Review of Congestion Management Methods for Power Systems

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Abstract. With the acceleration of China's new power reform, the grid congestion problem has become more and more prominent. It has been a hot spot of power industry that studying on the appropriate grid congestion management method of electricity market in every country or region, for ensuring the safe and economic operation of the power system. In recent years, many great researches have been published on grid congestion management. This paper reviews the literature on grid congestion management through two aspects: transmission network congestion and distribution network congestion. Besides, dynamic congestion, congestion pricing and congestion allocation are described by summarizing various publications. Finally based on the reviews of the existing methods for grid congestion, recommendations for transmission and distribution congestion management methods that are suitable for Chinese electricity are suggested market in the end.

1. Introduction

Currently, the power industry is at the stage of the transformation from a traditional monolithic regulated public utilities to a competitive market. Deregulation and introduction of competition have become the general trend in the development of electric power industry all over the world \cite{1}. With the In-depth reformation and the continuous development of the electricity market in China, major trading participants presents diversified trends. Besides, the varieties and methods of transactions are increasing under the circumstance of competition in the electricity market. The operating environment of the transmission network is becoming more and more complex because of the opening of the transmission grid and increasing proportion of trans-regional and inter-provincial power trading, which leads to increasingly prominent problems of transmission congestion in China. In addition, with the widespread access of renewable energy and large-scale flexible loads, as well as the maximization of participants and interests of power production or consumption behavior, which may result in excessive centralization of distribution network flow in time and space. It is that distribution network congestion problems arise from \cite{2}.

The occurrence of congestion will not only affect the safe and stable operation of the power network, but also have a significant impact on grid pricing and power plant bidding strategies \cite{3}. Grid congestion management is a kind of indispensable mechanism to ensure the safety of power systems and the orderly competition in the power market. Besides, it can provide economic signals for optimizing power supply construction and grid layout \cite{4}.

Grid congestion is caused by the contradiction between the grid network capacity and plans of the grid transmission or distribution \cite{5}. Extensive studies have been carried out to determine the best congestion management methods, suitable congestion pricing mechanisms, reasonable congestion cost allocation and equitable ways to deal with congestion surplus in different operating modes. But the
work of various publications used to focus on transmission network congestion. In recent years, the studying on the congestion of distribution networks have been gradually arousing the attention of scholars. In this paper, grid congestion management is reviewed from two aspects of transmission and distribution network. Of which, the transmission congestion management methods are divided into two major types of technical methods and market methods. Based on the characteristics of transmission network, the technology is mainly aimed at the application of transformer tap/phase shifter and FACTS technology in congestion management.

Market methods include congestion correction or system rescheduling (reducing trading contracts and transmission plans, increasing and decreasing generator output, load shedding and implementing interruptible load rights), and congestion price setting (based on OPF real-time electricity price/node price mechanism or its simplified mode - regional electricity price mechanism), including Flow-Gate Right. The review of congestion management methods for distribution network can be grouped into two categories: direct control methods and Indirect control methods (market-based methods). Direct control methods are comprised of distribution network reconfiguration, removal of loads, reduction of distributed power output, reactive power control and active power control. Indirect control methods consist of dynamic cost method, distributed capacity market, shadow price and flexible service market. Apart from the review of the power system congestion problem on both the transmission network and the distribution network, this paper briefly surveys the dynamic management congestion, congestion pricing and congestion cost allocation.

2. Transmission grid congestion management
In the electricity market, different methods are used to comprehensively deal with the transmission congestion for different electricity market models of different countries and regions. In literature [4], the research on congestion management at home and abroad was summarized, the close relationship between congestion management and market trading mode, market transaction scope, dynamic congestion management and congestion pricing was expounded in different classification. However, the congestion management caused by the optimization and control of network parameters using the FACTS device was not discussed. Transmission congestion management methods were classified as Figure 1 in this paper.

![Figure 1. Management method of transmission congestion](image)

2.1. Transmission Congestion Management Method Based on Technical Means
The physical characteristics of the network should be taken into consideration firstly when it comes to the ways of eliminating congestion because the transmission congestion is caused by the contradiction between the network transmission capacity and the transmission plan. From a long-term perspective, improving the transmission capacity of the network is the most fundamental solution to congestion problem.
At present, there are two main technical methods for improving the transmission capacity, one is to make full use of the resources of the existing network. E.g.: adjusting the transformer tap/phase shifter or installing the FACTS device to adjust the network parameters, and the other is to increase the appropriate investment in the power grid, expand or build some new lines. All above methods aimed at changing the network flow by adjusting the network structure and controller parameters to eliminate congestion, to avoid the change of power generation plan and the resulting congestion costs, so that the power generation scheme is optimal.

