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Power-balancing compensation mechanism and method for controllable load reduction

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In the coming renewable energy-dominated power systems, their uncertain nature calls for a controllable load to track the change of renewable energy. To achieve power balance during peak load, a compensation mechanism for the controllable load to reduce power consumption is constructed. First, a multi-round sequential auction method is used to determine the reduced and non-reduced loads. Second, based on the proportional distribution according to the reduction loss, a compensation method for the reduced load by the non-reduced load is proposed. Considering both the reduction of electricity consumption and the carbon emission rate indicator, a compensation method for the reduced load by new energy enterprises is proposed; then, the compensation method and process of the controllable load reduction are formed. Finally, simulations are performed on a practical test case, and the effectiveness of the proposed scheme is verified by the numerical results.

KEYWORDS

power vacancy, controllable load, power supply balance, sequential auction, compensation method

1 Introduction

With the rapid development of the economy, the demand for electricity has steadily increased, and the peak value of the daily load curve has been increasing. Meanwhile, with the large-scale new energy connected to the power grid, the peak shaving capacity of the system decreases. When the load is large and the output of new energy is small, the supply and demand balance of the power system is tense, resulting in an "absolute power vacancy." At the same time, during the peak load period, if the intra-day predicted value of the new energy output is far less than the pre-day predicted value, the prediction error exceeds the heat reserve reserved by the system, which will further cause the "prediction error vacancy." The combined effect of the two types of power shortage makes the power supply of a new energy power system more tense, and it is urgent to find regulation and economic measures to ensure the balance of the power supply and load demand (McPherson and stoll, 2020; Haley,et al., 2020). In the electricity market environment, some loads can be adjusted within a certain range of needs, which are called controllable loads (Dranka and Ferreira, 2019; Parrish et al., 2020). However, controllable load interruption or reduction of power consumption will cause economic losses. Therefore, it is very important to provide electricity price compensation to controllable loads and promote their enthusiasm and initiative to reduce power consumption (Dehghanpour and Afsharina, 2015).

In recent years, researchers have conducted a lot of research work in the field of controllable loads (Strbac, 2008). For adjustable loads such as electric vehicles and distributed energy storage with the bidirectional interaction ability, the proportion of access to a power grid is increasing (Bian et al., 2018). An energy interaction converter between electric vehicles is proposed to improve the service life (Wang et al., 2021). It is beneficial to improve the performance of electric vehicles with controllable loads. The load is included in the energy management system of the energy internet (Hua et al., 2019), and a bottom-up development of energy internet architecture is designed (Hua et al., 2022). Large-scale aggregation of demand-side adjustable load resources and timely and controllable participation in power system regulation and power market transactions have become important issues for the new generation of power systems. Based on price-based demand response items, such as real-time pricing (RTP) (Finck et al., 2020), time of use pricing (TOU) (Zhou et al., 2019), and critical peak pricing (CCP) (Li et al., 2018) demand response items, users' electricity demand is corrected through time-varying market prices. Finck,et al. (2020) dynamically modified the day-ahead price, according to the random behavior of residents and the dynamic behavior of buildings and heating systems so that energy consumption can adapt to the error in the prediction of new energy power generation. The comparative analysis of the modeling results (Zhou,et al., 2019) shows that the optimal use time pricing can support the charging and discharging behavior of residents and reduce the cost of the entire power supply chain. Li et al. (2018) confirmed that residential customers show promising potential for load reduction corresponding to the increasing electricity price. The price-based demand response project guides demand-side resources to respond interactively to the fluctuation of electricity prices, which can alleviate the impact of higher electricity prices on load demand fluctuation (Sioshansi, 2010). RTP is more economical than providing users with a unified fixed price in the short term (Paul et al., 2019). The more sensitive the response of demand response resources to the electricity price, the more intense will be the competition in the electricity market and the more reliable will be the system (Joung and Kim, 2013; Thomas et al., 2015). Due to the randomness, volatility, intermittence, uncertainty, and anti-peak regulation characteristics of wind and solar output (Zhang, et al., 2017), its large-scale access has brought severe challenges to the stable and safe operation of the power system (Liu et al., 2018; Saint-Drenan et al., 2016; Tasnim, et al., 2017), and the contradiction of new energy consumption has become increasingly prominent due to the constraint of the peak regulation capacity of the power system

