Analytical Research on the Exploitation of Flexible Resources and Power Grid Regulation Technologies Driven by Industrial Internet under Industrial Load

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Abstract. With the release and gradual implementation of the "carbon peaking and carbon neutrality" policy, renewable energy is integrated into power grids on a large scale, and its uncertain and intermittent supply challenges the stability of the power system. The new power system integrated with renewable energy is faced with a new challenge in terms of frequency security, while the extreme climate in recent years has made it more difficult to achieve power balance in the power system. As an integral part of the load side, the flexible power regulation of industrial enterprises is now attracting attention. With focus on the exploitation of flexible power regulation resources under industrial load, this paper builds various industrial load models for industrial enterprises, promotes the deep integration of Industrial Internet and Energy Internet, conducts research on the exploitation of flexible resources and power grid regulation technologies driven by Industrial Internet under industrial load, and analyzes the direct and indirect benefits of the research. The research results are of great significance to the safe and stable operation of the power system, the consumption of new energy, and the green and low-carbon transformation of the industry.

1 Introduction

With increasing global climate change, General Secretary Xi Jinping pledged to the world at the UN General Assembly in 2020 that China will actively promote the sustainable transformation of its energy system and aim to have carbon emissions peak before 2030 and achieve carbon neutrality before 2060. In this context, China has seen dramatic growth in installed new energy capacity, with total installed wind and solar capacity expected to exceed 1.2GW by 2030. The uncertainty of new energy sources such as wind and PV power can dramatically reduce the supply-side regulation capacity of the power system when they are integrated into the power grids on a large scale. As this new power system has little ability to load fluctuations like a traditional power system, its security, stability and economic viability decline, and its ability to maintain balanced grids is compromised. In addition, the frequency of extreme weather conditions, such as prolonged high temperatures and droughts in recent years, has caused the maximum electricity load on power grids to surge to new highs, while insufficient rainfall has led to reduced hydropower generation capacity. The combination of these many factors has increased the difficulty of maintaining balanced grids. In Jiangsu, for example, the electricity load of the whole province reached 131 million kW on August 5, 2022, and the rapidly growing electricity consumption led to a gap between supply and demand from that day onward, which worsened until August 20. The largest gap occurred on August 12, standing at 10.68 million kW. Given the current structure and operation mode of power supply in China, the lack of flexible power regulation resources will be a key issue affecting the consumption of renewable energy, which has a high share, and the safe and stable operation of power grids. Therefore, the exploitation of flexible power regulation resources to support balanced grids is in line with the national strategy for carbon peaking and carbon neutrality in the long term and provides a powerful method to address local power shortages and protect domestic production and life for the time being.

At present, the flexible grid regulation resources in China are mainly thermal power units. On the one hand, thermal power units have a lower ramp rate than other power regulation resources, and on the other hand, the share of installed coal power unit capacity will continue to decline in the future. Therefore, the use of thermal power units as the main regulation resource will not be sustainable. There are currently two possible solutions. One is to regulate the power grids with energy storage devices, but the technical indicators of energy storage devices need to be further improved at this stage, installation is costly, and the safety specifications of some forms of energy storage are not yet complete. Without major technological breakthroughs, it would be difficult to promote and deploy grid-side energy storage

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on a large scale. The other solution is to make full use of the flexible resources on the load side and to achieve a balanced system through the interaction of power, grid, load and storage. On the load side, the industrial energy consumption in China accounts for about 65% of the total social energy consumption, and the industrial load capacity has a large base. In typical industries such as metal smelting, cement, paper making, and glass, some technologies are not strict with real-time balance of electrical energy, and the existence of extensive transferable electricity load has good power regulation potential and can be ideally transformed into cheap flexible resources. In the metallurgical industry alone, electrolytic and electric arc furnace loads account for 16-18% of the total social electricity consumption, and their participation in power regulation can significantly increase the flexibility of the grids. However, to participate in grid demand response, some of the industrial load is often removed directly. Load outages can seriously disrupt normal social and industrial operations, causing huge economic losses and even more potential negative impacts. Therefore, industrial enterprises are not willing enough to participate in power regulation in this context. It is a key and urgent task to realize outrage-free flexible active power control and to exploit the flexible resources of the industrial load without affecting enterprise production as much as possible.

