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Optimal Allocation of Open Unified Power Quality Conditioner in Microgrid Environment with Distributed Energy Sources

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Abstract: High penetration of distributed energy sources (DER) leads to the negative impact on distribution system with microgrid such power quality (PQ) problems as well as high losses in the distribution network. Appropriate allocation of open unified power quality conditioner (UPQC-O) could be a viable solution for aforementioned problems. This paper introduces stochastic two-level coordinated optimization (TLCO) model for allocation of microgrid with DER and UPQC-O to improve energy efficiency as well as power quality (PQ). The proposed methodology is consisting of lower and upper-level optimization model, which representing decision-making at the operation and planning levels, respectively. In addition, impact of time varying voltage sensitive loads has been considered in the study. In addition, a multi-improved scaled whale optimization method (multi-ISWOA) solver was developed in order to tackle the challenge of nonlinear mixed integer programming. Verification of the suggested procedure on the IEEE 69 bus radial distribution system. The findings of this study demonstrate the significance of implementing a coordinated installation of UPQC-O and DER device that incorporates a voltage control mechanism. Such installations can lead to significant cost savings, with a reduction of up to 52.87% compared to cases where no such installation is done. Moreover, compared to the conventional deployment of UPQC and DER devices, a 15.88% cost savings can be achieved through the coordinated installation approach.

Keywords: Open unified power quality conditioner, Whale optimization algorithm, Distributed energy resources.

1. Introduction

1.1 Motivation

According to utilities face new planning and operation issues due to changes in the electricity system's structure. By linking distributed energy sources (DER) at the distribution level, microgrids can be formed from traditional distribution networks [1,2]. The integration of converter-based DER units and nonlinear loads into the network results in the introduction of harmonics, which in turn results in a degradation of the power quality (PQ). The UPQC allocation is one of the strategies to increase PQ and offer reactive power adjustment. In addition to this, it assists in increasing the network's energy efficiency as well as the bus voltages. As a result, a suitable technique is required for the allocation of UPQC along with DER in microgrids.

1.2 Literature survey

Distributed energy resources based on renewable energy sources (RES) can be strategically placed to reduce losses and carbon emissions in the distribution network [3,4]. For the best positioning and rating of DER in microgrids under unknown conditions, a hybrid optimization approach combining ant lion optimization (ALO), genetic algorithms, and general algebraic modelling system (GAMS) has been used in [5]. For the technoeconomic and environmental optimization method for MGs with various RES, an optimal operation approach based on equilibrium optimization (EO) was suggested in [6]. In order to increase the overall system resilience and save operational costs, a distributed power management method for multiple MG distribution networks was proposed in [7]. However, [1-7] does not incorporate the UPQC allocation.

Although the effects of UPQC allocation have been explored in [8] in the context of voltage dependent load models and load increase, optimal allocation has not been carried out. The advantages of using UPQC to adjust reactive power in the distribution system have been described in [9], but cost analysis has not been assessed. The optimum placement and size of OUPQC have been determined in ref. [10] in order to reduce the cost of the distribution network during the planning horizon. The open unified power quality conditioner (UPQC) may accommodate different PQ levels and pricing points to satisfy the needs of customers. It consists of several power-electronic shunt units located close to end users and an MV/LV substation's main power-electronic series unit [11, 12]. However, the design of the UPQC-O model with a microgrid to increase energy efficiency while maintaining a set PQ constraint has not yet been studied. This concept will operate as the key motivator for the work going forward, as it was chos

en for that role.

1.3 Metaheuristic approaches

The objective of the metaheuristic method is to find a solution that is either near-ideal, suboptimal, or acceptable. Unlike the exact method, which guarantees the discovery of the actual best choice, this approach does not guarantee the optimal choice. The fixed step average and subtraction-based optimizer (FA-ASBO) employed average knowledge to direct the population toward the optimal option by excluding the best and worst [13]. The best population member was combined with a random member using the mixed leader-based optimizer (MLBO), which produced a new algorithmic population leader [14]. The population members of the algorithm were updated in the issue search space using three significant population members—best, worst, and mean—by three powerful members-based optimizers (TIMBO) [15]. The random selected leader based optimizer (RSLBO) method updated population members based on random leaders to explore the search space [16]. The whale optimization algorithm (WOA), which was motivated by bubble-net hunting, imitates humpback whale hunting [17]. To solve the current challenging MINLP problem, the authors of this research employed the whale optimization algorithm with several changes.

