



## Distributed master-slave game optimization for microgrid clusters considering dual market coupling mechanism of electricity and carbon

Jinjie Ma<sup>1</sup>, Hangtong Zhang<sup>1,\*</sup>, Jingping Wang<sup>1</sup>, Yunhao Jiang<sup>1</sup> and Chao Wang<sup>1</sup>

<sup>1</sup> State Grid Jiangsu Electric Power Co., Ltd. Nanjing Power Supply Company

**SUMMARY:** *With flexible and efficient energy management, more and more microgrid clusters have been used in today's energy systems. To make full use of the microgrid cluster for the purpose of making profits in the economic field and reducing carbon emissions, the interaction between the electricity market and carbon trading market becomes increasingly crucial. In this regard, in this paper, we build up an optimization model based on distributed master-slave game to make reasonable decisions for microgrid cluster in the process of electricity transactions and carbon emission rights trading. First, with dual-market coupling of electricity and carbon as well as the master-slave game method, we study the optimization scheduling and game interaction of microgrid cluster under fluctuating market condition. Second, in view of multiple constraints faced by microgrid cluster under reality condition, an optimization model with the minimization of cost and carbon emissions as objectives is established, along with a corresponding distributed solving algorithm. Finally, we verify the feasibility of our proposed optimization model through simulation experiments. According to the simulation results, the optimization model presented in this paper can not only increase the economic benefits of microgrid cluster in the electricity-carbon market coupling environment but also effectively reduce the amount of carbon emissions. Through the proposed optimization strategy, microgrid cluster will become highly competitive players within the coupled electricity and carbon market environment. At the same time, this research is of great significance for the wider application of green low-carbon energy.*

**KEYWORDS:** *Master-slave game; Optimization model; Microgrid; Electricity-carbon dual market coupling; Economic and environmental benefits*

## 1 Introduction

To address the challenges of integrating distributed energy resources into the power grid, the idea of microgrid has evolved over time. Microgrids should be efficiently managed to incorporate distributed energy resources, loads, and energy storage devices. Simultaneously, other microgrids situated in various locations can be connected to form a microgrid cluster. To be more accurate, a microgrid cluster is a structure comprising at least two microgrids and having certain similarities and complementarities among them [2]. Also, every microgrid that constitutes this particular cluster should have at least one link to another unit [3]. The microgrid clusters are able to exchange energy with the mains grid or operate autonomously, i.e., in isolation or grid-connected mode [4].

One of the features of a future energy system that may be observed in conjunction with the implementation of the dual carbon policy will be the combined development of both the carbon

\*r1w0099ww@126.com

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market and the electricity market [5]. The process of integrating carbon and power markets will increasingly become inevitable due to the further development of these markets. Due to political considerations, the two markets must be interconnected in terms of the market players as well as tradable varieties and market mechanisms. Increasing relationship between carbon price and the cost of power generation leads to carbon neutrality in the energy sector, as well as economic effectiveness in energy production and consumption [6-8].

However, in microgrid cluster operation, the requirement of multi-interested subjects raises the problem of coordination of multiple interests, and different energy types and spatial and temporal scales will affect the operation effect of microgrid clusters, and the centralized optimization strategy does not have an efficient application effect [9-11]. In addition, the coupling of power market and carbon market lacks the global planning of systematic synergistic development to a certain extent, and there are a series of problems such as part of the market failing to form an effective interaction, high transition cost and difficult to transfer, and imperfect development of the market, which further deepens the difficulty of coordinating the interests of microgrid clusters [12-14].

The game optimization method can be used in a specific scenario, where multiple subjects with competitive relationships make strategies that are beneficial to their own interests or the interests of the group based on the information they have about themselves or their opponents, which can realize the optimization of energy coordination and other problems in the grid cluster and solve the problem of coordination of multi-interested subjects of microgrid clusters. Dong et al. guide microgrids and users through the price incentives and internal coordination, and propose a model based on hierarchical Stackelberg game for optimization of energy trading in microgrid clusters. For the area of energy trading in microgrid clusters, there have been some studies in which consumption patterns have been altered and energy trading optimization models have been developed for microgrid clusters based on Stackelberg game theory. They have proved through theoretical analysis that the solution in such scenarios is unique and that they improve the economic efficiency of the microgrid clusters along with the utilization of new energy sources [15]. In another study, Ali et al. have presented a planning framework for grid-connected microgrid clusters based on cooperative game theory. By allocating generation capacity and storage capacity to the participating microgrids based on Nash bargaining and using the PSO technique, they maximize the annual profit of the microgrid clusters along with the individual microgrids [16]. Yang et al. present a comprehensive approach towards microgrid clusters where factors like cooling, heating, electricity generation, energy storage, and uncertainties are taken into account. Through the use of Shapley value allocation, they have proposed a cooperative game theory-based optimal scheduling approach, resulting in improved profitability along with reduced dependency on the main power grid due to energy complementation [17].

When making decisions in a game-based way, every participant comes up with a response to their own strategy. The essence of this kind of model is to use the first-mover advantage, where the leader uses the timing priority to maximize the overall returns, and therefore, gives a more accurate description of the relationship between interested parties in a microgrid cluster. Ji et al. suggested a master slave game optimization scheme of a multi-energy microgrid with common energy storage. Through two-layer game construction between the microgrid side and the user side and heuristic combination with CPLEX solver, the overall system economy was successfully enhanced [18]. Jia et al. have created a master-slave game-based optimization approach to energy trading in multi-microgrid clusters. The method minimizes the overall cost of microgrids, raises the income of distribution grid operators, and achieves the entire system economic optimization with coordinated energy storage output and internal tariffs [19]. Guo et al. built a multi-level master-slave game optimization model, in which the microgrid is the

master node and the source-grid-load-storage system is the slave node. The structure realizes collaborative optimization of total operating cost, renewable energy consumption, storage safety regulation, and load power quality [20]. Chen et al. coordinated operator revenue and microgrid operating cost by means of a master-slave game and formulated a non-cooperative game model of peer-to-peer energy sharing and fair distribution. Through flexible integration of resources like electric vehicle clusters, the model has a significant improvement in the overall economic benefits of all parties [21]. Wang et al. have presented a master-slave game optimization model with an integrated energy operator and a load aggregator. In the model, the operator is the leader who introduces carbon capture and power-to-gas technologies and designs a pricing strategy to maximize revenue whereas the aggregator is the follower optimizing the demand response load so that the user surplus is maximized. The solution is found by a distributed algorithm based on genetic algorithm and CPLEX. This scheme helps reducing carbon emissions in the system and balance the interests of the two parties [22]. Sun et al. built a two-layer master-slave game model of a multi-microgrid integrated system, where the operator is the leader, and aggregators, energy storage, and wind farms are the followers. Using a modified particle swarm algorithm and an integrated demand response mechanism, the model is able to coordinate the heterogeneous demands of energy and the interests of numerous participants and also has a tremendous benefit on the overall economy and efficiency of operation of the system [23].