At the same time, as a new infrastructure for the deep integration of new-generation information and communication technology with the industrial economy, the Industrial Internet can build a new manufacturing and service system that covers the entire industry chain and value chain through the close-loop analysis of the manpower, machine, material, method and environmental data of industrial enterprises. It is an important method to perfectly integrate industrial enterprises with the power system through digital means. At present, the global Industrial Internet structure still needs to be improved, and the related industries in China are facing a window of opportunity in the wave of great new-generation digital industry development. Since 2015, China has successively introduced a number of plans and guidelines, including the Guidance on Promoting “Internet+” Smart Energy Development, in order to promote the deep integration of energy with new technologies such as information technology and to build Energy Internet that promotes the coordinated development, integration and complementarity of “power, grid, load and storage”. Under this trend, grid enterprises have participated in the construction of some Industrial Internet platforms by introducing the “power supply + energy efficiency” business in recent years, which accumulates massive industrial energy consumption data, builds databases for grid enterprises, and sets the stage for analyzing the energy consumption characteristics of typical industrial enterprises and exploiting the flexible power regulation resources under industrial load. However, most of the current Industrial Internet projects can only collate and display data on the production, management, energy and other aspects of enterprises by deploying sensors and building platforms to solve observable system problems. They are far from being “smart”. The massive amount of data collected does not create added value for enterprises, and various high-tech models and algorithms are not effective in suitable application scenarios. Further research is therefore needed to extend the value chain of Industrial Internet data and to combine the practical requirements of the power system with digital technologies.

To address the issues above, this paper focuses on the exploitation of flexible power regulation resources under industrial load, studies and analyzes the exploitation of flexible resources and power grid regulation technologies driven by Industrial Internet under industrial load, discusses domestic and foreign research on the planning of flexible grid resources, the participation of industrial load in grid regulation, and demonstration projects for the participation of controllable industrial load in grid regulation. This paper also demonstrates the direct and indirect benefits of the research and models various types of typical industrial load in industrial enterprises to tap the power regulation potential of industrial enterprises and industrial parks, accelerate the deep participation of industrial enterprises in grid interaction, create the added value of Industrial Internet platforms, and promote flexible and accurate outrage-free power regulation under industrial load.

2 Domestic and Foreign Research Status

2.1 Research on Modeling Methods and Adjustable Features of Typical Industrial Load

In terms of load power regulation, Reference [1] is the earliest research to control the load power of energy-intensive electrolytic aluminum to participate in primary frequency modulation based on grid frequency deviation. However, this control method is still similar to the principle of graded load shedding, which instructs the saturable reactor to adapt to the maximum pressure drop when the grid frequency deviation exceeds the threshold. This ignores the fact that the load is continuously adjustable and can cause frequency oscillations. A U.S. electrolytic aluminum company proposed a method of electrolytic aluminum load power regulation based on the control of the transformer tap on the load side, but it was also noted that continuous and frequent adjustment of the transformer can lead to mechanical wear and affect the service life of the equipment[2]. Based on the detailed technology process of energy-intensive load production, Reference [3] analyzed in detail the regulation potential of energy-intensive load from the technical aspect of power regulation and built a corresponding economic cost model that combined the technical and economic aspects to provide a power regulation method that industrial enterprises would be willing to accept. Based on isolated grids, Reference [4] proposed a control method of providing grid frequency deviation feedback for the saturated reactor of electrolytic aluminum, regardless of the voltage fluctuations of the electrolytic aluminum high-voltage bus. Grid frequency variations can trigger changes in the equivalent inductance and thus fast power response of the saturated reactor, which can effectively prevent frequency oscillations.

In the macro background of policy support for the development of new energy, China vigorously develops new energy power generation and makes full use of new energy sources such as PV and wind. However, the rapid growth of electricity load and the volatile and intermittent nature of new energy result in difficulties in different regions, mainly including insufficient regional new energy consumption capacity, lack of grid peak and frequency regulation, and immaturity of the grid auxiliary service market. Although the industrial load in China has a large base, high interaction potential, and good economics that can bring favorable benefits when it participates in new energy consumption, its participation in grid regulation is still beset with difficulties due to multiple factors such as process and security.

