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Design of a Stochastic Electricity Market Mechanism with a High Proportion of Renewable Energy

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Abstract: Renewable energy, such as wind power and photovoltaic power, has uncertain and intermittent characteristics and zero marginal cost characteristics. The traditional power market mechanism is difficult to adapt to the new power system with a high proportion of renewable energy, and the original market system needs to be reformed. This paper discusses the application of a VCG auction mechanism in the electricity market, proposes a two-stage VCG market-clearing model based on the VCG mechanism, including the day-ahead market and the real-time market, and discusses the nature of the VCG mechanism. In order to address the discrepancy between the actual output of stochastic generator sets in the real-time market and their pre-scheduled output in the day-ahead market due to prediction deviations, a method for calculating punitive costs is proposed. A reallocation method based on market entities' contributing factors to budget imbalance is proposed to address the issue of budget imbalance under the VCG mechanism, in order to achieve revenue and expenditure balance. Through an example, the incentive compatibility characteristics of the VCG mechanism are verified, the problems of the locational marginal pricing (LMP) mechanism in the stochastic electricity market with a high proportion of renewable energy are analyzed, the electricity prices of the LMP mechanism and the VCG mechanism under different renewable energy proportions are compared, and the redistribution of the budget imbalance of the VCG mechanism is analyzed.

Keywords: stochastic electricity market; VCG auction mechanism; budget imbalance; punitive cost

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Citation: Liu, Y.; Chen, M.; Fan, Y.; Ying, L.; Cui, X.; Zou, X. Design of a Stochastic Electricity Market Mechanism with a High Proportion of Renewable Energy. *Energies* **2024**, *17*, 3044. https://doi.org/10.3390/en17123044

Academic Editor: Jay Zarnikau

Received: 15 May 2024
Revised: 12 June 2024
Accepted: 15 June 2024
Published: 20 June 2024

1. Introduction

1.1. Research Background

In recent years, the issue of carbon emissions has received great attention around the world [1]. In March 2021, the Chinese government proposed the "3060 Goal", which aims to achieve carbon peaking by 2030 and carbon neutrality by 2060. At the same time, in order to ensure the utilization of sustainable energy, the operating form of the power grid has undergone significant changes, with rapid changes in power source types and a sustained and rapid increase in the proportion of new energy. In recent years, China's investment in new energy power generation has rapidly grown. By the end of 2023, China's installed power generation capacity was 2.92 billion kilowatts, of which 1.57 billion kilowatts are non-fossil energy power generation capacity, accounting for more than 50% of the total installed capacity for the first time in 2023, reaching 53.9% [2].

The new energy power generation, such as wind and photovoltaic power generation, has the characteristics of uncertain and intermittent, and it is uncontrollable or not completely controllable. From an economic point of view, new energy power generation has the characteristics of zero marginal cost. However, the design of the traditional locational marginal pricing (LMP) mechanism is based on conventional power sources, which are predictable and completely controllable. Furthermore, from an economic perspective, conventional power sources have a certain marginal cost. The purpose of market mechanism design is to expect power generation companies to quote at marginal cost in order to achieve maximum social benefits. Under the LMP mechanism, if an area is completely powered by new energy units, and the new energy power generation is quoted at zero marginal cost, the marginal electricity price of the node in the area is zero, which is obviously unreasonable. In addition, in a perfectly competitive electricity market, the LMP mechanism has incentive compatibility characteristics [3]. However, the actual electricity market does not have the conditions of perfect competition, and power generation companies have a certain degree of market power. Therefore, with the LMP mechanism, it is difficult to incentivize power generation companies to quote truthfully. Power generation companies seek maximum profits through strategic pricing, such as false reporting of high prices and capacity retention, thereby undermining social benefits and reducing market efficiency.

In view of the transformation of the power generation mode and the change in the power system operation mode, it is urgent to change the original market system or design a new market mechanism [4,5]. The design of the market mechanism needs to emphasize the synergy of new energy, traditional energy, and flexible resources to coordinate the technical characteristics and economic endowments of flexible resources, such as traditional coal-fired power generation, hydroelectric power generation, and new energy power generation. The government, industry, and academia are all aware of the inadaptability of the current market mechanism, and the exploration and research of the market mechanism has become one of the hot spots in the research of the power industry in the context of the new power system [6–11]. Zhu Yonggang et al. proposed a decentralized decision-making competition mechanism applied to the generation-side electricity market based on the theory of economic mechanism design, in order to reduce the strategic behavior of power generation enterprises and coordinate individual interests with overall interests [6].

Recently, the famous Vickrey Clark Groves (VCG) mechanism has attracted the attention of scholars. The market-clearing method of the VCG mechanism and the LMP mechanism is the same; that is, under the conditions of meeting the system (node) power balance constraints, line power flow constraints, and generator set performance parameter constraints, the pursuit is in maximizing social welfare or the lowest power purchase cost to arrange the unit commitment. Under the VCG mechanism, the payment of market participants is calculated based on their contribution to social welfare by participating in the market. On the one hand, the problem of zero marginal cost of large-scale intermittent power generation is solved. On the other hand, the VCG mechanism internalizes social welfare into the optimization goal of market participants, so that power producers have no incentive to use strategic quotation to seek profits and eliminate the hidden concern of generation companies exercising market power in the market. That is to say, under the equilibrium strategy of each power generation company quoting based on the actual cost, the total system cost is minimized, thereby achieving maximum social welfare. That is, the VCG mechanism is incentive-compatible.

1.2. Related Work

It has been proven in both theory and practice that it is difficult for the marginal price mechanism to promote the real quotation of market members, and it is difficult to solve the problem of information asymmetry in the power system. In order to promote the rational quotation of market members and realize the optimal allocation of power resources, Wang Jianxiao et al. [12] analyzed this phenomenon and reasons why the marginal price makes it difficult to guarantee the real quotation of generators, resulting in the loss of market efficiency. The market-clearing mechanism based on the VCG mechanism proved that the mechanism has the characteristics of incentive compatibility and individual rationality, and the effectiveness of the mechanism was verified by a numerical example. The paper did not discuss the problems of VCG mechanisms, such as balance of payments.

With the increase in the proportion of renewable energy, the demand for power ancillary services in the power system has further increased, especially the balance services of the system, such as reserve capacity, frequency response, and reactive power, so as to maintain the stability of the power system. There are different types of power ancillary services, different technical characteristics, their forms tend to be complex, and the cost of services is gradually increasing. One of the challenges faced by the system operator (SO) is how to determine the optimal quantity and quality of power ancillary services (e.g., frequency response) and ensure the balance between technology and economy. The VCG mechanism was used to identify the cost of ancillary services provided by thermal power units and quantify the externality value of ancillary services provided by thermal power units in [13]. Thomas Grevea et al. [14] took frequency regulation services as an example, combined with the response speed of different frequency regulation services to frequency deviation and other technical parameters. They proposed the utility function of the system operator, and the VCG auction mechanism was introduced to requisition the frequency regulation services required by the system. Addressing the problem of electric energy trading in multi-regional power systems, in [15], an incentive mechanism based on VCG auction was proposed. An economic dispatch model based on AC/DC hybrid was established for the joint clearing of a two-stage, multi-regional energy market and reserve market. The effectiveness and efficiency of the mechanism were verified by examples.

With the popularization of distributed renewable energy and plug-in electric vehicles, residential electricity consumers can participate in the regional electricity market and improve the regulation capacity of the power system by participating in the trading of surplus electricity. In [16], the VCG mechanism was applied to the emergency load trading between electric vehicles and the power grid, and a two-stage model was proposed. The model used the VCG mechanism to pay the winning bidder, while taking into account the mobility and battery degradation costs of EVs to ensure that EVs are sufficiently motivated to participate in peak shaving of the grid.

When applying the VCG mechanism to regional electricity markets, budget imbalance is a common problem. In [17], an automatic mechanism design method based on deep learning was proposed to improve VCG to solve the budget imbalance problem. The authors of [18] introduced the clearing reference price and designed a VCG mechanism based on that price. However, they noted that there may be certain social welfare losses, and the selection of social welfare losses and liquidation reference prices was more sensitive. Theoretically, the reference price was the best at the marginal price of the current transaction, but it often led to the failure of the incentive compatibility of the mechanism. The authors of [19] adopted the method of shared responsibility between power generation companies and users. The power generation side allocates a portion of the profits of the power generation companies, while the user side collects additional fees based on node collection methods to achieve system revenue and expenditure balance. In addition, some scholars have studied the issue of collusion-proof in VCG mechanisms and have made certain research progress [20–23].

