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Multi-Objective Economic Dispatch of Cogeneration Unit with Heat Storage Based on Fuzzy Chance Constraint

Xiuyun Wang ¹, Junyu Tian ¹, Rutian Wang ^{1,*} , Jiakai Xu ², Shaoxin Chen ¹, Jian Wang ³ and Yang Cui ¹

¹ Key Laboratory of Modern Power System Simulation and Control & Renewable Energy Technology, Ministry of Education, Northeast Electric Power University, Jilin 132012, China; wangxiuyun@neepu.edu.cn (X.W.); 2201600224@neepu.edu.cn (J.T.); 2201600093@neepu.edu.cn (S.C.); cuiyang@neepu.edu.cn (Y.C.)

² State Grid Weifang power supply company, Weifang, Shandong 252000, China; xujiakai@neepu.edu.cn

³ State Grid Sanmenxia power supply company, Sanmenxia, Henan 472000, China; 2201500033@neepu.edu.cn

* Correspondence: wangrutian@neepu.edu.cn; Tel.: +86-0432-6480-6691

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Abstract: With the increasing expansion of wind power, its impact on economic dispatch of power systems cannot be ignored. Adding a heat storage device to a traditional cogeneration unit can break the thermoelectric coupling constraint of the cogeneration unit and meet the economic and stable operation of a power system. In this paper, an economy-environment coordinated scheduling model with the lowest economic cost and the lowest pollutant emissions is constructed. Economic costs include the cost of conventional thermal power generating units, the operating cost of cogeneration units, and the operating cost of wind power. At the same time, green certificate costs are introduced into the economic costs to improve the absorption of wind power. Pollutant emissions include SO₂ and NO_x emissions from conventional thermal power units and cogeneration units. The randomness and uncertainty of wind power output are fully considered, and the prediction error of wind power is fuzzy treated according to the fuzzy random theory, and the electric power balance and spinning reserve fuzzy opportunity conditions are established, which are converted into the explicit equivalent. The improved multi-objective particle swarm optimization (MOPSO) was used to solve the model. With this method, the validity of the model is verified by taking a system with 10 machines as an example.

Keywords: cogeneration unit; wind power; green certificate; fuzzy stochastic theory; multi-objective scheduling model; multi-objective particle swarm optimization (MOPSO)

1. Introduction

In recent years, the energy crisis, the greenhouse effect and air pollution have become more and more serious. As a kind of abundant renewable resource, wind energy plays an important role in alleviating the crisis of traditional fossil energy and solving environmental damage [1,2]. The operation characteristics of thermoelectric coupling of cogeneration unit further limit the grid-connection consumption of other new energy sources such as wind power [3]. The installation of heat storage device on the cogeneration unit can effectively solve the problem of thermoelectric coupling [4,5].

The randomness and uncertainty of wind power leads to many access and scheduling problems [6–8]. More and more scholars consider the randomness of wind power into the economic dispatch of a power system. Álvaro Lorca and Andy Sun proposed an adaptive robust optimization model for multi-cycle economic scheduling, introduced the concept of dynamic uncertain sets and the method of constructing uncertain time and space correlation models. Simulation results showed

that this method is superior to the existing robust optimization model in cost and reliability [9]. In references [10–12], the uncertainty of wind power output is dealt with by using stochastic simulation technology. Xiong Hu et al. took the output and load of a large-scale intermittent power supply as fuzzy parameters, and studied the clear equivalence class of fuzzy opportunity constraints with multiple fuzzy parameters, which was used to deal with the opportunity constraints [13]. The above studies fully consider the randomness and uncertainty of wind power, and the established model meets the actual operation requirements of a power system.

Many scholars have carried out a lot of research on the joint scheduling of cogeneration units and wind power. Mueller S et al. studied and discussed the potential of cogeneration and heat pump electricity in Germany's future energy system to balance the fluctuations of renewable energy power generation [14]. Lu et al. established a low-carbon economic dispatch model for an integrated electric and thermal energy system. They proposed a model of minimum coordination between the rate of heat storage and the power of the electric boiler under the limit of wind power consumption, and compared the influence of different positions of the electric boiler on the heat loss of the heating network [15]. In references [16,17], the researchers established the combined system of the wind-electric boiler and heat-storage cogeneration unit, which can effectively reduce the peak valley difference of the wind abandoning quantity and electric load by increasing the load space. Through the above studies, it can be seen that the increase of thermal auxiliary equipment can effectively decouple the electric and thermal characteristics of the cogeneration unit, and through reasonable unit scheduling, the grid-connection consumption of new energy such as wind power can be achieved and operation costs can be reduced. Nguyen T.T. et al. proposed a cuckoo search algorithm (CSA) based on the breeding behavior of the cuckoo, which has the advantages of fewer control parameters, high solution quality and a fast calculation speed [18]. Chanda C K et al. proposed an optimization algorithm based on biogeography for the thermoelectric joint economic dispatch problem. The model is the optimal power and heat distribution within the operating range to meet the electrical load demand and to minimize the total cost [19]. In references [20–22], the researchers developed several optimal scheduling models to achieve economic coordinated operation based on the micro-grid system of the cogeneration units.

