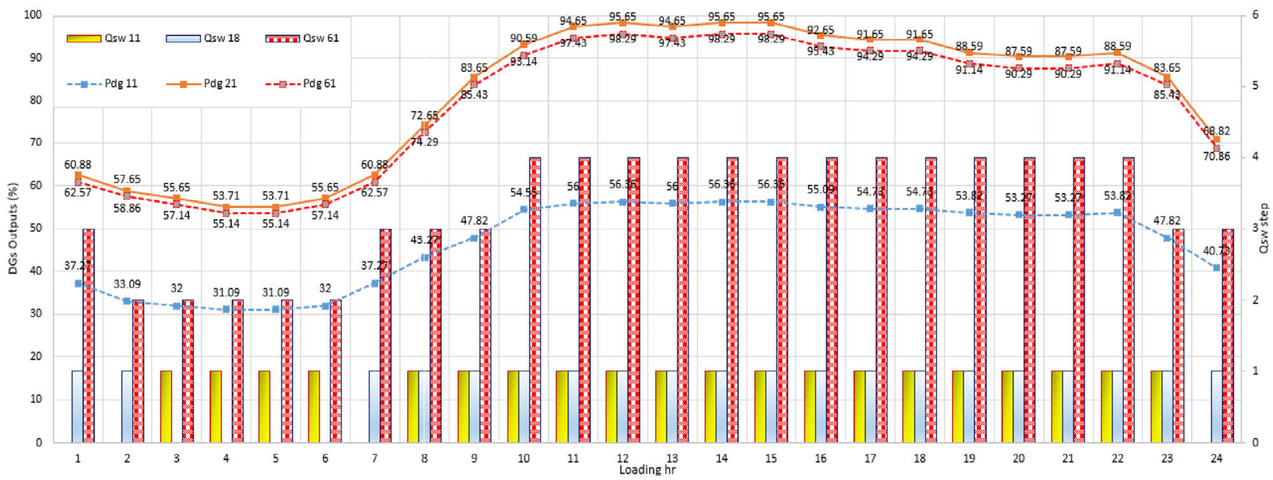

FIGURE 15. Output of DGs and Optimal switching of CBs at each load level of the 69-bus system with initial system configuration.

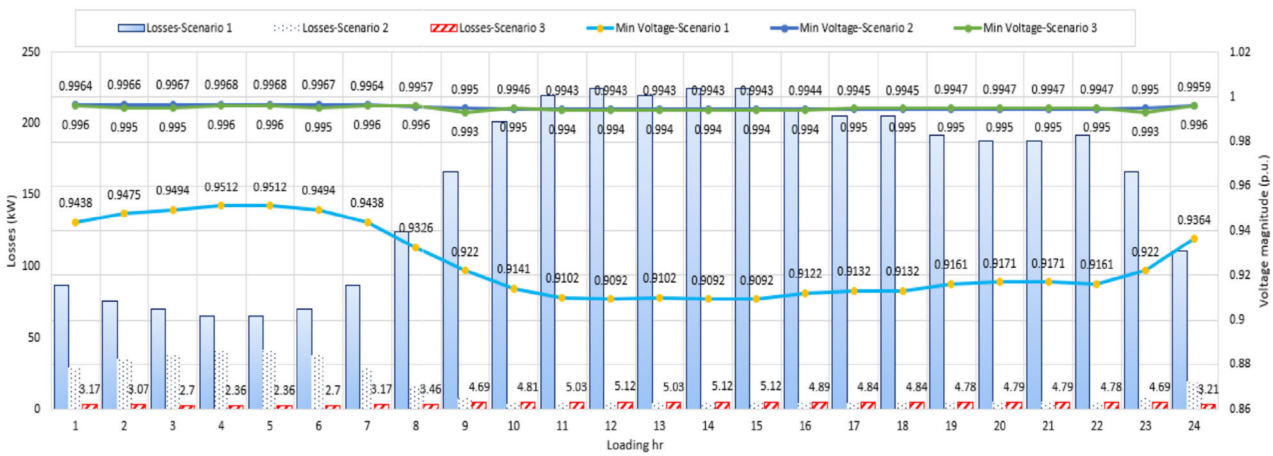

FIGURE 16. Voltage profile and hourly losses of the 69-bus system for diverse control scenarios.