1.3. Summary of Contributions

This paper introduces the VCG auction mechanism into the stochastic electricity market with a high proportion of renewable energy, and its main contributions include:

- A two-stage electricity market-clearing model based on the VCG mechanism is proposed, which includes the payments received by conventional generator units and stochastic power sources in the day-ahead market (DAM) and real-time market (RTM).
- A penalty fee calculation method based on the principle of responsibility sharing is proposed to address the issue of increased system operating costs caused by prediction bias in stochastic generators.
- A redistribution mechanism based on the contribution factors of participants to the budget imbalance in the VCG mechanism in the electricity market is proposed.

Finally, this paper verifies the incentive compatibility characteristics of the VCG mechanism through an example, analyzes the problems existing in the LMP mechanism in the stochastic electricity market with a high proportion of renewable energy, compares the electricity prices of the LMP and VCG mechanisms under different renewable energy proportions, and discusses the budget imbalance allocation ratio of the VCG mechanism.

2. General Issues in the Design of the Electricity Market Mechanism

The current typical, unilateral electricity market belongs to the reverse auction market. There are several bidders in the auction market for the subject matter. Each bidder i has a private true cost function c_i, and $c_i(0) = 0$. Each bidder i submits a bidding function to the system operator, denoted as b_i, and $b_i(0) = 0$. This forms a set of bidding functions, $\mathcal{B} = \{b_1, b_2, \cdots, b_m\}$, denoted as $\mathcal{B} = \{b_i\}_{i \in \mathcal{M}}$.

The market mechanism has predetermined allocation and payment rules. For a given set of bids, $\mathcal{B} = \{b_i\}_{i \in \mathcal{M}}$, the system operator determines whether the bidder has won the bid and the winning bid quantity, $q_i^*(\mathcal{B})$, based on the rules, and determines the payment, $p_i(\mathcal{B})$, received by the winning bidder. In the electricity market, distribution rules are generally determined by economic dispatch, which minimizes the cost of purchasing electricity under certain safety constraints:

$$\begin{gathered} J(\mathcal{B}) = \min \textstyle\sum_{i \in \mathcal{M}} b_i(q_i) \\ \text{s.t. } h(q) = 0 \; g(q) \leq 0 \end{gathered} \tag{1}$$

where, $h(q)$ is the equality constraint of the optimal problem, and $g(q)$ is the inequality constraint. When solving the optimal power flow, it is necessary to meet the constraints of the power network, such as the constraints of power balance, node voltage, and phase, the transmission capacity of the line, and the technical or economic constraints of the generator's output. The optimization issue is denoted as $J_{\mathcal{B}}$. The optimization problem can include general power market problems, such as the co-optimization problem of the energy market and reserve market, and the power market with stochastic resources, etc., and the objective function needs to be extended.

Let the optimal solution of $J_{\mathcal{B}}$ be represented as $q^*(\mathcal{B})$, the payment received by the bidder is $p_i(\mathcal{B})$, and its utility is $u_i(\mathcal{B})$:

$$u_i(\mathcal{B}) = p_i(\mathcal{B}) - c_i\left(q_i^*(\mathcal{B})\right) \tag{2}$$

If the bidder is not accepted, then $q_i^*(B) = 0$, so the payment is zero, i.e., $u_i(\mathcal{B}) = 0$. The total utility of the system operator can be expressed as:

$$u_{\text{op}}(B) = -\textstyle\sum_{i \in \mathcal{M}} p_i(\mathcal{B}) \tag{3}$$

The ideal market mechanism should have the following basic attributes: Nash equilibrium and dominant strategy equilibrium, incentive compatibility, individual rationality, and collusion-proof. The nature of bidders' marketing activities is to maximize profits, and they always build bidding strategies around market rules, so payment design plays a vital role in market operations.

In a typical electricity market, market participants include system operators, $i = 0$, and bidders, $\mathcal{M} = \{1, 2, \cdots, m\}$. The main subject matter in the electricity market is electricity, which can also include different types of power ancillary services, such as reserve, frequency regulation, peak shaving, etc. Bidders can bid on electricity or different types of ancillary services for which the subject matter is substitutable to the system operator or power user, such as reserve, which can be provided by different bidders.

Each bidder submits its bid function, b_i, to the system operator, which is generally the amount of electricity (volume of electrical auxiliary services) at different prices, or offers in stages, forming a set of bid functions: $\mathcal{B} = \{b_i\}_{i=1}^m$. The system operator determines the winning power of each bidder according to the market rules (lowest power purchase cost or maximum social welfare). According to the VCG mechanism, the winning bidder will be paid as:

$$p_i(\mathcal{B}) = J(\mathcal{B}_{-i}) - \left[J(\mathcal{B}) - b_i\left(q_i^*(\mathcal{B})\right) \right] \tag{4}$$

where $\mathcal{B}_{-i}$ is the set of bid functions excluding bidder i, $\mathcal{B}_{-i} = \{b_1, b_2, \cdots, b_{i-1}, b_{i+1}, \cdots, b_m\}$. The function $J(\mathcal{B}_{-i})$ is the objective function value of removing bidder i; that is, the minimum $J_{\boldsymbol{B}}$ objective function of the optimization problem when bidder i is removed from the objective function and constraints ($q_i = 0$).

This mechanism determines the payment of a bidder when there is a feasible distribution scheme to eliminate the bidder. This assumption can be satisfied in the general electricity market. However, in the oligopoly electricity market, if a certain power producer has a large market share and the system load demand is high, the payment of the bidder will be reduced. Unilateral market mechanisms make it difficult to meet this condition, and one solution is to enable a demand response to regulate load levels. In the optimization problem $J_{\mathcal{B}}$, the VCG mechanism satisfies individual rationality (IR), dominant strategy incentive compatibility (DSIC), and efficiency. Under the VCG mechanism, the utility of the system operator can be maximum, and the total payment generated can be minimum.

The electricity spot market generally has two stages. The first stage is the DAM, where system operators combine and pre-clear units based on the quotes declared by conventional generators, the predicted output, and quotes declared by renewable energy generators. The second stage is the RTM. Due to the unavoidably biased power prediction of stochastic generating units, such as wind power, it is necessary to adjust the output of the generating units or loads. The objective function is to minimize the generator or load adjustment cost. The adjustment cost includes the expected adjustment generation cost and the expected load reduction cost in real-time dispatching.

The stochastic power market includes both conventional and stochastic generators. There are M_{C} conventional generation units, M_{R} renewable energy generation units, and M_{D} power users in the market. The units' declared price or the quotation curves are as follows:

- The quotation and output of conventional units in the DAM

In the DAM, conventional generators declare the price of different output ranges. If K_i represents the total number of quoted segments of unit i, $\overline{P}_{i,k}^{\mathrm{CO}}$ and $\underline{P}_{i,k}^{\mathrm{CO}}$ represent the upper and lower limits of the k output segments declared by conventional unit i, respectively, $b_{i,k}^{\mathrm{CO}}$ represents the price corresponding to the output range of segment k declared by generator i, $P_{i,t,k}^{\mathrm{CO}}$ represents the bid power of generator i in the output interval of segment k at period t, then the output of generator i at period t is:

$$P_{i,t}^{\mathrm{CO}} = \sum\nolimits_{k=1}^{K_i} P_{i,t,k}^{\mathrm{CO}} \tag{5}$$

where $\underline{P}_{i,k}^{\mathrm{CO}} \le P_{i,t,k}^{\mathrm{CO}} \le \overline{P}_{i,k}^{\mathrm{CO}}$.

Then, under the declared pricing strategy, the cost of generator i at period t is:

$$b_{i,t}^{\mathrm{CO}}\left(P_{i,t}^{\mathrm{CO}}\right) = \sum\nolimits_{k=1}^{K_i} b_{i,k}^{\mathrm{CO}} P_{i,t,k}^{\mathrm{CO}} \tag{6}$$

- The increase and decrease of the output of conventional units in the RTM

Conventional generators need to increase or decrease output in the RTM. $b_{i,t}^{\mathrm{CO}+}$ and $b_{i,t}^{\mathrm{CO}-}$ are the quotations for increasing or decreasing the output of conventional unit i in the RTM at period t, respectively.

In addition, due to the need for system (node) power balance, a load may be forced to reduce the power consumption and thus let the value of loss of load d forced to reduce the load be V_d.