Most of the above studies only discussed the joint scheduling problem of cogeneration units and wind power from the perspective of a single objective, and did not consider the environmental pollution caused by long-term higher power levels of cogeneration units. Because economic benefit and environmental benefit are interrelated, a single goal cannot meet the actual operational demand of power systems. Therefore, in this paper, the cost of coal burning and wind power operation are comprehensively considered in the joint dispatching model of heat storage, heat generation and power generation combined with wind power, and the transaction cost of a green certificate is introduced into the economic cost. Meanwhile, the target function of pollutant emission is also taken into account in the scheduling model to further promote the low-carbon emission reduction of the system economic dispatch. In addition, aiming at the randomness and uncertainty of wind power output, this paper adopts the fuzzy random theory to deal with the prediction error of wind power, and establishes the spinning reserve fuzzy opportunity constraint condition to transform it into the clearing equivalent. The improved MOPSO was used to optimize the scheduling model, and finally the validity and rationality of the model were verified by an example.

The structure of this article is as follows: Section 2 introduces the operating characteristics of cogeneration units. Section 3 introduces the fuzzy opportunity constraint. Section 4 builds a multi-objective scheduling model that considers green certificates. Section 5 converts the fuzzy model into a clear equivalence class. Section 6 verifies the validity of the model in this paper through an example analysis. Finally, Section 7 summarizes the conclusions.

2. Operating Characteristics of a Cogeneration Unit

The cogeneration unit is divided into four types according to the different electric and thermal characteristics. This paper conducts relevant research based on the cogeneration units of exhaust

gas. A conventional cogeneration unit has thermoelectric coupling characteristics, which greatly limits the grid-connection consumption of new energy generation such as wind power. The addition of thermal energy storage devices by a traditional cogeneration unit can break the thermo-electric coupling characteristics of the unit and at the same time achieve the purpose of improving wind power and other new energy generation.

The electric and thermal characteristics of the conventional cogeneration unit are shown in Figure 1. In the figure, c_m is the elastic coefficient of electrical power and thermal power under back pressure. c_v is the reduction of electric power generated by more than one unit of heating heat when the intake volume remains constant. $P_{h,med}$ is the heating power of the steam turbine with the minimum generating power of the unit. $P_{hT,max}$ is the maximum heating power of the unit. $P_{e,min}$ and $P_{e,max}$ are the minimum and maximum active power output of the unit under the purification condition.

Figure 1. Electric and thermal characteristics of conventional cogeneration unit.

Adding heat storage device to the conventional cogeneration unit can decouple the electric and thermal characteristics of the unit. At this time, the electric and thermal characteristics are shown in Figure 2. For a certain power generation (such as P_B), set the maximum heating power of the turbine to $P_{hT,max}$, through the heat release of the heat storage device, its overall maximum heating power will increase by $P_{h,fmax}$ to $P_{hT,max} + P_{h,fmax}$, which is equivalent to AB and BC being shifted by the whole to the right by B. In addition, since the minimum heating power (CD) exists when the steam turbine power is between $P_{e,min}$ and P_C , the minimum heating power is shifted to the left $P_{h,fmax}$ after the heat storage device is disposed. After the heat storage device is configured, the overall operating range of the pumping unit changes from ABCD to AGIJKL. It can be seen that for a certain heating level P_h , after the heat storage device is configured, the power generation power adjustment range of the unit is changed from $[P_F, P_E]$ to $[P_M, P_H]$, which significantly improves the adjustability of the unit and reduces the thermoelectricity coupling characteristics.

Figure 2. Electric and thermal characteristics of conventional cogeneration unit with heat storage.

3. Fuzzy Chance Constrained Programming

3.1. Fuzzy Opportunity Constraints Based on Credibility Theory

Fuzzy decision and random decision are two common theories to solve the uncertainty phenomenon, which solves the mathematical problems with fuzzy variables and random variables respectively. The traditional fuzzy theory does not establish a complete axiomatization system, so that confusion often occurs in the application. For example, the membership degree is not self-dual, and the actual membership of 1 and 0 is not an inevitable event. Fuzzy stochastic theory is a fuzzy theory system that combines the theory of opportunity measurement and has a complete axiomatic basis. The optimization problem with constraints containing fuzzy parameters can be expressed as [23]:

$$\min f(x) \quad (1)$$

$$\text{s.t. } g(x, \xi) \leq 0 \quad (2)$$

where x is the decision vector, ξ is the fuzzy parameter vector, $f(x)$ is the objective function, $g(x, \xi)$ is the constraint function.

Due to the existence of ambiguity, the constraint cannot give a certain feasible set, the opportunity under the credibility measure is used to constrain the output, that is, the constraint condition is established with a certain confidence level α , and it is expressed as:

$$Cr\{g(x, \xi) \leq 0\} \geq \alpha \quad (3)$$

where α is the confidence level; $Cr\{\cdot\}$ is the probability of the event $\{\cdot\}$.