In the work by Wu et al., the master-slave game is used to achieve two-level optimal scheduling of low-carbon operations of integrated energy systems. In this case, the energy supplier acts as the leader in the upper layer who sets prices for electricity and heat production, while the energy storage company and load aggregator are the followers in the lower level. The model shows good potential to balance the interests of multiple parties involved, minimize carbon emission costs, and analyze the effect of carbon pricing [24]. The researchers by Dai et al. suggest using peak shaving and ladder carbon trading models based on the master-slave game framework. The integration of the genetic algorithm and quadratic programming methods leads to significant growth of profits of user aggregators and operators of the integrated energy systems. Besides, the Stackelberg equilibrium is achieved, which allows for reducing system carbon emissions [25]. Zhang et al. design a master-slave game-based optimal scheduling method for virtual power plant clusters in the context of coupled electricity and carbon markets. In this game, the system operator is the leader who sets the price for electricity and carbon emission, while each virtual power plant is a follower that plans its operations. A two-level game model is designed where the particle swarm algorithm is applied within CPLEX. The analysis reveals that such an approach significantly increases the efficiency of distributed resource utilization, as well as operator profits by 28.9% [26].

The present article discusses the coupling mechanism between the electricity market and the carbon market in detail and suggests an optimal scheduling scheme of microgrid clusters using a distributed master-slave game model. The model uses maximization of profit, minimization of costs and maximization of carbon emissions reduction as objective functions and solves the dispatch optimization problem of microgrid clusters with constraints of power balance, upper and lower limit and unit ramping. The model is updated iteratively until it meets the equilibrium condition whereby the optimal scheduling strategy can be derived. After that, the equilibrium solving process of the distributed master-slave game model is discussed, and some optimization algorithms are presented to compare them in order to determine whether microgrid cluster operation brings economic benefit to the economy and what its environmental effect is.

## 2 Method

### 2.1 Analysis of Market Coupling Mechanisms for Electrocarbons

The coupling relationship between carbon and electricity markets is mainly reflected in the following aspects. On the one hand, in the free electricity market, generating units are cleared in the spot market according to marginal cost. The marginal cost determines which units can be selected for dispatch. After carbon quota trading is introduced, coal-fired, gas-fired, and other conventional units will face additional energy costs or revenues. These changes alter the marginal cost and market priority of generating units, thereby affecting spot-market quotations, final transaction volume, and clearing price, which will be further analyzed and modeled in detail. On the other hand, the power-market generation of conventional units is directly associated with CO<sub>2</sub> emissions. Since the proportion of NCV emission offsets is also related to carbon emissions, purchases in the NCV market are connected with their electricity generation in the power market.

Second, since photovoltaic or wind renewable energy sources trade in the spot market, their carbon emissions reductions will be tied to both winning bids in the electricity market and installed capacity on the grid. On the other hand, investments are made based on the revenue from the NCV reduction market. One major difference between the carbon market and the electricity market in terms of their operation is in relation to their settlement process, where the outcome of the electricity market spot transaction must take physical form while that of the carbon market is mostly for financial settlements. In regards to time scale coordination, the carbon market valuation framework will necessitate carbon allowance surrender in the end of each compliance year, which corresponds to the total amount of carbon emissions resulting from electricity generation in a year. If the baseline approach is utilized in allocating carbon allowances, then carbon allowances will be valued based on the real-time carbon emissions intensity relative to the baseline carbon emission intensity. With this arrangement, annual costs of carbon allowances will be valued hourly based on electricity generation in the day-ahead wholesale market.

### 2.2 Microgrid dispatch optimization under market volatility

Market fluctuations will result in a mismatch between the power supplied by the microgrid cluster and the demand of customer loads, and the power system will need other flexible resources, such as the additional costs incurred by thermal units to meet the system demand by starting, stopping, and regulating their output. Specifically, microgrid costs due to market fluctuations include three components: operating costs, standby costs and regulation costs.

a. Running costs: Conventional generating units frequently start and stop and flexibly regulate output, resulting in an increase in their coal consumption for power generation and an increase in running costs.

b. Standby cost: when the wind power grid-connected capacity accounts for a certain proportion of the total system capacity (about 5%-10%), the wind power volatility will have an adverse effect on the grid frequency and voltage stability. Therefore, in order to ensure the stable operation of the system, it is necessary to increase part of the rotating standby capacity on the basis of the original power plan to cope with the problem of wind power volatility.

c. Adjustment costs: large-scale wind power grid, when the wind power output is large, if the conventional unit in accordance with the conventional power range, to ensure that the system power balance may cause wind abandonment. In order to effectively utilize the wind power resources, part of the traditional unit is arranged to run below the conventional minimum technical output, i.e., running in the deep peaking state.

Optimized scheduling through microgrid clusters can prioritize the scheduling of renewable energy sources while meeting load demand, reducing costs while enhancing environmental protection. To this end, the following section analyzes and solves the optimal scheduling problem for microgrid clusters using a distributed master-slave game optimization model.

### 2.3 Distributed master-slave game optimization model

Master-slave game studies the game problem of multi-level decision-making, which is suitable for solving optimization problems with a recursive structure. The leader prioritizes strategies from the perspective of self-interest, and the follower makes corresponding decisions in response to the leader's strategies, and the two make decisions in sequence and influence each other.

