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*Original Research*

# Studying Optimal Strategies of Transmission Congestion Management in the Spot Market

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## Abstract

With the continuous deepening of electricity marketization reform and the large-scale integration of clean energy into the system, the problem of transmission congestion in the power system is frequent, and research on congestion management methods has become a major focus. Therefore, this paper studies the optimization strategy of transmission congestion management in the power spot market. Firstly, the existing congestion management mechanisms were sorted out from two aspects: dynamic management mechanisms, and market steady-state mechanisms. At the same time, the advantages and disadvantages of various mechanisms were summarized. Then, optimization strategies for congestion management were proposed from three aspects: cost optimization, surplus diversion, and risk optimization. Firstly, based on the ATC reduction method and rescheduling method, a congestion cost optimization strategy is proposed. Secondly, a congestion cost pool and multidimensional allocation indicators, are established and a congestion surplus diversion strategy is proposed. Thirdly, a two-level market for transmission rights trading has been constructed to optimize congestion risk. Finally, a case study was conducted in a certain province in eastern and western China, and the results showed that: 1) Considering the rescheduling method and ATC reduction method to optimize congestion costs can reduce congestion costs by 8.22% and 18.83%, compared to only considering the scheduling method and using ATC reduction method. 2) Establishing a congestion cost pool and multi-dimensional allocation indicators to channel congestion surplus can form price guidance signals. 3) Constructing a two-level market for transmission rights trading can increase the efficiency of system operators by 62.75%.

**Keywords:** power spot market, transmission, congestion management, strategy optimization

## Introduction

With the proposal of the strategic goal of building a new type of power system with new energy as the main body, distributed power sources, electric vehicles, and energy storage devices have been extensively integrated into the power system, making the operational form and network structure of the power system more diverse and complex [1-2]. At the same time, it increases the difficulty of resource regulation in the distribution network, leading to issues such as voltage exceeding limits, power flow exceeding limits, and increased network losses in the system, making the distribution network prone to congestion [3-4]. Differently from

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the integrated market model, under the power Spot market model, the market subjects are diversified, the transaction frequency increases, and the transaction scope expands, making the power system operation mode more changeable and complex, and the probability of transmission congestion increases [5, 6]. Therefore, the study of transmission congestion management optimization strategy in the spot market has become the focus. At this stage, congestion management research mainly focuses on direct management and indirect management [7].

Direct congestion management methods include direct reduction, active power control, reactive power control, and network reconstruction [8-11]. For the network reconstruction method, Pippi et al. [12, 13] introduced a central controller, proposed a new system control architecture, and verified that this architecture can reduce network losses and improve system performance. Zhang et al. [14, 15] analyzed the internal structure and inter-station connections of 110kV substations, proposed a topology representation method for high-voltage distribution network substation unit groups, and implemented unit group reconstruction based on the feasible topological state set within the unit group. In response to the direct reduction method, Deepti et al. [16, 17] proposed a safety constrained optimal power flow generation rescheduling method to manage congestion issues in the system, in order to improve the absorption rate of photovoltaic power generation. Ingo et al. [18] proposed a Discrete optimization method to determine the optimal reduction of distributed generators based on the nonlinear AC power flow analysis of the network. Regarding the active power control method, Thang et al. [19] proposed using a multi-objective genetic algorithm for active power control of controllable series compensator devices. Xiao et al. [20] proposed a settlement right transfer transaction mechanism for congestion risk management in consideration of the actual characteristics and needs of China's current power Spot market. For the reactive power control method, Zou et al. [21-24] established a prevention control and correction control congestion management model, and proposed a coordinated control algorithm for prevention and correction congestion management based on the Benders decomposition algorithm.

The indirect management method mainly guides congestion management through market mechanisms [25-27]. The most widely studied indirect congestion management mechanism at present is transmission rights, which are divided into financial transmission rights and physical transmission rights. Most research mainly focuses on financial transmission rights. Yang et al. [28, 29] compared and analyzed the similarities and differences in financial transmission rights settlement under the traditional node marginal electricity price and unified settlement point electricity price mechanisms, and constructed a mathematical model for financial transmission rights settlement to mitigate congestion management risks. Wu et al. [30, 31] proposed that the use of financial transmission rights for congestion management is becoming a trend, and analyzed the impact of the introduction of transmission rights on the expansion and investment of transmission lines. Liu et al. [32, 33] introduced the concept of financial transmission rights to mitigate the risk of congestion electricity prices and prevent node congestion cost compensation from negatively affecting congestion management.

The analysis of current literature on both direct and indirect management provides a theoretical basis for this study. However, there are three shortcomings. Firstly, in terms of research methods, most of the aforementioned literature only considers implementing one type of congestion management measure, which may cause difficulty ensuring the completion and economy of congestion management. However, optimizing the combination of different measures can provide better solutions for distribution network congestion management. Secondly, from a research perspective, the above literature starts from a single perspective of congestion management and does not optimize congestion management from multiple dimensions. Thirdly, in terms of research objectives, research on congestion management mostly focuses on system control and active power control from a physical perspective, but does not consider the economic benefits of congestion management.

Therefore, on the basis of the above research, this paper studies the optimization strategy of transmission congestion management in the power spot market. Compared with the existing literature, this paper has the following innovations:

(1) A congestion management optimization strategy has been constructed from multiple perspectives, such as congestion cost optimization, congestion surplus diversion strategy, and congestion risk optimization, which compensates for the shortcomings of existing research that only focuses on a single perspective, such as congestion risk.

(2) A congestion cost optimization strategy was constructed by balancing the ATC reduction method and the rescheduling method. Through the optimization and integration of multiple congestion management measures, the optimal allocation of scheduling resources was achieved, filling the gap of only considering a single congestion management measure.

(3) Improved the existing congestion surplus diversion model by establishing a congestion cost pool for direct congestion cost allocation, and constructed a multidimensional allocation index system that includes contribution, deviation, and spatial distance. On the one hand, it can avoid the abnormal process of congestion cost sharing and return. On the other hand, multidimensional allocation factors are considered to guide prices and indirectly solve congestion problems.

(4) A transmission right transaction model based on the two-level market is constructed, in which the primary market implements the auction mechanism and the secondary market implements the two-way

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transaction mechanism. The construction of a two-level market can enable market participants to hedge against congestion risks and improve system and social benefits.

The other parts of this paper are composed of: the second part summarizes the congestion management mechanism from the perspective of dynamic management and market stability. The third part designs a full process congestion management optimization strategy from the aspects of congestion cost optimization, congestion surplus diversion, and congestion risk optimization. The fourth part is based on the signing model and takes a certain province in eastern and western China as an example for analysis, providing reference opinions for congestion management in the spot electricity market.

## Blockage Management Mechanism

Grid congestion refers to the inability to meet all transactions when the transmission line capacity is overloaded. In order to avoid this situation, the grid operators need to mediate from it, that is, to conduct congestion management. Its task is to ensure the maximization of the interests of various market participants in cross regional electricity trading under limited transmission capacity, without affecting the security of the transmission network. The commonly used congestion management methods include dynamic management mechanisms, such as short-term proactive adjustment strategies and market steady-state mechanisms.

### Dynamic Management Mechanism

The dynamic management mechanism refers to solving congestion related problems through non market means. Commonly used dynamic management mechanisms include distributed optimal power flow method, ATC based transaction reduction method, rescheduling method, and market splitting method.

#### *Based on Distributed Optimal Power Flow Method*

Based on the distributed optimal power flow method, it refers to decoupling the interconnection lines between regions to achieve zoning control. The decoupling methods include an indirect method and a direct method. The indirect method refers to adding a new virtual busbar on the interconnection line, and the power balance equation of the new virtual busbar serves as a decoupling constraint condition. Then, the coupling constraints are relaxed into the objective function by Lagrange relaxation method or augmented Lagrange method. The direct method means that the boundary conditions of the region are directly relaxed into the objective function using the Lagrange relaxation method or the augmented Lagrange method.

#### *ATC Based Transaction Reduction Method*

The ATC based reduction method refers to the system administrator reducing transactions on the transmission line according to certain rules when the transmission line is overloaded. The commonly used reduction methods include the proportional reduction method, the reduction method based on the contribution of transactions to blocked lines, and the first-in, first-in service method. The proportional reduction method refers to reducing the transmission volume on each line based on the ratio of theoretical transmission capacity to required transmission capacity.

#### *Rescheduling Method*

The rescheduling method refers to market participants trading according to their own plans without knowing the transmission capacity of the system, and then system operators making security corrections based on the submitted transactions. If these transactions can meet the network constraints, all transactions are accepted. If they cannot meet the network constraints, a rescheduling method is adopted to determine feasible transactions. For cross regional re scheduling, it is necessary to coordinate with system operators in adjacent regions. In the downstream area of congestion, system operators dispatch more expensive generator units, while in the upstream area of congestion, those relatively cheaper units are eliminated.

