Review of Research on Electric Energy Market Clearing Model

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Abstract. In recent years, the construction of China's electricity market has achieved many results, and the market transaction volume and the proportion of clean energy consumption have increased significantly. With the expansion of the market size and the scope of the main player, the establishment of a clearing model for the electric energy market has been fully studied. This paper first introduces the current research status of foreign clearing models, and then according to the development trend of the electric energy market in the process of new electricity reformation, it summarizes and combs the electricity market clearing models under various market members and different scenarios by domestic scholars in recent years. Finally, it puts forward suggestions and prospects for the research of the future market clearing model, hoping to provide reference for future research.

1. Introduction

In 2015, since the Central Committee of the Communist Party of China and the State Council issued the "Opinions on Further Deepening the Reformation of the Electricity Power System" ([2015] No. 9), a new round of electricity market construction has been accelerating[1]. Subsequently, a number of supporting documents for reformation were issued one after another, continuing to promote the process of "new electricity reformation", and initially completed the top-level design of the current round of electricity market, trying to build a medium and long-term transaction to avoid risks, spot transactions to find prices, optimize resource allocation, an electricity market system with complete varieties, complete functions, sufficient competition, and orderly development. At present, the construction of China's electricity market is still in its infancy, and the subject matter of the transaction is mainly electric energy. As one of the trading rules of the electric energy market, market clearing[2-3] plays an extremely important role. The establishment of its model is the core issue of market clearing, which is related to the economics of power system operation and reliability. It has a direct impact on transaction prices.

The electric energy market clearing model is a model in which the power generation side and the power consumption side will quickly reach the equilibrium of supply and demand under the adjustment of the price mechanism. It can clearly reflect the supply and demand relationship between...
the purchase and sale of electricity and the process of clearing the electricity energy market, so that both purchase and sale of electricity reduce operating costs and transmission costs, and promoting the maximization of social welfare based on the premise of meeting system constraints, unit constraints and network constraints. In recent years, the development trend of China's electric energy market is mainly reflected in the following aspects: In terms of time, a market system and trading mechanism close to actual operating conditions have been established, and the trading cycle has been continuously shortened[4]. Spatially, cross-regional and cross-provincial large-scale market construction is accelerated to promote the optional allocation of national resources[5]. The trading players are constantly enriched and diversified to promote clean energy consumption[6]. Therefore, the process of clearing the electricity energy market is relatively complicated, and multiple market participants and different scenarios need to be considered. A reasonably designed clearing model is a strong support for the construction of China's electricity market. When considering long-distance AC and DC transmission, fluctuations in renewable energy, and flexible resource access on the demand side, the price should be adjusted in time to balance the supply and demand of both parties, and promote market competition, which is very important for power generation companies, power grid companies and users.

In the context of the reform of the electricity market, the paper draws on the experience and research results of established foreign electricity energy markets and clearing models, and summarizes the researches of Chinese experts and scholars on electricity energy market clearing models. This paper first introduces the development status of European and American PJM electric energy market clearing models. Then, it briefly introduces the development of China's electric energy market clearing models. After that, according to the development status of China's electric energy market in the process of "new electricity reformation", the inter-provincial clearing model, the intra-provincial clearing model and the inter-provincial coupling clearing model were summarized. At the same time, it summarizes the research on clearing models of different market participants. Finally, it puts forward suggestions and prospects for the research of the future market clearing model, which can provide reference for my country's future market construction.

2. Current status of foreign market clearing models

For a long time, domestic and foreign scholars have done detailed research on the electric energy market clearing model. Due to the different development process, the domestic and foreign market clearing models are also different. The current typical foreign market clearing models are represented by the European electricity market[7] and the American PJM electricity market[8].