The existing research on the modeling and adjustable feature of industrial load is as follows: Reference [5] adopted a measurement-based modeling approach, built a comprehensive load static admittance model and a suitable comprehensive load mathematical model of distribution networks in industrial parks, and selected better-performing chaos particle swarm optimization for complete parameter identification of the model. Reference [6] built models of continuous load, strongly correlated load, front load and synchronous load in process flow by analyzing the process flow of the production equipment load in industrial load. In addition, it built an energy storage load model by analyzing the power relationships and constraints of energy storage under industrial load between different time periods. Using the prediction method of the ensemble of optimal input-pruned neural networks based on TRUST-TECH (ELITE), the research predicted the electricity consumption of industrial load by category for cycle optimization.

For the specific industrial load, according to the power impact characteristics of load, Reference [7] proposed a new mathematical model that considered the characteristics of electrolytic aluminum impact load based on a simplified physical model of electrolytic aluminum load; it also proposed a parameter identification method of electrolytic aluminum impact load based on the gray wolf algorithm and the conditions of bus voltage and power variables of the load. Reference [8] provided the first comprehensive analysis of the poly-silicon production process and an equivalent model of the key production steps from the electrical point of view. It finally established an equivalent electrical circuit that could describe the characteristics of poly-silicon production, completed online parameter identification using the least square method, and provided the active power regulation range, response time scale and regulation duration of poly-silicon while taking into account non-electrical quantity state constraints such as temperature. Reference [9] further proposed a modeling method for the continuous power regulation characteristics of different types of load, such as submerged arc furnaces, and provided the corresponding control implementation means.

2.2 Research on the Technologies for Load Participation in Grid Interaction

Using load-side adjustment as a grid peak and frequency regulation method is mainly achieved through demand-side response based on price incentive mechanisms in the more mature European and U.S. electricity markets. The United States is the country that first implemented demand-side response and now has the most mature mechanism, and its independent dispatching organization ISO accepts offers from demand response suppliers in the reserve market and makes unit mix plans with consideration to such offers as input to prior generation plans[10]. The target users of demand-side response in the United States are mainly residential end users, and there are two regulation methods: One is to encourage users to actively reduce electricity consumption during peak load periods by implementing policies such as time-of-use pricing and critical peak pricing[11]; the other method is to reach an agreement with the users who agree to participate in demand response so that the users allow power companies to cut peak load by using methods such as temperature controllers to exert cycle control of the users' air conditions[12]. Reference [13] considered packaging industrial load into industrial VPP and activating load response by adjusting the start-stop interruption of the process. When its power curve was adjusted, the role of the load could be interrupted and the load could participate in the economical and optimal operation of the industrial VPP. This approach was compared with other response modes in order to seek the most economical response strategy for users.

Clearly, the response-ability of industrial load to the power system has been universally recognized by domestic and foreign scholars, and the application of load response in grid optimization and dispatching has also attracted wide attention in the industry.

In China, the promotion of demand-side response in the industry is mainly restricted by the lack of a mature power market. With the gradual advancement of the domestic electricity market reform, Chinese scholars show strong interest in the participation of adjustable load in load response. Reference [14] proposed the participation of energy-intensive enterprises in the local consumption of wind power in microgrids and built a model for the interaction between these enterprises and wind farms. A pricing mechanism was designed, in conjunction with the peak-valley load constraints of power grids, to guide the adjustment of daily electrical load of energy-intensive enterprises based on the wind power output volatility and the peak-valley load size of power grids. With a cement plant as an example, Reference [15] introduced energy storage to compensate for the disadvantage of the load unit switch that could simply enable discrete power changes and proposed a kind of auxiliary service demand response that connected industrial load with energy storage. It should be noted that the ability of industrial load like electrolytic aluminum to meet the key process constraints in the control process is the most important prerequisite for it to participate in grid interaction control, and it is thus necessary to conduct detailed modeling of the impact of power regulation on core production parameters, so as to minimize the impact on the production of electrolytic aluminum during the power support process. Regarding the demand-side response process, Reference [16] was the only research to analyze the impact of power regulation on the electrolyzer temperature based on the principle of energy conservation. Reference [17] explained that the cost for energy-intensive electrolytic aluminum load to participate in the FM auxiliary service was twofold: On the one hand, the loss of energy in the regulation process could result in losses of product yield and profit; on the other hand, the service life of equipment could be affected by the overload regulation of energy-intensive electrolytic aluminum. In both cases, the regulation boundary of electrolytic aluminum load was not effectively constrained to ensure the production safety of electrolytic aluminum.

