Design of a Scarcity Pricing Mechanism for Electricity Market Based on Price Increment Pattern

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Abstract. In high-proportion renewable energy power systems, the existing marginal unified clearing mechanism based on a low-price cap in the electricity spot market can lead to trading welfare losses and the inability of clearing prices to reflect the supply-demand relationship during scarce periods, resulting in insufficient flexibility and capacity adequacy of the power system. To address this issue, this paper proposes a scarcity pricing mechanism for the electricity market based on a price increment pattern, which combines an operation reserve demand curve (ORDC) to establish a time-point scarcity electricity price calculation model. Additionally, a creative price risk prevention mechanism consisting of multiple modules is introduced to transform the reserve scarcity signal into a reasonable price increment during market clearing, fully restoring the scarcity signal of electricity, thereby improving market trading surplus welfare, promoting system flexibility, and capacity adequacy. Simulation examples verify that this mechanism can effectively meet the needs of new power systems for power generation capacity adequacy, reliability, and flexibility, and sensitivity analysis reveals the impact of key parameters on the implementation effect, providing reference value for the implementation of the mechanism.

Keywords: Electricity Market; Scarcity Pricing; Mechanism Design

1. Introduction

With the scale of renewable energy construction continues to expand, the current marginal unified clearing mechanism in the electricity spot market based on a low-price cap leads to trading surplus welfare losses and the inability of clearing prices to reflect the supply-demand relationship during scarce periods. In addition, the expanding scale of renewable energy with low marginal generation costs continues to squeeze the living space of thermal power units. To ensure that thermal power units serve as stable and reliable backup power sources, improve user-side adjustment flexibility to ease system supply-demand balance pressure, release price signals during supply-demand tense periods to ensure power system capacity adequacy, and adopting a scarcity pricing mechanism to incentivize thermal power units with backup capabilities to provide power supply guarantees during scarce periods is one of the most effective ways.

Domestic and foreign scholars have conducted extensive research on the scarce pricing mechanism in the electricity market. Previous studies have introduced various mechanisms,

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such as centralized capacity markets[1], reliability option auctions[2], decentralized capacity obligations[3], fixed capacity compensation [4], strategic reserve mode [5], and scarcity pricing [6], based on the typical international practice of capacity adequacy mechanism, but these studies only introduce the principles and overall framework of related mechanism designs abroad. References [7-8] have designed new capacity market mechanisms and capacity compensation mechanisms suitable for China's power system, respectively, proposing mechanism design schemes for market operating economic efficiency, energy transition needs and other objectives. However, these studies cannot simultaneously meet the requirements of capacity adequacy and system flexibility. References [9] have studied the effects of capacity mechanisms on the decision behaviour of various market entities and the development direction of the market from multiple perspectives. However, the focus of the study is on the verification of the effectiveness of individual mechanism aspects, and a complete design scheme for the scarcity pricing mechanism has not been proposed for the domestic environment.

To design a scarcity pricing method that is suitable for the domestic power market environment and ensures the adequacy, reliability, and flexibility of power generation capacity, this paper proposes a scarcity pricing mechanism based on the price increment model, which is adapted to the Chinese market environment.

2. Core design ideas

2.1. Existing problems

In market transactions, the market clearing constraint of the upper limit of the low price and strategic bidding deviating from actual production costs can lead to the inability of market supply and demand to reach the optimal balance, which in turn reduces the scale of transactions and causes net loss of surplus welfare. As shown in Figure 1, the existence of the upper limit of the low price and the strategic bidding on the generation side in the market will cause significant net loss of surplus welfare and user load shedding when the supply is scarce. In the case of stable supply, the marginal units of thermal power plants with relatively high costs will face the problem of net loss of electricity generation income. In addition, the upper limit of the low price suppresses the release of market price signals and weakens the elasticity of user demand, which will negatively affect the stability of the electricity market operation by the "cobweb effect".

