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Exploration of DG Placement Strategy of Microgrids via FMFO Algorithm: Considering Increasing Power Demand and Diverse DG Combinations

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Abstract: Distributed energy resource (DER) has been widely deployed, and distributed generation (DG) can complement the distribution system. Favorable DG deployment provides the grid-connected microgrid (MG) with stable voltage and reduces emission and power generation costs. DGs are considered distributed feeders, and MG is required to be operated under the optimal state. Reconfiguration is a practical approach to optimizing resource allocation. The optimal global solution is obtained via optimization algorithms. In this paper, three objectives are defined, namely, minimization of economic cost (ECC), emission cost (EMC), and voltage deviation (VD). Consequently, a fuzzy moth-flame optimization (FMFO) algorithm is proposed to coordinate the interests of multiple objectives. Moreover, the simulation is conducted based on the standard IEEE 33-bus radial distribution system (RDS), under which the impact of deployment of various DG type and quantity on the MG is explored. In particular, diverse DG combinations are tried under the increasing power demand, and a high-stable voltage strategy is proposed to meet the specific demands. The simulation results reveal that: (1) the DG type has a significant impact on ECC and EMC; (2) penetration level of DG shows a positive-like relationship with the MG stability; and (3) the proposed FMFO algorithm exhibits an efficient performance in convergence.

Keywords: microgrid; reconfiguration; distributed energy resource; DG placement; FMFO algorithm; DG deployment strategy

1. Introduction

Energy plays a vital role in social development. The massive consumption of traditional energy resources, represented by fossil fuels, has given rise to multiple problems, such as climate change [1] and environmental pollution [2]. With the rapid development of distributed energy resource (DER) technology, the demand for DER is also increasing dynamically, promoting profound changes in planning, configuration, operation, and control of the power system. Currently, DERs are accepted and deployed near houses as a part of the local power supply. A DER is a small-scale energy resource, making the traditional power generation mode undergo a significant transformation. In the traditional operation model, power is supplied by one or more centralized large-scale power plants, which provide power for long-distance loads through high-voltage transmission lines. The DER generation units, also called distributed generations (DGs), are integrated into the power network to provide power compensation for the power system [3]. The DER consists of controllable units (e.g., diesel engine (DE), microturbine (MT), and fuel cell (FC)) and uncontrollable units (e.g., wind turbine (WT) and

photovoltaic (PV) cell) [4]. It is more flexible and faster to deploy the DGs compare with traditional power generators. Moreover, DGs' deployment can bring higher reliability to the power system, provide higher power quality to the loads, reduce transmission loss in the distribution system, decrease power generation cost, and limit environmental pollution.

As the power system is deepening reform, traditional power systems are developing into smart grids (SGs). Microgrids (MGs) are considered cost-effective, environment-friendly, and user-satisfied solutions to the SG. The MG is a small-scale power generation and distribution system, which generally includes multiple components such as power converters (PCs), energy storage systems (ESSs), transformers, switchgears, transmission lines, and power consumers (loads) [5]. There are two operation modes of MG: grid-connected mode and islanded mode [6], respectively. However, considering unpredictable changes in the MG (such as transmission line failures, considerable fluctuations in loads, or DG faults) and the power distribution system's economic and environmental factors, a practical solution is conducting MG reconfiguration [7]. The MG reconfiguration improves the system reliability, reduces the power generation cost, limits the emission pollution, reduces the power transmission loss (PTL), and stabilizes the voltage deviation (VD) in MGs, keeping the MG operated under the optimal state.

Various management strategies, control technologies, and optimization methods related to MG have emerged in recent years to provide reliable technical support for MGs. In [8], the progress of intelligent distribution technology is reviewed concisely, and the emerging technology and future development trend are determined to support the active management of the distribution network. Different MG frameworks are proposed in [9–12] to support energy management, power distribution, DG placement, and renewable energy sources. Hierarchical structures of MG control methods are introduced in [13–17] to handle the system control, energy storage, power distribution, and market behaviors.

Investigation and study on MG reconfiguration are not sufficient [18] and still facing numerous critical challenges. The MG reconfiguration is regarded as a multiobjective optimization process that requires the high performance of optimization algorithms. Considering DG deployment, [19–21] conducted the reconfiguration of the power systems to reduce PTL by applying novel optimization methods. Novel intelligent algorithms [22–25] are springing out to provide options to the optimization problems. The intelligent algorithms are high-efficient in solving single-objective optimization problems but mostly cannot independently deal with multiobjective optimization problems. [26–30] proposed hybrid methods, which combined conventional optimization algorithms with multiobjective approaches, such as stochastic method, Pareto dominance method, and fuzzy decision-making theory, to provide opportunities for multiobjective optimization solutions.

The construction of the power system infrastructure is a significant issue related to the livelihood of people. As the future of the power system, the MG presents an evident value in research and application. In the present studies, the research on multiobjective optimization algorithms is not sufficient; and few works have explored the impact of DG deployment on optimizing the MG system, especially on DG deployment strategies under increasing power demand.

This paper focuses on obtaining and analyzing the optimal solution for reconfigurable MGs. Three objectives: minimization of economic cost (ECC), minimization of emission cost (EMC), and minimization of voltage deviation (VD) are defined to describe multiple requirements of the MG, and a multiobjective optimization algorithm is in need for coordinating the global interests of multiple objectives. To supplement the shortcomings of the existing multiobjective optimization solutions, a novel FMFO algorithm, hybridized the nature-inspired Moth-flame optimizer (MFO) and heuristic fuzzy method, is proposed to solve the multiobjective problem defined in this paper. While considering the integration of MG and DG, the deployment strategy is crucial to achieving the MG voltage stability, especially in the high-stable VD required scenarios. Thus, the analysis and comparison of diverse DG combinations are necessary for developing the DG deployment strategy. Furthermore, the employment of three types of controllable DER generation units, DE, MT, and FC, are considered to explore the

impact of diverse DG combinations on optimal reconfiguration results, such as the effect on load demand, bus voltage, and branch line current.

The main contributions of this paper are:

1. Uncontrollable DER generation units, DE, MT, and FC, are studied, and the corresponding models of ECC, EMC, and VD are established in mathematical expression patterns, respectively;
2. An FMFO algorithm is proposed to solve the multiobjective optimization problem and acquire the optimal global solution in MG reconfiguration;
3. An in-depth exploration of the potential impact of DG type and quantity on the power distribution system's performance is conducted by employing of penetration level of DG;
4. The step-by-step changing power demands of prosumers are considered to study the optimization strategy under critical situations;
5. A method to realize the high-stable voltage was studied that can provide a DG selection strategy for those who require high-quality power.

The remaining parts of this paper are organized as follows: Section 2 introduces the formation of mathematical models, including all relevant objective functions and the corresponding constraints. Section 3 presents the primary research process and the proposed hybrid optimization algorithm. Section 4 describes several related cases and scenarios, and the results obtained in the cases are analyzed. Finally, Section 5 gives a conclusion to this paper.

2. Problem Formulation

2.1. Objective Functions

Three objectives, minimization of ECC, minimization of EMC, and minimization of VD, are defined based on the desired changes in the MG. The relevant objective functions can be optimized through the novel intelligent algorithms while conducting system reconfiguration, and the mathematical models for the three objectives are established.

2.1.1. Minimization of ECC

In the test system of this paper, there are two primary sources of the power supply: one is from the utility grid (substation), and the other is from DER generation units (DGs). In this case, the total power generation cost can only be produced by these two types of energy supply. It should be equal to the sum of DGs' generation cost and the utility grid's generation cost. Due to the commercial nature of power generation, the power generation cost is considered the ECC. Therefore, the total ECC can be defined as:

$$T_{ECC} = G_{ECC} + DE_{ECC} + MT_{ECC} + FC_{ECC} \quad (1)$$

where T_{ECC} is the total ECC, G_{ECC} , DE_{ECC} , MT_{ECC} , and FC_{ECC} represent the ECC caused by utility grid, DE, MT, and FC, respectively. Furthermore, the G_{ECC} can be calculated as:

$$G_{ECC} = P_{grid} \times K_{grid} \quad (2)$$

where P_{grid} is the active power supplied from the utility grid, and K_{grid} is the coefficient for calculating the ECC of the utility grid. For the DGs, the calculation of the ECC depends on the type and quantity of DGs. This paper defines that the three types of DGs are DE, MT, and FC, respectively. The ECC of DE is expressed as:

$$DE_{ECC} = \sum_{i=1}^{n_{DE}} a_i + b_i P_{DE_i} + c_i P_{DE_i}^2 \quad (3)$$

where P_{DE_i} is the active power generated by the i -th DE, n_{DE} is the DE quantity, and a_i, b_i, c_i are the coefficients of the ECC of DE. Similarly, the ECC of MT is expressed as:

$$MT_{ECC} = \sum_{j=1}^{n_{MT}} \frac{c_{ng} P_{MT_j}}{\eta_{MT_j} Q_{LHV}} \quad (4)$$

where P_{MT_j} is the active power generated by the j -th MT, n_{MT} is MT quantity, c_{ng} is the price of the natural gas, η_{MT_j} is the operation efficiency of the j -th MT, and Q_{LHV} is the low-hot value of natural gas. The subsequent ECC of FC is expressed as:

$$FC_{ECC} = \sum_{k=1}^{n_{FC}} \frac{c_{ng} P_{FC_k}}{\eta_{FC_k} Q_{LHV}} \quad (5)$$

where P_{FC_k} is the power generated by the k -th FC, n_{FC} is the FC quantity, and η_{FC_k} is the operation efficiency of the k -th FC.