2.1. European electricity market

The European electricity market is a large-scale transnational electricity market[9], which realizes cross-border joint clearing through market coupling and implements a unified joint clearing model. Since 2006, in order to achieve cross-regional and large-scale cross-border power transactions, the European unified market requires its internal countries and regions to fully integrate the original market in the day-ahead market. The measure is to develop a price coupling of regions[10-11] (PCR), so that in the manner of trading rotation in various regions, various quotations in various regions are collectively coupled and cleared, and the mechanism of regional electricity prices[12] is used to form clearing prices in various price zones. At present, the PCR project only completes the coupling of the day-ahead electricity market. One of its key elements is the construction of a unified electricity price joint clearing algorithm to calculate the power flow and electricity price. The algorithm is called the EUPHEMIA[13-14] (Pan-European hybrid electricity market integration algorithm). EUPHERMIA algorithm deals with standards and more complex quotation types to meet all needs. Its goal is to quickly find a good first solution, and continue to work hard to improve and increase social welfare. It has no strict restrictions on the market, quotation, and network constraints. The same kind of quotations submitted by all participants are treated equally[15]. The EUPHEMIA algorithm uses the available transfer capacity (ATC) model to calculate cross-regional capacity allocation in the initial
stage. In 2015, it began to use the flow-based market coupling (FBMC) model to calculate cross-regional capacity allocation. It is an alternative publishing method for ATC network constraints. It aggregates the power transfer distribution factor (PTDF) matrix and converts the linear relationship between the line power flow and the injected power of each node into the linear relationship between the line power flow and the injected power of each area[16-17]. In addition, the FBMC model does not consider the transmission power limit of all lines, and only considers the key lines most likely to be affected by cross-regional transactions. It is expected that all PCR projects will adopt the FBMC model in the fourth quarter of 2020[18]. Reference [19] proposed a new type of market clearing model based on exchange and FBMC, which expressed the included condition mechanism as an intuitive clearing problem without modifying any parameters (such as power transfer distribution factor).

2.2. The American PJM Electricity Market
The American PJM electricity market is a typical regional electricity market[20]. The unit composition and economic dispatch model based on security constraints are used internally for market optimization and clearing, and the locational marginal price (LMP) mechanism is adopted[21]. LMP determines the market price. The market trading center uses the minimum operating cost power flow calculation model to formulate the scheduling plan for each period of the next day of the system according to the quotations of market members and the constraints of system security and transmission capacity, and calculates the LMP of each bus in the system during each period. It is a measure of the energy value of a certain node at this moment in the current system operation state. This pricing method provides users with economic signals, promotes market competition, and realizes its own benefits. Reference [22] adopts the nodal marginal electricity price model. When the load cluster increases, the power generation cost is the smallest. The model is implemented under the three conditions of unconstrained, transmission restriction and loss.

In a word, the European unified market only needs to simply consider the capacity constraints of the inter-regional connection line during the clearing process, and the requirements for the clearing model have not been greatly increased as the market scale expands. In contrast, the centralized and optimized clearing model adopted by the American regional electricity market needs to consider the physical parameters of each node in the network and unit operating parameters. As the market scale continues to grow, clearing models need to consider a large number of nodes and units.

3. Current Status of China's Market Clearing Model
China's electric energy market clearing model is different from Europe and the United States. Early, the domestic electricity market was mainly based on the regional electricity market, and the provincial power grid companies as the main transaction players would participate in the purchase of electric energy and complete a considerable proportion of the transaction volume[23-24]. Under the electricity market environment, the domestic traditional power generation plan is transformed into the calculation of power transactions between buyers and sellers. This is the market clearing. Traditional power generation plans are aimed at minimizing the cost of power generation, while in the electricity market, the objective function is to minimize the total power purchase cost, considering constraints such as grid power balance and unit power. The basic principle of the traditional electricity market transaction clearing model to determine the successful bidders and power generators is the high-low matching of market transactions[25-26,28]. Buyers are ranked according to the quotation from high to low, and sellers are ranked according to the quotation. There are priorities in descending order, and the transaction price is the average value of the quotations of both parties. Afterwards, most of them adopt unified clearing[27]. Under certain constraint conditions, the power generation load is allocated according to the order of the quotation of the power generation company or unit, and the last quotation of the power generation company or unit that meets the system load balance is the system marginal price. All traded electric energy is settled according to the system marginal price. Reference [28] takes regional electricity market transactions as a background, designs and establishes a regional electricity market transaction matching model that considers trans-provincial transmission transaction costs.

In
[29], on the basis of meeting the requirements of safe and stable operation of the power grid, considering the loss of transmission lines across provinces, a regional power grid clearing model based on matching replacement of unit coal consumption levels is given. Reference [30] proposed a market clearing model based on an improved genetic algorithm. The settlement rules are settled according to the unified marginal cost of the grid, and the unit startup and shutdown costs and electricity costs are separately settled, and the objective function is the lowest power purchase cost. The above clearing model is simple, considering fewer constraints. Market rules, market participants, transaction scale, transaction varieties, etc. are not perfect, which lacks consideration of the overall study of the electricity market.