#### *Market Splitting Method*

In the absence of system congestion, the price of the entire system will be unified. When blockages occur, the system is divided into several regions according to a predetermined partitioning plan, forming partitioned transaction volumes and prices, with no power exchange between regions. Then the system operators buy electricity from the low-priced area and sell it in the high-priced area until the power exchange between regions meets the transmission constraints. The price difference of regional clearance without power exchange between regions is greater than the price difference formed by system operators through limited power exchange. The congestion income generated by the price difference between regions belongs to the system operation center.

#### *Comparison of Dynamic Management Mechanisms*

Based on the implementation principles of various dynamic management mechanisms, the advantages and disadvantages of these mechanisms are summarized in Table 1. Due to the advantages and disadvantages of various dynamic management mechanisms, it is possible to consider combining multiple dynamic management mechanisms for blocking management. This paper utilizes the advantages of the rescheduling method that

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Table 1. Five kinds of Copula function evaluation index values.

| Dynamic management mechanism | Advantage | Disadvantage |
|---|---|---|
| Based on distributed optimal power flow method | Can provide price signal | The decoupling algorithm is complex and requires high information exchange requirements |
| Based on ATC transaction reduction method | Can effectively prevent blockages | Unable to provide effective price signal |
| Rescheduling method | Can provide effective economic signals | Requires system operators to master generator set information |
| Market splitting method | Can provide economic signals for long-term investment | Only applicable when blockage occurs in a fixed position |

can provide effective economic signals, and the ATC reduction method that can effectively prevent congestion, combining the two methods to optimize congestion costs.

## Market Steady State Mechanism

The market steady state mechanism refers to the use of price signals to match the supply and demand of the power system by improving the power market mechanism, and the reasonable market allocation of congestion costs, mainly including price allocation mechanism and transmission rights trading mechanism.

### *Price Allocation Mechanism*

The price allocation mechanism includes system marginal electricity price and node marginal electricity price. The system marginal electricity price refers to the minimum cost of purchasing electricity for each additional unit of electricity usage demand in the system, provided that the operation of the power grid system has been determined. Node marginal electricity price refers to the minimum purchase cost that the system increases to meet the unit active power demand of a certain node at the same stable operating level of the power grid, without affecting the safe and stable operation of the power grid.

### *Transmission Rights Trading Mechanism*

The transmission rights trading mechanism refers to the division of transmission energy rights from one node to another in the power grid system, allowing the owners of transmission rights to obtain the right to use the corresponding transmission capacity and corresponding economic benefits. By separating transmission rights from the electricity trading market, the electricity market and capacity market can be independent of each other, thereby enabling both to work together in the congestion management of the power system. The transmission rights trading mechanism is divided into physical transmission rights and financial transmission rights. The physical transmission rights refer to the transmission rights obtained by power generators through auction based on their own capacity usage needs. When the system experiences congestion, power generation companies with physical transmission rights can use the transmission capacity, while other power generation companies that have not purchased physical transmission rights are prohibited from using the transmission capacity. The financial transmission right refers to the pricing of congestion based on the theory of real-time electricity price through market mechanism, that is, the node marginal price is used to participate in the bidding in the spot market.

### *Comparison of Market Steady State Mechanisms*

Based on the implementation principles of various market steady-state mechanisms, the advantages and disadvantages of these mechanisms are summarized in Table 2. The transmission rights trading mechanism plays an important role in risk hedging for power generation companies, so this paper uses the transmission rights trading mechanism to optimize congestion risk.

Table 2. Advantages and disadvantages of various market steady-state mechanisms.

| Market steady state mechanism | Advantage | Disadvantage |
|---|---|---|
| Price allocation mechanism | Enables power generation enterprises to continuously reduce costs and increase efficiency driven by greater profits and a larger share, ensuring their competitiveness. | Difficulty in adjusting for unpredictable and sporadic power grid blockages, which may lead to short-term speculative pricing behavior among entities. |
| Transmission rights trading mechanism | Can avoid some unreasonable blockages, hedge risks, and promote full competition in the electricity energy market. | There are high requirements for the improvement of infrastructure and market mechanisms in the electricity market, making it difficult to promote them. |

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## Material and Methods

The blocking management mechanism is the theoretical basis of this section. Through the theoretical analysis of dynamic management mechanisms, it can be seen that the single distributed optimal power flow method, ATC transaction reduction method, rescheduling method, and market splitting method all have certain shortcomings. Based on this, this section considers the combination of multiple methods to achieve complementary advantages of multiple methods. According to the theory of transmission rights trading mechanism, it can be seen that the transmission rights trading mechanism plays an important role in risk hedging for power generation companies. Based on this, this section combines dynamic management mechanisms with market steady-state mechanisms, first minimizing congestion costs, and controlling congestion risks based on transmission rights. Finally, a reasonable allocation plan for congestion surplus is designed.

### Optimization Strategy for Congestion Cost

The mechanism of congestion cost generation is that if the transmission capacity of the power grid transmission line is not considered, the units are called from low to high according to the unit quotation to meet the node load demand. However, if considering the transmission capacity of the transmission line, calling low-cost units may cause line overload, and only higher cost units can be called to meet the node load demand. Therefore, congestion cost is defined as the incremental cost caused by ensuring the transmission capacity of the transmission line.

The optimization strategy for the congestion cost in this article is to first optimize through the scheduling method. If congestion still exists, the ATC reduction method is used to optimize the remaining congestion capacity. Among them, there are two methods for optimizing congestion management through rescheduling management. The first method is to cut off interruptible loads in the receiving area and increase load demand in the sending area. The second method is to increase the upper generation limit of the generator set in the receiving area and lower the lower generation limit of the generator set in the sending area. Both increasing or decreasing load and increasing or decreasing power generation will incur costs, with increasing or decreasing load leading to demand response costs and increasing or decreasing power generation leading to unit regulation costs. Adopting the ATC reduction method will result in the abandonment of wind and solar energy in the sending end area and the inability to meet the load in the receiving end area, resulting in the cost of wind and photovoltaic abandonment and load shedding. Therefore, the cost of demand regulation, the cost of unit regulation, the cost of wind and photovoltaic abandonment, and the cost of load shedding constitute the congestion cost.

#### *Objective Function*

On the basis of qualitative analysis of the existing market, this section quantifies congestion costs and, in order to guide the system in selecting appropriate congestion management methods, optimizes congestion costs with the objective function of minimizing congestion costs. The specific objective function is shown in Equation (1):

$$\min C_t^{\mathrm{ce}} = \min \left[ \begin{array}{l} \left( \sum_{j \in J} \Delta P_{j,t}^{\mathrm{up}} \cdot \overline{u}_{j,\mathrm{ge}}^{\mathrm{up}} \right) + \left( \sum_{i \in I} \Delta P_{i,t}^{\mathrm{down}} \cdot \overline{u}_{i,\mathrm{ge}}^{\mathrm{down}} \right) + \left( \sum_{s \in S} \Delta L_{s,t}^{\mathrm{up}} \cdot \overline{u}_{s,\mathrm{load}}^{\mathrm{up}} \right) + \\ \left( \sum_{h \in H} \Delta L_{h,t}^{\mathrm{down}} \cdot \overline{u}_{h,\mathrm{load}}^{\mathrm{down}} \right) + \left( \Delta P_{\mathrm{total},t}^{\mathrm{ab}} \cdot \overline{u}_{\mathrm{total},t}^{\mathrm{ab}} \right) + \left( \Delta L_{\mathrm{total},t}^{\mathrm{loss}} \cdot \overline{u}_{\mathrm{total},t}^{\mathrm{loss}} \right) + P_t^{\mathrm{block}} \overline{u}_t^{\mathrm{block}} \end{array} \right] \tag{1}$$

