The Supply-Demand Analysis Method for Power System with Considering the Demand Response and Multiple Scenarios

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Abstract. This paper proposes a mathematic model of time series production simulation, and presents a case study of the Shandong power grid and investigates the role of demand-side resources in ensuring power supply. Based on the supply-demand analysis method and the design of the demand-side resource regulation plan, the demand response of the Shandong power grid can essentially meet the power balance requirements by 2025 under the baseline scenario. Under the extreme scenario, the power deficit can also be addressed by orderly power consumption. It is suggested to pay more attention to the development and utilization of demand-side resources.

1. Introduction

Given the introduction of the "dual-carbon" goals and the accelerated construction of a novel power system, relying solely on regulation resources on the power generation and grid sides is no longer sufficient to meet the increasingly stringent requirements for system safety and efficiency. As a result, there is a pressing need to tap into the flexible regulation capabilities of demand-side resources, which have garnered growing attention. The Action Plan for Carbon Dioxide Peaking Before 2030, issued by the State Council in October 2021, explicitly calls for the development and utilization of demand-side resources: To actively promote the integration of source, grid, load, and storage, use multiple energy sources to supplement each other, make vigorous efforts to enhance the overall regulation capabilities of the power system, incorporate loads of traditional energy-intensive industries, interruptible industrial and commercial interruptible loads, electric vehicle charging networks, and virtual power plants into the power system regulation, and make grids more secure and reliable. The development and utilization of demand-side resources can yield multiple benefits, such as reducing redundant investment, ensuring grid security, lowering energy costs for users, promoting the development of energy storage industries across the source, grid, load, and storage sides, and reducing carbon dioxide emissions. These benefits will aid China in achieving its "dual-carbon" goals.

Currently, both domestic and foreign experts have conducted research in this area. [1] analyzed the comprehensive value of demand-side resources from the perspectives of the resources themselves, the market and society. [2] proposed a double-level planning model for an active distribution network that considers carbon emissions and demand-side management. This model optimized the planning of the active distribution network through demand-side management to minimize the comprehensive annual cost. [3] analyzed the price elasticity and cost-effective value associated with users' participation in power demand response. [4] analyzed the benefits for power generation companies, grid companies, and society involved in different demand-side management investment projects. [5] calculated the cost-effectiveness of demand-side shared energy storage stations, operators, and users. [6] developed demand response models for both electricity retailers and users and analyzed the long-term benefits of each entity. [7] analyzed the economic benefits of load aggregators and their contribution to the grid based on PJM market data in the United States. [8] calculated the total cost of comprehensive demand response service providers, as well as the benefits of user participation in demand response. In [9], a model of the electricity market that captures the uncertainties on both the operator and user sides is proposed, where an explicit characterization of the optimal user behavior using the Bayesian Nash equilibrium solution concept is derived. In [10], the optimal design of demand response and peak-time rebate programs in the electricity sector is studied. It is showed that compared to a conventional demand response program, the proposed approach significantly improves the targeting of demand response payments. In [11], an overview of AI approaches used for DR applications is presented. Both the Artificial Intelligence and Machine Learning algorithm(s) are employed while discussing commercial efforts (from both new and existing businesses) and large-scale innovation projects that have applied AI technologies for energy DR. In [12], a novel self-reported baseline mechanism (SRBM) where each agent reports its baseline and marginal utility is proposed. The authors show that SRBM is almost optimal in the

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metric of average cost of DR provision faced by the aggregator. However, these studies have not yet established a systematic and quantitative method to analyze the value of demand-side resources. This has resulted in an incomplete assessment of the value of demand-side resources in promoting the construction of a novel power system and achieving the "dual-carbon" goals.This paper establishes a time series production simulation model that considers the potential of demand response based on the actual demand response in China. Then we present a case study of the Shandong grid and investigates the role of demand-side resources in ensuring power supply through a supply-demand balance analysis under two scenarios: baseline and extreme scenarios. It proposes to mitigate the power deficit through demand response and orderly power consumption.

