energies

Article

A Comparative Analysis of Two Pricing Mechanisms, MCP and PAB, in the Chinese Frequency Regulation Market

Xian Huang * and Zhehan Li

School of Control and Computer Engineering, North China Electric Power University, Beijing 102206, China; tupolev_lizhehan@163.com
* Correspondence: hx@ncepu.edu.cn

Abstract: In the face of the new reform of China's "unified electricity market", the frequency regulation ancillary service market in each region of China is still divided between using the MCP and PAB pricing mechanisms. The purpose of this paper is to explore the different impact the laws of the above two pricing mechanisms have on the frequency regulation market and to provide relevant suggestions for this electricity market reform. This paper simulates the competitive activities of the frequency regulation market based on the multi-agent simulation model, conducts a comparative experiment by changing the pricing mechanism to a single variable based on the rules of the Sichuan frequency regulation market in China, and concludes that MCP can make the market fast and stable, and that its market settlement price is low, which is suitable for the "unified electricity market". Although PAB makes the market settlement price high, it can ensure the retention of high-performance units in the market, and the stable settlement price makes this model able to accurately reflect the "price signal", making it suitable for late adoption in the "unified electricity market".

Keywords: electricity frequency regulation markets; pricing mechanisms; MCP; PAB; multi-agent

check for updates

Citation: Huang, X.; Li, Z. A Comparative Analysis of Two Pricing Mechanisms, MCP and PAB, in the Chinese Frequency Regulation Market. *Energies* **2023**, *16*, 2876. https://doi.org/10.3390/en16062876

Academic Editor: Raymond Li

Received: 4 March 2023
Revised: 10 March 2023
Accepted: 17 March 2023
Published: 21 March 2023

1. Introduction

In January 2022, China's National Development and Reform Commission issued the "Guidance on Accelerating the Construction of a National Unified Electricity Market System" (Development and Reform [2022] No. 118), which pointed out that China's electricity market still has problems such as incomplete systems, imperfect functions, and non-uniform trading rules [1]. Additionally, this put forward a plan for the overall optimization of the overall design of the electricity market, the implementation of unified trading rules and technical standards, and the introduction of other general requirements. Among the functions of improving the unified electricity market system, it has been proposed that a system should guide the spot market to better discover real-time prices, accurately reflect the relationship between supply and demand of electric energy, establish and improve the ancillary service markets such as frequency regulation and standby, strengthen the orderly coordination among markets, and make good connections in terms of transaction timing, market access, and the price formation mechanism in use. Since the reform of China's ancillary services market, with the gradual expansion of the pilot scope, some provinces have introduced their own provincial frequency regulation ancillary services market construction programs, taking into account a province's power grid structure and power market construction. However, China's ancillary services market, in general, is still in the exploration period. As such, the market rules vary from region to region and province to province, the pricing and rationality of the transaction mechanism are open to debate and discussion, and many enterprises still maintain a wait-and-see mood.

According to the latest data released by the National Energy Administration in November 2022, the development China's wind power, solar power, and other new energy sources has gained momentum this year, with the scale of installed power maintaining rapid growth.

By the end of October, the country's cumulative installed power generation capacity was about 2.5 billion kilowatts, up 8.3% year on year. Among them, the installed capacity of wind power and solar power generation was about 350 million kW and 360 million kW, respectively, up 16.6% and 29.2% year-on-year, respectively [2], maintaining rapid growth. The large-scale development of random and intermittent new energy sources also poses a huge challenge to the safety and stability of the power system. The summary and improvement work of the frequency regulation market trading mechanism is particularly urgent and imperative under real demand and policy objectives.

Many scholars have conducted various studies on the market policies of ancillary services and the trading rules of competitive bidding mechanisms in the electricity market. In 2011, the U.S. Energy Regulatory Commission (FERC) issued Order 755, which introduced the new concept of "frequency regulation mileage" [3], i.e., the change in the actual output of a generating unit after receiving an AGC order. The new concept of "frequency regulation mileage" was introduced by FERC's Order 755, which is the change in the actual output of a generator unit after receiving an AGC order to quantify its frequency regulation performance. In this context, several states in the U.S. have responded by considering the measurement of the actual frequency regulation effect of the frequency regulation service [4–11] based on the actual situation of the Central Independent Operator (MISO) in the United States. Scholars have highlighted that, in addition to measuring the actual frequency regulation effect, such an operator should quantify frequency regulation operation, modify the market clearing process, and provide two-part compensation based on the actual frequency regulation performance of the units. As such, it should cover the above four aspects to strengthen the market rules. [12] emphasizes the importance of the priority deployment of generating units with high-performance parameters based on both frequency regulation capacity and frequency regulation mileage, and proposes a frequency regulation market model to achieve the above effect. The literature [13] evaluated the existing frequency regulation operation, dispatching, and compensation service mechanisms in the United States and proposed a comprehensive performance calculation method that includes the accuracy of commands issued by an AGC and the actual frequency regulation output performance of the units in order to motivate the generating units to provide more efficient and high-quality services. In addition, the literature presented a detailed description and comparative analysis of pricing mechanisms [14] for different electricity markets in the United States.

At the same time, other countries besides the United States have started discussions on the mechanisms of rules for the frequency regulation market. For Colombia, [15] analyzed the existing technical standards and compensation provisions for ancillary services in the Colombian National Interconnection System (SIN) and the functional characteristics of energy exchanges between Colombia and its neighbors, describing the main weaknesses and policy challenges that Colombia has to address, with the compensation mechanism for ancillary services as the main issue. [16] proposed multiple settlement systems consisting of a binding day-ahead market, intraday trading, and a balancing market to efficiently integrate a large amount of variable renewable energy in Colombia in response to the growing installed capacity of new energy sources. Working in the European electricity market, [17] analyzed the advantages and disadvantages of each change in the structure, services, and products of the European ancillary services market based on the level of agreement between the system operator and the ancillary services provider, providing a guide for regulators, market operators or participants for achieving efficient market arrangements. [18] explored the compensation mechanisms in the European ancillary services market and found that the specific design of the capacity compensation mechanism will always be skewed differently between various power technologies and that the use of a capacity compensation mechanism with call options and transaction prices can improve the competitiveness of energy storage devices relative to conventional power plants.

In terms of market mechanism models, [19] proposed a dynamic regulation market mechanism (DRMM) to meet demand response units and generate units to bid for frequency regulation services in real-time, ensuring optimal allocation and reducing the cost of frequency regulation services. Based on this research, [20] proposed an integrated dynamic market mechanism (DMM) that combines real-time market and frequency regulation. This should not only be open to new energy units but also incorporate energy consumers while the market shares real-time technical information. The literature [21] investigates the negotiation methodology and validates the effectiveness of smart power markets for data centers and supercomputing facilities in relation to their use in the provision of ancillary services. In addition to conventional generating units, the literature [22] proposes a collaborative optimization market model for electric energy and frequency regulation services based on the effect of frequency regulation, considering the charging and discharging schedule of energy storage devices as a way to improve the efficiency of the frequency regulation market. Ref. [23] incorporates wind power based on energy storage and proposes a real-time cooperative scheme for the joint participation of wind storage in the energy and ancillary services markets, taking advantage of their complementary nature and significantly increasing the overall revenue. The literature [24] proposes a predictive control scheme for coordinating the provision of ancillary services from heterogeneous complementary resources at different time scales. Additionally, the literature [25], thinking from the user side, proposes a two-way smart charging algorithm for electric vehicles considering user preferences, peer-to-peer power trading, and the provision of ancillary services to the grid.

The above-mentioned literature has conducted more studies on many issues such as the quantitative criteria of trading targets and the trading mechanisms of the frequency regulation market, providing theoretical support and optimization suggestions for the formation and initial improvement of a domestic frequency regulation ancillary service market from scratch. However, since China's current frequency regulation market has taken shape, in order to achieve better discovery of real-time price of electricity, accurately reflect the relationship between supply and demand, and integrate the ancillary service market in order to achieve the goals of better discovery of real-time electricity prices, accurate reflection of supply and demand, and integration of ancillary service markets, it would be more convenient and easier to implement policies based on the existing frequency regulation market rules in China. This would allow us to explore the laws of different mechanisms on the market impact so as to achieve the goal of an integrated design of domestic ancillary service markets. Based on the above analysis, this paper investigates the current open frequency regulation market in China and the differences between these market rules and conducts a control modeling simulation comparison experiment with the pricing mechanism as a single variable, using the Sichuan market as the basis for the pricing mechanism. A cost–benefit mathematical model is established for the participation of generating units in frequency regulation, and several market simulation scenarios are designed for multiple units, considering supply and demand, frequency regulation performance, and installed capacity, and the simulation model is built based on MATLAB software using the multi-agent simulation method. The paper is organized as follows: Section 2 describes the reform process and status of the Chinese frequency market and its general structure, listing the main differences between each market rule; Section 3 explains the differences between the two pricing mechanisms, MCP (market clearing price) and PAB (pay as bid); Section 4 describes the mathematical model and the multi-agent architecture, the set database and the supply and demand scenarios; Section 5 discusses the results obtained; and finally, Section 6 concludes.