CBs for each hour are depicted in Fig. 15. The related losses and minimum voltage are described in Fig. 16 for the three stated scenarios. The dissipated energy is calculated for the three scenarios in this case to be 3784.5585, 364.8141, and 99.52 kWh, respectively. As shown, the proposed MRFOA can optimally control the DGs and CBs for each hour to achieve the minimum dissipated daily energy. The minimum voltage is greatly increased in Scenarios 2 and 3 compared to Scenario-1.

E. COMPUTATIONAL COSTS OF THE PROPOSED MRFOA

The computational costs of the proposed MRFOA are estimated for the three cases studied and tabulated in Table 9. As shown, the time taken for each iteration is very small in the range of 0.241-0.271 sec and 0.256-0.286 sec for 33-bus and 69-bus test system, respectively.

TABLE 9. Computational costs (second) of the proposed MRFOA.

Index	33-Bus System	69-Bus System
Case 1	0.27105	0.28630
Case 2	0.25588	0.26963
Case 3	0.24081	0.256021

F. APPLICATION FOR PRACTICAL EXISTING SYSTEM OF 84-BUS RELATED TO TAIWAN POWER COMPANY

This network is an existing practical system due to Taiwan power company (TPC) which has 11 feeder, 95 line and 84-node while the status of 13 lines are open from 84 to 96. In this network, the overall active and reactive power demands are 28350 kW and 20700 kVAr, respectively while its nominal kV is 11.4 [42], [43]. In this system, the maximum number of CBs are 5 with maximum size of 3.6 MVAr which are handled in discrete nature with a step of 300 kVAr while the

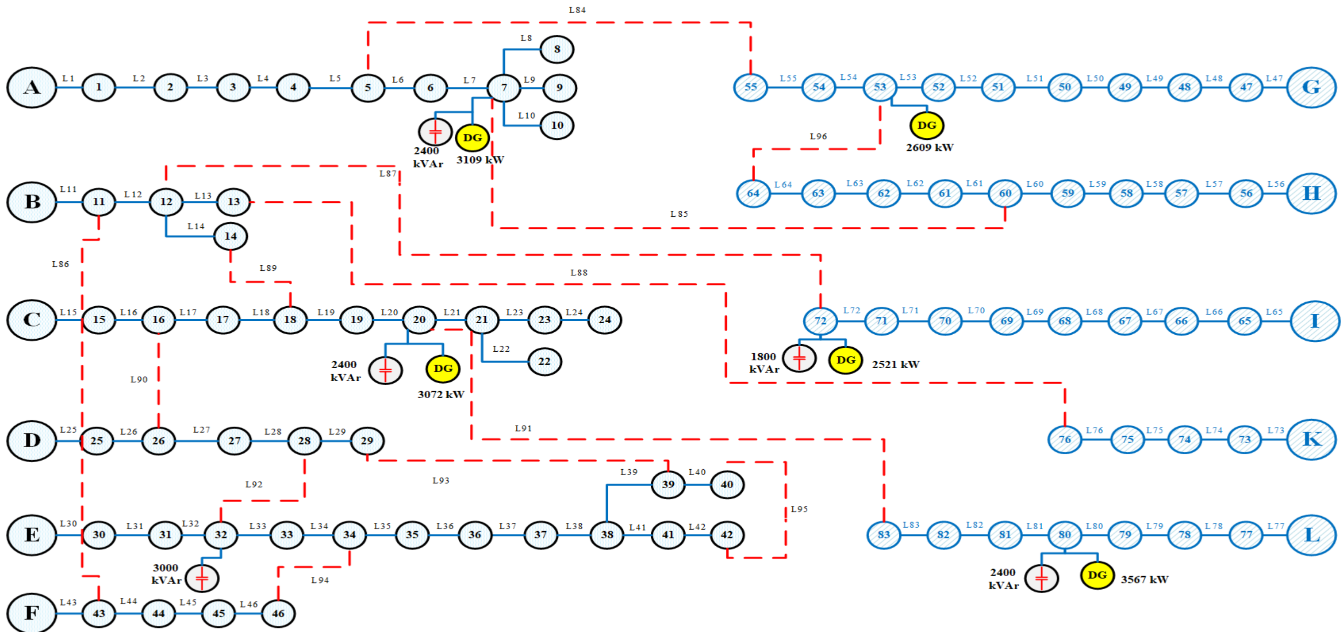

FIGURE 17. Modified 84-bus system with optimal allocated DGs and CBs.