With the advancement of China’s electricity market construction, the market scale and scope have gradually expanded, and the development of inter-provincial electricity markets has led to a diversified development of market participants. The traditional power generation planning model has changed. Fig.1 shows the schematic diagram of the clearing model modelling. It is necessary to comprehensively consider power balance, unit operating characteristics, grid security and other constraints, with the goal of minimizing the cost of the power generation side or maximizing the benefits of the whole society, the use of security constrained unit commitment[31] (SCUC) and security constrained economical dispatch[32] (SCED) method for clearing modeling.

![Fig.1 Schematic diagram of clearing model modeling](image)

In the process of new electricity reformation, domestic research scholars have carried out a lot of research on the market clearing model of electric energy, mainly based on two aspects of market space and market participants. Therefore, the third part mainly summarizes the inter-province market independent clearing model and the coupled clearing model, and the fourth part summarizes the domestic research on the clearing model of different market participants.

4. Inter-provincial and Intra-provincial Markets Clearing Model
In the new round of electricity reformation, the development of China’s electricity market started with the “two-level operation” of the inter-provincial and intra-provincial markets. Among them, the inter-provincial market is mainly based on medium and long-term contracts, and at the same time, it is developing the incremental spot transaction for renewable energy to meet the needs of a large-scale allocation of resources. Intra-provincial market has gradually transitioned from a medium- and long-term transaction-based development stage to a spot market-based development stage, mainly to ensure the optimal allocation of resources in the province, the balance of power and electricity supply and demand, and the order of safe power supply[33-34]. With reference to the current research status of various scholars on inter-provincial market clearing, the clearing model is divided into inter-provincial market clearing model, intra-provincial market clearing model and inter-provincial coupling clearing model.

4.1. Inter-provincial Market Clearing Model
With the full commissioning of UHV AC and DC projects, the AC grid structure of the power grid is gradually strengthened, and the scale of DC transmission continues to grow[35-36]. At present, most
of the inter-provincial transaction paths are composed of "AC channel + DC channel + AC channel" [37]. For this reason, when modeling the inter-provincial clearing model, based on considering basic constraints such as power balance and grid security and combing the operating characteristics of the AC/DC hybrid power grid, the inter-provincial market clearing model is improved and supplemented in terms of power optimization of AC and DC tie lines, processing of tie line loss, simplification of inter-provincial channel models, and modelling of power flow interface. Reference [38] extracts the key lines of the existing UHV AC/DC hybrid power grid. Based on the key section information, key node information and the sensitivity of the node to the key section, according to the node clustering method under the two transaction modes of power generation/load nodes directly participating in inter-provincial transactions and provincial grid agent power generation/load nodes participating in inter-provincial transactions, a physical network simplified model of inter-provincial transactions is constructed. The model takes the maximization of social welfare as the goal, considers the grid security constraints, and establishes an optimal settlement model for inter-provincial transactions that takes into account the available transmission capacity. Reference [39] combined with the provincial-level power spot market clearing model, focusing on constructing a regional power grid spot market clearing model including the security constrained unit commitment, security constrained economical dispatch and node electricity price model. The model is essentially a complex multi-constraint mixed integer nonlinear model. In the modeling process, various nonlinear factors are appropriately and acceptably linearized according to their physical characteristics.

4.2. Intra-provincial Market Clearing Model
The electricity markets in all provinces of China are designed according to the conditions of the province, so the electricity market clearing in the province shows a certain diversity, and the clearing models are different. At present, the spot market in 8 pilot provinces in China is trial operation[40]. In terms of medium and long-term trading and spot market coordination mechanisms, for the decomposition of medium and long-term electricity in the province, most pilot provinces stipulate that the decomposition curve is financial in nature, and a few pilot provinces stipulate that the decomposition curve is physical. The curve decomposition should consider some factors such as grid congestion, transmission cross-section and the maturity of market participants. In terms of the spot market model, most of the pilot provinces adopt a centralized market model, and the clearing model is more complicated, and the solution to the optimization model is demanding. Some pilot provinces adopt a decentralized model, and the clearing model has high requirements on the grid. Regarding the spot market pricing mechanism, the pilot regions mostly adopt the node electricity price pricing mechanism on the power generation side, and the weighted average pricing mechanism of node electricity prices on the user side. The clearing model considers congestion and various equipment constraints. In terms of spot market composition, all pilot provinces have introduced day-ahead and real-time markets, and some provinces have introduced intra-day markets. The clearing model should consider the physical model, and some clearing results will also be implemented physically. Reference [41] established a multi-day unit portfolio optimization model with the lowest total system power generation cost as the goal under the provincial power spot market environment, and set the optimization result as the boundary condition of the day-ahead market clearing model to achieve the effective connection between the multi-day unit combination and the day-ahead clearing link.