where $C_t^{\mathrm{ce}}$ is the blocking cost at time t. $\boldsymbol{J}$ is the set of units that increase power generation output in the receiving area. $\boldsymbol{I}$ is the set of units that reduce power generation output in the sending end area. $\boldsymbol{S}$ is load set for increasing load demand at the sending end. $\boldsymbol{Ç}$ is the load set for reducing load demand at the receiving end. $\Delta P_{j,t}^{\mathrm{up}}$ is the increase in power output of the j-th unit in the receiving end region at time t. $\overline{u}_{j,\mathrm{ge}}^{\mathrm{up}}$ is the unit output cost adjusted for the j-th unit in the receiving area. $\Delta P_{i,t}^{\mathrm{down}}$ is the reduction in power output of the i-th unit in the supply area at time t. $\overline{u}_{i,\mathrm{ge}}^{\mathrm{down}}$ is the unit output cost adjusted for the i-th unit in the supply area. $\Delta L_{s,t}^{\mathrm{up}}$ represents the increase in the s-class load in the transmitting area at time t. $\overline{u}_{s,\mathrm{load}}^{\mathrm{up}}$ is the compensation cost of Unit demand response of s-class load in the receiving end area. $\Delta L_{h,t}^{\mathrm{down}}$ is the reduction of the h-class load in the receiving area at time t. $\overline{u}_{h,\mathrm{load}}^{\mathrm{down}}$ is the compensation cost for unit demand response of the h-class load in the sending end area. $\Delta P_{\mathrm{total},t}^{\mathrm{ab}}$ is the total amount of wind and photovoltaic abandoned at time t. $\overline{u}_{\mathrm{total},t}^{\mathrm{ab}}$ is the unit cost of wind and photovoltaic abandonment at time t. $\Delta L_{\mathrm{total},t}^{\mathrm{loss}}$ is the total amount of load shedding at time t. $\overline{u}_{\mathrm{total},t}^{\mathrm{loss}}$ is the unit load shedding cost at time t. $P_t^{\mathrm{block}}$ is the remaining blocking amount at time t. $\overline{u}_t^{\mathrm{block}}$ is the average penalty cost per unit of blocking volume at time t.

#### *Constraint Condition*

When adjusting the output and load demand of the unit, it is not allowed to exceed the upper and lower limits of the unit and the adjustable load, as shown in Equation (2):

$$\begin{cases} P_j^{\min} \le \Delta P_{j,t}^{\mathrm{up}} + P_{j,t}^0 \le P_j^{\max} \\ P_i^{\min} \le \Delta P_{i,t}^{\mathrm{down}} + P_{i,t}^0 \le P_i^{\max} \\ 0 \le \left| \Delta L_{s,t}^{\mathrm{up}} \right| \le \Delta L_s^{\max} \\ 0 \le \left| \Delta L_{h,t}^{\mathrm{down}} \right| \le \Delta L_h^{\max} \end{cases} \tag{2}$$

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where $P_j^{\min}$ and $P_j^{\max}$ is the minimum and maximum output of unit j. $P_{j,t}^{0}$ is the output of unit j without transmission capacity constraints. $P_j^{\min}$ and $P_j^{\max}$ is the minimum and maximum output of unit i. $P_{i,t}^{0}$ is the output of unit i without transmission capacity constraints. $\Delta L_s^{\max}$ is the maximum regulating capacity of the s-class load. $\Delta L_h^{\max}$ is the maximum regulation amount of the h-class load.

## Blocking Surplus Diversion Strategy

Compared with constrained conditions, the system increases congestion costs. In order to solve the problem that the existing settlement process of congestion surplus is distorted and the average cost on the generation side cannot reflect the price signal. This section intends to introduce the "congestion cost pool" to divert congestion surplus and solve two existing problems. The dredging strategy is shown in Fig. 1:

From Fig. 1, it can be seen that the flow of the unblocking surplus is as follows: first, consider calculating the clearing price on the power generation side under unconstrained conditions. Then, based on the average electricity price and the determined transmission and distribution electricity price, the load electricity price under unconstrained conditions is obtained. Secondly, construct a congestion cost pool based on the optimization results of congestion costs. Constructing an allocation index system based on congestion cost pool and correcting node transmission and distribution electricity prices. Finally, the final settlement electricity price of the output load node. On the one hand, by directly determining the initial settlement electricity price through the average pricing on the power generation side, and streamlining the allocation process of congestion surplus, it can avoid the return of medium and long-term congestion costs after congestion cost allocation. On the other hand, the construction of congestion cost pool can guide the price signal.

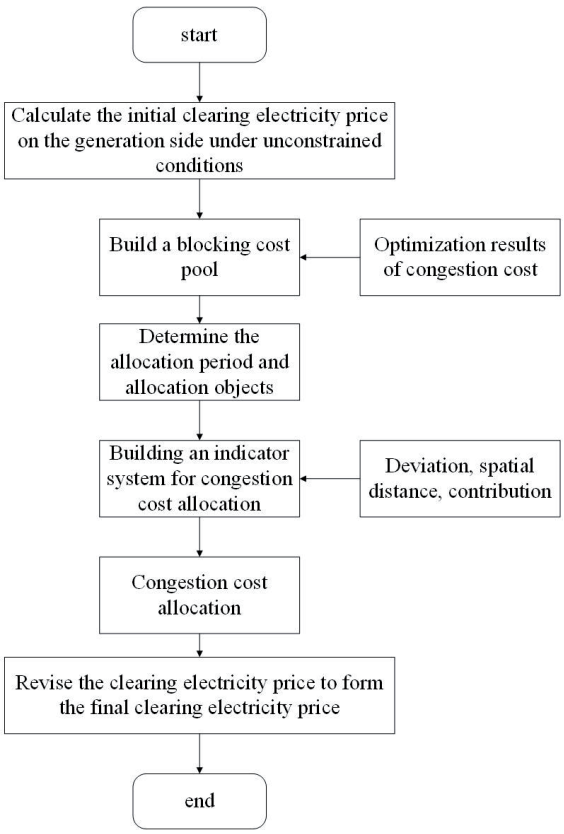


Fig. 1. Blocking surplus diversion strategy chart.

### *Initial Clearing Price on the Power Generation Side*

The clearance price is formed through unconstrained scheduling, which quotes the sending end generator units from low to high, and the units with low quotations are prioritized for clearance. The load demand of the receiving end is quoted from high to low, and users with high quoted load demand prioritize meeting it. Therefore, the low quoted unit and the high quoted load demand users reach a transaction, and the clearing price is the average value of the unit quotation and load quotation. This mechanism is in line with the principle of incentive compatibility. On the one hand, it encourages generator sets to quote low prices, which can reach transactions with high priced load demand users and improve profits. On the other hand, encouraging load demand users to quote high prices and be able to conclude transactions with low-priced power generation units. Through this clearing mechanism, the quotation of generator sets will reflect their own Cost of electricity by source as much as possible, while the load demand users will reflect their own power consumption cost as much as possible. Based on this, the generation side clearing price is formed as shown in Equation (3):

$$\overline{u}_{0,v}^{\text{clear}} = \frac{\overline{u}_v^{\text{ge}} + \overline{u}_v^{\text{load}}}{2} \tag{3}$$

where $\overline{u}_{0,v}^{\text{clear}}$ is the clearing price for the transaction reached in the v-th pair. $\overline{u}_v^{\text{ge}}$ is the generation side quotation for the v-th pair that reached the transaction. $\overline{u}_v^{\text{load}}$ is the load side quotation for the v-th pair to achieve the transaction.

### *Allocation Cycle and Allocation Objects*

Clarify that the allocation period for congestion costs is 1 hour, with balanced settlement conducted every hour and current allocation. Unbalanced settlement is conducted directly during each settlement cycle, so there is no need to establish a balance account for fund custody. The advantage of this method is that there is no need to establish a balance account, while the disadvantage is that each settlement cycle requires unbalanced cost calculation, which is relatively cumbersome in processing.

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The allocation targets are clearly defined as market-oriented users and market-oriented units, where market-oriented users (receiving area) refer to all market-oriented users participating in market transactions, and market-oriented units (sending area) refer to all units participating in market transactions.

*Allocation Indicator System*

When there is a deviation between the clearance demand of the receiving area and the actual demand, as well as the clearance supply of the sending area and the actual supply, it will lead to an increase in congestion costs. Therefore, deviation is introduced as one of the allocation indicators. The larger the deviation of the allocation object, the more congestion costs should be borne. The formula for calculating the deviation is shown in Equation (4):

$$\begin{cases} \Delta P_{j,t}^{\text{error}} = \left| P_{j,t}^{\text{ac}} - P_{j,t}^{\text{clear}} \right| \\ \Delta P_{i,t}^{\text{error}} = \left| P_{i,t}^{\text{ac}} - P_{i,t}^{\text{clear}} \right| \\ \Delta L_{s,t}^{\text{error}} = \left| L_{s,t}^{\text{ac}} - L_{s,t}^{\text{clear}} \right| \\ \Delta L_{h,t}^{\text{error}} = \left| L_{h,t}^{\text{ac}} - L_{h,t}^{\text{clear}} \right| \end{cases} \tag{4}$$

where $\Delta P_{j,t}^{\text{error}}$, $P_{j,t}^{\text{ac}}$ and $P_{j,t}^{\text{clear}}$ represents the deviation, actual supply, and clearance of unit j in the receiving area. $\Delta P_{i,t}^{\text{error}}$, $P_{i,t}^{\text{ac}}$ and $P_{i,t}^{\text{clear}}$ represents the deviation, actual supply, and clearance of unit i in the delivery area. $\Delta L_{s,t}^{\text{error}}$, $L_{s,t}^{\text{ac}}$ and $L_{s,t}^{\text{clear}}$ represents the deviation amount, actual demand amount, and clearance amount of users in the sending end area, respectively. $\Delta L_{h,t}^{\text{error}}$, $L_{h,t}^{\text{ac}}$ and $L_{h,t}^{\text{clear}}$ represents the deviation, actual demand, and clearance of user h in the receiving area.

