Review of Theoretical Research and Engineering Practice for Demand Response Market Mechanisms and Its Suggestions for China

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Abstract. As a substitute for the traditional generator units, the demand side resources can participate in peak-cutting and valley-filling in the power system by changing their operating power, which is called demand response (DR). The DR market mechanism will play a significant role in guiding power users to actively participate in DR. For a long time in the past, Chinese DR practice mainly relied on administrative methods. These methods have adapted to the monopoly power market environment, but it is difficult to adapt to the current state of the power system reform. Based on this background, this paper first summarizes the widely-used price-based DR market mechanism and incentive-based DR market mechanism. Besides, the point-based market mechanism recently proposed is analysed. Then, based on the theoretical research of the market mechanism, the DR engineering practice in the United States, Europe and China is introduced. The point-based market mechanism practice in Jiangsu Province is focused on. The advantages and disadvantages of each market mechanism are analysed. Finally, according to the current development situation of China’s power market, the suggestions about the DR mechanism are put forward for China.

1. Introduction
With the development of the economy, the peak-to-valley difference of the load of the power system caused by the laws of production and life has increased year by year. To cope with it, many traditional power plants (such as thermal power plants) are constructed to ensure that the power system has sufficient reserve capacity. However, since such power plants only operate during peak load, they will operate with a lower generating power or shutting down during periods of low power load. This operating mode has reduced the number of operating hours of power plants throughout the year and caused waste of resources.

Many studies have proven that when demand-side load resources participate in power system regulation, i.e. demand response (DR), they can play the same role as generation-side resources [1]. During peak load, reducing the load operating power through direct or indirect control can significantly reduce the load peak of the power system. Similarly, if the demand-side operating power is increased when the load is low, the load valley of the power system can be increased. Therefore, as an alternative to traditional power plants, demand-side load resources participating in DR can has great potential to reduce the peak-to-valley difference of the load curve [2].
In order to promote demand-side resources to actively participate in DR, a good DR market mechanism is essential. On the one hand, the DR market mechanism needs to reflect the supply-demand balance state of the power system in a timely manner [3]. During the peak load period, the market mechanism should attract more users to reduce their own load. During the low load period, the market mechanism should help increase the load power on the demand side. On the other hand, the DR market mechanism needs to reflect the willingness of the power system to increase/decrease the load. Its subsidy intensity must not only make up for the losses caused by changing the load of users, but also be able to give additional rewards to participating users.

With the reform of China's power system, many provinces and cities across the country are building their own power markets. The DR market mechanism should help demand-side resources to participate in the power market and promote demand-side development in the power market. Based on this, this paper first summarizes the theoretical development of the price-based DR market mechanism, the incentive-based DR market mechanism, and the point-based DR market mechanism in Section 2. Then, the United States, Europe, and China are used as examples to introduce the typical DR market in Section 3. Finally, Suggestions for the development of China's DR market mechanism are put forward based on the foreign advanced experience in the DR market mechanism in Section 4. Section 5 concludes this paper.

2. Theoretical research on DR market mechanism
As shown in Fig. 1, common DR market mechanisms mainly include price-based mechanisms and incentive-based mechanisms. Point-based market mechanisms have recently been proposed and practiced in Jiangsu Province. These three market mechanisms have their own characteristics and together form a complete framework of the DR market mechanism.

![Figure 1. DR market mechanism classification.](image)

2.1. Price-based mechanism
Price-based DR market mechanism is based on price signals to guide users to change the way they use electricity, thereby reducing peak load electricity consumption or increasing valley load electricity consumption. It mainly includes the time-of-use electricity price (TOU), the critical peak electricity price (CPP) and the real-time electricity price (RTP) [4].

