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A review of the research on price-type demand response of industrial users

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Abstract. With the continuous development and perfection of the power market, the interests of the power system are gradually diversified, and the role of demand-side resources in the competitive market is being reconsidered. This paper briefly introduces three kinds of price demand response projects in European and American countries, sums up and compared the research status of the demand response of industrial users in the Western countries and China, aiming at providing research directions for the research of Chinese demand response.

1. Introduction
Demand response means that when the cost of power supply market is high or the reliability of the power system is threatened, the electricity users in the direction of power supply will be given price guidance or economic incentive so as to make adjustments to their original power consumption modes so as to reduce the peak period of electricity load or make it the purpose of the migration period, thus ensuring the stable operation of the system, and curb short-term behaviour of rising electricity prices. From the perspective of the user's response motivation, the demand response items can be divided into “price-type demand response” and “incentive-type demand response”. Based on the research on demand response of industrial users in China and Western countries, this paper summaries the existing demand response projects and studies provided suggestions and ideas in order to solve the existing problems in the development of China's demand response.

2. Typical price-type demand response projects in Western countries
Since the concept of demand-side management emerged in the 1960s, Western power companies have been exploring the use of price-based demand responses in an attempt to find better and more user-friendly pricing models. Here are some typical price-based demand response projects in the exploration process.

2.1. TOU
Arizona Public Service Corporation of America offers two different pricing options for power users. 1. "time-benefit plan" is a one-part tariff suitable for users with shorter peak hours.2. “combined advantage plan” is a two-part tariff, which is composed of energy price and demand tariff, It is more suitable for users of peak-valley electricity difference.

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2.2. CPP
The TEMPO project in France is a typical and successful critical peak pricing project. It sets a higher critical peak price on the basis of TOU. TEMPO project started in 1996, the year divided blue day, white day and red day 3 kinds of electricity prices, and each day has been divided into two kinds of price: peak load and nonpeak load.

2.3. RTP
In the past ten years, the two-part real-time pricing developed by Georgia Electric Power Company has been relatively mature. In this mechanism, the real-time electricity price is charged when the user load is higher than the baseline load set by the historical load data, the standard electricity price is executed when the user load is equal to or lower than the baseline load and the lower portion will be returned to consumers at the standard price.

3. The Research Status on Demand Response of Industrial Users in Western Countries
Among many power users, large industrial users are more sensitive to tariff signals and have more flexibility in load, able to respond quickly to price changes or incentives and cut back on significant electricity demands, making them ideal for demand response projects. At present, there are many studies on the demand response of industrial users in western countries.

3.1. The early basic research
The study of user response to price-based demand responses in western countries started earlier. A.K.David studied the optimal user response under spot electricity price, put forward the user load classification theory, and proposed the load classification optimization method under user response. At the same time, it analyzed the potential price response and response bottleneck of industrial users. Daryanian B subsequently established a mathematical model of the response of real-world electricity prices to energy-consuming industrial users and simulated the measures that users could take to respond to the demand response and the electricity costs they could save[1], but since the model was too general to be heavily referenced. J.G.Roos et al focused on the response behavior of industrial users under the single system real-time electricity price and its avoidable cost-effectiveness[2]. They optimize the load dispatching method to minimize the cost of industrial users and use the marginal price curve to decide whether to respond to real-time price and set up a corresponding model to calculate the resulting cost savings.

A.K.David holds that it is necessary to set a mathematic model for the user's electricity consumption characteristics and propose a user response model based on the theory of demand elasticity, user's rational consumption level and tariff signal[3]. It provides a clearer idea of the follow-up study.

3.2. Research on electricity behavior
It is an important way to analyze the power consumption behavior of industrial users to establish the mathematical model of the electrical behavior of various industrial equipment. In [4], the production power of manufacturing industry is modeled, and the mathematical model of industrial users as a whole to participate in demand-side bidding is constructed, but the management of the specific equipment is not analyzed systematically. Shah N states that the state task network (STN) can be used to describe the industrial production process[5], while Ding Y M establishes the power model of the production equipment by combining the parameters of the STN with the equipment of the production task[6].