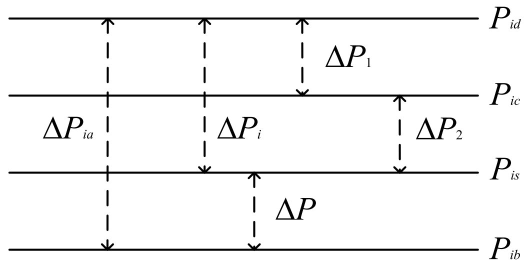

FIGURE 1
Power supply and demand.

(Zhao, et al., 2018). In order to meet the power supply demand and ensure the stable operation of the power grid and the reliability of the power supply system, it is necessary to accurately predict the power generation of new energy. Taking wind power as an example, the regional load characteristics are often opposite to the wind power characteristics, or they are called the anti-peak regulation characteristics of wind power, which increases the prediction difficulty of new energy power generation (Xie et al., 2014). A variety of intelligent prediction models and machine learning algorithms have been successfully applied to wind energy prediction, and good results have been achieved. Common intelligent prediction models include neural networks (Li et al., 2010), support vector machines (Hu et al., 2014; Liu, et al., 2013), and least squares support vector machines (Zhou et al., 2011). In the existing literature, research on the power market is more concentrated on the technical level, and research on the economic level of new energy in the power market is relatively rare.

In the aforementioned literature, the demand-side response subject is regarded as the price recipient, lacking the research and analysis of an active bidding strategy in the power market.

Motivated by the relevant research results of controllable loads, this study proposes a power-balancing compensation mechanism and method for controllable load reduction. The innovations of this study are as follows:

(1) Considering the absolute power vacancy and prediction error vacancy, the non-reduced load and new energy enterprises provide reasonable price compensation to the reduced load at the same time;
(2) According to the sequential auction method, the reduced and non-reduced loads are determined, and the corresponding compensation method is proposed based on the principle of proportional distribution of the reduction loss;
(3) According to the weighted index of the reduced electricity and carbon emission rate, the compensation method provided by new energy enterprises for the reduced load is proposed.

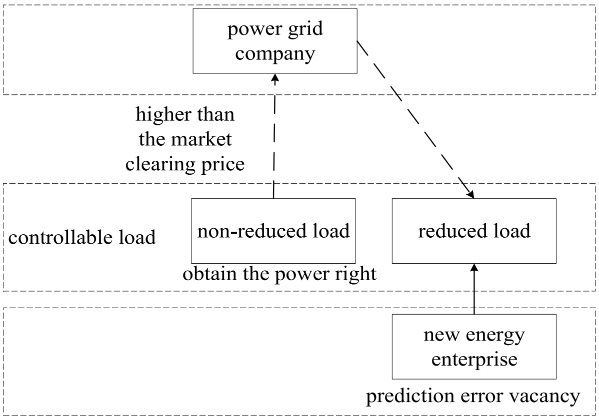

FIGURE 2
Schematic diagram of the consumption mechanism.

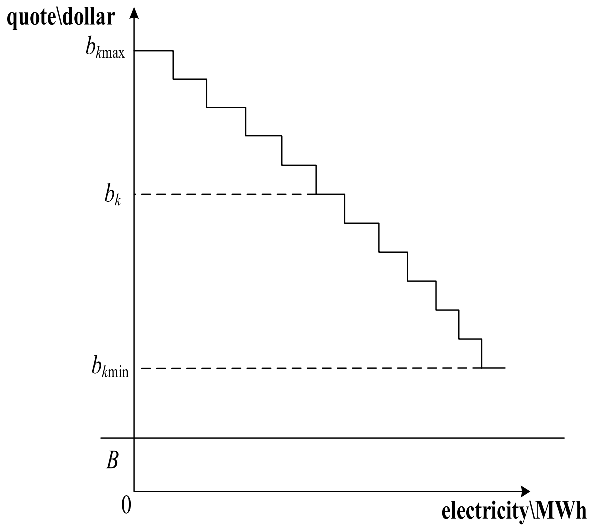

FIGURE 3
Schematic diagram of the bidding process.