This paper introduces a cluster operator (CO) that will facilitate energy trading between the microgrid clusters. The CO will be tasked with overseeing the energy trading center. Pricing behavior of the CO and reaction behavior of the seller (RIES) are represented in a master-slave game. Initially, the CO becomes the leader and establishes prices based on clusters so that it maximizes its own revenue. Next, the RIES, the follower, reacts to prices signals by organizing the output of internal equipment and changing purchases and sales of electricity, which should reduce operating expenses. It keeps going on until the game achieves equilibrium. The master-slave game model is given as follows:

$$G = \{(DSO \cup RIES), \pi^b, \pi^s, P^i, u_{CO}, u_{RIES}\} \quad (1)$$

In this model, it mainly consists of three parts:

- a. Participants: The CO and RIES clusters are the two parties in the game.
- b. Strategies: The decision variable of CO is the purchase and sale electricity prices, denoted as  $\pi_b$  and  $\pi_s$ . The decision variable of RIES is the purchase and sale electricity volume, but since the output of gas turbines and the charging and discharging volumes of energy storage devices in each period are all closely related to the purchase and sale electricity strategy, the output of the equipment is also regarded as a decision variable and participates in the game together, denoted as  $P^i$ .
- c. Payoff function: the payoff functions of CO and RIES are maximizing net profit  $J_{CO}$  and minimizing operating cost  $C_{RIES}$ , respectively.

Based on this, the master-slave game of CO and RIES is modeled as follows:

$$\begin{aligned} \max I_{CO} &= (\pi_t^b, \pi_t^s, P_t^i) \\ \text{s.t.} &\begin{cases} \pi_t^b, \pi_t^s \in \Omega_{CO} \\ P_t^i = \arg \min C^i(\pi_t^b, \pi_t^s, P_t^{i*}), \forall i \\ \text{s.t. } P_t^{i*} \in \Omega_{RIES}^i \end{cases} \end{aligned} \quad (2)$$

The trading tariffs set by the upper tier operator are the parameters of the lower tier game model, while the lower tier game model is the constraints of the upper tier operator's game model. The Nash equilibrium is sought through continuous gaming to find the optimal strategy.

According to the definition of Stacklberg-Nash equilibrium, if there exists strategy  $(\pi_t^{b*}, \pi_t^{s*}, P_t^{i*})$ , if and only if it is satisfied at the same time:

$$\begin{aligned}
I_{CO}(\pi_t^{b*}, \pi_t^{s*}, P_t^{i*}) &\geq I_{CO}(\pi_t^b, \pi_t^s, P_t^{i*}) \\
C_{RIES}^l(\pi_t^{b*}, \pi_t^{s*}, P_t^{i*}) &\leq C_{RIES}^l(\pi_t^{b*}, \pi_t^{s*}, P_t^{i*}, P_t^l), \quad \forall i \in N
\end{aligned} \tag{3}$$

This strategy is the master-slave game equilibrium solution, where  $P_t^{-i}$  is the strategy of the remaining *RIES* except  $RIES_i$ . When the strategies of all game participants are Stacklberg equilibrium strategies, there is no incentive for any participant to deviate from this equilibrium solution and cannot unilaterally and without authorization change their own strategies to achieve greater benefits.

## 2.4 Objective Functions and Constraints

This part describes the association between microgrids and users in the context of master-slave games. Microgrids and users are seen as rational and independent decision-makers who are able to make decisions independently, engage in competition within the marketplace, and seek the maximum benefits for their development. The operation of the microgrid is largely based on predictions regarding the generation of energy through wind power, photovoltaics, and base load power. In order to ensure electricity prices that will benefit the users, if there is a mismatch between the electricity production and consumption by the users, electricity from the primary grid can be utilized to cover the difference. In this process, the microgrid plays a leading role by sending the developed pricing strategy to the users first. The user, as a follower, proposes a power consumption strategy, and then reacts to the microgrid's scheduling by following the microgrid's price signals, their own power consumption status and the economic benefits brought by power exchanges with the microgrid, and feeds back the power consumption scheme to the microgrid, which also adjusts its own tariff scheme according to the user's fed-back strategy, and finally arrives at the Nash equilibrium scheme of a master-slave game.

Moreover, with the consideration of the dynamic carbon emission factor, low-carbon demand response participants would like to minimize their carbon emission level. Hence, the carbon emission objective function equation is:

$$\begin{cases} \max R = \sum_{t=1}^T (C_{price,t} P_{load,t} - C'_{SUM}) \\ \min C' = C_W + C_{WH} + C_{PV} + C_{PVH} + C_{MT} + C_{NET} + C_T \end{cases} \tag{4}$$

where:  $C_{price,t}$  is the price of power purchased from the microgrid by the user,  $P_{load,t}$  is the total load demand in time period  $t$ .  $\min C'$  is the minimum cost of microgrid operation,  $C_W$  and  $C_{PV}$  are the cost of wind and light abandonment penalties,  $C_{WH}$  and  $C_{PVH}$  are the maintenance costs of wind and solar power generation,  $C_{MT}$  is the operating cost of gas turbines,  $C_{NET}$  is the cost of exchanging power between the microgrid and the main grid, and  $C_T$  is the cost of carbon trading.

In addition, based on the dynamic carbon emission factor, the objective of user participation in low carbon demand response is to maximize their own carbon emission reduction. Therefore, the carbon emission objective function can be expressed as:

$$Q_T^u = \sum_{t \in T} (\Delta L_t^- - \Delta L_t^+) \Delta t \lambda_{C,j,t} \tag{5}$$

where:  $Q_T''$  is the carbon emission reduction of the electricity user in a single cycle.  $\Delta L_t^+$  and  $\Delta L_t^-$  are the load increases and reductions of the power users during time period  $t$  in the low-carbon response behavior.