Event A can be expressed by a credibility measure Cr , which is equivalent to a probability measure in probability theory, with self-duality. The expression of the credibility measure Cr is:

$$Cr(\xi \in A) = \frac{1}{2} \left[\sup_{x \in A} \mu(x) + 1 - \sup_{x \in A^C} \mu(x) \right] \quad (4)$$

where $\mu(x)$ is the credibility measure of the event A ; $\sup\{\cdot\}$ is the upper limit function; A^C is the opposite event A .

3.2. The Credibility Distribution of Wind Power Prediction Error

There are three common forms of wind power fuzzy modeling: one is to directly model the wind power output based on historical data [24]; the other is to directly model the uncertainty of wind power through simulation technology [25]; the third is to transform the ambiguity of wind power into the ambiguity of prediction error, considering the predicted value as deterministic, and fuzzy model as the error [26]. This paper takes the third form. The forecast error of wind power is:

$$\lambda_w = \frac{P_{wr} - P_w}{P_{wr}} \times 100\% \quad (5)$$

where λ_w is the wind farm power prediction error; P_{wr} and P_w are the predicted power and actual power of the wind farm respectively.

The membership degree of the prediction error is expressed by the Cauchy distribution as:

$$\mu_w = \begin{cases} \frac{1}{1 + \sigma \left(\frac{\lambda_w}{E_{w+}} \right)^2}, & \varepsilon_w > 0 \\ \frac{1}{1 + \sigma \left(\frac{\lambda_w}{E_{w-}} \right)^2}, & \varepsilon_w \leq 0 \end{cases} \quad (6)$$

where σ is the weight; E_{w+} and E_{w-} are the statistical average of positive error and negative error of power respectively.

According to Equation (3), the credibility measure of the prediction error ξ is:

$$Cr(\xi \leq \lambda_w) = \begin{cases} 1 - \frac{1}{2 \left[1 + \sigma \left(\frac{\lambda_w}{E_{w+}} \right)^2 \right]}, & \varepsilon_w > 0 \\ \frac{1}{2 \left[1 + \sigma \left(\frac{\lambda_w}{E_{w+}} \right)^2 \right]}, & \varepsilon_w \leq 0 \end{cases} \quad (7)$$

4. Multi-Objective Optimization Scheduling Model Considering Green Certificates

4.1. Objective Function

The economic indicators of this paper take into account the cost of a conventional thermal power generating unit, the operating cost of a cogeneration unit, the operating cost of wind power and the cost of green certificates; the environmental indicators take into account the SO₂ and NO_x emissions of a conventional thermal power unit and a cogeneration unit. Based on the above indicators, a green low-carbon multi-objective economic dispatching model with combined heat and power cogeneration unit and wind power is constructed.

The objective function of system economic cost can be expressed as:

$$\min F = F_G + F_e + F_w + F_R \quad (8)$$

where F is the economic cost of the system within the scheduling period T ; F_G is the economic cost of thermal power unit operation during the scheduling period T ; F_e is the economic cost of cogeneration unit operation during the scheduling period T ; F_w is the economic cost of the wind turbine operation during the scheduling period T ; F_R is the green certificate costs of the system during the scheduling period T .

The objective function of pollutant emission can be expressed as:

$$\min E = E_G + E_H \quad (9)$$

where E_G and E_H are the SO₂ and NO_x emissions of conventional thermal power units and cogeneration units during the scheduling period T .

4.1.1. Green Certificate Cost

We define the electricity generated by the thermal power unit and cogeneration unit as non-green power, and the electricity generated by wind power unit as green power. The power system can redeem and receive a green certificate for every 1 MW·h of green energy produced. The power system can redeem and receive a green certificate for every 1 MW·h of green energy produced. The government allocates a certain amount of green energy production indicators according to the system's output. The system uses green energy to exchange green certificates, and to hand in the required green certificates before the deadline, otherwise it will face high fines.

The government allocates certain green energy production indicators according to the output of the power system. Then the green certificate index given by the government to the system during the unit period is:

$$R_q^t = \beta P_D^t / \delta \quad (10)$$

where R_q^t is the green certificate production index of the system required by the government within the unit period t ; β is the system's green power distribution quota; δ is the green electrical energy required for the conversion unit green certificate; P_D^t is the sum of all conventional thermal power units, wind power units and cogeneration units in the unit period t , and the calculation formula is as follows:

$$P_D^t = \sum_{i=1}^n P_{Gi}^t + \sum_{j=1}^m P_{ej}^t + P_w^t \quad (11)$$

where n is the number of conventional thermal power units; P_{Gi}^t is the power output of thermal power unit i in unit period t ; m is the number of cogeneration units; P_{ej}^t is the electric output of the cogeneration unit j in the unit period t ; P_w^t is the electric output of the wind farm in the unit period t .

Among the electric power systems with wind farms, only the electric energy produced by the wind farm is green electric energy. Then the amount of green certificate convertible by the system in the unit time t is:

$$R_p^t = P_w^t / \delta \quad (12)$$

where R_p^t refers to the green certificate amount of green power conversion produced by the system in period t .