1.4 Contribution of present work

The following are the primary contributions of the current paper

- For the accommodating planning model of microgrid with distributed energy resources and Open UPQC in a distribution network, a new two-layer coordinated optimization approach has been put forth.
- DER and UPQC-O integrated planning approach covers operational, environmental and economic challenges. A stochastic module accounts for solar irradiation, wind speed variations and load demand uncertainty.
- The impact of voltage dependent loads on DER and UPQC-O allocation has been analyzed.

To the authors' knowledge, no reports of coordinated microgrid allocation with DER and UPQC-O taking voltage-dependent load models into account have been published. The use of the multi ISWOA technique to address DER and UPQC allocation issues in distribution systems has not yet been investigated. For DER and UPQC-O allocation issues with voltage-dependent load models, this work provides multi-improved scaled WOA (ISWOA). By applying numerous test cases and contrasting the results with those of other approaches described in the literature, the effectiveness of the proposed multi ISWOA is confirmed.

1.5 Structure of paper

The organization of the present paper is as follows: Section 2 provides the mathematical formulation of the research objective. Section 3 has detailed the multi improved whale optimization approach that has been proposed. The execution of the multi improved scaled whale optimization technique that was created to the microgrid allocation with DER and UPQC-O allocation problem is detailed in section 4. Section 5 provides a summary of the conclusions and conversations. Section 6 of the closing section covered the conclusion.

2. Problem formulation

The purpose of the current issue is to identify a resolution that minimises the total annual cost. This cost covers the expenses related to the acquisition of DER and UPQC-O, as well as the expenses related to their management and operation, the cost of grid electricity, and the cost of emissions.

2.1 Objective function

Mathematical The reduction of the total economic cost is the objective function (OF) of the proposed approach, which is defined in the following Eq. (1)

$$min. O\,F = INV_{COST} + OPER_{COST} \tag{1}$$

Where the first term in Eq. (1) is the investment cost (INV_{COST}) of DER such as PV and wind based DG, battery energy storage) as well as UPQC-O, which are derived from upper level; The mathematical expression of INV_{cost} follows

$$INV_{COST} = \begin{bmatrix} AC^{PV}\sum_{i\in\Omega_{PV}}\left(C_{PV}^{inv}P_{PV,i}^{rated}\right) \\ AC^{Wd}\sum_{i\in\Omega_{Wd}}\left(C_{Wd}^{inv}P_{Wd,i}^{rated}\right) \\ AC^{BES}\sum_{i\in\Omega_{BES}}\left(C_{BES}^{inv}P_{BES,i}^{rated} + C_{E,BES}^{inv}E_{BES,i}^{rated}\right) \\ AC^{UPQC}\sum_{ij\in\Omega_{UPQC}}\left(C_{UPQC}^{inv}Q_{UPQC,ij}^{rated}\right) \end{bmatrix} \tag{2}$$

Where

$$AC^{x} = \frac{d(1+d)^{LT_x}}{(1+d)^{LT_x-1}}; x \in \{PV, Wind, BES, UPQC\}$$

AC is an abbreviation for annual cost, which is the metric that is utilised in the process of converting total cost into yearly cost. Where LT is the asset life time period and d is the discount rate. The first and second term in Eq. (2), which represents the yearly cost PV (C_{PV}^{inv}) and wind based DG C_{Wd}^{inv} respectively. The third and fourth term represents the yearly cost of BES and UPQC-O respectively.

As lower level signifies the coordinated operation optimization through recurrent simulations for the purpose of minimization the total expected operating costs ($OPER_{COST}$), which is stated in Eq. (3).

$$OPER_{COST} = \left[\sum_{t=1}^{T}\left(\sum_{s=1}^{N_{rs}}\pi_s \times (exp\_oper)\right)\right] \times D_y \tag{3}$$

$$\exp\_oper = \begin{bmatrix} \sum_{ij\in\Omega_{UPQC}}C_{UPQC}^{OM,t}Q_{UPQC,ij,s}^{t} + \sum_{i\in\Omega_{BES}}C_{BES}^{OM,t}P_{BES,i,s}^{t} \\ +\sum_{i\in\Omega_{Wd}}C_{Wd}^{OM,t}P_{Wd,i,s}^{t} + \sum_{i\in\Omega_{PV}}C_{PV}^{OM,t}P_{PV,i,s}^{t} \\ +C_{loss}^{t}P_{loss,s}^{t} + C_{ens}^{t}P_{ens,s}^{t} + C_{emis}P_{sub,s}^{t} \end{bmatrix} \tag{4}$$