- Quotation and output of stochastic generator

Similar to conventional units, stochastic generators declare the quotation of different output ranges. If K_j represents the total number of quoted segments of stochastic generator j, $\overline{P}_{j,k}^{\mathrm{RE}}$ and $\underline{P}_{j,k}^{\mathrm{RE}}$, respectively, represent the upper and lower bounds of the k output interval declared by unit j, and $b_{j,k}^{RE}$ represents the energy price corresponding to the k output interval declared by stochastic generator j. $P_{j,t,k}^{\mathrm{RE}}$ represents the winning power of unit j in the output segment k at period t; then, the output of generator i at period t is:

$$P_{j,t}^{\mathrm{RE}} = \sum_{k=1}^{K_j} P_{j,t,k}^{\mathrm{RE}} \tag{7}$$

where $\underline{P}_{j,k}^{\mathrm{RE}} \leq P_{j,t,k}^{\mathrm{RE}} \leq \overline{P}_{j,k}^{\mathrm{RE}}$.

Under the declared quotation strategy, the cost of stochastic generator j at period t is:

$$b_{j,t}^{\mathrm{RE}}\left(P_{j,t,k}^{\mathrm{RE}}\right) = \sum_{k=1}^{K_j}\left(b_{j,k}^{\mathrm{RE}} \cdot P_{j,t,k}^{\mathrm{RE}}\right) \tag{8}$$

3. VCG Clearing Model in DAM

The quotation function set $\mathcal{B}$ of each generator manufacturer is assumed to contain two subsets, namely, the quotation function subset $\mathcal{B}^{\mathrm{C}}$ of the conventional generator manufacturer and the quotation function subset $\mathcal{B}^{\mathrm{R}}$ of the stochastic generator, namely, $\mathcal{B} = \left\{\mathcal{B}^{\mathrm{C}} \bigcup \mathcal{B}^{\mathrm{R}}\right\}$. $\mathcal{B}^{\mathrm{C}}$ contains the energy price $b_{j,k}^{\mathrm{CO}}$ of different output segments of each conventional generator, and $\mathcal{B}^{\mathrm{R}}$ contains the energy price $b_{j,k}^{\mathrm{RE}}$ of different output segments of each stochastic generator and the predicted output $\overset{\sim\mathrm{RE}}{P}_{j,t}$ of each period.

3.1. Objective Functions and System Constraints

Under the set of quotation functions, $\mathcal{B} = \left\{\mathcal{B}^{\mathrm{C}} \bigcup \mathcal{B}^{\mathrm{R}}\right\}$, the expected cost, $\mathbb{E}\left(C^{\mathrm{CO}}(\mathcal{B})\right)$, of conventional units is:

$$\mathbb{E}\left(C^{\mathrm{CO}}(\mathcal{B})\right) = \sum_{i=1}^{M_{\mathrm{C}}}\sum_{t=1}^{T} b_{i,t}^{\mathrm{CO}}\left(P_{i,t}^{\mathrm{CO}}\right) \tag{9}$$

where T is the number of periods in a scheduling cycle. If the time of a period is 15 min, the number of periods in a DAM is 96; that is, $T = 96$.

The expected cost, $\mathbb{E}\left(C^{\mathrm{RE}}\left(\mathcal{B}^{\mathrm{R}}\right)\right)$, of the stochastic generators under subset $\mathcal{B}^{\mathrm{R}}$ is:

$$\mathbb{E}\left(C^{\mathrm{RE}}\left(\mathcal{B}^{\mathrm{R}}\right)\right) = \sum_{j=1}^{M_{\mathrm{R}}}\sum_{t=1}^{T} b_{j,t}^{\mathrm{RE}}\left(\overset{\sim\mathrm{RE}}{P}_{j,t}\right) \tag{10}$$

It should be noted that the stochastic generators can be zero-quoted, then $b_{j,k}^{\mathrm{RE}} = 0$, $(j = 1, 2, \cdots, M_{\mathrm{R}}; k = 1, 2, \cdots, K_j)$; that is, $\mathbb{E}\left(C^{\mathrm{RE}}\left(\mathcal{B}^{\mathrm{R}}\right)\right) = 0$.

Under bidding set $\mathcal{B}$, the system operator arranges the generator output according to the minimum expected power purchase cost. The objective function in the optimization problem J_B is:

$$J(\mathcal{B}) = \min\left\{\mathbb{E}\left(C^{\mathrm{CO}}(\mathcal{B}) + \mathbb{E}\left(C^{\mathrm{RE}}\left(\mathcal{B}^{\mathrm{R}}\right)\right)\right\} \tag{11}$$

When optimizing the unit output, system operators should also meet power system operating constraints and generator units' technical and economic constraints, including (1) node power balance constraints, (2) constraints on the upper and lower limits of unit output, (3) system reserve capacity constraints, (4) constraints on the ability of generator ramp rate, and (5) constraints on power flow of transmission lines.

3.2. Market Clearing in the DAM under the VCG Mechanism

Referring to Formula (11), let $J^{\mathrm{CO}}(\mathcal{B}_{-i})$ represent the minimum expected cost of the system excluding conventional unit i (i.e., $P_{i,t} = 0$), and $J^{\mathrm{RE}}(\mathcal{B}_{-j})$ represent the minimum expected cost of the system excluding stochastic generator j (i.e., $\tilde{P}{}^{\mathrm{RE}}_{j,t}$ =0).

The VCG mechanism is used to pay for both conventional and renewable energy generators. Firstly, the expected cost of conventional generator i is obtained based on the optimal unit combination. Under the bidding set $\mathcal{B}$, considering the stochastic generator's output prediction $\left\{\tilde{P}{}^{\mathrm{RE}}_{j,t}\right\}_{j=1}^{M_{\mathrm{R}}}$, and the unit quotation $\left\{b_{i,k}^{\mathrm{CO}}\right\}_{i=1}^{M_{\mathrm{C}}}$, $\left\{b_{j,k}^{\mathrm{RE}}\right\}_{j=1}^{M_{\mathrm{R}}}$, (18) is solved to obtain the optimal unit combination for conventional generators (i.e., the optimal solution of (18)). Let $P_{i,t}^{\mathrm{CO}*}(\mathcal{B})$ represent the optimal scheduling output for conventional generator i, and the expected cost of generator i is:

$$\tilde{C}{}_{i}^{\mathrm{CO}}(\mathcal{B}) = \mathbb{E}\left\{\sum\nolimits_{t=1}^{T} b_{i,t}^{\mathrm{CO}}\left(P_{i,t}^{\mathrm{CO}*}(\mathcal{B})\right)\right\} \tag{12}$$

The VCG payment received by the conventional generator i is:

$$p_{i}^{\mathrm{CO}}(\mathcal{B}) = J^{\mathrm{CO}}(\mathcal{B}_{-i}) - \left(J(\mathcal{B}) - \tilde{C}{}_{i}^{\mathrm{CO}}(\mathcal{B})\right), \quad i = 1, \cdots, M_{\mathrm{C}} \tag{13}$$

where, $J^{\mathrm{CO}}(\mathcal{B}_{-i})$ is the total cost of other generators when excluding conventional generator i, and $\left(J(\mathcal{B}) - \tilde{C}{}_{i}^{\mathrm{CO}}(\mathcal{B})\right)$ is the total cost of other generators when including conventional generator i. The payment $p_{i}^{\mathrm{CO}}(\mathcal{B})$ for conventional generator i represents the difference in the (expected) total cost of other traditional generators without and with generator i.

Similarly, the expected cost of a stochastic generator j is:

$$\tilde{C}{}_{j}^{\mathrm{RE}}(\mathcal{B}) = \mathbb{E}\left\{\sum\nolimits_{t=1}^{T} b_{j,t}^{\mathrm{RE}}(\tilde{P}{}^{\mathrm{RE}}_{j,t})\right\} \tag{14}$$

The VCG fee paid by the system operator to the stochastic generator j is:

$$p_{j}^{\mathrm{RE}}(\mathcal{B}) = J^{\mathrm{RE}}(\mathcal{B}_{-j}) - \left(J(\mathcal{B}) - \tilde{C}{}_{j}^{\mathrm{RE}}(\mathcal{B})\right), \; j = 1, 2, \cdots, M_{\mathrm{R}} \tag{15}$$

If the stochastic generator j adopts zero-quotation, the above formula can be rewritten as $\tilde{C}{}_{j}^{\mathrm{RE}}(\mathcal{B}) = 0$:

$$p_{j}^{\mathrm{RE}}(\mathcal{B}) = J^{\mathrm{RE}}(\mathcal{B}_{-j}) - J(\mathcal{B}), \quad j = 1, 2, \cdots, M_{\mathrm{R}} \tag{16}$$

3.3. VCG Clearing Process in Day-Ahead Market

The previous text provided a detailed VCG clearing model for the DAM. Now, the clearing process of DAM is summarized, as follows:

Step i: The quotation for different output intervals of the conventional unit $i (i = 1, 2, \cdots, M_{\mathrm{C}})$ is submitted, along with the upper and lower bounds of the k^{th} output interval, denoted as $\overline{P}_{i,k}^{\mathrm{CO}}$ and $\underline{P}_{i,k}^{\mathrm{CO}} (k = 1, 2, \cdots, K_i)$. The cost of the unit i at period t is determined by Equation (6). The stochastic generator $j (j = 1, 2, \cdots, M_{\mathrm{R}})$ declares the predicted output $\tilde{P}{}^{\mathrm{RE}}_{j,t} \; (t = 1, 2, \cdots, T)$ for each period, as well as the quotes for different output intervals, $b_{j,k}^{\mathrm{RE}}$, the upper and lower bounds of the k^{th} output interval, $\overline{P}_{j,k}^{\mathrm{RE}}$ and $\underline{P}_{j,k}^{\mathrm{RE}} (k = 1, 2, \cdots, K_j)$, and calculates the cost of the unit j at period t. The system operator forms a bidding set, $\mathcal{B} = \{b_i\}_{i \in \mathcal{M}}$.