2.1.2. Minimization of EMC

The power generation may lead to varying degrees of environmental pollution according to the variety of power resources. Among the substances emitted, CO_2 , SO_2 and NO_x are considered to be the chief components that are the culprit for causing damage to the environment. For quantifying the degree of emissions, the EMC function is established as follows:

$$T_{EMC} = G_{EMC} + DE_{EMC} + MT_{EMC} + FC_{EMC} \quad (6)$$

$$G_{EMC} = (CO_2^{grid} + NO_x^{grid} + SO_2^{grid}) \times P_{grid} \quad (7)$$

$$DE_{EMC} = \sum_{i=1}^{n_{DE}} (CO_2^{DE_i} + NO_x^{DE_i} + SO_2^{DE_i}) \times P_{DE_i} \quad (8)$$

$$MT_{EMC} = \sum_{j=1}^{n_{MT}} (CO_2^{MT_j} + NO_x^{MT_j} + SO_2^{MT_j}) \times P_{MT_j} \quad (9)$$

$$FC_{EMC} = \sum_{k=1}^{n_{FC}} (CO_2^{FC_k} + NO_x^{FC_k} + SO_2^{FC_k}) \times P_{FC_k} \quad (10)$$

where T_{EMC} is the total EMC, G_{EMC} , DE_{EMC} , MT_{EMC} , and FC_{EMC} are the EMC of the utility grid, DE, MT, and FC, respectively. P_{DE_i} , P_{MT_j} , and P_{FC_k} represent the active power generated by the i -th DE, the j -th MT, and the k -th FC, respectively.

2.1.3. Minimization of VD

Voltage stability is a crucial index to reflect power quality. Controlling the bus VD within the tolerable range plays an essential role in improving the reliability of the distribution system [31]. VD refers to the difference between the real-time voltage and the reference voltage of all load buses, which can be expressed as:

$$VD = \sum_{i=1}^{N_B} |V_i - V_{ref}| \quad (11)$$

where V_i is the voltage of the i -th bus, V_{ref} is the reference voltage, and N_B is the number of load buses.

2.2. Constraints

When reconfiguring the MG, all possibilities should be considered to set the necessary constraints to meet the actual situation. According to the characteristics, this work divides the constraints into equality constraints and inequality constraints.

2.2.1. Equality Constraint

In this work, equation constraints are mainly discussing the power balance in the distribution system, and the total input power should be equal to the sum of all loads and transmission loss. The power balance formula is as follows:

$$\begin{cases} P_{grid} + P_{DE} + P_{MT} + P_{FC} = P_{loss} + P_{load} \\ Q_{grid} + Q_{DE} + Q_{MT} + Q_{FC} = Q_{loss} + Q_{load} \end{cases} \quad (12)$$

$$\begin{cases} P_{DE} = \sum_{i=1}^{n_{DE}} P_{DE_i}, P_{MT} = \sum_{j=1}^{n_{MT}} P_{MT_j}, P_{FC} = \sum_{k=1}^{n_{FC}} P_{FC_k} \\ Q_{DE} = \sum_{i=1}^{n_{DE}} Q_{DE_i}, Q_{MT} = \sum_{j=1}^{n_{MT}} Q_{MT_j}, Q_{FC} = \sum_{k=1}^{n_{FC}} Q_{FC_k} \end{cases} \quad (13)$$

where P_{grid} , P_{DE} , P_{MT} , and P_{FC} are the active power generated by the grid, DE, MT, and FC, respectively. Q_{grid} , Q_{DE} , Q_{MT} , and Q_{FC} stand for the reactive power generated by the grid, DE, MT, and FC, respectively. P_{loss} and Q_{loss} are the active and reactive power losses, P_{load} and Q_{load} are active and reactive load demands.

2.2.2. Inequality Constraint

Inequality constraints are a set of conditional constraints that consider all possibilities (such as the boundaries of variables) and can only be expressed with inequalities. Constraints on power generation operation:

$$\max(P_i^{\min}, P_i^0 - DR_i) \leq P_i \leq \min(P_i^{\max}, P_i^0 + UR_i) \quad (14)$$

$$P_i \in \begin{cases} P_i^{\min} \leq P_i \leq P_{i,1}^l \\ P_{i,j-1}^u \leq P_i \leq P_{i,j}^l \\ P_{i,n_i}^u \leq P_i \leq P_i^{\max} \end{cases} \quad (15)$$

where P_i is the current output power, and P_i^0 is the previous output power, UR_i is the up-ramp limit of the i -th generator (MW/time-period), and DR_i is the down-ramp limit of the i -th generator (MW/time-period). Due to the physical characteristics of power equipment, the constraints of line flows are:

$$P_i^{\min} \leq P_i \leq P_i^{\max} \quad 1 \leq i \leq N_G \quad (16)$$

$$Q_i^{\min} \leq Q_i \leq Q_i^{\max} \quad 1 \leq i \leq N_G \quad (17)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad 1 \leq i \leq N_B \quad (18)$$

$$|S_k| \leq S_k^{\max} \quad 1 \leq k \leq N_E \quad (19)$$

where N_G is the number of generator buses, and N_E is the number of line branches.

The constraints of DG Power factor:

$$0.8 \leq PF \leq 1 \quad (20)$$

Each kind of dispatchable DG's power handling capacity is limited because of its current and voltage control loops. Therefore, in any case, the power $P_{\text{gen},i,s}$ and $Q_{\text{gen},i,s}$ generated by DG follow the droop relationship:

$$P_{\text{gen},i,s} \leq P_{\text{gen},i,\text{max}}, \forall i \in N_{\text{droop}} \quad (21)$$

$$Q_{\text{gen},i,s} \leq Q_{\text{gen},i,\text{max}}, \forall i \in N_{\text{droop}} \quad (22)$$

The constraints of minimum in-service and out-service time:

$$\begin{cases} T_{\text{in},m}^{t,s} \geq T_{\text{in},m}^{\text{min}} \\ T_{\text{out},m}^{t,s} \geq T_{\text{out},m}^{\text{min}} \end{cases} \quad (23)$$

The constraints of storage battery:

$$E_{\text{SB}}^{t,s} = \begin{cases} E_{\text{SB}}^{t-1,s} - P_{\text{SB}}^{t,s} \Delta t \eta_{\text{ch}} P_{\text{SB}}^{t,s} < 0 \\ E_{\text{SB}}^{t-1,s} - P_{\text{SB}}^{t,s} \Delta t / \eta_{\text{dis}} P_{\text{SB}}^{t,s} \geq 0 \end{cases} \quad (24)$$

$$P_{\text{SB,ch}}^{\text{max}} \leq P_{\text{SB}}^{t,s} \leq P_{\text{SB,dis}}^{\text{max}} \quad (25)$$

$$E_{\text{SB}}^{\text{min}} \leq E_{\text{SB}}^{t,s} \leq E_{\text{SB}}^{\text{max}} \quad (26)$$

3. Hybrid FMFO Algorithm

Intelligent optimization algorithms with reliable performance and fast convergence came into being and have impressed many researchers and are successfully applied in many fields. Compared with traditional algorithms, intelligent optimization algorithms have many advantages and higher efficiency in optimizing nonlinear or multi-extreme complex functions. For acquiring the optimal DG placement in the reconfigurable MGs, this paper proposes a hybrid multiobjective optimization algorithm which applied the fuzzy method to the MFO algorithm.