The first and second term in Eq. (4) reflects the amount of money spent on the operation and maintenance (O & M) of the UPQC equipment and BES. The third and fourth terms each represent the O & M expenses associated with wind and PV-based DGs. The fifth term denotes the cost of the energy loss. The sixth terms denote the cost of energy not served. Last but not least, the seventh term denotes the cost of carbon emission, which is beneficial in lowering the amount of carbon emission produced by the substation. The total number of days in a year, denoted by D_y, is the factor that must be multiplied by in order to transform the daily cost into the annual cost

2.2 System operation constraints

The following constraints for proposed model to be satisfied.

a) Maximum installation of UPQC, wind-based DG and PV based DG at each bus

$$\left.\begin{array}{l} 0 \le Q_{UPQC,ij}^{rated} \le Q_{UPQC,ij}^{max} \\ 0 \le P_{Wd,i}^{rated} \le P_{Wd,i}^{max} \\ 0 \le P_{PV,i}^{rated} \le P_{PV,i}^{max} \\ 0 \le P_{BES,i}^{rated} \le P_{BES,i}^{max} \end{array}\right\} \tag{5}$$

b) power flow equations for each possible outcome

$$\left.\begin{array}{l} P_{i,s}^{t} = V_{i,s}^{t}\sum_{i\in\Omega_{bus}}V_{j,s}^{t}\left(G_{ij}\cos\theta_{ij,s}^{t} + B_{ij}\sin\theta_{ij,s}^{t}\right) \\ Q_{i,s}^{t} = V_{i,s}^{t}\sum_{i\in\Omega_{bus}}V_{j,s}^{t}\left(G_{ij}\sin\theta_{ij,s}^{t} - B_{ij}\cos\theta_{ij,s}^{t}\right) \end{array}\right\} \tag{6}$$

c) Constraint on the bus voltage for each possible scenario

$$V_i^{min} \le V_{i,s}^{t} \le V_i^{max} \tag{7}$$

d) Current capacity in branch constraint for each scenario

$$0 \le I_{l,s}^{t} \le I_l^{rated} \tag{8}$$

e) The OLTC transformer tap constraints

$$t_{oltc}^{min} \le t_{oltc}^{t} \le t_{oltc}^{min} \tag{9}$$

f) Voltage dependent load models: The real and reactive power of constant impedance, constant power and constant current load models have been expressed as given below

$$P_{L,m} = P_{L,m}^{ll}\left[Z_m^p\left(\frac{V_i}{V^n}\right)^2 + I_m^p\left(\frac{V_i}{V^n}\right) + P_m^p\right] \tag{10}$$

$$Q_{L,m} = Q_{L,m}^{ll}\left[Z_m^q\left(\frac{V_i}{V^n}\right)^2 + I_m^q\left(\frac{V_i}{V^n}\right) + P_m^q\right] \quad (11)$$

3. Solution algorithm: improved scaled whale optimization algorithm (ISWOA)

Each whale's position serves as a hunt agent for the whale optimization algorithm (WOA) [17]. The ISWOA recreation procedure may be applied in the following steps.

Step 1: Whales can detect their prey while hunting and circle around it. Because the precise location of the optimal design in the search region is unknown, the ISWOA approach makes the assumption that the best candidate solution at this time is either the target prey or really close to the optimum. These behaviours are represented by the equations that follow.

$$\vec{D} = \frac{1}{\lambda}\left|\vec{E}.\vec{X}_p(iter) - \vec{X}(iter)\right| \quad (12)$$

$$\vec{X}(iter+1) = \frac{1}{\lambda}\left(\overrightarrow{X_p}(iter) - \vec{R}.\vec{D}\right) \quad (13)$$

Here, a new parameter λ is a parameter employed to scale the distance properly and to keep the wolves in a better circle. *iter* specifies the current iteration. The values of $\vec{X}$ and $\overrightarrow{X_p}$, denotes the positions of the whale and its prey respectively. The subsequent formula could be employed to compute the vectors $\vec{R}$ and $\vec{E}$.

$$\vec{R} = 2\varepsilon.\overrightarrow{r_1} - \varepsilon \quad (14)$$

$$\vec{E} = 2\overrightarrow{r_2} \quad (15)$$

$$\varepsilon = 2\left(1 - \mu.\frac{iter^2}{iter^{max^2}}\right) \quad (16)$$

Here exploration rate 'ε' fluctuates nonlinearly, ensures the agents in trust of exploration and exploitation from sharing information about the current iteration, μ denotes nonlinear variation index ranges from (0,3).