2. Frequency Regulation Market Structure and Operation Process

Since the implementation of market-based reforms in China's power system, the market mechanism for the frequency regulation ancillary services has been launched in 13 provinces and regions as of June 2022, with each province and region establishing a regional electricity frequency regulation market rule system and implementing landing based on the local grid structure and administrative management system. Although there are differences in details among the markets, they remain unified in the structure of the market. The market for automatic generation control ancillary services was opened in Sichuan Province, China, in November 2018, and has continued until now after revisions to several details in December 2020. The market structure system is shown in Figure 1.

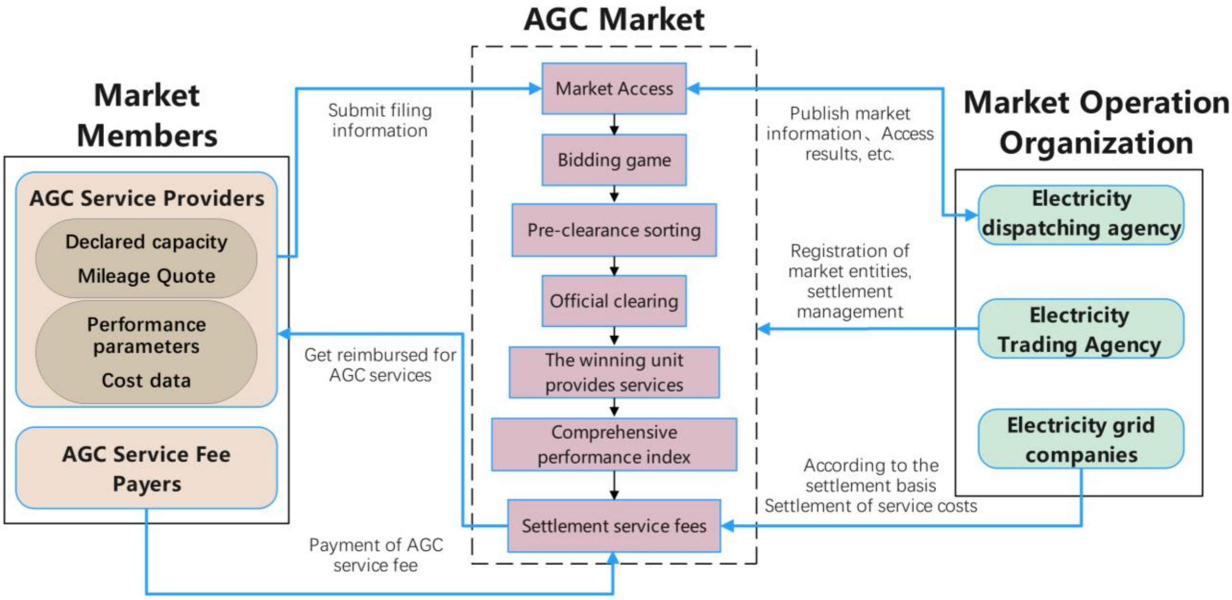


Figure 1. The framework structure of frequency regulation ancillary services market and its operation process.

The frequency regulation market mainly includes three modules: market members, AGC market, and market operators. According to the rules of the Sichuan market [26], market members include power generation enterprises belonging to hydropower and thermal power units that are directly dispatched by the Sichuan dispatch center, etc., and must have qualified AGC function. Additionally, the operating agency is the Sichuan power dispatch center, while electricity trading agencies and power grid enterprises are also involved in the scope of operation. The powers and obligations of the market members include participating in the AGC ancillary services market according to the rules, providing AGC ancillary services and will be the compensation revenue, obeying the instructions of Sichuan Provincial Dispatch Center, ensuring the safety of grid operation, etc. The powers and obligations of the operating agency include organizing and managing AGC ancillary service market transactions, calling and regulating resources according to the transaction results combined with grid operation, etc.

The Sichuan AGC ancillary service market has adopted the organization method of day-ahead listing transaction. Before 10:00 every day, Sichuan Dispatch Center releases the information on the AGC ancillary service market for the next day, including the control area and market demand. After the market opens, market members participate in the AGC ancillary services market as a unit of power generation units and submit declaration information, including the declared price, regulation capacity, etc. The minimum unit of declared price is 0.1 RMB/MW and the maximum declared price is 100 RMB/MW (The exchange rate in 2023: 1 RMB = 0.143844 USD). After the declared information is approved by the dispatching agency, each control area transaction is sorted from lowest to highest according to the declared frequency regulation mileage prices (the quotient of declared prices and performance indexes) of the participating generating units to form a pre-clearance sequence, and the declared information can be modified before market closure, with the last valid declaration made before market closure serving as the final declaration. When the market closes at noon every day, the dispatch center of the Sichuan Province will sort the power generation units according to their frequency regulation mileage price from lowest to highest. When the frequency regulation mileage price is the same, the units are sorted according to their comprehensive performance index from highest to lowest. When the comprehensive performance index is the same, the units are sorted according to their regulation range, regulation rate, and regulation accuracy from highest to lowest, until the capacity of the transacted power generation units is evident. The official clearing result will be formed and released after the sum of the capacity of the transacted generation units meets the required regulation capacity of the control area. The compensation cost of the winning generation unit is calculated based on the actual regulation performance and frequency regulation mileage of the AGC plant. The compensation cost of the winning generation unit is calculated based on the declared price (PAB pricing mechanisms).

Sichuan dispatching agencies provide the implementation of AGC ancillary service transactions for the previous month to Sichuan electricity trading agencies before the second half of each month, the electricity trading agencies determine and account for the price of AGC services, and the power grid companies compensate and settle the AGC units according to the accounting basis given by the electricity trading agencies. The AGC ancillary service market compensation cost is apportioned by the AGC service fee payers in proportion to the feed-in tariff.

As for the clearing aspect of the market trading process, there are currently divergent approaches to pricing mechanisms in various provinces and regions. The markets including Inner Mongolia, Shandong, and Gansu use the MCP pricing mechanism while Shanxi, Sichuan, and Jiangsu markets use the PAB pricing mechanism. The details are shown in Table 1.

Table 1. Pricing mechanisms used in the frequency regulation ancillary services market in various provinces and regions in China.

Pricing Mechanism	Market
MCP	Inner Mongolia [27], Shandong [28], Beijing–Tianjin–Tangshan [29], Gansu [30], Zhejiang [31], Fujian [32], Hubei [33], Jiangxi [34], Guangdong [35], Yunnan [36]
PAB	Shanxi [37], Sichuan [26], Jiangsu [38]

We will present the rationale of the two pricing mechanisms in Section 3 and lay the theoretical foundation for the subsequent analysis of their economic impact on the market and its members.

3. Two Pricing Mechanism Principles

At present, the mainstream pricing mechanisms for centralized bidding transactions in the electricity market include two types, PAB and MCP, and the rest of the mechanisms are variations of these two mechanisms. Both pricing mechanisms are based on the criterion of meeting market demand and their processes are consistent, with only the final transaction prices being different.

As shown in Figure 2, the PAB pricing mechanism means that AGC unit i, participating in the frequency regulation market transaction, submits declared capacity q_i and mileage quotation p_i on the operation day to the power dispatcher. Subsequently, the electricity dispatcher ranks the priority of all quotations in descending order, prioritizes the generator units with lower quotations and better frequency regulation performance, and accumulates the corresponding frequency regulation capacity until the accumulated frequency regulation capacity meets the market frequency regulation capacity. At this time, all AGC units whose quotations do not exceed the quotation of the last winning AGC unit (marginal unit) ($p_i \leq p_m$) are considered to be successful bids. After providing the frequency regulation service, the compensation of the winning unit will be calculated based on the mileage quotation declared by each unit, and its mileage quotation can be regarded as the transaction price of this bidding game.

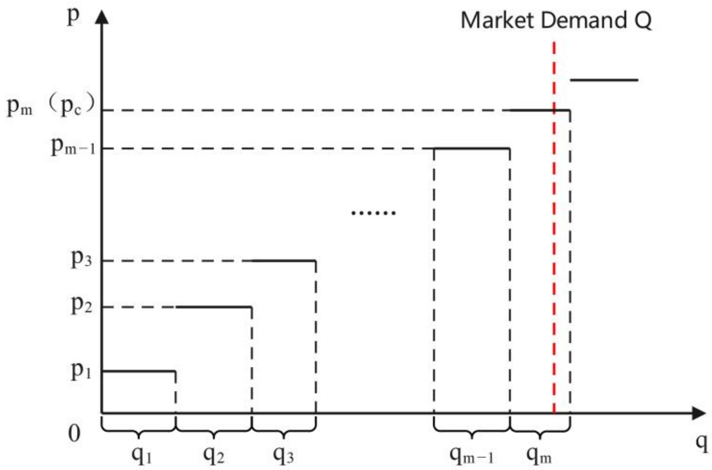


Figure 2. PAB, MCP pricing mechanism schematic.

In the MCP pricing mechanism, AGC units submit declare capacity q_i and mileage quotation p_i to the dispatching agency, and the accumulated capacity are calculated after the same sorting by the power dispatching agency until the market demand quantity is satisfied, at which time the quotation p_c of the marginal units is used as the unified clearing price of this bidding. Additionally, after the frequency regulation units have provided the frequency regulation service, the compensation of all the winning units is based on the unified clearing price p_c, which can be regarded as the transacted electricity price of this bidding game.

The marginal unit capacity is calculated in the same way for both MCP and PAB pricing mechanisms, and the marginal unit capacity is the difference between the market demand and the declared capacity of the non-marginal winning unit. The specific price and capacity calculation methods and their interrelationships are shown in Table 2.

