Systems Science & Control Engineering
An Open Access Journal

ISSN: (Print) 2164-2583 (Online) Journal homepage: https://www.tandfonline.com/loi/tssc20

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To cite this article: Rongbo Liang, Yongjin Yu & Feiran Yang (2018) Smart grid scheduling and control based on master–slave game, Systems Science & Control Engineering, 6:3, 162-168, DOI: 10.1080/21642583.2018.1539929

To link to this article: https://doi.org/10.1080/21642583.2018.1539929

Published online: 08 Nov 2018.

SYSTEMS SCIENCE & CONTROL ENGINEERING: AN OPEN ACCESS JOURNAL
2018, VOL. 6, NO. 3, 162–168
https://doi.org/10.1080/21642583.2018.1539929

Smart grid scheduling and control based on master–slave game

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ABSTRACT
Electric power dispatch is an effective management method used to ensure the safe and stable operation of the power grid, however, there will be some conflicts of interest between the power selling company and the power generation company during the dispatch process. This article aims to minimize the cost of electricity purchased by the power grid company and maximize the sales revenue of power generating company. In this paper, the decision-making space is based on the set of strategies for each power plant output and the on-grid price, proposing a master–slave game scheduling model in which the power grid company is used as the main game and power plants are the game followers. By using the cuckoo algorithm to optimize the master–slave game model, scheduling test results show that master–slave game scheduling provides better overall performance than economic dispatch.

ARTICLE HISTORY
Received 4 May 2018
Accepted 21 October 2018

KEYWORDS
Electric power dispatch; cost; power grid; interest; cuckoo algorithm; master–slave game

1. Introduction

In recent years, with the rapid development of China's electric power industry and the support of the country's policy for new energy power generation, the clean energy power plants have been developing rapidly in China. Hence, the scheduling of electric power among various power plants has already become an important research topic. Some researcher think that grid connection and unified planning of different power generation systems are effective measures to solve the current problems in power dispatching process (Chazarra, Perez-Diaz, & Garcia-Gonzalez, 2017; Wu, Tan, & Shan, 2010). However, this plan is difficult to be achieved, because the interest objectives pursued by the power grid company and the power plants are different, so how to realize the optimal scheduling of electric energy in various regions under current market environment has become a key issue worthy of studying.

At present, many scholars have studied the problem of electric energy dispatching and joint optimization in the world. Xu, Chen, and Jin (2013) came up with a theory that combining storage power plants with wind power plants, this method can reduce the uncertainty of wind power and the impact on grid system safety. Wang, Luo, & Wu (2013) have proposed the active power dispatch based on self-adaptive wind power scenario selection, the stability of the electricity system can be enhanced by selecting the common scenes to represent uncertainty of wind power output, but it does not consider other factor in real process. Meanwhile, a number of studies adopting the technique for power dispatch have been reported in the literature (Hong & Lian, 2012; Li & Zhu, 2013; Li, Shen, Tang, & Wang, 2011), their common idea is to use multi-power system complementary power generation improving the reliability of power generation systems. However, it can't meet large-scale power generation requirements. Xu, Wang, & Yang (2014) have suggested that using opportunity constraints method to formulate a wind and storage joint dispatching plan, in addition, they try using time-sharing on-grid tariffs to guide the formulation of scheduling strategies, Unfortunately, there are still deficiencies in the optimization of the environment and economic benefits.

Game theory, as a branch of the mathematics field, is still in its infancy in power dispatching applications. This method have been proposed by Ran, Lei, & Zhe (2015) and Yang, Fu, and Wang (2007), in order to improve environmental and economic benefits, they make use of master–slave game model to solve it.

This paper comprehensively analyses the operating characteristics of three kinds of power plants including thermal, wind and photovoltaic, and establishes a joint scheduling optimization model, which can enhance some stability and reliability of the system. Meanwhile, by optimizing the output distribution strategies and on-grid tariffs among various power plants, the problems of income inequality in the scheduling process of different power plants can be eliminated, besides, this method

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is conducive to improving economic and environmental benefits. Therefore, the main contribution of this paper is that remedying the deficiency of the above literature.

