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Research on the Optimal Economic Power Dispatching of a Multi-Microgrid Cooperative Operation

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Abstract: The economic power-dispatching model of a multi-microgrid is comprehensively established in this paper, considering many factors, such as generation cost, discharge cost, power-purchase cost, power sales revenue, and environmental cost. To construct this model, power interactions between the two microgrids and those between the micro- and main grids are considered. Furthermore, the particle swarm optimization (PSO) algorithm is utilized to solve the economic power-dispatching model. To validate the effectiveness of the proposed model as well as the solution algorithm, a practical project case is studied and discussed. In the case study, the impact of multiple scenarios is first analyzed. Then, the system operation economic costs under different scenarios are described in detail. Moreover, according to the optimization power-dispatching results of the multi-microgrid, power interactions between the two microgrids and those between the micro- and main grids are fully discussed.

Keywords: multi-microgrid; economic power dispatching; multiple scenarios; PSO

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1. Introduction

Green energy, such as wind and solar, has attracted more and more attention, especially in the background of the change in the world energy pattern and "dual carbon" goal. Microgrids have gradually become one of the important components of the new power system due to their advantages of a reliable power supply, cleanliness, and flexible [1,2].

As the extension and deepening of microgrids, the multi-microgrid can effectively overcome the instability and limited working capacity of the single microgrid. Furthermore, the multi-microgrid not only considerably improves the absorption rate of new energy, but also achieves the coordination of the supply and demand of power between the two microgrids and those between the micro- and main grids. The multi-microgrid can also enhance the reliability and security of the system's power supply, and effectively improve the robustness and economy of the system's operation [3–5].

At present, domestic and international research mainly focus on control strategies [6–8], frequency regulations [9–12], and optimal dispatching strategies [13–16] for the single microgrid. The research on multi-microgrids with two or more microgrids is gradually attracting the extensive attention of scholars.

In [17], Zhou et al. proposed a coordinated control strategy for the tie line power of a multi-microgrid system. In [18], Zhi et al. discussed the advantages and disadvantages of hierarchical, master–slave, multi-agent, and peer-to-peer control strategies, and proposed a constructive plan for the future development of the multi-microgrid. A multi-microgrid active-control strategy under a fault scenario was proposed by Yang et al. [19]. Zhao et al. [20] proposed a hierarchical system optimization scheme for a multi-microgrid, which integrated the functions of energy management, optimized operation, and coordination control. Based on the hierarchical control in the multi-microgrid system, the black start process and load recovery sequence were studied [21].

In [22], an uncertain optimal dispatching model for the multi-microgrid operation was established. In this model, the reliability and economic indicators were taken into account. In [23], an optimization strategy for the multi-microgrid power cooperation operation considering the uncertainty of electricity price and game fraud was proposed. Moreover, a multi-microgrid two-level optimal dispatching strategy considering demand response and shared energy storage was presented [24]. In [25], a multi-microgrid cooperative operation optimization strategy that takes into account the two-level carbon trading and demand response was considered.

For the multi-microgrid dispatching problem with the non-cooperative characteristic, a dynamic game framework of an intelligent distribution network based on a multi-agent system was designed [26]. With the goal of maximizing the benefits of the multi-microgrid system, the operation model of each unit in the microgrid and the transaction model between the two microgrids were established [27], and a multi-microgrid market game bidding strategy based on the Stackelberg game was also proposed. Considering the uncertainty of electric vehicles and the utilization of electric energy, a multi-microgrid Bayesian bidding game model was established [28].

Based on the above literature survey, the existing studies on multi-microgrids focus on the control strategies, optimal dispatching, and multi-microgrid game. However, there still remains a major challenge that the research on the safe coordination, economic control, and interaction inside the microgrid, between the two microgrids and between the multi-micro- and main grids, is not perfect and needs to be strengthened.

Based on the above research motivation and consideration factors, this paper proposes an economic power-dispatching model of a multi-microgrid system, comprehensively considering many factors, such as generation cost, discharge cost, power-purchase cost, power sales revenue, and environmental cost. To construct this model, power interactions between the two microgrids and those between the micro- and main grids are also considered. Additionally, the solution approach for the economic power-dispatching model based on the particle swarm optimization (PSO) algorithm is also presented. To validate the effectiveness of the proposed model as well as the solution algorithm, a practical project case is studied. In the case study, the impact of multiple scenarios is first analyzed. Then, the system operation economic costs under different scenarios are described in detail. In addition, according to the optimization power-dispatching results for the multi-microgrid, power interactions between the two microgrids and those between the micro- and main grids are fully discussed.