The green certificate transaction process of the power system analyzed in this paper has three conditions: (1) the amount of green certificates exchanged by the system is greater than the amount of government indicators, and the surplus green certificates are sold for profit; (2) the amount of green certificates exchanged by the system is smaller than the government indicator, but larger than the difference between the government indicator and the amount of green certificates available for purchase, and the green certificate purchase cost shall be paid; (3) the amount of green certificates exchanged by the system is smaller than the amount of government indicators and the amount of green certificates available for purchase. In addition to the purchase cost of green certificates, a fine of the amount of deficiency shall be paid. The calculation formula is as follows:

$$F_R^t = \begin{cases} K_R(R_q^t - R_p^t), & R_q^t \geq R_p^t \\ K_R(R_p^t - R_q^t), & R_q^t - R_L^t \leq R_p^t \leq R_q^t \\ K_R R_L^t + K_H(R_q^t - R_L^t - R_p^t), & R_p^t \leq R_q^t - R_L^t \end{cases} \quad (13)$$

$$R_L^t = \varphi R_q^t \quad (14)$$

$$F_R = \sum_{t=1}^T F_R^t \quad (15)$$

where K_R is the transaction price of green certificate; K_H is the price of green certificate fines; R_L^t is the amount of the green certificate that can be purchased by the system within the unit period of t ; φ is the purchase margin of green certificate; F_R^t is the green certificate cost of the system within unit period t .

4.1.2. Conventional Thermal Power Unit Power Generation Cost

As a controllable power source, the conventional thermal power unit mainly includes the fuel cost and start-stop cost of the unit. The calculation formula is as follows:

$$F_G = f_1(P_{Gi}^t) + f_2(u_i^t) \quad (16)$$

where f_1 represents the fuel cost of a conventional thermal power unit; f_2 represents the start-stop cost of the conventional thermal power unit; u_i^t indicates the running state of the conventional thermal power unit i at period t , $u_i^t = 1$ means running, $u_i^t = 0$ means stop.

The fuel cost and start-stop cost of a conventional thermal power unit are calculated as follows:

$$f_1(P_{Gi}^t) = \sum_{t=1}^T \sum_{i=1}^n u_i^t [a_i (P_{Gi}^t)^2 + b_i P_{Gi}^t + c_i] \quad (17)$$

$$f_2(u_i^t) = \sum_{t=1}^T \sum_{i=1}^n [u_i^t (1 - u_i^{t-1}) s_i] \quad (18)$$

$$s_i = \psi_i + \eta_i \left(1 - e^{-T_{Gii}^{off} / \tau_i} \right) \quad (19)$$

where a_i , b_i , and c_i represent the fuel cost coefficients of the conventional thermal power unit i . s_i represents the starting cost of the conventional thermal power unit i . ψ_i , η_i and τ_i are the starting cost coefficients of the conventional thermal power unit.

4.1.3. Operating Cost of Cogeneration Unit

For a cogeneration unit, the operating cost should be based on thermal output and electrical output. The electric and thermal output are converted into electric power under pure condensation conditions, and the calculation formula is as follows:

$$F_e = \sum_{t=1}^T \sum_{j=1}^m \left[a_{jr} (P_{ej}^t + c_v P_{hj}^t)^2 + b_{jr} (P_{ej}^t + c_v P_{hj}^t) + c_{jr} \right] \quad (20)$$

where P_{hj}^t is the heat power of the cogeneration unit at time t ; a_{jr} , b_{jr} and c_{jr} are the fuel cost coefficients of the cogeneration unit.

4.1.4. Wind Power Operating Costs

Wind power relies on wind energy and does not generate coal consumption costs during operation. In this paper, the operating cost of wind power is approximated as the linear relationship of wind power. The calculation formula is as follows:

$$F_w = \sum_{t=1}^T k_w P_w^t \quad (21)$$

where k_w is the operating and maintenance cost coefficient of the wind farm.

4.1.5. Pollutant Emission

Conventional thermal power units and cogeneration units generate SO_2 , NO_x and other polluting gases during operation which will have a certain impact on the ecological balance (such as smog, acid

rain, ozone layer damage and the greenhouse effect). The calculation formulas for E_G and E_H of pollutant emissions from conventional thermal power unit and combined heat and power unit are as follows:

$$E_G = \frac{f_1}{R_m} (J_S + J_N) \quad (22)$$

$$E_H = \frac{F_e}{R_m} (J_S + J_N) \quad (23)$$

where R_m is the unit price of coal burning; J_S and J_N are the emissions of SO_2 and NO_x when one ton of coal is used for power generation.

4.2. Constraints

(1) Power balance constraints

Electric power balance constraints:

On the basis of ignoring the network transmission loss, the sum of the output electric power of each generator set is equal to the grid load. The expression is as follows:

$$Cr \left\{ \sum_{i=1}^n P_{Gi}^t + \sum_{j=1}^m P_{ej}^t \geq P_l^t + P_{wr}^t \right\} \geq \alpha \quad (24)$$

where P_l^t is the electrical load in period t ; P_{wr}^t is the predicted wind power value at period t .