The paper is organized as follows. Game relationship between the grid and power plant is discussed in the Section 2. Master–slave game model is presented in the Section 3. Section 4 introduces algorithm for solving the model. Section 5 presents the detailed results of applying these techniques. Finally, conclusions drawn from the study are given in Section 6.

2. Game relationship analysis

The game model is mainly composed of two part that are the upper and lower participants (Shengwei & Wei, 2014). In particular, the upper participants and lower participants are called the leader and follower respectively. Upper and lower internal participants can make their own decisions at the same time so as to form a Nash game, however, A Stackelberg game will be formed between the upper participants and the lower participants. In this game, leaders will not interfere with the decisions of their followers, on the contrary, the lower participants must use the upper-level decision results as constraints or parameters. In this paper, the power grid company is the leader in master–slave game model, the thermal power plant, wind power plant and photovoltaic power plant are the follower. The game relationship is shown in Figure 1.

It is known to us that game theory is mainly used to solve the interest problems that exist among multiple decision-making bodies, in game, each decision-making body can make a lots of decisions that are beneficial to itself through cooperative or non-cooperative ways. A master–slave game model consists of four parts: game participants, game strategy, game revenue and game equilibrium strategy.

- Game participants. The power grid company is the leader of master–slave game which can be represented by D. Besides, thermal power plant, wind power plant, and photovoltaic power plant are the follower of the game which can be represented by F, W, and P.
- Game strategy. Thermal power plant, wind power plant, and photovoltaic power plant will use their own power generation output as a game strategy that can be expressed as $(p_{m,t}, p_{w,t}, p_{v,t})$. However, the grid company uses the on-grid power price of power plants as the game strategy and they can be expressed as $(\lambda_{m,t}, \lambda_{w,t}, \lambda_{v,t})$.
- Game revenue.(F_1, F_2, F_3) are used to represent the revenue of thermal power plant, wind power plant, and photovoltaic power plant, while the revenue of the grid company is expressed as F_0. The specific revenue of the master–slave model are shown in Section3.
- Game equilibrium strategy. There is a Stackelberg –Nash equilibrium solution for this scheduling model which is $(p^*_{m,t}, p^*_{w.t}, p^*_{v,t}, (\lambda^*_{m,t}\lambda^*_{w,t}, \lambda^*_{v,t}))$, if this solution is adopted, the maximum revenue of each power plant will be obtained, meanwhile, the power purchase cost of the power grid can reach the minimum. At this point the following conditions should be met:

$$p^*_{m,t} = \arg\max_{p_{m,t}} F_1(\lambda^*_{m,t}, p_{m,t}, p_{w,t}, p_{v,t}), \quad (1)$$

$$p^*_{w,t} = \arg\max_{p_{w,t}} F_2(\lambda^*_{w,t}, p_{m,t}, p_{w,t}, p_{v,t}), \quad (2)$$

$$p^*_{v,t} = \arg\max_{p_{v,t}} F_3(\lambda^*_{v,t}, p_{m,t}, p_{w,t}, p_{v,t}), \quad (3)$$

$$(\lambda^*_{m,t}, \lambda^*_{w,t}, \lambda^*_{v,t}) = \arg\min_{(\lambda_{m,t},\lambda_{w,t},\lambda_{v,t})} F_0(\lambda_{m,t}, \lambda_{w,t}, \lambda_{v,t}, p^*_{m,t}.p^*_{w,t}, p^*_{v,t}). \quad (4)$$

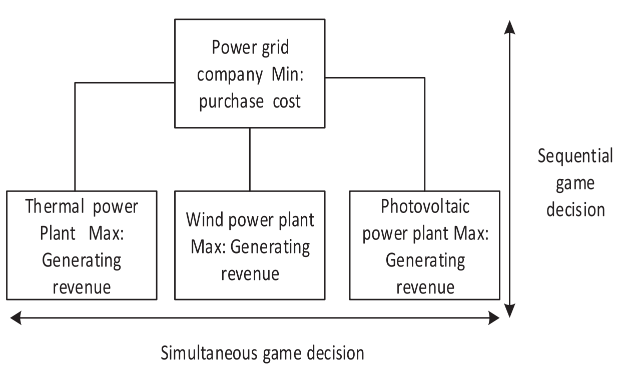

Figure 1. The structure of game relationship.

