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RESEARCH ARTICLE

Unit Maintenance Strategy Considering the Uncertainty of Energy Intensive Load and Wind Power Under the Carbon Peak and Carbon Neutral Target

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ABSTRACT The large-scale grid connection of renewable energy is an inevitable trend to realize the low-carbon development of the power system. Therefore, the impact of the uncertainty of high-energy enterprise load and renewable energy on the establishment of the maintenance strategy of power grid units cannot be ignored. Previous research methods usually only consider the grid side or the load side. Therefore, this paper proposes a method to determine the maintenance strategy of the unit through the information exchange between the grid side and the load side, while taking into account the impact of the uncertainty of renewable energy on the system. Introducing the tiered carbon transaction cost into the objective function can reduce the system's carbon emissions and increase the consumption of renewable energy. When establishing the grid-side model, the relevant constraints of robust performance are added, and the influence of the uncertainty of the wind turbine is fully considered. The results of the calculation example show that the unit maintenance strategy established after considering the uncertainty of high-energy enterprises and renewable energy sources has good economic efficiency.

INDEX TERMS Carbon trading, energy intensive load (EIL), renewable energy uncertainty, robust optimization, unit maintenance strategy.

I. INTRODUCTION

In recent years, with the carbon emission policies formulated by more and more countries, the future development trend of the power and energy industry is bound to move in the direction of energy saving and emission reduction and vigorous development of new energy sources [1], [2]. Such high energy-carrying loads with high energy consumption and high emission characteristics have become the main target of carbon reduction under the double carbon target and new power system construction. Therefore, considering the future to the national requirements of enterprise carbon emission, the literature [3], [4] proposed an optimization strategy to incorporate the carbon trading of enterprises into the side of high energy-intensive load enterprises, and divided the carbon trading cost into three parts: carbon right cost, carbon benefit and carbon emission penalty cost. Among them, the stepped carbon price calculation model is a mechanism that takes carbon emissions as a reference to determine the carbon price level. Introducing the stepped carbon price model into the power units containing large-scale wind power systems is beneficial to reasonably ensure the start and stop of units, reduce the output of self-provided units, and ensure safe and economic dispatch while reducing the carbon emissions of the system.

The power system containing clean energy and high energy-carrying enterprises are increasingly coupled in the areas of economic dispatch and planned maintenance as the

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energy consumption of the system continues to grow. Therefore, in power systems containing large-scale wind power, the uncertainty that exists in wind power, a volatile energy source, is a problem that we need to consider [5]. When wind power systems are integrated into the grid on a large scale, a large amount of wind has to be abandoned in order to ensure the safe and stable operation of the grid, which greatly reduces the economics. Likewise, the uncertainty of wind farm output somehow increases the uncertainty of the system equivalent load, which has a great impact on the operation and maintenance of the units [6], [7]. Therefore, when developing the maintenance strategy of the units, the historical data of the wind turbines need to be integrated and the impact of their uncertainty needs to be fully considered in order to achieve the best yield [8], [9], [10], [11]. In the literature [12], [13], [14], [15], a new method for estimating the uncertainty set of wind power generation was proposed, taking fully into account the uncertainty problem. However, these methods end up considering only the impact of new energy measurement uncertainty or only the impact of load side, and few of them really take into account the combined impact of high energy-loaded load side and new energy uncertainty on unit maintenance strategy development.

To integrate the above issues, the establishment of the unit maintenance strategy not only needs to consider the impact of wind power uncertainty, but also needs to combine the feedback information from the high energy load side to the grid side, take into account the carbon penalty cost factor, and develop the unit maintenance plan while ensuring the economic benefits of the load side. In this paper, the mathematical model of the system is divided into two layers, firstly, the unit overhaul is modeled, including the combined model of wind turbine uncertainty and carbon emission penalty cost; then the optimization model of high energy load-side dispatching is established, and the fine modeling of electrolytic aluminum load is combined with regional characteristics, and the influence of carbon emission penalty cost is also considered; finally, the unit overhaul model is verified by arithmetic examples, and the impact of high energy load and new energy uncertainty on the unit overhaul is tested. Finally, the unit overhaul model is validated by an example to test the impact of high energy load and new energy uncertainty on unit overhaul.

The contributions are as follows:

Firstly, in the procession of maintenance plan making, We consider both high energy-carrying loads and wind power output to increase wind power consumption.

Secondly, we consider introducing a carbon trading model into the overhaul plan to reduce carbon emissions as much as possible.

To sum up, considering the uncertainty of wind power and other renewable energy output, as well as the flexibility of high-load energy enterprises to coordinate the unit combination, this paper considers to develop a unit maintenance strategy that includes high-load energy and renewable energy.