2.3 Research on Demonstration Participation of Typical Industrial Enterprises in Grid Power Regulation

Although the participation of industrial load in grid interaction has been a clear development direction, the analysis of existing research results and the investigation of several industrial loads find that the methods and systems for designing flexible interaction between industrial load and the market supply and demand regulation and for operation optimization still need to be improved, and most demonstration projects fail to achieve the expected goals in practical operation. The main reasons are as follows: the theoretical research on the behavioral characteristics and flexibility assessment methods of industrial load is inadequate; there is a lack of detailed models for the operational and technical characteristics of multiple types of industrial load, which results in a lack of planning tools; the assessment and analysis of the behavioral characteristics of industrial load in electricity generation and consumption is inadequate and there is a lack of online monitoring technology and analysis of relevant external data, which results in unclear flexibility enhancement targets; the operation method of load-side response to grid frequency regulation is under-researched.

Based on isolated grids and because of their geographical proximity to an aluminum plant, Reference [18] finally realized load regulation in the aluminum plant by adjusting the excitation voltage control and changing the terminal voltage of generators to modify the voltage of the high voltage bus. Reference [19] analyzed in detail the calculation method of capacity curve in the virtual power plant. By combining sampling with OPF and considering the operation constraints of distributed power supply and the safety constraints of distribution networks, the research aggregated the irregular and non-convex active-reactive coupling output range of the virtual power plant. Reference [20] generated a capacity curve of the distribution system based on the assumption that the aggregation model can optimize the active and reactive power support of the distribution system to the grid. It then built a maximum dynamic ellipsoidal model for the feasible range of power consumption of the distribution system by solving a semi-definite programming problem. Finally, the AC-OPF for optimal dispatching of power transmission grids was solved with the aggregated distribution model. Reference [21] proposed a novel two-step projection calculation method to complete the evaluation of the output curve of a virtual power plant based on convex-hull approximation of the critical point. This method could be used to characterize the allowable active and reactive power output range of the virtual power plant and incorporate the operational constraints of the plant into transmission-level operation and market clearing.

Due to the increasing share of renewable energy sources, the power system’s demand for reserve capacity participating in grid operation and control is growing, and the regulation potential of demand-side response to participate in auxiliary services in the power market is attracting more and more attention. At present, auxiliary services in the domestic power market are developing rapidly, and many provincial power companies in Hebei, Zhejiang and Anhui have recognized the principal market position of demand-side response resources. Instead of simply being used for peak-load shifting, power demand response is priced and can be traded in the auxiliary service market and the spot market. The market-oriented choice of electricity consumption rests in users themselves.

At present, 13 provinces (regions) have put into operation demand response markets, mostly pursuing the basic goal of building a demand-side flexible peak regulation capacity equal to 3-5% of the maximum directly dispatched electricity load in the previous year. In Shanghai, Jiangsu, Jiangxi, Shanxi, and North China, which are early starters with mature conditions, many attempts have been made to exploit the response resources and start to explore the participation of electric vehicles, virtual power plants, and residential users. Shandong, Xinjiang and many other provinces have successively issued rules for the operation of electricity auxiliary services, sending a clear signal that the participation of demand-side response resources in the auxiliary services of the electricity market has become an inevitable trend.

In addition, due to different load structure characteristics and industrial layout plans in different regions, the focus of response resources exploitation varies, such as commercial buildings in Shanghai and Tianjin, electric vehicles in Shaanxi, Shanxi and Zhejiang, and residential users in Jiangxi and Tianjin. The load regulation potential of industrial enterprises is first exploited in the northern region, where industrial users are concentrated. In 2021, State Grid Jibei Electric Power Company Limited planned to implement the annual key work requirement of “actively exploring load resources that can be interrupted and adjustable to enhance demand-side response capacity” and build the demand response capacity based on the peak-shaving auxiliary service market in North China. In March 2021, the pilot industrial enterprise demand response project of the company completed commissioning for 168 hours, and the response load participated in the peak-shaving auxiliary service market in North China. During the commissioning, the maximum valley-filling load in a single day reached 42,000kW and the accumulated response power exceeded 1.60 million kWh. The grid-load interaction between the electricity load of industrial users and the peak-shaving auxiliary service market in North China was achieved.

