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Optimal scheduling of power systems with wind and solar power generation considering carbon trading and energy storage cost

Kai Guo*, Rulei Han, Yuqiang Wang, Chen Gao and Kai Yin

(Inner Mongolia Power (Group) Co., Ltd., Inner Mongolia Power Research Institute Branch, Hohhot 010020, China)

*Corresponding author's e-mail: 869563864@qq.com

Abstract. In the context of the sustainable development of low-carbon power, in order to reduce carbon emissions in the power generation process of the power industry, carbon trading mechanism is introduced into the power system optimization scheduling, and electric energy storage is introduced to improve the power system flexibility to promote the consumption of new energy. This paper firstly analyzes carbon trading cost model of thermal power unit. Then, an optimal scheduling model aiming at the lowest total cost is constructed, which comprehensively considers the conventional thermal power unit operation cost, energy storage operation cost, carbon trading cost, wind-photovoltaic operation cost and various system constraints. Finally, through the analysis of simulation examples, it is verified that energy storage and carbon trading can effectively optimize the energy structure and reduce the system carbon emissions.

Keywords: carbon trading; energy storage; optimization scheduling

1 Introduction

With the acceleration of the global climate and environmental crisis, it has posed a threat to human health and safety. To promote the green transformation of all sectors of society and reduce fossil energy consumption, China put forward the goal of carbon peak and carbon neutrality[1]. In order to achieve the double carbon goal, this paper introduces electric energy storage and carbon trading mechanism to optimize the energy structure and promote green development of the power industry[2].

Literature [3] proposed the cooperative operation framework of two-level carbon trading mechanism, established the optimal operation scheduling model of micro-grid based on demand response, which reduces the total operation cost and system carbon emissions. Literature [4] considers both the green certificate trading mechanism and the carbon trading mechanism when establishing the environmental economic dispatching model of the power system, and a multi-objective dispatching model with minimum economic cost and minimum pollutant emission was established.

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To improve the system flexibility and promote new energy consumption capacity, a lot of research has been done on the application of energy storage system. Literature [5] established optimal scheduling model of micro-grid containing energy storage model, and verified the effectiveness of scheduling model. Literature [6] puts forward the optimal scheduling strategy of the electrothermal combined system, which takes into account carbon trading cost and energy storage cost, and deeply analyzes the mechanism of energy storage operation about absorption of wind power.

This paper considers the introduction of carbon trading mechanism into power system optimal scheduling, and the electric energy storage introduction to enhance the power system flexibility to promote the consumption of new energy. Then, a power system optimal scheduling model with solar generation including carbon trading and energy storage cost is established, which comprehensively considered the cost of carbon trading mechanism, energy storage operation cost, conventional thermal power unit operation cost, wind-photovoltaic operation cost. At last, through the simulation, it is verified that energy storage can effectively optimize the energy structure and reduce the carbon emissions of the system.

2 Carbon trading scheme cost model

2.1 Carbon emission quota

Since creation of carbon trading market is just beginning, the carbon emission quota of our electric power industry is mainly paid purchase and free distribution. The free carbon emission quota adopts the "base-line method", which is allocated in proportion to the each conventional unit power generation. When the carbon emission of each conventional unit is greater than the free carbon emission quota, it needs to buy the carbon emission quota. At the same time, surplus carbon emission allowances can be sold to obtain certain benefits.

Free carbon emission quota for thermal power units is:

$$E_{q1} = \lambda \sum_{t=1}^{T} \sum_{i=1}^{N_G} P_{Gi,t} \tag{1}$$

Where E_{q1} is the free quota for thermal power units; T is optimized periods. λ is the regional power grid baseline emission factor; $P_{Gi,t}$ is the output of thermal power unit i at time t.

Free carbon emission quota for wind farms is:

$$E_{q2} = \lambda \sum_{t=1}^{T} P_{w,t} \tag{2}$$

Where $P_{w,t}$ is the wind power output at time t; E_{q2} is the free carbon emission quota for wind farms.

Free carbon emission quota of photovoltaic power station is:

$$E_{q3} = \lambda \sum_{t=1}^{T} P_{v,t} \tag{3}$$

Where $P_{v,t}$ is the photovoltaic power output at time t; E_{q3} is the free carbon emission quota for photovoltaic power station.

2.2 Carbon emission cost

Since wind power and photovoltaic are clean energy and do not produce CO2, CO2 emissions are considered to come from thermal power units. The thermal power unit carbon emission is proportional to active power output, which can be represented as:

$$E_c = \sum_{t=1}^{T} \sum_{i=1}^{N_G} \eta_i P_{Gi,t} \tag{4}$$

Where η_i is the carbon emission coefficient of thermal power unit i.