Thermal power balance constraint:

Ignoring the heat loss during the transmission process, the sum of the direct heating power of the cogeneration unit and the heating power of the heat storage device is equal to the heat load value. The expression is as follows:

$$P_{hj}^t + S_h^t = P_{hl}^t \quad (25)$$

where S_h^t is the heating power of the heat storage device; P_{hl}^t is the heat load.

(2) Constraints of conventional thermal power units.

Unit output constraint:

$$P_{Gi,min} \leq P_{Gi}^t \leq P_{Gi,max} \quad (26)$$

where $P_{Gi,max}$ and $P_{Gi,min}$ respectively represent the maximum and minimum output of conventional thermal power unit i .

Gradient constraint:

$$\begin{cases} P_{Gi}^t - P_{Gi}^{t-1} \leq P_{u,i} \\ P_{Gi}^{t-1} - P_{Gi}^t \leq P_{d,i} \end{cases} \quad (27)$$

where $P_{u,i}$ and $P_{d,i}$ respectively represent the maximum upward and downward slope climbing rate of conventional thermal power unit i .

Units start and stop time constraint:

$$\begin{cases} T_{Git}^{on} \geq T_{Git,min}^{on} \\ T_{Git}^{off} \geq T_{Git,min}^{off} \end{cases} \quad (28)$$

where T_{Git}^{on} and T_{Git}^{off} are the continuous starting and stopping time of the thermal power unit i within the unit period t ; $T_{Git,min}^{on}$ and $T_{Git,min}^{off}$ are the minimum startup and shutdown times of the thermal power unit i .

(3) Constraints of the cogeneration unit.

Electrical output constraint:

$$P_{ej,min} \leq P_{ej}^t \leq P_{ej,max} \quad (29)$$

where $P_{ej,max}$ and $P_{ej,min}$ are the upper and lower limits of electrical output of the cogeneration unit j .

Thermal output constraint:

$$0 \leq P_{hj}^t \leq P_{hj,max} \quad (30)$$

where $P_{hj,max}$ is the upper limit of thermal output of the cogeneration unit.

Gradient constraint:

For the cogeneration unit, the slope climbing ratio constraint requires us to convert the electric power and thermal power into the electric power under the purified condition (the conversion method is as shown in Equation (19)). The specific constraint is as follows:

$$\begin{cases} P_{ej}^t - P_{ej}^{t-1} \leq P_{uj}^r \\ P_{ej}^{t-1} - P_{ej}^t \leq P_{dj}^r \end{cases} \quad (31)$$

where P_{uj}^r and P_{dj}^r are the maximum upward and downward climb rates of cogeneration units.

(4) Reserve constraint.

$$Cr \left[\sum_{i=1}^n u_i^t P_{Gi,max} + \sum_{j=1}^m P_{ej,max} \geq P_l^t + R_u^t + P_{wr}^t \xi \right] \geq \alpha \quad (32)$$

where R_u^t is the spare for the load of period t .

(5) Heat storage device constraint.

Heat storage capacity constraint:

$$H_{c,min} \leq H_c^t \leq H_{c,max} \quad (33)$$

where H_c^t is the heat storage capacity of the heat storage device at period t ; $H_{c,max}$ and $H_{c,min}$ are the upper and lower limits of heat capacity of the heat storage device.

Power constraint of heat storage and release of heat storage device:

$$\begin{cases} H_c^t - H_c^{t-1} \leq P_{hj,c,max} \\ H_c^{t-1} - H_c^t \leq P_{hj,f,max} \end{cases} \quad (34)$$

where $P_{hj,c,max}$ and $P_{hj,f,max}$ are the maximum heat storage and exothermic power of the heat storage device.

Constraint of heat storage and release at the same time:

$$S_{hj,c}^t \cdot S_{hj,f}^t = 0 \quad (35)$$

where $S_{hj,c}^t$ and $S_{hj,f}^t$ are the heat storage and exothermic power of the heat storage device at period t , and the product of zero indicates that heat storage and heat release cannot take place simultaneously.

Heat storage constraint at the beginning and end of heat storage device:

$$H_c^0 = H_c^T \quad (36)$$

where H_c^0 and H_c^T are the starting and ending values of heat storage in one scheduling period of the heat storage device.

5. Fuzzy Chance Constrained Decision Model

In this paper, we use fuzzy equivalence classes to process fuzzy models. According to the opportunity function $g(x, \xi)$ in Equation (3), when $g(x, \xi) = \xi - h(x)$, $Cr = [g(x, \xi) \leq 0] \geq \alpha$ is established, at this time $h(x) \geq K_\alpha$. Among them:

$$K_\alpha = \begin{cases} \inf\{K | K = \mu^{-1}(2\alpha)\}, & \alpha < \frac{1}{2} \\ \sup\{K | K = \mu^{-1}(2(1-\alpha))\}, & \alpha \geq \frac{1}{2} \end{cases} \quad (37)$$

