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Review

Planning and Scheduling for Industrial Demand-Side Management: State of the Art, Opportunities and Challenges under Integration of Energy Internet and Industrial Internet

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Abstract: Industrial power has a large load base and considerable adjustment potential. Enterprises with a high degree of automation and adjustable potential can automatically adjust the production status according to the peak load, frequency of the power grid and the demand of new energy consumption, so as to realize automatic demand response. This paper analyzes the opportunities and challenges of industrial demand response under the integration of Industrial Internet and Energy Internet. At the same time, the development direction of industrial demand response under the new situation, such as comprehensive demand response, adjustable load resources and other technical and policy aspects are prospected.

Keywords: energy Internet; industrial Internet; integrated demand response

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1. Introduction

With the rapid economic development and market-oriented reform of China, the traditional "generation-follow-load" dispatching mode of power systems has almost exhausted the grid control means [1]. New types of loads such as electric vehicles and energy storage devices, as well as new forms of energy use such as load aggregators and smart buildings are emerging [2]. At the same time, China's "double carbon" target means that the proportion of new energy generation will embrace a quick growth and reach 50% of the whole energy consumption. Due to the intermittence, uncertainty and volatility of new energy power generation, it is necessary to have the support of load side for the security and stability of the power grid [3]. Therefore, relying on the construction of Energy Internet, Industrial Internet and power market, expanding the grid regulation resources, and carrying out in-depth research on load-side demand response, especially industrial load demand response with great regulation potential, are important means to solve the future problems of the grid.

Compared with commercial and residential users, industrial loads' interaction with the grid can be more flexible as it has large capacity, wide variety and easy, centralized management. In terms of controllable characteristics, heat storage-type industrial loads have stable power curve, outstanding regulation potential and low impact on production, such as electrolytic aluminum, electric arc furnace and polysilicon [4]. The means of industrial loads participating in grid optimization and dispatching can be divided into two main categories. First is to adjust the power generation plan of industrial loads. Many electrolytic aluminum plants, steel plants and other enterprises are equipped with captive power plants to reduce the cost of electricity. From the grid side, industrial loads and captive power plants can be regarded as an equivalent load. The second way is to directly start and stop the industrial load, under the premise of keeping the user's production efficiency unchanged to ensure that the industrial load easily involves scenarios such as peak and frequency regulation.

The development direction of industrial load participation in grid interaction is clear. The analysis of existing research on several industrial loads reveals that the challenges of industrial demand response are immense [5]. The details are as follows. The key multi-source data indicating the industrial production status are not effectively used. The production characteristics constraints are not considered. The regulation potential of industrial loads cannot be fully utilized. The control means are crude and difficult to be applied in practice. A wide variety of load-side resources and inadequate measurement, resulting in the inability to scale and regulate demand response resources efficiently. Theoretical research on industrial load behavior characteristics and flexibility assessment methods is still insufficient, and there is a lack of detailed models of operational technology characteristics of multiple types of industrial loads, which leads to a lack of planning tools. Assessment and analysis of industrial load generation and consumption behavior characteristics are insufficient, and there is a lack of online monitoring technology and analysis of relevant external data, leading to the unclear goal of flexibility improvement. Moreover, there is no clear conclusion on the mode, legal status and specific measures for industrial loads to participate in the implementation of grid supply–demand interaction. The lack of quantitative analysis models makes it difficult to fully explore the regulation potential of industrial loads.

To address the challenges of industrial demand-side response, the authors in this paper propose that it is necessary to study the operational characteristics of multiple types of industrial loads driven by production data, and the analysis method of industrial load interaction potential and the evaluation method of flexible and precise regulation needs to be proposed. This paper is organized to help better understand the mechanism and challenge of the industrial demand-side management. It gives a clear path for the development of industrial demand-side management in the future. To follow the future trend of Energy Internet, Industrial Internet and power market, industrial loads can be guided to participate in real-time supply and demand balance of the power grid, providing a basis for promoting coordinated interaction of source network, load and storage and supporting the high-capacity and high-proportion access of new energy. Continuously, it improves the power grid's ability to optimize resource allocation, security and intelligent interaction.

