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RESEARCH ARTICLE

Spot Market Clearing Model and Flexibility Premium Assessment Method Considering Flexible Regulation of Virtual Power Plants

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ABSTRACT As an emerging market participant, Virtual Power Plants (VPPs) are gradually gaining access in multiple market trading varieties. They aggregate flexible distributed resources to respond to system dispatch instructions and execute transaction results, expanding the adjustable resources for the new power system. Currently, VPPs primarily participate in the ancillary services market, with secondary involvement in the energy market. With the penetration of a high proportion of new energy sources, the transition of VPPs to the spot market becomes a crucial business expansion direction. This study explores a spot market clearing model adapted for VPPs participation. It allows VPPs to reflect their flexible regulation characteristics by introducing a flexible declaration method, aiming to enhance the matching rate between supply and demand in the electricity market. Through a comparative analysis of clearing results based on different transaction models, an assessment method for the flexibility premium of VPPs is established. This transition in pricing system allows VPPs to shift from energy pricing to a "energy + flexibility" pricing model, thereby improving the competitiveness and value recognition of flexible resource VPPs in the electricity market.

INDEX TERMS Virtual power plants, spot market, clearing model, flexibility premium.

I. INTRODUCTION

With the development of energy internet technology, Virtual Power Plants (VPPs) have become a crucial research area for the construction of a new power system due to their high reliability, low-cost, and environmentally friendly adjustable resource expansion capabilities. The "14th Five-Year Plan for the Modern Energy System" in China emphasizes that the flexibility transformation scale of demand-side resources should reach 3% to 5% of the total load demand, further accelerating the development level of VPPs business [1]. However, there are still three pressing issues in the field of VPPs operations in China that need to be addressed urgently: 1) Difficulty in recognizing the value and assessing market access in multiple business scenarios for VPPs, requiring the expansion of their status in various market trading categories. 2) Lack of standardized external characteristic representation technology for VPPs, making it challenging for power system dispatch to consider joint clearing of VPPs. Research is urgently needed on market trading models for VPPs representing multi-node resources. 3) Difficulty in designing flexible business models for VPPs and constructing a fair distribution grid operation ecosystem. There is an urgent need to improve the value transmission mechanism of VPPs in the retail market model, enhancing the willingness of flexible resources to autonomously participate in market operations. Therefore, researching the clearing model for VPPs participating in multiple market trading categories and

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developing flexible pricing mechanisms will be conducive to promoting the development of the energy internet ecosystem. This holds significant importance for upgrading the power grid to an energy internet, accelerating the construction of a new type of power system.

In fact, both domestically and internationally, there have been numerous research achievements in the mechanism design and trading models for VPPs participating in electricity markets. Fengshun Jiao et al. propose a clear mechanism according to the operation situation of VPPs, and conduct performance analysis from the ambiguity of source-load side to the two-stage robust stochastic optimal scheduling method of multi-power VPPs [2]. To facilitate the supply and efficient pricing of flexible resources such as VPPs in the electricity market, reference [3] proposes a novel mixed-integer linear programming optimization formulation for swing contract trading within ISO-managed day-ahead markets. Changsen Feng et al. consider the challenges brought to grid stability by a large proportion of distributed resources, proposing a VPPs market mechanism model that incorporates energy management in a point-to-point mode. This model can effectively reduce market risks [4]. Within a medium-term market horizon, literature [5] provides a methodology that allows a commercial virtual power plant (CVPP) to form an optimal coalition of heterogeneous distributed energy resources (DERs) based on weekly bilateral contracting, futures-market involvement, and pool participation. In terms of transaction models, Yizhou Zhou et al. took into account the uncertainty of renewable energy sources within VPPs and established a VPPs day-ahead market trading model that considered demand response and electric vehicles, providing technical support for market transactions of VPPs [6]. In [7], the authors considered the compatibility issues between VPPs and multi-level agency and the impact of prediction uncertainty. They construct a hybrid time-scale double-layer operation model for VPPs, effectively integrating distributed resources. Reference [8] discusses the process of market transaction regulation by the Distribution System Operator (DSO), outlining bilateral contracts and the mechanism through which agents adjust short-term transactions in real-time. Furthermore, it establishes a distributed optimization algorithm for real-time optimal social welfare and validates it using the IEEE 123-node test system. The results confirm the feasibility of the proposed approach for distribution systems. In terms of the pricing system, Wen Chen et al. proposed a frequency control ancillary service and critical peak rebate (FCAS-CPR) strategy based on cumulative prospect theory (CPT) for a VPP in coupled FCAS and DR markets. This method can efficiently reduce the peak loads to mitigate impacts of ETs on power systems, while achieving a win-win outcome in maximizing the utilities of both the retailer and VPP consumers [9], [10]. Researchers established a primary-secondary game model of multiple VPPs and control centers, and used genetic algorithm (GA) to find the equilibrium solution. This method can obtain the optimal transaction price quickly and reduce the operating cost of the VPPs [11]. In terms of bidding strategy, [12] makes a VPP that consists of generation, both renewable and conventional, and controllable demand enabled to participate in the wholesale markets. The main objective is to develop a framework that optimizes the bidding strategies and maximizes the VPP's profit on day-ahead and real-time bases. In [13], the bidding strategy models of VPPs at three different stages are built and the improved Artificial Bee Colony algorithm is utilized to solve the optimal bidding strategies of the VPPs. And considering the potential uncertainties caused by renewable energy sources and the demand response, [14] proposes a novel scheme for optimizing the operation and bidding strategy of VPPs. By scheduling the energy storage systems, demand response, and renewable energy sources, VPPs can join bidding markets to achieve maximum benefits. However, the above studies have not achieved the parametric analysis of the flexible characteristics of VPPs in the market clearing models, making it challenging to effectively assess the value contribution of VPPs' flexible regulation capabilities in the electricity market.

In recent years, China has been deepening the reform of the electricity market mechanism, with third-party market entities such as VPPs focusing mainly on peak shaving and demand response services. In terms of demand response, represented by the marketization of demand response in Guangdong and Jiangsu provinces [15], VPPs have become important participants. However, the participation of flexible resources in system operation is still invitation-based, and real-time online closed-loop response similar to traditional units has not yet been achieved. In the peak shaving market, represented by the marketization of peak shaving services in northern Hebei and Shanghai [16], VPPs as third-party entities are qualified for access. However, due to the market being in its early stages, third-party market entities participate as price takers in market clearance, with traditional peak shaving units forming pre-clearance results. Allocation of capacity to third-party market entities occurs during periods of highest clearance prices. This mechanism reduces the profitability of traditional peak shaving units due to non-market competition, and fails to reflect the true peak shaving costs of aggregating flexible resources by VPPs, highlighting the urgent need for innovative peak shaving service mechanisms for VPPs. Previous studies have mainly focused on optimizing scheduling strategies for maximizing the economic benefits of VPPs or optimizing bidding strategies. However, these studies have not achieved parameterized analysis of the flexible characteristics of VPPs in market clearance models, making it difficult to effectively evaluate the value contribution of the flexible regulation capability of VPPs in the electricity market and to stimulate the autonomous willingness of demand-side resources to coordinate.

To address these issues, this paper first reviews domestic and foreign case studies of VPP business models, analyzing the utilization value of VPPs in different market environments. Secondly, it proposes an adaptive spot market clearance model for VPP participation, discussing parameterization methods for the flexible characteristics of VPPs in the market clearance process. Then, based on the market clearance model under the declaration strategy of flexible hours and blocks, an evaluation method for the premium of VPP flexible regulation characteristics is established. This method can effectively quantify the benefits created by the spatiotemporal transfer of energy flows brought about by flexible resource regulation capabilities, enhancing the competitiveness and value certification of VPPs in the electricity market, and providing useful reference for the construction of China's next-stage electricity spot market. Finally, a flexible premium allocation mechanism is proposed, and the effectiveness of the proposed theory is verified, effectively cultivating the cognitive ability of market participants in the market trading process while ensuring supply-demand matching.

II. THE PRESENT SITUATION OF MARKET TRANSACTION TYPES INVOLVING VPPS PARTICIPATION

In recent years, power grids with high penetration of renewable energy face significant challenges in the scarcity of flexible resources. The capacity value of electricity commodities becomes prominent, and there is an urgent need to reliably tap into adjustable resources that are highly reliable, cost-effective, and environmentally friendly. Through platform-based operations, VPPs aggregate a massive amount of flexible resources on the demand side. Based on the concept of the sharing economy, VPPs inspire electricity users to optimize energy usage while providing collaborative services for grid operations, demonstrating important characteristics of low-carbon, high efficiency, and economic security. Since the development of VPPs, both domestically and internationally, diverse scheduling and control systems have been established based on different market operating environments, adapting to varied market transaction types, and granting VPPs independent status as market entities. This allows them to contribute value in different market scenarios, as shown in Table 1.