Step 2: The way that humpback whales navigate around their prey depends on whether they are swimming in a spiral or a decreasing circle. It is expected that there is a 50% possibility that the scrum methodology or the diminishing encircling mechanism will be utilised to modify the position of whales through optimization in order to reflect this simultaneous behaviour as given in Eq. (17).

If probability is less than 0.5, whale position updated by below Eq. (17a)

$$\vec{X}(iter+1) = \frac{1}{\lambda}\left(\overrightarrow{X_p}(iter) - \vec{R}\vec{D}\left|\vec{E}.\vec{X}_p(iter) - \vec{X}(iter)\right|\right) \quad (17a)$$

If probability is greater than or equal is to 0.5, whale position updated by below Eq. (17b)

$$\vec{X}(iter+1) = \frac{1}{\lambda}\left(\vec{D} \times e^{hk} \times cos(2\pi k) + \vec{X}_p(iter)\right) \quad (17b)$$

For better solution, further the updating of the whale positions has been utilise the data that was provided at the prior personal best and global best positions as given in Eqs. (18) and (19)

$$\vec{X}m(iter+1) = \vec{X}(iter+1) + \vec{v}(iter+1) \quad (18)$$

$$\vec{v}(iter') = \begin{Bmatrix} \chi.\vec{v}(iter) + c_1.r_2.\left(\overrightarrow{X_{pbest}}(iter) - \vec{X}(iter)\right) \\ +c_2.r_3.\left(\overrightarrow{X_{gbest}}(iter) - \vec{X}(iter)\right) \end{Bmatrix} \quad (19)$$

where c2 stands for the communication coefficient and c1 for the specific coefficient. The notation $(\overrightarrow{X_{gbest}})$ designates the area's historically best global position, while $(\overrightarrow{X_{pbest}})$ designates the area's best individual position. Eq. (20) contains the inertia weight χ

$$\chi(iter) = \frac{iter^{max}}{iter^{max} \times (\chi_{initial} - \chi_{final}) + \chi_{final}} \quad (20)$$

The first term in Eq. (19) where the best whales are located. This gives the search area agents the necessary push they need. The second term describes the numerous thoughts that go through each searcher's mind as they get closer to the best place that has been found so far. The third term demonstrates the cooperative role the whale agents performed in identifying the global optimal.

Step 3: During the exploration phase, we modify a search agent's candidate based on a randomly selected search agent rather than the best search agent so far found during the evaluation stage. The WOA algorithm can be used to execute a global search utilising this technique and |A| > 1 priority to exploration.

$$\vec{D} = \frac{1}{\lambda}\left|\vec{E}.\vec{X}_{rand}(iter) - \vec{X}(iter)\right| \quad (21)$$

$$\vec{X}(iter+1) = \frac{1}{\lambda}\left(\overrightarrow{X_{rand}}(iter) - \vec{R}.\vec{D}\right) \quad (22)$$

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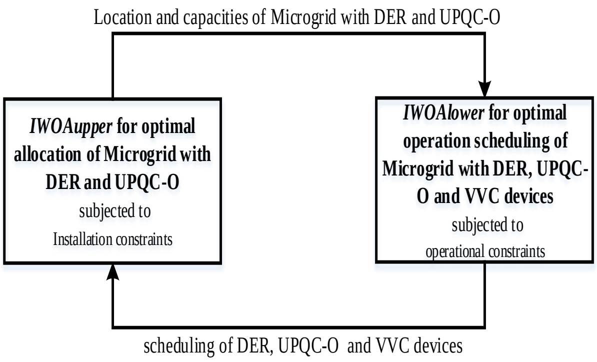