The paper is organized as follows. The definition and development of demand response is formulated in Section 2. The characteristics of industrial demand-side management (DSM) are introduced in Section 3. Section 4 explains the Controller, Economy and Adjustment strategy of DSM in detail, based on domestic and abroad references. The relevant information of Energy Internet and Industrial Internet is illustrated in Section 5. The planning and scheduling for industrial DSM under the environment of Energy Internet and Industrial Internet is stated in Section 6. Section 7 designs policy guarantees and market mechanisms for the development of Industrial DSM. Conclusions are finally presented in Section 8.

2. Definition of Demand Response

Demand response (DR) is when the wholesale electricity market price rises or system reliability is threatened, power users change the initial electricity consumption mode after receiving a direct compensation notice from the power supplier or a signal of the increasing power prices to reduce or delay the power load for a certain period, thereby ensuring the stability of the grid and restraining the rising electricity prices [6].

Demand response strategies are mainly divided into two types which are price-based and incentive-based. Price-based demand response strategies includes Time of Use Pricing (TUP), Critical Peak Pricing (CPP) and Real Time Pricing (RTP). TUP is a relatively common strategy in China. It guides users to change their electricity consumption behavior through different electricity prices during peak and valley periods to realize the transfer of peak and valley load. Its implementation effect is directly related to the stability and economy of the power system [7]. Incentive-based DR means that the DR implementing agency formulates corresponding policies based on the supply and demand status of the power system. Users can reduce their power demand when the system needs or when the power is tight, so as to obtain direct compensation or preferential electricity prices at other times. It includes Direct Load Control (DLC), Interruptible Load (IL), Demand-Side Bidding (DSB), Emergency Demand Response (EDR), Capacity Market Projects (CMP), Auxiliary Service Projects (ASP), etc. [8]. Before the implementation of the DR plan, the DR implementation agency usually signs a contract with participants in advance. The contract stipulates the content of the DR such as a reduction in power load size, response duration, maximum number of responses accounting standards, advance notice time, compensation or electricity price discount standards, etc.

There are generally three ways for users to participate in DR. (1) Users can reduce electricity consumption only during periods when the peak electricity price is high, without changing the electricity consumption patterns in other periods. This is only a short-term reduction and does not affect normal production and living. For example, it can be achieved when the setting of the heater or the thermostat of the air conditioner is temporarily changed. (2) Users can cope with the time-of-use high electricity price policy by shifting some peak demand operations to off-peak hours. For example, it can be achieved when some industrial or household activities (such as dishwashers, billiard pumps) shifted to off-peak hours. (3) Users can participate in demand response through distributed reserve batteries, which the user's power consumption pattern hardly changes [9].

DR is an important part of the emerging smart grid and an important element in market design to control potential forces of the supply market. The experience of the energy market shows that the lack of DR is the main factor leading to the collapse of the energy market. For example, California's energy crisis at the turn of the millennium can be alleviated to a large extent if there is enough DR [10]. DR can reduce electricity prices, improve system reliability and reduce price fluctuations [9]. By promoting user interaction and responsiveness and determining the short-term impact on the power market, it can bring economic benefits to users and power companies [6]

3. Characteristics of Industrial DSM

Industrial load refers to the electricity used for industrial production. The proportion of general industrial load ranks first in the composition of electricity consumption. It not only depends on the working mode of industrial users (including equipment utilization, enterprise work shift system, etc.), but also has a close relationship with the industry characteristics, seasonal changes, economic crises and other factors of various industries.

Industrial power load has the characteristics of a large base, large single equipment or process load and large adjustable capacity. Industrial demand response scenario is shown in Figure 1 which includes the collaborative operation of the source, network, industry load and storage, and they are all unified and dispatched by the cloud platform.

In the past, the demand response work carried out in Tianjin, Zhejiang, Jiangsu and other regions of China mainly focused on the commercial load and residential load. The main idea is to reduce the load by the aggregation regulation of the large amount of small and micro loads. For example, in the peak load time in summer, the load adjustment or load migration of central air conditioning, distributed air conditioning, electric water heater and other equipment can be realized through remote invitation.