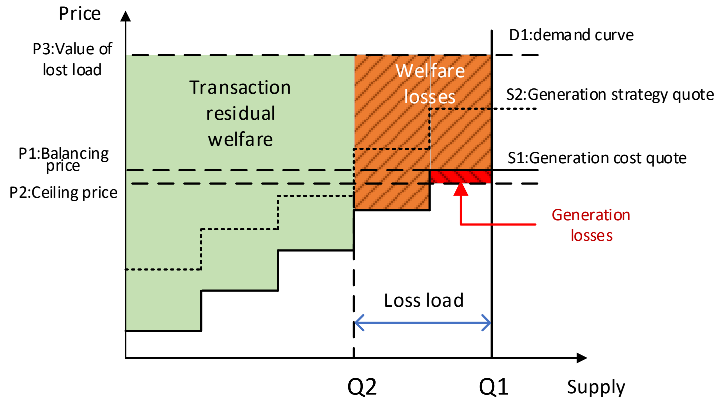

Figure 1. Analysis of supply and demand of electricity market transactions

Based on the above analysis, the issues that the scarcity pricing mechanism needs to address include: 1) the surplus welfare loss caused by the price ceiling and strategic bidding on the generation side in market transactions; 2) the problem of revenue loss for thermal power units and the resulting adequacy of the system's generating capacity; and 3) the inability of market prices to reflect the supply-demand relationship during scarce periods, insufficient user demand elasticity, and system flexibility.

2.2. Core ideas

With stable growth in installed capacity of photovoltaic renewable energy and electricity demand, the scarcity pricing mechanism should focus on the electricity scarcity periods during high peak loads. By breaking the constraints of the low-price cap during scarcity periods, the electricity supply scarcity pricing signal can be fully restored. This can increase the revenue of high-efficiency thermal power units, while also reducing the willingness of power generation side to engage in strategic bidding, thereby solving the problem of residual welfare loss in market transactions. Based on this core idea, guiding the investment and construction of flexible regulation resources such as efficient thermal power units and adjustable loads through the electricity market price signal can effectively improve the capacity adequacy and adjustment flexibility of the power system, thereby reducing the pressure on the supply-demand balance of the power system and ultimately alleviating the supply scarcity contradiction in the development process of the power system. The design scheme of the scarcity pricing mechanism is shown in Figure 2.

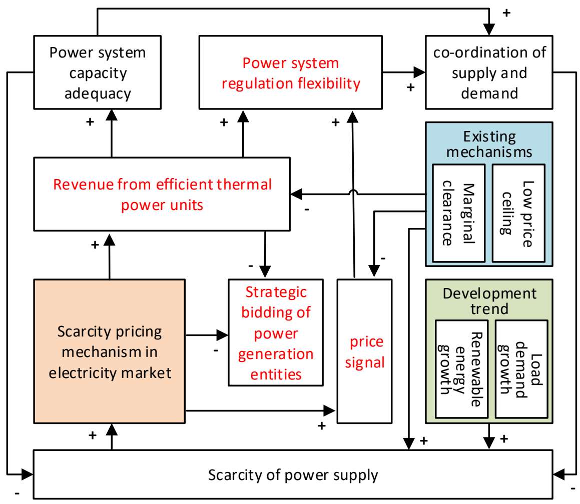

Figure 2. Core ideas of scarcity pricing mechanism

2.3. Design principles

To avoid systemic risks brought by the implementation of the mechanism, the design of the scarcity pricing scheme should adhere to the principles of adaptability, security, and controllability.

① Adaptability. In the exploratory process of market-oriented mechanism reform, the mechanism design should be adapted to the specific market environment, and the final implementation effect should be used as the evaluation standard.

②Security. The market-oriented reform of the power industry should promote the safe and reliable development of the power system while benefiting the widest range of people, reducing risks, and preventing a few groups from exploiting loopholes in the mechanism to obtain excessive profits.

③Controllability. The scheme design should consider the current situation and circumstances and be adjustable according to the development path of China's power system, while continuously exerting the value and vitality of the mechanism under overall controllability.

Currently, there are three main types of scarcity pricing mechanisms: high price cap, scarcity penalty factor, and price increment. Below, we will discuss the adaptability of each mechanism to China's electricity market based on design principles. The price increment pattern is suitable for use in environments where electricity and ancillary services are cleared separately. The principle is to calculate the price increment in the spot market by combining the ORDC, thus reflecting the scarcity of electricity supply. The price increment model is not only suitable for environments where multiple types of markets are decoupled, but also has key parameters that are determined by regulatory agencies, making the overall market price more controllable.

Above all, the price increment model is more suitable for the current electricity market environment in China for scarcity pricing. In the following, we will further design a specific implementation plan based on the actual situation of the electricity market in China.