TABLE 1. Domestic and foreign VPPs to participate in the electricity market trading varieties.

Trading varieties	Object of transaction	Country/Region	Aggregated resource types
Spot market	Electrical energy	German [17], United States [18], China [19], etc.	Mainly primary energy
Frequency regulation market (including secondary and tertiary frequency regulation)	Energy + Capacity	Australia [20], German [21], United States [22], etc.	Storage and load resources
Peak regulation market	Electrical energy	North China [23], Shanghai [24]	Load resources
Demand response service	Electrical energy	United States [20], Jiangsu [25], Beijing [26], etc.	Load resources
Capacity market	Generation capacity	United States [27]	Mainly storage resources
Reserve market (spinning, non-spinning)	Capacity	United States [28]- [30], etc.	Storage and load resources
Balancing services	Electrical energy	Europe [31]- [34]	Mainly load resources
Congestion management	Capacity	China [35]	Mainly storage resources

Currently, foreign electricity markets have a more mature market mechanism, a richer variety of trading products, and a broader range of participants. VPPs provide value-added services across multiple dimensions of market business needs. In terms of energy value, with a primary focus on the United States and certain regions in Europe, VPPs primarily act as agents for power generation, representing distributed resources participating in the spot market to generate revenue throughout all time periods or during peak hours. At the same time, VPPs demonstrate technological advantages in representing demand-side load resources and providing demand response services. In the European electricity market, the balancing market plays a crucial role in ensuring the secure and stable operation of the power system. VPPs, through coordinating flexible resources, offer upward and downward regulation services, generating market-driven revenue. Additionally, in the frequency regulation ancillary services market in the United States and Europe, VPPs obtain partial energy revenue based on a pricing system that combines regulation capacity and regulation mileage. In terms of capacity value, in addition to the previously mentioned capacity revenue in the frequency regulation ancillary services market, VPPs can also complete transaction fulfillment based on capacity targets in markets such as the reserve market and rotational inertia. Within congested areas of the transmission and distribution grid, VPPs leverage the value of energy storage and transmission assets to provide compensated services. It is worth noting that in the regional capacity market in the United States, VPPs are allowed to represent distributed resources across nodes to provide capacity assurance and gain market share. In terms of flexibility value, VPPs provide flexible regulation services in responding to renewable energy fluctuations, meeting grid ancillary service demands, incentivizing user energy behavior, etc. However, in the current mechanisms, compensation settlements are still completed through trading assets, lacking a recognized method for valuing flexibility. In the domestic electricity market, as the spot market is still in the trial operation stage in China, the market-oriented operation of VPPs has started with participation in ancillary service markets. VPPs have established market mechanisms primarily focusing on peak shaving and demand response in regions such as Guangdong, North China, Shanxi, Zhejiang, etc. Additionally, in the typical scenario of the Jiangsu power grid as a major recipient of renewable energy, it explores the service capabilities of demand-side flexible resources in solving inertia problems through a source-grid-load-storage friendly interaction system, providing precise load shedding, etc. Meanwhile, regions such as Guangzhou have successively amended "two regulations," allowing independent energy storage operators to participate in trading varieties in ancillary service markets, such as inertia and ramping, providing policy support for the business expansion of VPPs.

In the new power system, VPPs need to continuously expand its service capabilities in the ancillary service market and gradually transition to the energy market with spot transactions as the main focus. The driving forces mainly come from four aspects: 1) With the high proportion of new energy sources connecting to the grid, the proportion of spot market transactions continues to increase, and the spot market urgently requires more flexible resource participation to facilitate the market-oriented consumption of clean electricity. 2) With the national requirements for 5% to 20% energy storage configuration in new energy power stations, besides serving to stabilize output and fulfill frequency modulation responsibilities, the redundant capacity of energy storage will serve as a new power source for green electricity storage and sales. However, due to limitations in individual capacity scales, there is a lack of effective ways for them to participate in the wholesale market. 3) The national strategy of deploying county-wide photovoltaics promotes widespread deployment of distributed generation. When local consumption of distributed green electricity is insufficient, it can be aggregated through the transmission and distribution network gateway to participate in the spot market, achieving greater profits. 4) Driven by the market environment, some regions have seen the orderly development of small hydropower. However, there is still a lack of commercial operating models, as seen in places like Lishui, Zhejiang. It is crucial to improve market mechanisms to guide the rational investment and efficient utilization of distributed generation. Therefore, exploring the participation of VPPs in spot markets on behalf of distributed resources is of great significance. This approach not only reflects the energy value of distributed resources but also evaluates their green and flexibility values through the design of market trading models, thereby stimulating the upstream and downstream industrial ecology of distributed resources.

III. THE SPOT MARKET CLEARING MODEL ADAPTED FOR THE INVOLVEMENT OF VPPS

A. PROBLEM DESCRIPTION

At the present stage, the large-scale integration of renewable energy into the power system, coupled with a continuously increasing penetration rate, has led to the scarcity of flexible resources, causing significant challenges to the operational stability of the power system. Although China has successively proposed market mechanisms such as climbing and rotational inertia to address the challenges of the new power system, it remains difficult to fully incentivize the rapid expansion of adjustable resources due to the need for the cultivation and transition of market participants for new market trading varieties. Therefore, introducing the value recognition of resource flexibility into existing market trading varieties has become one of the key issues in market trading technology.

In fact, in order to reflect the value assessment of power system resources in different time and space dimensions, complementary mechanisms have been proposed in the design of the electricity market. For example: 1) Using nodal prices to reflect the energy supply and demand situation in different spatial locations of the power system; 2) Organizing the energy market with time-based energy blocks to reflect the value signals of energy in different time periods; 3) Using capacity compensation mechanisms to reflect the opportunity cost of different resources in ensuring the stable operation of the power system, and so on.

However, with the construction of new power systems, existing market technical means are insufficient for three reasons: 1) With user-side resources participating in the market through an agency model, existing technical means cannot meet the flexible demand for users to switch their electricity consumption behavior patterns; 2) Post-event price signals (such as nodal prices) cannot meet the real-time resource optimization and allocation needs of the power system, failing to fully leverage the flexibility of market entities; 3) Market entities lack the ability to deduce the clearing of electricity market, and existing technical means do not provide sufficient space for exploratory declarations by market entities, which is not conducive to cultivating the enthusiasm of market entities. In summary, this paper aims to introduce market declaration strategies and their clearing models that reflect the flexible adjustment characteristics of resources into existing spot market trading models to address the aforementioned market technical issues. The specific improvements in trading mechanisms and trading technologies are mainly in the following four aspects:

Firstly, building upon the existing unilateral market, we adopt a flexible bidding mechanism where both electricity buyers and sellers submit quantity and price bids separately, and the clearing process is centralized. This approach is designed to create a spot market clearing model suitable for VPPs participation, reflecting the dual role demands of users with flexible switching behavior between electricity generation and consumption. However, to curb speculative activities by the same market participant within the same trading period and simplify the regulation of market trading contracts, a restriction is imposed on VPPs, allowing them to participate in the market in only one role—either as a buyer or a seller—during the same trading period.

Secondly, within the bilateral centralized bidding model, we draw from the declaration mechanism experience in the

Nordic market. This entails allowing market participants to enhance the traditional declaration model by introducing flexible energy blocks and flexible hours. This addition aims to accurately depict the flexible regulatory characteristics of market participants, facilitating the transition from the traditional rigid configuration to a more flexible and optimized configuration in the power system. Furthermore, within the declaration mechanism, we introduce a preference parameter for adjustment priority. Market participants are required to label their preferences for their operating periods among multiple flexible energy blocks or flexible hours based on their bidding experiences in the market.

Thirdly, considering the immaturity of the current spot market in China, fully opening up the declaration methods for market participants might lead to reduced enthusiasm from market entities with disparate market perceptions and weaker regulatory capabilities. Therefore, in the initial stages of the market, there is an encouragement for new market entities like VPPs to participate in the market using more flexible declaration methods. These market entities, representing distributed resources, inherently possess flexible regulatory capabilities. Utilizing a more flexible market model aligns with their market demands and facilitates arbitrage, thus enhancing the exploration and utilization of the system's flexible regulatory resources.

Fourthly, in the settlement mechanism, an assessment method for flexibility premiums is used to identify the premium space for flexible regulatory market entities such as VPPs across different temporal and spatial dimensions. Beyond the pricing of electric energy, flexibility premiums are separately settled, and the premium space is returned to market entities. Combining each market transaction result to form a new market price signal, this approach, while ensuring the matching of supply and demand in the market trading process, effectively cultivates market entities' cognitive abilities toward the market. It incentivizes market entities to approach complete rationality from bounded rationality, thereby achieving greater societal cost benefits.