For the problems described in Equations (24) and (32), the confidence level generally needs to be greater than 0.5. Therefore, the Equation (7) and the Equations (24) and (32) are equivalent to:

$$\begin{cases} \frac{\sum_{i=1}^n u_i^t P_{Gi,max} + \sum_{j=1}^m P_{ej,max} - (P_l^t + R_u^t)}{P_w^t} \geq K_{aw} = \sup\{K | K = \mu_w^{-1}(2(1-\alpha))\}, & \alpha < \frac{1}{2} \\ \frac{\sum_{i=1}^n P_{Gi}^t + \sum_{j=1}^m P_{ej}^t - P_l^t}{P_w^t} \geq K_{aw} = \sup\{K | K = \mu_w^{-1}(2(1-\alpha))\}, & \alpha \geq \frac{1}{2} \end{cases} \quad (38)$$

Combined with Equation (6), the following conclusions can be obtained:

$$\begin{cases} \sum_{i=1}^n u_i^t P_{Gi,max} + \sum_{j=1}^m P_{ej,max} \geq P_l^t + R_u^t + P_w^t K_{aw} \\ \sum_{i=1}^n P_{Gi}^t + \sum_{j=1}^m P_{ej}^t \geq P_l^t + P_w^t K_{aw} \\ K_{aw} = E_{w+} \left[\frac{2\alpha-1}{2\sigma(1-\alpha)} \right]^{\frac{1}{2}} \end{cases} \quad (39)$$

6. Case Analysis

6.1. Model Solving

Considering that the multi-objective coordinated scheduling model established in this paper is a multi-stage, nonlinear complex problem, the traditional optimization algorithm is difficult to solve. Therefore, on the basis of the original MOPSO, the weight of inertia and the learning factor are modified to improve the search speed and reduce the local to the most effective level. The update of the particle's velocity and position is as follows:

$$v_{i,j}^{t+1} = w v_{i,j}^t + c_1 r_1 (p_{i,j} - x_{i,j}^t) + c_2 r_2 (p_{g,j} - x_{i,j}^t) \quad (40)$$

$$x_{i,j}^{t+1} = x_{i,j}^t + v_{i,j}^{t+1} \quad (41)$$

where t is the iteration number of the algorithm, i and j are particle number and dimension. w is inertia weight, c_1 and c_2 are self-learning factors and social learning factors respectively. r_1 and r_2 are uniformly distributed random numbers within (0,1). $p_{i,j}$ is the historical optimal solution of the current particle, and $p_{g,j}$ is the global optimal solution for all particles.

The arctangent function $y = \arctan(x)$ is an increasing function, the function value increases with the increment of the independent variable, but the speed of the function value gradually decreases. When the independent variable value is 1.56, the function value increases to 1. The improved inverse tangent function can meet the requirement of the particle swarm optimization (PSO) for the change of inertial weight. The weight improvement strategy is Particle swarm optimization

$$w(t) = (w_{start} - w_{end}) \times \arctan \left(1.56 \times \left(1 - \left(\frac{t}{t_{max}} \right)^k \right) \right) + w_{end} \quad (42)$$

where t is the number of iterations; t_{max} is the maximum number of iterations; w_{start} is the initial inertia weight; w_{end} is the termination inertia weight.

The learning factor c_1 and social factor c_2 were accelerated by nonlinear inverse cosine, c_1 increased first and then decreased, while c_2 decreased first and then increased. The basic idea is that in the initial stage of searching, the particle mainly refers to its historical information c_1 , and in the later stage, it pays more attention to social information c_2 . Constructed as follows:

$$c_1 = c_{1e} + (c_{1s} - c_{1e}) \left[1 - \frac{\arccos(-2t/t_{max} + 1)}{\pi} \right] \quad (43)$$

$$c_2 = c_{2e} + (c_{2s} - c_{2e}) \left[1 - \frac{\arccos(-2t/t_{max} + 1)}{\pi} \right] \quad (44)$$

where c_{1s} and c_{2s} are the initial values of iteration; c_{1e} and c_{2e} are the final iteration values; t is the current number of iterations, and t_{max} is the maximum number of iterations. In this paper, $c_{1s} = 2.5$, $c_{2s} = 0.5$; $c_{1e} = 0.5$, $c_{2e} = 0.5$.

The initial value of the improved MOPSO is a random particle swarm, and the initial global optimal position is obtained by evaluating each particle. In the iteration process, the particle keeps updating its speed and position by tracking the individual extremum and global extremum. The fitness function is used to evaluate the particle quality, update the new and historical optimal position, and iterate over and over to get the optimal solution. The flowchart is shown in Figure 3.

Figure 3. Model solving flow chart.