3. Scarcity pricing mechanism design

3.1. ORDC development

From the perspective of the invocation method, the ORDC represents a virtual reserve resource price level set by the market operator. The ORDC reflects the value of the electricity reserve capacity in a scarce period by setting different prices for different reserve scarcity levels and is used to derive the electricity incremental price.

The ORDC of the price increment method for scarcity pricing is a decreasing curve related to the level of reserve capacity. The construction of the ORDC is based on two key variables: the value of lost load (VOLL) and the loss of load probability (LOLP), and the expression is shown in Formula 1.:

$$
\begin{gathered}
C_{ORDC}(r) = C_{VOLL} \times F(r) \\
F(r) = \begin{cases} F_{LOLP}(\sigma, \mu, r - X) & , \ r - X > 0 \\ 1 & , \ r - X \le 0 \end{cases} \\
F_{LOLP}(\sigma, \mu, r) = 1 - F_{CDF}(\sigma, \mu, r)
\end{gathered} \tag{1}
$$

In the equation, $C_{ORDC}(r)$ represents the cost of reserve capacity, C_{VOLL} represents the value of lost load, and $F(r)$ represents the probability of system loss of load. When the reserve level r is less than the minimum emergency reserve requirement X, it is determined that there will be a loss of load in the system, denoted as $F(r)=1$; when $r > X$, the probability of loss of load is $F_{LOLP}(\sigma, \mu, r - X)$. Here, $F_{CDF}(\sigma, \mu, *)$ is the cumulative distribution function of the normal distribution with mean μ and standard deviation σ.

3.2. Scarcity price calculation model

The reserve capacity gap directly reflects the degree of capacity scarcity in a specific period, so the incremental pricing method essentially converts the reserve capacity gap reflecting the scarcity degree into an incremental price, and combines it with the marginal energy price to form the scarcity price.

Assume that during period t, the minimum reserve capacity, minimum emergency reserve capacity, and actual reserve capacity of the system are R_t, X_t, and r_t, respectively. When $r_t < R_t$, referring to ORDC, the calculation method for the scarcity price of node i is shown in Formula 2:

$$
C_{i,t}^{ESP} = C_{i,t}^{RPA} + \lambda_{i,t} = (C_{VOLL} - \lambda_{i,t}) \times F(r) + \lambda_{i,t} \tag{2}
$$

Where $C_{i,t}^{ESP}$ is the spot electricity scarcity price, $C_{i,t}^{RPA}$ is the incremental price, and $\lambda_{i,t}$ is the marginal price for clearing the spot electricity market at node i.

3.3. Price risk prevention mechanism

(1) Information Disclosure Mechanism

The dispatching agency should predict the scarcity period based on the latest data in advance and in real-time market, and disclose the prediction to the market participants. The prediction results are only for the reference of the market participants and not used as the settlement basis of the spot market.

(2) Price compensation mechanism

To avoid situations where the generator cannot recover its investment costs due to accumulated scarcity of time or excessively low prices, it is possible to select eligible units for price compensation by examining the cost recovery status of the units.

Assuming that the investment cost per unit installed capacity of unit j is C_j^{inv}, the service period is M_j months, and the discount rate is n, the monthly cost to be recovered per unit capacity P_j can be expressed as Formula 3:

$$P_j = \frac{n(n+1)^{M_j}}{(n+1)^{M_j} - 1} C_j^{inv} \tag{3}$$

If the installed capacity of the unit j is Ω_j, and the total power generation, operation and maintenance expenses, and average electricity and fuel costs in the month m are $E_{j,m}$, $O_{j,m}$, $F_{j,m}$, respectively, the total cost of the unit j in the month is shown in Formula 4:

$$C_{j,m} = E_{j,m} F_{j,m} + O_{j,m} + P_j \Omega_j \tag{4}$$

Set a price compensation coefficient $\theta (0 < \theta \leq 1)$. If the ratio of generating revenue $I_{j,m}$ to total cost $C_{j,m}$ of unit j in the current month is lower than θ, the unit will be given a price compensation fee $R_{j,m}$ to ensure that the unit recovers part of the cost while promoting healthy market competition, as shown in Formula 5.

$$R_{j,m} = \theta C_{j,m} - I_{j,m} \tag{5}$$

(3)High-frequency scarcity circuit breaker mechanism

To prevent market entities from distorting market scarcity price signals through the use of market power, a matching high-frequency scarcity circuit breaker mechanism should be designed. This method sets a monthly cumulative scarcity time limit k. If the cumulative time in the scarcity period reaches k hours in a given month, then the scarcity pricing for that month will be suspended until the next natural month.