B. MATH MODEL

1) OBJECTIVE FUNCTION

The optimization objective of the market clearing model is to maximize social welfare, which is expressed as the maximum difference between the purchasing cost and selling revenue. The function expression is as follows:

$$\max \left[\sum_{t=1}^{n} \left(\sum_{b=1}^{B} \gamma_{h,b,t} P_{h,b,t} C_{h,b,t} - \sum_{s=1}^{S} \gamma_{h,s,t} P_{h,s,t} C_{h,s,t} - \lambda_t \left(\beta_{b,t} P_{b,t} C_{b,t} + \varphi_{f,t} P_{f,t} C_{f,t} \right) \right) \right] \tag{1}$$

where n represents the number of trading periods within a day; B represents the total number of electricity purchasers; S represents the total number of electricity sellers; $\gamma_{h,b,t}$ and $\gamma_{h,s,t}$ are the winning status for hourly transactions on the purchasing side and the generating side, with values of 0 or 1; $P_{h,b,t}, C_{h,b,t}$ and $P_{h,s,t}, C_{h,s,t}$ are the declared electricity quantity and price for hourly transactions on the purchasing side and selling side in time period t; $\beta_{b,t}$ is the winning status for flexible block transactions in time period t, represented as a binary variable with values of 0 or 1; $P_{b,t}$, $C_{b,t}$ are the declared quantity and price for flexible block transactions in time period t; $\varphi_{f,t}$ is the winning status for flexible hourly transactions in time period t, represented as a binary variable with values of 0 or 1; $P_{f,t}, C_{f,t}$ are the declared quantity and price for flexible hourly transactions in time period t; λ_t takes values of 1, 0, or –1. When the value is 1, the VPP declares flexible hours and flexible block transactions as a seller. When the value is 0, the VPP does not declare flexible transactions. When the value is –1, the VPP declares flexible hours and flexible block transactions as a buyer.

2) CONSTRAINT CONDITIONS

1) Electricity generation and consumption balance constraint

$$\gamma_{h,s,t} P_{h,s,t} = \gamma_{h,b,t} P_{h,b,t} - \lambda_t \left(\beta_{b,t} P_{b,t} + \varphi_{f,t} P_{f,t} \right) \tag{2}$$

2) Market clearance constraint Considering the different bidding rules for the buying and selling sides of the market, where the buying-side market entity wins if the bid price exceeds the market clearance price, and the selling-side market entity wins if the bid price is less than the market clearance price. In summary, the expression for the market clearance constraint is as follows:

$$\begin{cases} \gamma_{h,b,t} \left(C_{h,b,t} - \theta_t \right) P_{h,b,t} \geq 0 \\ \gamma_{h,s,t} \left(C_{h,s,t} - \theta_t \right) P_{h,s,t} \leq 0 \end{cases} \tag{3}$$

$$\lambda_t \beta_{b,t} \left(C_{b,t} - \theta_t \right) P_{b,t} \geq 0 \tag{4}$$

$$\lambda_t \varphi_{f,t} \left(C_{f,t} - \theta_t \right) P_{f,t} \geq 0 \tag{5}$$

where θ_t is the market clearance price in time t.

3) Safety constraints In the market clearance model, safety constraints are reflected in both network security and unit safety aspects. Line safety constraints are essential in assessing network congestion, which affects the temporal and spatial supply-demand balance of energy. When there is line congestion, it can impact the clearance prices [36]. However, this study focuses on evaluating the premium of flexible regulation capability in the spot market. Therefore, it is assumed that the discussion takes place in scenarios where the grid's transmission and distribution capacity are adequate to simplify the factors affecting market clearance.

On the other hand, unit safety constraints involve the reliable operation of distributed resources, which relies on centralized monitoring and control. Transitional regulatory systems may reduce the willingness of distributed resource operators (i.e., owners) to participate in the market. In the clearance model mentioned above, there is no need to consider the safety boundary constraints of VPPs aggregating distributed resources. Instead, the operational control and regulatory authority are transferred to the resource operators. For operators lacking regulatory control capabilities, encouraging them to commission VPP operators for equipment management is proposed.

Conventional VPP regulation mainly relies on a two-layer scheduling model [37], which considers both economic maximization and grid safety constraints. Specifically, Commercial VPPs (CVPPs) aggregate the state parameters of Distributed Energy Resources (DERs), including the maximum and minimum output of controllable power sources and ramp rates. Based on data on power sources, loads, and electricity prices, combined with constraints such as ramp rates and single-period maximum and minimum output, a model is established and solved to develop the optimal economic scheme. Transmission VPPs (TVPPs) receive the optimal economic scheduling scheme from CVPPs and, based on conditions such as power grid topology and power flow constraints, establish a safety scheduling model to adjust the optimal economic scheduling scheme to ensure the safe and stable operation of the distribution network. Once a safety confirmation signal is received, TVPPs provide the revised optimal scheduling scheme to CVPPs, which submit bidding schemes to the electricity market after verification.

Therefore, in the clearance model proposed in this paper, when VPPs participate in the electricity market as third-party entities, the main research objective is to explore their flexibility benefits. Hence, it is assumed that the various distributed resources within the VPP comply with safety boundary constraints.

Furthermore, since commissioning VPPs to participate in the electricity market is a profitable behavior for operators, their revenue includes fixed income, which is obtained as long as they have the required regulation capabilities, and actual regulation income, which is based on providing positive and negative reserves as needed and obtaining returns based on the regulated power quantity. Currently, in some provinces of China [38], industrial users, energy storage, and charging station operators can directly participate in demand response or integrate through load aggregators. Residential users without regulatory capabilities must participate through load aggregators. Therefore, in this study, all operators without regulatory capabilities are assumed to commission VPPs for regulation. This operational model is conducive to satisfying the satisfaction of virtual power plant (VPP) business models under diverse stakeholder forms, striking a balance between safety control and operational willingness. It enables optimization of operational decisions for different levels of stakeholder interests, enhances market operators' control capabilities and flexibility over resources, all while fulfilling market transaction outcomes.

3) MODEL LINEARIZATION

The constraints involving flexible bidding methods in (3)-(5), including variables such as the bid status and market clearing price, constitute nonlinear relationships, increasing the difficulty of solving the nonlinear programming problem for the clearing model. Therefore, this paper introduces the following linearization methods to address this technical issue. Taking (3) as an example, the linearization expression is as follows:

$$\begin{cases} \gamma_{h,t} \leq 1-u \\ \theta_{min}(1-u) \leq \theta_1 \leq C_{h,t}(1-u) \\ C_{h,t}u \leq \theta_2 \leq \theta_{max}u \\ \theta_t = \theta_1+\theta_2 \\ u \in \{0,1\} \end{cases} \tag{6}$$

where u is the introduced binary variable (0-1); θ_1, θ_2 are intermediate variables related to the clearing price.

C. PARAMETERIZATION METHOD FOR FLEXIBILITY CHARACTERIZATION

Flexible hourly transactions require the declaration of the price and quantity of electricity within a unit hour, and multiple allowed bidding periods with the same declared price and quantity. Within the allowable bidding periods, flexible hourly transactions can be awarded at most once and cannot be partially awarded, but the bidding period is not fixed. Flexible block transactions involve declaring multiple bid periods with fixed prices and bid quantities, but the number of declared periods is limited. Each period needs to declare continuous electricity quantity and price for three hours or more. The clearing method is similar to flexible hourly transactions. Within multiple bidding periods, at most one block can be selected for award, and partial awards are not allowed. The clearing periods for both transaction modes are determined through centralized optimization by the market clearing model. Compared to flexible hourly transactions, flexible block transactions involve market participants considering their start-stop characteristics in the generation plan over a larger time dimension. They leverage flexible adjustment capabilities and greater time flexibility to secure more favorable bidding periods and increased market revenue. Diagrams for both transaction modes are illustrated in Fig.1 and Fig.2.

1) FLEXIBLE HOURLY TRADING

For certain market participants, it may be challenging to accurately predict their output or electricity consumption for all 24 time periods in a day. However, they can forecast the output or electricity consumption for certain periods more accurately. For instance, in the case of wind power on the generation side, it may be predicted that significant

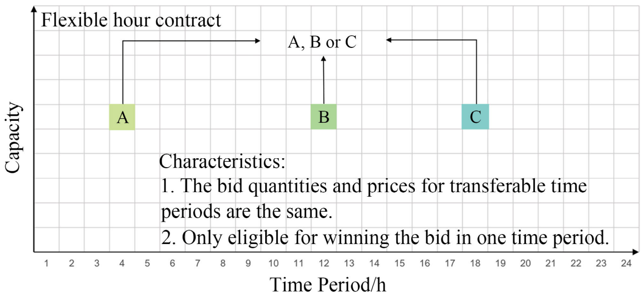

FIGURE 1. Diagram of flexible hourly contracts.