4.3. Inter-provincial Coupling Clearing Model
In the above-mentioned inter-provincial market clearing model, the province is the unit, and the whole province is equivalent to a single node. This means that the inter-provincial market clearing model does not fully consider the impact of inter-provincial transactions on the intra-provincial market. The clearing model also does not consider the impact of intra-provincial AC channels on inter-provincial transactions. Fig.2 is a schematic diagram of the modeling of the inter-provincial market coupling clearing model. In order to realize the optimal allocation of power resources on a large scale and promote the coordinated development of inter-province and intra-province, the coupling clearing of
inter-provincial and intra-provincial markets should be considered in market construction. Scholars have studied the inter-provincial coupling clearing model. Reference [42] proposes an inter-provincial and intra-provincial dual-level optimal clearing model for medium and long-term markets and day-ahead markets. The first layer is an optimal allocation model of inter-provincial transaction resources that considers the available transmission capacity of the AC/DC hybrid grid. The purpose is to achieve the optimal social surplus, consider the transmission cost of the cross-regional DC channel. The clearing algorithm of the inter-provincial and intraprovincial two-level optimization model is divided into three stages, which are hierarchical clearing mode, loosely coupled clearing optimized model, and tightly coupled clearing optimized model. Reference [43] proposed a two-layer nonlinear optimization model, which takes the intra-provincial electricity market and the inter-provincial electricity market transaction clearing as the upper and lower problems of the model, and the upper layer of the model aims at minimizing the expected operating cost of the provincial market to optimize inter-provincial power purchase demand, and lower-level optimizes inter-provincial operating costs.

5. Market Clearing Model Based on Different Market participants

With the increase of market participants in the construction of the electricity market, market transactions are diversified and transactions become more frequent. The main body of the power generation sides market includes clean energy units[44] to achieve large-scale consumption of clean energy. User-side market participants include distributed energy[45-46], microgrids[47], virtual power plants[48], electric vehicle[49-50], energy storage[51], etc. These diversified new small and micro market participants widely access, and gradually expand the number and scale of participation in the electric energy market transactions. The clearing models for the differences in purchase and sales demand of these market members have been fully studied. The following introduces various clearing models from the power generation-side market participants and the user-side market participants.

5.1. The Market Clearing Model Based on The Power Generation Side

After years of river basin development, China has built many cascade hydropower stations, and the reform of electricity marketization will make the ladder hydropower to compete with other types of resources. The Reference [52-53] first considers the power constraints, and then carries out the average period method of power transfer within the basin according to the upstream and downstream hydraulic coupling relationship. It expresses the downstream bid-winning electricity as a linear function of the upstream power station's bid-winning electricity and embed it in the clearing model, so as to realize the dry season method that the downstream power station can purchase the full amount of power generation. The model is constructed to minimize the power purchase cost from the perspective of market operation. In the process of clearing, preliminary optimization results are obtained through the security constrained unit commitment model for all generating units, and then the security constrained economic dispatch model is used to adjust the power transfer within the basin.
After wind power and photovoltaics are connected to the grid on a large scale, their randomness and uncertainty will affect the balance of supply and demand in the electricity market. The traditional day-ahead market clearing is usually carried out under a deterministic analysis framework\[54-55\], so clearing models considering wind power and photovoltaics are also difficult to establish. Reference \[55\] established a full-power model for wind turbines, and studied the clearing model of renewable energy participation in the day-ahead market based on cost minimization. Reference \[56\] uses forecast errors to describe the uncertainty of wind turbine output and load, and uses Latin hypercube sampling method to generate random scene sets. With the goal of low power purchase cost, high reliability of power supply, and maximum wind power consumption, the unit output, reserve capacity, wind abandonment and load loss are selected as decision variables, and AC power equation constraints are considered to establish a day-ahead electricity market clearing model.

### 5.2. The Market Clearing Model Based on The User side

Users are equipped with distributed power equipment such as wind power and photovoltaics, which can not only meet their own electricity demand, but the excess electricity can also be bid on the Internet\[57\] to obtain a certain profit. Reference \[58\] established a day-ahead and real-time balanced two-stage electricity market clearing model, and established a two-tier optimization model for distributed energy parks to participate in this market. Reference \[59\] considers the power transaction with the participation of new wind and solar storage players, and adopts blockchain technology\[60\] to propose a multi-party transaction clearing model in the electricity market that considers low-carbon benefits and comprehensive social benefits.