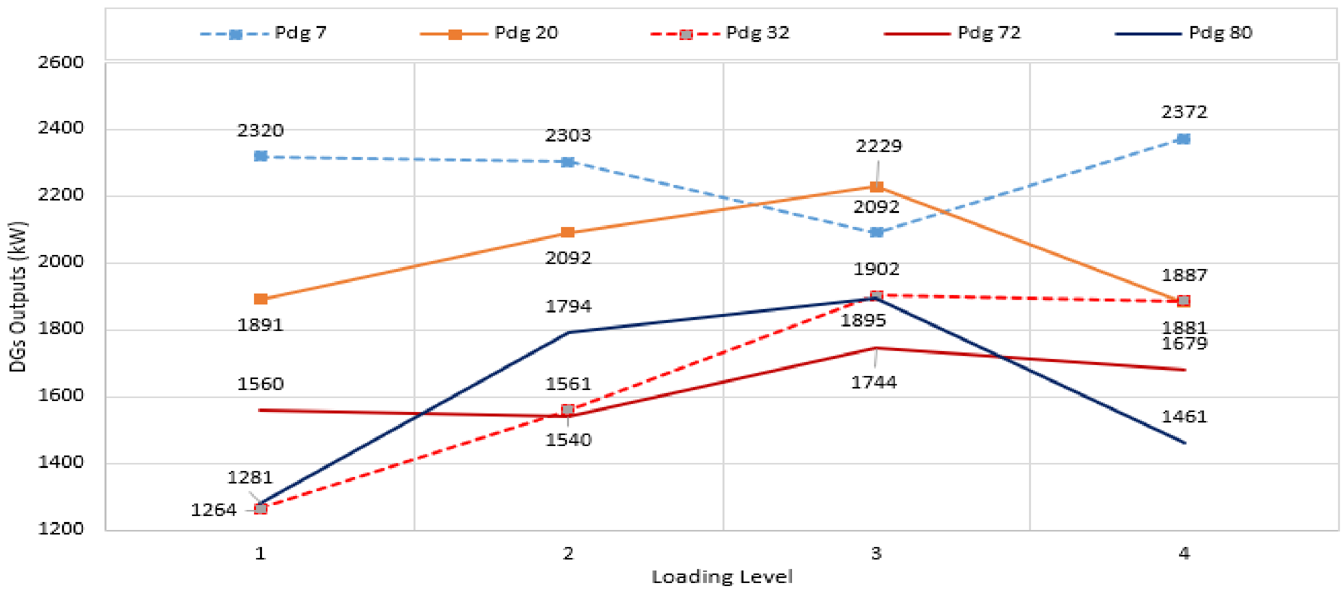

FIGURE 18. Dispatching of DGs for the 84-bus system at each load level using the MRFOA.

maximum number of DGs are 5 with maximum size of 5 MW. The proposed technique and PSO are applied for optimal sizing and siting of the DGs and CBs with initial system configuration and Table 10 illustrates the regarding results. In this table, the total power losses given for the developed MRFOA are sharply decreased from 531.9973 kW to 170.544 kW with reduction of 67.94%, where PSO achieves power losses of 179.45 kW.

Fig. 17 shows the 84-bus system with the optimal allocation of the DGs and CBs using the proposed MRFOA. In addition to that, MRFOA is applied for simultaneous operation of DGs, CBs and DNR with the daily load levels illustrated in Fig. 4. The optimal tie lines at each level are tabulated in Table 11, whilst the simultaneous dispatching of DGs and switching of CBs are depicted in Figs. 18 and 19, respectively. A comparison between the three previous scenarios is conducted in Table 12. As shown, the proposed MRFOA can optimally control the DGs, CBs, and tie switching simultaneously. The daily dissipated energy is reduced from 8997.88 kWh to 3354.1656 kWh with