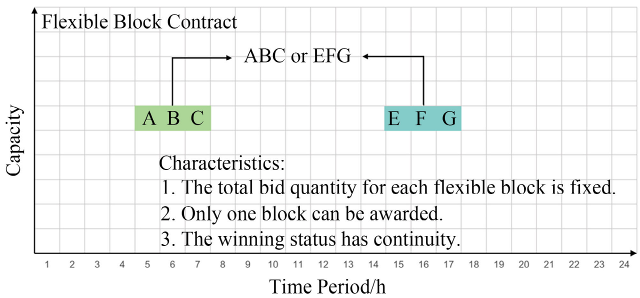

FIGURE 2. Diagram of flexible block contracts.

power generation will occur at 4:00, 13:00, and 20:00 the next day, considering various factors including forecasting. In the case of gas-fired power generation, a certain base load is ensured through long-term market bidding, guaranteeing the base output and cost recovery of the units. In such cases, aiming to maximize social welfare, it's possible to declare electricity quantities for peak periods the next day, meeting the demand during system peaks and transacting at high prices to earn more revenue. On the consumer side, for instance, with electric vehicle charging, users may have specific times available for charging the next day, such as 7:00, 9:00, and 14:00, without strict requirements on exact timing.

In these scenarios, the demand of market participants is more flexible and variable compared to independent hourly trading. There may be no need to declare electricity quantities for all 24 periods, as the focus may only be on specific periods to gain high profits or meet intermittent electricity needs. Considering these types of market participants, flexible hourly trading can be established to accommodate the uncertain nature of time periods. When declaring, factors such as accurate electricity quantity forecasting, price differentials across time periods the next day, and individual electricity consumption characteristics are considered, enabling declarations of acceptable times, quantities, and prices.

2) FLEXIBLE BLOCK TRADING

On the generation side, coal-fired power generation exhibits controllable output, with marginal costs increasing as output rises, but its start-up and ramp-up are slower with higher start-up costs. Nuclear power, on the other hand, maintains steady output with higher generation costs, and the planned outage time for nuclear plants is determined by overhaul schedules, resulting in longer periods without shutdowns. On the consumer side, large industrial electricity consumers typically have stable and continuous loads, with minimal fluctuations in usage patterns. These users can seek to lock in prices through medium to long-term trading to minimize their exposure to spot market volatility.

Both these types of market participants exhibit characteristics of continuity and stability in generation and consumption, suggesting the establishment of a continuous trading mechanism. This mechanism would involve assuming a portion of the base load, allowing participants to maintain stable generation or consumption over fixed periods, aligning perfectly with their characteristics. During trading, participants can declare the duration of their continuous electricity consumption, the total consumption, and the corresponding prices.

The parameterized representation model for flexible hourly transactions is as follows:

$$\begin{cases} \left[T_{f,m}, T_{f,n} \dots T_{f,q}\right], \forall (m, n, q) \in (1:24) \\ m \neq n \neq q \\ C_{f,m} = C_{f,n} = C_{f,q} \\ P_{f,m} = P_{f,n} = P_{f,q} \\ \varphi_{f,m} + \varphi_{f,n} + \varphi_{f,q} \leq 1 \end{cases} \tag{7}$$

The parameterized representation model for flexible block transactions is as follows:

$$\begin{cases} \left[T_{b,m}, T_{b,m+1} \dots T_{b,m+n}, \dots T_{b,q}, T_{b,q+1} \dots T_{b,q+n}\right], \\ \forall (m, q) \in (1:24) \\ C_{b,m} = C_{b,q}, C_{b,m+1} = C_{b,q+1}, C_{b,m+n} = C_{b,q+n} \\ P_{b,m} + P_{b,m+1} + P_{b,m+2} = P_{b,n} + P_{b,n+1} + P_{b,n+2} \\ \beta_{b,m} = \beta_{b,m+1} = \beta_{b,m+n} \\ \beta_{b,q} = \beta_{b,q+1} = \beta_{b,q+n} \\ \beta_{b,q} + \beta_{b,m} \leq 1 \end{cases} \tag{8}$$

IV. FLEXIBLE PREMIUM ASSESSMENT METHODS AND MECHANISM DESIGN FOR VPPS

A. FLEXIBLE PREMIUM ASSESSMENT METHODS FOR VPPS

Due to the dynamic influence of multiple factors such as social activities, natural environment, and market participant decisions on the supply-demand situation in the power system, the value of flexibility in the power system is also dynamic and cannot be determined through a single optimization cost. In traditional market declarations, each market participant only quotes in one temporal-spatial dimension, which may lead to inaccurate declarations and excessive transaction costs. With the introduction of flexible trading modes, VPPs can quote in different temporal-spatial dimensions, leveraging their flexible characteristics to unleash social welfare and enhance societal dividends. Based on this perspective, this paper proposes a method for evaluating the flexibility premium of VPPs in the spot market, where the difference in social welfare under various

TABLE 2. Priority parameter.

Priority N	Declaration willingness
00	Random assignment of priority
01	Set Priority to Low
10	Set Priority to Medium
11	Set Priority to High

clearing boundaries resulting from the flexibility matching in temporal-spatial dimensions is considered as the premium. This approach illustrates that the same transaction volume for the same market participant has different values in different temporal dimensions, reflecting the gains created by the temporal-spatial transfer of energy flows driven by flexible resource adjustment capabilities.

At the current stage, there is limited historical transaction information in the electricity market. Each market participant needs to make declaration decisions within limited boundary conditions. The compensation space for flexibility premium comes from the limited rational decisions of market participants. It is manageable in scale and does not require the establishment of separate compensation funds. Therefore, this paper designs the mechanism of flexibility premium space for VPPs. This mechanism introduces flexible declaration and adds declaration priority setting and settlement incentives. On the one hand, it can improve the matching rate between supply and demand in the electricity market in certain spatial and temporal dimensions. On the other hand, it helps cultivate the cognitive level of market participants regarding the supply-demand relationship in the market.

This paper adopts a binary approach for priority parameter setting. While declaring flexible transactions, each market participant simultaneously declares the parameters shown in Table 2, labeling their preferences for the bid-winning time slots. When there is no flexible declaration, time slots with higher priority preferences will be awarded to market participants. Newly participating market entities do not possess the ability to assess priorities, but still aim to explore their flexibility premium space. They can request the market trading institution to randomly assign priorities to the flexible trading time slots they declare. This setting allows market participants to undergo a process of understanding market-oriented supply and demand relationships and fosters space for development. During operation, market participants can improve their priority assessment capabilities by collecting historical operating data to adjust their future bidding behavior. Other market participants can set high, medium, and low priority preferences based on their individual bid-winning intentions.

1) METHODOLOGY FOR COMPUTING FLEXIBILITY PREMIUM SPACE

Using VPPs to participate in multi-scenario spot market clearing simulations, assessing flexibility premium space:

Scenario 1: Centralized clearing based on the highest priority declaration information in flexible bidding by VPPs.

Scenario 2: Building upon Scenario 1, the VPPs introduce flexible block and flexible hourly transactions, simulating market clearing through centralized clearing.

Based on the aforementioned simulation process, the social cost calculation for spot market clearing simulations by VPPs in different scenarios is obtained.

As mentioned above, the value assessment method for the flexibility premium of VPPs involves simulating and deducing in multiple scenarios. It calculates the space released by the VPP's flexible adjustment ability for the overall social cost of market transactions. The flexible value created by the introduction of flexible bidding strategies by VPPs is computed according to (9).

$$C_{pa} = C_{fle} - C_{tra} \tag{9}$$

where C_{pa} is the space released for social costs, C_{fle} is the social costs incurred with the use of flexible trading mechanisms, C_{tra} is the social costs incurred with the use of traditional trading mechanisms.

The calculated value of (9) may fall into multiple scenarios: 1) If the value is 0, it indicates that the power system supply and demand are stable, and the flexible characteristics of adjustable resources will not alter the market dynamics. In this case, the clearing is based on the priority of flexible bidding strategies declared by the VPPs, meeting the preferred operating periods for the VPPs. 2) If the value is greater than 0, it suggests that adjustable resources, by changing the market supply conditions, have brought about a better societal welfare space. The created value should be distributed among the market entities declaring flexible transactions. In this scenario, with the optimization objective of maximizing societal welfare, the optimal operating periods for the flexible transactions declared by the VPPs are selected for clearing.