Commercial and residential demand response has the characteristics of simple regulation, safety and reliability. Users' participation in demand response mainly sacrifices part of the cooling/heating experience to achieve the demand response incentive funds, and then due to its massive user participation characteristics, it also brings the characteristics of difficult publicity and popularization, low convertible rate and long investment recovery cycle.

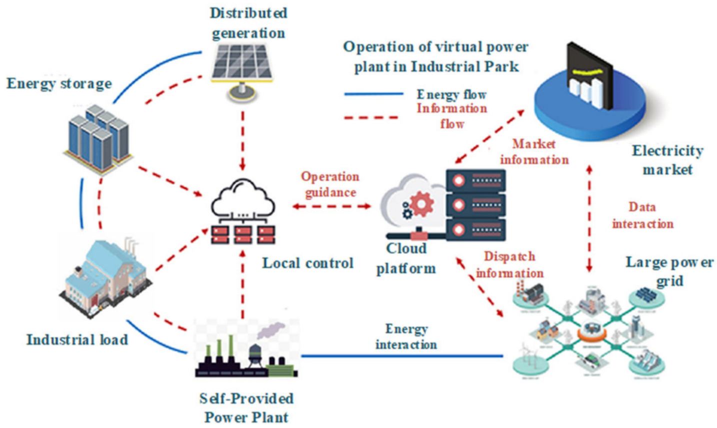
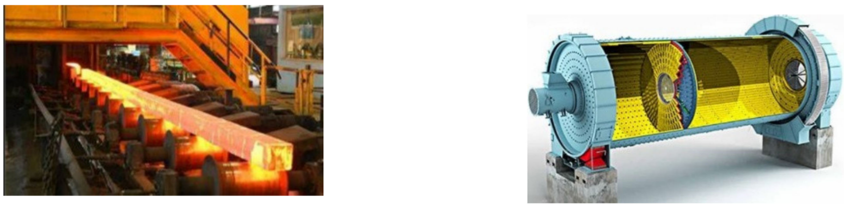


Figure 1. Industrial demand response scenario.

3.1. Advantages of Industrial Demand Response

(1) The industrial equipment/process load base is large, and the regulation potential is considerable, typical industrial adjustable load is shown in Figure 2 including (a) Steel rolling and (b) Ball mill. Through the integration of Industrial Internet and Energy Internet, for enterprises with high automation and large redundancy space for industrial adjustment of production, automatic demand response can be realized, and the production state can be automatically adjusted according to the peak load, frequency of the power grid and the demand for new energy consumption.



(**a**) (**b**)

Figure 2. Typical industrial adjustable load. (**a**) Steel rolling. (**b**) Ball mill.

(2) The incentive benefits are obvious. The existing demand response is mainly based on government funds, such as special financial funds, inter-provincial renewable energy trading spread surplus, seasonal peak tariff, renewable energy consumption subsidy, spot market balance funds and auxiliary markets. Future investment in demand response can be realized by incorporating transmission and distribution tariffs. Due to the large adjustable potential of industrial loads, large orders of magnitude of load shaving and valley filling can be achieved to obtain the significant demand response benefits.

(3) Propaganda and communication costs are low. Through resource census and adjustability assessments, a limited number of high-quality industrial demand response resources can be screened. Load regulation tasks can be accomplished by carrying out targeted and normalized industrial response business extension.

(4) Industrial Internet will be the advantage. Industry 4.0 and other strategies can promote the integration and empowerment of information technology, artificial intelligence technology, physical network technology and other industrial systems. The application of massive sensing and automatic control technology also provides the necessary data and technical support for industrial enterprises to achieve demand response business extensions.

3.2. Difficulties of Industrial Load Participation in Demand Response

(1) Industrial enterprise loads contain primary and secondary loads. The adjustment of primary industrial loads may affect production safety and product quality.

(2) Industrial production load, production process and production orders are strongly coupled, requiring the construction of integrated scheduling models for industrial production operation and power demand response scheduling for specific production equipment and industries. Such models are generally poor in generality and migrability.

(3) The Industrial Internet construction level of enterprises varies in different industries. The industrial automation sensing and control level of some enterprises is not sufficient to support business extensions such as industrial demand response.