An assessment of the limitations on power balance, maximum and minimum output limits, ramping constraints for individual units, constraints for battery charging and discharging, constraints for main grid electricity exchange, constraints for carbon trading, and electricity price constraints is performed. The limitations are outlined as follows.

a. Power balance constraint:

$$\begin{cases} P_{load,t} = P_{PDR,t} + P_{t,1} - P_{t,2} \\ P_{PV,t} + P_{W,t} + \sum_{i=1}^N P_{MT,i,t} + P_{net,t} + P_{dis,t} = P_{cha,t} + P_{load,t} \end{cases} \quad (6)$$

where:  $P_{cha,t}$  for  $t$  hours of battery charging power,  $P_{dis,t}$  for  $t$  hours of battery discharging power,  $P_{load,t}$  for  $t$  hours of the total load of the microgrid.  $P_{t,1}$ ,  $P_{t,2}$  respectively, can be shifted loads, can cut loads,  $P_{W,t}$ ,  $P_{PV,t}$  respectively, for the moment of wind power, photovoltaic power,  $P_{MT,i,t}$  for the gas turbine  $i$  in the  $t$  moment of the effective power.

b. Upper and lower limit constraints of output power:

$$\begin{cases} 0 \leq P_{W,t} \leq P_W^{\max} \\ 0 \leq P_{PV,t} \leq P_{PV}^{\max} \\ P_{MT,i}^{\min} \leq P_{MT,i,t} \leq P_{MT,i}^{\max} \end{cases} \quad (7)$$

where:  $P_{MT,i}^{\max}$  is the maximum value of gas turbine  $i$  effective power.  $P_{MT,i}^{\min}$  is the minimum value of gas turbine  $i$  effective power.

c. Unit climbing constraint:

$$-D_i \Delta T \leq P_{MT,i,t} - P_{MT,i,t-1} \leq U_i \Delta T \quad (8)$$

where:  $U_i$  is the up-climbing capability of the gas turbine  $i$ ,  $D_i$  is the down-climbing capability of the gas turbine  $i$ , and  $\Delta T$  is the scheduling period, which is taken as 1h for the study.

d. Battery charging and discharging constraints:

$$\begin{cases} 0 \leq P_{cha,t} \leq P_{cha}^{\max} \\ 0 \leq P_{dis,t} \leq P_{dis}^{\max} \\ SOC_t = SOC_{t-1} + \frac{\eta_c P_{cha,t}}{E_{battery}} - \frac{P_{dis,t}}{\eta_d E_{battery}} \\ SOC_{\min} \leq SOC_t \leq SOC_{\max} \\ SOC_0 = SOC_T \end{cases} \quad (9)$$

where:  $P_{cha,t}$  and  $P_{dis,t}$  satisfy  $P_{cha,t} \times P_{dis,t} = 0$ ,  $P_{cha}^{\max}$  is the maximum value of charging power,  $P_{dis}^{\max}$  is the maximum value of discharging power.  $\eta_c$  is the charging efficiency,  $\eta_d$  is the discharge efficiency.  $SOC_{\max}$  is the maximum charging state of the battery,  $SOC_{\min}$  is the minimum charging state of the battery, and  $E_{battery}$  is the battery capacity.

e. Main network power exchange constraints:

$$P_{net,t} \geq 0 \quad (10)$$

f. Carbon trading constraints:

$$\begin{cases} E_{MT,i,t} = \delta_i P_{MT,i,t} \\ Q_{MT,t} = e_i \sum_{i=1}^G P_{MT,i,t} + \mu P_{net,t} \end{cases} \quad (11)$$

where:  $\delta_i$  is the carbon allowance factor for gas turbine  $i$ ,  $e_i$  is the carbon emission factor for gas turbine  $i$ , and  $\mu$  is the equivalent carbon emission factor for purchasing electricity from the higher grid.

g. Electricity price constraint

To ensure that the electricity price set by the microgrid system is appropriate for the consumer, upper and lower limits of the electricity price, together with restrictions on the average price of electricity, are established.

$$\begin{cases} D_g \leq C_{price,t} \leq D_f \\ \frac{1}{T} \sum_{t=1}^T C_{price,t} \leq D_p \end{cases} \quad (12)$$

## 2.5 Model Solving Microgrid Scheduling Optimization

On the basis of the objectives, functions and constraints defined previously, the MATLAB and CPLEX optimizer has been utilized to solve the model of the present work. Figure 1 shows the process flow of solving the optimal scheduling model in the master-slave game of microgrids and users, and detailed steps are given as follows:

a. Gather the historical information on wind and photovoltaic power generation, operating parameters of gas turbines, energy storage devices, and energy consumption of consumers at every time interval.

b. The demand response on the load will give you the load after the demand response.

c. Develop a pricing policy of the microgrid to meet the goals of the objective function and the customer develops their response strategy based on the utility function.

d. Compute the load after demand response based on the utility function of users.

e. On the basis of the conditions presented, the microgrid and the consumer engage in the game till both of them reach the optimal outcome.

f. The termination of the iterations will happen at equilibrium, and the best equilibrium solutions will have been found, provided that equilibrium conditions are satisfied; otherwise, repeat step c.