Among the technical means, researches about FACTS device is the most. The FACTS device has characteristics of responding rapidly and regulating system parameters and currents, so it can effectively improve system transmission capacity, reduce network loss, and improve system stability. Literature [12] proposes a calculation model for the maximum transmission capacity considering common FACTS devices (such as UPFC, TCPS, TCSC, etc.). The optimal installation location of the FACTS device is discussed in [6-8]. The optimal control strategy of FACTS devices is studied in [9-13]. Literatures [14-16] evaluate the application of FACTS devices in obstruction management.

2.2. Transmission Congestion Management Method Based on Market Means

Physical and technical methods are limited by factors such as equipment performance and capital investment, as well as geographic environment. At the same time, when the transmission system cannot meet the desired transmission plan, under the conditions of fair competition and resource optimization, with the purpose of the economy, many governments establish a competition mechanism and adopt price means to adjust the reduction or increase of the transaction volume, thereby reducing the overload line power flow. The congestion management method based on the electricity market economy has been widely used in domestic and international power systems. Any congestion management mechanism in electricity market must face how to guide market participants to adjust their power generation injection and power load. This is a key issue in the design of power market mechanism. Because of it, this paper divides the congestion management methods based on market means two types:

One is congestion correction method (system rescheduling), and the other is congestion price setting method, which can also be called nodal pricing mechanism or its simplified mode-zonal pricing mechanism. The most important feature of the two methods is whether the network security constraints are considered when the market clears out.

2.2.1. Methods of Congestion Correction. There are two stages when congestion correction method is adopted. Market clearing without grid security constraints should be carried out in the first stage, then, transmission system operator (TSO) judges whether power flow corresponding to the result of electricity market clearing causes transmission congestion. If there is transmission congestion, then the market operator adjusts the power generation plan (or electricity plan) formed by the generator (or user) in the first unconstrained clearing in the next stage. The UK power market congestion management is a typical representative of this method. The counter-trading of congestion management in the Nordic power market is also part of this approach.

Study [17] proposes a model for real-time congestion management using sensitivity analysis. When congestion occurs in the system, TSO can adjust the power generation output or load that has the greatest influence on the congestion line, according to the sensitivity of the injection power and the branch power flow, thereby effectively eliminating congestion. This method adopts measures such as partial inversion and sparse vector method for the real-time requirements of congestion management and the characteristics of congestion only related to local power grid. Achieving a viable operational solution quickly and efficiently. In the paper [18], the line power flow sensitivity method is improved. Considering the multiple line congestion conditions, the generator with the highest sensitivity is selected to adjust the output or reduce the load with the highest sensitivity. Literature [19] discusses the different price elasticity levels of different users, introduces the electricity price as the power-off threshold price when the consumer’s profit is zero. When the transmission congestion occurs, TSO can
schedule users’ power generation according to the power-off threshold price from low to high, and the interruptible load can get some compensation from it. This method regulates the relationship between supply and demand in the electricity market, so that users can avoid the risk of high-priced electricity and alleviate the transmission congestion in the system.

2.2.2. Method of Congestion Price Setting. The congestion price setting method considers cyber security constraints when the market clears, restricts the power trading of market members, and only the power transactions that can produce feasible trends are allowed. Once the transmission congestion is present, the market clearing prices of the different nodes are different to reflect the different costs that meet the new load requirements at different nodes. Nodal pricing mechanism are used in most of the US electricity market, such as the US PJM, New York, New England, California, Texas and other power markets. The Australian national electricity market is a typical representative of regional electricity prices, it will gradually transition to nodal pricing mechanism in the future.

Firstly, the optimal tidal current (OPF, Optimal power flow) is the most studied in the congestion management of the electricity market. Literature [20] proposed a method to realize congestion scheduling control in the electricity market by nonlinear interior point algorithm of optimal power flow. The method takes the minimum increase of electricity purchase cost as the objective function, considers the factors such as system active balance, line capacity limitation and generator climbing rate, and uses the nonlinear internal point method to achieve the congestion control in the electricity market. It solves the problem that the step-jump quotation curve is difficult to be derivative, besides, it obtains the optimal scheduling plan with economy and security. In paper [21], the optimal power flow problem of a large system is decomposed into multiple regions by using lagrangian relaxation decomposition method. Combined with the sequential quadratic optimization parallel computing algorithm, the power generation scheduling in the region can be optimized with the dispatch coordination between the regions, eliminating the transmission congestion between regions. This method is fast and has high accuracy, which improves the reliability of the power system.