II. SYSTEM DESCRIPTION

This paper takes into account the operation of energy-intensive enterprises, power grid side and iterates information between them. The overall mathematical model consists of two layers. The upper model optimizes the operating costs of power networks with clean energy and formulates corresponding unit maintenance strategies. The system uses the available clean energy as output variable in each run-time of the maintenance plan to optimize the economic operation model of lower high-energy load enterprises. The purpose is to make high-energy load enterprises operate with the uncertainty of new energy and make corresponding adjustments. Make the high-energy load enterprises have the highest economic benefit under this condition, and the decision is made to selectively purchase clean energy from the grid side. This requires that the information interaction between the power grid side with new energy and the high-load can be achieved. The interactive diagram of both sides is as follows:

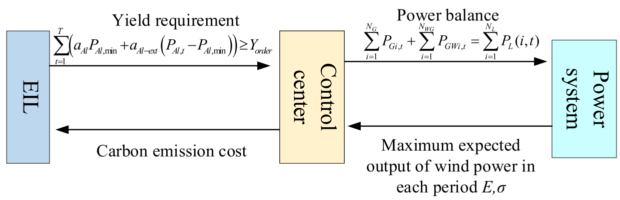

FIGURE 1. Information exchange diagram between high-energy enterprise side and power grid side.

In the upper model, the objective function on the power grid side not only considers the cost of power generation and maintenance, but also introduces penalties for carbon emissions and input for demand response on the high-load side. The penalty for carbon emissions is introduced to promote the consumption of clean energy. Carbon emissions, as a emission reduction mechanism, contribute to the consumption of clean energy such as wind power. In view of the growing scale of wind power development and as a typical new type of clean energy, this paper selects wind power as a new type of clean energy incorporated into the power grid. To solve the upper model for unit maintenance strategy, in addition to the traditional constraints such as power flow, unit power, unit output, and unit climb constraints, the uncertainty of wind power in power grid should be handled. The idea of this paper is to provide an uncertainty set as a description of wind power uncertainty, and introduce parameter α to meet different robust performance requirements, so as to adjust the new energy sources that introduce uncertainty at the system level to safely consume within a given confidence level and provide a more reliable robust maintenance strategy within an uncertainty range.

For the load side of high-energy enterprises, the calculation model of step electricity price is considered, and a coordinated mode based on power balance is adopted. The power grid side provides the load level and the power output

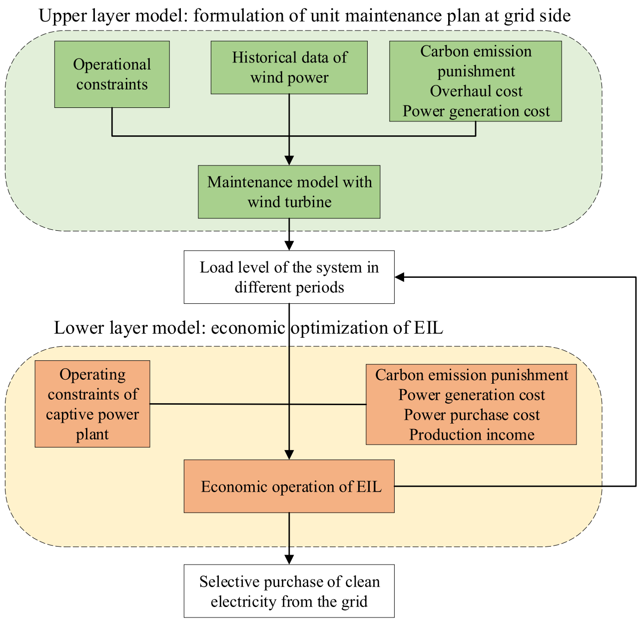

FIGURE 2. Schematic diagram of the two-layer optimization model.

information of clean energy to the high-energy load enterprises to achieve real-time information exchange, while the high-load enterprises will make decisions on purchasing power according to their own operation constraints and objective functions. It can promote the consumption of clean energy and improve the problem that it is difficult to coordinate the power balance of the power grid after the introduction of clean energy. The electrolytic aluminum load is the typical one in the high-energy load. It is also the focus of this article. The production equipment of electrolytic aluminum load should be in continuous production state in normal operation. Because of the input and exit operations of electrolytic cell and its complexity, it is generally no frequently surrender operation in normal production process. Therefore, the model of aluminum electrolysis in this paper does not consider the adjustment of input and exit operation of electrolytic cell in the process of aluminum electrolysis.