3. The establishment of master–slave game model

3.1. The revenue model of thermal power generation

In normal conditions, for the traditional thermal power plant, its business expense is composed of the revenue from electricity sales and cost of power generation. Therefore, its profit F_1 can be expressed as

$$F_1 = \sum_{t=1}^{T}\sum_{i=1}^{N_m}(\lambda_{m,t}p_{m,i,t} - f(p_{m,i,t})), \quad (5)$$

$$f(p_{m,i,t}) = a_i p^2_{m,i,t}/2 + b_i p_{m,i,t} + c_i, \quad (6)$$

where T is the length of the scheduling time and N_m is the number of generating units, while $\lambda_{m,t}$ is the thermal power feed-in tariff, the meaning of $p_{m,i,t}$ is active power, however, a_i, b_i, c_i are the coefficient of power generation cost for thermal power units.

3.2. The revenue model of wind power generation

The business expense of wind power plant is similar to thermal power plant, which consist of selling revenue, scrapping revenue, along with operating and maintaining cost. So the profit F_2 can be expressed as

$$F_2 = \sum_{t=1}^{T} \sum_{i=1}^{N_w} (\lambda_{w,t} p_{w,i,t} + b_{w,i,t} - u_{w,i,t}), \tag{7}$$

where N_w represents the number of wind units, $\lambda_{w,t}$ is the feed-in tariff of wind power and $p_{w,i,t}$ represents active power of units, furthermore, $b_{w,i,t}$ is the scrapping revenue at time t, $u_{w,i,t}$ is the sum of operating and maintaining expenses.

3.3. The revenue model of PV power generation

Photovoltaic power is only suitable for small-scale power generation due to the limit of light. The main business expense of photovoltaic power generation includes three parts: revenue from electricity sales, operating expenses, hence, the profit of photovoltaic power generation F_3 can be expressed as

$$F_3 = \sum_{t=1}^{T} \sum_{i=1}^{S_v} (\lambda_{v,t} p_{v,i,t} - c_{v,i,t}), \tag{8}$$

where the parameter S_v is the area of photovoltaic panel, $\lambda_{v,t}$ is the feed-in tariff, in particular, $p_{v,i,t}$ and $c_{v,i,t}$ are the feed-in tariff and operating cost of generation.

3.4. Unit's overall constraints

(1) System power balance constraint

$$\sum_{i=1}^{N_m} p_{m,i,t} + \sum_{i=1}^{N_w} p_{w,i,t} + \sum_{i=1}^{S_v} p_{v,i,t} = p_{d,t} + p_{l,t}. \tag{9}$$

(2) Rotate standby constraint

$$\begin{aligned} &\sum_{i=1}^{N_m} (p_{m,i}^{\max} - p_{m,i,t}) + \sum_{i=1}^{N_w} (p_{w,i}^{\max} - p_{w,i,t}) \\ &+ \sum_{i=1}^{S_v} (p_{v,i}^{\max} - p_{v,i,t}) \geq \rho p_{d,t}, \end{aligned} \tag{10}$$

where $p_{d,t}$ is the actual load of the system and $p_{l,t}$ is the power loss, besides, the parameter of ρ is the rotational standby rate of power system.