4. CASES STUDIES

4.1. Case Model Settings

In this chapter, an electricity system energy time-sharing balance model is established to simulate annual electricity transactions in specific scenarios and obtain the hourly clearance results for one year. The input data includes basic data and scarcity pricing parameters.

(1)Basic data

The basic data includes electricity demand, generation capacity, and generation cost. The electricity demand and generation capacity are based on typical load decomposition curves, which are further subdivided into the clearing periods for four typical days: workdays, Saturdays, Sundays, and holidays for each month.

(2)Scarcity pricing parameters

In the mechanism, C_{VOLL} uses the gross industrial and commercial production data per unit of electricity in Guangdong Province, and considers that the cumulative function of load loss probability is $F_{CDF}(\sigma,\mu,r)=F_{CDF}((R-X)/3,0,r)$, and the minimum standby is $R=L_{\max}\times r_1+R_1$, where $L_{\max}$ is the maximum load for the whole day, r_1 is the load coefficient, and R_1 is the maximum loss load for a single fault. All parameters of the scarcity pricing mechanism are shown in Table 1.

Table 1. Parameter table of scarcity pricing mechanism.

Parameter	Value	Unit	Parameter	Value	Unit
C_{VOLL}	16.95	¥/kWh	n	5%	-
X	2000	MW	M_j	480	month
r_1	2%	-	θ	70%	-
R_1	5000	MW	k	50	hour

4.2. Simulation and analysis

Considering that the future renewable energy penetration rate in Guangdong Province will gradually increase from 20% to 60%, four typical scenarios are designed for comparison analysis based on the presence or absence of scarcity pricing mechanisms, price compensation, and high-frequency circuit breakers for scarcity.

4.2.1. Impact on electricity scarcity levels

As shown in Figures 3 and 4, Scenario 4 has incremental pricing mode and scarce pricing, while Scenario 1 does not. It can be seen that as the penetration rate of wind and solar renewable energy continues to increase, the cumulative scarcity duration and loss of load duration of the two scenarios continue to increase. Compared with Scenario 1, Scenario 4 significantly reduces the overall scarcity level of the system by introducing an incremental pricing model for scarcity pricing. The cumulative loss of load duration under different renewable energy penetration rates decreases by more than 70%, and the cumulative scarcity duration also decreases by more than 50% in most cases. In addition, the scarcity pricing mechanism effectively reduces or offsets the cost shortfall of thermal power generation units, which reflects the positive role of the scarcity pricing mechanism in reducing revenue loss of thermal power generation units and improving the flexibility and reliability of the power system.

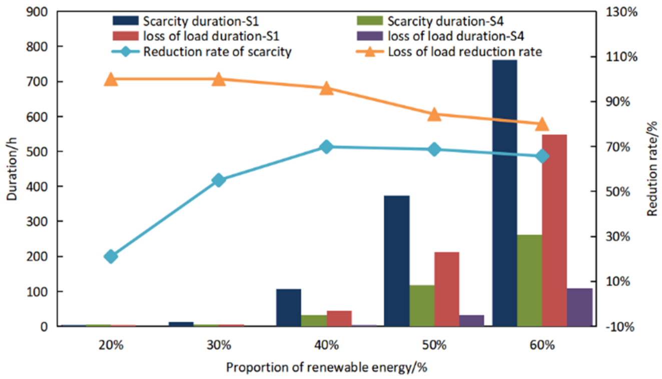

Figure 3. Impact of scarcity pricing mechanism on scarcity level

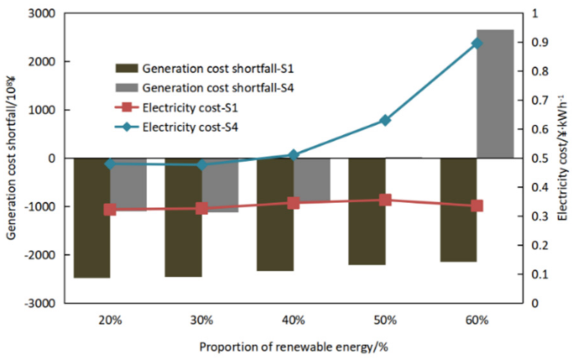

Figure 4. Impact of scarcity pricing mechanism on power generation and electricity cost

4.2.2. Effect of risk prevention mechanism

On the basis of scenario 4, scenario 3 is obtained by reducing the high-frequency circuit breaker mechanism, and scenario 2 is obtained by further reducing the price compensation mechanism. The simulation results of the three scenarios are shown in the following figure.