3.1. MFO Algorithm

The MFO algorithm [25] is a novel nature-inspired algorithm first proposed by Seyedali Mirjalili in 2015. The algorithm sets a fixed number of moths to wander in the variable space to search for the flame, the optimal solution of the objective function. The execution process of the MFO algorithm is summarized and described in Algorithm 1.

3.2. Heuristic Fuzzy

The MG optimization involves three objectives: minimization of ECC, EMC, and VD. The scheme of heuristic fuzzy combined with the MFO algorithm is proposed to balance the benefit of multiple objectives. The fuzzy membership functions are employed for each objective function with upper and lower limits to enjoy high flexibility for making decisions. The developed membership functions can be modified to change the contribution of each objective function of the problem based on their requirements. The objective functions involved are described in detail below.

3.2.1. Membership Function for ECC

The total power generation cost of the solution should be minimized. Therefore, for a given load level ECC, the ratio of the total power generation cost before and after optimization of the distribution system is defined as follows:

$$ECC = \frac{ECC_{\text{after}}}{ECC_{\text{before}}} \quad (27)$$

Algorithm 1 MFO Algorithm**Initialization**

N: number of moths
V: number of variables
 F_{obj} : objective function
M: the matrix for moth and its variables
F: current optimal solutions (flames)
 M_{pre} : the M in the previous iteration
 OM_{pre} : the OM in the previous iteration
OM: fitness value of M
OF: fitness value of F
CI: current number of iterations
MI: maximum number of iterations
FN: number of flames
UB: upper bound of the variable
LB: lower bound of the variable
D: the distance between M_i and F_j

Begin

```

For  $CI = 1$  to  $MI$ 
     $FN = \text{round}((N - CI * (N - 1)) / MI)$ 
    For  $i = 1$  to  $N$ 
         $OM = \text{sort}(OM)$ 
        For  $j = 1$  to  $V$ 
             $a = (M_{i,j} < LB_j), b = (M_{i,j} > UB_j)$ 
             $M_{i,j} = M_{i,j} * (\sim(a + b)) + a * LB_j + b * UB_j$ 
        End
         $OM_i = F_{obj}(M_i)$ 
    End
     $M_{tmp} = M$ 
     $OM_{tmp} = OM$ 
    If  $CI = 1$ 
         $M = \text{sort}(M)$ 
         $OM = \text{sort}(OM)$ 
         $F = M$ 
         $OF = OM$ 
    Else
         $M = [M_{pre}, M]$ 
         $OM = [OM_{pre}, OM]$ 
         $M = \text{sort}(M)$ 
         $OM = \text{sort}(OM)$ 
         $F = M$ 
         $OF = OM$ 
    End
     $M_{pre} = M_{tmp}$ 
     $OM_{pre} = OM_{tmp}$ 
    For  $i = 1$  to  $N$ 
        For  $j = 1$  to  $V$ 
            If  $i < FN$ 
                 $M_{i,j} = D \times e^{bt} \times \cos(2\pi t) + F_{i,j}$ 
            Else
                 $M_{i,j} = D \times e^{bt} \times \cos(2\pi t) + F_{FN,j}$ 
            End
        End
    End
End
Return  $F(1, :)$ 
End of algorithm

```

In the equation, for lower ECC values, the solution can get more benefits. The membership function corresponding to ECC minimization is expressed as:

$$\mu_{ECC} = \begin{cases} 1 & ECC \leq ECC_{min} \\ \frac{ECC_{max} - ECC}{ECC_{max} - ECC_{min}} & ECC_{min} < ECC < ECC_{max} \\ 0 & ECC \geq ECC_{max} \end{cases} \quad (28)$$

In this work, ECC_{min} and ECC_{max} equal to 0.5 and 1, respectively. The value of ECC_{min} refers to the minimum acceptable amount of saving to 50%.

3.2.2. Membership Function for EMC

The same as ECC , the EMC should be minimized, and the EMC is defined as follows:

$$EMC = \frac{EMC_{after}}{EMC_{before}} \quad (29)$$

The membership function corresponding to the minimization of EMC is expressed as,

$$\mu_{EMC} = \begin{cases} 1 & EMC \leq EMC_{min} \\ \frac{EMC_{max} - EMC}{EMC_{max} - EMC_{min}} & EMC_{min} < EMC < EMC_{max} \\ 0 & EMC \geq EMC_{max} \end{cases} \quad (30)$$

where EMC_{min} and EMC_{max} are equal to 0.5 and 1, respectively. The value EMC_{min} refers to the minimum acceptable amount of saving to 50%.

3.2.3. Membership Function for VD

Among the power flow constraints, bus voltage constraints are more sensitive when external equipment is connected to the system. Therefore, minimization of VD was considered as one of the objectives, along with the reduction of total PTL. The minimum bus voltage (MBV) of the system was obtained from the load flow equation for each new population of MFO. This membership function determines the deviation of the VD of the new population (VD_{after}) to the initial VD (VD_{before}). The membership function for the population can be expressed as follows:

$$\mu_{VD} = \begin{cases} 1.0 & \text{for } VD_x \leq VD_{max} \\ \frac{VD_{max} - VD_x}{VD_{max} - VD_{min}} & \text{for } VD_{min} < VD_x < VD_{max} \\ 0.0 & \text{for } VD_x \geq VD_{max} \end{cases} \quad (31)$$

where VD_{min} and VD_{max} are considered as 0.05 and 0.1, respectively. The VD_{min} reflects the maximum voltage of network buses is <1.05 (or the minimum voltage of network buses is >0.95), then $\mu_{VD} = 1$. The value of VD_x is calculated and expressed below:

$$VD_x = \frac{VD_{after}}{VD_{before}} \quad (32)$$

From the Equations (28), (30), and (31), the fuzzified values for the ECC , EMC , and VD can be obtained as μ_{ECC} , μ_{EMC} , and μ_{VD} , respectively. In order to obtain a compromise solution among these three fuzzified values, the fuzzy decision set is introduced, which is expressed as

$$\mu_D = \min(\mu_{ECC}, \mu_{EMC}, \mu_{VD}) \quad (33)$$

The equation is considered as the fitness function for the MFO algorithm. As a result, each population of the MFO produces a compromised solution among the three objective functions.

4. Simulation and Discussion

The simulations are prepared in a desktop computer installed with Microsoft Windows 10 Enterprise Edition as the operating system for coding and testing. The CPU of the computer is Intel Core (TM) i5-4660, equipped with an 8G Samsung DDR3-1600 as the memory. In terms of software, the Java NetBeans IDE 7.2 is adopted as a development tool to simulate the standard IEEE 33-bus RDS, which integrated with MGs deployed according to the loops. Figure 1 shows the schematic diagram of the test system. Since there are five loops in the standard IEEE 33-bus RDS, the test system maximizes the deployment of the hypothetical MGs in these loops to ensure that the MGs can generally work in the grid-connected mode and are also able to operate in the islanded mode under the specific conditions [32].

Figure 1. A single-line diagram of standard IEEE 33-bus radial distribution system (RDS).

The primary purpose of the simulation is to obtain the optimal global solution for optimization and explore the optimal DG placement strategy. For evaluating the performance of the FMFO algorithm, the simulations are conducted for the case study, and numerous results are gathered for analysis.

4.1. Initialization and Settings

In the standard IEEE 33-bus RDS, the initial basic kV and MVA of the test system are set to 12.66 kV and 100 MVA, and the basic active power and reactive power demands are 3.715 MW and 2.3 MVAR, respectively. For facilitating the research, the simulations take the basic load as a reference. It assumes that the MBV limit is 0.9 per unit (pu) and that each line has a maximum branch current capacity of 400 A (excluding lines connected to the feeder). There are 33 buses in the test system (from 0 to 32). In the initial state, the normally open (NO) switches are S_{33} , S_{34} , S_{35} , S_{36} , and S_{37} , and the normally closed (NC) switches are from S_1 to S_{32} . Table 1 shows the initial state of the lines and buses in the test system.

This investigation divides the primary parameters or variables involved in the optimization process into two categories: one is called generation-parameter, which plays a crucial role in energy generation, and the values can be collected from the corresponding objective models. Another category is named optimization-variable, which plays a decisive role in the simulation results, and the values are the optimal locations of DGs and the open switches. Tables 2 and 3 list the primary generation-parameters and corresponding values in our simulation.

Table 1. The initial state of the distribution test system.