Table 2. Transaction price and transaction capacity of AGC units under PAB pricing mechanism and MCP pricing mechanism.

Relationship between Quotation and Settlement Price	PAB Transaction Price	MCP Transaction Price	PAB, MCP Transaction Capacity
$p_i < p_m\ (p_c)$	p_i	p_c	q_i
$p_i = p_m\ (p_c)$	p_i	p_C	$\begin{cases} Q - \sum_{j=1}^{m-1} q_j \\ q_i \end{cases}$
$p_i > p_m\ (p_c)$	0	0	0

The market clearing price described in this paper is the uniform clearing price under the MCP mechanism and the average clearing price under the PAB mechanism, and we will also compare the market clearing prices under the two different mechanisms in subsequen experiments.

4. Methods & Data

4.1. Frequency Regulation Ancillary Services Market Based on Multi-Agent Model

At present, multi-agent approaches are widely used in the study of power systems [39] and power markets [40,41], and agent-based modeling and simulation (ABMS) has been certified by many experts and scholars as a suitable modeling approach and scientific tool for use in complex socio-technical problems. The frequency regulation ancillary service market is a typical type of complex adaptive system and it is necessary to use complex adaptive system modeling and simulation methods to realize an objective simulation of the frequency regulation ancillary service market trading process.

The framework diagram of the frequency regulation market model designed in this paper is shown in Figure 3. Individual AGC units are encapsulated as agents, and several agents interact with each other for objective simulation of the frequency regulation market through the ISO platform of the power dispatcher. Each agent includes the number of the AGC unit, comprehensive performance index K, cost information, mileage quote, and regulation range. Through such interactions, the agents can continuously adjust their bidding strategies to maximize their revenue until the whole market reaches equilibrium. The model relationship between the market information released by the power dispatcher and the AGC unit agents allows the market bidding to constitute a multi-agent system capable of sensing market dynamics. Due to the advantages of simplicity, generality, and robustness of the genetic algorithm, this paper uses it as a superiority-seeking decision mechanism for each agent.

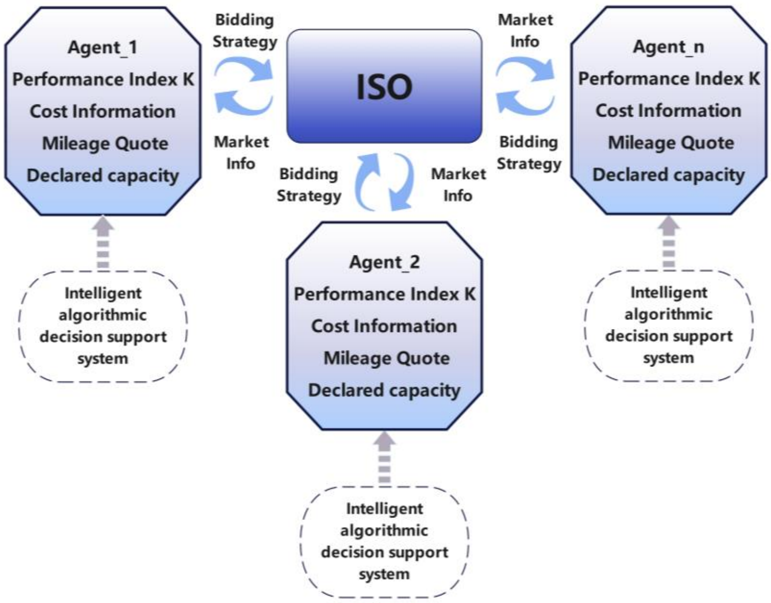


Figure 3. Schematic diagram of the multi-agent-based frequency regulation market model.

4.2. Cost and Benefit Mathematical Model

4.2.1. Objective Function

In this paper, the overall objective is to maximize the returns of individual market members as a prerequisite for exploring the performance patterns of markets and market members under different mechanisms, and the overall objective function is as follows.

$$maxR_p = R - C_{AGC}, \tag{1}$$

where $maxR_p$ represents the profit of each unit; R represents the compensation received by the frequency regulation unit in the frequency regulation market; C_{AGC} represents the cost of the frequency regulation unit in the frequency regulation service.

4.2.2. Frequency Regulation Compensation Mathematical Model

Frequency regulation compensation, that is, the revenue of frequency regulation units in the frequency regulation market, according to the rules of the Sichuan frequency regulation market, constitutes a system of compensation and mileage compensation. The calculation formula is shown in Equations (2) and (3).

$$R = Mp^{mp}K, \tag{2}$$

$$p^{mp} = \alpha p^{cp}, \tag{3}$$

where M represents the market clearing price, K denotes the performance index of the frequency regulation unit, p^{mp} represents the frequency regulation mileage of the frequency regulation unit in the frequency regulation service and p^{cp} represents the winning capacity of the frequency regulation unit in the frequency regulation market. Additionally, in the general frequency market study, the assumption is made based on the historical data of the frequency market that the frequency mileage is a certain ratio of the actual winning capacity of the unit. As such, this paper sets the frequency mileage and the winning capacity as a positive relationship and the formula is shown in the above equation, where α is set to 0.8, to establish the relationship between the winning capacity and the frequency mileage.

4.2.3. Frequency Regulation Service Cost Mathematical Model

The cost of AGC refers to the total cost involved in the process of providing frequency regulation services by AGC units under the premise of meeting the system requirements. There are differences in the cost composition of AGC units compared with non-AGC units. To provide AGC ancillary services, a generator set must first construct an AGC closed-loop control system, which requires investment in relevant equipment from both the dispatching side and the power plant side. Secondly, AGC units incur certain operation and maintenance costs during operation. Furthermore, the unit characteristics make its active output available for only one use in the same period, thus giving rise to the opportunity cost and combination cost of AGC units. Therefore, this paper will study the composition of AGC cost and its causes from the power plant side and use this information as the basis for building various cost mathematical models. The total cost equation is shown in Equation (4).

$$C_{AGC} = C_{op} + C_{oc} + C_{eq} + C_{loss}, \tag{4}$$

1. Operating Costs;

Among them, C_{op} represents the operating cost of the frequency regulation unit when it is put into AGC state, which is the most significant part of the cost. Many relevant studies have fitted the data of the power generated by thermal generating units with fuel and, based on the stability of fuel price relative to the electricity market price, implied the fuel price in the cost function. After this, these studies determine the relationship between the unit generation cost and power generated, i.e., the cost function, is expressed as Equation (5).

$$C_{op}(P) = a + bP + (1/2)^d cP^2, \tag{5}$$

where P represents the operating power value of the unit (unit: MW), a represents the operating cost of the unit at no load, b represents the intercept value of the marginal cost curve of the unit, c represents the slope value of the marginal cost curve of the unit, and d represents the discriminating mark of the power source, with hydropower taking the value of 1 and thermal power taking the value of 0.

2. Opportunity Costs;

In period Δt, if the actual output value of AGC unit i is within the regulation range of the unit then the opportunity cost of this AGC unit is zero; if the actual output value of this AGC unit exceeds the regulation range of the unit then the opportunity cost is incurred in that period, which is calculated as shown in Equation (6).

$$C_{oc} = (P - P_{AHL})(\rho_{tmp} - \rho_{bid})\Delta t, \tag{6}$$

where P_{AHL} is the regulation upper limit of the unit, ρ_{tmp} is the main market marginal electricity price in period Δt, and ρ_{bid} is the unit's electricity bid price in period Δt.

3. Additional fixed costs;

Additional fixed cost refers to the investment cost of AGC equipment. Currently, there are two commonly used methods to calculate the depreciation cost of the total investment cost of thermal power plants, which are the equal payment discounting method and the annual average discounting method. The latter algorithm is used in this paper to calculate the recovery value of an AGC service according to its provision time. The investment cost of an AGC unit in Δt time is calculated as shown in Equation (7).

$$C_{eq} = C_{inv} \frac{i(1+i)^T}{(1+i)^T - 1}, \tag{7}$$

C_{inv} is the investment cost of AGC equipment and equipment maintenance cost; T is the service life of the equipment; and i is the weighted average return on capital.

4. Cost of power generation efficiency losses;

The cost of generation efficiency loss for unit i during service time Δt is calculated as shown in Equations (8) and (9).

$$C_{loss} = \left| C_{op}(P'') - C_{op}(P') \right| \times \frac{T_{\Delta t}}{60}, \tag{8}$$

$$P_{ALL} \le P'' \le P_{AHL} \tag{9}$$

where P'' is the actual output value after the unit provides AGC service, P' is the original output value before the unit provides AGC service, $T_{\Delta t}$ is the unit's AGC service time within Δt (unit: min), and P_{ALL} is the regulation lower limit of the unit.

4.2.4. Bidding Constraints for AGC Units in the Market

The mileage quotes and declared capacities of the market members in the frequency regulation market have upper and lower constraints in the market as their two declared information types. The mathematical models of the constraints are shown in Equations (10) and (11).

$$c_{min} \le c \le c_{max} \tag{10}$$

$$p_{min} \le p \le p_{max} \tag{11}$$

where c represents the mileage offer of the frequency regulation unit, c_{min} and c_{max} represent the lower and upper limits of the mileage offer in the market, respectively, and their specific values are determined according to the market rules; p represents the declared capacity of the frequency regulation unit, p_{min} and p_{max} represent the upper and lower limits of the declared capacity of the unit, respectively. As most domestic frequency regulation markets set limits on the declared capacity of frequency regulation units, and the focus of this paper is on the study of bidding behavior, the simulation design draws on the relevant regulations of other frequency regulation markets and sets 3–20% of the rated installed capacity of the thermal power units participating in each frequency regulation market as a uniform restriction condition.