Figure. 4 Multi-IWOA solver for TLCO

Table 1. Pseudo code of the proposed multi-ISWOA for UPQC-O allocation problem

Input: Read the load data, line data and generation data of distribution system
Initialize parameters for both upper level ($ISWO_{upper}$) and lower layer ($ISWOA_{lower}$).
Initiate the outer layer $ISWOA_{upper}$ for optimal location and rating of DER and UPQC-O
Initialize the arbitrary population of the agents for location and size of DER and UPQC-O within permissible limit.
Set the iteration count for $ISWOA_{upper}$
Initiate the lower level $ISWOA_{lower}$ for scheduling of DER and UPQC-O and setting of VVC devices in allowable limit
Set the iteration count for $ISWOA_{lower}$
FOR {$ISWOA^{lower}$ stopping condition not satisfied}
FOR {each hour}
Calculate the fitness function by appropriate dispatching of DER, UPQC-O and VVC devices using (3)
ENDFOR
Evaluate the $ISWOA_{lower}$ subject to constraints (6) to (11) got the current iteration
IF{ $ISWOA_{lower}$ stopping condition not satisfied }
Conduct the $ISWOA_{lower}$ procedure to the current iteration
ENDIF
ENDFOR
perform the load flow analysis using settings obtained from ($ISWOA_{upper}$) and evaluate the fitness function by appropriate allocation of DER and UPQC-O using (2)
IF{ $ISWOA_{upper}$ stopping criterion not satisfied }
Conduct the $ISWOA_{upper}$ procedure to the current iteration
ENDIF
Output: Admit the location and capacity of DER and UPQC-O, active and reactive power scheduling of DER and UPQC-O and setting of VVC devices.

4. Execution of multi improved whale optimization algorithm

The problem discussed in the section above is complicated, which makes it hard to solve with traditional optimization techniques. As a means of finding a solution to the problem, we have partitioned it into two section, which we will refer to, respectively, as the planning section and the operating section. In order to solve these models, the technique that was proposed and consisted of two levels was utilised. A multi-ISWOA (i.e. $ISWOA_{upper}$ and $ISWOA_{inner}$ for upper and lower levels optimization respectively) has been used in this research for the purpose of allocating microgrid with DER and UPQC-O. This was done in order to accomplish the goal of allocating microgrid with DER and UPQC-O. Fig. 4 provides an illustration of the proposed solution technique, which involves using a multiple ISWOAs.

$ISWOA_{upper}$ was successful in determining the upper level with regard to the appropriate position of DER and UPQC-O site ratings. The lower level was successfully resolved thanks to the efforts of $ISWOA_{lower}$, which enabled optimal dispatch of DER, UPQC-O, and the configuration of VVC devices. The decision factors in this scenario are the active power dispatch of DER, the reactive power dispatch of UPQC-O devices, in addition to OLTC taps. At the same time, the solutions were found for both the higher and lower levels. Table 1 contains an illustration of the pseudo code for the proposed multi-IWOA solution to the current situation.

5. Results and discussions

A typical IEEE 69-bus distribution system [19] has been employed to validate the accuracy of the proposed methodology. The typical load profile data and PV generating output data are taken into consideration from [20]. The cost parameters for UPQC-O, DER have been considered from [12, 20]. Megawatt hour (MWh) prices for unserved electricity are expected to be $2,000 [20]. The emission cost is assumed to be $100 per tCO2e, and the emission rate is assumed to be 0.4 tCO2e/MWh [20]. It is assumed that the total harmonic distortion (THD) is 20%. The maximum population size and iterations taken were 30 and 100, respectively. Using the Monte Carlo simulation, 1000 scenarios were generated, and the Keans clustering technique was used to decrease the number of scenarios to 50. A MATLAB environment is used to implement the suggested TLCO methodology. The problem was solved using a multi-improved whale optimization algorithm (multi-ISWOA) strategy.

Table 2. Cases studied

Cases	DER	UPQC/UPQC-O	VVC
Case 1	×	×	×
Case 2	✓	×	×
Case 3	✓	UPQC	×
Case 4	✓	UPQC-O	×
Case 5	✓	UPQC-O	✓

✓: means considered, ×: means not considered

Table 3. Simulation results under different cases

Parameters	Case 1	Case 2	Case 3	Case 4	Case 5
Investment cost ($\times 10^3$ $)	------	513.993	647.568	514.138	720.616
O & M cost ($\times 10^3$ $)	------	27.488	34.209	27.197	41.430
Energy loss cost ($\times 10^3$ $)	5097.246	2981.951	2396.436	1671.333	1339.477
Energy not served cost ($\times 10^3$ $)	560.076	554.910	553.376	550.881	544.389
Emission cost ($\times 10^3$ $)	1120.151	640.821	638.607	727.087	548.105
Total cost ($\times 10^3$ $)	6777.473	4719.163	4270.195	3490.637	3194.016
Savings in total cost ($\times 10^3$ $)	------	2058.310	2507.278	3286.836	3583.457
Total cost reduction (%)	------	30.370	36.994	48.496	52.873

5.1 Cases studied:

Five different studies of the suggested methodology's effectiveness have been done, as shown in Table 2, in five different situations. Out of the five cases, Case 1 is the most common.