MG	NC Switches	NO Switch	Buses
1	$S_4, S_5, S_6, S_7, S_{19}, S_{20}$	S_{33}	{3,4,5,6,7,18,19,20}
2	$S_8, S_9, S_{10}, S_{11}, S_{21}$	S_{35}	{8,9,10,11,21}
3	S_{12}, S_{13}, S_{14}	S_{34}	{12,13,14}
4	$S_{23}, S_{24}, S_{25}, S_{26}, S_{27}, S_{28}$	S_{37}	{22,23,24,25,26,27,28}
5	$S_{15}, S_{16}, S_{17}, S_{29}, S_{30}, S_{31}, S_{32}$	S_{36}	{15,16,17,29,30,31,32}

Table 2. Primary parameters of economic cost (ECC) models [33].

Parameter	Value	Parameter	Value
K_{grid}	0.044 \$/kWh	c_{ng}	0.3
a_i	6.0	η_{MT_j}	0.8
b_i	0.012	Q_{LHV}	9.7 kWh/m ³
c_i	0.00085	η_{FC_k}	0.9

Table 3. Emission coefficients related to grid and distributed energy resources (DERs) [34,35].

Emission Type	Emission Factors (lb/MWh)			
	Grid	DE	MT	FC
CO ₂	2031	1494	1596	1078
SO ₂	11.6	0.008	0.008	0.006
NO _x	5.06	1.15	0.44	0.03

According to the characteristics, this study further divides the optimization-variable into the location-optimization variable, type-optimization variable, and quantity-optimization variable. The location-optimization variables refer to the locations of the switches and DGs, the type-optimization variables describe the types of DGs, and the quantity-optimization variables define the number of active DGs. The simulations also restricted each MG to one open switch to keep the radial structure. By changing the location of the open switches, the topology of the power distribution system is changed. Table 4 lists the boundaries of the location-optimization variable values.

Table 4. Boundaries of location-optimization variable values.

Variable	Lower Boundary	Upper Boundary	Variable	Lower Boundary	Upper Boundary
LOS ₁ ¹	1	7	LOS ₄ ¹	1	7
LOS ₂ ¹	1	6	LOS ₅ ¹	1	8
LOS ₃ ¹	1	4	LDG _i ²	1	32

¹ LOS: location of the open switch; ² LDG_i: location of the *i*-th distributed generation (DG).

4.2. Simulation and Case Study

Simulations are conducted in the test system, which has integrated the standard IEEE 33-bus RDS and five MGs. For exploring the optimal DG placement strategy, DE, MT, and FC are deployed with holistic consideration of the ECC, EMC, MBV, and PTL. It is assumed that all DGs operate at rated power, where the rated power of DE, MT, and FC are set to 0.4 MW/h, 0.6 MW/h, and 0.5 MW/h, respectively. Then, the changes of crucial parameters in reconfiguration were analyzed, and the obtained performance feedback is discussed from the perspective of multiple DG combinations. Through analyzing the results, the changes and their trends can be found to assist in formulating the DG placement strategy in different cases.

4.2.1. Case 1: Simple DG Deployment

In this phase, the number of DE, MT, and FC deployed in the test system is restricted to 1, but the types of DGs are not limited in simulation. The results of system reconfiguration shown in Table 5 are effectively obtained due to the low computational complexity. For better comparing the changes brought by reconfiguration after deploying DG(s), a simulation without DG deployment is conducted as a reference. The open switches were changed to the optimal locations after reconfiguration.

Table 5. Reconfiguration results for single DG and corresponding combinations.

DG Combination	Open Switches	DG Location	ECC (\$/h)	EMC (lb/h)	P_{loss} (kW)	MBV (pu)
–	7,9,14,32,37	–	169.6002	7892.8072	139.5497	0.9378 (31)
DE	7,9,14,31,37	31	297.4400	7608.5086	108.6374	0.9503 (30)
MT	7,9,14,30,37	31	164.5486	7536.1043	97.5624	0.9522 (30)
FC	7,9,14,30,37	31	163.1596	7332.4768	102.6693	0.9450 (30)
DE/MT	7,10,14,28,31	29/17	293.0848	7284.2087	82.4746	0.9619 (30)
DE/FC	7,9,14,28,31	29/32	291.6111	7076.6456	85.6595	0.9603 (31)
MT/FC	7,10,14,28,31	17/29	158.9070	7012.9580	78.8414	0.9637 (31)
DE/MT/FC	7,9,14,28,30	11/31/28	287.5922	6767.9967	67.1399	0.9584 (30)
Auto-select (3 FCs)	7,11,14,28,30	7,28,31	156.5836	6922.2014	62.1813	0.9661 (30)

Since a DE deployed in the MGs, the EMC, MBV, and PTL are improved in evidence, while ECC is increased on the contrary due to the higher generation cost of DE. However, Table 5 discloses the apparent improvements in all aspects if any MG is deployed with an MT or FC. The ECC, EMC, and PTL were efficiently reduced, the MBV is significantly optimized, and the MBV trended to be more stable with the increasing usage of DGs. Different types of DG bring different changes to MG, which is closely related to their physical and electrical characteristics. Due to the ECC, DE has a negative contribution to reducing ECC. Therefore, the ECC of DG should be fully considered in the selection of MG before the deployment of DG. Compared with DE, FC and MT play a positive role in ECC and EMC, which can be considered while selecting DGs.

4.2.2. Case 2: Effect of DG Quantity

Most of the changes caused by DG deployment are positive, but the qualitative or quantitative measurement of the impact of DG type and quantity on the test system is still an issue. To make up for the deficiencies, Case 2 gradually increased the number of different types of DG from 1 to maximum and monitored the changes in system parameters. It is assumed that the DGs deployed in the test system are active and running at the rated power. Owing to the limitation of the total load demand, DGs cannot be deployed endlessly. According to the generation capacity of different DG types, the total DG generation should be less than or equal to the sum of load demands and line transmission losses. The maximum number of DE, MT, and FC are restricted to 9, 6, and 7, respectively. Moreover, the penetration level (PL) [36] of DG is employed to measure the impact of DG deployment on MG optimization. The PL of DGs PL_{DG} is calculated as:

$$PL_{DG} = \frac{P_{DE} + P_{MT} + P_{FC}}{P_{load} + P_{loss}} \times 100\% \quad (34)$$

In this phase, the simulation is carried out for probing the impact of increasing DG number on total ECC. Figure 2 shows the impact on ECC, EMC, MBV, and PTL in reconfiguration by increasing DE, MT, and FC quantity, limiting the maximum number of DG to 6 for comparison. Figure 2a indicates that the increase of DE has the opposite effect on reducing ECC, while with the increase in the number of MT and FC, the total ECC shows a linear-like slow downward trend. In the aspect of EMC shown in Figure 2b, with the increase of three types of DG, the EMC reduced in varying degrees, and the performance of FC is outstanding, followed by MT, and the improvement of DE is the lowest. In terms of voltage stability, it can be found in Figure 2c that there is a significant correlation between EMC and

DG rated power. Finally, in terms of line transmission loss, pointed in Figure 2d, various types of DGs brought varying degrees of improvement, with FC still performs best among the three types.

Figure 2. ECC, emission cost (EMC), minimum bus voltage (MBV), and power transmission loss (PTL) changing curve with the increasing number of DGs.

The utilize of PL quantified the impact of DG with different generation capacities on the MG system targets and lessened the difference caused by distinct DG rated power. From the perspective of DG PL, as shown in Tables 6–8, the increasing number of DE, MT, and FC leads to an increase in DG penetration levels. In contrast, ECC, EMC, PTL, and MBV all show divergent trends and degrees on the change. Moreover, the increase of PL makes DG play a more significant role in MGs and profoundly impacts the optimal fitness values of essential objectives and the MG configurations.

Table 6. Reconfiguration results of the increasing diesel engine (DE) deployment.

Quantity of DE	PL (%)	ECC (\$/h)	EMC (lb/h)	P _{loss} (kW)	MBV (pu)
—	0.0000%	169.6002	7892.8072	139.5497	0.9378 (31)
1	10.1722%	297.4400	7608.5086	108.6374	0.9503 (30)
2	20.5395%	425.8185	7349.2727	89.9649	0.9542 (32)
3	31.0433%	554.3726	7098.2168	75.2871	0.9577 (30)
4	41.6333%	683.0777	6854.1817	64.0380	0.9653 (32)
5	52.2608%	811.9232	6616.6833	55.9812	0.9633 (30)
6	62.8975%	940.8761	6384.1838	50.3656	0.9640 (31)
7	73.5551%	1069.8767	6153.9055	45.8348	0.9709 (31)
8	84.1063%	1199.0336	5930.8969	44.8543	0.9699 (31)
9	94.6364%	1328.2187	5709.2035	44.5161	0.9677 (30)

Table 7. Reconfiguration results of the increasing microturbine (MT) deployment.