4.3. Data Base

To explore the difference in the impact of the two pricing mechanisms in the frequency regulation market, in this paper the Sichuan frequency regulation market rules are used as the basis for the market, and a single variable model is used to simulate the original use of the PAB mechanism. After this, PAB is changed to the MCP mechanism and then simulated to form a control group and an experimental group, respectively, as a way to compare the evolution of market members' offer behavior and market clearing prices in the frequency regulation market under two different pricing mechanisms.

In terms of frequency regulation resources, four typical hydropower units (No. 1–4) and six typical thermal units (No. 5–10) are selected in this paper. Hydropower is divided into two capacity classes of 100 MW and 200 MW and thermal power is divided into three capacity classes of 300 MW, 600 MW, and 900 MW. The regulation performance and cost–output characteristics of each capacity class differ greatly, and the parameters of two units of the same capacity class also have advantages and disadvantages in terms of cost–output and regulation performance. In this paper, by consulting the relevant information on domestic thermal and hydropower units, the specific parameters of the above 10 frequency regulation resources are reasonably set, and their specific parameters are shown in Table 3.

Table 3. Technical data of frequency regulation unit.

Unit Number	Type	Unit Capacity (Unit: MW)	Adjustment Rate (% Rated Capacity/min)	Adjustment Accuracy (% Rated Capacity)	Response Time (Unit: s)	Adjustable Range (Unit: MW)	Performance Index K
1	Hydroelectric units	100	55	0.32	8	3–20	0.855
2	Hydroelectric units	100	56	0.35	9	3–20	0.842
3	Hydroelectric units	200	60	0.48	13	6–40	1.441
4	Hydroelectric units	200	61	0.50	12	6–40	1.454
5	Thermal power units	300	3.2	0.23	36	9–60	0.638
6	Thermal power units	300	3.3	0.25	37	9–60	0.610
7	Thermal power units	600	3.7	0.34	44	18–120	0.798
8	Thermal power units	600	3.8	0.35	42	18–120	0.796
9	Thermal power units	900	4.5	0.48	52	27–180	1.063
10	Thermal power units	900	4.6	0.50	50	27–180	1.064

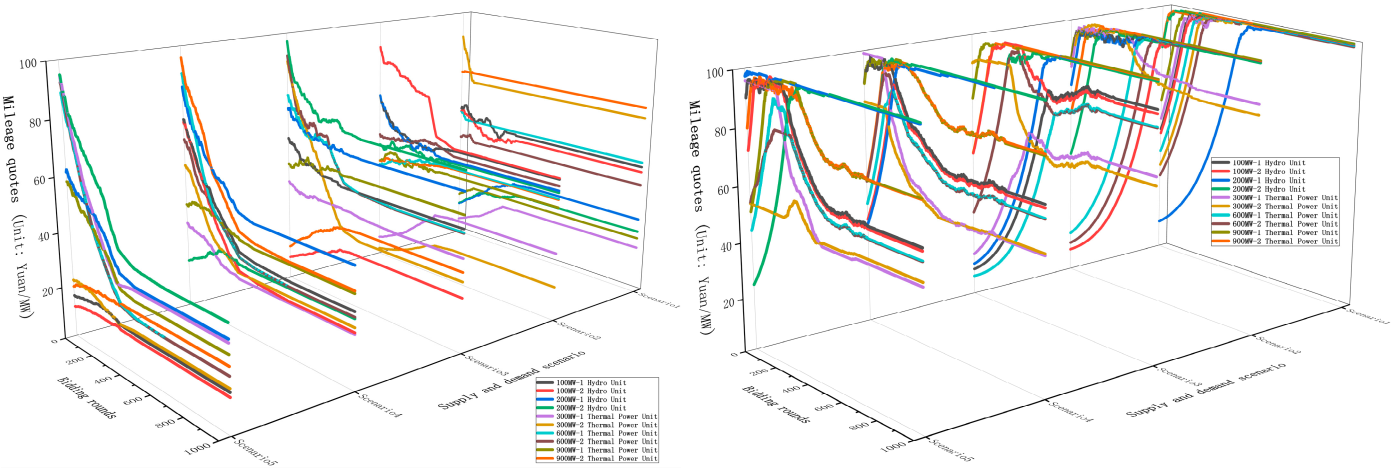
In terms of supply and demand scenarios, five supply and demand scenarios are set in this paper (Scenario 1: Demand 840 MW, Scenario 2: Demand 800 MW, Scenario 3: Demand 750 MW, Scenario 4: Demand 670 MW, Scenario 5: Demand 600 MW, on the basis of Table 3 where the supply is the sum of the maximum output of 10 units, i.e., 840 MW) to simulate the market environment. This ranges from supply and demand balance (840 MW) to different scenarios of oversupply (600 MW). By observing the bidding performance and final clearing results of different units under different market mechanisms and supply and demand scenarios, the laws and impacts of each market rule are explored and evaluated.

5. Results

5.1. Difference in the Evolution of the Quotation Behavior of the Unit

We simulated the original Sichuan market and changed the pricing mechanism rule to MCP as the experimental control. The offered behaviors of 10 units under different supply and demand scenarios are shown in Figure 4, where (a) is the MCP experimental image and (b) is the PAB experimental image.

The image shows the changes in the quotation of the 10 units under the MCP pricing mechanism in the five supply and demand scenarios. In the supply–demand balance scenario, the 10 frequency regulation units will choose a more stable quotation strategy according to their actual performance level in the market, and as the number of bidding rounds increases, the quotation strategy of the frequency regulation units will show the phenomenon of approaching the middle level of the market quotation range. As the supply–demand ratio in the market gradually increases, the competition among the frequency regulation units becomes more and more intense, and the frequency regulation units will reduce their final quotations to different degrees according to their performances. The overall price change of frequency regulation units under the MCP mechanism manifests in the form of a variable strategy change for each unit in the early fluctuation range. However, the overall unit will be quickly centered and reach a stable level, and most of the units will converge to different price levels according to the supply and demand situation in the market and the intensity of competition.



(**a**) (**b**)

Figure 4. Evolution of unit offer when MCP (**a**) and PAB (**b**) are adopted in Sichuan.

In the PAB bidding mechanism, the price changes of the 10 frequency regulation units will be different: under the scenario of balanced supply and demand, the mileage quotes of the 10 units will gradually rise to the upper limit of the range as the number of bidding rounds increases. At this point, strategies are maintained and the market reaches a stable state. As the market demand gradually decreases and the competition in the market becomes more intense, the frequency regulation units will change their final offer strategy according to their performance level. As such, the lower the performances of units are, the more obviously the change of strategy will be affected by supply and demand.

The overall price change of frequency regulation units under the PAB mechanism manifests in the form of each unit trying to raise its price in the early stage, and under the influence of supply and demand, units of different performance levels raise their price and then lower their prices until the market stabilizes. The overall fluctuation before market stabilization is not obvious compared with MCP, but the period of stabilization is longer compared with MCP, and the final offers of units with different performance levels will show the phenomenon of "stratification". This is demonstrated by comparing the final stabilized offers of 10 units in Scenario 5 under the PAB mechanism with their respective performance indicators, as shown in Figure 5.

5.2. Changes in Market Clearing Prices

We compare the market clearing prices of these two sets of experiments: as shown in Figure 6, (a) the MCP mechanism is used and (b) the PAB mechanism is used.

Since the uniform clearing price is determined by the last unit's offer, the clearing price under the MCP mechanism is influenced by the marginal units. As shown in the above analysis of the unit's quoting behavior under the MCP mechanism, the trend of the frequency regulation units' quotes under the MCP mechanism is to converge to a certain level. Before prices reach stability, according to the market clearing order (based on the "quoting price/performance index K" in descending order), the uniform clearing price is the unit with high quoting price and low performance. Therefore, under the MCP mechanism, the uniform price of frequency regulation units in the market shows a gradual decrease with the increase in bidding rounds until a stable phenomenon is achieved.