2 Compensation mechanism of controllable loads in the power supply shortage period

2.1 Power supply and demand balance analysis

As shown in Figure 1, absolute power vacancy ΔP_1 occurs; however, the pre-day predicted value of the total power generation P_{ic} is less than the total load power P_{id}. P_{id} is composed of the conventional load P_{ib} and the controllable load ΔP_{ia}.

When the intra-day predicted value of the total power generation P_{is} is less than P_{ic}, there is prediction error vacancy ΔP_2.

Total power vacancy ΔP_i ($\Delta P_i = \Delta P_1 + \Delta P_2$) occurs under combined action. In the case of ensuring conventional load power consumption, the controllable load needs to compete with the power consumption ΔP ($\Delta P = \Delta P_{ia} - \Delta P_i$). The controllable load that does not compete with the electricity right needs to be reduced.

2.2 Market subsidy mechanism design

According to the analysis of the supply and demand balance during the peak load period, the main market players involved in ancillary services are power grid companies, controllable load enterprises, and new energy enterprises. According to the market behavior, the controllable load can be divided into two categories: the controllable load that competes with the power right is called the non-reduced load; the controllable load that is not competitive with the power consumption right needs to limit the power consumption, which is called the reduced load.

It is necessary to subsidize the contribution of the reduced load to power balance. Based on the principle of who benefits and who compensates, two subsidies are designed as follows.

First, the reduced load is compensated by the non-reduced load through the power grid company. The non-reduced load obtains the power right in a way higher than the market clearing price in the competition, and the power grid company receives the profit higher than the market clearing price. As an intermediate link, the power grid subsidizes the reduced load with surplus earnings. Second, the new energy enterprise compensates for the reduced load, according to the prediction error vacancy ΔP_2 caused by themselves, as shown in Figure 2.

3 The compensation method for the reduced load by the non-reduced load

In this section, the controlled loads are first auctioned by a sequential auction to determine the reduced and non-reduced loads, as well as the excess electricity fee paid by the non-reduced loads to the power grid company. Second, the power grid company will compensate for the reduced loads, according to the principle of reduction loss distribution.

3.1 Sequential auction method

Step 1. The basic information of the auction suppliers and demanders is determined. During the peak power consumption statistical period T, the power grid company will auction the bidding electricity ($\Delta P*T$). The whole auction is divided into three rounds, and the power ratio of the three rounds is X: Y: Z. The reference electricity price is B. Moreover, the set of controllable loads participating in the bidding is $N = \{1, 2, ...n\}$, and the total demand of controllable loads is ΔE_{ia}:

$$\Delta E_{ia} = \Delta P_{ia}*T. \tag{1}$$

Step 2. The kth round of declaration. According to its own needs, each controllable load will declare the adjustable power in three stages: $[a_{k,1}, a_{k,2})$, $[a_{k,2}, a_{k,3})$, and $[a_{k,3}, a_{k,4}]$, and the corresponding quotations are $b_{k,1}$, $b_{k,2}$, and $b_{k,3}$, respectively. If the declaration results by the controllable load do not meet the basic principles of the sequential auction, a re-declaration opportunity will be given. If the second declaration still does not meet the requirements, the controllable load will be out.

Step 3. The kth round of auction. As shown in Figure 3, the transaction priority is obtained by arranging the final prices in descending order. Transactions are completed in order until the declared electricity of the power grid or the electricity of the controllable load is exhausted, and the lowest transaction price b_k of this round is obtained. The controllable load whose quotation is higher than b_k shall be concluded at the declared price. Then, the auction results of this round are published. The controllable loads that failed in bidding will be out, and the ones that succeeded will enter the (k+1)-th round.