4. Literature Review

4.1. Overview of Industrial Demand Response Business

Different concepts of demand-side management programs in [11] have shown the methodology used to develop these programs in the main countries of electricity demand-side management (Europe, Japan and the United States) and provide an overview of the current status of electricity demand-side management in Latin American countries. The demand-side management programs designed and implemented in the study case countries presented the planning and scheduling for industrial demand-side management. Advances and challenges have been outlined in [12]. The study provides an introduction to demand-side management and presents a comprehensive review of existing work plans and scheduling for industrial demand-side management, including four main challenges: (1) accurately modeling operational flexibility, (2) integrating production and energy management, (3) optimizing across multiple time scales, and (4) decision-making under uncertainty. Two real-world case studies demonstrate the capabilities of state-of-the-art models and solution methods. Finally, we highlight research gaps and future opportunities in the field. Zhang et al. [13] introduce the fundamentals of power system economics, provide a definition of power demand-side management that better reflects the consumer perspective and provide a comprehensive review of existing industrial power demand-side management efforts. The review is divided into four sections that correspond to the four main challenges we have identified: (1) accurate modeling of operational flexibility, (2) integration of production and energy management, (3) decision making across multiple time and space scales, and (4) optimization under uncertainty. An industrial demand-side management status report can be found in the reference [14]. The paper provides an overview of industrial demand-side management. The rationale for DSM programs is outlined. Benefits and barriers are described, and potential savings from industrial energy efficiency measures are estimated using data from manufacturing energy consumption surveys. Two in-depth case studies (Boise Falls and Eli Lilly) are presented in detail to illustrate two effective demand-side management programs. A comprehensive bibliography, descriptions of technical assistance programs and an example of a method for evaluating potential or actual savings from a project are also given. Palensky et al. [15] provide an overview and classification of power demand-side management. They analyze the various types of power demand-side management and provide an outlook on the latest demonstration projects in the field. Albadi et al. [16] point out the current state of research in electric market demand response (DR). The definition and classification of demand response as well as the different potential benefits and cost components of demand response are presented. The most commonly used indicators for demand response assessment are highlighted. A bottom-up view narrative of how demand response actually works from the perspective of typical customers, system operators, utilities and regulators is presented in [17].

4.2. Analysis of Industrial Load Characteristics

Comparison of the effects of industrial demand-side management and other flexibilities on the performance of the energy system is analyzed through the flexibility of aluminum electrolysis and other flexibilities in the power system and adjacent sectors. The results point out that the contribution of the cost reduction of aluminum electrolysis flexibility is significant, and the absolute effect is small compared to other options due to the limited number of processes available for it [18]. The potential and limitations of industrial demand-side management have also been introduced in [19]. The paper investigates the potential and limitations of demand-side management in about 15 different companies in Sweden, suggesting different demand-side management possibilities as well as limitations and assessing the potential savings achieved by demand-side management based on historical electricity prices in different countries.

4.3. Controller

In another work [20], the adaptive fuzzy decentralized control problem for a class of pure feedback nonlinear interconnected large systems is studied. In the controller design process, a fuzzy logic system is used to model the unknown nonlinearity and the adaptive fuzzy decentralized controller is constructed using the backstepping technique. The results show that the proposed control scheme can guarantee that all signals in the closed-loop system are semi-globally consistent and eventually bounded. The main advantage of this study is that only one adaptive parameter needs to be estimated online for each subsystem. Simulation results further illustrate the effectiveness of the method. Another paper [21] presents a hardware structure and software design scheme of a smart controller as a platform for a smart grid system. The smart controller is installed in the electrical plug of the appliance. The smart controller keeps track of the electricity consumption of the appliances and transmits the electricity consumption to the AMI/EMS (Energy Management Server). In addition, the energy use of the appliances is limited according to the change in electricity prices and shows that it is feasible to be applied in households to control the electrical energy consumption effectively [21].