3 Industrial Load Model

Different from the flexible and independent residential load, industrial load operates in line with the production target and is strongly coupled and sequentially correlated. The change of one load may trigger the change in the process flow. Therefore, the modeling of industrial load is particularly important.

3.1 Load of Production Equipment

Production equipment follows strict process steps and involves in the process flow of the industry. Therefore, they must strictly follow the process steps in Fig 1.

U is the set of production equipment load in the demand management of industrial load, $U=\{1,...,N\}$, and the production equipment load includes N load units. One optimization cycle T of demand management of industrial load is divided equally into K periods. Demand management is conducted in each of these periods.

As shown in Fig 1, each load unit, such as $d1$ and $d2$, represents one set of production equipment, each of which has its specific power and operation task. The production equipment is marked with and without an asterisk. The production equipment with an asterisk, such as $d3*$, represents a continuous load that cannot be interrupted before the operation task is completed. The coupling between two units of production equipment is expressed by directed edges $e1$ and $e2$, representing the sequences of production and processing. For example, $e2$ represents that $d2$ is the front load of $d3*$, which means that only when the production of $d2$ is completed, will $d3*$ be started. The directed edges include 0 and 1. 0 represents that the rear load can be started after an interval or as soon as the front load is completed, and the rear load can be translated horizontally; 1 represents that the rear load is strongly correlated to the front load and must be started as soon as the production of the front load is completed.

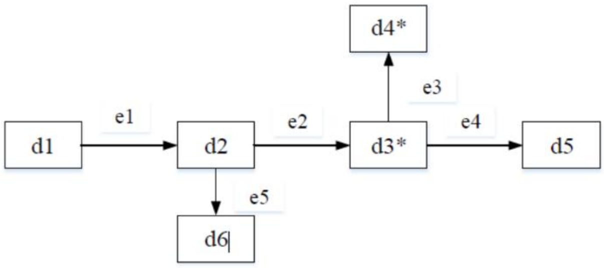

Fig. 1. Flow Chart of Production Equipment Load.

3.2 Load of Air Conditioning

In addition to production and operation equipment, industrial enterprises also use air conditioners, heat pumps, etc. Different from the load of operation equipment, air conditioning load is independent of other loads. It is used in relatively fixed time periods, and its power can be adjusted through temperature control. However, the temperature control and adjustment of the air conditioner will affect the satisfaction and comfort of workers. Therefore, the air conditioning load is modeled with a dual objective.

$$0 \le P_t^{AC} \le P_{\max}^{AC}$$
$$(T_{set}^{in} - \Delta C) \le T_t^{in} \le (T_{set}^{in} + \Delta C)$$
$$P^{AC}(t) = \sum_{t=1}^{T} \omega_t^{AC} \Delta t P_t^{AC}$$
$$T_{t+1}^{in} = \varepsilon T_t^{in} + (1-\varepsilon)\left(T_t^{out} \mp \frac{COP * P_t^{AC}}{A}\right) \tag{1}$$

In which: P_t^{AC} and T_t^{in} are the air conditioner power and the indoor temperature at t; $P_{\max}^{AC}$ is the maximum operating power of the air conditioner; T_{set}^{in} is the set temperature of the air conditioner; ΔC is the maximum temperature offset; + and - are heating and cooling modes of the air conditioner, respectively; ω_t^{AC} is the variable of 0-1, representing the cooling of the air conditioner at t: 1 represents cooling while 0 represents no cooling; $P^{AC}(t)$ is the total operating power of the air conditioner; ε is the inertia coefficient of indoor temperature change; T_t^{out} is the outdoor temperature at t; COP is the performance coefficient; A is the coefficient of thermal conductivity.