III. GRID MAINTENANCE MODELS THAT CONSIDER CLEAN ENERGY UNCERTAINTY

A hierarchical model for the combined operation of high-energy enterprises and power networks with new energy sources is established below. Under the constraints, the optimization is carried out according to the priority level. After making the maintenance plan for the units with fans on the upper power grid side and satisfying the relevant robust performance, the decision on purchasing power from the power grid side under high-energy load is made in this range, and the information exchange between the upper and lower levels is made to reach the optimal decision of the whole and each part. The relationship between the two-level optimization models is shown below:

A. GRID-SIDE UNIT MAINTENANCE MODEL

The upper model is a maintenance model for power-side units which considers access to new energy units represented by wind power.

1) THE OBJECTIVE FUNCTION OF THE OVERHAULED MODEL

The objective function of unit maintenance needs to consider not only the economic cost of traditional unit maintenance such as power generation cost and maintenance cost, but also the penalty for carbon emissions and the additional electricity sales benefits reflected by the interaction with the lower model. The specific manifestations are as follows:

$$\min f_{\text{upper}} = \sum_{t=1}^{T}\{\sum_{i=1}^{N_G}[C_{Gi,C} + C_{Gi,CO_2} + C_{Gi,M}] + \sum_{i=1}^{N_{GW}} C_{GWi,M} - S_{\text{sold}}\} \quad (1)$$

In the above formula, N_G and N_{WG} represent the number of traditional unit busbars and fan unit busbars in the system, respectively, $C_{Gi,C}$ represents the power generation cost of traditional units in the system, $C_{Gi,CO2}$ represents the carbon penalty brought by conventional units, $C_{Gi,M}$ and $C_{GWi,M}$ represent the maintenance cost of conventional units and wind turbines, S_{sold} represents the electricity sales revenue sold to high-energy loads, that is, electrolytic aluminum load side.

2) MAINTENANCE MODEL CONSTRAINTS

On the basis of considering the constraints of the traditional unit maintenance model, it is also necessary to introduce restrictions on wind power maintenance, and the wind speed fluctuates greatly in the short term, which leads to large short-term fluctuations in wind power output. However, considering that the interannual and seasonal fluctuations of wind farms are small, the output of wind power still has long-term statistical characteristics. Hydropower, on the other hand, mainly relies on atmospheric precipitation and natural water volume, and is less affected by the season in the short term, which can maintain the stability of power generation, but in the long term, fluctuations will change with seasonal differences. Therefore, the treatment method is different when introducing two different units.

For wind power, the set of uncertainties can be used to describe the randomness of the output. The expected value and standard deviation of potential wind power output need to be known, and in order to reflect the robustness of the post-wind power maintenance plan, the parameter α of the set needs to be adjusted to meet different robust performance requirements. The specific form is as follows:

$$I_W^{i,t} = \{w_{i,t}|w_{i,t} = \bar{w}_{i,t} + az_{i,t}\}|z_{i,t}| \leq 1 \quad (2)$$

Wind power is treated as a boxed uncertainty set. The wind power output predicted according to the current scenario is approximately blurred into a certain interval, which is then transformed into a box uncertainty set, which is the basis of the robust optimization used in this paper. Where I_W^{it} represents the set of uncertainties for the output of the wind turbine, and $w_{i,t}$ represents the maximum possible wind power output of the *ith* wind turbine at time t, referred to as the potential wind power output. $\bar{w}_{it}$ represents the expected value of the potential output of the wind turbine, and the parameters $z_{i,t}$ describe the output constraint interval for the wind power above and below the $\bar{w}_{it}$ value, and the standard deviation is used instead in this paper, and the parameter α is used to control the width of the uncertainty interval. After knowing the expected value and standard deviation of the wind turbine output, different α values are set to meet different robust performance requirements.

The constraints for combining wind turbines with conventional units to develop a maintenance strategy for units containing new energy sources are as follows:

a: MAINTENANCE STATE VARIABLE CONSTRAINT

$$m_{i,t} \in \{0, 1\} \tag{3}$$

Define 0, 1 integer variables $m_{i,t}$ to describe the variables that arrange whether the unit is in the maintenance state. 1 means that the t time unit i is put into operation, and 0 means that the t time i unit is out of operation.