Step 4. Multi-round auction. If $k < 3$, let $k = k+1$, and return to step 2 for the next round of auction. The maximum demand of the controllable load entering the next round of auction is

$$a_{(k+1),4} = a_{k,4} - A_k, \tag{2}$$

where A_k represents the electricity obtained by the kth round auction of the ith controllable load. a_{k4} and $a_{(k+1)4}$ represent the maximum demand of the i-th controllable load at the k-th and the k+1-th rounds, respectively. If $k = 3$, the auction ends.

Step 5. At the end of the auction, the controllable loads and their transaction price and electricity quantity that have been successfully auctioned in three rounds will be announced. The controllable loads that have not been successfully auctioned shall be reduced for the power consumption.

Step 6. The excess electricity fees (R) paid to the grid company by the non-reduced load are calculated as

$$R = \sum_{i=1}^{n}\sum_{k=1}^{3}\sum_{j=1}^{3}\Delta E_{k,i}^{j}\left(b_{k,i}^{j} - B\right), \tag{3}$$

where $\Delta E_{k,i}^{j}$ and $b_{k,i}^{j}$ represent the transaction price and electricity quantity of the i-th controllable load at the j-th stage in the k-th round, respectively. The sequential auction process is shown in Figure 4.

In order to improve the efficiency of the sequential auction, the basic principles are as follows:

(1) The re-quotation submitted for the same controllable load in each round must be greater than or equal to the first quotation.
(2) The quotation of the same controllable load in the next round must be greater than or equal to the quotation of the previous round.
(3) The controllable load of the previous round is forbidden to participate in the next round.

3.2 Compensation method according to the reduction loss

When the controllable loads are reduced, the following loss will generally be caused:

$$C_i = \Delta E_i \cdot f_i \cdot F_i + \eta_i\left(1 - \xi_i \cdot \frac{E_i - \Delta E_i}{E_i}\right)J_i + G_i, \tag{4}$$

$$\Delta E_i = \sum_{k=1}^{3}\sum_{j=1}^{3}\Delta E_{k,i}^{j}, \tag{5}$$

where ΔE_{i} refers to the reduced electricity quantity of the i-th reduced load, f_i is the unit electric energy output, and F_{i} refers to the unit output income. η_i and E_i represent the rated efficiency and electricity of the i-th reduced load during the statistical period, respectively. ξ_i refers to the loss coefficient. J_i and G_i are the unit efficiency loss cost and the regulation cost of the i-th reduced load, respectively.

According to the proportional distribution of the reduction loss, the compensation R_i provided by the grid company for each reduced load is determined by the following equation:

$$R_i = R\frac{C_i}{\sum_{i=1}^{n}C_i}. \tag{6}$$

4 Compensation method for new energy enterprises for the reduced load

4.1 Total compensation provided by new energy enterprises for the reduced load

When the intra-day predicted value of the new energy output is less than the pre-day predicted value, there will be a risk of power supply imbalance during the peak period of power consumption. This section adopts the punishment of the loss