2) THE CLEARING PROCESS CONSIDERING PRIORITY PARAMETERS

The clearing process starts by introducing the declared information from various market participants as input parameters into the clearing model. Next, optimization is performed with the goal of maximizing social welfare in scenarios 1 and 2. The results of the market-clearing process in scenario 2 are then evaluated. If the winning time periods match the priority of scenario 1, the clearing results are locked. If the priorities do not match, further assessment is conducted to determine whether social welfare has increased. If social welfare has not improved, the clearing results are adjusted based on the highest priority declared time period. Otherwise, the clearing results are directly locked. The detailed clearing process is illustrated in Fig.3.

B. DESIGN OF FLEXIBILITY PREMIUM ALLOCATION MECHANISM FOR VPPS

The flexibility premium space is caused by the limited rationality declarations of various market participants. If the traditional settlement allocation method is followed, the

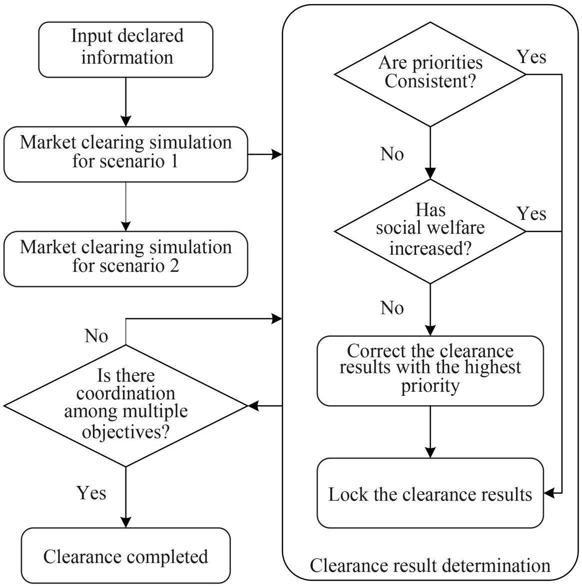

FIGURE 3. Flow chart of market clearing process considering priority.

revenue from this portion can only be allocated by the market participants who generate the premium space, which is not conducive to stimulating the enthusiasm of market participants to declare priorities. Therefore, in this section, based on the incentive compatibility principle, a flexible premium allocation mechanism that meets the needs of VPPs benefit sharing is proposed. The characteristics are mainly in three aspects: 1) The premium incentive space is constrained by the limited rationality of market participants, with a controllable compensation scale, eliminating the need for a separate establishment of a value transmission fund pool. 2) Under the incentive of the allocation mechanism, market participants have the motivation to independently seek optimization, moving from limited rationality towards absolute rationality. 3) To prevent speculative profits resulting from false declarations of flexible adjustment capabilities by market participants, regulatory penalty measures are introduced to curb such speculative behavior. Specifically, in this allocation mechanism, the flexible premium space is shared collectively by all market participants who declare flexible trading contracts. The flexible premium revenue is distributed in proportion to the flexible adjustment power, along with the electricity settlement prices, to calculate the VPPs' revenue per unit of electricity. This ensures that market participants with accurate priority declarations can obtain greater profits.

In order to contrast and analyze the enhancing effect on the VPPs' yield after the introduction of the flexible premium allocation mechanism, the methods for calculating the per-unit electricity benefits in Scenario 1 and Scenario 2 are provided separately: For Scenario 1, the per-unit electricity revenue during the time period with the highest priority for the VPPs is calculated based on the bid revenue and the declared total electricity quantity in that period, as expressed in (10). For Scenario 2, the per-unit electricity revenue is calculated by summing the ratio of settlement prices and allocation prices to the declared electricity quantity. This is expressed in (11).

$$C_u = \frac{C_e}{q_b} \tag{10}$$

$$C_u = C_{cl} + \frac{C_{ap}}{q_b} \tag{11}$$

In order to prevent market participants from falsely declaring adjustment capabilities for profit, the power system dispatching agency should, in addition to executing market clearance results, introduce random capability tests. The random testing period should be chosen as much as possible when market participants do not hold winning contracts. Any operational deviations caused by this should be guaranteed by the grid operation agency. For market participants who fail the test, they should be ordered to refund all historical allocations and be restricted from participating in flexible premium allocation for a certain period in the future. This measure aims to curb speculative behavior among market participants.

V. SIMULATION ANALYSIS

To simulate the spot market clearing process accommodating the participation of virtual power plants, this paper introduces 7 market entities, including 3 traditional electricity retailers, 3 electricity buyers, and 1 virtual power plant. The effectiveness of the proposed methods and models is verified using the IEEE RTS-96 system. It is assumed that the virtual power plant represents various types of flexible resources, including distributed generation and user-side adjustable resources, with both upward and downward adjustment capabilities. Therefore, it can participate in the market as both a seller and a buyer, while the other market entities do not introduce flexible bidding. They satisfy supply and demand through conventional quantity and price bidding. The case study in this paper utilizes the YALMIP toolbox in MATLAB and invokes the Cplex solver to solve the model. The solving time is 6.5412 seconds, and the solving platform is a computer equipped with an Intel Core i7-12700 (2.10 GHz) processor.

The spot market is organized into 24 trading intervals, during which electricity generators and consumers need to declare their supply and demand quantities along with their willingness to transact at a specified price. The VPP can additionally choose to declare flexible blocks and conduct flexible-hourly transactions, specifying preferred time intervals for priority transactions. After the declaration phase, the market organizing body carries out market clearing and assesses flexibility premiums. Once the transaction results are confirmed, they are sent to the power trading center for market settlement.

A. MARKET CLEARANCE SIMULATION FOR THE VPP ACTING AS A POWER PURCHASER

When the VPP agent purchasing power, bid data for each market participant can be found in Appendices A1 and A2,

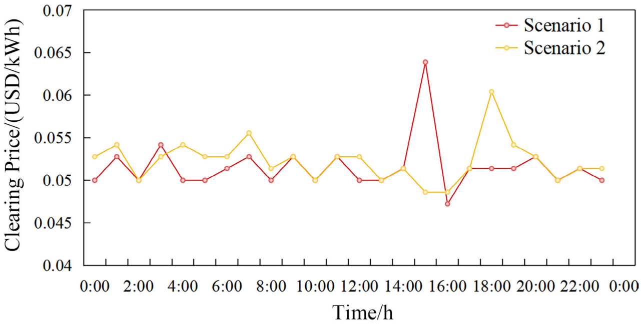

FIGURE 4. Clearing price diagram of VPP acting as a purchaser.

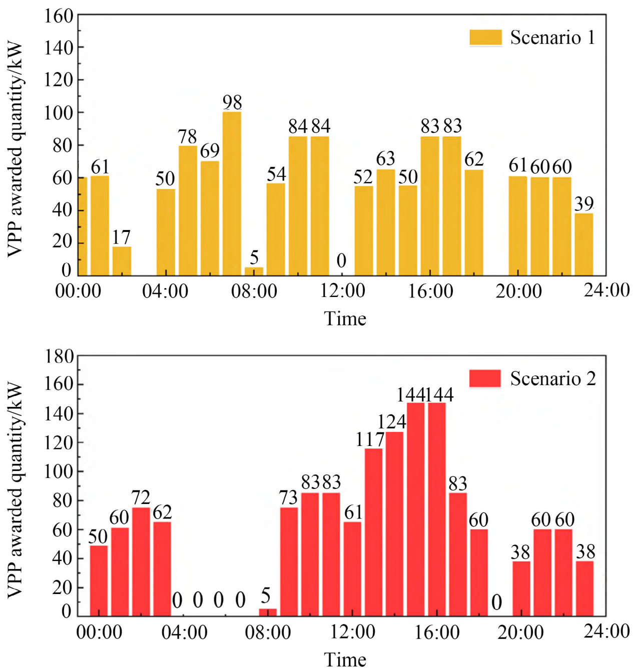

FIGURE 5. Bid-winning scalar of VPP acting as a purchaser.

with Market Participant 4 representing the VPP. The VPP declares flexible block transactions during the 05:00—07:00 and 13:00—15:00 intervals, with higher priority declared for the 05:00—07:00 period. Additionally, flexible hourly transactions are declared at 04:00, 10:00, and 17:00, with the highest priority given to the declaration at 04:00.

The market clearing prices in two scenarios for the spot market are shown in Fig.4, and the VPP's bid-winning scalar in both scenarios is illustrated in Fig.5. The bid status of the VPP in both scenarios is detailed in Table 3, where '1' signifies complete award, '0' indicates no award, and other parameters denote partial awards. The market clearing results for the two scenarios are presented in Table 4.

From the charts, it can be observed that prior to the introduction of flexible bidding strategies, the VPP only partially won conventional hourly transactions during the 06:00—08:00 interval. After implementing flexible bidding strategies, the VPP continued to win all conventional

TABLE 3. Bid-winning state of VPP acting as a purchaser.