Step ii: Under the constraints of power system operating, the system operator arranges the pre-output of each unit with the minimum expected purchase cost according to Equation (11). The pre-output of conventional unit i is $P_{i,t}^{\text{CO}*}(\mathcal{B})$, and the pre-output of stochastic generator j is $P_{j,t}^{\text{RE}*}(\mathcal{B})$.

Step iii: Calculate the operating cost of the system, i.e., the objective function value of Equation (18) under optimal scheduling.

Step iv: For conventional unit i, calculate the expected cost, $\overset{\sim \text{CO}}{C_i}(\mathcal{B})$, by Equation (12), the objective function value of Equation (11), where conventional unit i does not participate in the market, and the VCG payment of the unit by Equation (13).

Step v: Similarly, for a stochastic generator j, calculate its expected cost using Equation (14) and the system operating cost $J^{\text{RE}}\left(\mathcal{B}_{-j}\right)$ for the unit not participating in the market, and finally, calculate the VCG payment of the unit by Equation (16).

4. VCG Clearing Model in the RT Market

It is difficult to predict the output of stochastic generators and the power consumption on the load side with absolute accuracy, so it is necessary to adjust the output of conventional generators in the RTM, and even reduce the load. According to the quotation of unit increase or decrease declared by each conventional power generation manufacturer, the system operator arranges unit output adjustment and load reduction with the goal of minimizing output (load) adjustment, calculates the cost of increasing or decreasing the output of conventional units according to the VCG mechanism, and adjusts the payment of stochastic generators.

4.1. Objective Functions and Constraints of the RTM

The system operator calculates the unit increase or decrease output quotations declared by conventional power generation companies, and the set of increase or decrease output quotations is denoted by $\mathcal{B}^{\text{RT}}$. The objective function for arranging unit increase or decrease output is:

$$J^{\text{RT}}\left(\mathcal{B}^{\text{RT}}\right) = \sum_{i=1}^{M_C}\sum_{t=1}^{T}\left\{b_{i,t}^{\text{CO}+}\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{+} + b_{i,t}^{\text{CO}-}\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{-}\right\} + \sum_{d=1}^{M_d}\sum_{t=1}^{T} V_d P_{d,t}^{\text{shed}} \tag{17}$$

where, $b_{i,t}^{\text{CO}+}$ and $b_{i,t}^{\text{CO}-}$ are the quotes for increasing or decreasing the output of conventional unit i at period t in the RT market, $P_{i,t}^{\text{CO}*}$ is the output of conventional unit i under the optimal market scheduling at period t in the DAM, $P_{i,t}^{\text{CO,RT}}$ is the output of conventional unit i at period t in the RT market, $P_{d,t}^{\text{shed}}$ is the forced load reduction amount for load d at period t, and V_d is the load reduction loss for load d. Define the functions $(X - x)_{+} = \max\{X - x, 0\}$ and $(X - x)_{-} = \max\{-(X - x), 0\}$; then, in (24), $\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{+}$ is the increased output and $\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{-}$ represents the decreased output of conventional unit i at period t in the RT market.

The first term on the right side of (17): $\sum_{i=1}^{M_C}\sum_{t=1}^{T}\left\{b_{i,t}^{\text{CO}+}\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{+} + b_{i,t}^{\text{CO}-}\left(P_{i,t}^{\text{CO,RT}} - P_{i,t}^{\text{CO}*}\right)_{-}\right\}$, represents the cost of adjusting the output of conventional unit i in the RT market, and the second item: $\sum_{d=1}^{M_d}\sum_{t=1}^{T} V_d P_{d,t}^{\text{shed}}$, represents the loss caused by forced load reduction.

The constraints of the RT market are similar to those in DAM, including node power balance constraints.

4.2. VCG Payment for the Increase or Decrease of the Output of Conventional Generators

The system operator solves Equation (24) to obtain the optimal combination of unit increase and decrease output for conventional generators. Let $P_{i,t}^{\text{CO,RT}*}$ be the optimal dispatch output of conventional generator i in the RT market, and the cost of increasing or decreasing the output of the conventional generator i is:

$$c_i^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)=\sum_{t=1}^{T}\left\{b_{i,t}^{\mathrm{CO}+}\left(P_{i,t}^{\mathrm{CO,RT}*}-P_{i,t}^{\mathrm{CO}*}\right)_{+}+b_{i,t}^{\mathrm{CO}-}\left(P_{i,t}^{\mathrm{CO,RT}*}-P_{i,t}^{\mathrm{CO}*}\right)_{-}\right\} \tag{18}$$

The system operator pays the VCG cost for the increase or decrease of unit output to the conventional generator i, which is:

$$p_i^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)=J^{\mathrm{RT}}\left(\mathcal{B}_{-i}^{\mathrm{RT}}\right)-\left(J^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)-c_i^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)\right), \quad i=1,\cdots,M_{\mathrm{C}} \tag{19}$$

where, $J^{\mathrm{RT}}\left(\mathcal{B}_{-i}^{\mathrm{RT}}\right)$ is the total cost of output adjustment for other generators in the RTM, excluding conventional generator i, and $\left(J^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)-c_i^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)\right)$ is the total cost of adjusting the output of other generators when including conventional generator i.

4.3. Stochastic Generator Cost Adjustment

The actual output, $\hat{P}_{j,t}^{\mathrm{RE}}$, of stochastic generators in the RTM may be different from the pre-scheduled market output, $P_{j,t}^{\mathrm{RE}*}$, and may be different from the predicted output, $\overset{\sim\mathrm{RE}}{P}_{j,t}$, declared by the units, and then the adjustments need to be made to the pre-clearing payment in the market.

Stochastic generators are responsible for the increase in operating costs caused by this; that is, they need to pay corresponding punitive fees. According to the deviation between actual output, pre-scheduled output, and predicted output, there are three situations, as follows:

(1) The actual output of the RTM unit did not reach the pre-scheduled market output, i.e., $\hat{P}_{j,t}^{\mathrm{RE}} \le P_{j,t}^{\mathrm{RE}*}$; thus, the unit will deduct the pre-clearance fee and pay a punitive fee:

$$\Delta p_{j,t}^{\mathrm{RT}}=\rho_{j,t}^{\mathrm{RE}}(\mathcal{B})\left(\hat{P}_{j,t}^{\mathrm{RE}}-P_{j,t}^{\mathrm{RE}*}\right)+\rho_t^{\mathrm{RT}-}\left(\hat{P}_{j,t}^{\mathrm{RE}}-P_{j,t}^{\mathrm{RE}*}\right) \tag{20}$$

where, $\rho_{j,t}^{\mathrm{RE}}(\mathcal{B})$ is the VCG electricity price that stochastic generator j received, and $\rho_t^{\mathrm{RT}-}$ is the punitive price for reducing the unit output. $\Delta p_{j,t}^{\mathrm{RT}}$ is a negative value, indicating the fees that should be paid to the system operator.

(2) The actual output of the unit in the RTM exceeds the pre-scheduled output of the market before the day, but does not exceed $\overset{\sim\mathrm{RE}}{P}_{i,t}$, the predicted output of the generator; that is, $P_{j,t}^{\mathrm{RE}*} \le \hat{P}_{j,t}^{\mathrm{RE}} \le \overset{\sim\mathrm{RE}}{P}_{j,t}$, and the excess part will be settled according to the VCG price:

$$\Delta p_{j,t}^{\mathrm{RT}}=\rho_{j,t}^{\mathrm{RE}}(\mathcal{B})\left(\hat{P}_{j,t}^{\mathrm{RE}}-P_{j,t}^{\mathrm{RE}*}\right) \tag{21}$$

This deviation is not caused by stochastic unit predictions and there is no need to pay punitive fees.