Power balance constraints for the system:

$$\sum_{i=1}^{N_G} P_{Gi,t} + \sum_{i=1}^{N_{WG}} P_{GWi,t} = \sum_{i=1}^{N_L} P_L(i, t) \tag{4}$$

In the above formula, N_L represents the number of load busbars; $P_{Gi,t}$ and $P_{GWi,}$ are the output of traditional unit i and wind turbine i at time t respectively; $P_{Li,t}$ is the actual power at the t time at load bus i.

b: SYSTEM BACKUP CONSTRAINTS

$$\begin{aligned} \sum_{i=1}^{N_G} P_{Gi\max} \cdot m_{i,t} &\geq C_t^+ \sum_{i=1}^{N_L} P_{L\max}(i, t) \\ \sum_{i=1}^{N_G} P_{Gi\min} \cdot m_{i,t} &\geq C_t^- \sum_{i=1}^{N_L} P_{L\min}(i, t) \end{aligned} \tag{5}$$

In the above formula, $P_{Gi\max}$ and $P_{Gi\min}$ refer to the maximum power and minimum power that can be generated by conventional generator sets, respectively; C_t^+ and C_t^- are the margin coefficients for positive and negative backup at time t, respectively. $P_{L\max}(i,t)$ and $P_{L\min}(i,t)$ are the maximum and minimum load values of load bus i at time t, respectively.

c: MAINTENANCE TIME CONSTRAINTS

$$\begin{aligned} m_{i,t} &= 0, \quad s_i \leq t \leq s_i + d_i \\ m_{i,t} &= 1, \quad t < s \text{ or } t > s_i + d_i \\ e_i &\leq s_i \leq l_i \end{aligned} \tag{6}$$

e_i is the earliest time allowed for maintenance of unit i; l_i is the latest period allowed for unit i to start maintenance and d_i is the maintenance duration of unit i. s_i is the maintenance start time of unit i, and maintenance time constraints all types of units should meet the requirements of maintenance time in the cycle.

d: MAINTENANCE RESOURCE CONSTRAINTS

$$\begin{aligned} \sum_{i=1}^{N_{GM}} (1 - m_{i,t}) &\leq N_{GM\max} \\ \sum_{i=1}^{N_{GM}} P_{Gi,t\max}(1 - m_{i,t}) &\leq P_{GM\max} \end{aligned} \tag{7}$$

In the above formula, N_{GM} is the sum of the groups to be repaired, and $N_{GM\max}$ is the maximum number of groups to be repaired at the same time. $P_{GM\max}$ is the maximum capacity allowed to be repaired at the same time.

e: TRANSMISSION CAPACITY CONSTRAINTS

$$-P_{Maxij} \leq P_{ij} \leq P_{Maxij} \quad i, j \in N \tag{8}$$

In the above formula, N is the collection of all the buses in the system, P_{ij} is the active power transmitted by the line from bus i to bus j in the system, and P_{Maxij} is the maximum capacity allowed by the line.

f: THE UPPER AND LOWER LIMIT CONSTRAINTS AND FOR CONVENTIONAL UNIT OUTPUT

$$P_{Gi\min} \leq P_{Gi,t} \leq P_{Gi\max} \quad i \in N_G \tag{9}$$

The potential maximum output $w_{i,t}$ of the wind turbines in the system is described using the uncertainty interval above.

g: POTENTIAL OUTPUT CONSTRAINTS OF WIND POWER

$$0 \leq P_{GWi,t} \leq w_{i,t} \quad w_{i,t} \in I_W^{i,t} \tag{10}$$

B. LOWER LAYER (OPTIMAL PURCHASE OF POWER ON HIGH-ENERGY LOAD SIDE)

In the lower model, not only the constraints and parameters of the model, but also the information conveyed by the upper model need to be coordinated. Finally, the optimal decision for high-energy load enterprises to purchase power on the grid side is obtained. In this paper, the lower model is described as an example of the electrolytic aluminum load in a power plant.

1) OBJECTIVE FUNCTION OF LOWER LAYER OPTIMIZATION

The objective functions for the lower-layer model optimization are as follows:

$$\min f_{lower} = F_{buy} + F_{ru} + F_{CO_2} - S_{al} \tag{11}$$

F_{buy} is the power purchased from the power grid for the electrolytic aluminum side, F_{ru} is the power generation cost of the power plant owned by the electrolytic aluminum enterprise, F_{CO2} is the carbon emission cost of the electrolytic aluminum load, and S_{al} is the income from the production of electrolytic aluminum.

In the economic dispatch on day scale, Based on constraint (8), the conventional unit output should also need to follow the ramping rate constraint:

$$\Delta P_{Gi}^{\min} m_{i,t} \leq P_{Gi,t} - P_{G,t-1} \leq \Delta P_{Gi}^{\max} m_{i,t} \quad i \in N_G \tag{12}$$

$\Delta P_{Gi}^{\min}$ and $\Delta P_{Gi}^{\max}$ are the the maximum and minimum power variation scale that the unit can accept in the dispatching stage.