3.5. The grid company operating cost model

During the power dispatching process, the operating costs of the power grid company are mainly composed of the purchasing expenses from the thermal power plant, wind power plant, and photovoltaic power plant. It can be expressed as

$$F_0 = \sum_{i=1}^{N_m} \lambda_{m,t} p_{m,i,t} + \sum_{i=1}^{N_w} \lambda_{w,t} p_{w,i,t} + \sum_{i=1}^{S_v} \lambda_{v,t} p_{v,i,t}, \tag{11}$$

where the feed-in tariff of electric energy is represented by $\lambda_{m,t}, \lambda_{w,t}, \lambda_{v,t}, p_{m,i,t}$, $p_{w,i,t}$ and $p_{v,i,t}$ are active power which belong to power plants.

4. Master–slave game model

4.1. Existence proof of equilibrium solution

In order to solve the mathematical models that have been established, the first thing we need to do is to prove the existence of Stackelberg–Nash equilibrium solution. Since the solution sets of this paper's scheduling model are non-empty compact convex sets in the European space, hence, it is merely necessary to prove that the strategy set corresponding to the respective revenue functions of thermal power plant, wind power plant, photovoltaic power plant and power grid are respectively continuous quasi-concave, the detailed proof can be seen in (Yang et al., 2017; Mei & Wei, 2014). In the process of model solving, on-grid price is known while optimizing the slave module, so we can simplify the master–slave model into a non-cooperative model. Such as taking $p_{m,t} = p_{w,t} = 0$ the relationship between revenue function and the output power of photovoltaic generator at a certain time can be obtained, just as shown in Figure 2.

Meanwhile, as for remaining power plants, the output power and revenue are the quasi-concave function when the feed-in tariff is known. On the contrary, the output

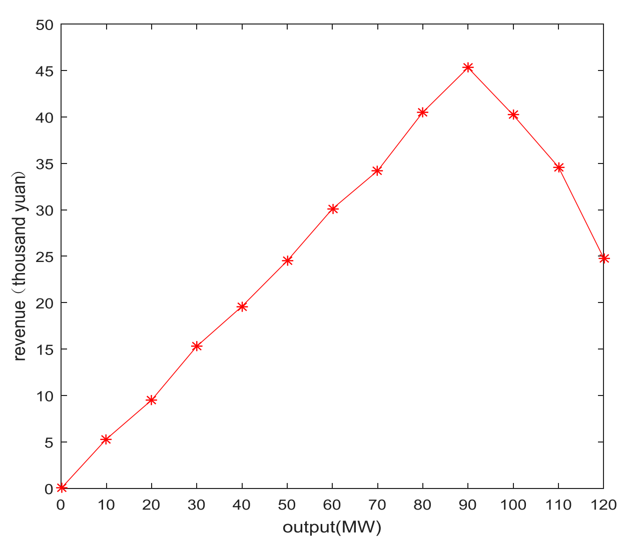

Figure 2. Photovoltaic power output and revenue.

strategies of each power plant are known to us while optimizing the main module, and similar to optimization of slave module, we can get that (F_1, F_2, F_3) are continuous quasi-concave functions of $(\lambda_{m,t}, \lambda_{w,t}, \lambda_{v,t})$, respectively. Therefore, according to above description, there exists a Stackelberg–Nash equilibrium solution for this scheduling model.

4.2. Game model solution process

In this section, the master–slave model is decomposed into two modules so as to improve the calculation speed in the solution process. When the main and slave module are optimized, the optimal result from the last round is used as the input, in this way, the optimal strategy of this round can be obtained, and we will get the optimal solution of the master–slave game in the end. The paper uses the cuckoo algorithm to find the optimal solution (Mei, Zhang, & Wang 2014). The specific process is as follows:

Step 1. Set-related data and operating parameters. It consists of power generation date, load parameters, and the parameters of revenue function.

Step 2. Establish the master–slave game model. These models have already been given in Section3.

Step 3. Set the initial value of the Stackelberg–Nash equilibrium solution. Selecting an initial value from the game strategy space $((\lambda_{m,t}, \lambda_{w,t}, \lambda_{v,t}), p_{m,t}, p_{w,t}, p_{v,t})$.