The TOU is based on the characteristics of the load curve, and the electricity price is divided into peak-valley periods during the year or day. Because the electricity price is different at different times of the day, power users can shift the demand for electricity during the peak load period to the valley load period. CPP is a higher electricity price than the TOU during the peak load and it have high but short-term electricity price. CPP can effectively reduce the electricity demand of power users during peak load. RTP is the most advanced form of price-based DR market mechanism. The electricity price...
in this mechanism is determined by the market in real time. It can timely reflect the balance level of power supply and demand in the market to change users’ electricity consumption.

2.2. Incentive-based mechanism
Incentive-based DR market mechanism can adjust users' electricity consumption habits through incentives. It is usually a market mechanism that is implemented at a specific time rather than continuously. It mainly includes direct load control (DLC), interruptible load (IL) and auxiliary service market mechanism (AS) [5].

DLC means that the grid company directly controls the users’ load at a specific time according to the contract with the user. Since the grid company wants to directly control the user's load, the control equipment must be installed for each participating user. Users may be unhappy because of privacy issues. Therefore, the control times and control duration are limited. IL is the DR mechanism in which users decide whether participate in it or not after the IL invitation is issued by the grid company. This market mechanism places more emphasis on user autonomy, which is mainly determined by the user's willingness. Therefore, the uncertainty of the IL is relatively larger than DLC. AS is part of the electricity market. In this market, users have to bid and quote, and participate in market competition like generators. It is a market-oriented DR market mechanism just like RTP.

2.3. Point-based mechanism
China's power market is not advanced enough, and it is difficult to be suitable for the current level of development in China if market-oriented DR programs abroad are directly adopted. Therefore, point-based DR market mechanism is proposed and it includes price-based DR based on points and incentive-based DR based on points [6].

The price-based DR based on points is a monthly unit point that is provided to users for 96 time periods of one day (15 minutes per time period). This unit point is similar to the unit price, and the points accumulated each month can be exchanged for goods. In the peak load period, the negative unit point is given to guide the user to reduce the load and in the low load period, the positive unit point is given to guide the user to increase the load.

Incentive-based DR based on points can give reward points or penalty points to users according to their performance in DR. This type of points is mainly composed of three parts: reward points for participating user as reserve capacity, reward points for user’ successful response, and penalty points for user’ failed response.

3. Engineering practice on DR market mechanism
This Section uses the United States, Europe, and China as examples to summarize the engineering practice for above-mentioned DR market mechanism. Due to the developed electricity markets in the United States and Europe, the marketization of their DR mechanisms is obvious. However, China is in the initial stage of the electricity market and DR market mechanisms that are adapted to the development phase of the power market are adopted.

3.1. Foreign practice on DR
The United States leads the world in DR engineering practices. As of 2013, the demand-side load resources in the United States have reached 29.5GW. The experience of the Arizona APS project in the United States is a representative TOU project, which includes the one-part tariff system and the two-part tariff system. One of the earliest CPP projects in the United States was implemented by Gulf Power Company in 2000. A variety of peak electricity price mechanism has been developed. Annual capacity resources of the IL project in the United States contribute more than 7.5 million kW, which the largest of all DR projects [7].

The DR in the UK includes three types of TOU, DLC, and AS. Its TOU rate is diverse and meets multi-period requirements. DLC participates in system standby to reduce the demand for power
generation resources. Participant is also quoted with power generators in AS, which can effectively prevent the occurrence of market power [8].

Spain has adopted two methods of TOU and IL [9]. In terms of TOU, Spain divides an annual electricity prices into three seasons: peak season, medium season and low season. In addition, based on the annual peak-valley electricity price, the daily peak-valley electricity price is added. A total of six different TOU have been formed. In terms of IL, Spain has requirements for the response period and response time, which includes a total of six responses model. The total number of responses and total response time in a year are limited.

3.2. Domestic practice on DR

Shenzhen has carried out demand-side management practices very early. To promote the development of DR, two measures were adopted [10]. On the one hand, the reliability electricity price is tried and the peak-valley electricity price policy is widely used. On the other hand, the peak-cutting and valley-filling plan and emergency plan are formulated and the “storage pond” load for emergency peak shift is established.