Quantity of MT	PL (%)	ECC (\$/h)	EMC (lb/h)	P_{loss} (kW)	MBV (pu)
–	0.0000%	169.6002	7892.8072	139.5497	0.9378 (31)
1	15.3448%	164.5486	7536.1043	97.5624	0.9522 (30)
2	31.0358%	160.3848	7220.7150	75.7511	0.9637 (31)
3	46.8828%	156.5836	6922.2014	62.1813	0.9661 (30)
4	62.8166%	152.9678	6632.3140	52.8242	0.9667 (31)
5	78.7368%	149.5330	6350.8534	47.5824	0.9745 (31)
6	94.5581%	146.2633	6077.0741	46.0918	0.9781 (30)

Table 8. Reconfiguration results of the increasing MT deployment.

Quantity of FC	PL (%)	ECC (\$/h)	EMC (lb/h)	P_{loss} (kW)	MBV (pu)
–	0.0000%	169.6002	7892.8072	139.5497	0.9378 (31)
1	12.7540%	163.1596	7332.4768	102.6693	0.9450 (30)
2	25.7797%	157.4328	6805.3679	82.0131	0.9604 (31)
3	38.9600%	151.9786	6290.9430	67.5513	0.9596 (30)
4	52.2406%	146.6842	5783.9509	56.7194	0.9679 (31)
5	65.5179%	141.5872	5286.1513	50.3767	0.9687 (30)
6	78.7867%	136.5933	4793.1452	46.3750	0.9670 (30)
7	92.0122%	131.6894	4304.3318	44.4209	0.9819 (31)

The highest PL of DE, MT, and FC in tables are 94.64%, 94.56%, and 92.01%. Comparing the corresponding results of the maximum PL, the FC manifests the overall advantages over the other two types of DGs: the lower ECC, fewer EMC, less PTL, and more stable bus voltage.

4.2.3. Case 3: Diverse DG Combinations

This phase fixed the DG quantity to 5 in the simulation, based on which diverse combinations of DE, MT, and FC are considered to study the potential impact in system optimization on the essential parameters. Moreover, both manual mode and automatic mode are implemented while coding, where the manual mode is to simulate system reconfiguration in the case of specified DG type and quantity. In contrast, the automatic mode can automatically choose an optimal combination for system reconfiguration according to the given DG quantity. As listed in Table 9, the reconfiguration results of six given combinations and an auto-select combination show some different performance between two modes and all combinations. On account of the significant advantages of FC presented in Section 4.2.2, the automatic mode tends to consider the high performance of FC and the generation capacity of MT in choosing DGs, thus obtaining better configuration than the other six fixed combinations in terms of synthesis.

4.2.4. Case 4: Under Changing Power Demand

Power demand is usually not fixed but continually changing. MGs need to deal with sudden high-power demand, so it is necessary to consider the DG placement and system reconfiguration under various complicated conditions. Based on the forecasts of power demand and consumption in [37], this phase adjusted each bus's energy demand within an acceptable range to imitate the changes in real power demands. For investigating the significance of system reconfiguration and DG placement under the changing power demand, the simulation increases the total power demand from 100% of the reference power demand to 200%, by 10% for each step.

Moreover, the simulation performed three scenarios based on the changing power demands (shown in Table 10). Scenario 1 simulates with a fixed DG combination, in which the number of DE, MT, and FC are set to 2 separately. Scenario 2 conducted an auto-select mode and set the DG quantity to 6, which decided the six FCs as the optimal combination. For obtaining more results, this simulation

maximizes the deployment of DGs in Scenario 3 and lets the proposed strategy decide the DG quantity and the optimal DG combination. The comparison of the scenarios is shown in Figure 3.

Figure 3. Comparison of ECC, EMC, PTL, and MBV under changing power demand in three scenarios.

The results obtained in the three scenarios are shown in Tables 11–13. It is significant that with the increase of power demand from reference quantity to 200%, the total ECC, total EMC, and PTL in the three scenarios increase to varying degrees; only the voltage stability shows a fluctuating decrease. Scenario 2 shows more significant advantages from a scenario perspective than Scenario 1 in terms of ECC and EMC. In terms of PTL and voltage stability, Scenario 2 performs slightly better than Scenario 1 in the reference power demand's vicinity. As the power demand increases to 200%, the PTL and MBV of Scenario 2 are getting higher than those in Scenario 1. Scenario 3 performs significantly better than Scenario 1 and Scenario 2 in EMC, ECC, PTL, and voltage stability. Moreover, as power demand increases, this advantage becomes more apparent.

4.3. Analysis and Discussion

The significance of MG optimization is to achieve the optimal allocation of resources. DER plays a prominent role in regulating the peak energy demands, considering both economic and environmental protection. Deploying DGs in the reconfiguration of MG can solve many problems encountered in the development of SG.

4.3.1. Evaluation of Algorithm

This paper proposed an FMFO algorithm to solve the multiobjective issue. As shown in Figure 4, the improvement of system optimization by employing the FMFO algorithm is evident in the bus voltage and line current in MGs. The MBV was improved to 0.9378 (pu) after system reconfiguration without deploying DG. While deploying a DE, the MBV has reached 0.9503 (pu), even reached 0.9661 (pu) while deploying a simple DG combination. Simultaneously, the line current is optimized with the appropriate utilization of DG(s) or DG combination; each line's current is significantly decreased.

(a) Minimum voltage of each bus.

(b) Branch current of each line

Figure 4. Effect of DG deployment on bus voltage and line current of system reconfiguration.

In order to reflect the convergence of the proposed algorithm, our simulation randomly selected ten results in the case of without DG deployment, with DE deployment, with MT deployment, and with FC deployment, respectively. Figure 5 shows the convergence of the proposed algorithm on ECC that the optimal solutions are obtained within a maximum of 20 iterations without DG deployment and within 44 iterations among the 30 runs while DG is deployed. Moreover, a fuzzy genetic algorithm (FGA) and fuzzy particle swarm optimization (FPSO) are implemented in the simulation to compare the convergence with the proposed FMFO on the PTL. As shown in Figure 6, 20 runs of FGA, FPSO, and FMFO are conducted separately to calculate the average PTL. The proposed FMFO algorithm shows advantages in both simulations deployed without DG and deployed with an MT. In the simulations without DG deployed, the FMFO, FPSO, and FGA obtained the optimal solutions at the average iteration numbers of 9.7, 14.9, and 34.2, respectively; and in the simulations with an MT deployed, the FMFO, FPSO, and FGA obtained the optimal solutions at the average iteration numbers of 13.6, 18.5, and 46.3, respectively.

Figure 5. The convergence of the proposed algorithm on ECC.

Figure 6. Comparison of convergence of fuzzy genetic algorithm (FGA), fuzzy particle swarm optimization (FPSO), and fuzzy moth-flame optimization (FMFO) on power transmission loss (PTL).

The effect of the DG penetration level on improving PTL is usually positive [36]. As shown in Table 14, this simulation obtained better results in which the PTL is 62.18 kW under the auto-select mode, in the case where the DG penetration level was 47.65%. Compared with the optimal results in [38], the PTL obtained in this paper was reduced by 7.35%; meanwhile, the MBV was still kept at a considerable level.

4.3.2. Data Analysis and DG Placement Strategy

The deployment of DG(s) leads to a significant impact on MG optimization, as shown in Table 5. Compared with no DG deployed, employing a DE has increased the ECC from \$169.6002/h to \$297.4400/h by 75.38%. In contrast, the deployment of an MT and FC have decreased the corresponding ECC by 2.98% and 3.80%. In terms of EMC, the applying of a DE, MT, and FC has reduced the total EMC from 7982.8072 lb/h to 7608.5086 lb/h, 7536.1043 lb/h, and 7332.4768 lb/h by 3.60%, 4.52%, and 7.10%, respectively. Similarly, by applying a DE, MT, and FC, the PTL decreased by 22.15%, 30.09%, and 26.43%, and the MBV increased from 0.9378 pu to 0.9503 pu, 0.9522 pu, and 0.9450 pu, respectively. When DE, MT, and FC are combined, the effects of different DGs on system optimization are superimposed.