Step 4. Slave module optimization. In the optimization process, the slave module optimization is the inner layer of the main module optimization, however, the i round slave module optimization need to take the $i-1$ round feed-in price $(\lambda_{m,t,i-1}, \lambda_{w,t,i-1}, \lambda_{v,t,i-1})$ as input.

Step 5. Determine whether to find Nash-equilibrium solution. If it find the equilibrium solution, go to step 6, otherwise go back to step 4.

Step 6. Main module optimization. The i round main module optimization need to take the $i-1$ round solution $(p^*_{m,t,i-1}, p^*_{w,t,i-1}, p^*_{v,t,i-1})$ as input.

Step 7. Determine whether to find the Stackelberg–Nash equilibrium solution of the model. If it can find an equilibrium solution, go to step 8, otherwise go back to step 4.

Step 8. Output equalization solution.

5. Simulation of examples

The subsection presents one examples in the applications to the power dispatch system in order to illustrate the main techniques in the paper.

5.1. Example description

The example of this section is based on the simulation of the multi-power generation system of thermal power plant, wind power plant and photovoltaic power plant to verify the effectiveness of the model built in this paper, as shown in Figure 3. It contains three thermal power units, one wind power unit and one photovoltaic power unit, and their installed capacity are 60, 15, and 12 MW, respectively, moreover, the initial feed-in tariff of electric energy are 500 yuan/(MW H), 600 yuan/(MW·H) and 550 yuan/(MW·H). In Figure 3, G1, G2, G3 are thermal power units, G4 is wind power unit and G5 is photovoltaic unit, besides, the total scheduling time is one year and the scheduling interval is one month in example.

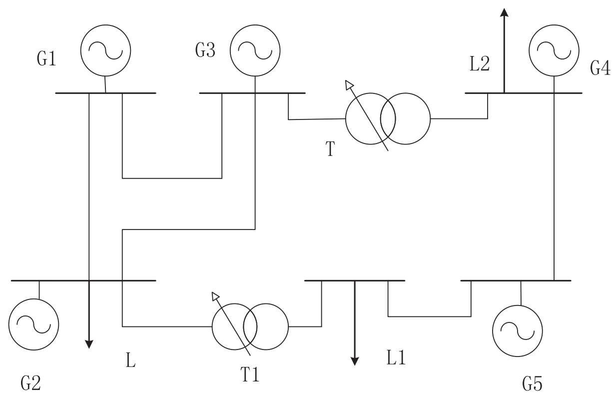

Figure 3. The composition of the dispatching system unit.

Table 1. Thermal power unit parameters.

Unit	G1	G2	G3
Maximum output (MW)	20	25	15
Minimum output (MW)	10	15	5
Minimum downtime (h)	−1	−1	−2
Minimum boot time (h)	2	1	2
Climb rate (MW/h)	8	9	6
Start costs (yuan)	6000	7000	5500

Table 1 is the parameters of the thermal power unit in the simulation, since the output range of the thermal power unit can reach 90%, therefore, the number of thermal power plants in China are more than that of other types of power plants.

The output of the generator set is usually determined by the generator's own characteristics, and the actual output is often related to the load demand. Therefore, these two conditions must be considered in the scheduling process.

In Table 2, p_{dt} is used to represent the demand load of the system, in general, its change is small. What's more, p_{wt} and p_{vt} are the output power offered by the wind power and photovoltaic power units, Δp_{dt} is the demand load minus output value of wind power and photovoltaic power generation.

Table 2. The forecast demand load and power plant output.