The air conditioning temperature offset must be controlled within a certain range. Although an excessive offset can reduce the operating power of the air conditioner and the electricity demand of industrial load to achieve energy saving and loss reduction and save considerable electricity costs, it will affect the comfort and satisfaction of workers, reduce their efficiency, affect the production, and cause unpredictable losses. Therefore, the relationship between the indoor temperature controlled by air conditioning and the comfort and satisfaction of workers is modeled and expressed by a quadratic function.

$$\lambda^{AC} =- \sum_{t=1}^{T} \gamma_t^{AC} (T_t^{in} - T_{set}^{in})^2 + 100 \quad (2)$$

In which: λ^{AC} is the comfort and satisfaction of workers under the temperature; T_{set}^{in} is the set indoor temperature; T_t^{in} is the indoor temperature at *t*; γ_t^{AC} is the impact of air conditioning temperature adjustment on the satisfaction of workers at *t*, which can be set as 0 when the workers are out of work or when the plant is empty, in order to avoid unnecessary electricity consumption. The comfort and satisfaction of workers under the temperature is expressed as percentages.

The dual-objective model can effectively control the temperature of the air conditioner to reduce electricity consumption without affecting the comfort and satisfaction of workers. Thus, the industrial enterprise can reduce the electricity consumption of air conditioners based on the electricity demand and also reduce the electricity demand to achieve energy saving and loss reduction and save considerable electricity costs without affecting the comfort and satisfaction of workers at work.

3.3 Load of Energy Storage

With the progress of science and technology, energy storage technology becomes increasingly mature and is ready for vigorous promotion. Industrial enterprises equipped with mature energy storage systems can reduce instantaneous power and electricity consumption while improving stability and reducing the volatility of electricity consumption, achieving energy saving and loss reduction, and saving considerable electricity costs. Coordinating and optimizing the production process of industrial enterprises with the supporting energy storage can not only reduce load volatility and achieve peak-load shifting (by controlling the rate, valley-to-peak difference and variance of industrial load) but also improve the electricity consumption stability of the industrial load.

This paper selects the battery to build an energy storage system model, in which the state of charge characterizes the stored capacity of the battery, reflecting the percentage of the remaining capacity to the total capacity. Meanwhile, the stored capacity of the battery at *t* is a function of the remaining capacity at *t*-1 and the charging and discharging capacity at *t*. The formula is expressed as.

$$E(t) = E(t-1)(1-\delta_E) + (P_E^{cha}(t)\eta_E^{cha} - \frac{P_E^{dis}(t)}{\eta_E^{dis}})\Delta t \quad (3)$$

In which: $E(t)$ and $E(t-1)$ are the stored capacity of the battery at *t* and *t*-1; $P_E^{cha}(t)$ and $P_E^{dis}(t)$ are the charging and discharging power of the battery at *t*, respectively; η_E^{cha} and η_E^{dis} are the charging and discharging efficiency of the battery; δ_E is the self-discharge rate of the battery.

The life of the battery is related to not only the number of charges but also the charging and discharging depths, which will cause battery losses and further affect the life of the battery. Therefore, the battery should not be overcharged or over-discharged. The stored capacity constraint of the battery is expressed as:

$$E_{min} \le E(t) \le E_{max} \quad (4)$$

In which: E_{min} and E_{max} are the allowable maximum and minimum stored capacity of the battery, respectively.

Since the capacity of the battery must be balanced within the optimization cycle *T* and should not disrupt the use in the next cycle, its constraint is expressed as:

$$E(0) = E(t) \quad (5)$$

In which: $E(0)$ and $E(t)$ are the stored capacity of the battery at the beginning and end of the optimization cycle, respectively.

The maximum charging and discharging power of the battery is also constrained, which is expressed as:

$$\begin{gathered} 0 \le P_E^{cha}(t) \le E^{nom}\alpha_E^{cha} \\ 0 \le P_E^{dis}(t) \le E^{nom}\alpha_E^{dis} \end{gathered} \quad (6)$$

In which: E^{nom} is the rated power of the battery; α_E^{cha} and α_E^{dis} are the allowable maximum charging and discharging rates of the battery, respectively.