Through analyzing the impact of DG type on system optimization and the superposition effect of DG quantity, the simulation results where DG quantity increases from 1 to the maximum are shown in Tables 6–8. In corresponding Figures 2–4, the ECC curves and EMC curves present a quasi-linear decrease with the increase of DG quantity except for DE; meanwhile, the PTL shows an exponent-like reduction, and the MBV shows an irregular improvement. The changing trends of ECC and EMC rely mainly on the characteristics of DGs.

As further exploring the reconfiguration under diverse DG combinations, Table 9 shows that the EMC, ECC, PTL, and the MBV improved to varying degrees under various DG combinations. Compared with Table 5, the MBV is more stable, illustrating the importance of DG quantity increment to voltage stability. However, it is worth noticing that the MBV value of auto-select mode is high, reaching 0.9739 pu, due to its higher DG penetration level among all DG combinations. From the perspective of MBV stability, the performance of an appropriate multitype DG combination is slightly better than that of the optimal single-type DG combination in case that the DG quantity is fixed.

Thus, if the high voltage stability is required, it is needed to maximize the utilization of DGs, and then choose the appropriate multitype DG combination to meet the different power replenishment needs of buses.

Table 9. Reconfiguration results under various combinations of 5 DGs.

DG Combination (DE/MT/FC)	Open Switches	DG Location (DE/MT/FC)	PG ¹ (MW)		ECC (\$/h)			EMC (lb/h)			P _{loss} (kW)	MBV ² (pu)	BN ³	PL (%)
			DG	Grid	DG	Grid	Total	DG	Grid	Total				
1/1/3	6,9,14,31,37	10/24/7,29,32	2.5	1.265	221.542	55.661	277.203	3172.986	2590.325	5763.311	50.017	0.9722	31	65.5302%
1/2/2	11,28,30,33,34	13/7,24/23,31	2.6	1.164	227.556	51.217	278.773	3591.837	2383.518	5975.355	49.021	0.9643	30	68.1870%
1/3/1	6,9,14,30,37	11/7,24,32/28	2.7	1.064	233.570	46.796	280.365	4010.688	2177.757	6188.444	48.534	0.9658	30	70.8277%
2/1/2	10,28,31,33,34	13,32/7/24,29	2.4	1.366	351.160	60.093	411.254	3232.031	2796.610	6028.641	50.759	0.9702	31	62.8845%
2/2/1	11,28,30,33,34	14,28/7,24/31	2.5	1.265	357.174	55.653	412.826	3650.882	2589.940	6240.822	49.829	0.9658	30	65.5367%
3/1/1	10,28,31,33,34	14,29,32/24/7	2.3	1.467	480.778	64.547	545.325	3291.076	3003.880	6294.957	51.982	0.9717	31	60.2258%
auto-select	9,14,27,30,33	-7,23,28,31/11	2.9	0.862	109.966	37.947	147.912	4370.493	1765.950	6136.444	47.424	0.9739	30	76.1185%

¹ PG: power generation; ² MBV: minimal bus voltage; ³ BN: bus number.**Table 10.** The changing power demands of all buses from 100% to 200%.

Bus Number	100% (MW)		110% (MW)		120% (MW)		130% (MW)		140% (MW)		150% (MW)		160% (MW)		170% (MW)		180% (MW)		190% (MW)		200% (MW)	
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
1	0.1000	0.0600	0.1408	0.0929	0.0640	0.0422	0.1709	0.1025	0.1610	0.1014	0.2533	0.1520	0.1824	0.1116	0.1834	0.1100	0.1500	0.0945	0.1744	0.1110	0.3086	0.1944
2	0.0900	0.0400	0.1056	0.0516	0.1520	0.0743	0.1337	0.0654	0.1330	0.0621	0.1200	0.0560	0.1568	0.0711	0.1669	0.0742	0.2040	0.0952	0.2075	0.0978	0.1714	0.0800
3	0.1200	0.0800	0.0968	0.0710	0.1280	0.0939	0.1189	0.0872	0.1470	0.1029	0.1400	0.0980	0.1760	0.1197	0.2019	0.1346	0.1980	0.1386	0.1861	0.1315	0.1829	0.1280
4	0.0600	0.0300	0.1144	0.0629	0.1680	0.0924	0.2303	0.1151	0.1447	0.0760	0.2044	0.1073	0.2197	0.1121	0.2452	0.1226	0.2700	0.1418	0.2124	0.1126	0.2495	0.1310
5	0.0600	0.0200	0.1320	0.0484	0.0880	0.0323	0.1114	0.0409	0.1120	0.0392	0.1333	0.0467	0.0896	0.0305	0.0556	0.0185	0.1020	0.0357	0.1871	0.0661	0.2000	0.0700
6	0.2000	0.1000	0.1584	0.0871	0.1840	0.1012	0.1040	0.0572	0.2147	0.1128	0.1444	0.0758	0.2005	0.1023	0.2102	0.1050	0.2340	0.1229	0.2982	0.1580	0.2267	0.1190
7	0.2000	0.1000	0.1848	0.0924	0.1360	0.0748	0.1263	0.0695	0.2287	0.1201	0.2178	0.1143	0.2069	0.1055	0.2040	0.1020	0.1980	0.1040	0.2865	0.1518	0.3067	0.1610
8	0.0600	0.0200	0.0968	0.0355	0.2000	0.0733	0.0891	0.0327	0.0957	0.0335	0.0044	0.0016	0.0885	0.0301	0.0742	0.0248	0.1920	0.0672	0.2368	0.0837	0.0667	0.0233
9	0.0600	0.0200	0.0792	0.0290	0.1140	0.0418	0.2303	0.0844	0.1353	0.0474	0.2406	0.0842	0.2411	0.0819	0.2947	0.0982	0.2535	0.0887	0.1379	0.0487	0.2576	0.0902
10	0.0450	0.0300	0.1056	0.0774	0.1520	0.1115	0.1857	0.1238	0.1178	0.0825	0.1522	0.1066	0.1659	0.1128	0.1741	0.1161	0.2190	0.1533	0.1963	0.1387	0.1990	0.1393
11	0.0600	0.0350	0.0792	0.0508	0.0960	0.0616	0.1560	0.1001	0.1120	0.0686	0.1667	0.1021	0.1664	0.0990	0.1916	0.1118	0.1800	0.1103	0.1345	0.0831	0.1943	0.1190
12	0.0600	0.0350	0.0968	0.0621	0.1040	0.0667	0.1411	0.0906	0.1120	0.0686	0.1467	0.0898	0.1408	0.0838	0.1463	0.0853	0.1620	0.0992	0.1598	0.0988	0.1886	0.1155
13	0.1200	0.0800	0.1408	0.1033	0.1680	0.1172	0.2006	0.1337	0.1843	0.1290	0.2156	0.1509	0.2315	0.1574	0.2535	0.1690	0.2640	0.1848	0.2485	0.1756	0.2762	0.1933
14	0.0600	0.0100	0.1056	0.0194	0.2320	0.0425	0.1634	0.0300	0.1213	0.0212	0.0689	0.0121	0.1579	0.0268	0.1648	0.0275	0.2700	0.0473	0.2592	0.0458	0.1276	0.0223
15	0.0600	0.0200	0.1144	0.0419	0.1760	0.0645	0.1569	0.0575	0.1216	0.0446	0.1100	0.0385	0.1460	0.0496	0.1435	0.0478	0.2168	0.0759	0.2279	0.0805	0.1686	0.0590
16	0.0600	0.0200	0.0792	0.0290	0.1040	0.0381	0.1634	0.0599	0.1143	0.0419	0.1689	0.0591	0.1739	0.0592	0.2019	0.0673	0.1920	0.0672	0.1393	0.0492	0.1962	0.0687
17	0.0900	0.0400	0.1056	0.0516	0.1520	0.0744	0.1040	0.0508	0.1237	0.0605	0.0844	0.0394	0.1269	0.0575	0.1257	0.0559	0.1800	0.0840	0.2114	0.0996	0.1410	0.0658
18	0.0900	0.0400	0.1848	0.0903	0.1200	0.0587	0.1560	0.0763	0.1610	0.0751	0.1933	0.0902	0.1312	0.0595	0.0865	0.0385	0.1440	0.0672	0.2602	0.1226	0.2857	0.1333
19	0.0900	0.0400	0.1496	0.0731	0.0720	0.0352	0.1634	0.0799	0.1540	0.0718	0.2333	0.1089	0.1600	0.0725	0.1463	0.0650	0.1380	0.0644	0.1890	0.0891	0.2971	0.1387
20	0.0900	0.0400	0.1320	0.0587	0.0880	0.0430	0.0966	0.0472	0.1283	0.0609	0.1356	0.0633	0.1035	0.0469	0.0783	0.0348	0.1080	0.0504	0.1919	0.0904	0.2019	0.0942

Table 10. Cont.