2) LOAD MODEL FOR ELECTROLYTIC ALUMINUM

Establishing load constraints for electrolytic aluminum can be expressed as:

$$P_{Al,\min} \leq P_{Al,t} \leq P_{Al,\max} \tag{13}$$

In the formula, $P_{Al,t}$ is the power consumption of the electrolyte slot at time t, $P_{Al,\min}$ and $P_{Al,\max}$ are the minimum and maximum power allowed for production respectively.

Adjusting power constraints in the production of electrolytic aluminum can be expressed as:

$$\Delta P_{Al,\min} \leq \left| P_{Al,t} - P_{Al,t-1} \right| \leq \Delta P_{Al,\max} \tag{14}$$

In the formula, $\Delta P_{Al,\min}$ and $\Delta P_{Al,\max}$ are the minimum and maximum allowable power limits for the production of electrolytic aluminum.

Generally, the voltage of the electrolytic cell remains constant during normal operation. If the output power of the load needs to be adjusted, the output current of the rectifier can be adjusted. This method is very fast. However, in order to ensure that the status of raw electrolytic materials does not change significantly, the adjustment frequency of the electrolytic cell should not be too high, so there should be a minimum time interval constraint between the adjacent two adjusting power of the electrolytic cell.

Considering the need for a minimum time interval between each power adjustment, the resulting constraints are as follows:

$$P_{Al,t} - P_{Al,t+x} = 0, x \in [t, t + \Delta t] \tag{15}$$

In the formula, Δt is the minimum unit time required for the electrolytic aluminum enterprise to adjust the power interval.

The requirements for the production of electrolytic aluminum for high-energy enterprises are as follows:

$$\sum_{t=1}^{T} \left(a_{Al} P_{Al,\min} + a_{Al-ext} \left(P_{Al,t} - P_{Al,\min} \right) \right) \geq Y_{order} \tag{16}$$

In the formula, a_{Al} is the output per unit power level when the load level of the electrolytic cell is $P_{Al,\min}$; a_{Al-ext} is the output change corresponding to the power adjustment per unit of the electrolytic cell. T is the operating cycle of the electrolytic cell. Y_{order} is the order demand for electrolytic aluminum products for high-energy enterprises during this cycle.

3) UNIT MODEL OF CAPTIVE POWER PLANT

Consider the captive power plants owned by high-energy enterprises, which contain the following constraints: upper and lower limit of output power, climbing power constraint, start-stop variable constraints, maximum and minimum start-stop time constraints, etc. expressed as follows:

$$\begin{aligned}
&P_{ru,\min} x_t^G + r_t^{G,d} \leq P_{ru,t} \leq P_{ru,\max} x_t^G - r_t^{G,u} \\
&\quad \Delta P_{ru,\min} x_t^G \leq P_{ru,t} - P_{ru,t-1} \leq \Delta P_{ru,\max} x_t^G \\
&\quad x_t^G - x_{t-1}^G \leq x_\tau^G, \\
&\qquad\qquad \forall \tau \in \left[t+1, \min\left\{ t + T^{G,on} - 1, T \right\} \right] \\
&\quad x_{t-1}^G - x_t^G \leq 1 - x_\tau^G, \\
&\qquad\qquad \forall \tau \in \left[t+1, \min\left\{ t + T^{G,off} - 1, T \right\} \right]
\end{aligned} \tag{17}$$

In the formula, $P_{ru,t}$ represents the output of the self-provided unit at time t; $P_{ru,\min}$ and $P_{ru,\max}$ represent the minimum and maximum output of a self-provided unit; x_t^G indicates the working status of the self-provided unit at time t, and considers that when its value is 1, it represents the operation of the self-provided unit and 0 represents the outage of operation. $r_t^{G,d}$ and $r_t^{G,u}$ indicate downhill and uphill power limits of the unit; $\Delta P_{ru,\min}$, $\Delta P_{ru,\max}$ represents the minimum and maximum adjustable power value per unit time of the unit. $T^{G,on}$ and $T^{G,off}$ indicate the minimum time for the unit to be switched on and off.

4) STEPPED CARBON PRICE CALCULATION MODEL

Establishing trapezoidal carbon price calculation model is an important way to establish the relationship between upper and lower models. High-energy enterprises can use the power of clean energy on the side of the power grid as feedback information after optimizing the purchase of power on the side of the power grid to increase the consumption of clean energy in time.

The system's carbon emission calculation formula is:

$$T_{\varepsilon mi} = \sum_{t=1}^{T} P_{Al,t} \psi + \sum_{t=1}^{T} Y_t \gamma \tag{18}$$

In the formula, $T_{\varepsilon mi}$ is the total carbon emission of the system in a scheduling cycle; Ψ It is the intensity of carbon emission during electrolysis. γ For the intensity of carbon emissions during power generation; Y_t is the total power generation (including captive power plants and purchased power from the grid).