T(month)	Pdt(MW)	Pwt(MW)	Pvt(MW)	△Pdt(MW)
1	42,012	7800	3476	30,736
2	41,000	7756	3496	29,758
3	41,106	7723	3505	29,878
4	41,035	7698	3512	29,825
5	41,275	7702	3522	30,051
6	41,987	7718	3534	30,735
7	42,095	7696	3550	30,789
8	42,002	7701	3552	30,749
9	41,764	7713	3541	30,510
10	41,087	7736	3495	29,856
11	42,012	7741	3502	30,769
12	41,803	7768	3592	30,442

5.2. Analysis of examples

The content of this section is that contrasting with the joint economic dispatch (Shuqiang, Yang, & Yan, 2014; Jiayan, 2014) to evaluate the superiority of the proposed scheduling method. In the process of solving the model, the program runs for 10 times and the results are shown in Table 3, the output power of the generator set in two different types of dispatch models can be obtained in Table 4. The results of economic dispatching are p_{wt1}, p_{vt1}, and p_{wt2}, p_{vt2} are the results of master–slave scheduling. It can be seen that the value of master–slave scheduling is higher than that of economic scheduling. This implies that using game scheduling method gives better performance compared to using the economic scheduling in improving the quality of environment.

In the optimization process, the accuracy of the data obtained is higher by the method of averaging, and it is conducive to highlighting the changes of the data and facilitating the analysis of the data.

Table 3. Scheduling optimization data result.

Index	Average	Standard deviation rate
Thermal power price (yuan/MW h)	503.25	0.23
Wind power price (yuan/MW h)	601.38	0.21
PV prices (yuan/MW h)	552.21	0.30
Thermal power (MW/month)	30,341.5	0.29
Wind power (MW/month)	7729.3	0.26
Photovoltaic power (MW/month)	3522.9	0.24

Table 4. The actual output data of power plant.

T(M)	Pwt1(MW)	Pwt2(MW)	Pvt1(MW)	Pvt2(MW)
1	7720	7781	3321	3362
2	7651	7695	3332	3374
3	7626	7673	3423	3458
4	7523	7569	3435	3462
5	7603	7671	3442	3479
6	7615	7686	3451	3487
7	7518	7565	3463	3495
8	7607	7655	3472	3501
9	7614	7668	3449	3470
10	7635	7672	3419	3449
11	7645	7686	3337	3381
12	7701	7746	3309	3335

Table 5. The scheduling revenue of this paper.

T(M)	T revenue(million)	W revenue(million)	P revenue(million)
1	10.767	3.496	1.343
2	10.722	3.451	1.365
3	10.588	3.397	1.379
4	10.532	3.256	1.383
5	10.592	3.261	1.416
6	10.731	3.188	1.429
7	10.778	3.196	1.443
8	10.695	3.234	1.426
9	10.628	3.269	1.402
10	10.595	3.322	1.379
11	10.591	3.426	1.352
12	10.768	3.498	1.344

Table 6. The revenue of economic dispatch.

T(M)	T revenue(million)	W revenue(million)	P revenue(million)
1	10.608	3.438	1.329
2	10.554	3.406	1.357
3	10.641	3.365	1.379
4	10.398	3.254	1.386
5	10.435	3.241	1.428
6	10.595	3.211	1.411
7	10.641	3.221	1.424
8	10.585	3.193	1.408
9	10.626	3.225	1.393
10	10.645	3.321	1.382
11	10.402	3.359	1.346
12	10.611	3.432	1.330

As mentioned in Section 3, the revenue of scheduling system is related to a number of factors which include electricity sales, operating costs, maintenance costs and so on. According to the final calculation and optimization result, we are able to obtain the revenue data of each power plant in two different situations of master–slave game scheduling and economic dispatch, as shown in Tables 5 and 6. In this table, *T* is the revenue of thermal power, *W* means wind power and *P* is photovoltaic power.

From the following table, it can be seen that the revenue is proportional to the output of the unit, if the output of power is larger, then the more gains can be obtained, on the contrary, there will be less revenue.

Through the comparison of data, we can find that the benefit of using the scheduling method of this paper is higher than that of the optimal scheduling method. In other words, the power generation cost of each power plant obtained by this method is lower than the cost of economic dispatch, and the power purchase cost of the power grid is reduced.

The effectiveness of the model and optimized solution algorithm are explained by using the simulation graph of the operating results to analyse the changes in the revenue of each power plant in different months, and the operating costs of the grid company. The specific analysis is as follows.