2. Cooperative Operation Dispatching Model of a Multi-Microgrid

2.1. Multi-Microgrid Structure

The structure of a multi-microgrid composed of an active distribution network is shown in Figure 1. Each microgrid can be independent and connected with each other [29]. At the same time, the power coordination between the two microgrids and that between the micro- and main grids can be achieved through the microgrid control center and the multi-microgrid intelligent controller, respectively. Each microgrid includes distributed generation, load, an energy storage system (e.g., battery), and other devices. Distributed power generation mainly includes wind turbine (WT) and photovoltaic (PV) energy.

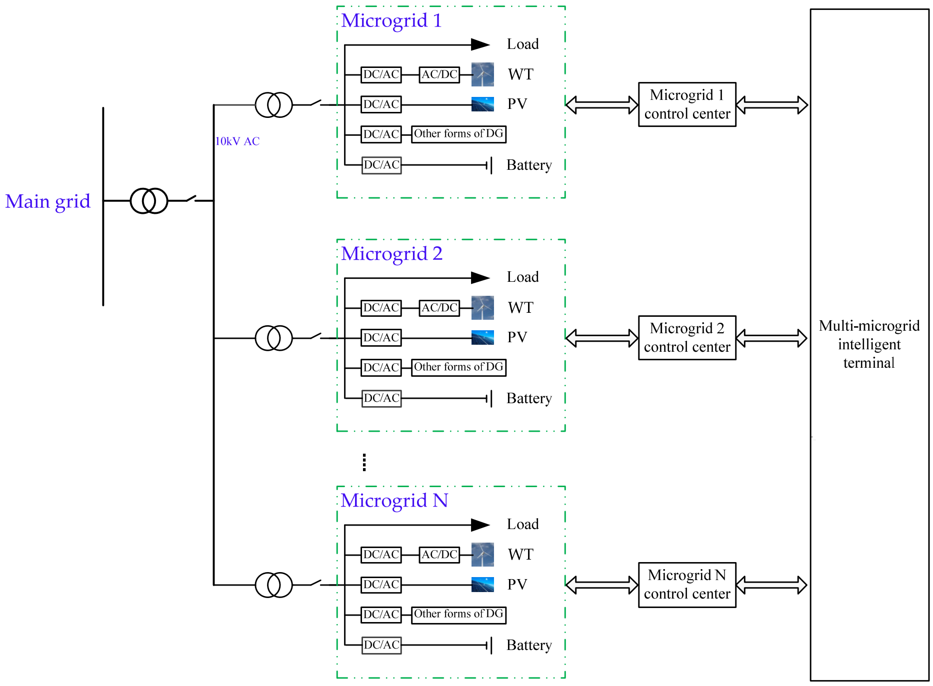


Figure 1. Multi-microgrid typical structure.

2.2. Hierarchical Dispatching Strategy

The distributed power generation of renewable energy in a microgrid changes over time in engineering practice, and the load demand is also different in different periods [30,31]. To ensure the orderly and coordinated operation of the power supply inside the microgrid, between the two microgrids, and between the multi-micro- and main grids, the microgrid control center and the multi-microgrid intelligent controller are used to formulate hierarchical dispatching strategies for the multi-microgrid. Additionally, the structure is divided into three levels.

(1) Inside the microgrid

This study aims to absorb all the renewable energy produced by the microgrid and improve the efficiency of the microgrid. First, we should judge whether or not the distributed power generation of renewable energy in a microgrid can meet the load demand. If it meets the load demand, the surplus electric energy is used for battery charging or supplied to other microgrids, or uploaded to the main grid. Additionally, if the load demand cannot be met, the battery discharges or other microgrid inputs, or electricity energy is purchased directly from the main grid.

(2) Between the two microgrids

The microgrid control center collects the power generation information and the load information of each microgrid at different times. When the microgrid has sufficient power generation, it gives priority to charging the battery, and then sells power to the main grid. If renewable energy power generation in a microgrid is insufficient, taking the lowest total operating cost as the objective function, the power of the microgrid in a multi-microgrid is coordinated and dispatched to maximize the local consumption of renewable energy.

(3) Between the main grid and microgrid

The intelligent control terminal combines the power generation information, load information, battery conditions, and electricity price factors of each microgrid. Taking the lowest total operating cost of the multi-microgrid as the objective function, an optimal economic power-dispatching strategy is formulated by comparing the sell-and-purchase electricity prices and the power generation cost through the intelligent control terminal. It can be better to achieve the optimal coordinated operation of power between the main grid and microgrid.