The system carbon quota calculation formula is:

$$T_{all} = Y_{order} S \tag{19}$$

In the formula, T_{all} is the total carbon emission quota for the system in one operating cycle; S is the carbon emission quota per unit production.

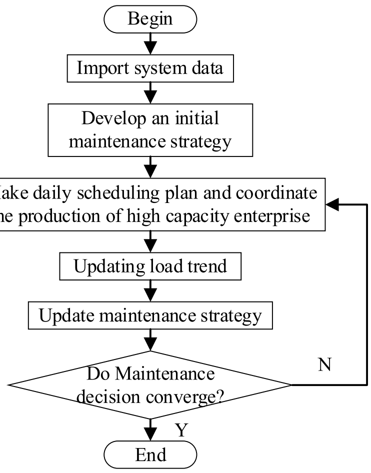

FIGURE 3. The solving procession.

In order to better control carbon emissions, the stepped carbon transaction cost calculation model used in this paper is as follows:

$$F_{CO_2} = \begin{cases} \lambda k, & k \le d \\ \lambda d + (1+\sigma)\lambda(k-d), & d < k \le 2d \\ (2+\sigma)\lambda d + (1+2\sigma)\lambda(k-2d), & 2d < k \le 3d \\ (3+3\sigma)\lambda d + (1+3\sigma)\lambda(k-3d), & 3d < k \le 4d \\ (4+6\sigma)\lambda d + (1+4\sigma)\lambda(k-4d), & 4d < k \end{cases} \tag{20}$$

where $k = T_{\varepsilon mi}$- T_{all}, λ is the unit carbon price; d is the length of the interval per unit carbon emission; σ indicates the growth rate of carbon trading prices in the adjacent two intervals, F_{CO2} is the cost of carbon emissions. In addition, it should be noted that if the k-value obtained is less than zero, indicating that the actual emission of the system is less than the quota set by the state, enterprises can trade the excess carbon emission quota to make the system obtain carbon benefits.

IV. SOLVING ALGORITHM

In order to solve the optimization problem proposed in the third section, this section describes how to solve the upper and lower models jointly.

The flowchart of the solving procession is shown in Figure.3:

Firstly, initialize the system data, then develop an initial maintenance strategy, which is the basis of making economic dispatching plan and purchasing power for enterprises with high energy load. Then update the load trend on a longer time scale and update the overhaul plan continuously until it converges.

V. EXAMPLE ANALYSIS

A. EXAMPLE INFORMATION

Taking the modified IEEE-RTS96 test system as an example, the test system contains hydroelectric units, gas turbines, nuclear power units and other units, whose operation constraints and original data remain unchanged. Change the generator set where node 107 is located to a wind generator set and the bus load to an electrolytic aluminum enterprise. The capacity of wind turbines is set to 300 MW, there are 20 traditional units to be repaired and 1 wind turbines to be repaired in the system. The cost of equipment used is 10% of the average production cost of the unit. The total repair time is 52 weeks, approximately one year.

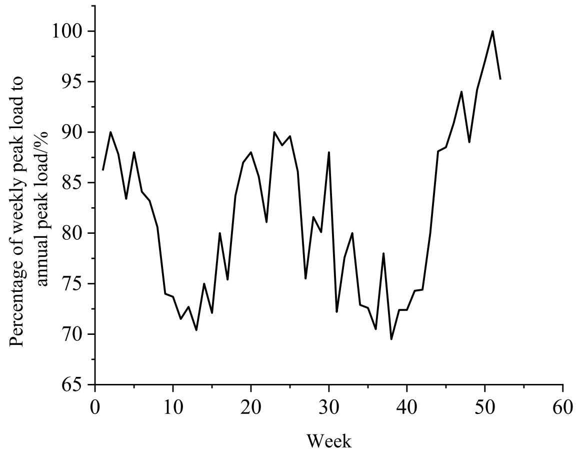

FIGURE 4. Percentage of weekly peak load to annual peak load.

The annual peak load of the system is 2850 MW, and the trend of the weekly peak load as a percentage of the annual peak load is as follows:

For the uncertain set parameter of the wind turbine α select 0.4, refer to the wind power data provided by [16], give the expected value and standard deviation of the potential output of wind power in each month of the year (standardized according to the capacity of the wind farm), consider the uncertainty of wind power output, and give the confidence interval of wind power output according to the conservativeness selected above, as the basic data for maintenance:

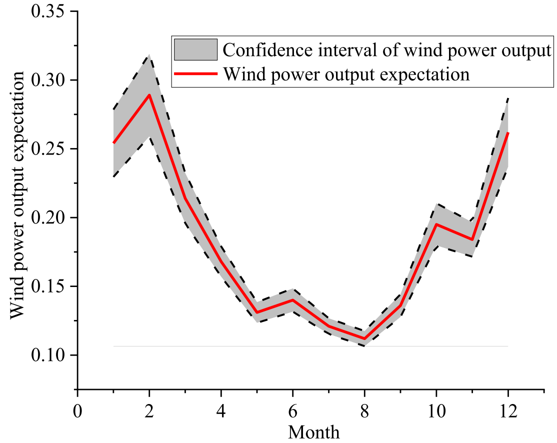

FIGURE 5. Potential output expectations for wind farms in one year.