Fifty samples obtained under scheduling were used as the training data set and all 100 samples obtained were

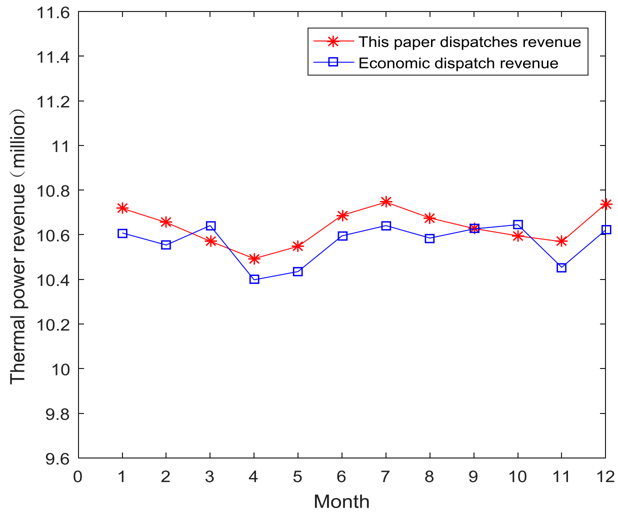

Figure 4. Thermal power revenue diagram.

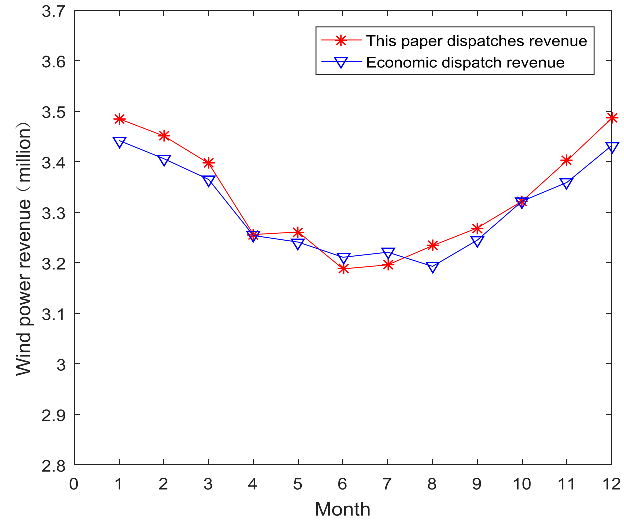

Figure 5. Wind power revenue diagram.

used as test data, in this way, by using the results of scheduling can form a thermal power simulation graph. It can be seen from Figure 4 that the results obtained by this article model are obviously higher than the economic dispatch, meanwhile, according to the revenue curve and data in Tables 5 and 6, It is not difficult to find that the revenue of master–slave model is about 1.5% higher than the revenue from economic dispatch in January, February, May, July, November and December, besides, the revenue in April, June, August is about 1% higher than the revenue from economic dispatch. However, there is no significant difference in September, and the revenue in March and October are about 0.5% lower than those in economic dispatch. In a word, the model and algorithm presented by this paper provide more revenue compared to using economic dispatch.

The revenue charts for wind power and photovoltaic power generation are shown in Figures 5 and 6, the result shows that the wind power generation revenue obtained in this paper is about 1.8% higher than that of economic dispatch in January, November and December, while it is slightly lower than economic dispatch in June and July, this implies that wind power revenue from the economic dispatch is lower than the revenue obtained in this paper; as for photovoltaic power unit, the revenue obtained in this paper is 1.3% higher than the economic dispatch in June, July and August, and is 0.2% lower than economic dispatch in April and October, the others month revenue are higher or approximately equal to the revenue from economic dispatch. Thus, the model and algorithm in this paper are equally applicable to wind power plants and photovoltaic power plants.