According to the principle of carbon trading mechanism, system carbon trading cost is:

$$F_c = P_{co_2} \times \left(E_c - E_{q1} - E_{q2} - E_{q3} \right) \tag{5}$$

3 Energy storage cost model

The electric energy storage system can store electric energy through certain medium and release the stored energy to generate electricity when needed. The introduction of electric energy storage technology will effectively reduce the load peak valley difference, reduce the power supply cost, and effectively realize the demand side management. As a flexible control device, the electric energy storage device can utilize its own time migration ability to increase the grid-connected space of new energy. Meanwhile, the electric energy storage device has the advantages of real-time adjustment, and its operation cost is expressed as:

$$F_n = P_{ch} \sum_{t=1}^{T} P_{c,t} \tag{6}$$

Where F_n is the operating cost of system energy storage; P_{ch} is the operating cost coefficient of energy storage device.

4 Optimal scheduling model

4.1 Objective function

The cost of a conventional thermal power unit is usually expressed as a quadratic function of its generating power:

$$F_{\mathrm{G}} = \sum_{t=1}^{T} \sum_{i=1}^{N_{\mathrm{G}}} \left(a_i P_{\mathrm{G}i,t}^2 + b_i P_{\mathrm{G}i,t} + c_i \right) \quad (7)$$

Where a_i , b_i and c_i are the fuel cost factor of unit *i*.

The maintenance cost of wind-photovoltaic power generation equipment will be generated during operation. The output cost of wind-photovoltaic power is:

$$F_{\mathrm{w}} = \mu_{\mathrm{w}} \sum_{t=1}^{T} P_{\mathrm{w},t} \quad (8)$$

$$F_{\mathrm{k}} = \mu_{\mathrm{k}} \sum_{t=1}^{T} P_{\mathrm{k},t} \quad (9)$$

Where μ_{w} and μ_{k} are the wind power and photovoltaic power output cost factor.

In summary, the objective function of establishing the minimum operating cost of the system is:

$$\min F = F_{\mathrm{c}} + F_{\mathrm{n}} + F_{\mathrm{G}} + F_{\mathrm{w}} + F_{\mathrm{k}} \quad (10)$$

4.2 Constraint condition

4.2.1 Power balance constraint.

$$\sum_{i=1}^{N_{\mathrm{G}}} P_{\mathrm{G}i,t} + P_{\mathrm{w},t} + P_{\mathrm{k},t} + P_{\mathrm{c},t} = P_{\mathrm{D},t} \quad (11)$$

4.2.2 System rotation reserve capacity constraints.

To cope with the impact of the uncertainty of new energy output on the system, the system needs to reserve a certain reserve capacity.

$$\begin{cases} \sum_{i=1}^{N_G} P_{Gi,t\max} + P_{w,t} + P_{k,t} - P_{D,t} \geq u_f P_{D,t} \\ P_{D,t} - \sum_{i=1}^{N_G} P_{Gi,t\min} - P_{w,t} - P_{k,t} \geq d_f P_{D,t} \end{cases} \quad (12)$$

Where u_f and d_f are respectively the up and down rotation reserve rates with the increase of load prediction error.

4.2.3 Constraint of thermal power unit output.

$$P_{Gi,\min} \leq P_{Gi,t} \leq P_{Gi,\max} \quad (13)$$

$$-\Delta P_{di} \leq P_{Gi,t} - P_{Gi,t-1} \leq \Delta P_{ui} \quad (14)$$

Where $P_{Gi,\max}$ and $P_{Gi,\min}$ are respectively the upper and lower limits of the output of conventional thermal power units; ΔP_{ui} and ΔP_{di} are the maximum upslope and downslope output of unit i respectively.

4.2.4 Wind power and photovoltaic output constraints.

The output of wind-photovoltaic should be within the forecast range:

$$P_{wf,t} \geq P_{w,t} \quad (15)$$

$$P_{vf,t} \geq P_{v,t} \quad (16)$$

4.2.5 Operation power constraint of electric storage.

The energy storage constraints refer to the literature [6], and the specific requirements will not be described in detail.

5 Analysis of examples

5.1 Example parameter

The optimization model is simulated by calling CPLEX on the Matlab software platform. In this paper, six thermal power units are used as simulation, and Table 1 shows the specific unit parameters. To verify positive effect of carbon trading mechanism on scheduling operation of the power system containing solar power generation and the advantages of introducing energy storage device to the system's scheduling, four scheduling modes are simulated and compared:

Scenario 1: The system does not contain carbon capture equipment and demand side low-carbon resources;

Scenario 2: The system only contains demand side low-carbon resources;

Scenario 3: The system only contains carbon capture equipment;

Scenario 4: The system contains carbon capture equipment and demand side low-carbon resources.

Table 1. Parameters of thermal power unit

unit	Pmax/MW	Pmin/MW	a/(\$/(MW^{2}h))	b/(\$/(MWh))	c/(\$/h)	ΔP_d	ΔP_u	λ
1	455	150	0.0048	16.19	1000	130	130	0.98
2	455	150	0.0031	17.26	970	130	130	0.95
3	130	20	0.0025	16.6	700	60	60	0.93
4	130	20	0.00211	16.5	680	60	60	1.13
5	162	25	0.00398	19.7	450	90	90	1.15
6	80	20	0.00712	22.36	370	40	40	0.86

5.2 Optimization Result Analysis

Table 1 shows the comparison results of carbon trading cost, system operation cost, energy storage operation cost and carbon emission under this four scheduling Scenarios. Table 2 shows that scenario 2 has the lowest operating cost because scenario 2 introduces energy storage on the basis of scenario 1. It promotes the consumption of wind power at night, reduces the output of thermal power units during peak load, reduces the power generation cost of the units and carbon emissions .