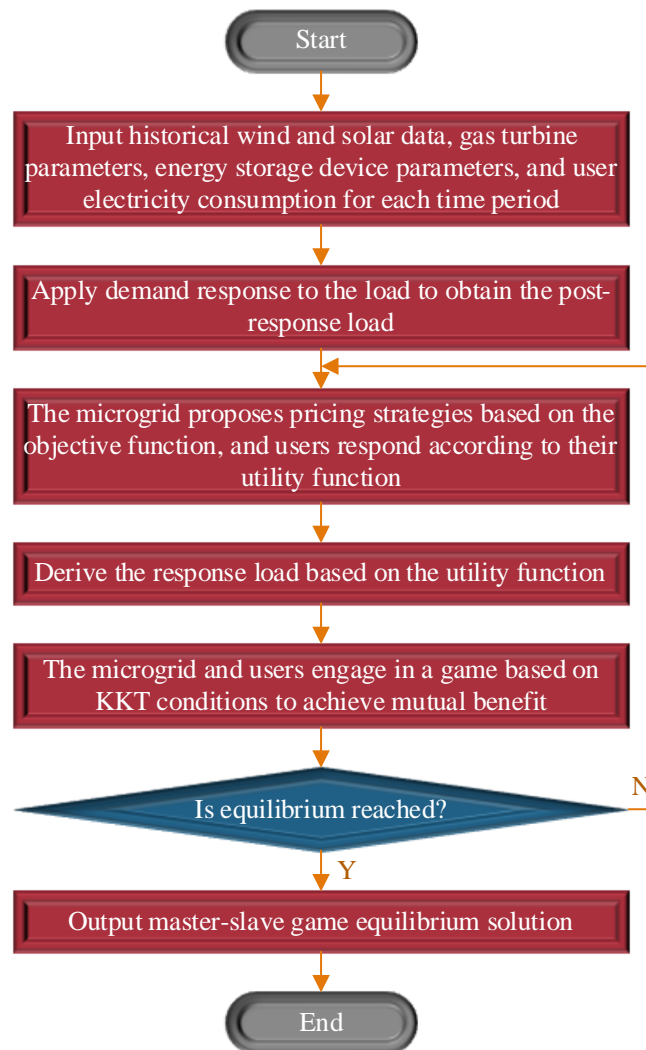


Figure 1: The optimization scheduling model of the game is solved

### 3 Results and analysis

The hardware environment for the simulation experiments is Windows 10 (X64) operating system, Intel Core i5-7200U processor with 2.5GHz main frequency and RAM 8G memory, and the software environment is Matlab 2018a.

#### 3.1 Master-slave game equilibrium solution process

In real-time optimization of microgrid scheduling, each buyer participates in a master-slave game and determines the proportion of electricity to be purchased from a particular seller. The iterative algorithm proposed above enables price competition between the microgrid (seller) and the user (buyer), while the Stackelberg game is utilized for interactive negotiation between the buyer and the seller. In the whole game, since the seller is the leader, the solution of the Stackelberg game is the final response of the buyer to the electricity price announced by the seller.

Figure 2 illustrates the path towards the buyer's probability of buying electricity from the seller. Figure 2 depicts that through many iterations, the probability of buying tends to stabilize around the equilibrium point. It is equally true that the buyer's decision making approach

reaches a certain level of stability, which enables the buyer to earn a better payoff through his stable strategy.

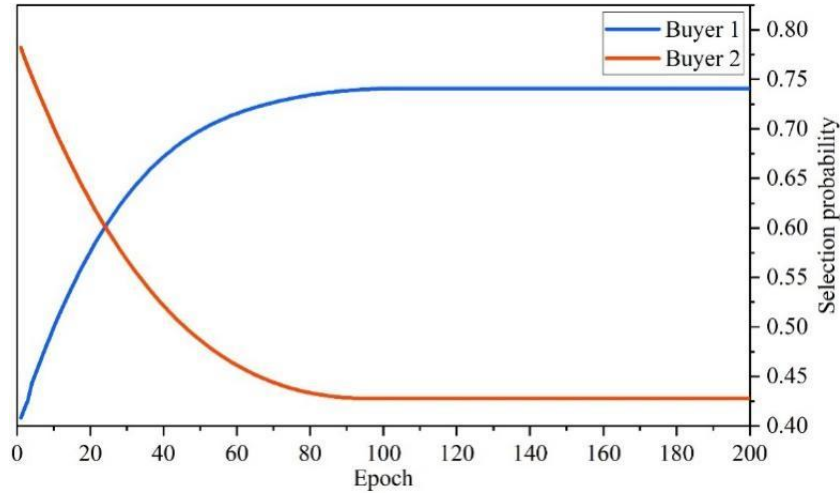


Figure 2: The probability convergent process of the buyer's purchase of electricity

Figure 3 illustrates the convergence of the seller electricity price. As the number of iterations grows, the price of the seller converges to a constant value indicating that the competitive equilibrium of prices between the seller and buyer with non-cooperative game has been achieved. Equilibrium conditions of both the buyer and the seller are the equilibrium conditions of the Stackelberg game of the two players.

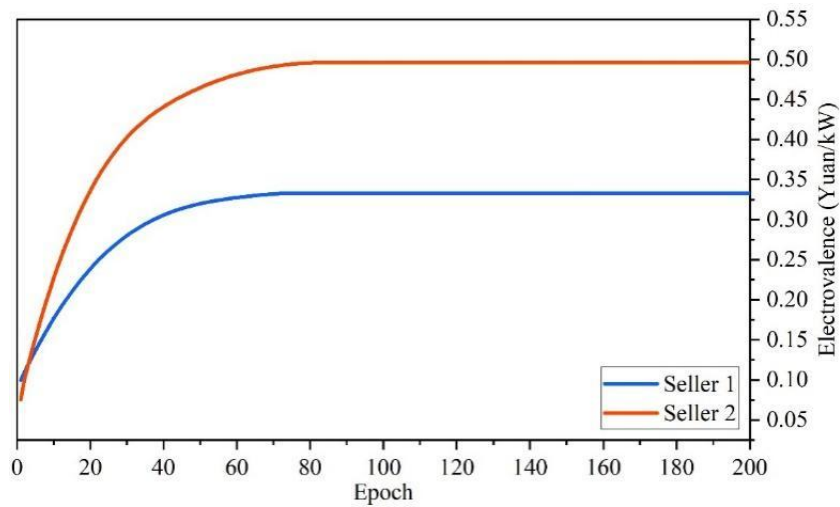


Figure 3: The convergence of the price of the seller's price

The convergence characteristics of the buyer's electricity demand are shown in Figure 4, which shows that after about 100 iterations, the buyer's electricity demand reaches the convergence value, at which time the buyer reaches the equilibrium of the evolutionary game. Through the seller's electricity price and the buyer's electricity demand can be seen, when the seller increases the price of electricity, the buyer's electricity demand is a downward trend, will be consistent with their own actual power consumption behavior.