2. The Mathematic Model of Time Series Production Simulation

The time series production simulation of the power system aims to minimize the operating cost, meet the constraints of power and electricity balance and equipment operation characteristics at each time period, simulate the operation of units, and calculate the generation cost and electricity profit and loss. Demand response can bring flexibility to the operation of the power system. Firstly, the objective function is:

$$\min_{p_{it},q_t}\sum_{t=1}^{T}(\sum_{i=1}^{I}(f_i(p_{it})+h_i s_{it})+g(q_t)) \quad (1)$$

Where I is the number of units; T is the time periods; p_{it} is the power output of unit i at hour t, which is a continuous variable; f_i is the fuel cost function of unit i, which is a quadratic function generally; h_i is the start-up cost of a thermal power unit (if unit i is not a thermal power unit, this item is 0), s_{it} is a binary variable, if unit i starts up at hour t, it is 1, otherwise it is 0. q_t is power of demand response, which is a positive value for peak shaving demand response, it is a negative value for valley filling demand response. g is the cost function of demand response, the typical function of g is:

$$g(q_t)=c^+q_t^+ + c^-q_t^- \quad (2)$$

$$q_t^+ \geq 0,\ \ q_t^+ \geq q_t \quad (3)$$

$$q_t^- \geq 0,\ \ q_t^- \geq -q_t \quad (4)$$

Where q^+_t and q^-_t are auxiliary variables, c^+ and c^- are prices of peak shaving and valley filling demand response, respectively. When peak shaving demand response is executed at hour t, from (1)、(3) and (4), q^+_t is equal to q_t, q^-_t is equal to 0. Similarly, When valley filling demand response is executed at hour t, q^+_t is equal to 0, q^-_t is equal to q_t. Therefore demand response power q_t is the sum of q^+_t and q^-_t, that is

$$q_t = q_t^+ + q_t^- \quad (5)$$

Then, in terms of constraints, each time period satisfies power balance.

$$\sum_{i=1}^{I}p_{it}+q_t=l_t,\ \ \forall t \quad (6)$$

Where l_t is the load at hour t. p_{it} is between the maximum and minimum power outputs

$$p_i^{\min}u_{it} \leq p_{it} \leq p_i^{\max}u_{it}, \forall i,t \quad (7)$$

Where $p^{max}{}_i$ 和 $p^{min}{}_i$ are maximum and minimum power outputs of unit i at hour t. u_{it} is a binary variable, if unit i operates at hour t, it is 1, otherwise it is 0. s_{it} and u_{it} are correlated by

$$s_{it} \geq u_{it} - u_{it-1} \quad (8)$$

The power of demand response is constrained by its potentiality.

$$-q_t^{\text{v}\max}d_t \leq q_t \leq q_t^{\text{p}\max}d_t \quad (9)$$

Where q_t^{pmax} is the maximum potentiality of peak shaving demand response, q_t^{vmax} is the maximum potentiality of valley filling demand response; d_t is a binary variable, if demand response is executed at hour t, it is 1, otherwise it is 0.

The operation of demand response organizations requires a significant investment in costs, and usually can be implemented at most for a certain period of time throughout the year. Therefore, the implementation duration of demand response has the following constraints

$$\sum_{t=1}^{T}d_t \leq D \quad (10)$$

Where D is total time periods of demand response.

3. Scenario Design

Two scenarios, baseline, and extreme scenarios, are designed, considering factors such as economic development and meteorological conditions. The baseline scenario assumes that power demand will maintain relatively fast growth during the "14th Five-Year Plan" period, considering current stock and approval, ongoing construction, planned power sources, as well as measures such as demand response, reserve sharing, and inter-provincial assistance. The extreme scenario assumes that the probability of extreme weather events will increase due to global climate change, resulting in a significant increase in cooling and heating loads and unexpected growth in maximum load. Coupled with extreme cold and hot weather, wind and solar power may not be able to achieve their generation peak, and therefore may not participate in the power balance.

The application scenario of demand response has shifted from "mitigating the power supply-demand gap" to "improving the level of energy and power fine management and grid operation flexibility, and promoting the consumption of clean energy". This effectively alleviates grid regulation pressure and addresses new issues currently facing the power system. Orderly power consumption has played a significant role in the rational adjustment of China's supply-demand balance and better prioritizing normal power consumption for people's livelihoods, key enterprises, key industries, and key locations.

Orderly power consumption and demand response are both important means of developing and utilizing adjustable resources during the "14th Five-Year Plan" period. The implementation plan should prioritize demand response and use orderly power consumption as a fallback to ensure it is more scientifically precise and effective.

Demand response should be the preferred method, and its large-scale development depends on the maturity of the electricity market mechanism. Priority should be given to adjusting well-performing air conditioning loads and actively developing energy storage resources such as electricity-based thermal energy storage and ice-based thermal energy storage to create the most cost-effective response plan.

Orderly power consumption is an important fallback measure to address power supply-demand tension, which requires government management, grid implementation, and user cooperation. Users should be classified reasonably and treated differently. For example, orderly power consumption should be prioritized for "two-high" users; while for other users, it should be executed in a classified order.

4. Supply-Demand Balance Results

Based on the time series production simulation model of the power system, we investigate the supply-demand balance of the case study system. The supply-demand balance situation of the Shandong grid was analyzed based on the two scenarios mentioned above. It is proposed to alleviate the power deficit through demand response and orderly power consumption.