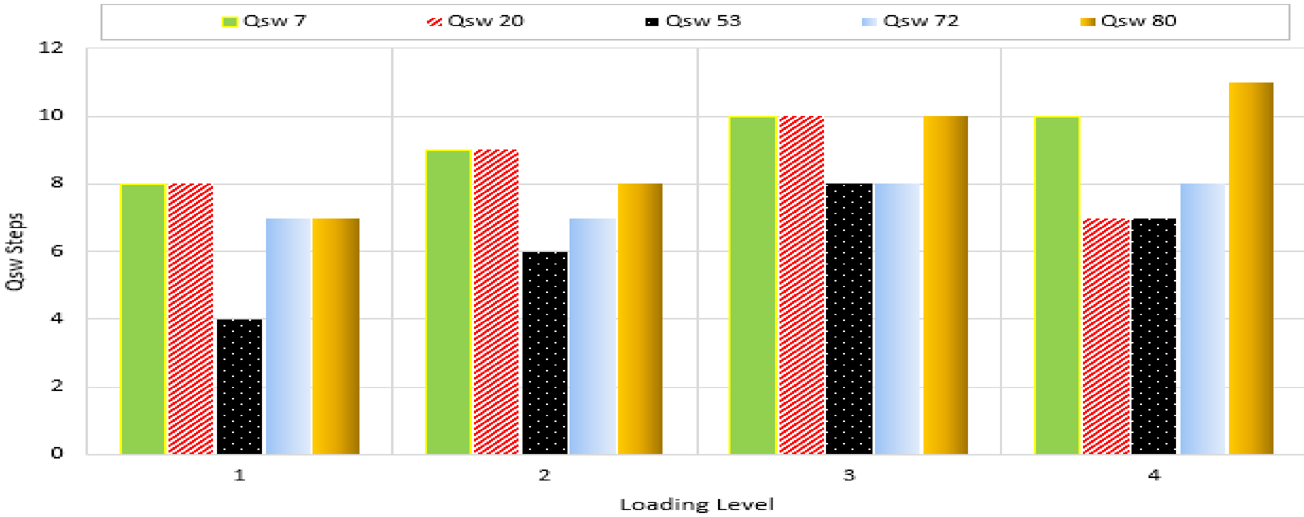

FIGURE 19. Optimal switching of CBs for the 84-bus system at each load level using the MRFOA.

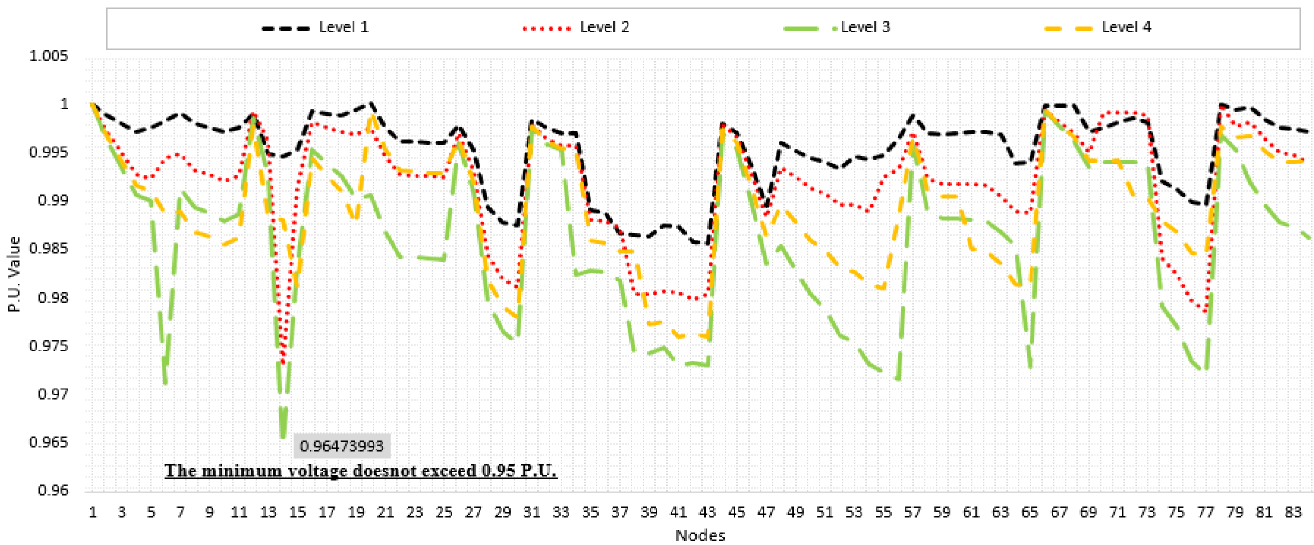

FIGURE 20. Voltage profile of the 84-bus system at each load level with control of DGs, CBs, and DNR.

TABLE 10. Optimal allocations of simultaneous DGs and CBs at nominal loading condition for the 84-bus system.

	CBs size in kVAr (bus)	DGs size in kW (bus)	kW Losses
Initial	-	-	531.9973
PSO	2400(7), 2400(20), 2700(32), 2100(72), 2700(80)	3109(7), 2713(13), 3072(20), 525(35), 3567(80)	179.4508
Proposed MRFOA	2400(7), 2400(20), 3000(32), 1800(72), 2400(80)	3109(7), 3072(20), 2609(53), 521(72), 3567(80)	170.544

TABLE 11. Optimal tie line of the 84-bus system at each load level via MRFOA.