The output of wind power has certain seasonal characteristics, so the maintenance strategy of the generator set should be

TABLE 1. Statistics of potential output for each month of a wind farm.

Month	E	σ
1	0.254	0.241
2	0.289	0.259
3	0.214	0.214
4	0.168	0.163
5	0.131	0.143
6	0.140	0.151
7	0.121	0.118
8	0.112	0.123
9	0.136	0.151
10	0.195	0.196
11	0.184	0.170
12	0.262	0.238

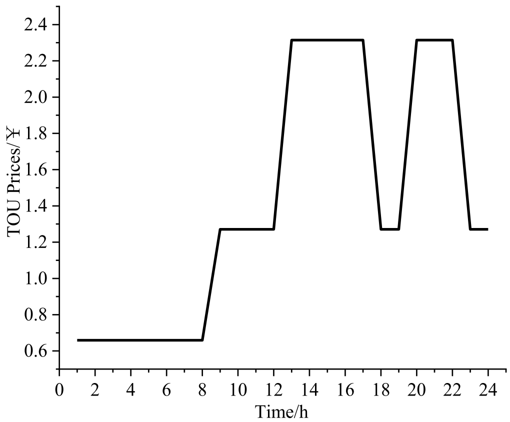

FIGURE 6. Hourly electricity price per day for electrolytic aluminum enterprises.

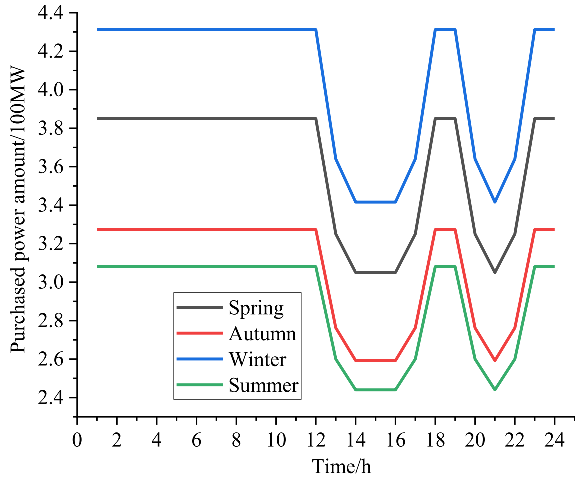

FIGURE 7. Power purchase strategy for electrolytic aluminum enterprises in one day.

TABLE 2. Statistics of potential output for each month of a wind farm.

α	Spring	Summer	Autumn	Winter
0.3	34.74	25.44	32.67	40.635
0.4	32.67	23.67	30.51	38.58
0.5	30.6	21.9	28.35	36.525
0.6	28.53	20.13	26.19	34.47

formulated according to the different seasons. Based on the above data, the maintenance plan is drawn up in the upper model.

In order to reflect the uncertainty of considering new energy, this paper established two other groups of schemes as a comparison.

Scheme 1: The treatment method of wind power mentioned in this paper is used in the maintenance decision, and the response of high load energy load is considered to absorb the possible residual wind power in time;

Scheme 2: The response of high load is considered, but the wind power is set to fluctuate within a certain range. In this paper, it was set to ±5%;

Scheme 3: Consider the wind output uncertainty, But the high energy load response is not considered.

Combining the objective functions and constraints of the lower model in this paper, the operation strategies of the high-energy load side are solved in different seasons. The units put into operation in different periods solved in the upper model are different, and the corresponding strategies for daily power purchase in different periods are formulated.

When electrolytic aluminum load purchases power from the grid side, it gives priority to cheaper wind power while guaranteeing the reliability of power supply. Therefore, it is necessary to combine the coefficients α introduced above to robust performance description of the reliability of wind power supply, that is, wind power is considered to be reliable within this range, that is, this part can be understood as the amount of electricity that electrolytic aluminum enterprises can choose to purchase.