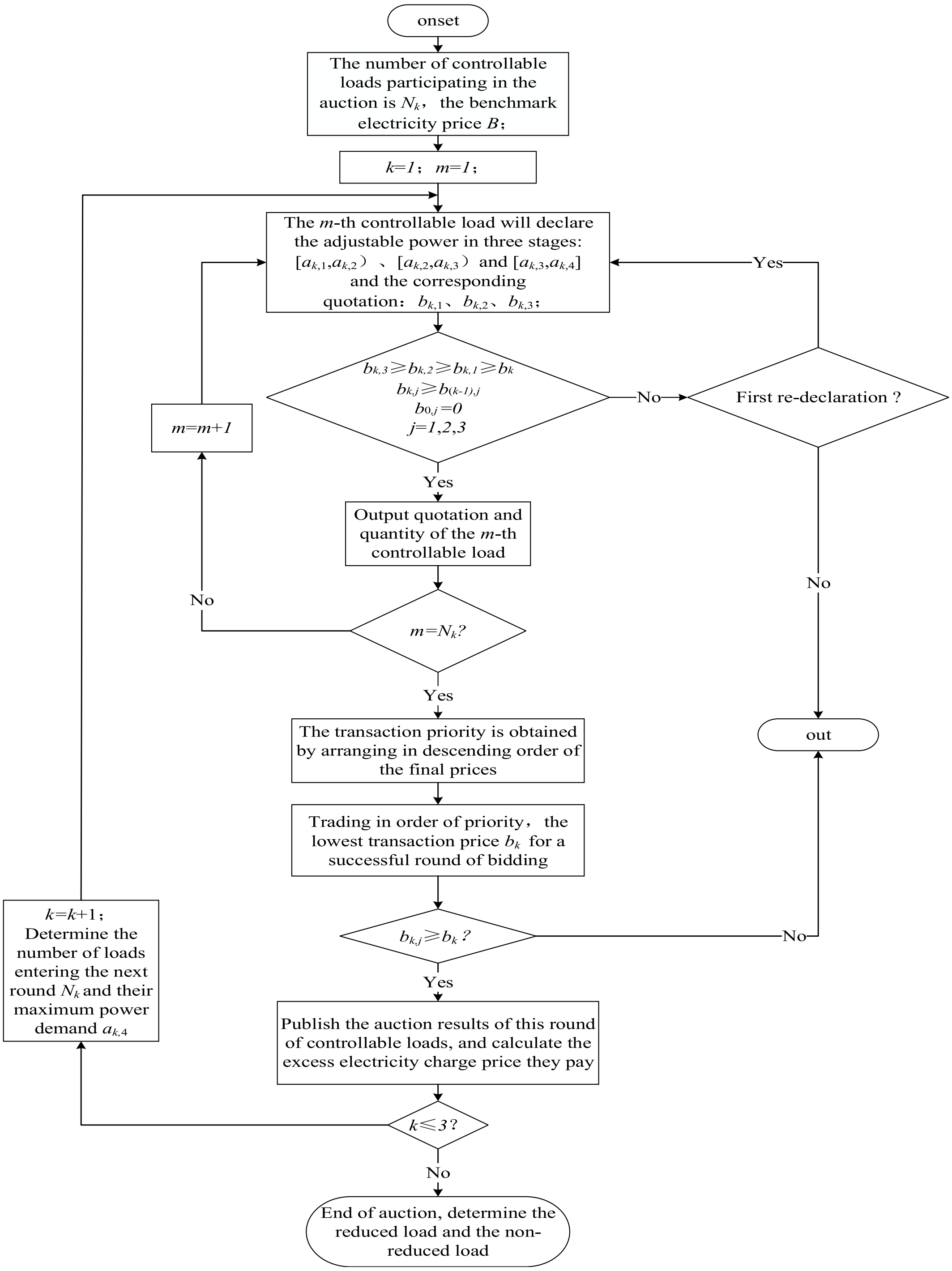

FIGURE 4
Flow chart of the sequential auction.

of load caused by prediction errors as a high penalty for new energy enterprises. When the controllable load is reduced, the loss of load will decrease, and the corresponding punishment w will be reduced. The calculation process is as follows:

$$w = \mu \sum_{t=1}^{T} (\Delta P_2 \times t), \tag{7}$$

$$d_t = \Delta P_2 \times t, \tag{8}$$

where μ is the punishment factor for the loss of load and d_t is the amount of the loss of load in period T.

The new energy enterprise compensates for the reduced load. The overall compensation cost w' is calculated as follows:

$$w' = \alpha w \tag{9}$$

with the compensation coefficient α.

4.2 Individual compensation method for the reduced load

Suppose the carbon emission rate of the i-th reduced load is H_i, the comprehensive index after standardization is y_i:

$$y_i = \beta \cdot \frac{\Delta E_i}{\Delta E_{i,\max}} + (1-\beta) \cdot \frac{1/H_i}{1/H_{i,\min}}, \tag{10}$$

with weight β.