The closer the distance between the sending unit and the receiving unit, the smaller the capacity of the transmission channel it occupies, and the smaller the congestion cost it needs to bear. Therefore, spatial distance is introduced as the second indicator for allocation, as shown in equation (5):

$$\begin{cases} D_i = \sum_{h \in H} \left( D_{io} - D_{ih} \right)^2 \cdot \sigma_{ih} \\ D_h = \sum_{i \in I} \left( D_{ho} - D_{hi} \right)^2 \cdot \sigma_{hi} \\ D_j = \sum_{s \in S} \left( D_{jo} - D_{js} \right)^2 \cdot \sigma_{js} \\ D_s = \sum_{j \in J} \left( D_{so} - D_{sj} \right)^2 \cdot \sigma_{sj} \end{cases} \tag{5}$$

where $D_i$ is the total spatial distance of the power transmission unit i at the sending end. $D_{io}$ is the initial spatial position of the sending end unit i. $D_{ih}$ is the spatial location where the sending unit i is sent to the receiving user h. $\sigma_{ih}$ is a boolean variable. If the sending unit i transmits electricity to the receiving user h, then $\sigma_{ih} = 1$, otherwise $\sigma_{ih} = 0$. $D_h$ is the total spatial distance of the receiving user h receiving electricity. $D_{ho}$ is the initial spatial position of the receiving user h. $D_{hi}$ is the spatial location of receiver group i for the receiving user h. $\sigma_{hi}$ is a Boolean variable. If the receiving user h receives the electricity from the sending unit i, i, $\sigma_{hi} = 1$, otherwise $\sigma_{hi} = 0$. $D_j$ is the total spatial distance of the power transmitted by the receiving unit j. $D_{jo}$ is the initial spatial position of the receiving unit j. $D_{js}$ is the spatial location where the receiving unit j is sent to the receiving user s. $\sigma_{js}$ is a boolean variable. If the receiving unit j transmits electricity to the sending user s, then $\sigma_{js} = 1$, otherwise $\sigma_{js} = 0$. $D_s$ is the total spatial distance received by the sending end user s for receiving electricity. $D_{so}$ is the total spatial distance received by the sending end user s for receiving electricity. $D_{sj}$ is the spatial position of the sender user s receiver group j. $\sigma_{sj}$ is a boolean variable. If the sending user s receives the electricity from the receiving unit j, then $\sigma_{sj} = 1$, otherwise $\sigma_{sj} = 0$.

When the unit provides more electricity and the user's load demand is higher, the impact on line congestion is greater, and the congestion cost it bears should also be greater. Therefore, contribution degree is introduced as the second indicator for allocation, as shown in Equation (6):

$$\begin{cases} \eta_{j,t} = \dfrac{P_{j,t}^{\text{ac}}}{P_{j,t}^{\text{ac}} + P_{i,t}^{\text{ac}} + L_{s,t}^{\text{ac}} + L_{h,t}^{\text{ac}}} \\ \eta_{i,t} = \dfrac{P_{i,t}^{\text{ac}}}{P_{j,t}^{\text{ac}} + P_{i,t}^{\text{ac}} + L_{s,t}^{\text{ac}} + L_{h,t}^{\text{ac}}} \\ \eta_{s,t} = \dfrac{L_{s,t}^{\text{ac}}}{P_{j,t}^{\text{ac}} + P_{i,t}^{\text{ac}} + L_{s,t}^{\text{ac}} + L_{h,t}^{\text{ac}}} \\ \eta_{h,t} = \dfrac{L_{h,t}^{\text{ac}}}{P_{j,t}^{\text{ac}} + P_{i,t}^{\text{ac}} + L_{s,t}^{\text{ac}} + L_{h,t}^{\text{ac}}} \end{cases} \tag{6}$$

where $\eta_{j,t}$, $\eta_{i,t}$, $\eta_{s,t}$ and $\eta_{h,t}$ represents the contribution of receiving unit j, sending unit i, sending user s, and receiving user h at time t.

*Congestion Cost Allocation*

Due to the fact that deviation, spatial distance, and contribution are all cost based indicators, equation (10) is used to standardize the three congestion allocation indicators:

$$\tilde{\theta}_o = \frac{\theta_{\max} - \theta_o}{\theta_{\max} - \theta_{\min}} \tag{7}$$

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where $\tilde{\theta}_o$ is the standardized treatment value of indicator o. $\theta_{\max}$ and $\theta_{\min}$ represent the maximum and minimum values of the indicator.

Based on equation (10), the standardized values of three types of indicators are obtained, and the comprehensive indicator values of the unit and user are shown in Equation (8):

$$\begin{cases} \beta_{j,t} = \omega_1 \Delta \tilde{P}_{j,t}^{\text{error}} + \omega_2 \tilde{D}_j + \omega_3 \tilde{\eta}_{j,t} \\ \beta_{i,t} = \omega_1 \Delta \tilde{P}_{i,t}^{\text{error}} + \omega_2 \tilde{D}_i + \omega_3 \tilde{\eta}_{i,t} \\ \beta_{s,t} = \omega_1 \Delta \tilde{L}_{s,t}^{\text{error}} + \omega_2 \tilde{D}_s + \omega_3 \tilde{\eta}_{s,t} \\ \beta_{h,t} = \omega_1 \Delta \tilde{L}_{h,t}^{\text{error}} + \omega_2 \tilde{D}_h + \omega_3 \tilde{\eta}_{h,t} \end{cases} \tag{8}$$

where $\beta_{j,t}$, $\beta_{i,t}$, $\beta_{s,t}$ and $\beta_{h,t}$ represents the comprehensive indicator values of receiving unit j, sending unit i, sending user s, and receiving user h at time t. $\tilde{}$ represents the standardized indicator value. $\omega_1$, $\omega_2$ and $\omega_3$ represents the weights of the indicators of deviation, spatial distance, and contribution, as shown in Equation (9):

$$\omega_1 + \omega_2 + \omega_3 = 1 \tag{9}$$

Based on the comprehensive indicator values of various units and users, the congestion cost allocation result is shown in Equation (10):

$$\begin{cases} C_{j,t}^{\text{ce}} = \left( \dfrac{\beta_{j,t}}{\beta_{j,t} + \beta_{i,t} + \beta_{s,t} + \beta_{h,t}} \right) \cdot C_t^{\text{ce}} \\ C_{i,t}^{\text{ce}} = \left( \dfrac{\beta_{i,t}}{\beta_{j,t} + \beta_{i,t} + \beta_{s,t} + \beta_{h,t}} \right) \cdot C_t^{\text{ce}} \\ C_{s,t}^{\text{ce}} = \left( \dfrac{\beta_{s,t}}{\beta_{j,t} + \beta_{i,t} + \beta_{s,t} + \beta_{h,t}} \right) \cdot C_t^{\text{ce}} \\ C_{h,t}^{\text{ce}} = \left( \dfrac{\beta_{h,t}}{\beta_{j,t} + \beta_{i,t} + \beta_{s,t} + \beta_{h,t}} \right) \cdot C_t^{\text{ce}} \end{cases} \tag{10}$$

where $C_{j,t}^{\text{ce}}$, $C_{i,t}^{\text{ce}}$, $C_{s,t}^{\text{ce}}$ and $C_{h,t}^{\text{ce}}$ represents the congestion allocation costs of the receiving unit j, the sending unit i, the sending user s, and the receiving user h at time t.