According to the operating characteristics of electrolytic aluminum enterprises, the power of electrolytic aluminum enterprises under standard conditions is 665-735MW. In order to consider that the shutdown of electrolytic aluminum enterprises has too great impact, the unit start-stop state is not set, and the self-provided unit has no carbon emission rights, so it is necessary to spend money to purchase quota for the self-provided unit.

The hourly electricity price of electrolytic aluminum enterprises is set as:

Under the condition of ensuring the annual output of the electrolytic aluminum enterprise of 100,000 tons, the above model is used to optimize the power purchase strategy as much as possible, in which the carbon emissions of the purchased electricity should also be calculated, and the grid emission factor of the region is set to 0.6671tCO2/tAl. The total carbon emissions per ton of aluminum consumed were 11.77 tons.

B. RESULT ANALYSIS

After establishing a stepped carbon emission cost model, the power purchase strategy of electrolytic

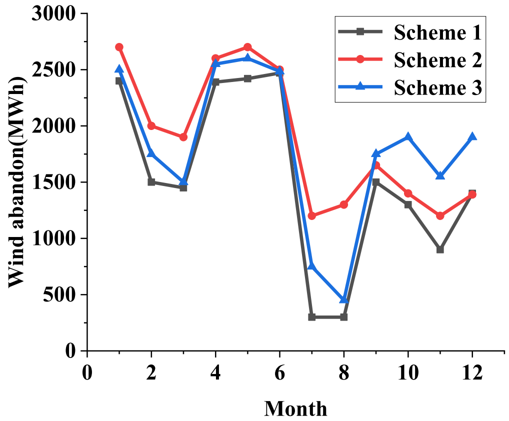

FIGURE 8. Monthly Wind abandonment under different schemes.

TABLE 3. Statistics of potential output for each month of a wind farm.

	Total wind abandon /MWh	Maintenance cost/k$	Carbon emission cost/k$	Total cost/k$
Scheme 1	1 768.26	342.22	2110.48	1 768.26
Scheme 2	1 768.41	383.87	2152.13	1 768.41
Scheme 3	1 767.54	362.97	2130.65	1 767.54

aluminum enterprises within one day is calculated as follows:

The maintenance strategy of wind turbines has been introduced to provide more additional purchasable power for the operation of electrolytic aluminum enterprises. The average daily purchased power in different periods will change with the seasons. The following table shows the average daily purchased power of high-energy loads in different periods.

It can be seen from the above figure that the wind power purchased by electrolytic aluminum load at different times changes with the α parameters, and decision makers can flexibly adjust the value of this variable to meet different degrees of robust performance requirements for scenarios with different robust performance requirements.

The wind abandonment volume of each period under the three schemes is shown in Figure 8, and the total wind abandonment volume and economic cost of the system are shown in Table 3:

It can be seen that considering the wind power output in the maintenance plan can reduce the abandoned wind power volume by 14.9% compared with the situation without considering wind power. After longitudinal comparison of the three schemes, July and November are more typical. The difference between scheme 1 and scheme 2 lies in the way of describing the uncertainty of clean energy. More accurate uncertainty treatment will reduce the air abandonment volume of scheme 1 compared with scheme 2 by 18.68% while ensuring the required robust performance. Comparing scheme 1 and Scheme 3, the air abandonment rate of Scheme 1 will be reduced by 15.47% compared with scheme 3 due to the consideration of high energy load response. The carbon emission cost of the high-load energy load is reduced by absorbing the wind power that can be invoked. The carbon emission cost of scheme 1 is reduced by 10.85% and 5.71%, respectively, compared with scheme 2 and Scheme 3.

Therefore, the introduction of a more accurate uncertainty analysis of wind power output and the consideration of the response absorption of high load can not only provide a more flexible power purchase strategy for the high load side, but also help the power grid decision makers to increase the consumption of wind power on the basis of ensuring the confidence of demand. Compared with Scheme 2 and Scheme 3, Scheme 1 reduces 1.94% and 0.95% respectively in the sum of grid side maintenance and power generation costs and carbon emission costs of enterprises with high energy load, so as to optimize the optimization space of unit combination of each operation section.

VI. CONCLUSION

It can be seen from the above that considering the inclusion of high-capacity enterprises in the maintenance strategy containing wind turbines, and the introduction of carbon emission penalty mechanisms, can increase the consumption of wind power and increase the revenue of high-capacity enterprises under the premise of ensuring reliable power supply on the system side. For the grid side, additional electricity sales can not only reduce costs, but also increase production on the high load side. This paper provides a broad idea for the maintenance of system units connected to high-energy enterprises and new clean energy.

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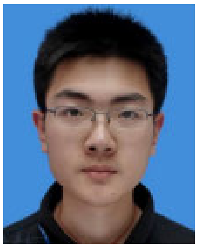

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