Bus Number	100% (MW)		110% (MW)		120% (MW)		130% (MW)		140% (MW)		150% (MW)		160% (MW)		170% (MW)		180% (MW)		190% (MW)		200% (MW)	
	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q	P	Q
21	0.0900	0.0400	0.1144	0.0559	0.1680	0.0821	0.1560	0.0763	0.1423	0.0664	0.1356	0.0633	0.1739	0.0788	0.1855	0.0824	0.2280	0.1064	0.2251	0.1060	0.1905	0.0889
22	0.0900	0.0500	0.1232	0.0753	0.1040	0.0636	0.1337	0.0817	0.1377	0.0803	0.1644	0.0959	0.1461	0.0828	0.1422	0.0790	0.1560	0.0910	0.1900	0.1119	0.2210	0.1289
23	0.4200	0.2000	0.1496	0.0784	0.1520	0.0796	0.1560	0.0817	0.3827	0.1822	0.3778	0.1799	0.4693	0.2280	0.6120	0.2914	0.3900	0.1950	0.2806	0.1416	0.4210	0.2105
24	0.4200	0.2000	0.1848	0.0968	0.1120	0.0587	0.1411	0.0739	0.3873	0.1844	0.4022	0.2011	0.4331	0.2103	0.5419	0.2581	0.3240	0.1620	0.2884	0.1456	0.4648	0.2324
25	0.0600	0.0250	0.0792	0.0363	0.2000	0.0916	0.1857	0.0851	0.1213	0.0531	0.1156	0.0506	0.1963	0.0834	0.2328	0.0970	0.2820	0.1234	0.2066	0.0912	0.1505	0.0658
26	0.0600	0.0250	0.1144	0.0524	0.0880	0.0403	0.1263	0.0579	0.1120	0.0490	0.1467	0.0642	0.1152	0.0490	0.1010	0.0421	0.1260	0.0551	0.1676	0.0740	0.2000	0.0875
27	0.0600	0.0200	0.1320	0.0484	0.1200	0.0440	0.1189	0.0436	0.1143	0.0400	0.1156	0.0404	0.0971	0.0330	0.0659	0.0220	0.1320	0.0462	0.2095	0.0740	0.1848	0.0647
28	0.1200	0.0700	0.1496	0.0960	0.1920	0.1232	0.1634	0.1024	0.1750	0.1021	0.1533	0.0923	0.1888	0.1123	0.1896	0.1106	0.2460	0.1507	0.2796	0.1729	0.2286	0.1400
29	0.2000	0.6000	0.1705	0.5115	0.2160	0.6156	0.2154	0.6463	0.2529	0.7586	0.2542	0.7625	0.3052	0.9199	0.3477	1.0357	0.3398	0.9989	0.3190	1.0104	0.3286	0.9973
30	0.1500	0.0700	0.1672	0.0858	0.1840	0.0859	0.1189	0.0610	0.1867	0.0871	0.1311	0.0612	0.1621	0.0772	0.1463	0.0683	0.2100	0.1029	0.3001	0.1485	0.2210	0.1083
31	0.2100	0.1000	0.1848	0.0880	0.1360	0.0712	0.1709	0.0814	0.2497	0.1189	0.2778	0.1323	0.2613	0.1269	0.2802	0.1334	0.2400	0.1195	0.2816	0.1421	0.3581	0.1790
32	0.0600	0.0400	0.1144	0.0765	0.0880	0.0645	0.1411	0.0941	0.1167	0.0778	0.1644	0.1096	0.1301	0.0885	0.1216	0.0811	0.1380	0.0966	0.1656	0.1171	0.2152	0.1507
Total	3.7150	2.3000	4.0865	2.5300	4.4580	2.7600	4.8295	2.9900	5.2010	3.2200	5.5725	3.4500	5.9440	3.6800	6.3155	3.9100	6.6870	4.1400	7.0585	4.3700	7.4300	4.6000

Table 11. Scenario 1: system reconfiguration results of DG combinations under 6 DGs and increasing power demand.

PD (%)	Open Switches	DG Locations (DE/MT/FC)	PG ¹ (MW)		ECC (\$/h)			EMC (lb/h)			P _{loss} (kW)	MBV ² (pu)	BN ³	PL (%)
			DG	Grid	DG	Grid	Total	DG	Grid	Total				
100	7,9,14,28,30	7,11/23,32/6,28	3.0	0.7602	374.3560	33.4484	407.8044	4189.9	1556.6109	5746.5109	45.1901	0.9686	30	79.7832%
110	7,9,14,28,32	7,31/11,26/17,24	3.0	1.1360	374.3560	49.9828	424.3388	4189.9	2326.0859	6515.9859	49.4727	0.9756	13	72.5343%
120	7,10,14,28,36	5,32/8,29/11,15	3.0	1.5267	374.3560	67.1750	441.5310	4189.9	3126.1722	7316.0722	68.7047	0.9657	17	66.2734%
130	9,14,28,31,33	9,13/24,26/3,14	3.0	1.9066	374.3560	83.8918	458.2478	4189.9	3904.1321	8094.0321	77.1310	0.9664	31	61.1417%
140	7,9,14,28,32	14,32/9,28/26,30	3.0	2.3010	374.3560	101.2425	475.5985	4189.9	4711.5958	8901.4958	99.9659	0.9619	13	56.5935%
150	9,14,28,31,33	13,29/15,24/11,32	3.0	2.6842	374.3560	118.1055	492.4615	4189.9	5496.3611	9686.2611	111.7157	0.9602	31	52.7777%
160	9,14,28,31,33	26,31/12,15/24,29	3.0	3.0905	374.3560	135.9813	510.3373	4189.9	6328.2596	10,518.1596	146.4836	0.9500	31	49.2572%
170	9,14,28,30,33	4,31/8,12/17,28	3.0	3.4959	374.3560	153.8207	528.1767	4189.9	7158.4646	11,348.3646	180.4244	0.9455	30	46.1828%
180	7,10,14,27,32	9,30/12,29/14,17	3.0	3.8918	374.3560	171.2403	545.5963	4189.9	7969.1351	12,159.0351	204.8254	0.9405	32	43.5298%
190	7,9,14,28,36	14,30/12,17/24,32	3.0	4.2900	374.3560	188.7605	563.1165	4189.9	8784.4862	12,974.3862	231.5121	0.9427	13	41.1522%
200	7,9,14,27,32	15,17/10,24/13,3	3.0	4.6822	374.3560	206.0161	580.3721	4189.9	9587.5195	13,777.4195	252.1833	0.9325	31	39.0514%

¹ PG: power generation; ² MBV: minimal bus voltage; ³ BN: bus number.

Table 12. Scenario 2: system reconfiguration results of auto-select DG combination under 6 DGs and increasing power demand.

PD ¹ (%)	Open Switches	DG Locations (DE/MT/FC)	PG ² (MW)		ECC (\$/h)			EMC (lb/h)			P _{loss} (kW)	MBV ³ (pu)	BN ⁴	PL (%)
			DG	Grid	DG	Grid	Total	DG	Grid	Total				
100	7,10,14,28,30	−/6/8,21,24,28,32	3.1	0.6620	109.1065	29.1268	138.2333	3652.9588	1355.4939	5008.4527	46.9722	0.9677	30	82.4036%
110	9,14,28,32,33	−/11,26/5,24,30,32	3.2	0.9362	115.1203	41.1917	156.3120	4071.8096	1916.9690	5988.7786	49.6754	0.9790	13	77.3662%
120	7,9,14,28,36	−/5,10,16/7,24,32	3.3	1.2242	121.1340	53.8630	174.9970	4490.6604	2506.6615	6997.3219	66.1591	0.9687	13	72.9417%
130	7,10,14,28,36	−/8,12,25,28/15,32	3.4	1.5036	127.1478	66.1597	193.3074	4909.5112	3078.9202	7988.4314	74.1286	0.9670	17	69.3364%
140	7,9,14,28,32	−/8,12,25,31/16,28	3.4	1.8955	127.1478	83.3999	210.5477	4909.5112	3881.2427	8790.7539	94.4527	0.9646	30	64.2060%
150	9,13,17,28,33	−/6,9,15,24,29/17	3.5	2.1795	133.1615	95.8995	229.0610	5328.362	4462.9456	9791.3076	107.0345	0.9636	31	61.6248%
160	7,10,13,17,28	−/8,15,24,31/11,29	3.4	2.6859	127.1478	118.1781	245.3259	4909.5112	5499.7397	10,409.2509	141.8657	0.9530	17	55.8672%
170	7,11,28,31,34	15/24,32/9,13,29	3.1	3.3938	244.7381	149.3270	394.0651	4130.8548	6949.3383	11,080.1931	178.2950	0.9344	31	47.7379%
180	7,10,14,28,36	14/12,16,29/25,31	3.2	3.6872	250.7519	162.2360	412.9879	4549.7056	7550.0949	12,099.8005	200.1819	0.9419	17	46.4631%
190	7,11,14,28,36	13/9,16,29/25,32	3.2	4.0825	250.7519	179.6307	430.3826	4549.7056	8359.6038	12,909.3094	224.0156	0.9334	17	43.9409%
200	7,11,14,28,36	16/12,14,28/31,32	3.2	4.4733	250.7519	196.8256	447.5775	4549.7056	9159.8176	13,709.5232	243.3098	0.9396	10	41.7030%