5.2 Discussions on numerical results:

The most significant components are shown in Table 3 and include installation cost, operation and maintenance (O & M) expenses of RES-based DGs, BES and UPQC-O, energy loss cost (ELC), cost of energy not served (ENS), and cost of CO_2 emission of different cases. Even though the investment cost of DGs increased by k$ 513.993, the findings of case 2 show savings of about k$ 2058.310, or 30.37% more than those of case 1. This demonstrates the importance of RES-based DG and BES allocation in distribution networks. In a manner analogous, case 3 results in a saving of around k$ 2507.278, which results in a savings percentage of 36.994% when compared to case 1, despite the fact that the investment cost has increased to k$ 647.568. This demonstrates the importance of placing RES-based DG and UPQC devices in distribution systems. However, UPQC-O device allocation combined with DER results in savings of 48.496% as compared to case 1. It discloses that relevance of coupled allocation of UPQC-O and DER. Last but not least, case 5 emphasizes the importance of coordinated UPQC-O and DER device allocation, incorporating voltage control method, and savings up to K$ 3583.457 (i.e. 52.873% savings in total cost compared to that of case 1).

The best location and size for UPQC-O, wind-based DG, and PV-based DG, BES installations are listed in Table 4 for various scenarios. Table 4 shows that the capacities of these devices have increased as a result of the incorporation of VVC operation, as seen in case 5. To fulfil the total demand, this causes percentage share of RES-based DG has been increased, which lowers grid carbon emissions.

5.3 Evaluation of proposed multi ISWOA and other metaheuristic approaches

Due to the complexity of case 5, an evaluation of the efficacy of various metaheuristic algorithms, including MLBO [14], TIMBO [15], RSLBO [16], WOA [17], PSO [18], improved WOA (IWOA)[21] and multi-ISWOA has been performed. The values of the minimum, the average, and the standard deviation of the aforementioned metaheuristic algorithms are depicted in Table 5. The proposed multi-ISWOA is getting closer and closer to its minimal value, which has converged at k$ 3194.02, but the MLBO [14], TIMBO [15], RSLBO [16], WOA [17], PSO [18] and IWOA [21] have all converged at k$ 4719.16, k$ 5165, k$ 5534, k$ 3490.64 and k$ 4270.2, and k$ 3310.4 respectively. It cannot be denied that the proposed multi ISWOA is more effective than the metaheuristic approaches that have been published. Adjusting the balance between diversification and intensification while considering track of previous bests enables the multi-ISWOA approach to produce results that are significantly nearer to the global solution.

6. Conclusion

In this article, two-level integrated optimization methodology has been presented as a solution for the

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Table 4. Optimal location and sizes of DER and UPQC-O

Cases	DER/ UPQC-O	(location, size in kVA)	Total capacity (kVA)
Case 2	PV	(20, 180), (49, 500), (56, 500)	1180
	Wind	(16, 260), (52, 450), (64, 500)	1210
	BES	(15, 250;1000), (28, 250;1000), (59, 250;1000)	750; 3000
Case 3	PV	(20, 170), (49, 500), (56, 500)	1170
	Wind	(16, 260), (52, 450), (64, 500)	1210
	BES	(15, 250;1000), (28, 250;1000), (59, 250;1000)	750; 3000
	UPQC	(54, 320), (55, 830)	1150
Case 4	PV	(20, 50), (49, 50), (56, 50)	150
	Wind	(16, 260), (52, 450), (64, 500)	1350
	BES	(15, 250;1000), (28, 250;1000), (59, 250;1000)	750; 3000
	UPQC-O	(17, 250), (61, 900)	1150
Case 5	PV	(20, 290), (49, 500), (56, 500)	1290
	Wind	(16, 430), (52, 500), (64, 500)	1430
	BES	(15, 250;1000), (28, 250;1000), (59, 250;1000)	750; 3000
	UPQC-O	(17, 350), (61, 1000)	1350

Table 5. Relative study of different metaheuristic approaches

Metaheuristic approach	**Minimum value** ($\times 10^3$ \$)	**Mean value** ($\times 10^3$ \$)	**Standard deviation** ($\times 10^3$)
MLBO [14]	4719.16	5045.65	766.03
TIMBO [15]	5165	5587.65	939.82
RSLBO [16]	5534	6049.81	1042.11
WOA [17]	3490.64	3789.5	664.56
PSO [18]	4270.2	4687.54	843.164
IWOA [21]	3310.4	3623.65	672.657
Proposed ISWOA	3194.02	3425.9	544.074

combined planning model of microgrids with distributed energy resources and UPQC-O. The outcomes of the simulation demonstrate that the proposed planning model and multi-improved WOA solver are both capable of producing the desired results and are operationally feasible. The use of voltage control devices, UPQC-O, and DER can reduce network energy loss, energy demand, reliability costs, and CO2 emissions. The multi ISWOA solution generates superior results when contrasted with the PSO solver and the IWOA solver. It is possible to infer that the implementation of voltage control schemes, along with the planning of Microgrids with DER and UPQC-O devices, can simultaneously improve the financial advantages of distribution networks while also boosting their dependability, flexibility, and environmentally friendly performance.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