Nolde.K takes the steel plant as the research object and uses a mixed integer linear programming to complete the production schedule on the basis of the given load curve[7]. Based on the above, Haït.A presents a continuous time model based on the description of the relative relations between the factory production tasks and the divided periods[8], which greatly improves the efficiency of the solution.

3.3. Research on Industrial user response behavior

In the study of industrial users, Bjørner T B uses the Panel unit root and the panel cointegration technology to do a deep research on the power demand of Danish industrial company[9]. The feasibility of cross-subsidy for power users in India is calculated by using the time-varying price elasticity of industrial power demand[10]. In [11], based on the principle of market equilibrium, the paper studies the response behavior of the user to electricity price under different marginal cost pricing rules.

In the aspect of formulating industrial electricity price plan, Geng J adopts the method of optimal load dispatching to minimize the electricity bill of industrial users[12]. According to whether the decision-making of continuous curve of hourly electricity price margins responds to the real-time electricity price, a corresponding model is established to calculate the cost- Side management and savings in electricity costs.

3.4. Research on Demand response assessment

In the research of demand response evaluation, many kinds of characteristic quantities are used to characterize the demand response behavior of industrial users from different perspectives. Literature [13] shows that it is very important to examine the adjustment of user load curve under demand response, the reliability and predictability of user's long-term and short-term behavior, and response speed when assessing the effectiveness of demand response in saving electricity generation investment. North American Electric Reliability Corporation summarizes the characteristics of demand response assessment should pay attention to, such as response power, response speed, implementation frequency and load recovery time[14]. These feature quantities are the focus of modeling demand response behavior.

It can be seen from the above studies that in the process of research on the field of industrial users' demand response, western scholars have established a systematic research system that includes user's electricity consumption behavior, demand price elasticity, electricity pricing scheme and response efficiency evaluation. The research ideas of this system are also applicable to China's exploration of the field of demand response. These studies provide a guiding ideology for the related research in China.

4. The Research Status on Demand Response of Industrial Users in China

In the field of domestic demand response research, Taiwan Province of China carried out the study and practice of time-of-use electricity price for industrial users earlier. J.N.Sheen and others analyzed the user's response to the selectable time-of-use electricity price from the nineties of last century for Taiwan's industrial power users[15]. Research on demand response started late in mainland China, and research on demand response of industrial users began to appear even after 2000[16].

4.1.Research on Electricity behavior

In the research on the inherent electricity consumption behavior of industrial users, L Kun takes into account the characteristics of high energy-consuming enterprises, such as the steel industry, that their production methods are special and the demand for electricity fluctuates with time. Aiming at the large random variation of industrial load, a deterministic model and a stochastic model for optimal scheduling of large consumers are established[17]. Y J Dang analyzes the impact of user industrial users on the production of the shift, process flow, product scale, energy consumption per unit of product output, characteristics of production machines and so on[18]. The research on the response of large industrial users after implementing the TOU price in Nanjing was conducted[19]. However, the analysis simply analyzed the data before and after the demand response and did not discuss how to control the possible influencing factors.

4.2.Research on Industrial user demand response model

Rational modeling of demand side's response behavior will instruct the formulation of time-of-use electricity price more reasonable. In different ideas of model building, literature [20] uses consumer psychology principles to establish a users' response model of time-of-use electricity price.A parameter identification model of users' response curve is established based on weighted least square method.For industrial users who have been implemented time-of-use electricity pricing, a simulation process of users' response behavior at the TOU price has been established.

J H Yuan adopts the method of multi-agent simulation and establishes the response rules of multi-users' decentralized decision based on fuzzy logic[21].Based on the previous ideas, J J Tan establishes an agent system including government, power supply department and user side, explore the mutual influence between them and establishes a model of multi-agent-based users' time-of-use price response[22]. The literature [23] presents the concept of price response lag and establishes a mathematical model based on this.