3. Optimal Economic Power-Dispatching Model

3.1. Objective Function

The electric energy exchange among microgrids is conducive to improve the utilization rate of renewable energy by regional autonomous consumption, the internal dynamic balance of the power supply, and power demand of the multi-microgrid. Considering the generation cost, discharge cost, power-purchase cost, power sales revenue, and environmental cost, the economic power-dispatching model of a multi-microgrid, which takes the maximum comprehensive benefits as the objective function for dispatching, was established. The objective function can be formulated as follows:

$$\min C = \sum_{i=1}^{n} (C_{i,1} + C_{i,2} + C_{i,3} + C_{i,4} + C_{i,5} + C_{i,6})$$
$$\begin{cases} C_{i,1} = \sum\limits_{t=1}^{N_T} (\lambda_w P_{i,w,t}\Delta t + \lambda_g P_{i,s,t}\Delta t) \\ C_{i,2} = \sum\limits_{t=1}^{N_T} [a_i \sigma_{1,t}(P_{i,l,t} - P_{i,w,t} - P_{i,g,t})\Delta t] \\ C_{i,3} = \sum\limits_{t=1}^{N_T} (\lambda_{bat,t} P_{i,b,t})\Delta t \\ C_{i,4} = \sum\limits_{t=1}^{N_T} [b_i \sigma_{2,t}(P_{i,w,t} + P_{i,g,t} - P_{l,t})]\Delta t \\ C_{i,5} = \lambda_{jh} P_{i-j}\Delta t \\ C_{i,6} = \sum\limits_{k=1}^{N} (C_i^k \gamma_{grid}^k) P_{i-z} \end{cases} \tag{1}$$

In Equation (1), n is the number of microgrids in a multi-microgrid; $C_{i,1}$ is the generation cost of the microgrid i; and $P_{i,w,t}$ is the power generation of the wind turbine in a microgrid i at time t. $P_{i,g,t}$ is the power generation of photovoltaic energy in a microgrid i at time t. λ_w and λ_g represent the average power generation cost of a wind turbine and photovoltaics, respectively. $C_{i,2}$ is the power-purchase cost generated by the daily periodicity of a microgrid i. $P_{i,l,t}$ represents the load power of a microgrid i at time t; $\sigma_{i,l,t}$ represents the power-purchase price at time t. $a_i(a_i = \{0,1\})$ represents the power-purchase identification of microgrid i. When the power supply of a microgrid i is greater than the load demand, $a_i = 0$, the microgrid i can be self-sufficient. On the contrary, $a_i = 1$, microgrid i purchases power from the main microgrid to ensure a power supply. $C_{i,3}$ is the battery discharge cost generated by the daily periodicity of the microgrid i. $\lambda_{i,B,t}$ is the battery discharge cost. $C_{i,4}$ is the electricity sales revenue generated by the daily periodicity of the microgrid i. $\sigma_{i,2,t}$ represents the price of electricity sold by the microgrid i to the main grid at time t. $b_i(b_i = \{0,1\})$ represents the power sale identification of the microgrid i. When the power generated by renewable energy in a microgrid i is greater than the load power at time t, the microgrid has sufficient power production; then, $b_i = 1$. Additionally, microgrid i sells electricity to the main grid. When the power generated by renewable energy in the microgrid i is less than the load power at time t, then $b_i = 0$ and there is no surplus electricity available for sale in the microgrid i. $C_{i,5}$ is the transaction cost of the microgrid i supplying power to other microgrids.C_i^k is the cost of treating k-type pollutants in a microgrid i. k represents the type of pollutant emitted (CO_2, CO, SO_2, NO_x, etc.). γ_i^{jk} represents the emission coefficient of pollutants per KWH generated by the jth power-generation unit of a microgrid i.

3.2. Constraints and Limits

(1) System power balance:

$$\sum_{i=1}^{n}(P_{i,w,t}+P_{i,g,t}+P_{i,b,t}+P_{i-grid}-P_{i-z})=\sum_{i=1}^{n}P_{loadi} \tag{2}$$

In Equation (2), $P_{i,w,t}$ and $P_{i,g,t}$ represent the output power of the wind turbine and photovoltaics in a microgrid i, respectively. $P_{i,b,t}$ ($P_{i,cha,t}$ or $P_{i,dis,t}$) represents the output power of a battery in microgrid i. When the battery is charged, $P_{i,b,t} < 0$, and when the battery is discharged, $P_{i,b,t}$ >0. $P_{i\text{-}grid}$ represents the interaction power between the microgrid i and other microgrids. If microgrid i supplies power to other microgrids, $P_{i\text{-}grid} < 0$, and if microgrid i is powered by other microgrids, $P_{i\text{-}grid} > 0$. P_{i-z} is the interaction power between the microgrid i and main grid. If the microgrid i purchases power from the main grid, P_{i-z} <0, and if the main grid sells power to the microgrid i, P_{i-z} >0. P_{Loadi} represents the load demand of the microgrid i.