¹ PD: power demand; ² PG: power generation; ³ MBV: minimal bus voltage; ⁴ BN: bus number.**Table 13.** Scenario 3: system reconfiguration results of auto-select DG combination under maximum DG quantity and increasing power demand.

PD ¹ (%)	Open Switches	DG Locations (DE/MT/FC)	PG ² (MW)		ECC (\$/h)			EMC (lb/h)			P _{loss} (kW)	MBV ³ (pu)	BN ⁴	PL (%)
			DG	Grid	DG	Grid	Total	DG	Grid	Total				
100	8,14,28,31,33	23,30/1,5,7,11,24	3.7	0.0603	132.3024	2.6546	134.9570	4610.8276	123.5389	4734.3665	45.3317	0.9747	31	98.3956%
110	10,14,28,32,33	25/2,7,12,15,20,24,30	4.1	0.0341	143.4708	1.5014	144.9722	4730.9948	69.8708	4800.8656	47.6223	0.9780	32	99.1746%
120	9,14,28,31,33	−/1,5,10,14,17,21,24,26,30	4.5	0.0195	154.6392	0.8582	155.4974	4851.162	39.9409	4891.1029	61.5056	0.9717	31	99.5684%
130	9,14,28,31,33	6,10,23/13,15,19,25,29,32	4.8	0.0961	172.6804	4.2303	176.9107	6107.7144	196.8680	6304.5824	66.6429	0.9788	31	98.0364%
140	9,14,28,31,33	20,24/3,4,13,15,23,26,28,32	5.2	0.0830	183.8488	3.6520	187.5008	6227.8816	169.9539	6397.8355	81.9991	0.9739	31	98.4289%
150	9,14,27,30,33	7/1,2,6,10,12,17,20,24,28,31	5.6	0.0601	195.0172	2.6438	197.6609	6348.0488	123.0349	6471.0837	87.5856	0.9739	30	98.9384%
160	9,14,28,31,33	15,23,13,8,19,3,29,24,2,9,31,25	6.0	0.0500	206.1856	2.2006	208.3862	6468.216	102.4104	6570.6264	106.0134	0.9700	30	99.1733%
170	7,9,14,27,31	12,23,28,29/4,7,10,16,17,19,23,25	6.4	0.0429	230.2405	1.8885	232.1291	8143.6192	87.8873	8231.5065	127.4209	0.9649	31	99.3338%
180	7,10,13,28,36	3,11,29/1,6,9,14,16,20,23,24,25,30	6.8	0.0279	241.4089	1.2267	242.6356	8263.7864	57.0876	8320.8740	140.8794	0.9522	17	99.5917%
190	7,9,14,28,32	11,31/3,4,6,7,13,14,18,19,23,26,28,32	7.2	0.0076	252.5773	0.3324	252.9098	8383.9536	15.4707	8399.4243	149.0553	0.9568	17	99.8952%
200	11,28,32,33,34	1,2,5,7,9,12,15,17,19,21,23,24,27,29,31	7.5	0.0890	257.7320	3.9167	261.6486	8085.27	182.2735	8267.5435	159.0155	0.9607	32	98.8270%

¹ PD: power demand; ² PG: power generation; ³ MBV: minimal bus voltage; ⁴ BN: bus number.

Table 14. Comparison of reconfiguration results under the deployment of 3 DGs.

Reconfiguration without DG		Literature Results				Proposed
		Ref. [39]	Ref. [40]	Ref. [41]	Ref. [38]	
Open switches	7,9,14,32,37	7,10,14,28,32	7,10,14,28,32	7,10,14,28,31	7,10,14,28,32	7,11,14,28,30
Size of DG (MW)	–	0.5258 (32)	0.5258 (32)	0.6311 (18)	0.5315 (18)	0.6 (7)
(Bus number)	–	0.5586 (31)	0.5586 (31)	0.5568 (32)	0.6158 (29)	0.6 (28)
	–	0.5840 (33)	0.5840 (33)	0.5986 (22)	0.5367 (32)	0.6 (31)
PTL (kW)	139.55	73.77	73.05	72.23	67.11	62.18
MBV (pu)	0.9378	0.9700	0.9700	0.9724	0.9713 (14)	0.9661 (30)
Penetration level of DG	–	44.02%	44.15%	47.17%	45.33%	47.65%
Considered objectives	PTL	PTL	PTL	PTL	PTL and voltage stability	PTL, ECC, EMC, and VD

Compare Table 11 with Table 12, when the power demand increases from 100% to 200%, the PTL and MBV of the combination with two DEs, two MTs, and two FCs are 252.1833 kW and 0.9325 pu; the combination of auto-select mode are 243.3098 kW and 0.9396 pu. The optimal DG combination showed more considerable advantages in PTL and MBV with increased power demand. Nevertheless, the ECC and EMC of auto-select mode are \$447.5775/h and 13,709.5232 lb/h that is much better than that of the fixed 6 DGs \$580.3721/h and 13,777.4195 lb/h. With the increase of power demand in the distribution system, the fixed DG quantity makes the penetration level decreased. Table 13 shows relatively stable DG penetration levels by maximizing DGs' deployment under the auto-select mode. Compared with Tables 11 and 12, the ECC, EMC, PTL, and MBV in Table 13 are comprehensively improved due to the higher DG penetration level. The ECC, EMC, PTL, and MBV have also been improved to \$261.6486/h, 8267.5435 lb/h, 159.0155 kW, and 0.9607 pu under the 200% power demand.

As a result of the bus voltage's reliable stability in the simulation, the FMFO algorithm paid more attention to energy saving and emission reduction while ensuring high-quality power supplying. Maximizing the DG penetration level can effectively optimize the power distribution system's output, but the appropriate DG combination is necessary to improve system parameters further. The fundamental cause is that making the current average and at a lower level will stable the bus voltage and minimize the energy transmission loss.

5. Conclusions

This paper conducted the system optimization of MGs based on the standard IEEE 33-bus RDS and proposed an FMFO algorithm to solve the multiobjective optimization problem. The proposed FMFO algorithm showed an efficient performance on convergence comparing with classical FGA and FPSO. The obtained optimal solution via MG reconfiguration has considered integrating with DGs and achieved minimum PTL, ECC, EMC, and VD comparing with existing research. Moreover, our simulations have considered various DG combinations to explore the effect of DG type and quantity on MG reconfiguration results. Furthermore, we have investigated the results in four step-by-step cases and gained the optimal solution for each. The optimal DG placement and combination were explored under the increasing power demand, which formed a DG deployment strategy for decision-making. The simulation results reveal that: the proposed FMFO algorithm is a reliable supplement for multiobjective optimization approaches in MG reconfiguration; it requires fewer iterations to obtain the optimal solution than other optimizers; appropriate DG selection and deployment strategy is conducive to obtaining the optimal global solution, especially under the critical power demand conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

DE	Diesel engine
DER	Distributed energy resource
DG	Distributed generation
ECC	Economic cost

EMC	Emission cost
ESS	Energy storage systems
FC	Fuel cell
FMFO	Fuzzy moth-flame optimization
MG	microgrid
MT	microturbine
MBV	Minimum bus voltage
MFO	Moth-flame optimizer
NC	normally closed
NO	normally open
PL	Penetration level
PV	photovoltaic
PC	Power converter
PTL	Power transmission loss
RDS	Radial distribution system
SG	Smart grid
VD	Voltage deviation
WT	Wind turbine

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