Conceptualization, Priyanka; methodology, Priyanka; software, Priyanka; validation, Priyanka; formal analysis, Priyanka; investigation, Priyanka; resources, Raghuram; data curation, Raghuram; writing—original draft preparation, Priyanka; writing—review and editing, Raghuram; visualization, Raghuram; supervision, Raghuram.

Nomenclature

Indices

i/j, s	Index for bus/node, scenario
T,t	Index for Total time duration, time

Sets

$\boldsymbol{\Omega_{bus}/\Omega_{UPQC}}$	Set of buses/ set of buses mounted with UPQC
Ω_{Wd}/Ω_{PV}	set of buses mounted with wind/PV generation

Parameters

N_L/N_{PV}	Total number of loads, installed PV
$Q_{UPQC}^{rated}, P_{WD}^{rated}, P_{PV}^{rated}$	Rated capacity of UPQC, Wind and PV based DG
$C_{UPQC}^{inv}, C_{WD}^{inv}, C_{PV}^{inv}$	Investment cost of UPQC, Wind and PV based DG
$C_{UPQC}^{OM,t}, C_{WD}^{OM,t}, C_{PV}^{OM,t}$	Cost of operation and maintenance of UPQC, Wind and PV based DG

$C_{loss}^{t}, C_{ens}^{t}, C_{emis}$	Cost of losses, energy not served and emission
$Q_{UPQC,ij}^{max}, P_{Wd,i}^{max}, P_{PV,i}^{max}$	Maximum rating capacity of UPQC, Wind based DG and PV based DG
V_{i}^{min}, V_{i}^{max}	Minimum/maximum bus voltage magnitude
$t_{oltc}^{min}, t_{oltc}^{min}$	Minimum/ maximum settings of OLTC tap
I_{l}^{rated}	Rated current in the line *l*

Variables

$P_{loss,s}^{t}, P_{ens,s}^{t}, P_{sub,s}^{t}$	Power loss, energy not served, power from substation at t^{th} hour for s^{th} scenario
$Q_{UPQC,i,s}^{t}, P_{WD,i,s}^{t}, P_{PV,i,s}^{t}$	Reactive power from UPQC, active power from wind and PV based DG at t^{th} hour for s^{th} scenario
$P_{i,s,}^{t} Q_{i,s}^{t}$	Active/ reactive power at i^{th} bus at t^{th} hour for s^{th} scenario
$V_{i,s}^{t}$	Voltage magnitude at i^{th} bus at t^{th} hour for s^{th} scenario
t_{oltc}^{t}	OLTC transformer tap position at t^{th} hour
$I_{l,s}^{t}$	current through branch *l* at t^{th} hour for s^{th} scenario

References

[1] M. Debouza, A. A. Durra, T. H. E. Fouly, and H.H. Zeineldin, "Survey on microgrids with flexible boundaries: Strategies, applications, and future trends", *Electric Power Systems Research*, Vol. 205, p. 107765, 2022

[2] S. A. Arefifar, Y. A. R. I. Mohamed, and T. H. E. Fouly, "Supply-adequacy-based optimal construction of microgrids in smart distribution systems", *IEEE Transactions on Smart Grid*, Vol. 3, No. 3, pp. 1491-1502, 2012.

[3] P. V. Babu, S. Singh, and S. P. Singh, "Distributed generators allocation in distribution system", In: *Proc. of IEEE Power & Energy Society General Meeting*, Chicago, USA, pp. 1-5. 2017.

[4] A. Kumar, P. V. Babu, and V. V. S. N. Murty, "Distributed generators allocation in radial distribution systems with load growth using loss sensitivity approach", *Journal of The Institution of Engineers (India), Series B 98*, No. 3, pp. 275-287, 2017.

[5] V. V. S. N. Murty, and A. Kumar, "Multi-objective Planning Model for Reconfigured Microgrids with Distribution Generation and Capacitors under Uncertainty Environment", In: *Proc. of 2020 IEEE 9th Power India International Conference (PIICON)*, pp. 1-6, 2020.