(2) In order to protect the distributed power supply and prolong its service life, its output should meet the following constraints:

$$\begin{cases} P_{i,w,t}^{\min} \le P_{i,w,t} \le P_{i,w,t}^{\max} \\ P_{i,g,t}^{\min} \le P_{i,g,t} \le P_{i,g,t}^{\max} \end{cases} \tag{3}$$

In Equation (3), $P_{i,w,t}^{\min}$ and $P_{i,w,t}^{\max}$ represent the minimum and maximum output power values of a wind turbine in the microgrid i, respectively. $P_{i,g,t}^{\min}$ and $P_{i,g,t}^{\max}$ represent the minimum and maximum output power values of photovoltaics in the microgrid i, respectively.

(3) Operating constraints of energy storage system:

The operation constraints of an energy storage system, such as a battery, include the state-of-charge (SOC), the power constraints of charge and discharge, the time constraints of charge and discharge, and the states constraint of start and end.

a SOC constraints

$$SOC_{\min} \le SOC_t \le SOC_{\max} \tag{4}$$

In Equation (4), SOC_t is the state-of-charge of the battery at t time. $SOC_{\max}$ and $SOC_{\min}$ are the maximum and minimum values of the battery, respectively. Generally, $SOC_{\min}$ = 0.1~0.2 and $SOC_{\max}$ = 0.8~0.9. In this paper, $SOC_{\min}$ is set to 0.2 and $SOC_{\max}$ is set to 0.9. During the unit period Δt, the SOC value of the battery changes uniformly, and the state of charge can be expressed as:

$$\begin{cases} S_t^{SOC} = S_{t-1}^{SOC}(1-\delta) + \eta_c \frac{P_{i,cha,t}\Delta t}{E_{ESS}} X_t \\ S_t^{SOC} = S_{t-1}^{SOC}(1-\delta) - \eta_d \frac{P_{i,dis,t}\Delta t}{E_{ESS}} Y_t \end{cases} \tag{5}$$

To prolong the life of the battery, the state difference of the battery charge or discharge in the adjacent time period should satisfy:

$$\left| S_t^{SOC} - S_{t-1}^{SOC} \right| \le 0.2 \tag{6}$$

b Charge and discharge power constraints

To improve the reliability and safety factors, the battery cannot be charged or discharged at the same time on one side, and on the other side, the maximum charging and discharging power of the battery cannot higher than 20% of the battery-rated capacity E_b, namely:

$$\begin{cases} X_{i,t} \cdot Y_{i,t} = 0 \\ 0 \le P_{i,cha,t} \le 0.2 E_{i,b} X_{i,t} \\ 0 \le P_{i,dis,t} \le 0.2 E_{i,b} Y_{i,t} \end{cases} \tag{7}$$

In Equation (7), $X_{i,t}$ and $Y_{i,t}$ are the charge and discharge state signs, respectively, in the microgrid i, namely, $X_{i,t}$ = {0,1}, $Y_{i,t}$ = {0,1}. $P_{i,cha,t}$ and $P_{i,dis,t}$ are the charge and discharge power rates, respectively, of the battery at t time in microgrid i.

c Charge–discharge time constraints

The charge and discharge frequencies of the batteries are closely linked to their service life. Consequently, the charge and discharge frequencies are, respectively, constrained by the higher values $N_{i,1}$ and $N_{i,2}$, namely:

$$\begin{cases} \sum |X_{i,t+1} - X_{i,t}| \le N_{i,1} \\ \sum |Y_{i,t+1} - Y_{i,t}| \le N_{i,2} \end{cases} \tag{8}$$

(4) To prevent line and equipment damage, the switching power constraints between the microgrid and other microgrids should be meet:

$$P_{i-grid}^{t,\min} \le P_{i-grid}^{t} \le P_{i-grid}^{t,\max} \tag{9}$$

In Equation (9), $P_{i-grid}^{t,\min}$ and $P_{i-grid}^{t,\max}$ are the minimum and maximum values of the exchange power between the microgrid and the microgrid at time t.

In a similar manner, the exchange power constraints between the micro- and main grids should be meet:

$$P_{i-z}^{t,\min} \le P_{i-z}^{t} \le P_{i-z}^{t,\max} \tag{10}$$

In Equation (10), $P_{i-z}^{t,\min}$ and $P_{i-z}^{t,\max}$ are the minimum and maximum values of the exchange power between the microgrid i and main microgrid at time t.