Loading Level	Initial tie lines	Optimal tie lines
1	84 to 96	4, 14, 34, 39, 52, 63, 68, 78, 86, 88, 90, 92, 95
2	84 TO 96	5, 13, 14, 34, 37, 42, 54, 59, 69, 78, 86, 90, 92
3	84 to 96	5, 6, 13, 14, 33, 37, 40, 64, 69, 79, 86, 90, 92
4	84 to 96	5, 13, 14, 25, 28, 29, 34, 41, 59, 63, 70, 79, 86

62.72% reduction. Besides, it achieves a great reduction compared to Scenario-2 which reduces the energy losses to 2438.3901 kWh with 72.9% reduction. Additionally, the optimally control the DGs, CBs, and tie switching simultaneously using the proposed MRFOA successfully improves the minimum and maximum voltages to be close to the preferred at 1 p.u. approximately at all loading levels. Fig. 20 illustrates the voltage profile of the system for the considered four load levels with simultaneous control of DGs,

TABLE 12. Corresponding results of optimal control of DGs, CBs, and DNR of the 84-bus system at each load level.

Loading Level		1	2	3	4
Initial system (Scenario-1)	Losses	176.3947	297.8488	509.9765	409.3635
	Min-V (bus)	0.9595(10)	0.947 (10)	0.9301 (10)	0.9376 (10)
	Max-V (bus)	1 (1)	1 (1)	1 (1)	1 (1)
	Energy losses per day = 8997.8841 kWh				
CBs and DGs without DNR (Scenario-2)	Losses	117.0665	117.8785	163.8549	137.2545
	Min-V (bus)	0.9812 (65)	0.9756 (65)	0.9682 (65)	0.9715 (65)
	Max-V (bus)	1.03 (7)	1.0189 (7)	1.0038 (7)	1.0105 (7)
	Energy losses per day = 3354.1656 kWh				
CBs and DGs with DNR (Scenario-3)	Losses	38.7443	75.0535	147.0953	109.4923
	Min-V (bus)	0.9857 (43)	0.973 (14)	0.9647(14)	0.976 (41)
	Max-V (bus)	1.0002 (20)	1 (1)	1 (1)	1 (1)
	Energy losses per day = 2438.3901 kWh				

CBs, and DNR. It is greatly improved where the minimum voltage at load levels 1-4 is increased from 0. 9595 p.u., 0.947 p.u., 0.9301 p.u., 0.9376 p.u., to 0. 9875 p.u., 0.973 p.u., 0.9647 p.u., and 0.976 p.u., respectively. Overall loading levels, the minimum recorded voltage is 0.9647 p.u. which does not exceed the minimum permissible limit (0.95 p.u).

V. CONCLUSION

In this article, a recently developed Manta Ray Foraging Optimization Algorithm has been employed for control and optimal allocation of Distributed Generators, Capacitor Banks, and Distribution Network Reconfiguration simultaneously. Daily load variations have been introduced on the level and hour basis to analyze the dynamic operation of automated distribution systems. Various cases have been demonstrated for both the 33-bus, 69-bus and practical distribution network of 84-bus due to the Taiwan Power Company (TPC). The MRFOA is heavily supported for the simultaneous allocation of DGs/CBs, considering the peak loading condition. The proposed MRFOA shows higher superiority in comparison with other recent strategies such as PSO, IMDE, TSA, EGA, GA, SMA CSO, TSA and ITSA. Subsequently, the proposed MRFOA is being used with DSA for optimal coordination of the DNR, the DGs power output and the operating step for losses minimization considering the loading variations. For all load values, the proposed MRFOA offers improved convergence and efficiency compared to the recent TSA and ITSA levels. Ultimately, the proposed MRFOA offers significant minimization of the daily dissipated energy for semi-automated distribution systems. Additionally, the proposed MRFOA shows small computational costs which makes it very suitable for the studied real time problem. Added to that, the proposed method has been validated for single, double and triple of combined DGs/CBs numbers. The proposed MRFOA has good system performance for all tested cases.

In the future extension of this work, based on the high ability of MRFOA that was noticed in handling the target problem. The proposed MRFOA is distinguished with high performance and effective output which demonstrates great superiority compared with several algorithms. Consequently, with increasing the complexity of the system and higher degree of non-linearity as well as the unbalanced distribution systems considering the existence of soft open points [44], it will be benefited to study the behavior of MRFOA under these stressed conditions.

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