At present, many modeling methods are based on the analysis or simulation of the users' response behavior. Other modeling methods can also be used when a large amount of industrial user data is available. Such as using the expert system based on knowledge-based learning rules for large-users' time-of-use electricity price response modelling[24]. Using fuzzy comprehensive evaluation method which is based on users' data-based electricity attitude modelling[25]. Using statistical linear regression algorithm for real-time price response of air-conditioning load modelling[26] etc. Based on obtaining a large amount of data of user's electrical activity, the literature [27] conducts regression data mining using support vector machines to establish a model of response behavior of power users at time-of-use price. The model realizes the simulation of electric user's response behavior under time-sharing electricity price.

4.3.Research on Industrial User Elasticity Coefficient

In all kinds of response models, the user's demand elasticity coefficient is needed as the support to reflect the relationship between the valence signal and the user response behavior. In the earlier studies in China, the paper [25] first adopted the method of fitting the production cost function of various industries and using the coefficients of cost function to determine the price elasticity of time-sharing power demand, and made an assessment of the elasticity coefficient of electricity demand for the five most important industries of Taiwan Province. Such as textile, papermaking, petrochemical, nonmetal mineral and metal processing industry.

Z F Qin gives a complete establishment process of the electricity price elasticity matrix and analyzes the difference of the elastic matrix structure caused by the different electricity consumption characteristics of industrial users[28]. On this basis, Qin proposed a simplified method of elastic matrix.

Using the theory of factor derived demand in production economics, J Q Xin proves the characteristics of the short-term price elasticity of electricity demand to the peak-valley electricity price, and presents the zero-sum property of short-term time-share price elasticity of electricity demand[29] and proves the practical data of price elasticity which is applicable to the literature [25].

4.4.Research on pricing schemes for industrial users

In the literature [30], the price elasticity of demand is used to analyze the change of users' electricity consumption with electricity price. Taking the minimum difference between peaks and valleys as the goal, a constrained nonlinear programming single-layer model with a relatively simple peak-trough TOU is established considering the constraints of guaranteeing users' benefits and peak-to-valley electricity price ratio within a certain range.

In a more complicated study, literature[31] proposed a two-tier model of sales and purchasing decision-making for a sales company considering the user's demand response to the ever-increasing ability of users to respond to market prices and incentive information. In the upper model, corporate profit maximization as the goal, and the lower model to maximize user power utility as the goal. In the bivariate model of literature [32], the main power users of industrial power plants with self-provided power plants are the main body of the study, and the solution to such users' problems of using power supply and self-power generation is simulated to balance the problems of the power companies and power users Interests between.

The above documents respectively studied the demand response model and the demand-response time-demand price of industrial users from different perspectives. They also optimized and tested them according to the actual data, both of which have their own engineering application value. However, in general, compared with the developed theory and practice of industrial demand response in China, the theoretical level of China's research is still at the stage of conceptual interpretation. The institutional environment, technical means, implementation requirements and project evaluation for introducing demand response Tools and other core content has not been an in-depth study. In practice, most of them belong to incentive control for large industrial users. There are few demand response projects to achieve the goal through electricity price method, and the lack of analysis of the implemented electricity price projects. In these aspects, Chinese scholars need to conduct further research.

5. Conclusion and Prospect

The price-type demand side response is the direction and main form of the demand side response under the electricity market conditions. There are innumerable kinds of price theory designs in theory. There are many experiences in Europe and the United States in the practice and study of responding to the price-type demand side for learning in China. In contrast with the countries in Europe and the United States, the relevant theoretical research is constantly improving in various aspects under the continuous efforts of Chinese scholars. However, in addition to the time-of-use price mechanism, the application is still in its infancy. At present, the most important point in China is to set up a sound power market system as soon as possible and provide a platform for implementation of various new electricity price mechanism projects. Only when the actual interaction with users in the mechanism exploration gets the user's response can they be given more opportunities China's customer satisfaction effect better price mechanism.

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