(3) The actual output of the RTM unit exceeds the predicted output of the generator, i.e., $\hat{P}_{j,t}^{\mathrm{RE}} \ge \overset{\sim\mathrm{RE}}{P}_{j,t}$, and the excess part will be settled according to the VCG price, but the amount of electricity exceeding the predicted output needs to pay a punitive fee:

$$\Delta p_{j,t}^{\mathrm{RT}}=\rho_{j,t}^{\mathrm{RE}}(\mathcal{B})\left(\hat{P}_{j,t}^{\mathrm{RE}}-P_{j,t}^{\mathrm{RE}*}\right)-\rho_t^{\mathrm{RT}+}\left(\hat{P}_{j,t}^{\mathrm{RE}}-\overset{\sim\mathrm{RE}}{P}_{j,t}\right) \tag{22}$$

where $\rho_t^{\mathrm{RT}+}$ is the punitive price for units exceeding the predicted output at period t.

The following is a discussion of the calculation method of punitive tariffs, $\rho_t^{\mathrm{RT}+}$ and $\rho_t^{\mathrm{RT}-}$.

The total cost paid by the system operator to the conventional generator for the increase or decrease of unit output is $C_{\Sigma}^{\mathrm{RT}}=\sum_{i=1}^{M_c} p_i^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)$. The cost incurred by increasing the output of the unit at period t under the optimal scheduling in the RTM is $C^{\mathrm{RT}}_{t,\Sigma+}$, and the cost of reducing output is $C^{\mathrm{RT}}_{t,\Sigma-}$, with:

$$\begin{cases} C^{\mathrm{RT}}_{t,\Sigma+} = \sum_{i=1}^{M_{\mathrm{C}}} \left\{ b^{\mathrm{CO}+}_{i,t} \left(P^{\mathrm{CO,RT}*}_{i,t} - P^{\mathrm{CO}*}_{i,t} \right)_{+} \right\} \\ C^{\mathrm{RT}}_{t,\Sigma-} = \sum_{i=1}^{M_{\mathrm{C}}} \left\{ b^{\mathrm{CO}-}_{i,t} \left(P^{\mathrm{CO,RT}*}_{i,t} - P^{\mathrm{CO}*}_{i,t} \right)_{-} \right\} \end{cases} \tag{23}$$

The total reduced output caused by the prediction deviation of the stochastic generator is:

$$Q^{\mathrm{RT}}_{t,\Sigma-} = \sum_{j=1}^{M_{\mathrm{R}}} \left(\hat{P}^{\mathrm{RE}}_{j,t} - P^{\mathrm{RE}*}_{j,t} \right) \tag{24}$$

The total increased output due to the forecast deviation is:

$$Q^{\mathrm{RT}}_{t,\Sigma+} = \sum_{j=1}^{M_R} \left(\hat{P}^{\mathrm{RE}}_{j,t} - \tilde{P}^{\mathrm{RE}}_{j,t} \right) \tag{25}$$

The increase in output does not take into account the non-stochastic units' responsibility in the above equation; that is, the actual output of the RTM unit exceeds the pre-scheduled output of the market but does not exceed the predicted output.

Then, the punitive price for reducing the output of the stochastic generator at period t is:

$$\rho^{\mathrm{RT}-}_{t} = C^{\mathrm{RT}}_{t,\Sigma+} / Q^{\mathrm{RT}}_{t,\Sigma-} \tag{26}$$

The punitive price for increasing the output of the stochastic generator at period t is:

$$\rho^{\mathrm{RT}+}_{t} = C^{\mathrm{RT}}_{t,\Sigma-} / Q^{\mathrm{RT}}_{t,\Sigma+} \tag{27}$$

It should be noted that the punitive price calculation approach proposed in this paper is based on the adjustment of output of other units due to prediction bias in stochastic power generation units, and the resulting costs need to be borne by the stochastic power generation units. If the output deviation of a stochastic generator is not the responsibility of the unit itself, this part of the electricity needs to be excluded when calculating the punitive price and punitive fee.

4.4. VCG Clearing Process in Real-Time Market

The clearing process of RTM is summarized as follows:

Step i: The conventional generators declare the unit to increase the output quotation $b^{\mathrm{CO}+}_{i,t}$ and reduce the output quotation $b^{\mathrm{CO}-}_{i,t}$ (the declaration is submitted simultaneously when the unit declares the output quotation).

Step ii: The system operator decides to increase or decrease the output of each unit: $\Delta P_{i,t} = P^{\mathrm{CO,RT}*}_{i,t} - P^{\mathrm{CO}*}_{i,t}$, according to the minimum cost of adjusting the output of each unit.

Step iii: Calculate the total cost of adjusting the output of each unit, $J^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}\right)$.

Step iv: Calculate the adjustment cost, $J^{\mathrm{RT}}\left(\mathcal{B}^{\mathrm{RT}}_{-i}\right)$, generated by the system when the conventional generator i does not participate in the adjustment.

Step v: Calculate the VCG cost for the increase or decrease of unit output paid by the system operator to the conventional generator i by Equation (19).

Step vi: Calculate the punitive electricity prices, $\rho^{\mathrm{RT}-}_{t}$ and $\rho^{\mathrm{RT}+}_{t}$, for reducing and increasing the output of stochastic generator units at period t by Equations (26) and (27).

Step vii: For a stochastic generator j, calculate the punitive cost, $\Delta p^{\mathrm{RT}}_{j,t}$, based on the deviation between actual output, pre-scheduled output, and predicted output.

Step viii: Calculate the total payment of each unit.

5. Budget Imbalance Redistribution under VCG Mechanism

The budget imbalance under the VCG mechanism is due to the fact that the total cost to the consumer is not equal to the payment of the generator, resulting in either an economic deficit (the generator pays more than the consumer pays) or an economic surplus (the generator pays less than the consumer pays). Budget imbalances can be dealt with through redistribution. The redistribution of budget imbalances can have different mechanisms. This paper proposes a simple idea of redistribution; that is, according to the proportion of the contribution of each market participant to the budget imbalance, which is in line with market fairness and easily accepted by market participants.

The contribution factor, λ_j, of bidder j to the budget deficit is measured by calculating the change in budget imbalance caused by whether bidder j participates in the market:

$$\lambda_j = \frac{v_0^{\mathrm{BI}} - v_{-j}^{\mathrm{BI}}}{v_0^{\mathrm{BI}}} \tag{28}$$

where, v_0^{BI} is the VCG budget deficit value cleared by the original optimization problem $J_{\mathcal{B}}$: v_0^{BI} is defined here as the fee collected from the electricity users minus the fee paid to the generators, and v_0^{BI} is negative. v_{-j}^{BI} is the budget deficit value when bidder j does not participate in the market. If $v_{-j}^{\mathrm{BI}} = v_0^{\mathrm{BI}}$, that is, when $\lambda_j = 0$, bidder j's participation in the market does not cause any change in the budget deficit, which means that bidder j's contribution to the budget deficit is 0. If $\lambda_j > 0$, it means that bidder j's participation in the market increases the budget deficit; that is, it has a positive effect on the budget deficit. If $\lambda_j < 0$, the participating market reduces the budget deficit; that is, it has the opposite effect on the budget deficit.

Bidders who have a positive effect on the budget deficit (an increase in the budget deficit) should bear more of the budget deficit, and participants who have a negative effect on the budget deficit (reducing the deficit) should be rewarded. Therefore, when calculating the apportionment value (proportion) of each bidder to the budget deficit, it is divided into three situations:

(1) All bidders have a positive effect on the budget deficit (the λ_j values are all positive), and the budget imbalance payment that should be shared by the participant j is:

$$\Delta p_j = \frac{\lambda_j}{\sum_{k=1}^{m} \lambda_k} v_0^{\mathrm{BI}} \tag{29}$$

(2) All bidders have a reverse effect on the budget deficit (the λ_j values are all negative), and the budget imbalance payment that should be shared by the participant j is:

$$\Delta p_j = \frac{|\lambda^{\min}| + \lambda_j}{\sum_{k=1}^{m} (|\lambda^{\min}| + \lambda_k)} v_0^{\mathrm{BI}} \tag{30}$$

where $|\lambda^{\min}|$ is the absolute value of the minimum value of contribution factor λ_j. The greater the absolute value of v_{-j}^{BI}, the stronger the inverse effect of player j on the budget deficit.

(3) Bidders have positive and negative effects on the budget imbalance. The allocation rules shall reward bidders who have the opposite effect.