Table 2. Cost and carbon emissions under the four scenarios

Scenario	system cost (\$)	Carbon trading cost (\$)	Energy storage operating cost(\$)	emission(ton)
1	463209.1	0	0	18957.2
2	458908.7	0	2437.2	18781.4
3	527908.7	89201.5	0	18362.5
4	518891.6	86108.4	2974.3	18207.6

Scenario 3 further considers carbon trading on the basis of scenario 1. The excess carbon emission quota of thermal power units needs to be purchased, but wind power and photovoltaic, as clean energy, can benefit from the carbon trading market, which can further promote the consumption of clean energy and reduce the carbon emissions of the system. Tab.2 shows that the carbon trading mechanism has a good effect on reducing system carbon emissions and promoting new energy output. Meanwhile, considering carbon trading scenario 4 compared with scenario 3, its economic cost will increase, but carbon emissions will be further reduced. Therefore, the establishment of an orderly carbon trading market and energy storage operation mechanism are very important in emission reduction of power system and promotion of new energy consumption.

5.3 Effect of carbon trading price on scheduling results

To verify the effect of carbon trading price on the system carbon emissions, this paper takes scenario 4 as an example to change the system carbon trading price and obtain the system costs. Table 3 and fig.1 shows the system carbon emission decreases, but the total system cost increases with the increase of carbon trading price. When the carbon trading price rises to $18 /t, the carbon emissions of the system remain basically unchanged, and the system carbon emission reduction capacity reaches the upper limit.

Table 3. Scheduling results under different carbon trading prices

Scenario	carbon trading price ($/ton)	Carbon trading cost ($)	system cost ($)	emission(ton)
1	13	77108.4	508764.6	18412.4
2	15	86108.4	518891.3	18207.6
3	17	97006.2	527639.1	17913.1
4	18	102801.7	532540.6	17826.8
5	19	108508.8	538248.3	17824.7

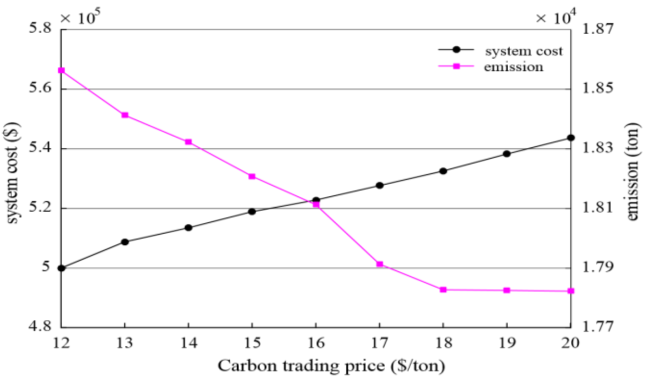

Fig. 1. The influence of carbon trading prices on scheduling results

5.4 The impact of energy storage cost on scheduling results

This paper considers the effects of different energy storage cost factors on system operating costs and carbon emissions. Three operation scenarios are set in this paper.

Table 4 shows the result analysis of different energy storage cost coefficients under the three operation scenarios.

Table 4. Scheduling results under different energy storage cost coefficients

Scenar-io	Operating cost coefficient($)	Energy stor-age operating cost($)	Carbon trad-ing cost ($/ton)	system cost ($)	emis-sion(ton)
1	4	2421.5	85719.3	506573.1	18159.4
2	5	2974.3	86108.4	518891.6	18207.6
3	6	3501.6	86373.1	526132.7	18243.9

Table 4 shows that both system carbon emissions and system operating costs increase with the increase of energy storage cost factors, so reducing energy storage operating cost coefficient is beneficial to the reduction of economic operating costs and system carbon emissions.

6 Conclusions

In this paper, the power system introduce carbon trading mechanism and electric energy storage in the meantime, and the optimal scheduling model of wind-solar power system is constructed, which considers the cost of carbon trading mechanism, the operating cost of energy storage, conventional thermal power units, wind power and photovoltaic power.

(1)This paper first proposed that the introduction of electric energy storage into optimal scheduling of power system, the energy storage can further promote the consumption of wind power at night, reduce conventional thermal power output units during peak load period, resulting in a relative reduction in the power generation cost of thermal power units, although the energy storage device will generate operating costs, but the total cost and carbon emissions of the system are reduced.

(2)This paper introduces the carbon trading mechanism into the power system in the meantime, and considers the carbon emissions of conventional thermal power units when ensuring a certain proportion of renewable energy output, reducing the environmental benefits of the system and promoting renewable energy consumption.

(3)This paper analyzes the effects of different carbon trading prices and different energy storage costs on system scheduling. The results show that the system carbon emission decreases, but the total system cost increases with the increase of carbon trading price. When the carbon trading price rises to a certain level, the system carbon emission basically remains unchanged. Meanwhile, the higher the energy storage cost factor, the system carbon emissions and system operating costs will further increase.

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