According to the proportional distribution of the comprehensive index, the compensation W_i provided by the new energy enterprise for each reduced load is determined, as shown in Eq. 11.

$$W_i = w' \cdot \frac{y_i}{\sum_{i=1}^{n} y_i}. \tag{11}$$

5 Power-balancing compensation method of controllable load reduction

Combining the aforementioned two types of compensation, a power-balancing compensation method for controllable load reduction is formed. The whole process is as follows:

(1) Data prediction. The prediction value of the total load power P_{id} and conventional load power P_{ib} is obtained, as well as the pre-day and intra-day forecast of the total power generation P_{ic} and P_{is}.
(2) Vacancy prediction. The absolute power vacancy $\Delta P_1 = P_{id} - P_{ic}$ and the prediction error vacancy $\Delta P_2 = P_{ic} - P_{is}$ are calculated. Then, we can obtain $\Delta P = P_{id} - P_{ib} - \Delta P_1 - \Delta P_2$. If $\Delta P > 0$, step 3 is performed for the competitive electric power; otherwise, other compensation will be carried out.
(3) Sequential auction. According to the method described in Section 3.1, the reduced and non-reduced loads are determined, and the excess fee paid for the non-reduced load is obtained.
(4) Based on the method in Section 3.2, the non-reduced load is compensated by the reduced load through the power grid company.

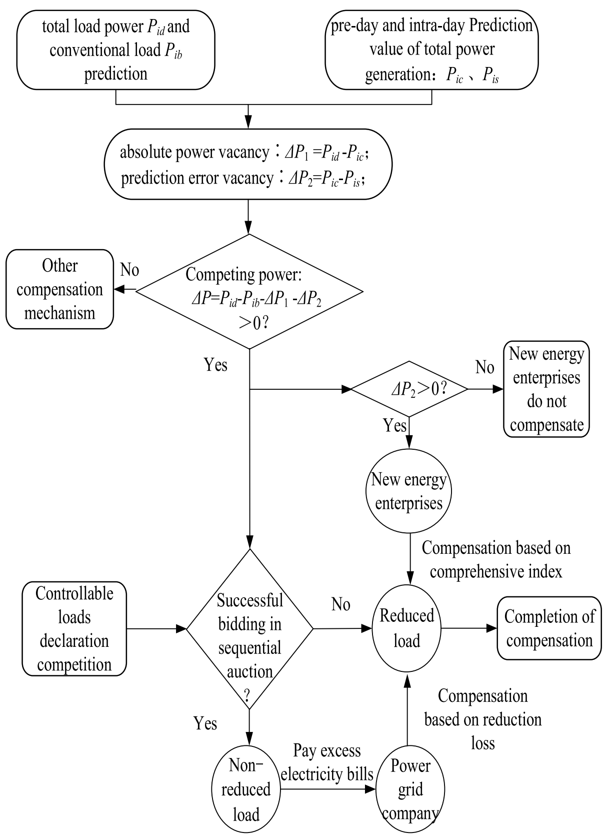

FIGURE 5
Flow chart of the power-balancing compensation method.

(5) If $\Delta P_2 > 0$, as described in Section 4, the new energy enterprise compensates for each reduced load, according to the principle of proportional distribution of the comprehensive indicator. If not, the new energy enterprise will not compensate. The flowchart of the whole method is shown in Figure 5:

6 Example analysis

6.1 Example setting

In a regional power grid, the total installed capacity of the wind turbine is 3,500 MW, the maximum capacity of the conventional load is 10,000 MW, the total capacity of the power supply is 13,000 MW, and the controllable load is 560 MW. Taking 4 h as the intra-day prediction and control step of the controllable load, the maximum load demand at the peak of power consumption from 20:00 to 22:00 predicted at 16:00 in the day is 10,400 MW, and the total output of the power supply is 10,120 MW. Moreover, the predicted intra-day wind power is 2,400 MW, which is less than the pre-day prediction 2,500 MW.

TABLE 1 Regulation information of controllable loads.