*Final Clearing Price on the Power Generation Side*

Based on the clearing results of congestion costs, the clearing results of various units and users are obtained as shown in Equation (11):

$$\begin{cases} \overline{u}_{zz,t,j}^{\text{clear}} = \overline{u}_{0,v}^{\text{clear}} - \dfrac{C_{j,t}^{\text{ce}}}{P_{j,t}^{\text{ac}}} \\ \overline{u}_{zz,t,i}^{\text{clear}} = \overline{u}_{0,v}^{\text{clear}} - \dfrac{C_{i,t}^{\text{ce}}}{P_{i,t}^{\text{ac}}} \\ \overline{u}_{zz,t,\text{s}}^{\text{clear}} = \overline{u}_{0,v}^{\text{clear}} + \dfrac{C_{s,t}^{\text{ce}}}{L_{s,t}^{\text{ac}}} \\ \overline{u}_{zz,t,\text{h}}^{\text{clear}} = \overline{u}_{0,v}^{\text{clear}} + \dfrac{C_{h,t}^{\text{ce}}}{L_{h,t}^{\text{ac}}} \end{cases} \tag{11}$$

where $\overline{u}_{zz,t,j}^{\text{clear}}$, $\overline{u}_{zz,t,i}^{\text{clear}}$, $\overline{u}_{zz,t,\text{s}}^{\text{clear}}$ and $\overline{u}_{zz,t,\text{h}}^{\text{clear}}$ represents the final clearance results of receiving unit j, sending unit i, sending user s, and receiving user h at time t.

## Optimization Strategy for Blocking Risk

According to the market steady-state mechanism, financial transmission rights are introduced to optimize congestion risk. The transmission right proposed in this paper includes two markets. In the primary market, market participants bid to obtain the financial transmission right. Participants holding financial transmission rights in the secondary market can freely trade with other participants. The transaction process of the secondary market is shown in Fig. 2.

Both the primary market and the secondary market are composed of registration, declaration, matching and clearing. In the primary market, first of all, market participants across regions and provinces register in the transmission rights market system and fill in their own nodes and other relevant information. Then, market participants declare the demand and price of transmission rights based on their own transmission capacity needs. Secondly, the system operator matches the winning bidder of the transmission rights to maximize efficiency based on the application situation of market participants. Finally, the clearing price of the Primary market is formed and the clearing results are settled.

In the Secondary market, first of all, the participants who win the bid in the Primary market and other participants who want to trade in the Secondary market register in the Secondary market and fill in relevant information. Then participants declare their purchasing and selling needs and prices; Secondly, the system operator matches the purchasing and selling parties to reach a transaction. Finally, a clearing pass in the Secondary market will be formed and the clearing results will be settled.

On the one hand, due to the large number of participants in the primary and secondary markets, transactions between participants are negotiated by the trading center, and participants do not need to pay information search costs. On the other hand,

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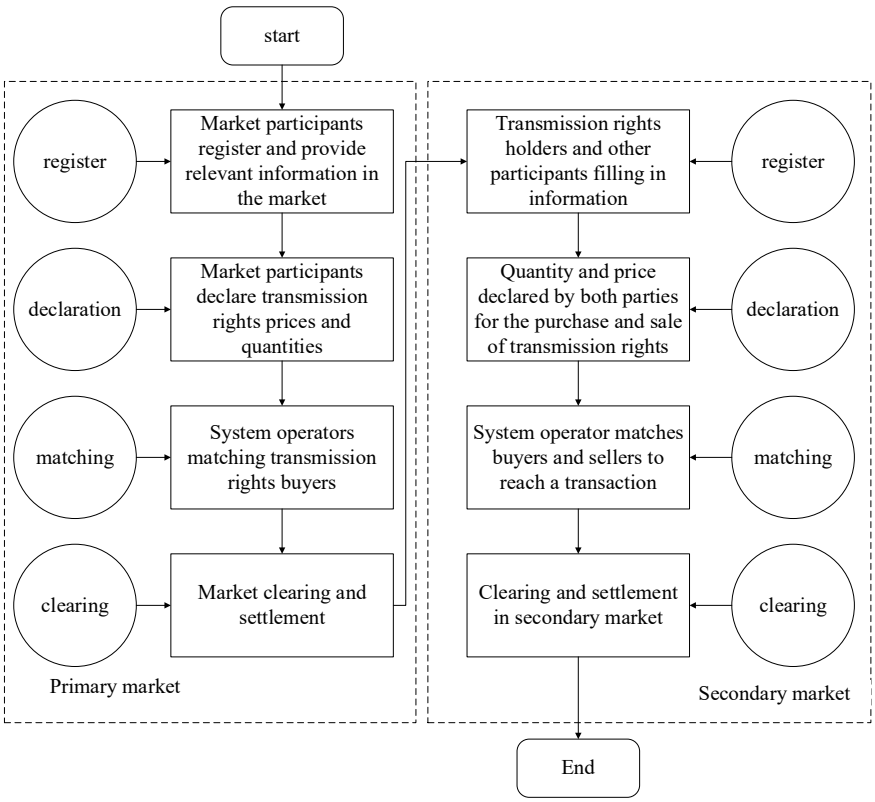


Fig. 2. Two level market transaction process.

participants' transactions are conducted on the market trading organization platform, without the need to pay platform costs. Therefore, it is assumed that the transaction cost of participants in the primary and secondary markets is 0.

*Primary Market Optimization Strategy*

1) Optimization strategy of market participants in primary market

In the primary market, market participants declare their own needs and prices to maximize benefits, as shown in Equation (12):

$$\max R_{1v} = \max \sum_{t=1}^{T_v} \left[ Q_{1v,t}^{\mathrm{tr}} \cdot \overline{p}_{\mathrm{ex},v,t}^{\mathrm{LMP}} - Q_{1v,t}^{\mathrm{tr}} \cdot \overline{p}_{\mathrm{de},v,t}^{\mathrm{tr}} \right] \tag{12}$$

where $R_{1v}$ represents the returns of market participant v in the primary transmission rights market. $T_v$ is the holding period of transmission rights for market participant v. $Q_{1v,t}^{\mathrm{tr}}$ is the declared volume of market participant v in the Primary market at time t. $\overline{p}_{\mathrm{ex},v,t}^{\mathrm{LMP}}$ is the expected benefit of unit transmission rights for market participant v at time t. $\overline{p}_{\mathrm{de},v,t}^{\mathrm{tr}}$ is the declared unit transmission rights price of market participant v at time t.

The declaration capacity of market participants in the primary market cannot exceed their maximum declaration capacity, as shown in Equation (13):

$$0 \le Q_{1v,t}^{\mathrm{tr}} \le Q_{1v,\max}^{\mathrm{tr}} \tag{13}$$

where $Q_{1v,\max}^{\mathrm{tr}}$ is the maximum declared capacity of market participants.

2) Primary market system operator optimization strategy

Rank the transmission rights prices declared by market participants from high to low, and obtain the order of declared prices as $\left[ \overline{p}_{\mathrm{de},1,t}^{\mathrm{tr'}}, \overline{p}_{\mathrm{de},2,t}^{\mathrm{tr'}}, \cdots, \overline{p}_{\mathrm{de},v,t}^{\mathrm{tr'}}, \cdots, \overline{p}_{\mathrm{de},\mathrm{V},t}^{\mathrm{tr'}} \right]$. Where, $\overline{p}_{\mathrm{de},v,t}^{\mathrm{tr'}}$ is the unit transmission right price ranked in the v position at time t, and the declared price of the market participant who purchased the last unit transmission right is taken as the clearing price of the primary market. The system operator takes the maximization of revenue as the objective function to form the clearing volume of the primary market, as shown in Equation (14):

$$\max R_{1,\mathrm{so}}^{\mathrm{total}} = \max \sum_{t=1}^{T_v} \sum_{v=1}^{V} Q_{1v,t}^{\mathrm{clear}} \cdot \overline{p}_{\mathrm{clear},t}^{1,\mathrm{tr}} \tag{14}$$

where $R_{1,\mathrm{so}}^{\mathrm{total}}$ represents the revenue of the system operator in the primary transmission rights market. $Q_{1v,t}^{\mathrm{clear}}$ and $\overline{p}_{\mathrm{clear},t}^{1,\mathrm{tr}}$ represents the clearing volume and clearing price of market participant v at time t in the primary transmission rights market.

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The overall clearing capacity of all participants cannot exceed the maximum existing transmission capacity, as shown in Equation (15):

$$0 \le \sum_{v=1}^{V} Q_{1v,t}^{\text{clear}} \le Q_{\text{total}}^{\text{so}} \tag{15}$$

where $Q_{\text{total}}^{\text{so}}$ is the maximum transmission capacity.

*Secondary Market Optimization Strategy*

1) Optimization strategy of market participants in secondary market

In the Secondary market, if the participants are buyers, the optimization strategy is consistent with Equation (12) in the Primary market. If the participants are sellers of transmission rights, the optimization strategy is to maximize the revenue from selling rights in the secondary market and the revenue from purchasing rights in the primary market, as shown in Equation (16):

$$\max R_{2v} = \max \sum_{t=1}^{T_v} \left[ Q_{2v,t}^{\text{sale}} \cdot \left( \overline{p}_{\text{sale},t}^{2,\text{tr}} - \overline{p}_{\text{clear},t}^{1,\text{tr}} \right) \right] \tag{16}$$

where $R_{2v}$ is the income of participant v from selling transmission rights in the Secondary market. $Q_{2v,t}^{\text{sale}}$ and $\overline{p}_{\text{sale},t}^{2,\text{tr}}$ is the sales volume and selling price of the transmission right of participant v at time t in the Secondary market.