The nodal pricing mechanism originates from literature [22] that proposes the concept of real-time electricity price, which reflects the real-time production cost of the system and the supply and demand relationship of the market. The power system self-regulates through real-time price signals that take safety and economic operational constraints into account.

Reference [23] describes the process of congestion management using the nodal pricing method in the PJM power market in the United States, indicating the role that location marginal pricing (LMP) and fixed transmission rights (FTR) plays in congestion management in the PJM power market. Nodal pricing method and cost sharing method are compared, and the characteristics of the two are analysed. The advantages of PJM congestion management method are shown in this paper, which are based on nodal marginal price, physically significance is obvious, the introduction of FTR can protect its holder from the influence of electricity price fluctuation caused by line congestion, it also shows the economic signal of investment.

In literature [24], the price of each node is decomposed in detail. It is considered that the node price can correspond to the conditions of power generation constraint, transmission capacity constraint and voltage constraint. The node price information is beneficial to improve the operating efficiency of the power system. the node price information is beneficial to improve the operation efficiency of power system, and it is an effective congestion management method, which provides economic signals for the investment of power generation and transmission. However, under the nodal pricing method, the fluctuation degree of electricity price is relatively large. Furthermore, the congestion surplus will be generated.

Literature [25] suggests that the transmission plug surplus should be used to alleviate the line congestion. It combines with the characteristics of the congestion line shadow price and the user demand price elasticity coefficient, along with introduces the node marginal price-re-scheduling cost influence factor, as a basis for measuring the impact of node price changes on system rescheduling costs. On the base of this, the paper puts forward a reward voucher mechanism for user response in the
real-time market by using the day-ahead congestion surplus as a source of funds, which encourages users to change their electricity usage plans and actively shift the load to the low valley period, to effectively alleviate or even eliminate the transmission congestion in the real-time market.

To avoid the risk of transmission congestion, Transmission rights can be divided into two categories: physical transmission rights and financial transmission rights.

The concept of Flow-Gate Right (FGR) is present firstly in literature [26]. Flow-Gate Right define specific time periods, paths, and directions, besides, the right to use the transmission capacity of the transmission and distribution port has been allocated by FGR. The key issue of FGR is to match the transaction with the actual generated power flow, which is generally solved by the power flow distribution coefficient based on DC current. Instead of considering all the lines in the network, it defines a set of possible critical paths with congestion based on the network topology and system operating conditions, and only settles the congestion costs of the critical paths. The physical transmission rights are applicable to the electricity market that allows physical bilateral transactions, and traders can arrange energy trading plans according to their own transmission rights to avoid price risks. However, due to the large number of critical paths with congestion, and the power transmission distribution coefficients will change with the running state of the line, the physical transmission power is more complicated in practical applications. The concept of financial transmission rights is first proposed by literature [27], which is based on the real time electricity price theory and allocates the congestion surplus with the power transmission capacity. It overcomes the shortage of contract path rights, that is, the network externality caused by the circulation, which is defined between nodes and nodes, and does not have to consider the tradable transmission power of the internal structure of the network. Financial transmission rights are a purely financial instrument, with no capacity limits and no restrictions on the amount of transmission [28].

2.3. Dynamic Congestion Management

When the power system is subjected to large disturbances and enters the dynamic process, if the power of electricity traded in the power market cannot guarantee the dynamic stability of the system at this time, then dynamic congestion is caused, and the corresponding scheduling means for eliminating the congestion is also called dynamic congestion management. At present, the main methods of dynamic congestion management are divided into two types, one is to adjust through the system's control equipment, such as the FACTS device, the breaking road, etc. The other is to control the system's power flow mode, such as rescheduling method, trading plan adjustment. Due to the limitation of article length, the author elaborates the second method in detail in this paper.

The main problem of dynamic congestion management is how to incorporate the dynamic security constraints of the system into the optimal scheduling of ISO, how to make market members participate in dynamic congestion management, and how to measure the cost of dynamic congestion management.