Time Period	Scenario 1	Scenario 2
0	1.0000	1.0000
1	1.0000	1.0000
2	0.4512	1.0000
3	0	1.0000
4	1.0000	0.0000,(0)
5	1.0000	0.0000,[0]
6	0.8486	0.0000,[0]
7	1.0000	0.0000,[0]
8	0.0799	0.0831
9	1.0000	1.0000,(0)
10	1.0000	1.0000
11	1.0000	1.0000
12	0	1.0000
13	1.0000	1.0000,[1]
14	1.0000	1.0000,[1]
15	1.0000	1.0000,[1]
16	1.0000	1.0000,(1)
17	1.0000	1.0000
18	1.0000	1.0000
19	0.0000	0.0000
20	1.0000	1.0000
21	1.0000	1.0000
22	1.0000	1.0000
23	1.0000	1.0000

TABLE 4. Market clearing results when VPP acting as a purchaser.

Scenario	VPP transaction quantity/kW·h	Electricity selling revenue/ USD	Electricity purchasing cost/USD	Social welfare /USD
Scenario 1	203.6	128.4	157.8	29.4
Scenario 2	225.1	178.8	216.4	37.6

hourly transactions during the 14:00—17:00 interval. Moreover, in the flexible block intervals of 06:00—08:00 and 14:00—16:00, the VPP selected suboptimal intervals and won bids, prioritizing the 16:00 interval with the lowest flexibility hourly transaction priority. Although the social welfare increased, the VPP's transaction volume also increased by 189 kW·h, effectively improving its probability of winning bids in the electricity spot market.

To explore the social value created by the flexible characteristics of the VPP, firstly, from Table 4, it can be observed that the maximum values of social welfare optimization for the two scenarios are 29.4 and 37.6, respectively. Next, combining the flexible premium assessment method proposed in Section III of this paper, the maximum social welfare values of Scenario 2 and Scenario 1 are substituted into (9). The calculated value for the flexible characteristic premium assessment of the VPP is 8.2 USD. It is evident that the introduction of flexible bidding strategies by the VPP reflects its inherent flexibility value, contributing to a greater social welfare for the system.

B. MARKET CLEARANCE SIMULATION FOR THE VPP ACTING AS A POWER SELLER

When the VPP acts as the seller, bid data for each market participant can be found in Appendices A3 and A4,

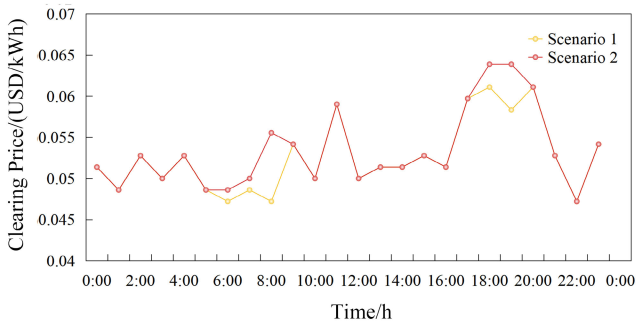

FIGURE 6. Clearing price diagram of VPP acting as a power seller.

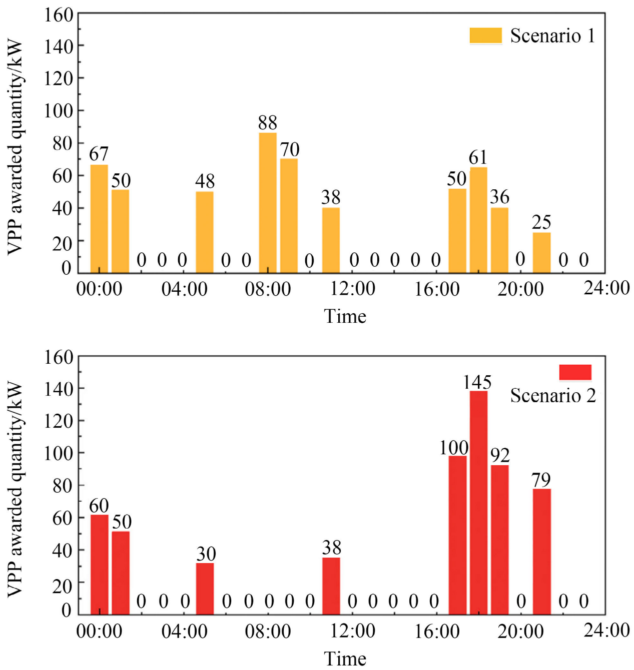

FIGURE 7. Bid-winning scalar of VPP acting as a power seller.

with Market Participant 6 representing the VPP. The VPP declares flexible block transactions during the 06:00—08:00 and 17:00—19:00 intervals, with higher priority declared for the 06:00—08:00 period. Additionally, flexible hourly transactions are declared at 09:00, 16:00, and 21:00, with the highest priority given to the declaration at 09:00.

When the VPP participates as the seller in the spot market, the market clearing prices for the two scenarios are shown in Fig.6. The awarded quantity for the VPP in the two scenarios is illustrated in Fig.7, and the bidding status at each moment is detailed in Table 5. The market clearing results for the two scenarios are presented in Table 6.

From the charts, it can be observed that before the introduction of flexible bidding strategies, the VPP's conventional hourly transactions between 06:00 and 08:00 were only fully awarded during the 07:00 and 08:00 intervals. After the introduction of flexible block bidding strategies, the VPP's flexible block hourly transactions were entirely

TABLE 5. Bid-winning state of VPP acting as a power seller.

Time Period	Scenario 1	Scenario 2
0	1.0000	1.0000
1	1.0000	1.0000
2	0.0000	0.0000
3	0.0000	0.0000
4	0.0000	0.0000
5	1.0000	1.0000
6	0.0000	0.0000,[0]
7	0.0000	0.0000,[0]
8	1.0000	0.0000,[0]
9	1.0000	0.0000,(0)
10	0.0000	0.0000
11	0.3915	0.4563
12	0.0000	0.0000
13	0.0000	0.0000
14	0.0000	0.0000
15	0.0000	0.0000,(0)
16	0.0000	0.0000
17	1.0000	0.1564,[1]
18	1.0000	1.0000,[1]
19	0.5333	0.0000,[1]
20	0.0000	0.0000
21	1.0000	0.3344,(1)
22	0.0000	0.0000
23	0.0000	0.0000

TABLE 6. Market clearing results when VPP acting as a power seller.

Scenario	VPP transaction quantity/kWh	Electricity selling revenue/USD	Electricity purchasing cost/USD	Social welfare /USD
Scenario 1	85.3	169.1	198.2	29.1
Scenario 2	85.3	168.9	202.9	34.1

awarded during the 17:00—19:00 interval, and flexible hourly transactions were awarded at 21:00, although only partially. The overall transaction volume of the VPP increased by 60 kW·h.

From Table 6, it can be seen that when the VPP acts as the seller, the maximum values of social welfare optimization for the two scenarios are 29.1 and 34.1 USD, respectively. Substituting the maximum social welfare values of Scenario 2 and Scenario 1 into (9), the calculated value for the flexible characteristic premium assessment of the VPP is 5 USD.

C. MARKET CLEARING SIMULATION FOR THE FLEXIBLE PREMIUM ALLOCATION OF THE VPPS

To explore the impact of the accuracy of market priority declarations on their own revenue, this section continues to simulate with seven market participants, including three electricity buyers and four electricity sellers. Among the sellers, two are VPPs, and among the buyers, one is a VPP. The three VPPs only declare flexible block transactions, with the highest priority interval consistently from 07:00 to 09:00, and the declared prices and total quantities are fixed. The declaration parameters can be found in Appendices A5 and A6.

The bid statuses of the three VPPs in the two scenarios are shown in Tables 7 and 8, and the market clearing results

TABLE 7. Bid-winning state of VPPs in Scenario 1.

Time	VPP1	VPP2	VPP3
0	0.0000	1.0000	1.0000
1	1.0000	0.0000	1.0000
2	0.5962	1.0000	0.0000
3	1.0000	0.3667	1.0000
4	1.0000	1.0000	0.0000
5	1.0000	1.0000	0.0000
6	1.0000	0.0000	0.0000
7	0.7609	0.0000	0.0000
8	1.0000	1.0000	1.0000
9	1.0000	0.8684	1.0000
10	1.0000	1.0000	0.0000
11	1.0000	1.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	1.0000	0.0000
14	0.0000	1.0000	0.0000
15	0.0000	1.0000	0.0364
16	1.0000	1.0000	0.0000
17	0.0777	1.0000	1.0000
18	0.7826	1.0000	1.0000
19	1.0000	1.0000	0.5467
20	1.0000	0.4727	0.0000
21	0.0000	1.0000	1.0000
22	0.0000	1.0000	0.0000
23	0.0000	0.0000	0.0000

TABLE 8. Bid-winning state of VPPs in Scenario 2.