(i) First, calculate the reward given to the bidders with negative λ_j. The reward intensity (reward per unit distance) is:

$$dv_{+}^{\mathrm{BI}} = \frac{|v_0^{\mathrm{BI}}|}{\sum_{k=1}^{m} |\lambda_k|} \tag{31}$$

The sum of the rewards to bidders with negative λ_j is:

$$v_{\Sigma+}^{\mathrm{BI}} = dv_{+}^{\mathrm{BI}} \cdot \sum_{i \in \Omega_-} |\lambda_i| \tag{32}$$

where Ω_- is the set of bidders with negative λ_j, and the bidder j is rewarded for:

$$\Delta p_j\big|_{j\in\Omega_-}=\frac{|\lambda_j|}{\sum_{i\in\Omega_-}|\lambda_i|}v_{\Sigma+}^{\mathrm{BI}} \tag{33}$$

(ii) Calculate the budget deficit shared by the bidder with positive λ_j. $v_0^{\mathrm{BI}}-v_{\Sigma+}^{\mathrm{BI}}$ needs to be apportioned among bidders with positive λ_j, and the amount apportioned by bidder j' is:

$$\Delta p_{j'}\Big|_{j'\in\Omega_+}=\frac{\lambda_{j'}}{\sum_{i\in\Omega_+}\lambda_i}\left(v_0^{\mathrm{BI}}-v_{\Sigma+}^{\mathrm{BI}}\right) \tag{34}$$

where Ω_+ is the set of bidders with positive λ_j.

If the incentive for the bidder with negative λ_j is not considered, the calculation can be performed according to (30).

The above redistribution approach is suitable for both unilateral and bilateral electricity markets. The budget imbalance value can be positive or negative, and the contribution factor of participant j to the budget imbalance λ_j can also be positive or negative. According to (29), it can be seen that $\sum_{j=1}^{m}\Delta p_j=v_0^{\mathrm{BI}}$; that is, budget balance under the VCG mechanism can be achieved through the redistribution.

The proposed redistribution method has the following characteristics:

(1) Reassign based on the contribution of each bidder to the budget imbalance. Rewards will be given to participants who contribute to the budget balance, and a certain fee will be charged if participants have a negative impact on the budget balance. This meets market fairness.

(2) The calculation of the redistribution payment is independent of the bidder's strategy; that is, the contribution factor is calculated by the change in the budget imbalance when a bidder participates in the market or not, and the incentive compatibility of the VCG mechanism is maintained.

(3) After redistribution, the budget balance of the VCG mechanism can be ensured.

6. Case Simulation and Analysis

6.1. Basic Data

The IEEE30 testing system consists of six generators with an installed capacity of 335 MW. The cost function of the units is $C_i(P_i)=a_iP_i^2+b_iP_i+c_i$, and the cost coefficients of the generators are shown in Table 1. In addition, the software we used in the case simulation is MATLAB R2023a.

Table 1. Generator cost coefficients for the original IEEE30 testing system.

Unit No.	a_i/(USD/MW^2)	b_i/(USD/MW)	c_i/USD
1	0.02	2	0
2	0.0175	1.75	0
3	0.0625	1	0
4	0.00834	3.25	0
5	0.025	3	0
6	0.025	3	0

To study the operation of the two-stage market mechanism of VCG under different proportions of renewable energy, we modified the node parameters. We added stochastic generators to the system or modified the original conventional units to stochastic generators. The predicted output of the units was adjusted according to the output of typical wind generators, while the load side adjusted the node load according to the typical load curve of a power grid. For example, in scenario 1, we added a wind generator at node 7 with a rated capacity of 50 MW. In scenario 2, we added a stochastic generator and changed the conventional generator to a wind generator. The installed capacity and proportion of stochastic energy for each scenario are shown in Table 2.

Table 2. The installed capacity of the system, the capacity of stochastic generators, and their proportions in each scenario.

Scenario	Total Installed Capacity/MW	Conventional Unit Capacity/MW	The Node Where the Stochastic Generator is Located and the Installed Capacity/MW	Stochastic Genset Capacity/MW	Proportion of Stochastic Energy Installed Capacity/%.
1	385	335	25, 50 MW	50	12.99%
2	385	305	25, 50 MW; 23, 30 MW	80	20.78%
3	435	305	25, 50 MW; 23, 30 MW; 6, 50 MW	130	29.89%
4	435	255	25, 50 MW; 23, 30 MW; 6, 50 MW; 22, 50 MW	180	41.38%
5	435	200	25, 50 MW; 23, 30 MW; 6, 50 MW; 22, 50 MW; 27, 55 MW	235	54.02%

It should be noted that, when constructing the output curve of wind generators, the actual output curve of wind generators in a certain region was first selected for standardization to obtain the output contour lines. Then, the contour lines were multiplied by the installed capacity to obtain the output curve of the unit. The setting of node load curves was also similar. Firstly, several typical operating days of a certain region were selected and standardized to obtain the load contour lines. Then, the contour lines were multiplied by the setting maximum load to obtain the load curves. In the real-time market simulation, the output deviation of wind generators was also set to a certain extent, which was considered representative.

6.2. Incentive Compatibility Characteristics of VCG Mechanism

The incentive compatibility characteristics of the VCG mechanism were tested. The generator output and LMP and VCG mechanism profit of unit 1 under different quotation coefficients are shown in Table 3 and Figure 1. The quotation ratio coefficient in Table 3 is 1, which means that the unit was quoted based on the actual cost. According to Table 3, under the VCG mechanism, the unit obtained the maximum profit by quoting based on the actual cost. The same applied to other units, which proved the incentive compatibility of the VCG mechanism.

Table 3. The generator output of unit 1 under different quotation coefficients, the profit of the LMP mechanism, and the profit of the VCG mechanism.

Quotation Ratio Coefficient	Output of the Generator/MW	Profit under LMP/(USD/h)	Profit under VCG/(USD/h)	Quotation Ratio Coefficient	Output of the Generator/MW	Profit under LMP/(USD/h)	Profit under VCG/(USD/h)
0.75	62.1351	7.5402	25.1596	1.05	35.7666	31.7201	37.7042
0.80	56.6490	15.8497	30.5762	1.10	32.5441	31.9276	36.8958
0.85	51.6835	21.8915	34.2094	1.15	29.5572	31.5815	35.6898
0.90	47.1676	26.1630	36.4647	1.20	26.7808	30.7941	34.1745
0.95	43.0407	29.0409	37.6508	1.25	24.1931	29.6557	32.4199
1.00	39.2539	30.8174	38.0032	1.30	21.7755	28.2387	30.4818

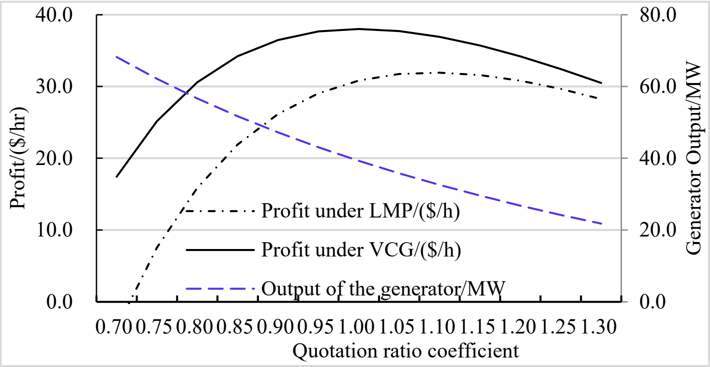

Figure 1. Profit of the LMP and VCG mechanisms of generator 1 under different quotation ratio coefficients.

6.3. Comparison of LMP Mechanism and VCG Mechanism

(1) High proportion of new energy access, LMP mechanism problem

If a stochastic generator adopts a zero-quotation strategy, as the proportion of new energy increases, the marginal electricity price in certain regions and certain periods is very low, even zero. For example, in scenario 1, the installed capacity of new energy accounted for 12.99%, and there were 26 periods when the output of unit 7 was not zero, but the LMP was zero. Tables 4 and 5, respectively, show the unit output and LMP of the node where the unit was located during certain periods in scenario 1.

Table 4. The output of each unit at periods 16–20 in scenario 1(MW).

	Unit 1	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 6**	**Unit 7**
Period 16	21.5525	31.9762	17.6858	0.0000	5.4967	2.2874	33.8948
Period 17	21.4266	31.8304	17.6512	0.0000	5.4228	2.1941	33.8971
Period 18	21.4794	31.8919	17.6662	0.0000	5.4559	2.2348	33.8998
Period 19	21.4958	31.9110	17.6639	0.0000	5.4466	2.2369	33.9037
Period 20	21.5641	31.9900	17.6922	0.0000	5.5168	2.3044	33.9046

Table 5. The node electricity price of each unit at periods 16–20 in scenario 1.