4. Optimization Model-Solving Algorithm

The optimal economic power-dispatching model described in Equations (1)–(10) is a complex nonlinear optimization model with continuous and discrete variables. In the proposed model, $P_{i,w,t}$, $P_{i,s,t}$, $P_{i,g,t}$, $P_{i,b,t}$, P_{i-j}, and $P_{i\text{-}Z}$ are continuous variables, and the discrete variables are a_i, b_i, $X_{i,t}$, and $Y_{i,t}$. The traditional enumerative search algorithm can hardly solve this model in reasonable time. Evolutionary algorithms, such as particle swarm optimization, genetic algorithm, ant colony algorithm, and fish swarm algorithm, are widely used to solve this model due to strong portability and good adaptability. Particle swarm optimization (PSO) is an evolutionary algorithm in the field of intelligence. It has a strong global search ability, few adjustment parameters, high precision, and rapid convergence speed [32]. This paper used this algorithm to solve it. It should be explained that other evolutionary algorithms can also be applied to solve the model, and the comparisons among these evolutionary algorithms were outside the range of our study. The iterative formula of the particle swarm optimization algorithm is the following:

$$\begin{aligned} V_{zd}^{new} &= wV_{zd} + c_1 r_1 (P_{zd} - X_{zd}) + c_2 r_2 (P_{gd} - X_{zd}) \\ X_{zd}^{new} &= X_{zd} + V_{zd}^{new} \end{aligned} \tag{11}$$

In Equation (11), d = 1, 2,. . ., D. z = 1, 2,. . ., N. V_{zd} is the D-dimensional particle Xz of the flight velocity vector; V_{zd}^{new} is the D-dimensional particle X_{zd}^{new} of the flight velocity vector; P_{zd} is the D-dimensional individual extremum, and P_{gd} is the D-dimensional global extremum. c_1 and c_2 are non-negative constants called learning factors. r_1 and r_2 are random numbers distributed in the interval [0, 1]. In order to prevent the blind search of particles, their positions and speeds are generally limited to certain intervals: $[-X_{min}, X_{max}]$ and $[-V_{min}, V_{max}]$.

The specific solution steps are listed below and a flowchart of the solution algorithm is presented in Figure 2.

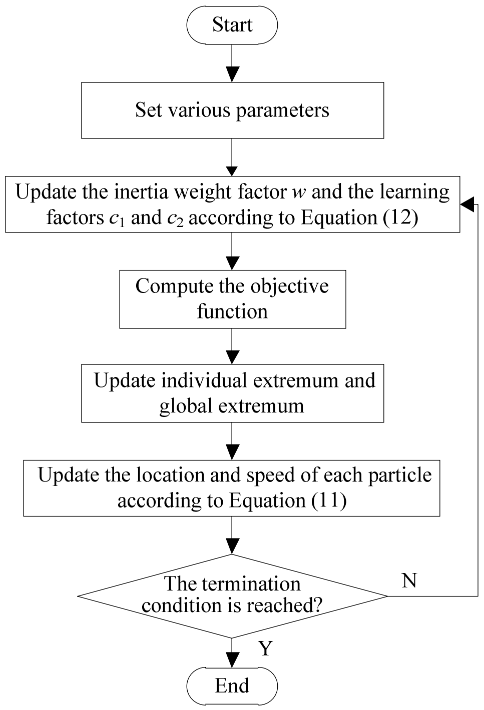


Figure 2. Flowchart of the solution algorithm.

Step 1: Set various parameters, including algorithm-control and multi-microgrid parameters.

Step 2: Update the inertia weight factor w and learning factors c_1 and c_2 according to Equation (12):

$$\begin{cases} w = w_{max} - \frac{(w_{max} - w_{min})}{\text{Maxiter}}\text{Iter} \\ c_1 = c_{max} - \frac{(c_{max} - c_{min})}{\text{Maxiter}}\text{Iter} \\ c_2 = c_{min} + \frac{(c_{max} - c_{min})}{\text{Maxiter}}\text{Iter} \end{cases} \quad (12)$$

In Equation (12), w_{max} and w_{min} are the maximum and minimum values of the inertia weight factors, respectively. At the beginning of the iteration, the larger the value of the inertia weight factor w, the stronger the global optimization ability of the algorithm. At the end of iteration, the smaller the value of the inertia weight factor w, the stronger the convergence ability of the algorithm. In this study, we took w_{max} = 0.9 and w_{min} = 0.4. Iter and Maxiter are the iteration numbers at present and the maximum number of iterations, respectively. c_{max} and c_{min} are the maximum and minimum values of the learning factors, respectively. At the beginning of the iteration, the larger the value of c_1 and the smaller the value of c_2, the stronger the global optimization ability of the algorithm. At the end of the iteration, the smaller the value of c_1 and the larger the value of c_2, the stronger the convergence of the algorithm. In this study, c_{max} was set to 2.5 and c_{min} was set to 0.5.

Step 3: Compute the objective function to obtain the fitness of the current particle;

Step 4: Update the individual and global extrema.

Step 5: Update the location and speed of each particle according to Equation (11).

Step 6: Stop criterion judgment. If the termination condition is achieved, end and output the results. Otherwise, turn to Step 2.