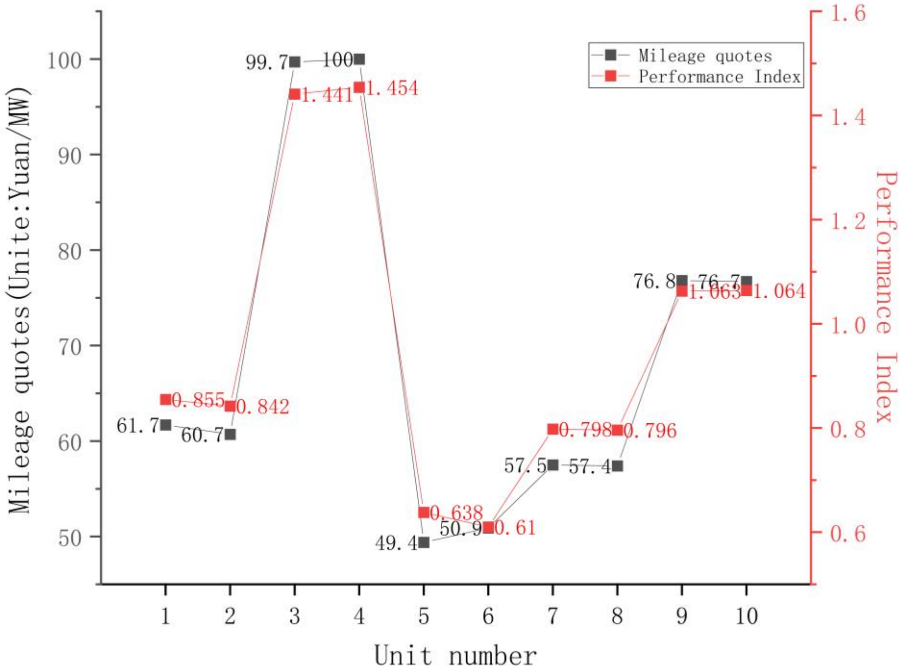
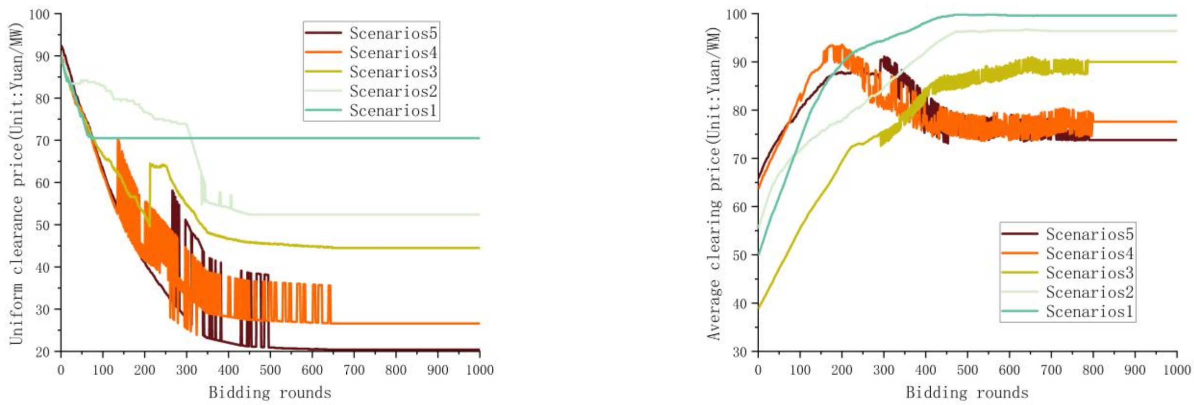


Figure 5. Sichuan uses the PAB pricing mechanism to compare unit price and performance index under scenario 5.



(**a**) (**b**)

Figure 6. Evolution of market clearing prices when MCP (**a**) and PAB (**b**) are adopted in Sichuan.

In the PAB bidding mechanism, the average clearing price is calculated based on the average of the quotations of each unit in the clearing result. As such, the trend of the average clearing price is mainly influenced by the overall quotations of each frequency regulation unit, which is similar to the trend of the quotations of the frequency regulation units in the PAB mechanism, showing the trend of trying to gradually increase in the early stage, and then gradually decrease to a certain level under the influence of different supply and demand situations.

5.3. Analysis of Bidding Results under Changes in Supply and Demand

To facilitate the analysis of the clearing prices under the two different mechanisms as affected by supply and demand, in combination with the clearing result table, we made the clearing the clearing prices of the two markets dimensionless using the two different mechanisms: the clearing price minus the lower limit of the offer divided by the range of the offer, and the corresponding market demand divided by the supply, the values of which reflect the supply and demand. The results of processing are shown in Table 4.

Table 4. Unmeasured market clearing prices.

Demand: Supply	PAB	MCP
0.714286	0.738	0.204
0.797619	0.776	0.266
0.892857	0.9	0.445
0.95238	0.964	0.524
1	0.996	0.705

From the data in Table 4, the clearing prices of the two markets under the two different bidding mechanisms can be drawn as influenced by supply and demand.

As shown in Figure 7, the average clearing price of the PAB pricing mechanism is higher than that of MCP, with a higher degree ranging from 0.29 to 0.53 of the quoted price range and the overall characteristics of a larger gap with less demand. The overall clearing price under the two different bidding mechanisms is affected by supply and demand, and the less demand there is, the more intense the competition among frequency regulation units will be, and as a result the overall clearing price will appear to vary by degrees. In terms of the degree of decline, MCP as a whole has a greater slope of decline than PAB, especially in intervals 3 and interval 4, and its slope of decline is shown in Table 5.

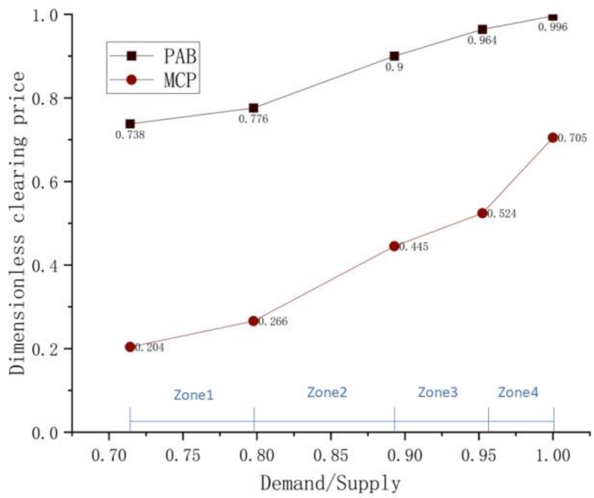


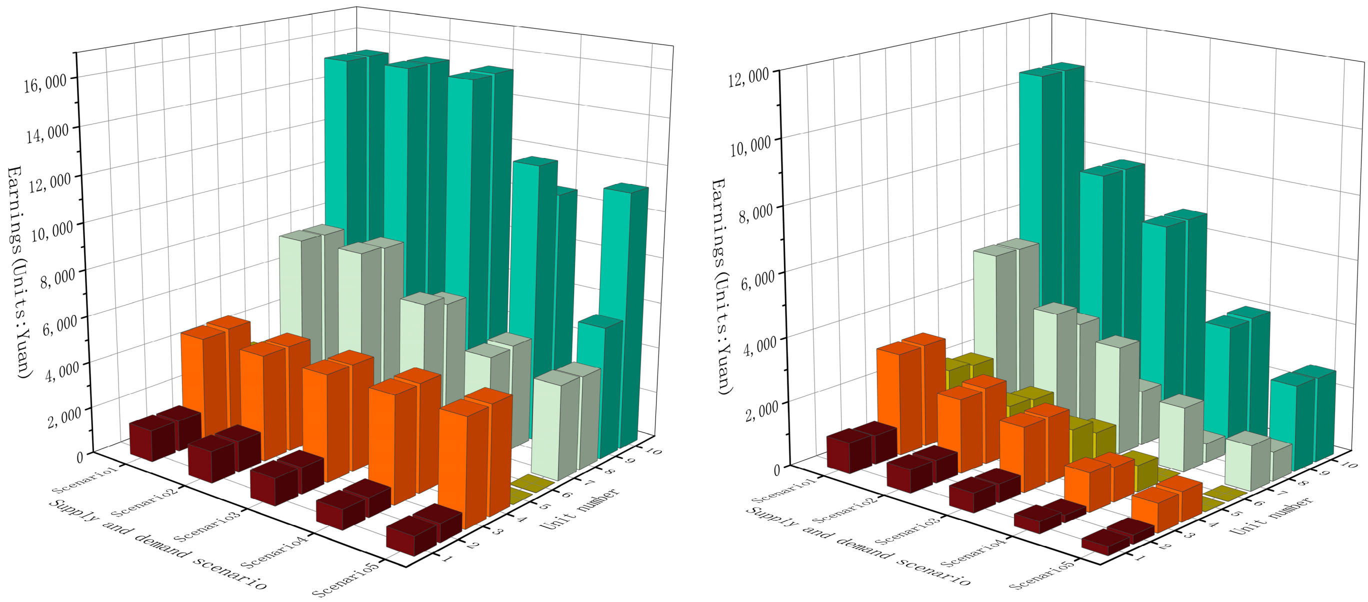
Figure 7. Variation in dimensionless supply/demand ratio and clearing price.

Table 5. Slope of settlement price change under the influence of supply and demand.

Supply and Demand Change Zone	PAB Slope	MCP Slope
Zone1	0.456	0.744
Zone 2	1.302	1.8795
Zone 3	1.075217	1.327221
Zone 4	0.671987	3.800924

5.4. Unit Profit

Based on the data in the clearing results table for both markets, the gains of frequency regulation units under the PAB and MCP mechanisms are shown in Figure 8.



(**a**) (**b**)

Figure 8. Benefits of frequency regulation units when PAB (**a**) and MCP (**b**) are adopted in Sichuan.