4.4. Economy

The economization study of demand-side response in the reference [22] is on the intraday IDSM potential of a paper mill active in the Nordic electricity market. A cost optimization model is developed, and it is found that the market potential is largely influenced by the cost of implementing regulatory power tenders. The results suggest that transmission system operators and decision makers should consider economic factors when assessing the potential of a market-based intelligent decision support system. Bel et al. [23] present a methodology to evaluate and quantify the economic parameters (costs and benefits) attached to a customer's electricity consumption by analyzing the different "blocks" of electricity absorbed by the services offered. The first step of the methodology is to perform a process-oriented market segmentation to identify segments according to their flexibility potential. Based on this, an integrated simulation-based approach is proposed to identify and quantify the actual demand that can be managed in the short term and to perform the necessary economic analysis. The method not only helps users to integrate into flexible distribution systems, but also provides the necessary economic parameters for integration in the electricity market. The close relationship between cutting parameters and energy consumption during aluminum alloy milling was modeled. The corresponding multi-objective optimization function was developed to finally achieve the goal of low energy consumption and high productivity [24]. Sharma et al. [25] propose a new "economic dispatch" model that combines the economic and ecological aspects of multi-component, multi-machine installations under time-of-use tariffs as one of the more environmentally friendly strategies for manufacturing without significantly increasing the cost of electricity under time-of-use tariffs. Archetti et al. [26] investigate the problem of economic lot size determination with cost discounts, initially studying two different cost discount functions, with a modified all-unit discount cost function using alternating incremental and flat sections, starting with a flat section that represents the minimum cost for small lots. Then, the incremental discount cost function is studied, which is a segment-by-segment linear increasing function without a flat section. Finally, the polynomial algorithm was tested computationally using CPLEX. Zhou et al. [27] study a class of single-item two-stage stochastic batch problems with uncertain cost parameters. Assuming that the cost parameter increases or decreases with some probability after a time period p, it minimizes the total expected cost of the problem with a finite horizon. It develops an extended linear programming formulation in a high-dimensional space that provides an integral solution by showing that its constraint matrix is fully Young's modulus. We also project this extended formulation to the lower dimensional space and obtain the corresponding extended formulation in the lower dimensional space. The final computational experiments show that the extended formulation is more efficient and stable than the two-stage stochastic mixed integer programming formulation. Another paper proposes a hybrid Nelder–Mead algorithm and scattering search algorithm SSNM, whose studied model and solution procedure are relatively new in the literature of joint economic lot determination (JELS) problems [28]. Yao et al. [29] first analyze demand response characteristics of industrial users based on their production process and electricity consumption distribution. Two typical IDRRs, a cement plant and an aluminum smelter, are selected and their types of AS provision and response mechanisms are analyzed. The low-carbon benefits of IDRRs providing AS are analyzed based on data from some Chinese provinces.