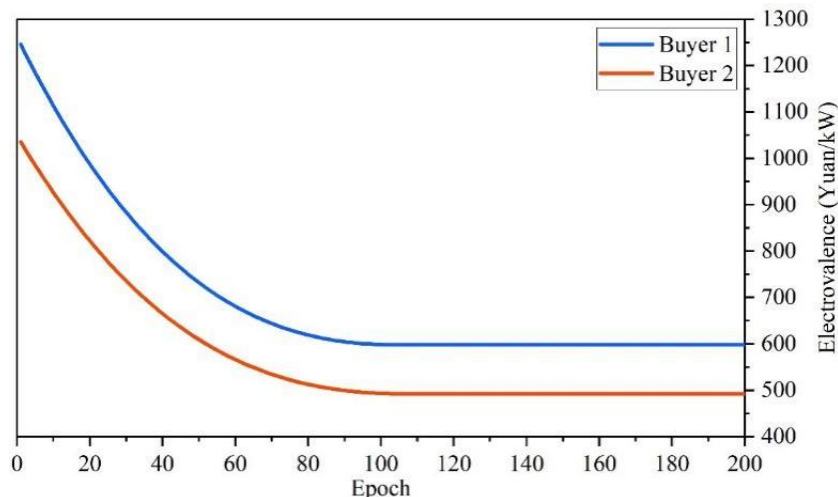


Figure 4: The convergence of the buyer's power demand

Figure 5 shows the convergence process of the seller's benefits, comparing the benefits under the presence and absence of a game between sellers. When there is a game between the sellers, the seller's benefit gradually increases with the number of iterations until it reaches the maximum value. Compared with the no-game situation, the economic benefits are higher when there is a game between sellers. At this point in the game, the seller as a leader, can set the price of electricity according to their own benefits. That is, the price of electricity is no longer an external price, but can optimize the adjustment of the price of electricity according to its own benefits. Therefore, the existence of the game between the microgrid to improve their own economic efficiency plays a role in promoting.

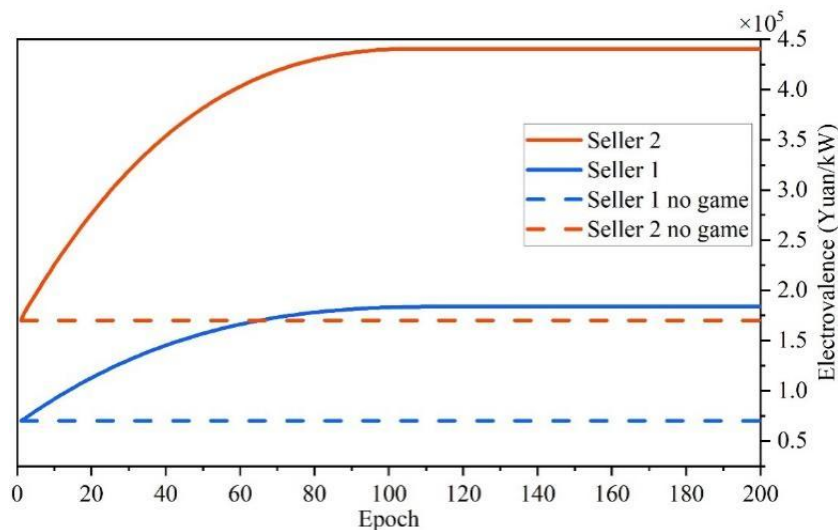


Figure 5: The process of convergence of seller benefits

### 3.2 Comparison of multi-algorithm scheduling optimization for microgrids

To assess the efficiency of the master-slave game model, this chapter proposes three comparative algorithms, namely genetic algorithm (GA), particle swarm optimization algorithm (PSO), and simulated annealing algorithm (SAA). With the use of these four algorithms, the optimum scheduling problem is addressed under the market fluctuations

scenario in the microgrid cluster. In Figure 6, the optimal operating cost of the microgrid can be seen in 30 iterations between 15:00. It may be concluded based on the data that of all the three comparative algorithms, the minimum operating cost is achieved with SAA and the lowest cost is 100.85 yuan. When the suggested model is used, the optimal operating cost drops to 93.84 yuan or over seven yuan less than the comparative models. Moreover, the 30 values of the operating costs are relatively concentrated implying increased stability.

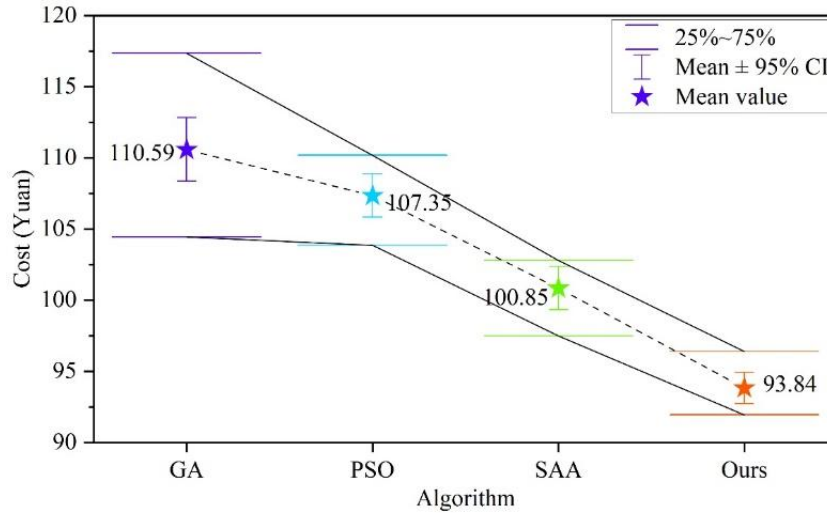


Figure 6: The optimal operating cost results for 30 times

In addition, the carbon reduction effects of several optimization strategies are further compared. Figure 7 shows the results of carbon emission during microgrid operation after scheduling optimization. The microgrid has basically no carbon emission in the time period from 1:00 to 6:00, and after 6:00 the power consumption of users starts to increase, resulting in a gradual increment of carbon pollutants. After applying the suggested strategy, the highest carbon emission of the microgrid occurs at the maximum value of 135.66 kg, resulting in decreases of 158.32 kg, 141.34 kg, and 134.98 kg compared to the values found using the GA, PSO, and SAA methods, respectively. Additionally, it can be noted that the suggested strategy allows for a considerable smoothing of the carbon emission curve, which leads to an improvement in peak-load periods.