We can see by looking at the compensation formula that the main factors determining the amount of frequency regulation benefits, in addition to price, include performance indicators, the winning capacity and frequency regulation mileage. In addition, the winning capacity and frequency regulation mileage are usually positively correlated (in this paper, the experimental frequency regulation mileage is simplified to the winning capacity * 0.8), and the gap between the performance indicators is very limited, and so the level of frequency regulation benefits mainly depends on the winning capacity size. By looking at the revenue graph, we can find that the overall frequency regulation benefits of the units are roughly arranged in a stepwise manner according to the size of the installed capacity, with the larger installed capacity having higher benefits and the opposite size having relatively lower benefits. As the market demand decreases, the revenue of lower-performance units decreases more, and they also face the situation of aborted bids, resulting in the revenue of small-capacity, low-performance thermal units being lower than that of smaller-capacity hydropower units under competitive conditions, so that their revenue in the PAB mechanism is reduced to 0.

In the dimension of supply and demand changes, the PAB mechanism and the MCP mechanism also show relatively obvious differences in changes, i.e., under the MCP bidding mechanism, the overall revenue of the units is affected by the uniform clearing price, and their overall revenue level shows an overall decreasing trend. Conversely, under the PAB bidding mechanism, the revenue of low-performance units is more seriously affected by supply and demand, and the revenue of high-performance units (especially hydropower units) remains unchanged. We divided the revenue change for each unit in the clearing result between different market demands by the change in the supply–demand ratio and took the average value of the slope of the four changes. Subsequently, we divided the average value by its installed capacity to obtain the average revenue change of each unit under the change in supply and demand, and quantified the revenue by taking the standard deviation of the average revenue change for 10 units under the change in supply and demand. The resultant data are shown in Table 6.

Table 6. Average change in unit revenue under changes in supply and demand.

Unit Number	PAB	MCP
1	18.23	26.93
2	18.59	23.62
3	−0.52	44.23
4	0.31	43.67
5	49.39	25.78
6	34.67	25.4
7	19.32	25.04
8	20.43	31.87
9	30.16	33.84
10	11.47	34.01
Standard deviation	14.38	7.19

5.5. Standard Deviation of Market Clearing Prices in Equilibrium

To investigate the stability of market clearing prices under the two pricing mechanisms, MCP and PAB, this paper uses two different bidding mechanisms and runs them five times in five supply and demand situations to explore their clearing price laws. The results are shown in Tables 7 and 8.

Table 7. Uniform clearance prices for five times under the MCP pricing mechanism.

Scenario	Scenario 5	Scenario 4	Scenario 3	Scenario 2	Scenario 1
Uniform clearance price	20.4	26.6	44.5	52.4	70.5
	18.7	21.8	37.3	54	68.1
	37.9	38	36.5	55.6	79.1
	19.5	29.1	39.4	49.7	75.4
	27.9	41.6	50.9	48.9	60.2
Standard deviation σ	7.29	7.32	5.37	2.53	6.48
Average standard deviation $\overline{\sigma}$			5.80		

Table 8. The average clearing price for the five times under the PAB pricing mechanism.

Scenario	Scenario 5	Scenario 4	Scenario 3	Scenario 2	Scenario 1
Average settlement price	73.8	77.6	90	96.4	99.6
	75.9	75.2	88.8	96.2	99.8
	76.4	77.2	90.5	96.4	99.7
	77.2	77.1	93.6	96.1	99.9
	75.6	75.2	96.2	96.1	99.9
Standard deviation σ	1.13	1.04	2.70	0.14	0.12
Average standard deviation $\overline{\sigma}$			1.03		

From Tables 7 and 8, it can be concluded that the standard deviation of the average clearing price of PAB is lower than the standard deviation of the uniform clearing price under the MCP mechanism for the same supply and demand scenarios. When calculating the mean value of the standard deviation under the five market demands, it is found that the average standard deviation of MCP is nearly 5.8 times higher than that of PAB, as shown in Figure 9. This also proves that the PAB pricing mechanism is more stable than the MCP bidding mechanism in terms of market clearing prices.

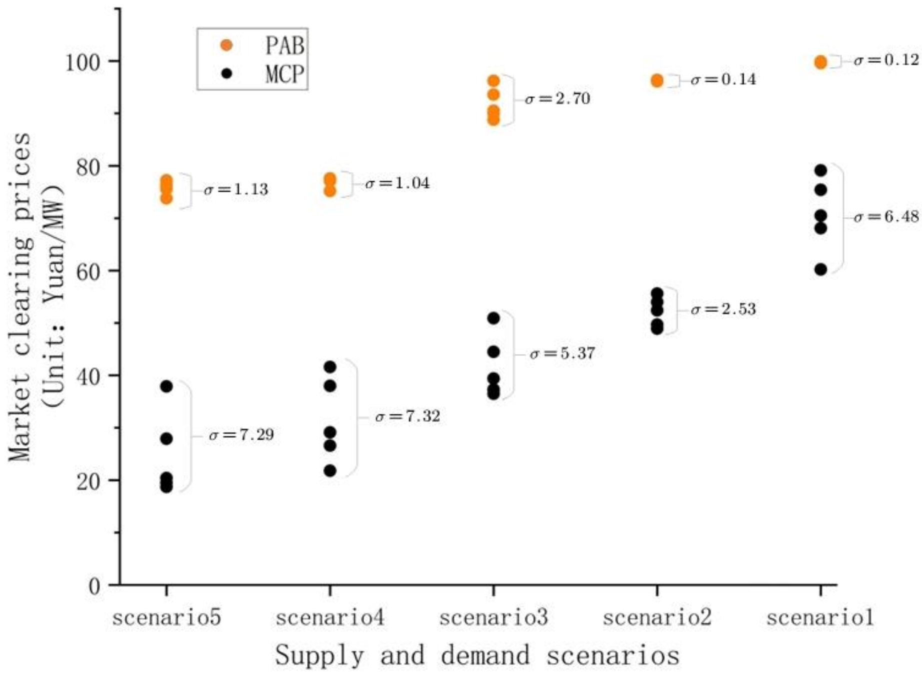


Figure 9. Settlement price distribution in Sichuan when two different pricing mechanisms are adopted, respectively.

6. Discussion

We present the detailed clearing results in Appendices A and B. Tables A1–A5 and Tables A6–A10 represent the five supply and demand scenarios under the two pricing mechanisms of PAB and MCP, respectively.

In terms of market dynamics, under the MCP pricing mechanism, the frequency regulation units choose a more stable frequency regulation mileage price declaration strategy according to their situation, and there is no fixed evolution form of the change in the offer strategy of each unit. In such circumstances, the offer strategy is more flexible, with a larger fluctuation in the bidding strategy in the early stage. The uniform clearing price in the supply–demand equilibrium until the market reaches a moderate level is near the upper and lower limits of the declared price in the steady state, and gradually decreases with the increase in bidding rounds. Ultimately, the uniform clearing price in the steady state will be reduced to a certain extent. Under the PAB pricing mechanism, the average clearing price of frequency regulation units will be close to the upper limit of declared frequency regulation mileage set by the market when supply and demand are in balance, and the average clearing price will decrease to some extent as the supply–demand ratio increases. Before reaching stability, the offer strategy of units under the MCP mechanism changes more drastically than that of PAB, but the market reaches a stable state faster under the MCP pricing mechanism than PAB.

In terms of settlement prices, the uniform clearing price settlement price under the MCP mechanism will show a trend of gradually decreasing from high prices to reach equilibrium, while the average settlement price under the PAB mechanism will first gradually increase and then gradually decrease according to the supply and demand situation. In the supply and demand changes, the MCP mechanism changes more than the PAB mechanism and more obviously (especially in the more conventional demand: supply = 1, 0.95, 0.9 competitive environments). Through experiments it can be concluded that, in different supply and demand situations, the average clearing price under the PAB mechanism compared to the MCP unified clearing price market clearing price, although higher and less discrete, is more stable.

The overall revenue of frequency regulation units under the PAB mechanism is higher than that of the MCP, which results in a much higher total cost for the government to purchase frequency regulation services than under MCP. It beneficial for the government to incentivize the share of high-performance frequency regulation units in the market and to ensure the provision of better-quality frequency regulation services.

7. Conclusions and Policy Recommendations

This paper presents the differences in the current frequency regulation market in various regions of China regarding the adoption of PAB or MCP, analyzes the mathematical significance of the above two pricing mechanisms, establishes a mathematical model of revenue and cost in the frequency regulation market based on the Sichuan frequency regulation ancillary service market, sets up five supply and demand scenarios, simulates 10 frequency regulation units with different parameters participating in the market competition activities using the multi-agent model, and presents the evolution of the AGC unit's quotations, benefits, and market clearing price under two pricing mechanisms. In summary, we give the following policy recommendations for building a unified electricity market, which may have implications for China's "unified electricity market" reform.

China's electricity frequency regulation ancillary is in the early stage of market integration. As such, it is recommended to adopt the MCP pricing mechanism, whose fast and stable performance can make it easier for the government and regulators to observe and regulate the market at a later scale. Considering that more types and higher quantities of renewable energy and energy storage devices will join the frequency regulation market in the future, adopting the MCP pricing mechanism can observe the signals of different traditional energy sources participating in the market not only at the early stage but also at a later stage. The MCP pricing mechanism can observe the signal of different traditional energy sources participating in the market not only in the early stage but also observe the price impact of new energy sources joining the market in the later stage. After the unified use of the MCP pricing mechanism, the market members can also recognize their performance indicators in the market competition, modify their equipment or no longer participate in the frequency regulation market. When the time is ripe, the pricing mechanism will be changed from MCP to PAB, which will have higher requirements on the performance index of the units and further increase the retention rate of high-performance units in the market. Additionally, its accurate price signals will allow the government and regulators to regulate in the process of further reforming the power market.