Time	VPP1	VPP2	VPP3
0	0.0000	1.0000	1.0000
1	1.0000	0.0000	1.0000
2	0.5164	1.0000	0.0000
3	1.0000	0.3261	1.0000
4	1.0000	1.0000	0.0000
5	1.0000	1.0000	0.0000
6	0.0000,[1]	0.0000,[0]	0.0000,[0]
7	0.0000,[1]	0.0000,[0]	0.0000,[0]
8	0.0000,[1]	0.0000,[0]	0.0000,[0]
9	1.0000	0.8345	1.0000
10	1.0000	1.0000	0.0000
11	1.0000	1.0000	0.0000
12	0.0000	0.0000	0.0000
13	0.0000	1.0000	0.0000
14	0.0000	1.0000	0.0000
15	0.0000	1.0000	0.0299
16	1.0000	1.0000	0.0000
17	1.0000	0.8869,[1]	0.0000,[1]
18	1.0000	1.0000,[1]	0.6923,[1]
19	1.0000	1.0000,[1]	0.0000,[1]
20	1.0000	0.3987	0.0000
21	0.0000	1.0000	1.0000
22	0.0000	1.0000	0.0000
23	0.0000	0.0000	0.0000

for the two scenarios are presented in Table 9. Through a comparative analysis of the bidding outcomes for the VPPs in the two scenarios, it can be observed that in Scenario 1, VPP 2 and VPP 3 only win all bids in the 08:00 interval. Considering the non-winning status in the other two intervals with flexible declarations, VPP 1 has a higher success rate in the highest-priority interval. In Scenario 2, VPP 2 and VPP 3 shift their flexible block intervals to the 17:00—19:00 period, winning all bids and increasing their transaction volumes. VPP 1 chooses to win all bids in the highest-priority interval.

Combining Table 8 with (9), the calculated flexibility premium is 3.8 USD, and this is allocated among the three VPPs. The calculation of the VPPs' revenue per kilowatt-hour for flexible block transactions is then performed. Compared to the traditional method, the revenue per kilowatt-hour for flexible block transactions is shown in Table 9. From Table 9, it can be observed that with traditional settlement methods, the VPPs with accurate priority declarations have the lowest revenue per kilowatt-hour for flexible block transactions. However, with the new settlement mechanism, even though VPP 1 did not generate a flexibility premium, it can still share in this portion of revenue, resulting in an increase of 0.005 USD/(kW·h) in revenue per kilowatt-hour, thereby motivating all market participants to optimize their declarations.

In summary, when the VPPs act as agents, participating in the spot market with various flexible resources, including distributed generation and adjustable resources on the user side, through both flexible hours and flexible blocks, it not only effectively increases the transaction volume of the VPPs in the electricity market but also provides the option to win bids in non-preferred intervals. Furthermore,

TABLE 9. Market clearing results in two scenarios.

Scenario	VPPs transaction quantity/kWh	Electricity selling revenue/USD	Electricity purchasing cost/USD	Social welfare /USD
Scenario 1	356.5	242.5	204.0	38.4
Scenario 2	457.1	242.1	199.9	42.2

by leveraging its inherent flexibility value, it creates a greater degree of social welfare and enhances the competitiveness and value validation of the VPPs in the electricity market.

The primary objective of the model proposed in this paper is to calculate the spot market clearing with the participation of virtual power plants, aiming to maximize social welfare on a larger scale. The focus lies in studying the participation of virtual power plants as a collective entity in flexible bidding mechanisms, evaluating the flexibility premium of virtual power plants, and establishing profit-sharing mechanisms. Modeling of internal economic dispatch within different types of virtual power plants and aggregation calculations for virtual power plants have been addressed in other literature [39], and thus are not the main focus of this paper's methodology. Certain simplifications and equivalences were made during the modeling process. However, as more market participants join the virtual power plant-mediated electricity market, their considerations regarding grid security should also be increasingly emphasized. In future studies involving larger-scale calculations, such as those involving virtual power plant participation across provinces or multiple provinces, simulation and modeling should be conducted using interconnected IEEE RTS-96 systems, with detailed modeling of security constraints.

TABLE 10. VPPs' revenue for flexible block transactions in two scenarios.

VPPs	Scenario 1/ ((USD/(kW·h))	Scenario 2	
		Traditional method/ (USD/(kW·h))	New settlement mechanism/ (USD/(kW·h))
VPP 1	0.040	0.051	0.056
VPP 2	0.015	0.060	0.054
VPP 3	0.019	0.065	0.060

TABLE A1. 24h bidding data of the power sellers.

Time	Generator 1	Generator 2	Generator 3
0	0.0542, 105	0.0611, 84	0.0528, 65
1	0.0500, 121	0.0500, 78	0.0528, 60
2	0.0486, 110	0.0542, 95	0.0542, 65
3	0.0528, 115	0.0528, 80	0.0486, 37
4	0.0500, 58	0.0486, 70	0.0486, 35
5	0.0542, 85	0.0500, 95	0.0514, 60
6	0.0569, 105	0.0514, 60	0.0569, 80
7	0.0542, 80	0.0528, 60	0.0597, 85
8	0.0542, 115	0.0500, 60	0.0639, 70
9	0.0583, 95	0.0486, 60	0.0667, 90
10	0.0569, 120	0.0528, 75	0.0569, 60
11	0.0653, 105	0.0528, 80	0.0472, 60
12	0.0514, 115	0.0597, 100	0.0528, 60
13	0.0458, 95	0.0486, 90	0.0542, 60
14	0.0556, 120	0.0472, 65	0.0667, 85
15	0.0556, 90	0.0486, 65	0.0597, 70
16	0.0486, 100	0.0500, 65	0.0639, 80
17	0.0500, 140	0.0556, 105	0.0625, 75
18	0.0514, 130	0.0514, 65	0.0611, 70
19	0.0778, 100	0.0708, 110	0.0528, 80
20	0.0486, 90	0.0528, 80	0.0472, 60
21	0.0694, 100	0.0514, 70	0.0500, 65
22	0.0667, 135	0.0509,80	0.0411,60
23	0.0472, 95	0.0388,70	0.0472,65

VI. CONCLUSION

To ensure the stability of the power system operation and incentivize the rapid expansion of flexible resources, this paper references the trading model of the Nordic spot market and conducts in-depth research on the market clearing model and algorithm considering the complex bidding of flexible block contracts in the electricity spot market. The aim is to introduce market declaration strategies that reflect the flexible adjustment characteristics of resources and their clearing models onto the existing spot market trading model. The paper establishes a premium assessment method for the flexibility of VPPs, designs a flexible premium space allocation mechanism, and thus encourages market entities to provide flexible adjustment capabilities while approximating rational decisions under limited rationality. This research provides valuable insights for the future matching of green electricity supply and demand in the spot market. The conclusions obtained are as follows:

TABLE A2. 24h bidding data of power purchasers.

Time	User 1	User 2	User 3	User 4
0	0.0431, 56	0.0528, 30	0.0500, 60	0.0431, 75
1	0.0431, 50	0.0528, 35	0.0514, 60	0.0528, 61
2	0.0514, 38	0.0514, 30	0.0500, 60	0.0417, 65
3	0.0639, 35	0.0431, 30	0.0417, 60	0.0514, 65
4	0.0528, 80	0.0500, 75	0.0667, 70	(0.0444, 70)"11"
5	0.0500, 50	0.0514, 55	0.0458, 80	[0.0500, 70]"11"
6	0.0736, 35	0.0514, 31	0.0528, 60	[0.0500, 80]"11"
7	0.0667, 32	0.0528, 55	0.0417, 70	[0.0500, 100]"11"
8	0.0500, 35	0.0597, 55	0.0514, 60	0.0514, 60
9	0.0514, 33	0.0514, 55	0.0681, 60	(0.0444, 85)"10"
10	0.0708, 30	0.0542, 55	0.0500, 60	0.0819, 65
11	0.0458, 55	0.0431, 30	0.0528, 60	0.0806, 35
12	0.0806, 35	0.0500, 50	0.0792, 60	0.0736, 70
13	0.0500, 30	0.0653, 60	0.0500, 65	[0.0722, 70]"01"
14	0.0653, 30	0.0417, 35	0.0514, 70	[0.0528, 75]"01"
15	0.0486, 35	0.0500, 35	0.0528, 60	[0.0500, 65]"01"
16	0.0778, 60	0.0514, 30	0.0458, 60	[0.0542, 65]"01"
17	0.0472, 60	0.0500, 35	0.0708, 55	0.0444, 60
18	0.0903, 60	0.0514, 35	0.0667, 55	0.0514, 65
19	0.0486, 60	0.0778, 35	0.0736, 55	0.0514, 68
20	0.0417, 30	0.0472, 50	0.0528, 60	0.0458, 65
21	0.0570, 30	0.0528, 35	0.0500, 55	0.0458, 60
22	0.0514, 35	0.0514, 35	0.0514, 60	0.0458, 70
23	0.0500, 30	0.0444, 35	0.0444, 55	0.38, 68

Note: [Price, Quantity] represents flexible block transactions; (Price, Quantity) represents flexible hourly transactions; Price, Quantity without parentheses represents hourly transactions; "N" represents priority parameters.