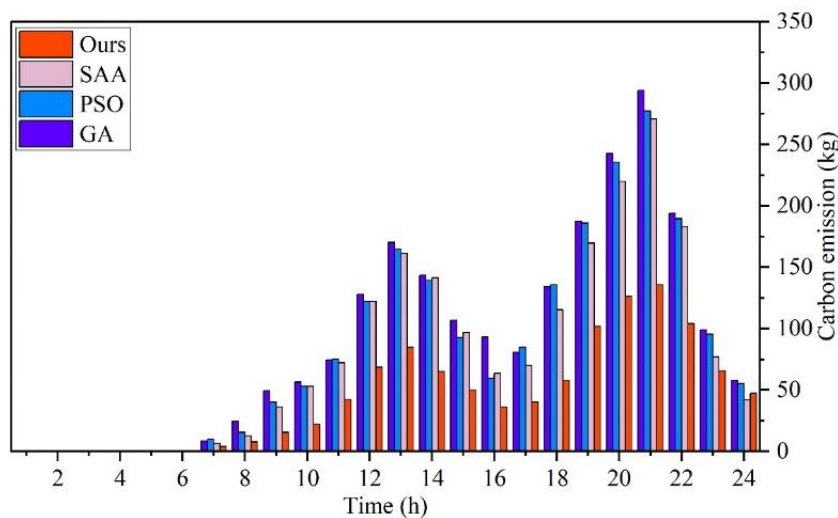


Figure 7: Carbon emission of microgrid operating time

This section adopts the IEEE 33-bus system to construct the network topology of a multi-microgrid network. Moreover, three microgrids are structured to form a multi-microgrid network with the distribution network operator. The purpose of this configuration is to study and evaluate the performance of the master-slave game optimization framework of the microgrid network suggested by us.

The comparison between the operations of the microgrid clusters using different operating methods is shown in Table 1. In comparison with the optimization approaches using GA, PSO, and SAA algorithms, the optimal model proposed in this study gives the lowest operational cost in all three clusters. In particular, the total cost comes to 3,564.35 yuan, a drop of 611.40 to 803.80 yuan compared with other approaches. Analysis also shows that the carbon quota trading contributes significantly to diversification of the forms of carbon trades. At the same time, carbon prices make price incentive stronger and give the opportunity to flexibly operate the microgrid systems. As there is plenty of clean energy during the day and consumers react positively to low-carbon demands, carbon price will be relatively lower and carbon cost lower for the microgrid. There are many chances for the microgrid to use clean energy cheaply and gain profits from such actions. During the peak load, the operator will raise the carbon trading price to ensure that there are opportunities for microgrids with sufficient clean energy to sell more carbon quotas and earn more money. Finally, considering carbon emissions of the microgrid clusters, compared with GA, PSO, and SAA, it can be seen that the carbon quota trading between the microgrid cluster and consumers helps to cut down carbon emissions, with around 300-446 kg.

Considering carbon quota trading in operation makes microgrid cluster operation more flexible, promotes clean energy consumption and reduces carbon emissions. Combined with the carbon emission objective function, it can make the carbon trading in the system more specific and detailed, so that the decision-making of the microgrid is more scientific and reasonable, and the clean energy consumption rate can be improved. This will significantly improve the environmental benefits of microgrid and system operation, and achieve effective and powerful carbon emission reduction.

*Table 1: The results of the microgrid cluster operation effect*

Method		GA	PSO	SAA	Ours
Cost(Yuan)	Microgrid 1	3030.68	2869.83	2908.25	2598.03
	Microgrid 2	883.45	845.21	824.85	651.08
	Microgrid 3	454.02	460.71	468.06	315.24
	Total	4368.15	4175.75	4201.16	3564.35
Total earnings(Yuan)		563.12	585.77	575.61	695.15
Total Carbon emission(kg)		1556.92	1513.45	1659.27	1212.98

### 3.3 Economic and environmental impacts of scheduling optimization

The existing section discusses the outcomes following the optimization of the scheduling procedure of every single microgrid at the point of equilibrium. This process of optimization is done every day during the 24-hour period which is split into one-hour segments. Figure 8 shows that it is feasible to see the price per unit that the distribution system operator buys and sells electricity at after optimization. Electricity selling prices are also quite high in the 08:00-12:00 and 14:00-20:00 intervals, and they are both 0.45 yuan/kW. In the hours between 01:00 and 03:00 and 22:00 and 24:00, the lowest selling price per unit is 0.20 yuan/kW. The demand of electricity at the microgrid level is quite high at 08:00-12:00 and 14:00-20:00 time frames, so the DSO increases the price of selling to make more profits.

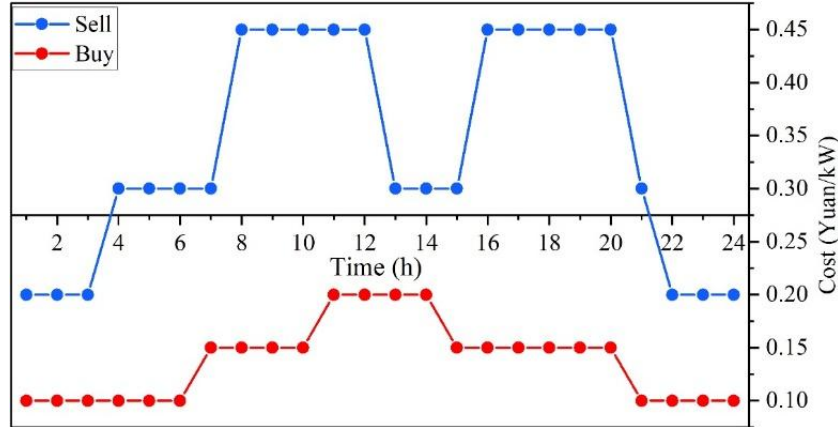


Figure 8: The distribution network operator buys/sells the electricity price

Fig. 9 shows the operation results after the optimization of microgrid scheduling, which generally includes the following main components within the microgrid: photovoltaic (PV), wind turbine (WT), micro gas turbine (MT), electrical energy storage equipment (EES), and electrical load (Load). The study counts MT output, PV, WT and ESS charging and discharging, as well as trading power with the distribution grid. The MT will generate more electricity when there is a higher cost of electricity in the real-time electricity market. The ESS charges when the electricity demand is low and discharges when the electricity demand is high. The microgrid performs electricity exchange with the distribution grid, where the electricity is sold when the demand is low and purchased when the demand is high. If there is a high price for the electricity to be sold in the distribution grid, then the microgrid will increase its generation capacity to minimize the cost of buying electricity from the grid or even sell excess electricity to the distribution grid. Therefore, the DMCGO strategy under the coupled electricity-carbon market framework can minimize the microgrid operation cost and maximize economic benefits..