8. Limitations and Outlook

There are some issues in this paper: this paper only models and analyzes the participation of thermal and hydro units in the frequency regulation market. However, there are different power supply structures in different regions, as well as different demand for frequency regulation. Additionally, there are different members of the frequency regulation market, such as "thermal power", "thermal power + hydro" and "thermal power + hydro + energy storage facilities", etc. Follow-up studies are needed to integrate actual conditions in greater detail for a more comprehensive analysis of the frequency regulation market rules. Additionally, with the rapid rise in installed renewable energy capacity and the increasing maturity of integrated energy systems, it is expected that subsequent studies will include integrated energy systems in the frequency regulation contributor sequence.

Author Contributions: Conceptualization, X.H.; methodology, X.H.; software, Z.L.; validation, Z.L.; formal analysis, Z.L.; investigation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, Z.L.; visualization, Z.L.; supervision, X.H.; project administration, X.H.; funding acquisition, X.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the National Key R & D Plan Foundation of China (Grant No. 2021YFB2601300).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Final Outcome of Frequency Regulation Units under PAB Pricing Mechanism

Table A1. Scenario 1.

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	100	99.6	20	20	1368
2	100	99.6	20	20	1347.2
3	99.4	99.6	40	40	4583.533
4	99.9	99.6	40	40	4648.147
5	99.5	99.6	60	60	3047.088
6	99.5	99.6	60	60	2913.36
7	99	99.6	120	120	7584.192
8	98.8	99.6	120	120	7549.901
9	100	99.6	179	179	15,222.16
10	99.5	99.6	180	180	15,244.99

Table A2. Scenario 2.

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	99.9	96.4	20	20	1366.632
2	99.9	96.4	20	20	1345.853
3	100	96.4	40	40	4611.2
4	99.3	96.4	40	40	4620.23
5	84.8	96.4	55	26	1125.33
6	80.9	96.4	55	55	2171.356
7	99.9	96.4	120	120	7653.139
8	99.8	96.4	119	119	7562.764
9	100	96.4	180	180	15,307.2
10	99.9	96.4	180	180	15,306.28

Table A3. Scenario 3.

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	90.0	90.0	19	19	1169.64
2	88.5	90.0	19	19	1132.658
3	100.0	90.0	40	40	4611.2

Table A3. *Cont.*

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
4	99.3	90.0	40	40	4620.23
5	67.3	90.0	55	0	0
6	64.2	90.0	53	53	1660.469
7	84.0	90.0	113	113	6059.693
8	83.8	90.0	113	107	5709.931
9	100.0	90.0	179	179	15,222.16
10	99.8	90.0	180	180	15,290.96

Table A4. Scenario 4.

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	66.5	77.6	19	19	864.234
2	65.3	77.6	19	19	835.7355
3	100	77.6	40	40	4611.2
4	100	77.6	40	40	4652.8
5	49.7	77.6	53	0	0
6	50.3	77.6	54	0	0
7	61.9	77.6	114	114	4504.933
8	61.8	77.6	117	117	4604.446
9	82.4	77.6	172	172	12,052.55
10	82.8	77.6	173	149	10,501.42

Table A5. Scenario 5.

Unit Number	Quotation (Unit: Yuan/MW)	Average Settlement Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	61.7	73.8	19	19	801.8532
2	60.7	73.8	19	19	776.8629
3	99.7	73.8	40	40	4597.366
4	100	73.8	40	40	4652.8
5	49.4	73.8	35	0	0
6	50.9	73.8	34	0	0
7	57.5	73.8	112	112	4111.296
8	57.4	73.8	111	111	4057.308
9	76.8	73.8	172	88	5747.343
10	76.7	73.8	171	171	11,164.08

Appendix B. Final Outcome of Frequency Regulation Units under MCP Pricing Mechanism

Table A6. Scenario 1.

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	51.5	70.5	20	20	964.44
2	49.5	70.5	19	19	902.2872
3	30.6	70.5	39	39	3169.624
4	25.6	70.5	39	39	3198.218
5	19.1	70.5	59	59	2123.009
6	70.5	70.5	59	59	2029.836
7	53.2	70.5	118	118	5310.85
8	44.3	70.5	118	118	5297.539
9	22.9	70.5	177	177	10,611.72
10	74.5	70.5	177	177	10,621.7

Table A7. Scenario 2.

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	54.9	52.4	20	20	716.832
2	55.3	52.4	20	20	705.9328
3	50.6	52.4	38	38	2295.455
4	49.9	52.4	39	39	2377.116
5	27	52.4	57	57	1524.463
6	14	52.4	57	57	1457.558
7	47.5	52.4	117	117	3913.903
8	52.4	52.4	119	100	3336.832
9	44.4	52.4	176	176	7842.729
10	47.4	52.4	176	176	7850.107

Table A8. Scenario 3.

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	46.0	44.5	20	20	608.76
2	21.4	44.5	19	19	569.5288
3	59.1	44.5	39	39	2000.684
4	66.5	44.5	39	39	2018.734
5	35.6	44.5	59	59	1340.055
6	27.2	44.5	44	44	955.504

Table A8. *Cont.*

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
7	44.6	44.5	118	118	3352.238
8	44.5	44.5	118	60	1700.256
9	51.0	44.5	176	176	6660.333
10	30.6	44.5	176	176	6666.598

Table A9. Scenario 4.

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	28.5	26.6	20	20	363.888
2	21.4	26.6	13	13	232.9309
3	43.9	26.6	39	39	1195.915
4	26.1	26.6	34	34	1051.998
5	20.8	26.6	59	59	801.0218
6	23.1	26.6	59	0	0
7	26.6	26.6	118	118	2003.81
8	26.6	26.6	118	35	592.8608
9	34.6	26.6	175	175	3958.612
10	35.5	26.6	177	177	4007.62

Table A10. Scenario 5.

Unit Number	Quotation (Unit: Yuan/MW)	Uniform Clearance Price (Unit: Yuan/MW)	Declared Capacity (Unit: MW)	Winning Capacity (Unit: MW)	Earnings (Unit: Yuan)
1	15.2	20.4	19	19	265.1184
2	13.6	20.4	20	20	274.8288
3	32.1	20.4	38	38	893.6506
4	37.2	20.4	39	39	925.4419
5	30.9	20.4	55	0	0
6	16.4	20.4	43	0	0
7	20.4	20.4	108	108	1406.523
8	20.4	20.4	106	70	909.3504
9	27.2	20.4	154	154	2671.617
10	23.5	20.4	152	152	2639.401

References

1. National Development and Reform Commission of China and National Energy Administration of China. Guidance on Accelerating the Construction of a Unified National Electricity Market System. 2022. Available online: http://www.gov.cn/zhengce/zhengceku/2022-01/30/content_5671296.htm (accessed on 12 February 2023). (In Chinese)
2. National Energy Administration of China. China's New Energy Installation Has Grown Significantly, Accelerating the Energy Transition. 2022. Available online: http://www.nea.gov.cn/2022-11/24/c_1310679256.htm (accessed on 12 February 2023). (In Chinese)