TABLE A3. 24h bidding data of power purchasers.

Time	Purchaser 1	Purchaser 2	Purchaser 3
0	0.0583,105	0.0569,107	0.0458,65
1	0.0542,100	0.0611,90	0.0667,72
2	0.0611,120	0.0625,75	0.0583,65
3	0.0597,110	0.0514,78	0.0625,60
4	0.0486,57	0.0542,90	0.0486,60
5	0.0486,85	0.0528,80	0.0611,37
6	0.0458,105	0.0486,70	0.0542,35
7	0.0542,95	0.0638,90	0.0569,60
8	0.0611,110	0.0472,60	0.0597,85
9	0.0569,90	0.0528,65	0.0611,80
10	0.0583,100	0.0611,60	0.0667,90
11	0.0681,90	0.0486,65	0.0542,80
12	0.0528,115	0.0528,75	0.0528,60
13	0.0653,90	0.0667,140	0.0542,120
14	0.0681,125	0.0431,110	0.0431,134
15	0.0417,90	0.0486,150	0.0625,120
16	0.0625,105	0.0638,125	0.0542,105
17	0.0819,135	0.0569,95	0.0638,100
18	0.0542,120	0.0500,105	0.0625,90
19	0.0792,90	0.0472,100	0.0750,105
20	0.0500,90	0.0514,65	0.0528,90
21	0.0611,100	0.0819,110	0.0542,85
22	0.0722,130	0.0708,85	0.0486,60
23	0.0514,95	0.0472,75	0.0458,60

TABLE A4. 24h bidding data of the power sellers.

Time	User 1	User 2	User3	User 4
0	0.0638,40	0.0472,41	0.05,61	0.0583,70
1	0.0667,38	0.0458,42	0.0542,65	0.0486,55
2	0.0444,30	0.0514,48	0.05,48	0.0583,40
3	0.0458,40	0.0638,40	0.0556,70	0.0514,65
4	0.0625,70	0.0638,40	0.0528,80	0.0528,65
5	0.0597,65	0.0542,75	0.0472,110	0.0486,50
6	0.0667,85	0.0472,85	0.0486,96	[0.05,110]"11"
7	0.0638,75	0.0472,82	0.0486,100	[0.0472,80]"11"
8	0.05,85	0.0556,105	0.0472,85	[0.0486,100]"11"
9	0.0528,35	0.0653,55	0.0542,76	(0.0472,70)"11"
10	0.0708,40	0.0681,55	0.05,60	0.0764,85
11	0.0569,35	0.0569,50	0.0528,40	0.0653,80
12	0.0778,30	0.05,45	0.0792,75	0.0736,65
13	0.0569,45	0.0514,50	0.05,70	0.0778,45
14	0.0514,65	0.0556,60	0.0514,60	0.0611,60
15	0.0625,35	0.05,40	0.0528,60	(0.0583,55)"10"
16	0.0528,70	0.0514,45	0.0472,70	0.0542,45
17	0.0638,85	0.05,70	0.0542,65	[0.0542,60]"01"
18	0.0638,75	0.0514,53	0.0528,85	[0.0653,60]"01"
19	0.0611,90	0.0638,55	0.0472,70	[0.0556,70]"01"
20	0.0542,45	0.0542,50	0.0528,55	0.0611,65
21	0.0583,35	0.0528,60	0.05,50	(0.0542,60)"01"
22	0.0542,55	0.0542,45	0.0514,65	0.0597,75
23	0.0472,35	0.0597,45	0.0583,55	0.0667,40

Note: [Price, Quantity] represents flexible block transactions; (Price, Quantity) represents flexible hourly transactions; Price, Quantity without parentheses represents hourly transactions; "N" represents priority parameters.

TABLE A5. 24h bidding data of power purchasers.

Time	User 1	User 2	VPP 1
0	0.0681,85	0.0486,95	0.0528,45
1	0.0583,120	0.0528,90	0.0542,70
2	0.0542,100	0.0653,85	0.0542,52
3	0.0486,110	0.0569,74	0.0667,34
4	0.0542,79	0.0681,85	0.0542,65
5	0.0472,84	0.0667,75	0.0514,47
6	0.05,75	0.0486,85	[0.0583,70]"11"
7	0.0486,94	0.05,56	[0.0638,100]"11"
8	0.05,85	0.05,60	[0.0653,90]"11"
9	0.0638,75	0.0667,60	0.0653,74
10	0.0486,124	0.0514,55	0.0638,80
11	0.0583,90	0.0542,62	0.0667,36
12	0.0638,109	0.05,75	0.0638,54
13	0.0514,100	0.0542,132	0.0486,62
14	0.0625,125	0.0569,123	0.0542,103
15	0.0444,90	0.0625,139	0.0569,121
16	0.0486,106	0.0542,129	0.0681,104
17	0.0638,139	0.0625,97	[0.0458,105]"01"
18	0.0653,135	0.0542,115	[0.0542,90]"01"
19	0.0792,101	0.0625,103	[0.0653,90]"01"
20	0.0486,85	0.0638,75	0.0611,70
21	0.0694,120	0.0556,112	0.0638,80
22	0.0542,105	0.0472,75	0.0458,60
23	0.0583,110	0.0611,95	0.075,72

1) By introducing the declaration methods of flexible hours and flexible blocks in the spot market, the flexible characteristics of the VPPs' adjustable resources are fully utilized. Through the flexible and autonomous declaration approach, it effectively unleashes social welfare and increases market transactions during periods of insufficient supply and demand matching.
2) By comparing and analyzing the premium evaluation results before and after the introduction of flexible trading modes by the VPPs, it can be observed that the same transaction volume from market participants can have different values in different time dimensions. This effectively reflects the gains created by the spatiotemporal transfer of energy flows resulting from the flexible resource adjustment capability. It enhances the competitiveness and value validation of the VPPs in the electricity market, providing valuable insights for the construction of China's future electricity spot market.
3) In the premium space assessment and allocation mechanism proposed in this paper, by comparing the results of multiple VPPs in terms of winning bids and electricity revenue, it can be observed that market participants with accurate priority declarations can not only increase market transaction volume but also obtain greater profits. This effectively incentivizes each market participant to independently optimize their strategies, reducing the efficiency losses caused by suboptimal decisions.

TABLE A6. 24h bidding data of the power sellers.

Time	User 1	User 2	VPP 2	VPP3
0	0.0597,32	0.0625,34	0.0597,52	0.0542,45
1	0.0611,64	0.0444,49	0.0542,60	0.0458,65
2	0.0444,55	0.0642,76	0.0597,54	0.0597,50
3	0.0514,45	0.0542,73	0.0556,43	0.0542,45
4	0.0542,65	0.0778,84	0.0611,95	0.0653,70
5	0.0472,85	0.0472,75	0.0472,99	0.0458,70
6	0.0458,106	0.0319,98	[0.0486,105]"11"	[0.0486,85]"11"
7	0.0486,90	0.0486,120	[0.0486,80]"11"	[0.0486,76]"11"
8	0.0625,130	0.0472,100	[0.0486,92]"11"	[0.0486,80]"11"
9	0.0542,74	0.0472,105	0.0458,76	0.0458,70
10	0.0681,86	0.0625,80	0.0542,60	0.0764,80
11	0.0542,35	0.0472,55	0.0653,45	0.0653,90
12	0.0681,35	0.075,50	0.0528,75	0.0736,65
13	0.0569,40	0.0514,51	0.0778,70	0.0778,60
14	0.0778,60	0.0542,60	0.075,60	0.0472,45
15	0.0486,35	0.050,55	0.0542,60	0.0542,55
16	0.0792,60	0.0583,45	0.0569,70	0.075,60
17	0.0514,82	0.050,45	[0.0486,75]"01"	[0.0472,60]"01"
18	0.0472,80	0.0638,55	[0.0486,65]"01"	[0.0611,65]"01"
19	0.0556,89	0.0638,50	[0.0597,80]"01"	[0.0542,75]"01"
20	0.0597,39	0.0667,60	0.0444,55	0.0611,65
21	0.0458,55	0.0417,41	0.0417,50	0.0486,85
22	0.0597,50	0.0431,60	0.0583,65	0.0472,65
23	0.0576,35	0.0576,55	0.0576,55	0.0583,40

APPENDIX A

See Tables A1–A6.

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