	Unit 1	**Unit 2**	**Unit 3**	**Unit 4**	**Unit 5**	**Unit 6**	**Unit 7**
Period 16	2.8621	2.8692	3.2107	1.9446	3.2748	3.1144	0.0000
Period 17	2.8571	2.8641	3.2064	1.9360	3.2711	3.1097	0.0000
Period 18	2.8592	2.8662	3.2083	1.9392	3.2728	3.1117	0.0000
Period 19	2.8598	2.8669	3.2080	1.9427	3.2723	3.1118	0.0000
Period 20	2.8626	2.8696	3.2115	1.9437	3.2758	3.1152	0.0000

The main reason for the occurrence of zero LMP is the stochastic generators, which have the characteristic of zero marginal electricity price and adopt zero-quotation. The proportion of zero LMP is closely related to the proportion of renewable energy. From scenario 1 to scenario 5, the proportion of renewable energy increased from 12.99% to 54.02%, and the proportion of generator zero LMP periods increased from 3.39% to 21.22%. As the proportion of renewable energy increased, there was a significant decrease in the average LMP of the system and each unit. Figure 2 shows the average LMP of the system under different proportions of new energy, the average LMP of unit 1 (conventional generator), and the average LMP of unit 7 (stochastic generator). This will seriously affect the profits of power generation companies.

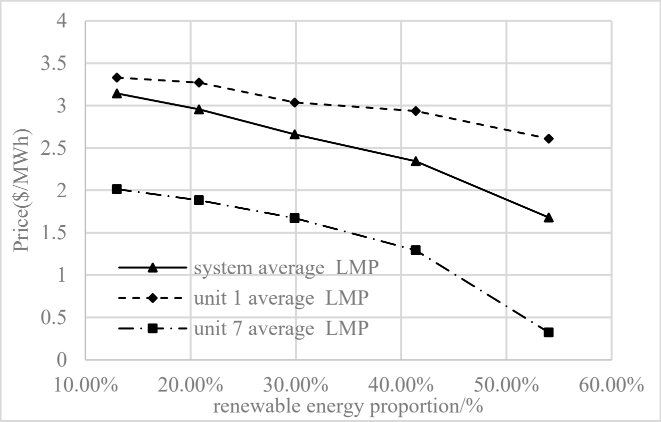

Figure 2. Different renewable energy proportions, unit LMP, and system average LMP.

(2) Comparison of electricity prices of the two mechanisms

Figure 3 shows the trend of changes in the average LMP and average VCG electricity prices of systems with different proportions of new energy. The VCG electricity price of each generator was higher than the LMP electricity price, which is determined by the nature of the VCG mechanism. The proportion of budget imbalance under the VCG mechanism is related to factors such as power generation costs, load characteristics, and network structure of power generation companies. From the trend of electricity price changes, as the proportion of new energy increased, the average LMP of the system decreased significantly, while the VCG electricity price of stochastic generators decreased but was relatively stable.

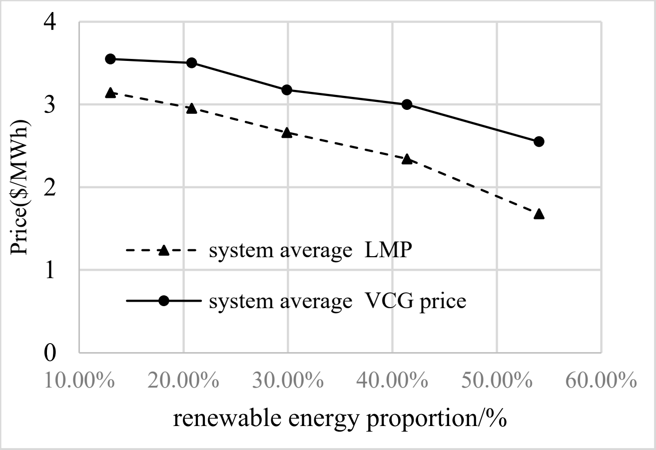

Figure 3. The average LMP and average VCG electricity prices of different renewable energy proportions.

Figure 4 shows the comparison of average electricity prices between the conventional generator (unit 1) and stochastic generator (unit 7) under two mechanisms. For conventional units, the price difference between LMP and VCG was not too large, but as the proportion of new energy increased, the difference gradually increased. For stochastic generators, there was a significant difference in LMP and VCG electricity prices. This was mainly due to the lower marginal electricity prices of nodes containing new energy units, and the greater decrease with the increase in the proportion of new energy. Therefore, with the increasing proportion of new energy, there is an urgent need to reform the electricity market mechanism.

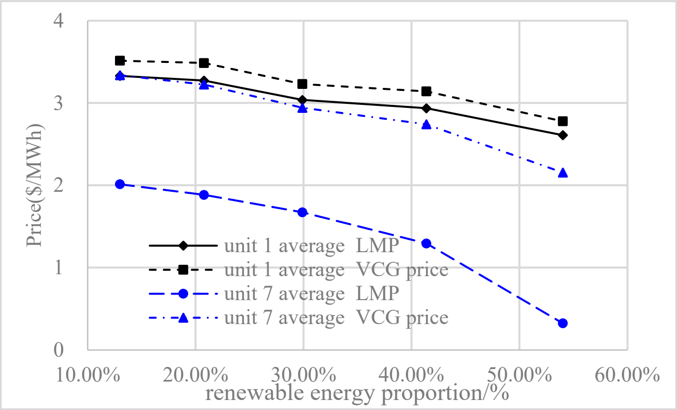

Figure 4. The average LMP and average VCG electricity prices of unit 1 (conventional generator) and unit 7 (stochastic generator) are accounted for by different renewable energies.

6.4. Budget Imbalance

The VCG mechanism suffered from budget imbalance issues. Table 6 shows the proportion of system budget imbalance (absolute value) for different proportions of new energy, and Figure 5 shows the trend of the proportion of system budget imbalance (absolute value). As mentioned earlier, under the VCG mechanism, the payments received by power generation companies are calculated based on the overall net benefits (total cost savings) brought by the market participants. In the case of a high proportion of new energy grid-connected capacity, if stochastic power generation units participated in the market with zero quotes, although the VCG revenue of the units decreased, the fees charged from the user side decreased more, resulting in a significant increase in the proportion of system budget imbalance (absolute value).

Table 6. Proportion of system budget imbalance with different renewable energy proportions (absolute value).

Proportion of Renewable Energy	Percentage of Budget Imbalance in VCG Mechanism (Absolute Value)
12.99%	5.17%
20.78%	7.18%
29.89%	7.55%
41.38%	8.79%
54.02%	9.27%

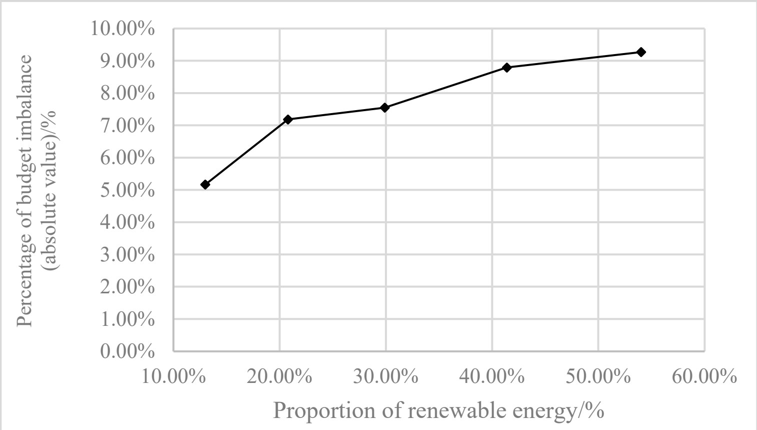

Figure 5. The trend of the imbalance ratio (absolute value) of the system budget with different renewable energy proportions.

Budget imbalance can be resolved through system reallocation. This paper compared and analyzed two redistribution methods based on the VCG payment ratio of power generation companies and the contribution factor of power generation companies to budget imbalance. Table 7 presents the redistribution of a conventional unit and a new energy generator under different new energy capacity ratios, while Table 8 presents the adjustment of budget imbalances for stochastic generators. In Tables 7 and 8, ζ_1 is the budget deficit allocation ratio adjusted according to the VCG revenue ratio, and ζ_2 is the budget deficit allocation ratio adjusted by the budget deficit contribution factor.

Table 7. Budget deficit adjustments for units 1 and 7.

Proportion of New Energy Capacity	Unit 1		Unit 7	
	ζ_1	ζ_2	ζ_1	ζ_2
12.99%	21.59%	9.49%	18.64%	39.84%
20.78%	20.06%	5.66%	18.28%	31.32%
29.89%	14.26%	3.39%	18.78%	23.27%
41.38%	11.69%	4.10%	17.95%	18.62%
54.02%	3.69%	9.95%	11.00%	8.36%

Table 8. Stochastic generator budget deficit adjustments.