The sales volume of market participants in the Secondary market shall not exceed their bid winning volume in the Primary market, as shown in Equation (17):

$$0 \le Q_{2v,t}^{\text{sale}} \le Q_{1v,t}^{\text{clear}} \tag{17}$$

2) Secondary market operator optimization strategy

In the secondary market, the system operator takes the maximum system benefit as the objective function to match the buyers and sellers of transmission rights to reach a transaction, as shown in Equation (18):

$$\max R_{2,\text{so}}^{\text{total}} = \sum_{s \in \boldsymbol{S}} \sum_{b \in \boldsymbol{B}} \sum_{t=1}^{T_v} \left[ \begin{pmatrix} \overline{p}_{\text{sale},s,t}^{2,\text{tr}} + \overline{p}_{\text{buy},b,t}^{2,\text{tr}} \\ -p_{\text{clear},t}^{2,\text{tr}} \end{pmatrix} \cdot Q_{2,t}^{\text{clear}} \right] \tag{18}$$

where $R_{2,\text{so}}^{\text{total}}$ is the social benefits of system operators in the secondary market. $\overline{p}_{\text{sale},s,t}^{2,\text{tr}}$ is the declared price of seller s at time t in the secondary market. $\overline{p}_{\text{buy},b,t}^{2,\text{tr}}$ is the declared price of buyer b at time t in the Secondary market. $p_{\text{clear},t}^{2,\text{tr}}$ is the clearing price of the secondary market. $Q_{2v,t}^{\text{clear}}$ is the clearing volume of the Secondary market. $\boldsymbol{S}$ is a collection of sellers and sellers. $\boldsymbol{B}$ is a collection of buyers.

The clearing price of the Secondary market is the average of the declared price of the seller and the declared price of the buyer, as shown in Equation (19):

$$p_{\text{clear},t}^{2,\text{tr}} = \frac{\overline{p}_{\text{sale},s,t}^{2,\text{tr}} + \overline{p}_{\text{buy},b,t}^{2,\text{tr}}}{2} \tag{19}$$

The total clearing amount in the secondary market cannot exceed the total clearing amount in the primary market, as shown in Equation (20):

$$0 \le \sum_{v=1}^{V} Q_{1v,t}^{\text{clear}} \le Q_{2,t}^{\text{clear}} \tag{20}$$

## Solving Process

The overall solution process for congestion management optimization is shown in Fig. 3:

Step 1: Based on channel constraints, unit constraints, and demand response constraints, a congestion cost optimization strategy is used to solve and minimize the congestion cost.

Step 2: Calculate the initial clearance electricity price, and further allocate the minimum congestion cost

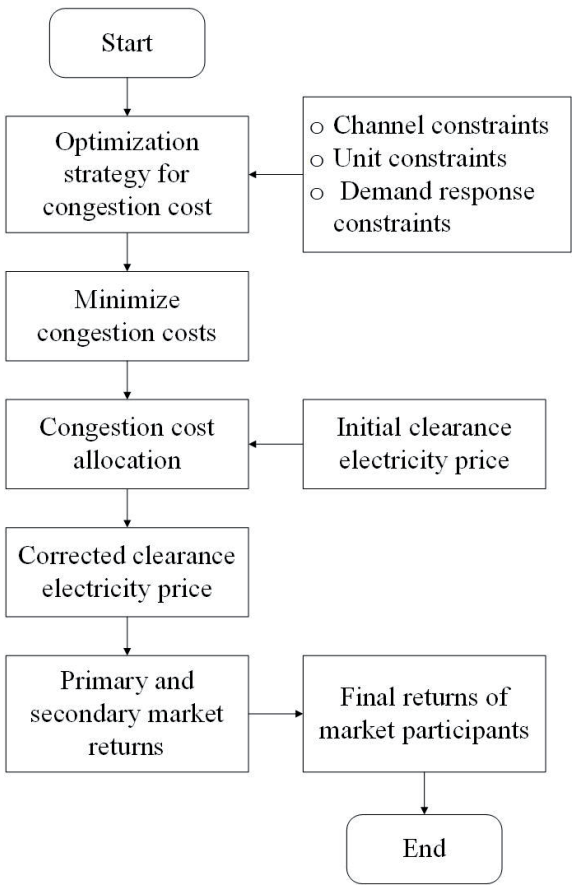


Fig. 3. Solving process.

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based on deviation, spatial distance, and contribution allocation indicators. Solve the congestion surplus diversion results and correct the initial clearing electricity price;

Step 3: Solve the congestion risk optimization model, obtain the returns of market participants in the primary and secondary markets, and combine with the corrected clearing electricity price to obtain the final returns of market participants.

## Results and Discussion

### Basic Data

This paper conducts empirical analysis using a province in western China as the sending end and a province in eastern China as the receiving end. The sending end is met by wind turbine 1 and wind turbine 2 to meet the load needs of selling users 1 and 2. This paper does not consider the scenario of reverse power transmission from the receiving end to the transmitting end, therefore, it does not involve the receiving end's units and the transmitting end's users. The maximum capacity of the transmission channel between the sending end and the receiving end is set to be 6000kW. In case of congestion, the unit output cost of adjusting the output of the thermal power generating units in other areas is 0.389 yuan/kWh, the Unit demand response compensation cost is 0.405 yuan/kWh, the unit wind and light rejection cost is 0.276 yuan/kWh, and the unit load shedding cost is 0.217 yuan/kWh [34-36]. The output range of wind turbine 1 is [05000kW], and the output range of wind turbine 2 is [06000kW]. The maximum call volume for demand response is 70kW, and the maximum call volume for thermal power generation units is 600kW. The requirements of user 1 and user 2 in the receiving area are shown in Fig. 4 [37]:

The supply of wind turbine 1 and wind turbine 2 in the power supply area is shown in Fig. 5 [38, 39]:

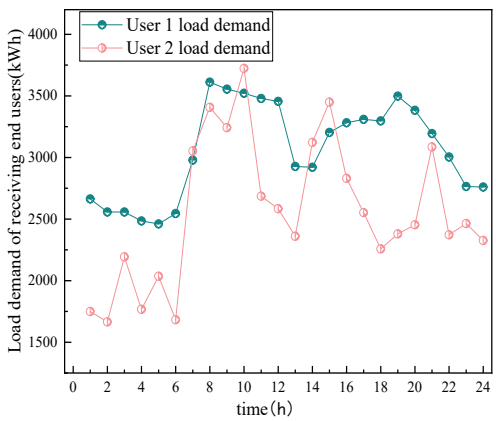


Fig. 4. User load demand in the receiving area.

### Result Analysis

#### *Optimization Results of Congestion Cost*

Based on the required transmission capacity of the sender and receiver, as well as the existing transmission capacity of the system, the blocking capacity for each time period is obtained as shown in Fig. 6.

From Fig. 5, it can be seen that the blocking capacity of the system occurs during periods of 7:00-12:00, 14:00-16:00, and 21:00. Due to high load demand and high wind power output during these periods, the transmission demand exceeds the existing transmission capacity limit of 6000kW. Based on the blocking capacity and the blocking cost optimization strategy proposed in Section 3.1 of this article, the blocking management optimization strategy is obtained as shown in Fig. 7:

From Fig. 6, it can be seen that the blocking problem during time periods such as 7:00, 11:00, 12:00, 14:00, 16:00, and 22:00 is resolved by calling thermal power generation in other regions, as the blocking capacity during these time periods does not exceed the upper limit of thermal power generation regulation. The blocking problem at 15:00 is jointly met by calling

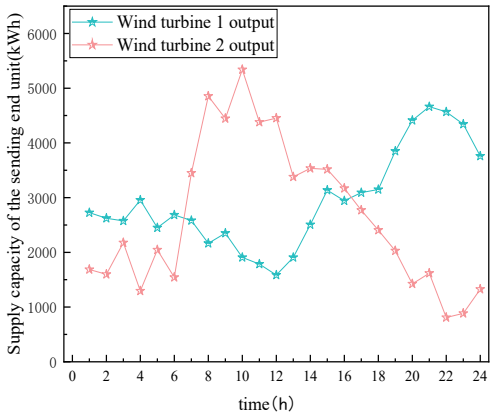


Fig. 5. Supply of wind turbines in the power supply area.