In the study of the electricity market clearing model with the participation of microgrids, in order to make the operation of microgrids more flexible, Reference \[61-62\] assumes that the microgrids with abundant electricity and conventional energy have their agents for power generation based on the environmental protection characteristics of microgrids. Around the participation of micro-grid agent generators and conventional power agent generators in the bidding trading market, a new electricity market clearing model that takes into account low-carbon benefits is proposed.

Compared with traditional power generation units, virtual power plants contain multiple flexible resources such as new energy equipment, energy storage devices, and active users\[63-64\]. In order to promote the integration of virtual power plants into the operation of the electricity market, some scholars have studied the matching them clearing model and pricing method. Reference \[65\] establishes the quotation function model of each entity based on the marginal quotation of traditional power producers and virtual power plants and the marginal revenue of electricity sellers, and uses the piecewise linearization method to linearize the continuous quotation function to obtain the piecewise quotation function model. Bring it into the proposed electricity market clearing model under the open environment of the retail side, and get the clearing result. Reference \[66\] takes into account the virtual power plant participant bidding model, line power flow and node voltage safety constraints, and aims at minimizing the operation and regulation costs of all market participants in the distribution system, and proposes a distribution-side market suitable for virtual power plants joint clearing model, which can realize joint optimization and coordinated pricing of multiple types of electricity market products.

Electric vehicle in the market can be used as both a load and as a power output. When they are connected to the grid as a load, they may increase the marginal electricity price of nodes, and as a power source, they may alleviate the peak electricity price when they are connected to the grid during peak electricity prices. Therefore, the access of electric vehicle affects the price of electricity. In recent years, scholars have also studied the clearing model of electric vehicle. Reference \[67\] constructs a marginal electricity price market clearing model with electric vehicle load scenarios. In reference to the decision-making problem of participating in the day-ahead energy market, the Reference \[68\] regards electric vehicle aggregators as price influencers, and establishes a two-layer model of day-ahead operation optimization and day-ahead market clearing. The upper model uses electric vehicle aggregators to minimize day-ahead purchases. Electricity cost is the goal, considering the driving characteristics of electric vehicles in the jurisdiction and the constraints of the physical characteristics.
of batteries. With the goal of maximizing social welfare, the lower level simulates the clearing process of the energy market before the day.

6. Suggestions and Prospects for Research on Electric Energy Market Clearing Model

In the future, in terms of academic research and market practice, the research on the electric energy market clearing model is still a problem worthy of continuous exploration and development. This section summarizes the problems that will be faced in the research of the clearing model from three aspects, and puts forward corresponding suggestions.

First, on the one hand, the national cross-regional transmission capacity has been strengthened, and the complexity and calculation of the inter-provincial and intra-provincial market clearing model have been significantly increased, making it difficult to meet the needs of inter-provincial and intra-provincial transactions. It is necessary to introduce and select reasonable methods to model the power of AC and DC tie lines, cross-sectional power flow, etc., and establish an optimized clearing model. On the other hand, the inter-province coupling clearing model can consider a joint clearing model to promote global optimization.

Second, large-scale grid connection of new energy units introduces more randomness and uncertainty. The research on the clearing model of new energy units mainly considers the uncertainties of new energy, risk constraints, and the income of generators. In order to improve the feasibility of the clearing plan, the clearing model should also consider factors such as system reliability, network loss and power quality.

Third, in view of the integration of multiple flexible resources into the power system, market participants are diversified. Various market participants should clarify the primary tasks and hierarchical relationships, and their market clearing model should consider multiple power products and take all products into consideration. The coupling relationship of each market entity is tapped to promote the long-term economic development.

7. Conclusion

In the process of electricity market construction, in order to ensure the economy and reliability of the system and promote the optimal allocation of resources, the establishment of a clearing model for the electricity energy market is essential. The paper introduces the development status of European and American PJM electricity market clearing models, analyzes the differences between these two foreign clearing models, introduces the development status of China’s electricity market clearing models, and summarizes the research on the inter-provincial clearing model, the intra-provincial clearing model, the inter-provincial and intra-provincial coupling clearing model and the research on the clearing model of different market participants in the process of new power reformation. Finally, it puts forward suggestions and prospects for the research of the future market clearing model, which can provide reference for my country's future market construction.

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