	Electrolytic aluminum 1	Electrolytic aluminum 2	Silicon carbide 1	Silicon carbide 2	Chemical fiber 1	Chemical fiber 2
Adjustable capacity/MW	200	80	100	60	80	40
f_i/kg	0.07	0.08	0.01	0.015	1.8	2
F_i/(dollar/kg)	1.01	1.16	3.62	4.35	0.13	0.14
η_i	0.9	0.91	0.4	0.45	0.85	0.9
J_i/dollar	5.79	2.90	2.17	2.90	5.07	5.79
G_i/dollar	145	145	116	116	29	29
ξ_i	0.1	0.3	0.01	0.01	0.9	0.9
H_i	0.65	0.6	0.7	0.75	0.8	0.85

TABLE 2 First round declaration results of controllable load enterprises.

Controllable load	Power demand/(MWh)	Quote/(dollar/MWh)
Electrolytic aluminum 1	First stage [0,150)	130
	Second stage [150,360)	148
	Third stage [360,400]	161
Electrolytic aluminum 2	First stage [0,80)	130
	Second stage [80,130)	152
	Third stage [130,160]	159
Silicon carbide 1	First stage [0,100)	130
	Second stage [100,180)	143
	Third stage [180,200]	152
Silicon carbide 2	First stage [0,50)	133
	Second stage [50,80)	142
	Third stage [80,120]	156
Chemical fiber 1	First stage [0,70)	142
	Second stage [70,90)	158
	Third stage [90,160]	165
Chemical fiber 2	First stage [0,20)	138
	Second stage [20,30)	155
	Third stage [30,80]	164

The industrial electricity benchmark price during the peak period of electricity consumption is 127 dollars/MWh. The punishment factor for the loss of load μ is 72 dollars/MWh. The control information for a total of six controllable load enterprises is shown in Table 1.

6.2 Process calculation

Step1. Calculation of the deficiency. The absolute power shortage vacancy ΔP_1 = 280 MW, the prediction error vacancy ΔP_2 = 100 MW, and the competing power ΔP = 180 MW are calculated.

Step 2: Bidding auction. During the 20–22 o ‘clock period of peak electricity consumption, the power grid company auctions the bidding power 360 MWh as commodities. The whole auction is divided into three rounds, and the power ratio of the three rounds of the auction was 6: 3: 1. The first round of demand declaration shall be conducted for the controllable load, according to an adjustable maximum capacity of 2 h. The upper limit of the declared electricity price is 150% of the benchmark, and the three-stage quotations of the controllable load enterprises are shown in Table 2.

TABLE 3 First round bidding results of controllable load enterprises.

Controllable load	Trading stage	Transaction value/(dollar/MWh)	Transaction power/(MWh)
Chemical fiber 1	Third stage	165	70
Chemical fiber 2	Third stage	164	50
Electrolytic aluminum 1	Third stage	161	40
Electrolytic aluminum 2	Third stage	159	30
Chemical fiber 1	Second stage	158	20
Silicon carbide 2	Third stage	156	6

TABLE 4 Second round sequential auction adjustable electricity of controllable load enterprises.

Electrolytic aluminum 1/(MWh)	Electrolytic aluminum 2/(MWh)	Silicon carbide 2/(MWh)	Chemical fiber 1/(MWh)	Chemical fiber 2/(MWh)	Sum/(MWh)
360	130	114	70	30	704

TABLE 5 Second round bidding results of controllable load enterprises.

Controllable load	Trading stage	Transaction value/(dollar/MWh)	Transaction power (MWh)
Chemical fiber 1	Third stage	172	50
Electrolytic aluminum 1	Third stage	169	30
Chemical fiber 2	Third stage	167	20
Electrolytic aluminum 2	Third stage	162	8

TABLE 6 Third round bidding results of controllable load enterprises.

Controllable load	Trading stage	Transaction value/(dollar/MWh)	Transaction power (MWh)
Chemical fiber 1	Third stage	174	10
Chemical fiber 2	Third stage	172	5
Electrolytic aluminum 1	Third stage	171	21

The priority order is arranged in descending order of the price, and the transaction is completed in order until the declared capacity or adjustable load capacity of the power grid is exhausted. The first-round bidding results are shown in Table 3.