5. Case Study

5.1. Case Introduction

The multi-microgrid composed of three microgrids in the Xiongan New Area was employed as the study object, as indicated in Figure 1. The multi-microgrid can be linked to the main grid by the circuit breakers. The wind turbines and photovoltaics are taken into consideration. Each microgrid as well as the multi-microgrid need to meet the coordination of power supply and demand. The remaining power in the microgrid is stored by the battery or transferred to other microgrids with insufficient power by the link. In addition, the remaining power may also be uploaded to the main grid by the link between the micro- and main grids. Hence, optimal energy dispatching in the multi-microgrid is achieved, and the stability of the whole multi-microgrid is guaranteed. In order to better reflect the dynamic dispatching occurring in the multi-microgrid, the calculation period was set as 1 day(d), which was divided into 24 periods. Additionally, each period was 1 h. The relevant parameters of the multi-microgrid system are presented in Tables 1–4 [33,34].

Table 1. Microgrid configuration parameters.

Parameters	WT	PV	Battery
Microgrid1	3.5 MW	8 MW	5 MW
Microgrid2	9 MW	30 MW	20 MW
Microgrid3	13 MW	18 MW	12 MW

Table 2. Time-of-use electricity price.

Prices (Yuan/kWh) \ Time	0:00–7:00	7:00–10:00	10:00–14:00	14:00–20:00	20:00–23:00	23:00–0:00
Sell prices	0.40	0.78	1.18	0.78	1.18	0.40
Purchase prices	0.60	0.95	1.35	0.95	1.35	0.95

Table 3. Power generation cost of wind turbine and photovoltaic.

Category	Wind Turbine Power Generation	Photovoltaic Power Generation
Cost (CNY/kw·h)	0.61	0.75
Subsidy (CNY/kw·h)	0.2	0.18

Table 4. Pollutant-emission factors.

Pollutant Type	Pollution Control Cost (Yuan/kw·h)	Pollutant-Emission Coefficient		
		PV	WT	Main Grid Network
CO_2	0.210	0	0	889
CO	0.125	0	0	12.1
SO_2	14.842	0	0	1.8
NO	62.964	0	0	1.6

5.2. Multi-Scenario Impact Analysis

Four scenarios in the engineering application were set according to whether the energy storage system and the microgrid participated in power dispatching or not, as presented in Table 5.

Table 5. Comparison of operation costs in different scenarios.

Scenario	Energy Storage System Does Not Participate in Dispatching		Energy Storage System Participates in Dispatching	
	No Power Dispatching between the Two Microgrids	Power Dispatching between the Two Microgrids	No Power Dispatching between the Two Microgrids	Power Dispatching between the Two Microgrids
Cost	3.30×10^5 (Scenario 1)	3.18×10^5 (Scenario 2)	3.19×10^5 (Scenario 3)	3.12×10^5 (Scenario 4)

Scenario 1: The energy storage system does not participate in power dispatching, and no power dispatching is conducted between the two microgrids. The microgrid in a multi- microgrid directly participates in the power dispatching with the main grid. In this scenario, the distributed power generation in the microgrid gives priority to meet the load needs in the corresponding microgrid. If it cannot be met, the corresponding microgrid purchases electric energy from the main grid.

Scenario 2: The energy storage system does not participate in power dispatching, and power dispatching is conducted between the two microgrids. The main grid and microgrid in the multi-microgrid jointly participate in power dispatching. In this scenario, the distributed power generation in the microgrid gives priority to meet the load needs in the corresponding microgrid. If it cannot be met, the corresponding microgrid obtains electric energy from other microgrids, firstly. Additionally, if it still cannot be met, the corresponding microgrid purchases electric energy from the main grid.

Scenario 3: The energy storage system participates in the dispatching, and no power dispatching is conducted between the two microgrids. The main grid and microgrid in the multi-microgrid jointly participate in power dispatching. In this scenario, the distributed power generation in the microgrid gives priority to meet the load needs in the corresponding microgrid. If it cannot be met, the energy storage system in the corresponding microgrid discharges electric energy to supplement this. Additionally, if it still cannot be met, the corresponding microgrid purchases electric energy from the main grid.

Scenario 4: The energy storage system participates in power dispatching, and power dispatching is conducted between the two microgrids. The main grid and microgrid jointly participate in power dispatching. In this scenario, the distributed power generation in the microgrid gives priority to meet the load needs of the corresponding microgrid. If it cannot be met, the energy storage system in the corresponding microgrid discharges electric energy to supplement this. However, if it cannot be met, the corresponding microgrid purchases electric energy from other microgrids, and if it still cannot be met, the corresponding microgrid purchases electric energy from the main grid. Table 5 presents the total operation cost of the multi-microgrid in different scenarios.