Paper [29] presents a dynamic congestion management mode in the electricity market environment. In this model, market participants with different market attributes enter the dynamic congestion management market that is specifically set up in the real-time market, providing the services available at the time of dynamic congestion and corresponding quotations. When dynamic congestion occurs, ISO uses the resources available in the dynamic congestion management market to operate dynamic congestion management with the principle of minimizing the total dynamic congestion cost of the system. Study [30] adopts motion energy function method to find the key machine under specific faults, so that congestion is eliminated by scheduling the critical machines of the system. Literature [31] also proposed to eliminate the dynamic congestion management mode through the market mechanism. Literature [32] puts forward a dynamic congestion management model based on the joint venture trading model in the real-time electricity market. The model uses the optimal control principle to transform the power angle transient stability constraint into the active output constraint of the relevant unit, thus forming the optimal problem of dynamic congestion management. To solve this problem, the processing of the generator set in the system can be adjusted to achieve the lowest
electricity price. At the same time eliminate network congestion and ensure the safe operation of the system.

However, some of the above-mentioned literatures on dynamic congestion management not only adopt inappropriate transient stability assessment methods, but also do not reflect the influence of regulators on the market behaviours of power producers. The literatures [30, 32] simply rely on the preventive control method before the failure to eliminate the dynamic congestion. Literature [31] does not consider preventive control at all, relying only on emergency control after failure. Based on this document [33], the instability risk under working conditions resulted from predictive market clearing is defined as the product of fault probability and emergency control cost. The optimal emergency control is determined by search for the minimum value of risks. The risk assignment plan among the critical machines is announced in real time to guide the competing market participants to consider risk cost through rebidding. Bidding iterations give the point where minimum sum of market clearing price (MCP)-based purchasing cost and instability risk is obtained. It better coordinates the preventive control of the power market risk (congestion risk sharing) and the emergency control of the power system (cutting, load shedding).

The development of dynamic congestion management makes up for the shortcoming that the previous congestion management research only considers the constraint of line power flow. However, there are few research literatures on dynamic congestion management in recent years. In addition, researches on the allocation of dynamic congestion costs is also worthwhile.

3. Distribution network congestion management

Unconstrained or unguided power usage behaviour and unreasonable scheduling strategies may lead to problems of load spikes and congestion in the power distribution system, affecting the safety and economic operation of the power distribution system [34-35]. For the congestion problem of the distribution network, distribution system operator (DSO) usually adopts two methods to solve [36], direct control and indirect control.

3.1. Direct Control Method

Direct control methods include using network reconfiguration, cutting off loads, or reducing distributed power output [36-39]. The literatures [37-38] solve the congestion problem of the distribution network by the network reconstruction method. In paper [37], genetic algorithm is applied to determine the optimal network layout. Literature [38] proposes two defined factors to describe and quantify distribution network congestion, pointing out that DSO can force distributed generators to reduce power injection into the power grid in order to reduce distribution network congestion, or even shut down specific generators at a certain time. Literature [39] introduces two power flow management (PFM) approaches. One approach is modelled as a constraint satisfaction problem (CSP), while another is based on an optimal power flow (OPF) approach. In comparison with a traditional inter-trip approach typically used by distribution network operators, these PFM algorithms are deployed on real substation hardware. The two approaches to managing power flows can significantly increase the output of DG units in a thermally constrained network. The purpose of these methods is to alleviate line congestion by reducing the distributed power output.

3.2. Indirect Control Method

From the perspective of DOS, the adjustments of system operation mode often involve problems such as switching operation, ring current surge and so on. It is impossible to achieve continuous adjustment of the distribution line power flow in multiple periods, and it is difficult to meet the congestion management requirements under the conditions of large-scale renewable energy and flexible load access. Therefore, another indirect control method is needed. The market mechanism is adopted to adjust congestion problem of the system. Literature [40] adopts the capacity market method. The DSO verifies the user's reported power plan and sets the congestion cost according to the congestion level of the line. Then the user adjusts the power plan according to the congestion cost and reports the DSO
again. Papers [41-42] put forward the dynamic cost method, that is, DSO uses the node marginal electricity price to obtain the congestion cost reflecting the congestion of the distribution network. DSO releases the congestion cost to the user, and then solves the problem by the user responding to the congestion cost and changing the power consumption plan. Literature [43] proposes a market mechanism to circumvent system congestion. Firstly, the residential house model and the temperature control type controllable load model are introduced, besides, the charging and discharging load characteristics of electric vehicles are analyzed, and the resident load and electric vehicle load can be guided by market mechanism to optimize operation of the system under the precondition of satisfying electricity demand. After that, a mathematical model for determining congestion price using the optimal power flow method is constructed. According to scheduling result and congestion price, each agent adjusts the controllable load and the charging and discharging load arrangement of the electric vehicle on the premise of satisfying the user's electricity demand, avoid the load peak and the power distribution system congestion caused by centralized power consumption.