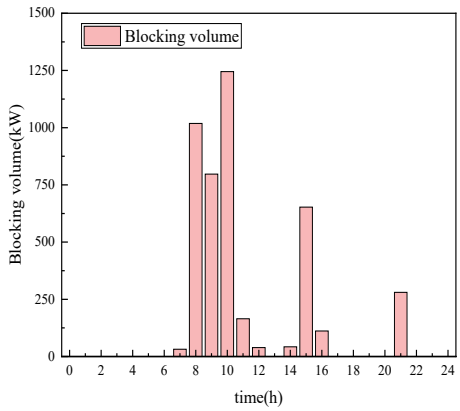


Fig. 6. Blocking capacity at each time period.

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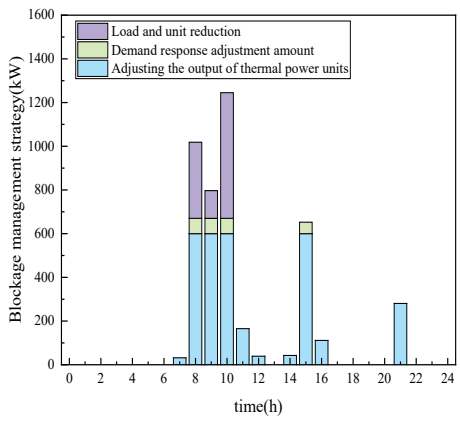


Fig. 7. Optimization strategy for blockage management.

the demand response and other thermal power units in other regions, because the blocking capacity during this time period has exceeded the upper limit of the thermal power unit regulation, and the demand response needs to be called to solve the remaining blocking capacity. The blocking problem during time periods such as 8:00 to 10:00 is solved by calling for demand response, thermal power generation units, and reducing the demand of the receiving end. This is mainly because during this period of severe blocking, both thermal power generation units and demand response have exceeded the upper limit of regulation, and ATC needs to apply the reduction method to compensate for the remaining blocking capacity. From this, it can be found that when optimizing congestion management, the priority order of various strategies is to call other regions' thermal power generation>call demand response>reduce the demand of the receiving end. This is mainly because the cost of calling other regions' thermal power generation is lower than other methods. From an economic perspective, other regions' thermal power generation will be prioritized to solve the congestion problem.

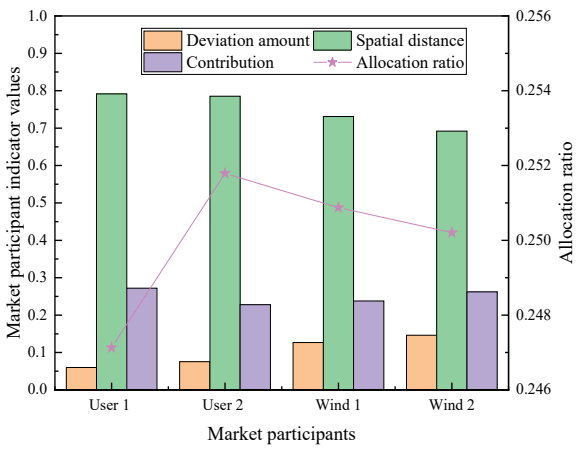


Fig. 8. Index values and allocation ratios of each market participant.

*Blocking Surplus Diversion Results*

According to the congestion cost allocation index system constructed in section 3.2, calculate the values of wind turbine 1, wind turbine 2, user 1, and user 2 indicators. Set the weights of contribution, deviation, and spatial distance to one-third, and calculate the congestion cost allocation ratio for market participants. As shown in Fig. 8.

From Fig. 7, it can be seen that in terms of deviation performance, the minimum deviation for User 1 is 6%, and the maximum deviation for Wind Turbine 2 is 14.63%. In terms of spatial distance performance, the maximum spatial distance for user 1 is 0.7917, while the minimum spatial distance for wind turbine 2 is 0.6921. In terms of contribution, User 1 has a maximum contribution of 0.2722, while User 2 has a minimum contribution of 0.2278. The size of the allocation ratio is 0.2518 for User 2>0.2509 for Wind Turbine 1>0.2502 for Wind Turbine 2>0.2471 for User 1, indicating that User 1 has the smallest allocation ratio for congestion costs. This may be because User 1's deviation is much smaller than other market participants, and under the same weight, User 1's superior deviation performance allows User 1 to bear lower congestion costs. User 2 bears the highest proportion of congestion costs, mainly because it performs mediocrely in various indicators.

Set the initial clearing result on the power generation side to 0.6084, and based on the allocation ratio, obtain the congestion costs that each market participant needs to bear at each time. This is used to correct the initial clearing result and obtain the final clearing price of the unit and user, as shown in Fig. 9.

As shown in Fig. 8, there are differences in clearing prices among market participants during the time periods of 7:00, 11:00, 12:00, 14:00, 16:00, and 22:00 when congestion capacity occurs. On the one hand, compared to other time periods, the clearance prices of wind turbine 1 and wind turbine 2 during the period of congestion capacity have decreased, indicating that during the period of congestion capacity, the efficiency of the generator unit has decreased. Compared to

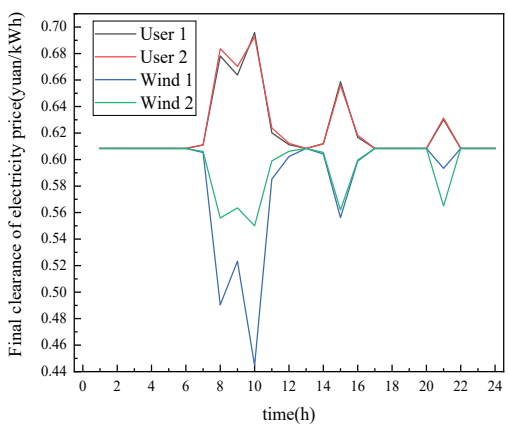


Fig. 9. Final clearing price for each market participant.

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Table 3. Declared volume and price in the primary market.

| | User 1 load demand | User 2 load demand | Wind turbine 1 output | Wind turbine 2 output |
|---|---|---|---|---|
| Declaration volume (kW) | 3611 | 3723 | 4662 | 5339 |
| Declaration price (yuan/kW) | 0.0063 | 0.0073 | 0.0065 | 0.0069 |

other time periods, the clearing prices of users 1 and 2 during the period of congestion capacity increase, indicating that during the period of congestion capacity, the electricity cost of users increases. By reducing the efficiency of generator sets and increasing the cost of electricity consumption for users, it is possible to determine whether congestion occurs during the time period. On the other hand, during the period of severe congestion from 8:00 to 10:00, the adjustment of clearing prices by market participants is higher than that of other time periods.

*Optimization Results of Blocking Risk*

According to the congestion surplus dredging results of Wind 1, Wind 2, User 1 and User 2, in order to hedge the congestion risk, market participants are allowed to apply for bidding transmission rights in the Primary market of transmission rights. The declared volume and declared price of each participant in the primary market are shown in Table 3.

From Table 3, it can be seen that User 2 has the highest declared price, mainly because User 2 shares more congestion costs in the congestion surplus. Compared to User 1 and other units, User 2 is more motivated to participate in the primary and secondary markets. Therefore, the system operator will give priority to User 2 winning the bid of 3723 kW when matching and clearing. The overall transmission rights of the system operator are 6000 kW, and based on the upper limit of transmission rights trading, the remaining 2277 kW will be included in the bid for wind turbines with higher declared prices. Therefore, the clearing result in the Primary market is shown in Table 4, and it is calculated that the total revenue of the system operator in the Primary market is 42.89 yuan.

In the secondary market, bidders in the primary market may sell the transmission rights they have won, while users 1 and wind turbines 1 who have not won the bid in the primary market may buy the transmission rights they have sold. The declared volume and declared price of each participant in the Secondary market are shown in Table 5 in combination with their own benefit function. A negative declared quantity represents the quantity of transmission rights sold, while a positive declared quantity represents the quantity of transmission rights purchased.

As can be seen from Table 5, User 1 and Wind 1 predict that the probability of future congestion is relatively high, so they will increase the declared price in the Secondary market to purchase the transmission right. User 2 and Wind 2 predict that the probability of future congestion is small, and declare in the secondary market at a price higher than the clearing price in the Primary market to obtain the market price difference. Arrange user 1 and unit 1 of the buyer in descending order of quotation, and user 2 and unit 2 of the seller in descending order of quotation. The seller with lower price shall have priority in entering into transactions with the buyer with higher price, and the average declared price between the buyer and seller shall be used as the clearing price. The clearance results are shown in Table 6.