Baseline Scenario: It is expected that during the "14th Five-Year Plan" period, Shandong will maintain rapid economic growth, achieve significant results in optimizing and adjusting its industrial structure, and experience a steady increase in cooling and heating loads. The maximum load of the Shandong power grid is projected to reach 145 million kilowatts by 2025, as shown in Figure 1, with an average annual growth rate of 4.9% during the "14th Five-Year Plan" period. Considering the current stock and approval, ongoing construction, planned power sources, as well as measures such as demand response, reserve sharing, and inter-provincial assistance, Shandong is expected to achieve a tight balance in 2025.

Extreme Scenario: By 2025, taking into extreme weather factors, the maximum load is expected to increase by 4.50 million kilowatts, accounting for about 3% of the maximum load. New energy sources will not participate in the balance, which will affect the output by 1.40 million kilowatts, accounting for about 5% of the total output. As a result, there will be a maximum power deficit of 7.90 million kilowatts as shown in Table 1 (considering the implementation of demand response, which will reduce the deficit by about 6 million kilowatts).

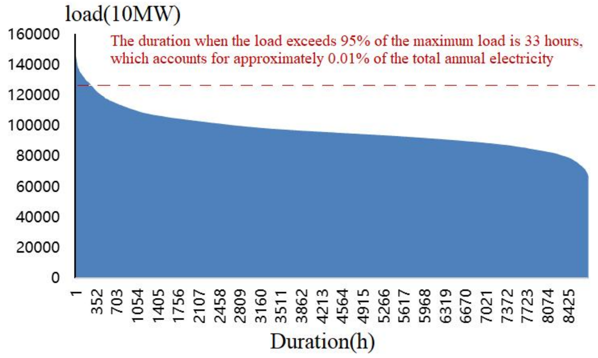

Figure 1 Continuous Load Curve of Shandong in 2025

Table 1 Power Surplus/Deficit in Shandong during the "14th Five-Year Plan" Period (unit: 10,000 kW)

	2023	2024	2025
Baseline Scenario	0	10	20
Extreme Scenario	-760	-780	-790

5. Demand-Side Resource Regulation Plan

Baseline Scenario: Considering factors such as policies, costs, and technological maturity, the demand response of the Shandong grid can achieve a scale of approximately 6 million kilowatts by 2025, which can meet the requirements of power balance. When formulating demand response plans, priority should be given to aggregated air conditioning loads in commercial buildings and residential areas, followed by industrial and commercial production loads and emerging loads. The order and scale of load dispatch are determined based on the response capacities and response costs of different users, and the most cost-effective load dispatch plan is formulated.

Extreme Scenario: In 2025, there is a power deficit of approximately 7.90 million kilowatts in Shandong's grid. The deficit is addressed through orderly power consumption, and according to the principle of "guaranteed supply with limitations", priority is given to the implementation of orderly power consumption for businesses that are subject to development restrictions. The specific plan is divided into three tiers, which are executed in sequence, as shown in Table 2. The first tier involves "two high" projects and industrial power users. The second tier involves high-energy-consuming enterprises such as the papermaking, rubber, and plastics industries that are not categorized as "two high" projects. The third tier involves users in industries such as construction, wholesale and retail, accommodation and catering, real estate, leasing, and commercial services.

Table 2 Demand-Side Resource Regulation Plan

	Scale (10, 000 kW)	User Category
Demand response	290	Air conditioning load regulation

		260	Industrial and commercial production load regulation
		50	Emerging load regulation
Orderly power consumption	**First tier**	709	“Two high” projects and industrial power users
	Second tier	1747	High-energy-consuming enterprises such as the papermaking, rubber, and plastics industries that are not categorized as “two high” projects
	Third tier	1207	Users in industries such as construction, wholesale and retail, accommodation and catering, real estate, leasing, and commercial services

6. Conclusion

Based on the supply-demand analysis and the design of the demand-side resource regulation plan, the demand response of the Shandong grid can essentially meet the power balance requirements by 2025 under the baseline scenario. Under the extreme scenario, the power deficit can also be addressed by orderly power consumption. The development and utilization of demand-side resources are of great importance in ensuring power supply and building a novel power system, as they effectively reduce the load during peak hours and ensure reliable power supply.

It is suggested to pay more attention to the development and utilization of demand-side resources. China should fully recognize the important role and value of developing and utilizing demand-side resources in promoting the smooth energy transition and achieving the goal of “dual-carbon”, and garner recognition of the whole society for this concept through multi-channel publicity.

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