The combination of the direct control method and the indirect control method will have a better effect on the distribution network congestion management. An active distribution network congestion management method based on intelligent soft switch and market mechanism is proposed in Literature [2]. Considering the response characteristics of flexible loads under the market environment, a distribution network congestion management model based on intelligent soft switch and electricity price mechanism is established to solve the congestion problem of the active distribution network by combining the direct control method with the market regulation mechanism.

Distribution network congestion management has gradually attracted the attention of relevant scholars and power grid workers in recent years, and research on this issue will become a hot spot in a certain period time in the future.

4. Congestion pricing and congestion cost allocation

To solve congestion problem, it will inevitably cause additional congestion costs. It is essentially because the power transaction demand for power transmission capacity exceeds the capacity limit of the transmission network itself, so that the units with the original low price must reduce the electricity generation, transferred by the other units with high price, thereby increasing the electricity generation cost [4]. Congestion pricing is concerned with how much it is, and congestion cost allocation is concerned with how the cost is equitably shared among market participants. This paper classifies the congestion pricing and allocation method as the node price method and the cost allocation method.

4.1. Implicit Congestion Pricing and Cost Allocation

The implicit congestion pricing and cost allocation method is based on the OPF node price model. After the network is constrained, there are different prices in different node or area, and the generator and load are paid according to the node price. The cost is not reflected obviously, but implicitly shared by the payment node electricity price. In paper [44], the linear relationship between the marginal price of the node and the shadow price of the congestion cost is derived. According to the relationship between them, a linear mathematical model for calculating the marginal price of the node and the shadow price of the congestion cost in Pool mode or Pool and bilateral trading mode is established. This congestion pricing and allocation method is relatively simple. However, in literatures [45-47], some scholars have questioned the practicality and long-term economic stability of this method in a market with close system and many bilateral transactions. It is considered that when there are bilateral transactions in the market, the marginal price obtained by the nodal electricity price method can’t provide the correct position signal and doubts the fairness of the method. Besides, this approach will generate a trading surplus. This allows the ISO to take revenue in congestion management, which has an inverse incentive for congestion mitigation.

4.2. Explicit Congestion Pricing and Cost Allocation

Explicit congestion pricing and cost allocation method is to allocate congestion cost as an additional
cost to the market participants. The methods are mainly divided into two categories: the average allocation method and the responsibility allocation method. The average apportionment method is simple to calculate, but the distribution rules are rough and lack of fairness. The responsibility allocation rule is based on the unit's participation in congestion adjustment of the power generation cutting amount and the degree of utilization. In Literature [48], bilateral transactions allocate congestion cost based on the principle that the proportion to the amount of flow changes in congestion line before and after congestion is eliminated. The method of [49] allocation is to spread congestion cost to the congestion line, and then distribute the cost of congestion line to each transaction. For the dynamic congestion cost allocation method, literature [50] proposes a method of allocation of dynamic congestion cost. The method needs to calculate the contribution factors of each unit's output adjustment to each hazardous fault, and then weights the contribution factors to obtain the contribution of the unit to the transient stability of system, as well as allocating the dynamic congestion cost accordingly. However, the fairness of the above congestion allocation method remains to be discussed.

5. Conclusion
This paper makes a comprehensive summary of the research results of transmission resistance management in the power market environment. The grid congestion management is divided into three aspects: transmission network congestion, distribution network congestion, and congestion pricing and allocation. The congestion management has a wide range of connotations which is also very complex. It’s closely related to all aspects of market transactions and system operations. Due to article length limit, some side issues of transmission congestion management, such as the interrupt management of the interruptible load, the impact of the elastic load on the congestion management, and the congestion management model considering the low-carbon emissions are not involved. In addition, there is no description of the management of regional congestion and different national congestion management methods.

China's electricity market is still in the initial stage of reform. According to the compilation of power system reform documents of various provinces (autonomous regions and municipalities), there are various trading modes and transaction types in China's electricity market. All provinces (autonomous regions and municipalities) should adopt different congestion management methods for different transaction modes and transaction types. Transmission network congestion and power distribution network congestion are equally important. In addition, attention should be paid to the connection between provinces and provinces to solve regional congestion management. In the end, it is necessary to make reasonable pricing of the congestion cost, realize the fair sharing of the congestion cost among the market members, and promote the effective use of the transmission network, thereby reducing the occurrence of congestion.

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