The battery cannot be under the charging mode and the discharging mode at the same time, and the constraint is expressed as:

$$P_E^{cha}(t)P_E^{dis}(t) = 0 \quad (7)$$

An energy storage system can reduce the instantaneous maximum electricity demand of industrial load and electricity consumption of industrial enterprises while improving stability and reducing the volatility of electricity consumption, achieving energy saving and loss reduction, and saving considerable electricity costs. Coordinating and optimizing the production process of industrial enterprises with the supporting energy storage can fully leverage the advantages of energy storage, increase the space for scheduling of production process, minimize the electricity demand of industrial load, improve the economics, and reduce energy pollution in the production process.

4 Benefits Analysis

4.1 Direct Benefits

The research on the exploitation of flexible resources driven by Industrial Internet under industrial load can primarily contribute to the regulated, market-oriented, commercial and normalized application of multiple types of typical and controllable industrial load in friendly grid interaction, which is in line with the national strategies to ensure the safe and stable operation of power grids and to pursue low-carbon green development and adapts to the industrial application prospects of controllable industrial load resources participating in the interactive regulation of power grids in the context of massive access of new energy and intensified pressure of grid regulation. Specifically, the flexible control of typical controllable industrial load power can avoid the economic loss caused by direct removal of industrial load during load peak hours, minimize the impact of power outages on the electricity consumption of users, and improve the production efficiency of enterprises. In addition, the participation of controllable industrial load in interactive grid control can address the problem of large-scale new energy consumption, effectively reduce the "abandoned wind and PV" energy that could have been used for power generation, and reduce the energy storage configuration requirements and input costs of the power system.

4.2 Indirect Benefits

With the support of the Industrial Internet platform, the regulation potential of controllable industrial load, once fully exploited, will enable the participation of industrial load in interactive grid control, which can improve the regulation ability and adaptability of power grids while reducing the production cost and net carbon emissions of enterprises and facilitating industrial enterprises to help achieve the carbon peaking and carbon neutrality goals.

The participation of industrial load in interactive grid control can help power grid enterprises develop new load-side regulation resources, effectively alleviating the reduced flexible regulation capacity on the power supply side caused by large-scale integration of new energy into power grids. In addition, it can alleviate the operational pressure of power grids while reducing the inefficient output on the power generation side during load peak hours and preventing excessive investment and construction of power generation, transmission and distribution resources due to the short-term peak load of power grids.

By participating in interactive grid control such as peak regulation and new energy consumption, industrial users can reduce the electricity costs and net carbon emissions of production, improve the overall economic and environmental benefits, promote new energy consumption in the context of extensive integration of new energy into power grids, achieve energy saving and emissions reduction, and promote green energy development.

In addition, consistent scientific research practice and data accumulation basis can be provided for the participation of typical controllable industrial load in friendly interactive grid control. When they learn from demonstration applications in this regard, industrial users can be motivated to participate in interactive grid control, promote the coordinated control of industrial adjustable load resources, promote the integrated development of Industrial Internet and Energy Internet in China, and contribute to the realization of the "3060" carbon peaking and carbon neutrality goal.

5 Conclusion

In the existing electricity auxiliary service market environment, the research on the participation of controllable industrial load in the regulation and control of power grids to achieve friendly grid interaction can effectively address problems such as "the extent, duration and method" of grid peak and frequency regulation and other many types of auxiliary services by the participation of industrial load. The research can be important to promoting the active participation of controllable industrial load in grid interaction, which can help power grid companies to address new energy consumption and power supply-demand balance and to achieve the safety, stability and economic operation of the power system. Focusing on the exploitation of flexible resources and power grid regulation technologies driven by Industrial Internet under industrial load, this paper discusses domestic and foreign research on the planning of flexible grid resources, the participation of industrial load in grid regulation, and demonstration projects for the participation of controllable industrial load in grid regulation. It goes on to build industrial load models by category and analyze its direct and indirect benefits, and proposes to realize information interconnection between the energy system and industrial enterprises through Industrial Internet, promote the transformation of industrial load into flexible grid resources, and form mutually beneficial mechanisms to support new energy consumption and the realization of low-carbon goals in society.