From Table 6, it can be seen that User 1 purchased 1719 kW of transmission rights from Wind 2, and the clearance price for both was 0.0079 yuan/kW. Wind 1 purchases transmission rights of 723 kW and 2162 kW from Wind 2 and User 2, respectively, with a clearance price of 0.0078 yuan/kWh for wind turbine

Table 4. Clearing results in the primary market.

| | User 2 load demand | Wind turbine 2 output |
|---|---|---|
| Declaration volume (kW) | 3723 | 5339 |
| Declaration price (yuan/kW) | 0.0073 | 0.0069 |

Table 5. Declared volume and price of secondary market.

| | User 1 load demand | User 2 load demand | Wind turbine 1 output | Wind turbine 2 output |
|---|---|---|---|---|
| Declaration volume (kW) | 1719 | -2400 | 2885 | -2442 |
| Declaration price (yuan/kW) | 0.0081 | 0.0083 | 0.0079 | 0.0077 |

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Table 6. Secondary market clearance.

| | User 1 load demand | User 2 load demand | Wind turbine 1 output | Wind turbine 2 output |
|---|---|---|---|---|
| User 1 load demand(kW) | — | 0 | 0 | 1719 |
| User 2 load demand(kW) | 0 | — | -2162 | 0 |
| Wind turbine 1 output(kW) | | 2162 | — | 723 |
| Wind turbine 2 output(kW) | -1719 | — | -723 | — |

2 nd 0.0081 yuan/kWh for User 2. In the secondary market, the overall situation is that supply exceeds demand, so the transmission purchase demand of user 1 and Wind 1 is met, but the supply capacity of Wind 1 with high declared price is still surplus.

*Validity Analysis*

1) Effectiveness analysis of congestion cost optimization strategy

In response to the optimization of congestion costs by considering the rescheduling method and ATC reduction method proposed in this article, in order to verify the effectiveness of this method, three scenarios are set as follows:

Scenario 1: Using only the rescheduling method for congestion cost optimization;

Scenario 2: Using only ATC reduction method for congestion cost optimization;

Scenario 3: Balancing the rescheduling method and ATC reduction method for congestion cost optimization, which is the method proposed in this article.

Based on the above three scenarios, using congestion cost as an evaluation indicator, the congestion costs under the three scenarios are shown in Fig. 10.

From Fig. 10, it can be seen that the blocking costs under the three scenarios are 1968.15 yuan, 2161.02 yuan, and 1818.62 yuan, respectively. Scenario 3 has the lowest blocking cost. Compared to Scenario 3, Scenario 1 and Scenario 2 have increased their congestion costs by 8.22% and 18.83%, respectively. This is mainly because scenario 1 using only the rescheduling method may result in high unit adjustment costs and demand response call costs. However, using only the ATC reduction method will result in high costs of wind and photovoltaic abandonment and load shedding. Scenario 3, which combines ATC reduction method and rescheduling method, can fully allocate scheduling resources in the system and achieve optimal configuration efficiency, indicating that Scenario 3 is more effective in reducing congestion costs compared to other scenarios.

2) Analysis of the effectiveness of blocking surplus diversion strategies

This paper establishes a congestion cost pool for direct allocation and constructs a multidimensional allocation indicator system to channel congestion surplus. To verify the effectiveness of this method, three scenarios are set up as follows:

Scenario 1: Using the traditional unblocking method to unblock congestion surplus, that is, first allocating congestion costs, and returning them to the user when the allocation results deviate from the actual costs;

Scenario 2: Establish a congestion cost pool for direct allocation, using contribution as a single allocation indicator;

Scenario 3: Establish a congestion cost pool for direct allocation, and construct multidimensional allocation indicators for contribution, spatial distance, and deviation, which is the method proposed in this article.

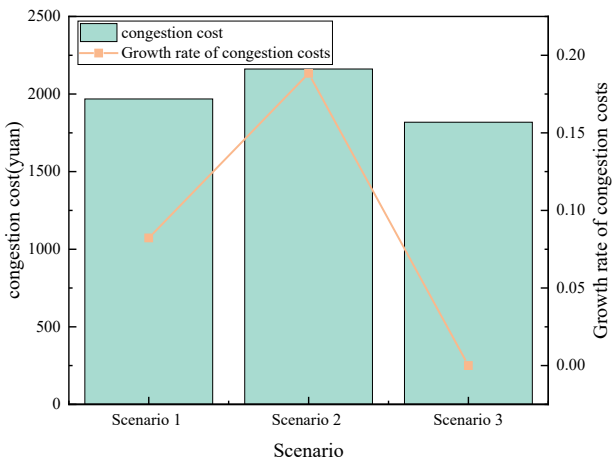


Fig. 10. Blocking costs in three scenarios.

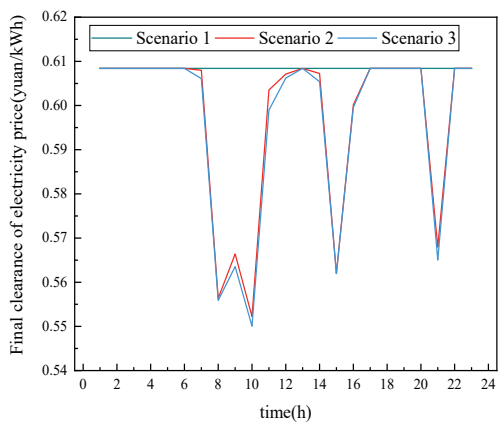


Fig. 11. Final clearance electricity prices for three scenarios.

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Table 7. Systematic and social Benefits of three scenarios.

| | System benefits (yuan) | Social benefits (yuan) | Total benefit (yuan) |
|---|---|---|---|
| Scenario 1 | 0 | 0 | 0 |
| Scenario 2 | 17.5024 | 0 | 17.5024 |
| Scenario 3 | 42.8894 | 4.0993 | 46.9887 |

Based on the above three scenarios, the final clearance price of wind turbine unit 2 is taken as the research object, and the market price guidance of the above three scenarios is compared, as shown in Fig. 11.

From Fig. 11, it can be seen that in scenario 1, regardless of whether it is a blocking period or a non blocking period, the final clearance electricity price is 0.6084 yuan/kWh, indicating that the difference between blocking and non blocking periods cannot be reflected through allocation and return. The market price during the blocking period in scenario 2 is lower than the market price during the non blocking period. Although it can serve as a blocking signal guide, compared to Scenario 3, the price during the blocking period is still higher than scenario 3. This is mainly because Scenario 2 only considers contribution and does not take into account the significant output deviation in Scenario 2, resulting in a smaller actual congestion cost that should be borne by Wind Turbine Unit 2 in Scenario 2. Based on this, it indicates the effectiveness of establishing a congestion cost pool and multi-dimensional allocation indicators.

3) Effectiveness analysis of congestion risk optimization strategies

This paper constructs a transmission rights trading hedging congestion risk based on a two-level market. To verify the effectiveness of this method, three scenarios are set up as follows:

Scenario 1: In congestion management, the construction of a transmission rights market is not considered to hedge congestion risks;

Scenario 2: Consider hedging congestion risk in the transmission rights market, but only constructing a primary bidding market;

Scenario 3: Consider hedging congestion risk in the transmission rights market and construct a two-level market, with the first level being a bidding market and the second level being a two-way market.

Based on the above three scenarios, the effectiveness of the above three scenarios is compared using system benefits and social benefits as evaluation indicators, as shown in Table 7.

From Table 7, it can be seen that scenario 1 without constructing a transmission rights market has a total benefit of 0, while scenario 2 with considering a primary bidding market has a total benefit of 17.5024 yuan, which is much lower than scenario 3 with constructing a secondary market. This is mainly because there is no secondary two-way trading market, and market participants cannot transfer or purchase after bidding, which will lead to more conservative bidding strategies of market participants in the primary market, reduce the declared price of market participants in the primary market, and thus reduce the system efficiency. This indicates that constructing a two-level market for transmission rights trading can enhance the enthusiasm of participants in the primary bidding market and the overall efficiency of system operators.

## Conclusions

Based on the existing congestion management mechanisms, this article proposes optimization strategies for congestion management from three aspects: congestion cost optimization, congestion surplus diversion, and con-gestion risk optimization. A numerical analysis is conducted using a certain western and eastern province in China as an example. The calculation results show that:

1) When optimizing congestion costs, the priority order of various strategies is to call other regions for thermal power generation>call demand response>reduce demand at the receiving end, because calling other regions for thermal power generation has higher economic efficiency.

2) Balancing ATC reduction method and rescheduling method for congestion cost optimization can fully allocate scheduling resources in the system and achieve optimal configuration efficiency.

3) Establishing a congestion cost pool and multi-dimensional allocation index based congestion surplus diversion strategy can not only guide congestion signals, but also fully reflect the real congestion costs that the unit and users should bear.

4) Building a two-level market for transmission rights trading to hedge congestion risks can enhance the enthusiasm of participants in the primary bidding market and the overall efficiency of system operators.

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## Conflict of Interest

The authors declare no conflict of interest.

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