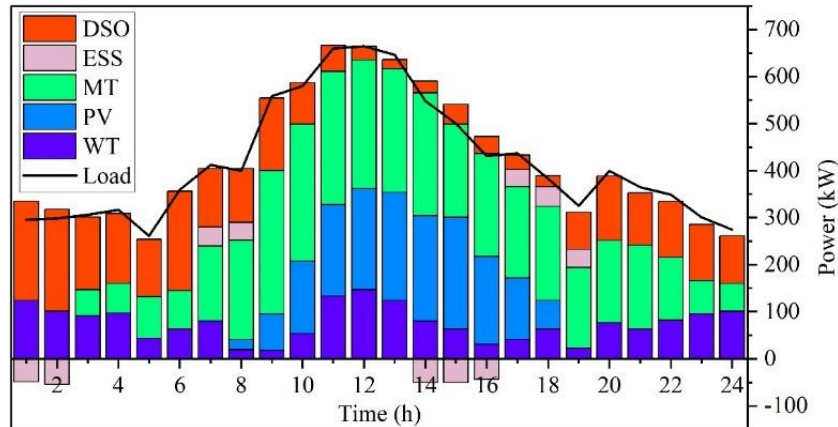


Figure 9: The results of the optimization of microgrid scheduling optimization

In order to confirm the validity of the model presented in this paper, this sub-section has used the model on three different cases of microgrid operation and evaluated its economic advantages as well as its effects on the reduction of carbon emissions. Simulation outputs of the three considered scenarios are presented in Table 2.

In all three scenarios, after the implementation of optimization scheduling, the profits gained by operating in the microgrid are 17,296, 17,435, and 17,721, respectively. These are substantial economic benefits in comparison with benchmarks prior to optimization. Wind energy utilization grows to 87.62% (Scenario 1), 88.45% (Scenario 2) and 89.93% (Scenario

3). Also, carbon emissions decrease by 112.78 kg, 153.96 kg, and 188.64 kg, indicating that the carbon emission profile of the microgrid is improving. Besides, the gap between peak and valley loads is 1,628.84 kW, 1,574.39 kW, and 1,440.36 kW, respectively, which eases the burden on generation resources. Also, power purchases of the grid are 1,393.41 kW, 1,214.74 kW, and 1,108.79 kW, respectively, which reduces the reliance of carbon intensive grid power.

Table 2: Simulation results of three scenarios

Scenario	1	2	3
Microgrid profits(Yuan)	17296	17435	17721
Wind utilization(%)	87.62	88.45	89.93
Peak valley difference(kW)	1628.84	1574.39	1440.36
Purchase electricity quantity(kW)	1393.41	1214.74	1108.79
Carbon reduction (kg)	112.78	153.96	188.64

The Figure 10 compares the loads in Scenario 1, Scenario 2, and Scenario 3. The load peak-to-valley gap starts reducing considerably once the demand response strategy is implemented during operation, and the results of the peak shaving and valley filling become more visible. Specifically, the differences between load peaks and valleys are observed to be 1.88MW in the case of Scenario 3, 2.00MW in the case of Scenario 2, and 2.244MW in the case of Scenario 1. This shift alleviates the strain on the output capability of units and guarantees the safety of the microgrid. Moreover, users could reduce the amount of money they spend on their electricity bill by lowering their power use during times when the cost of electricity is high and raising their consumption during times when the price of electricity is low.

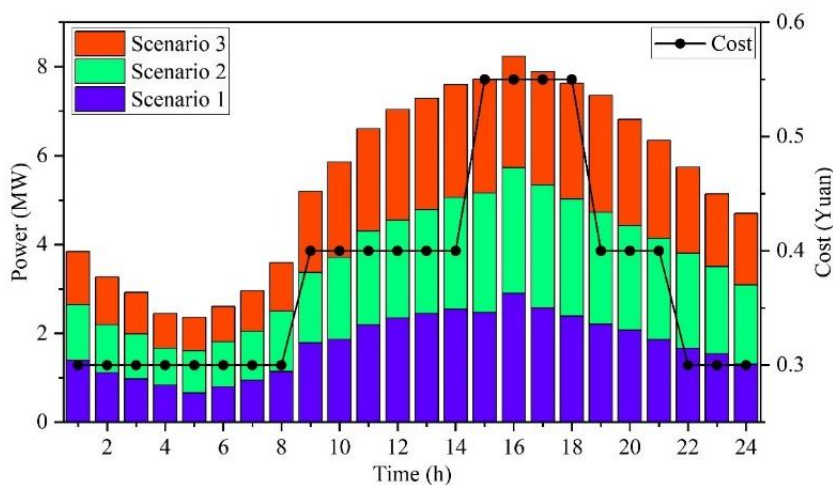


Figure 10: The load comparison results of the three scenarios

## 4 Conclusion

The paper proposes a distributed master slave game optimization algorithm as a solution to the scheduling problem of microgrid clusters due to variations in market conditions. This model comprises the variables associated with wind power production, gas turbines, energy storage systems, and the periodical electricity requirement of consumers. In this case, a multi-objective optimization problem is introduced, which considers maximizing the profits of the microgrid cluster, minimizing the operational expenses, and reducing the carbon footprint. Concerning this point, the effectiveness of the suggested model is validated through different experiments

undertaken. Throughout the solution process, the buying rate of the consumers, the selling price policy of the buyers, and the demands of the consumers, as well as the economic benefits accrued to the seller, converge to the equilibrium in the game. It must be mentioned that the distributed master-slave game model offered has good convergence properties. When compared with other models that are employed to optimize, the proposed model yields the minimum possible amount of microgrid operation costs, i.e., 93.84 yuan, and also achieves carbon emission savings ranging between 134.98 -158.32 kg. The economic gains resulting in the microgrid cluster have been proven to be higher than those of other competing models. In three cases of microgrid operation, the proposed model improves the economic efficiency, reduces the carbon emissions, and reduces the difference between the peak and valley load and the import of electricity.

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