6.2. Basic Data and Result Analysis

The system analyzed in this paper contains 10 generator sets, 8 of which are conventional thermal power units and 2 are cogeneration units of the same type. The data of conventional thermal power units and cogeneration units are shown in Tables 1 and 2. The predicted values of power load, thermal load and wind power in the dispatching cycle are shown in Figure 4. The reliability parameters of wind power prediction error are distributed as follows: $E_{w+} = E_{w-} = 20\%$, $\sigma = 2.333$, and the confidence level α is 0.85. The load reserve is set at 5% of the total load. The system's green power distribution quota β is 0.2, and the green certificate purchase margin φ is 0.4. The green electric energy required to redeem the unit green certificate δ is 1 MWh/copy. Wind power generation cost coefficient k_w is 39 \$/MW, and coal cost R_m is 80 \$/t. The transaction price is 3 \$/copy. The price of green certificate fine is 8 \$/copy. J_S and J_N of the units are 8.6 kg/t and 7.4 kg/t.

Figure 4. The predicted values of electricity load, thermal load and wind power.

Table 1. The parameters of conventional thermal power units.

Unit	$R_{u,i}$ (MW/h)	$R_{d,i}$ (MW/h)	a_i (\$·(MW ⁻² ·h ⁻¹))	b_i (\$/(MW·h))	c_i (\$/h)	$P_{Gi,max}$ MW	$P_{Gi,min}$ MW	ψ_i (\$/h)	η_i (\$/h)	τ_i (h)
1	130	130	0.00048	16.19	1000	455	150	5500	5500	5
2	90	90	0.00211	16.50	680	130	20	550	550	2
3	40	40	0.00398	19.70	450	162	25	700	700	2
4	40	40	0.00712	22.26	370	80	20	170	170	2
5	40	40	0.00079	27.74	480	85	25	200	200	2
6	40	40	0.00413	25.92	660	55	10	30	30	1
7	40	40	0.00222	27.27	665	55	10	30	30	1
8	40	40	0.00173	27.79	670	55	10	30	30	1

Table 2. The parameters of cogeneration units.

Unit	$P_{ej,max}$ MW	$P_{ej,min}$ MW	$P_{hj,max}$ MW	a_r (\$·(MW ⁻² ·h ⁻¹))	b_r (\$/(MW·h))	c_r (\$/h)	c_v	P_{uj}^r (MW/h)	P_{dj}^r (MW/h)
1,2	350	150	400	0.00576	16.336	969.44	0.15	90	90

In this example, three scheduling schemes are compared and analyzed:

- Scheme 1: Take the lowest cost of the system economy as the objective function;
- Scheme 2: Take the minimum pollutant emission of the system as the objective function;
- Scheme 3: Multi-objective scheduling in this paper.

6.2.1. Analysis of Scheduling Results

In the three scheduling schemes, the economic cost and pollutant emission results of the system are shown in Table 3. The consumption power of wind power is shown in Figure 3. Green certificate costs of Scheme 3 in each period are shown in Figure 4.

Table 3. Results of three scheduling schemes.

Scheme	The Economic cost, F (k\$)	Pollutant Emission, E (t)
1	567.83	96.34
2	594.2	71.05
3	581.75	82.32

It can be seen from Table 3 that in the scheduling Scheme 1 with only the lowest system economic cost as the scheduling target, the conventional thermal power unit and the cogeneration unit are given priority to generate electricity with the wind turbine, so that the total economic cost of the system is the lowest. However, because the thermal power units and the cogeneration units emit pollutants while generating electricity, the pollutant emission of the system under this scheme is the highest among the three scheduling schemes. In scheduling Scheme 2 with only the minimum pollutant emissions of the system taken as the scheduling target, the wind turbine is given priority to generate electricity, so the pollutant emissions of the system is minimal. However, since the power generation cost of the wind turbine is higher than that of the thermal power unit and the cogeneration unit, the economic cost of the system is the highest among the three scheduling schemes. In Scheme 3, the scheduling result is between Scheme 1 and Scheme 2. This scheme not only guarantees the economic efficiency of the system dispatch, but also reduces the pollutant emissions of the system to a certain extent.

In a comprehensive comparison of the above three schemes, Scheme 1 only pursues economic benefits and ignores the negative impact of the system on the environment. On the contrary, Scheme 2 only pursued the lowest emission of pollutants, which resulted in a high economic cost. Scheme 3 not only meets the low economic cost, but also reduces the emission of pollutants, achieving an effective balance between the economic and environmental benefits of the system.

As can be seen from Figure 5, due to the inverse modulating peak characteristic of wind power, wind power is relatively low during the period of 10–18h with high electrical load, and all wind power is grid-connected at this time. In the periods of 1–9h and 19–24h with low loads, wind power is relatively high. In order to meet the balance of electric load and thermal load, only a part of wind power can be allowed to be connected to the grid. Wind power consumption of the three scheduling schemes are 55.06%, 79.41% and 66.42% respectively.

Figure 5. Wind power consumption of three schemes.

As can be seen from Figure 6, during the period of 10–20 h with high load, the wind power is relatively low. The system's green certificate costs during this time include not only the cost of buying the green certificate, but also a large number of fines. In times 1–9 h and 21–24 h, the system only purchased a small number of green certificates, so the cost is low. It can be seen that green certificate costs are mainly affected by wind power and load. The green certificate fines mainly exist in periods of high load and low wind power.

Figure 6. Green certificate in each period.