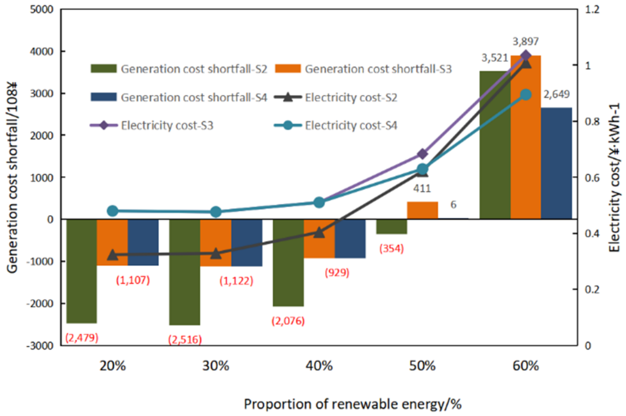

Figure 5. Impact of risk prevention mechanism on power generation and electricity cost

The simulation results for the three scenarios are shown in Figure 5. Scenario 3, which eliminates the high-frequency tripping mechanism, easily leads to excessive compensation of the cost shortfall of thermal power units, resulting in higher electricity costs. This effect is exacerbated as the penetration rate of renewable energy increases. In Scenario 2, both price compensation and high-frequency tripping mechanisms are cancelled, making it difficult to recover the cost shortfall of thermal power units when the penetration rate of renewable energy is low, and leading to excessively high electricity costs when the penetration rate is high. Comparison shows that Scenario 4 with a complete risk prevention mechanism can help thermal power units to recover cost shortfall reasonably in all cases, while avoiding the rapid increase of user-side electricity costs caused by the scarcity pricing mechanism.

4.2.3. Sensitivity analysis of key parameters

In order to scientifically formulate the key parameters of the scarcity pricing mechanism, the sensitivity analysis of electricity cost P_{ele} and generation cost shortfall L_{gen} is conducted for three parameters: C_{VOLL}, θ, and k. Taking the sensitivity analysis of P_{ele} versus θ as an example, the calculation formula for the relative sensitivity δ is shown in Formula 6:

$$\delta = \frac{P_{ele2} - P_{ele1}}{P_{ele2}} \div \frac{\theta_2 - \theta_1}{\theta_2} \tag{6}$$

Sensitivity analysis was conducted for C_{VOLL}, θ, and k within certain ranges, and the results are shown in Table 2.

Table 2. Parameter sensitivity analysis results

C_{VOLL}	δ		θ	δ		k	δ	
	P_{ele}	L_{gen}		P_{ele}	L_{gen}		P_{ele}	L_{gen}
10.17	0.478	3.587	40%	0.024	0.125	20	0.380	1.122

11.86	0.526	2.672	50%	0.044	0.217	30	0.040	0.134
13.56	0.562	2.223	60%	0.070	0.336	40	0.118	0.344
15.25	0.591	1.958	70%	0.081	0.375	50	0.362	0.895
16.95	0.616	1.789	80%	0.091	0.407	60	0.217	0.521

Based on the sensitivity analysis of the value of lost load, price compensation coefficient, and cumulative scarcity duration within a certain range, it can be seen that the electricity cost and cost shortfall increase with the increase of these parameters. The sensitivity of the cost shortfall to C_{VOLL} is the highest and decreases as the parameter increases. The sensitivity of electricity cost to θ is the lowest and increases with the increase of the parameter.

5. Conclusion

This paper proposes a scarcity pricing mechanism for the electricity market based on the price increment model. By adapting to the electricity market environment and the development path of the new power system in China, a simple, feasible, and risk-controlled scarcity pricing scheme is presented. By restoring reasonable price signals in scarce periods, the mechanism ensures the recovery of cost deficiencies for thermal power units and promotes healthy competition, thereby improving system capacity adequacy and flexibility.

The simulation section verifies that the proposed mechanism can release market scarcity price signals through incremental pricing, which has significant positive effects on improving the power system's generating capacity, flexibility, reliability, and overcoming price risks. Sensitivity analysis of key parameters of the mechanism is also conducted, pointing out two key parameters that need special attention when formulating scarcity pricing policies.

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