Scenario	Proportion of New Energy Capacity	VCG Total Revenue	Budget Imbalances	Stochastic Generator			
				VCG Earnings	Percentage of VCG Revenue	ζ_1	ζ_2
1	12.99%	49,378.48	−2552.31	8205.15	16.62%	18.64%	39.84%
2	20.78%	48,767.13	−3502.91	8386.22	17.20%	30.04%	54.70%
3	29.89%	44,106.83	−3329.69	14,841.76	33.65%	50.26%	55.65%
4	41.38%	41,684.94	−3665.47	18,436.39	44.23%	67.22%	62.97%
5	54.02%	35,536.43	−3294.62	15,799.84	44.46%	79.20%	67.53%

Comparing the budget deficit adjustment ratios of units 1 and 7 in Table 7, it can be seen that when the proportion of renewable energy generation was relatively low, due to the fluctuation of output of stochastic generators and the zero-quotation characteristic, the contribution to budget imbalance was relatively large. According to the budget deficit contribution factor, the proportion of allocation for this type of unit was relatively large. When the proportion of renewable energy generation was relatively high, such as in scenarios 4 and 5, the proportion of allocation between units 1 and 7 decreased. This does not mean that the contribution of stochastic generators to budget imbalance decreased, but rather that other stochastic generators allocated a budget imbalance.

From Table 8, it can be seen that when the proportion of new energy capacity was relatively low, as in scenario 1, the proportion of new energy capacity was 12.99%. When the budget deficit was reallocated according to the VCG revenue ratio, the budget deficit allocation ratio of stochastic power generation units was roughly equivalent to the VCG revenue ratio. The new energy VCG revenue ratio was 16.62%, and the budget deficit allocation ratio was 18.64%. If the contribution factor of budget deficit was redistributed according to market entities, the proportion of budget deficit allocation for stochastic generating units was relatively high, at 39.84%. This is because stochastic generating units adopt a zero-quotation strategy, and stochastic generating units contribute significantly to the budget deficit.

When the proportion of new energy capacity was relatively high, as in scenario 5, the proportion of new energy capacity was 54.02%. The two redistribution methods tended to have the same proportion of budget deficit allocation for stochastic generators. On the one hand, the contribution of stochastic generators to budget deficit was still relatively large, and the proportion of new energy capacity increased, which increased the contribution to budget deficit. On the other hand, the proportion of VCG revenue for stochastic generators increased, and the proportion of budget deficit allocation based on VCG revenue proportion also increased.

7. Conclusions

In response to the problems existing in the traditional market mechanism under the high proportion of new energy, this paper proposed a two-stage clearing model based on the VCG mechanism for the DAM and the RTM. The case analysis showed that:

(i) In the electricity market with a high proportion of renewable energy sources, if stochastic generators quoted at marginal cost, the marginal electricity price in some regions and some periods was very low, or even zero. As the proportion of renewable energy increased, the average LMP of the system and each unit significantly decreased, which would seriously affect the profits of power generation companies. Therefore, with the increase in the proportion of renewable energy, it is urgent to examine the adaptability of the current market mechanism to the large-scale integration of renewable energy into the grid, and to reform the electricity market mechanism.

(ii) Under the VCG mechanism, the payment of market participants is calculated based on their contribution to social welfare by participating in the market. The VCG mechanism has characteristics such as individual rationality, dominant strategy incentive compatibility, and efficiency, and can deal with the problem of zero marginal cost of large-scale intermittent power generation and is suitable for the electricity market with a high proportion of renewable energy.

(iii) In response to the problem of increased system operating costs caused by prediction bias, this paper proposed a punitive cost calculation method based on the principle of responsibility. Due to the prediction deviation, the actual output of the stochastic generators in the RTM may be different from the pre-scheduled output in the DAM, so the output of other generators needs to be adjusted, resulting in an increase in the system operation cost. This paper proposed a punitive cost calculation method based on the principle of responsibility, based on the deviation between actual output, pre-scheduled output, and predicted output. The punitive costs incurred by the responsible generator are related to the forecast deviation, and quotes of other generators' quotation. The output prediction deviation of the stochastic generators in case simulation was not significant, and the proportion of punitive costs was not high.

(iv) This paper proposed the contribution factor method to solve the budget imbalance problem in the VCG mechanism. The proportion of budget imbalance is closely related to the characteristics of unit pricing. Under the marginal cost pricing strategy of stochastic generators, as the proportion of stochastic generator capacity increased, the proportion of budget imbalance increased significantly. If a stochastic generator adopts a zero-quotation strategy, then the stochastic generator contributes significantly to the budget imbalance. The problem of budget imbalance can be solved through payment redistribution. The contribution factor redistribution method based on market entities to budget imbalance proposed in this paper is in line with market fairness and is easily accepted by market participants. This method also has the drawback of large computational complexity. During the transition period of the market mechanism, the method of sharing VCG returns proportionally can also be adopted.

At present, there are few solutions to the collusion prevention problem of the VCG mechanism, and power generation companies may cause a significant increase in system operator payments through collusion. Further research is needed on market-clearing models, such as pricing function constraints and objective functions.

Author Contributions: Conceptualization, Y.L. and L.Y.; Methodology, M.C.; Software, Y.L., M.C., Y.F. and L.Y.; Validation, X.C. and X.Z.; Formal analysis, M.C.; Resources, Y.L.; Data curation, M.C., L.Y. and X.Z.; Writing—original draft, Y.L., L.Y. and X.C.; Writing—review & editing, Y.F. and X.C.; Visualization, X.C. and X.Z.; Supervision, Y.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by State Grid Hubei Electric Power Company, China grant number SGHBJY00NYJS2310178 and SGHBJY00NYJS2310179.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Yifeng Liu and Meng Chen were employed by the Hubei Power Exchange Center Co., Ltd., Yuhong Fan was employed by the State Grid Hubei Electric Power Co., Ltd. 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.

Nomenclature

Abbreviation	
DSIC	dominant strategy incentive compatible
DAM	day-ahead market
LMP	locational marginal pricing
IR	individual rationality
RTM	real-time market
VCG	Vickrey Clark Groves
Main part symbol	
u	utility of bidder
P	output of a generator
p	payment
b	quotation of a bidder
ρ	price
C, c	cost
Superscript	
+	superscript for increased (output)
-	superscript for decreased (output)
*	superscript for optimal scheduling output
CO,C	superscript for conventional generators
DA	superscript for day-ahead market
RE,R	superscript for renewable generators
RT	superscript for real-time market
Subscript	
d	subscript for user
i	subscript for bidder, conventional generator
j	subscript for renewable generator
k	subscript for segment
t	subscript for period
Set	
$\mathcal{B}$	set of bidders
$\mathcal{B}_{-i}$	set of bid functions excluding bidder i
$\mathcal{B}^{\mathrm{C}}$	subset of the conventional generators
$\mathcal{B}^{\mathrm{R}}$	subset of the stochastic generators
Constants	
M	number of bidders
M_{C}	number of conventional generators
M_{R}	number of renewable generators
M_{D}	number of loads (users)
T	number of periods

Main Variables	
c_i	cos t of bidder i
b_i	quotation of bidder i
q_i	bid quantity of bidder i
q_i^*	winning bid quantity of bidder i
$p_i(\mathcal{B})$	payment of bidder i
$u_i(\mathcal{B})$	utility of bidder i
$u_{\text{op}}(\mathcal{B})$	total utility of the system operator
$b_{i,t}^{\text{CO}}$	the bid of conventional generator i at period t
$P_{i,t}^{\text{CO}}$	the output of conventional generator i at period t
$P_{i,t}^{\text{CO}*}$	optimal scheduling output for conventional generator i at period t
$b_{j,t}^{\text{RE}}$	the bid of renewable generator j at period t
$\tilde{P}_{j,t}^{\text{RE}}$	the pre $-$ output of renewable generator j at period t
$P_{j,t}^{\text{RE}}$	the output of renewable generator j at period t
$P_{j,t}^{\text{RE}*}$	optimal scheduling output for renewable generator j at period t
$b_{i,t}^{\text{CO}+}$	the bid for increasing output of conventional unit i
$b_{i,t}^{\text{CO}-}$	the bid for decreasing output of conventional unit i
$P_{i,t}^{\text{CO,RT}}$	the output of conventional generator i at period t in RTM
$P_{d,t}^{\text{shed}}$	the forced load reduction amount for load d at period t
V_d	the load reduction loss for load d
$\hat{P}_{j,t}^{\text{RE}}$	the actual output of renewable generator j at period t in the RTM
$\rho^{\text{RT}-}$	the punitive price for reducing the output
$\rho^{\text{RT}+}$	the punitive price for increasing the output

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