6.2.2. Analysis of Different Scheduling Models

In order to verify the influence of green certificates on the economic dispatch of this paper, two different economic dispatch models were compared in Scheme 3:

- Model 1: Multi-objective scheduling model considering green certificates;
- Model 2: A traditional multi-objective scheduling model that does not consider green certificates.

The scheduling results of the two models are shown in Table 4.

Table 4. Scheduling results for different models.

Model	The Economic Cost, F (k\$)	Pollutant Emission, E (t)	Wind Power Consumption
1	581.75	82.32	66.42%
2	572.59	89.45	58.53%

As shown in Table 4, the economic cost of Model 1 increased by 9.16 k\$ compared with Model 2, but at this time, the pollutant emission decreased by 7.13 t and the wind power consumption increased by 7.89%. Therefore, it can be seen that after the introduction of the green certificate in the dispatching model, although the economic cost of the system is increased to some extent, the consumption of wind power is increased, and the pollutant emission is also reduced, which meets the requirements of promoting the development of new energy power generation and energy conservation and emission reductions in China.

6.2.3. Analysis of Different Parameters

Under the multi-objective scheduling scheme in this paper (Scheme 3), Figure 5 shows the curve of the change of system economic costs F and pollutant emissions E with the different price of green certificate fine K_H . Figure 6 shows the curve of green certificate cost F changing with purchase margin φ . Figure 7 shows the curve of the change of economic cost F system with the confidence level α .

Figure 7. The economic cost and pollutant emission with different price of green certificate fines.

As can be seen from Figure 7, with the increase in the price of green certificate fines K_H , the economic costs F of the system also increases. However, the pollutant emission of the system tends to decrease with the increase of the price of green certificate fines, and finally tends to be stable. This is because the increase in the price of the green certificate penalty will increase the economic cost of the system, and make the system absorb more wind power to reduce the cost of the green certificate. Due to the relatively high price of green certificate fines, the system economic cost still increases. When the price of green certificate penalty is higher than a certain value, the system cannot continue to increase wind power consumption, the economic cost of the system continues to increase, and the pollutant emission remains at a fixed value. It can be seen that the economic cost and pollutant emission of the system can be controlled reasonably by controlling the price of green certificate fines.

As can be seen from Figure 8, when the green certificate purchase margin φ is small, the number of green certificates that can be purchased is small, and the system has to pay a large amount of fines in addition to the purchase cost of the green certificate. As the purchase margin increases, the purchase cost of green certificates increases and the penalty cost decreases. However, since the price of fines is much higher than the purchase price of green certificates, the transaction cost of green certificates is decreasing.

Figure 8. Green certificate cost with different purchase margin.

It can be seen from Figure 9 that when the confidence level α is low, the economic cost of the system F is small. With the gradual increase of the confidence level α , the requirements for the rotation reserve caused by the wind power prediction error are also increasing, the total economic cost F of the system is gradually increasing, and the risk of the system is gradually decreasing. In actual

operation, the decision maker controls the risk by controlling the confidence level α , and selects a unit combination scheme with the lowest economic cost and meeting the set confidence level.

Figure 9. The economic costs with different confidence levels.

6.2.4. Algorithm Performance Analysis

In this paper, an improved MOPSO and the traditional MOPSO are used to solve the scheduling model. The comparison results of the economic cost convergence curves of the above two algorithms are shown in Figure 10a, and the comparison results of pollutant emission convergence curves are shown in Figure 10b.

Figure 10. (a) Comparison of convergency among different algorithms. (b) Comparison of convergency among different algorithms.

It can be seen from two figures that the improved MOPSO proposed in this paper has a faster convergence speed and a stronger global search ability. The improved algorithm is beneficial to the solution of the model.

7. Conclusions

In this paper, a multi-objective scheduling model for cogeneration units with heat storage is presented. The model takes into account economic costs and pollutant emissions. In order to further promote wind power consumption, green certificate costs are added into the economic cost. Aiming at the randomness and uncertainty of wind power output, the prediction error of wind power is fuzzily

processed, and the electric power balance and spinning reserve fuzzy opportunity conditions are established, which are converted into the explicit equivalent. The improved MOPSO was used to solve the multi-objective scheduling model. The following conclusions can be drawn: (1) The traditional single-objective scheduling model with the lowest economic cost as the objective function ignores the impact on the environment. The multi-objective model proposed in this paper not only guarantees the economy, but also reduces the negative impact on the environment to some extent. (2) Although the addition of green certification increases the economic cost, it promotes the consumption of wind power. In addition, the purchase margin and price of green certificates can be adjusted to control the economic cost of the system and pollutant emissions. (3) The uncertainty of wind power output makes the traditional scheduling experience feasible domain change, and the scheduling idea needs to change from deterministic to uncertain. The combination of units considering uncertainty should meet the confidence level required by the system so as to achieve a decision result which takes into account both the economy and reliability. In this paper, the fuzziness of wind power output is transformed into the fuzziness of prediction error, and the fast solution is realized by transforming fuzzy opportunity constraint into the explicit equivalent. (4) The improved MOPSO improves the solving speed and precision, which is suitable for the scheduling model in this paper.

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