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References

1. Aguero J L, Beroqui M, Achilles S. Aluminum plant load modeling for stability studies[C]. IEEE Power Engineering Society Summer Meeting, Alberta, Canada, 1999: 1-6.
2. Xu J, Liao S, Sun Y, et al. An isolated industrial power system driven by wind-coal power for aluminum productions: a case study of frequency control[J]. Power Systems, IEEE Transactions on, 2015, 30(1): 471-483.
3. Paulus M, Borggrefe F. The potential of demand-side management in energy-intensive industries for electricity markets in Germany[J]. Applied Energy, 2011, 88(2): 432-441.
4. Jiang H, Lin J, Song Y. Demand side frequency control scheme in an isolated wind power system for industrial aluminum smelting production[J]. IEEE Transactions on Power Systems, 2014, 29(2): 844-853.
5. Li Duo. "Study on Integrated Load Modeling of Distribution Networks in Industrial Parks with

Distributed Generation from Multiple Energy Sources" [D]. North China University of Water Resources and Electric Power, 2018.

6. Song Yuexin. "Research on the Key Technology for Precise Management of Electricity Demand under Industrial Load" [D]. University of Jinan, 2020.
7. Guo Cheng, Zhu Runlin, Meng Xian, Xie Hao, He Peng, Ye Zhuang, and Yang Lei. "Modeling Method of Electrolytic Aluminum Impact Load Based on Gray Wolf Optimization Algorithm" [J]. Electric Engineering, 2021(11): 65-70.
8. Chen Yuanfeng. "Research on Frequency Control Strategy of Isolated Grids with High-Permeability Wind Power Based on Poly-Silicon Load Control" [D]. Wuhan: Wuhan University, 2018.
9. Tu Xiazhe. "Research on Frequency Control of Local Area Network in the Iron and Steel Industry Based on Load Regulation of Submerged Arc Furnace" [D]. Wuhan University, 2018.
10. Ruan Wenjun, Liu Sha, and Li Yang. "A Review of Demand Response in the United States" [J]. Power Demand Side Management, 2013 (2): 61-64.
11. Wang Haibo and Zhang Li. "Supply-Demand Interactive Scheduling Model Considering Short Production Process of Steel Enterprises" [J]. Automation of Electric Power Systems, 2021, 45(15): 64-76. DOI:10.7500/AEPS20201002004.
12. Liao S, Xu J, Sun Y, et al. Control of Energy-Intensive Load for Power Smoothing in Wind Power Plants[J].Power Systems IEEE Transactions on, 2018,33(6):6142-6154.
13. Nosratabadi S M, Hooshmand R A, Gholipour E. Stochastic profit-based scheduling of industrial virtual power plant using the best demand response strategy[J]. Applied Energy, 2016, 164:590-606.
14. Ji Jin. "Research on the Chance Constrained Model on the Participation of Energy-Intensive Enterprises in Wind Power Consumption" [D]. Lanzhou University of Technology, 2014.
15. X. Zhang, G. Hug, J. Z. Kolter and I. Harjunkoski, "Demand Response of Ancillary Service From Industrial Loads Coordinated With Energy Storage", in IEEE Transactions on Power Systems, vol. 33, no. 1, pp. 951-961, Jan. 2018, Doi: 10.1109/TPWRS.2017.2704524.
16. Liao S, Xu J, Sun Y, Bao Y. Control of Energy-Intensive Load for Power Smoothing in Wind Power Plants. IEEE Transactions on Power Systems 2018; 33(6): 6142-54.
17. Bao Yi. "Research on the Participation of Energy-Intensive Electrolytic Aluminum Load in the Frequency Regulation of the Power System and Auxiliary Service Strategy" [D]. Wuhan University, 2019.
18. Xu J, Liao S, Sun Y. An isolated industrial power system driven by wind-coal power for aluminum production: a case study of frequency control[J]. IEEE Transactions on Power Systems, 2015, 30(1): 471-483.
19. Huang C, Yue D, Xie J. Economic dispatch of power systems with virtual power plant based interval optimization method[J]. CSEE Journal of Power and Energy Systems, 2016, 2(1): 74-80.
20. Samimi A, Nikzad M, Kazemi A. Coupled active and reactive market in smart distribution system considering renewable distributed energy resources and demand response programs[J]. International Transactions on Electrical Energy Systems, 2017, 27(4): 2268-2280.
21. Muller F L, Szabo J, Sundstrom O. Aggregation and disaggregation of energetic flexibility from distributed energy resources[J]. IEEE Transactions on Smart Grid, 2019, 10(2): 1205-1214.