The cost data and charts for the grid company are shown in Table 7 and Figure 7. The EC represents the cost of economic dispatch, while TC represents the cost

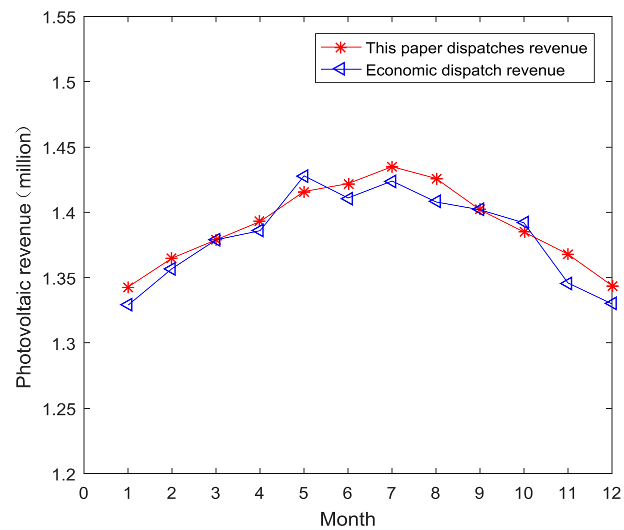

Figure 6. Photoelectric power revenue diagram.

Table 7. The cost of purchases electricity.

T(M)	EC(million)	TC(million)
1	20.890	20.731
2	20.747	20.481
3	20.568	20.502
4	20.691	20.408
5	20.543	20.548
6	20.748	20.543
7	20.765	20.557
8	20.724	20.438
9	20.526	20.525
10	20.609	20.405
11	20.684	20.459
12	20.759	20.757

of scheduling in this paper, it can be seen that the annual cost of economic dispatch is higher than the cost of this article. In addition, the results show that the cost of economic dispatch is about 1.4% higher than the cost we

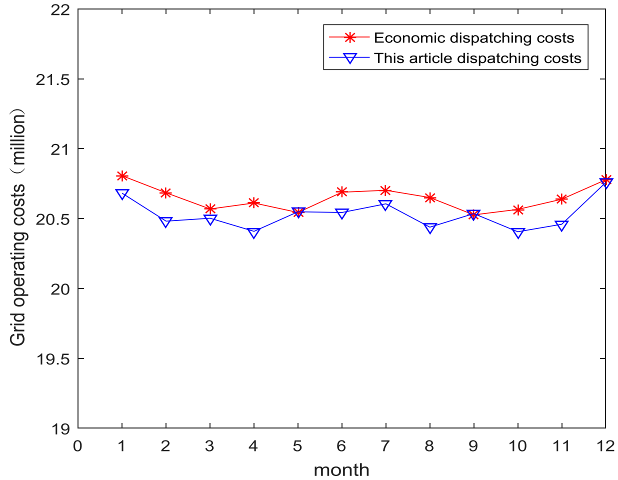

Figure 7. Grid operating cost diagram.

obtained in February, April and August, however, the purchases costs of the two case are not much different in March, May, September and December, besides, the cost are about 1% higher than the scheduling in this paper in June, July, October, January and November. This implies that by optimizing the feed-in tariff and the power generation strategy of each power plant, the annual cost of the grid company can be reduced, therefore, according to the description above, the practicality of the model and algorithm in this paper can be demonstrated, besides, We can conclude that the method proposed in this paper has a good effect in solving the dispatching application of power system.

6. Conclusion

This paper applies the master–slave game theory in math to the power system scheduling problem, which can reduce the conflicts of interest between the power plant and power selling company in the scheduling process and realize the maximization of their own interests. In this approach, the cuckoo algorithm is used to optimize the on-grid price and the power plant's output strategy, which improves the speed of data processing. Meanwhile, wind power and photovoltaic power generation are complementary, thus, the low-carbon operation of the dispatch system can be achieved.

The technique was applied to power dispatch and its performance was compared with economic dispatch, the overall results showed that the revenue of various power plants has increased, and the power purchase costs of the power selling company have reduced. In a word, this paper provides a practical and feasible solution to the conflicts of interest problem of the joint dispatch system.

Disclosure statement

No potential conflict of interest was reported by the authors.

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