3. Federal Energy Regulatory Commission. *FERC Issues Order No. 755: Frequency Regulation Compensation in the Organized Wholesale Power Markets*; Federal Energy Regulatory Commission: Washington, DC, USA, 2011; Volume 137.
4. PJM. Manual 11: Balancing Operations [EB/OL]. Available online: https://www.pjm.com/-/media/documents/manuals/m12-redline.ashx (accessed on 20 November 2022).
5. PJM. ISO/RTO Regulation Market Comparison [EB/OL]. Available online: https://www.pjm.com/-/media/committees-groups/task-forces/rmistf/20160113/20160113-item-06-iso-rto-regulation-market-comparison.ashx (accessed on 20 June 2020).
6. California ISO. Report on Performance of Resources Under the CAISO's Order 755 Market Design [EB/OL]. Available online: http://www.caiso.com/Documents/Jun30_2016_Report_Performance_Resources_Order755MarketDesign_MinimumPerformanceThreshold_ER15-554.pdf#search=Docket%20No%2E%20ER12%2D1630%2D000 (accessed on 20 June 2020).
7. California ISO. Pay for Performance Regulation Year 1 Design Changes [EB/OL]. Available online: http://www.caiso.com/Documents/DraftFinalProposal_PayForPerformanceRegulationYearOneDesignChanges.pdf#search=Pay%20for%20Performance%20Regulation (accessed on 20 June 2020).
8. California ISO. Pay for Performance Regulation Draft Final Proposal [EB/OL]. Available online: http://www.caiso.com/Documents/LSPowerComments_PayForPerformanceDraftFinalProposal.pdf#search=Pay%20for%20Performance%20Regulation%20Draft%20Final%20Proposal (accessed on 20 May 2017).
9. ERCOT. Day-Ahead Market [EB/OL]. Available online: https://www.ercot.com/glossary?term=Day-Ahead%20Market%20(DAM) (accessed on 20 June 2020).
10. ERCOT. Settlement of Ancillary Service Assignment in Real-Time Operations [EB/OL]. Available online: https://www.ercot.com/mktrules/issues/NPRR689 (accessed on 20 June 2020).
11. Chen, Y.; Leonard, R.; Keyser, M.; Gardner, J. Development of performance-based two-part regulating reserve compensation on MISO energy and ancillary service market. *IEEE Trans. Power Syst.* **2015**, *30*, 142–155. [CrossRef]
12. Wang, Z.; Zhong, J.; Li, J. Design of performance-based frequency regulation market and its implementations in real-time operation. *Electr. Power Energy Syst.* **2017**, *87*, 187–197. [CrossRef]
13. Papalexopoulos, A.D. Performance-Based Pricing of Frequency Regulation in Electricity Markets. *IEEE Trans. Power Syst.* **2014**, *29*, 441–449. [CrossRef]
14. Ko, K.S.; Han, S.; Sung, D.K. Performance-based settlement of frequency regulation for electric vehicle aggregators. *IEEE Trans. Smart Grid* **2018**, *9*, 866–875. [CrossRef]
15. Carvajal, S.; Serrano, J.; Arango, S. Colombian ancillary services and international connections: Current weaknesses and policy challenges. *Energy Policy* **2013**, *52*, 770–778. [CrossRef]
16. Mastropietro, P.; Rodilla, P.; Rangel, L.E.; Batlle, C. Reforming the Colombian electricity market for an efficient integration of renewables: A proposal. *Energy Policy* **2020**, *139*, 111346. [CrossRef]
17. Rancilio, G.; Rossi, A.; Falabretti, D.; Galliani, A.; Merlo, M. Ancillary services markets in Europe: Evolution and regulatory trade-offs. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111850. [CrossRef]
18. Fraunholz, C.; Keles, D.; Fichtner, W. On the role of electricity storage in capacity remuneration mechanisms. *Energy Policy* **2021**, *149*, 112014. [CrossRef]
19. Shiltz, D.J.; Baros, S.; Cvetkovic, M.; Annaswamy, A.M. Integration of automatic generation control and demand response via a dynamic regulation market mechanism. *IEEE Trans. Control. Syst. Technol.* **2017**, *27*, 631–646. [CrossRef]
20. Shiltz, D.J.; Cvetkovic, M.; Annaswamy, A.M. An integrated dynamic market mechanism for real-time markets and frequency regulation. *IEEE Trans. Sustain. Energy* **2015**, *7*, 875–885. [CrossRef]
21. de Oca, S.M.; Muraña, J.; Monzón, P.; Nesmachnow, S.; Iturriaga, S.; Belcredi, G. Demand Response program for Supercomputing and Datacenters providing Ancillary Services in the Electricity Market. In Proceedings of the 2020 IEEE PES Transmission & Distribution Conference and Exhibition—Latin America (T&D LA), Montevideo, Uruguay, 28 September 2020–2 October 2020.
22. Wang, Z.; Zhong, J. Procuring and pricing performance-based frequency regulation services in the electricity market. *IET Gener. Transm. Distrib.* **2017**, *11*, 2633–2642. [CrossRef]
23. He, G.; Chen, Q.; Kang, C.; Xia, Q.; Poolla, K. Cooperation of wind power and battery storage to provide frequency regulation in power markets. *IEEE Trans. Power Syst.* **2016**, *32*, 3559–3568. [CrossRef]
24. Fabietti, L.; Qureshi, F.A.; Gorecki, T.T.; Salzmann, C.; Jones, C.N. Multi-time scale coordination of complementary resources for the provision of ancillary services. *Appl. Energy* **2018**, *229*, 1164–1180. [CrossRef]
25. Al-Obaidi, A.; Khani, H.; Farag, H.E.; Mohamed, M. Bidirectional smart charging of electric vehicles considering user preferences, peer-to-peer energy trade, and provision of grid ancillary services. *Int. J. Electr. Power Energy Syst.* **2021**, *124*, 106353. [CrossRef]
26. Sichuan Energy Regulatory Office of National Energy Administration. Sichuan Automatic Generation Control Auxiliary Services Market Trading Rules (for Trial Implementation) (2020 Revised Version) (Draft for Comments). 2020. Available online: https://guangfu.bjx.com.cn/news/20201214/1122153.shtml (accessed on 12 February 2023). (In Chinese).
27. North China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China. Notice of the North China Energy Regulatory Bureau on the Issuance of the Implementation Rules for the Trading of Two Ancillary Services for Frequency Regulation and Standby in the Mengxi Power Market. 2022. Available online: http://hbj.nea.gov.cn/adminContent/initViewContent.do?pk=0000000072a334090172c6aba497002c&columnId= (accessed on 11 February 2023). (In Chinese)

28. Shandong Energy Regulatory Office of National Energy Administration of the People's Republic of China. Shandong Energy Regulatory Office Issued "Shandong Electricity Ancillary Services Market Operation Rules (for Trial Implementation)". 2017. Available online: http://sdb.nea.gov.cn/jgdt/content_3550 (accessed on 10 February 2023). (In Chinese)
29. North China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China Letter from the North China Energy Regulatory Bureau on the Consultation on the Operating Rules for the Frequency Regulation Ancillary Services Market of Beijing-Tianjin-Tangshan Power Grid (for Trial Implementation) (Draft for Comments). 2018. Available online: https://news.bjx.com.cn/html/20180907/926552.shtml (accessed on 13 February 2023). (In Chinese).
30. Gansu Energy Regulatory Office of National Energy Administration. Gansu Energy Supervision Office Completed the Revision of "Gansu Province Electricity Ancillary Services Market Operation Interim Rules". 2021. Available online: http://gsb.nea.gov.cn/view.asp?id=5041&typeid=0 (accessed on 12 February 2023). (In Chinese)
31. Zhejiang Energy Regulatory Office of National Energy Administration. Zhejiang Province, Third-Party Independent Entities Involved in Power Ancillary Service Market Trading Rules (for Trial Implementation) (Draft for Comments). 2021. Available online: https://zjb.nea.gov.cn/u/cms/www/202105/2011352186my.pdf (accessed on 10 February 2023). (In Chinese)
32. Energy Regulatory Office of National Energy Administration of the People's Republic of China. Fujian Regulatory Office of the National Energy Administration on the Issuance of the "Fujian Province Electricity Frequency Regulation Ancillary Services Market Trading Rules (for Trial Implementation)" Notice. 2018. Available online: http://fjb.nea.gov.cn/news_view.aspx?id=29459 (accessed on 12 February 2023). (In Chinese)
33. Central China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China. Draft of Trading Rules of Hubei Electricity Frequency Regulation Ancillary Services Market for Comments. 2022. Available online: https://power.in-en.com/html/power-2406242.shtml (accessed on 11 February 2023). (In Chinese)
34. Central China Energy Regulatory Bureau of National Energy Administration of the People's Republic of China. Notice of Central China Energy Regulatory Bureau on the Issuance of "Jiangxi Electricity Frequency Regulation Ancillary Service Market Operation Rules". 2022. Available online: http://hzj.nea.gov.cn/adminContent/initViewContent.do?pk=F0E33C659A78CD5CE050A8C0C1C82281 (accessed on 11 February 2023). (In Chinese)
35. South China Energy Regulatory Office of National Energy Administration. Southern Energy Regulatory Bureau Releases "Guangdong Frequency Regulation Ancillary Services Market Trading Rules (for Trial Implementation)". 2018. Available online: http://nfj.nea.gov.cn/adminContent/initViewContent.do?pk=7168984 (accessed on 9 February 2023). (In Chinese)
36. Yunnan Energy Regulatory Office of the National Energy Administration of the People's Republic of China. Notice of the Yunnan Regulatory Office of the National Energy Administration on the Issuance of the Supplementary Provisions on the Optimization and Adjustment of the Operating Rules of the Yunnan Frequency Regulation Ancillary Services Market (for Trial Implementation). 2021. Available online: http://ynb.nea.gov.cn/front/article/104460.html (accessed on 11 February 2023). (In Chinese)
37. Shanxi Energy Regulatory Office of National Energy Administration of the People's Republic of China. Notice of Shanxi Energy Regulatory Office on the Issuance of "Shanxi Electricity Frequency Regulation Ancillary Service Market Operation Rules". 2017. Available online: https://mpower.in-en.com/html/power-2284034.shtml (accessed on 10 February 2023). (In Chinese)
38. Jiangsu Energy Regulatory Office of National Energy Administration. Notice on the Issuance of "Jiangsu Electricity Ancillary Services (Frequency Regulation) Market Trading Rules" (for Trial Implementation). 2020. Available online: http://jsb.nea.gov.cn/news/2020-7/202073154200.htm (accessed on 8 February 2023). (In Chinese)
39. Amanbek, Y.; Kalakova, A.; Zhakiyeva, S.; Kayisli, K.; Zhakiyev, N.; Friedrich, D. Distribution locational marginal price based transactive energy management in distribution systems with smart prosumers—A multi-agent approach. *Energies* **2022**, *15*, 2404. [CrossRef]
40. Wang, J.; Wu, J.; Shi, Y. A Novel Energy Management Optimization Method for Commercial Users Based on Hybrid Simulation of Electricity Market Bidding. *Energies* **2022**, *15*, 4207. [CrossRef]
41. Shandilya, S.; Szymanski, Z.; Shandilya, S.K.; Izonin, I.; Singh, K.K. Modeling and Comparative Analysis of Multi-Agent Cost Allocation Strategies Using Cooperative Game Theory for the Modern Electricity Market. *Energies* **2022**, *15*, 2352. [CrossRef]