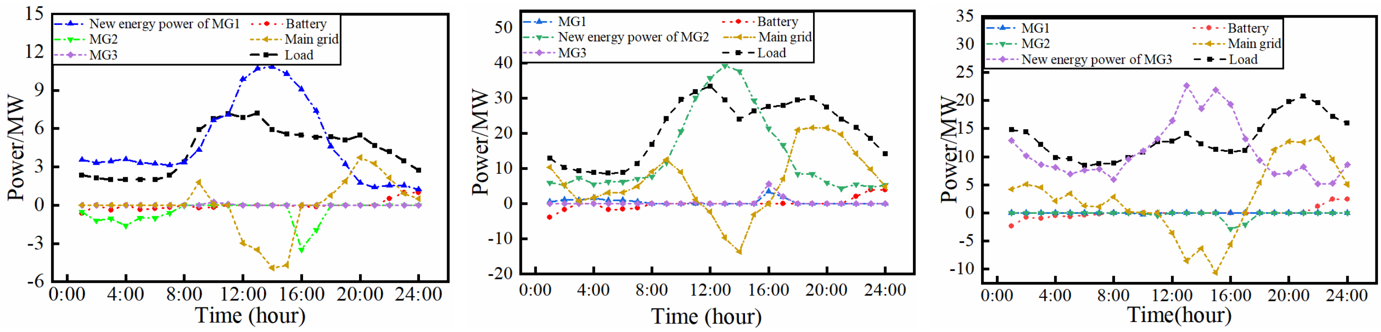
Table 5 shows that the economy of the total operation cost of the multi-microgrid in Scenario 4 is better than that in the other three scenarios. The reasons are analyzed as follows:

(1) The energy storage system plays an important role in peak shaving and valley filling for both the main grid and the multi-microgrid in Scenario 4. When the electricity price is low, a high amount of electric energy is stored by the battery, and electric energy is released when the electricity price is high or the load is at a peak. Consequently, Scenario 4 is more economical than Scenarios 1 and 2.

(2) Compared with Scenario 3, when the priority output of the distributed generation units in the microgrid cannot meet the load needs, the microgrid can dispatch electric energy from the microgrid with residual power. The cost of dispatching is low; consequently, Scenario 4 is better than Scenario 3 in terms of economy.

5.3. Interconnection Dispatching Analysis in a Multi-Microgrid

With the balance of the supply and demand of power, the optimal distribution of electric energy is achieved so as to maximize the comprehensive benefits of the multi-microgrid, as presented in Figures 3 and 4. Taking microgrid 1 as an example, the detailed analysis is presented as follows:



(**a**) (**b**) (**c**)

Figure 3. Multi-microgrid optimization results. (**a**) Microgrid 1 system optimization results; (**b**) microgrid 2 system optimization results; (**c**) microgrid 3 system optimization results.

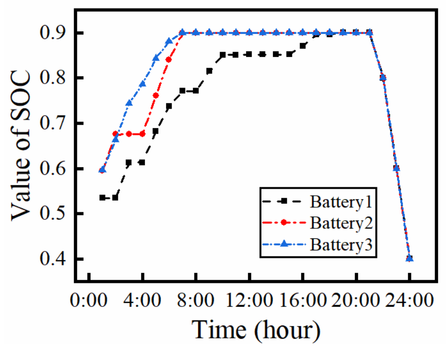


Figure 4. Change in SOC values of storage battery.

At 0:00–8:00, the new energy power can meet the load demand of microgrid 1. Meanwhile, the surplus electricity in microgrid 1 is transmitted to microgrid 2 or the battery. From 8:00 to 11:00, the new energy power of microgrid 1 cannot meet the load demand, and the deficit of power in microgrid 1 needs to be supplemented from the main grid. From 11:00 to 17:00, the new energy power of microgrid 1 generates enough power to meet the load demand without purchasing power from other sources. At the same time, it can sell the surplus power to the main grid or transmit the surplus power to microgrid 2. The new energy power of microgrid 1 is insufficient from 17:00 to 24:00, where electricity is purchased from the main grid from 17:00 to 21:00. From 21:00 to 24:00, the part deficit of electricity is purchased from the main grid, and the part deficit of electricity is supplemented by the battery.

5.3.1. Interconnection Dispatching Analysis between the Two Microgrids

Figure 5 presents the following:

At 0:00 to 8:00, there is no power dispatching between microgrids 1 and 3, and the same is true for microgrids 2 and 3. Moreover, microgrid 1 supplies surplus power to microgrid 2.

During 9:00–12:00, microgrid 3's power interacts with the microgrids 1 and 2, respectively. The deficit of power in microgrid 3 is supplemented by microgrids 1 and 2. No power dispatching is conducted between microgrids 1 and 2.