At the end of the first round of the auction, silicon carbide enterprise 1 does not get electricity distribution and is forbidden to participate in the next round of the auction. Then, the adjustable power of the controllable load enterprises entering the second round of auction changes, as shown in Table 4.

The aforementioned steps are repeated for the second and third rounds of auctions, and the bidding results are shown in Tables 5, 6.

Step 3: The compensation from the non-reduced load to the reduced load is calculated. The excess electricity charge R paid to the grid company by the non-reduced load is 13,833 dollars. According to the proportion of electricity distribution, calculations of the compensation are shown in Table 7.

Step 4: The compensation of new energy to the reduced loads is calculated. In this study, the coefficient of new energy compensation is biased toward the reduced load, so $\alpha = 0.8$, $d_t = 200\,\mathrm{MW}h$, $w = 14485$ dollars, $w_1 = 11588$ dollars, and $\beta = 0.7$. According to the proportion of comprehensive index y_i, the calculation of the compensation is as shown in Table 8.

TABLE 7 Loss and compensation of the reduced loads.

Controllable load	Reduced power/(MWh)	C_i/dollar	Compensation/dollar
Electrolytic aluminum 1	301	21,514	5,753
Electrolytic aluminum 2	122	11,458	3,064
Silicon carbide 1	200	7,359	1,968
Silicon carbide 2	114	7,548	2,018
Chemical fiber 1	10	2,376	635
Chemical fiber 2	5	1,478	395

TABLE 8 Comprehensive index of the reduced loads and their new energy compensation.

Controllable load	y_i	New energy compensation/dollar
Electrolytic aluminum 1	0.98	3,473
Electrolytic aluminum 2	0.58	2,075
Silicon carbide 1	0.72	2,567
Silicon carbide 2	0.51	1,796
Chemical fiber 1	0.25	883
Chemical fiber 2	0.22	794

6.3 Result analysis

According to the known conditions of the calculation example, the vacancy of 2 h is 380*2 = 760 (MWh). From Tables 3, 5, 6, the powers traded in the three stages are 216 MWh, 108 MWh, and 36 MWh, respectively. The reduction power is 560*2–216–108–36 = 760 (MWh), which is equal to the vacancy. It means that the power supply balance is realized through controllable load reduction.

The lowest transaction price in the first round is 156 dollars/MWh, while the quotation of silicon carbide 1 in the third round is only 152 dollars/MWh. Therefore, it is out in the first round and cannot participate in the subsequent declaration. Through this principle, competition can be formed to avoid monopolizing the power use right.

Moreover, it can be seen from Tables 7, 8 that during the peak period of power consumption, the total compensation paid for by the non-reduced load and the new energy enterprises to the reduced load is 13,833 and 11,588 dollars, respectively, and the two types of compensation are similar. The parameter α is an important factor affecting the enthusiasm of the reduced load. The increase in α can further improve the compensation value paid for by the new energy enterprises.

7 Conclusion

With respect to the shortage of power supply in the peak period of a new energy power system, this study has proposed a mechanism and method of controllable load reduction to ensure power supply balance. Specifically,

(1) On one hand, the sequential auction method has been used to determine reduced and non-reduced loads. On the other hand, double compensation has been carried out according to the reduction loss, the reduced electricity quantity, and the weighted index of the carbon emission rate.
(2) The example analysis shows that the sequential auction can effectively guarantee the power supply balance. In the traditional power system, the prediction error is small, and the compensation for the reduced load is mainly paid for by the non-reduced load through the power grid company. However, in the new energy power system, the compensation paid for by the new energy enterprises is an important factor to improve the enthusiasm of the reduced load. When the total power vacancy is greater than the adjustable capacity of the controllable loads, other compensation mechanisms need to be further developed to achieve more interruptible loads to ensure power supply balance.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, YS and YL; methodology, KD and WD; validation, YS and YL; resources, CY; data curation, CY and WD; writing—original draft preparation, WD and YL; and writing—review and editing, YS, YL, and KD. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

Authors YS, KD, and CY were employed by the company the Economic and Technological Research Institute of the State Grid Gansu Electric Power Company.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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