[6] A. A. Abou, E. Ela, R. A. E. Sehiemy, S. M. Allam, A. M. Shaheen, N. A. Nagem, and A. M. Sharaf, "Renewable Energy Micro-Grid Interfacing: Economic and Environmental Issues", *Electronics*, Vol. 11, No. 5, p. 815, 2022

[7] Z. Shahooei, L. Martin, H. Nehrir, and M. Bahramipanah, "A Novel Agent-Based Power Management Scheme for Smart Multiple-Microgrid Distribution Systems", *Energies*, Vol. 15, No. 5, p. 1774, 2022.

[8] M. S. Kumar, A. Kumar, and A. R. Gupta, "Distribution System Analysis with UPQC Allocation Considering Voltage Dependent Time-Variant and Invariant Loads including Load Growth Scenario", *Journal of The Institution of Engineers (India): Series B*, pp. 1-17, 2022.

[9] S. Ganguly, "Unified power quality conditioner allocation for reactive power compensation of radial distribution networks", *IET Generation, Transmission & Distribution*, Vol. 8, No. 8, pp. 1418-1429, 2014.

[10] M. M. Amini, and A. A. Jalilian, "Optimal sizing and location of open-UPQC in distribution networks considering load growth", *International Journal of Electrical Power & Energy Systems*, Vol. 130, p. 106893, 2021.

[11] B. Morris, R. Faranda, and E. Tironi, "A new proposal for power quality and custom power improvement: OPEN UPQC", *IEEE Transactions on Power Delivery*, Vol. 24, No. 4 pp. 2107-2116, 2009.

[12] S. Lakshmi and S. Ganguly, "An on-line operational optimization approach for open unified power quality conditioner for energy loss minimization of distribution networks", *IEEE Transactions on Power Systems*, Vol. 34, No. 6, pp. 4784-4795, 2019.

[13] P. D. Kusuma and A. Dinimaharawati, "Fixed Step Average and Subtraction Based Optimizer", *International Journal of Intelligence Engineering and Systems*, Vol. 15, No. 4, pp. 339-351, 2022, doi: 10.22266/ijies2022.0831.31.

[14] F. A. Zeidabadi, S. A. Doumari, M. Dehghani, and O. P. Malik, "MLBO: Mixed Leader Based Optimizer for Solving Optimization Problems",

International Journal of Intelligent Engineering and Systems, Vol. 14, No. 4, pp. 472-9, 2021, doi: 10.22266/ijies2021.0831.41.

[15] F. A. Zeidabadi, M. Dehghani, and O. P. Malik, "TIMBO: Three influential members based optimizer", *International Journal of Intelligent Engineering and Systems*, Vol. 14, No. 5, pp. 121-128, 2021, doi: 10.22266/ijies2021.1031.12.

[16] F. A. Zeidabadi, M. Dehghani, and O. P. Malik, "RSLBO: Random Selected Leader Based Optimizer", *International Journal of Intelligent Engineering and Systems*, Vol. 14, No. 5, pp. 529-538, 2021, doi: 10.22266/ijies2021.1031.46.

[17] S. Mirjalili and A. Lewis, "The whale optimization algorithm", *Advances in Engineering Software*, Vol. 95, pp. 51-67, 2016.

[18] Y. D. Valle, G. K. Venayagamoorthy, S. Mohagheghi, J. Hernandez, and R. G. Harley, "Particle swarm optimization: Basic concepts, variants, and applications in power systems", *IEEE Trans. Evol. Comput.*, Vol. 12, No. 2, pp. 171–195, 2008.

[19] M. E. Baran and F. F. Wu. "Optimal sizing of capacitors placed on a radial distribution system", *IEEE Trans Power Delivery*, Vol. 4, No.1, pp. 735-743, 1989.

[20] P. V. Babu, and S. P. Singh, "Coordinated allocation of BESS and SOP in high PV penetrated distribution network incorporating DR and CVR schemes", *IEEE Systems Journal*, Vol. 16, No. 1, pp. 420-430, 2022.

[21] Y. Priyanka and M. Raghuram, "Performance Analysis of Distribution System with Optimal Allocation of Unified Power Quality Conditioner considering Distribution Network Reconfiguration", *International Journal of Intelligent Engineering and Systems*, Vol. 16, No. 1, pp. 364-374, 2023, doi: 10.22266/ijies2023.0228.32.