Hebei Province is the province with the earliest practice of demand-side management in the country. In order to solve the difficulties of special funds for demand-side management, it has issued the Opinions on Vigorously Carrying Out Demand-side Management [11]. In the field of demand-side management, the "Ten Green Projects" project is launched, and DR is combined with the construction of the power market to promote the development of the demand-side management industry.

3.3. Practice on point-based mechanism

In 2016, the National Key Research and Development Program (NKRDP) Urban District Users and Power Grid Supply and Demand Friendly Interaction System was started in Jiangsu Province. The purpose of the project is to reduce peak-to-valley difference and comprehensive energy consumption through appropriate DR market mechanisms, advanced remote monitoring and control equipment, and innovative central monitoring systems. In 2017, the point-based market mechanism was formally proposed innovatively. Now the price-based DR based on points (also known as the "Firefly Project") has begun to bear fruit. The client application for this project is shown in Fig. 2.

Figure 2. Client application of “Firefly Project”: (a) main page; (b) coupon acquisition page.
It is expected that in the near future, 160,000 residents will gradually participate in it [12]. In cooperation with incentive-based DR based on points in Suzhou and Changzhou, the project will build the world's largest DR demonstration area. It will serve as a model for DR practices in other regions.

4. Suggestions for development of China's DR

As shown in Fig. 3, based on the above analysis, three suggestions are put forward for the development of China's DR market mechanisms.

The price-based mechanism should be taken as a key task for long-term development, and the DR mechanism based on RTP should be gradually realized. In the early stage of the construction of the electricity market, due to the lack of conditions for implementing RTP, a combination of TOU and CPP is required. With the development of China's power market, the combination of forward wholesale market, day-ahead market and real-time market has gradually matured. By that time, no other price-based DR mechanism but RTP is needed to adjust the power supply-demand relationship. RTP can directly affect the electricity consumption behaviour of market participants.

The incentive-based mechanism should be taken as a short-term DR method, and it should be gradually developed into an auxiliary means of the price-based mechanism. Incentive-based mechanism is more focused on short-term but repeatedly DR demand. It is to cope with the abnormal load of the power system, and it does not require continuous participation. However, in the early stage of the electricity market, the price-based mechanism is weak. The incentive-based mechanism could guide industrial and commercial electricity consumption behaviour. Therefore, this mechanism should be vigorously developed. In the mature stage of the electricity market, RTP can meet DR requirements. At that time, the incentive-based mechanism serves as an auxiliary means for RTP to prevent RTP from not working.

The point-based mechanism is used as an alternative to RTP in the early stages of the electricity market, and it should gradually become an important market mechanism for the retail market. The point-based mechanism is similar to RTP, and it's just that this mechanism is based on points. Therefore, in the early days of the electricity market, like Jiangsu Province, the point-based mechanism should be widely implemented among users. This can not only make up for the lack of power market, but also help users develop market concepts. At the maturity stage of the electricity market, the point-based mechanism should be used as a guide for participating users under retail-side aggregators to help the aggregators benefit from the electricity market.
5. Summary
When the peak-to-valley difference in power systems is increasing year by year, demand-side resources can play a similar role as power plants in peak-cutting and valley-filling or emergency situations through DR. With the construction of China's power market, the DR market mechanism also needs to be gradually improved in order to be more attractive to participating users. Based on the research of the DR market mechanism, this paper analyses the price-based DR market mechanism and the incentive-based DR market mechanism, and introduces the point-based DR market mechanism proposed by the NKRDP. Then taking the United States, Europe, and China as examples, the engineering application status of the price-based mechanism and incentive-based mechanism was reviewed, and the point-based mechanism practice in Jiangsu Province is analysed. Finally, based on the above analysis, suggestions are provided for China's DR market mechanism.

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