During 16:00–18:00, microgrid 2's power interacts with microgrids 1 and 3, respectively. The deficit of power in microgrid 2 is supplemented by microgrids 1 and 3. No power dispatching is conducted between microgrids 1 and 3. There is no power dispatching among microgrids 1, 2, and 3 at other times.

In a word, each microgrid provides surplus power for others and serves as a backup for the others. The interconnection dispatching principle is to maximize the local consumption of microgrid load and minimize the exchange power between the two microgrids, so as to achieve optimal interconnection dispatching among the microgrids in a multi-microgrid.

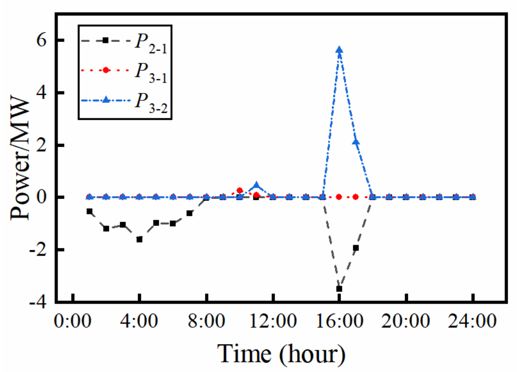


Figure 5. Interconnection dispatching optimization results between the two microgrids.

5.3.2. Interconnection Dispatching Optimization Analysis between the Main Grid and Multi-Microgrid

Figure 6 presents the following:

(1) As for microgrid 1: from 8:00 to 10:00, the main grid transmits electric energy to microgrid 1. From 11:00 to 15:00, microgrid 1 transmits electric energy to the main grid. From 17: 00 to 24:00, the main grid transmits electric energy to microgrid 1. On other occasions, there is no power dispatching between microgrid 1 and the main grid.

(2) As for microgrid 2: from 0:00 to 11:00, the main grid transmits electric energy to microgrid 2. From 11:00–15:00, the microgrid 2 transmits electric energy to the main grid. The main grid transmits electric energy to microgrid 2 during 16:00–24:00. On other occasions, there is no power dispatching between microgrid 2 and the main grid.

(3) As for microgrid 3: from 0:00 to 9:00, the main grid transmits electric energy to microgrid 3. From 11:00 to 16:00, microgrid 3 transmits electric energy to the main grid. From 17:00 to 24:00, the main grid transmits electric energy to microgrid 3. During 9:00–11:00 and 16:00–17:00, there is no power exchange between microgrid 3 and the main grid.

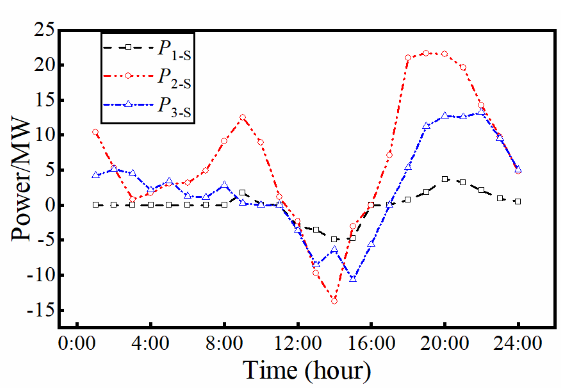


Figure 6. The power-dispatching optimization between the main grid and the multi-microgrid.

6. Conclusions

In order to consume all the renewable energy and improve the efficiency of the multi-microgrid, an economic dispatching model for multi-microgrid was proposed, considering factors, such as generation cost, discharge cost, power-purchase cost, power sales revenue, and environmental cost. The power interactions between the two microgrids and those between the microgrid and main grid were considered in the model proposed in our study. The verification analysis was performed by taking the multi-microgrid composed of three microgrids as an example, and different optimization operation results for the multi-microgrid were obtained under four scenarios in the engineering application. The results verify the effectiveness of the proposed method, and the following conclusions can be drawn:

(1) Allowing the multi-microgrid to freely exchange power with the main grid can improve the economy of a multi-microgrid operation.
(2) The use of a battery in a multi-microgrid can mitigate the impact of renewable energy output volatility on the multi-micro- and main grids. In addition, when the electricity price is low, a high amount of electric energy is stored by the battery, and the electric energy is released when the electricity price is high or the load demand is at its peak. It plays the role of the "time–space complementation" of electric energy.
(3) Interconnection dispatching and the mutual power supply of a multi-microgrid can enhance power supply reliability, and the stability and economy of the system.

In conclusion, an economic dispatching of the multi-microgrid has a certain significance for the operation decision for a multi-microgrid, especially for the construction of a novel power system. In addition, a multi-objective optimization algorithm for a multi-microgrid cooperative operation, which simultaneously considers the factors of environment, satisfaction, and economy, will be studied further in the future, based on the research of our paper. It is helpful to improve the reliability and comprehensive benefits of the power system.

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