4.5. Adjustment Strategy

Reference [30] proposes methods that can provide regulation or load tracking with the support of an on-site energy storage system, thus overcoming this low granularity limitation of on/off load devices in cement plants and other industrial loads where only discrete power variations can be achieved. A scheduling model for continuous industrial processes providing interruptible loads is presented in the paper. Uncertainty is modeled using a tunable robust optimization method that utilizes linear decision rules for resource decisions. The model is applied to an example and an actual air separation process. The results show the benefits of selling interruptible loads and the value of considering recourse in decision-making [31]. In the reference [32], an intelligent energy management architecture that can be used to perform energy storage and appliance scheduling schemes is presented. By employing appliance scheduling, customers can achieve cost savings by properly scheduling their power consumption during low peak hours. Further savings can be achieved through intelligent power storage. With the high prevalence of consumer-owned storage devices, battery charging must be properly coordinated and scheduled to avoid creating new peaks. Therefore, the paper proposed an autonomous smart charging framework that ensures grid stability and saves users money. The mean cross decomposition is used to solve the production scheduling and energy cost optimization integration problem, and the method is applied to the pulping process and the steel production process. The MILP-based model is used for both scheduling problems, while the minimum cost flow network model is used for energy cost optimization. High-quality solutions are obtained in a reasonable computational time [33]. The steelmaking process scheduling problem considering variable electricity prices is studied. A decomposition method of SMSPVEP is proposed. The two-stage model is validated on a randomly generated example using the actual production process of a steelmaking plant in China. The computational results show the effectiveness of the method [34]. BI Kim et al. proposed a simple particle swarm optimization (PSO) method for solving the vehicle path scheduling problem (CVRP). The proposed particle swarm algorithm uses a probability matrix as the main device for particle encoding and decoding. Its innovation is that it can be applied to both customer assignment and customer ranking [35]. Gong et al. [36] propose a general approach to reduce the energy use cost per unit production process. It develops a mixed integer linear programming mathematical model for the single machine energy cost-aware order scheduling problem, and proposes a general algorithm for finding economically efficient scheduling of energy with energy price fluctuations with lead time constraints, which improves the energy use efficiency per unit production process [36]. Z Tao et al. describe the problem as a set prize vehicle path problem, which is a complex combinatorial multi-objective optimization problem based on the process rules used in steel production practice. A new heuristic algorithm is proposed [37] by improving the framework of the particle swarm optimization algorithm. This method is very effective in passing high-quality and practical solutions [37]. SJ Jia et al. also described the problem as a multi-objective set prize vehicle path problem (PCVRP) model, which was solved using a multi-objective optimization algorithm based on the Pareto advantage. The experimental results showed that the proposed model and algorithm were effective [38]. Furnace charging and hot rolling play an important role in reducing energy consumption and production costs. In paper [39], a multi-objective mathematical model for slab selection and heater scheduling is developed based on the production process and constraints of the heater charging and hot rolling process. A multi-objective ant colony optimization algorithm is designed to solve the model, which embeds multiple optimization strategies. The results of the real-world simulation experiments show that the proposed model and algorithm are effective for selecting slabs and scheduling the heating furnace [39]. A flexible job shop scheduling model based on constraint planning and mixed integer planning methods with the objective of minimizing the total production cost is proposed in the reference [40]. Arnaout et al. [41] proposed an ant colony optimization (ACOI) algorithm for minimizing the completion time of scheduling on uncorrelated parallel machines with serially correlated setup times [41]. Furthermore, it improved the algorithm by proposing the ant colony algorithm (ACO-II) and comparing its performance with the existing ant colony algorithms (ACO-I, MetaRaPS and SA). The superiority of the improved ant colony algorithm was demonstrated through extensive experiments [42]. An improved continuous-time mixed-integer linear programming model is developed and a two-stage heuristic algorithm is proposed to solve the scheduling problem of unassociated parallel machines under time-sharing tariffs [43]. Moon et al. [44] studied the productivity and energy efficiency of the unrelated parallel machine scheduling problem, optimizing the weighted sum of two criteria of minimum production maximum completion time and minimum time-varying power cost. They proposed a hybrid genetic algorithm and blank job insertion algorithm are proposed. Its performance is demonstrated in simulation experiments. Ying et al. [45] propose a restricted simulated annealing algorithm (RSA) that incorporates a restricted search strategy to minimize the manufacturing cycle time. It effectively reduces the search effort required to find the best neighborhood solution by eliminating invalid work moves. Z Wang et al. investigated an integrated optimization model for generation and mass production load scheduling in EIE to obtain the lowest electricity cost without violating the production process constraints and used mixed integer linear programming (MILP) for the model solution [46]. In the reference [47], a mathematical model is proposed with the objective of minimizing the cost of energy consumption for a single production plan in the production process, which can significantly reduce energy costs by avoiding high energy price cycles. Drexl et al. [48] summarize recent work in the area of batching and scheduling. Differences in formal models are explained and some first reading suggestions are provided, and current practice and deficiencies are described. The paper studies the continuous-time models and multilevel batch scheduling in detail and proposes some suggestions for future research activities. A.L. Chen et al. proposed a vehicle path problem (VRP) to model and an easy-to-implement hybrid approach (QPSO-SA) to solve the problem, improving the feasibility and scheduling efficiency of the solution [49]. BI Kim proved that the model of A.L. Chen et al. was flawed and changed the model to a linear programming model [50]. Bahrain Alida et al. found that even though BI Kim made some corrections to the model, it was still flawed. They revised the model by reducing a large number of variables and proposed a relatively complete model based on CVRP [51]. Jia et al. described the hot-rolling batch scheduling problem as a multi-objective vehicle path problem with a dual time window model and proposed a decomposition-based recursive order optimization algorithm for the complexity of this model and the priority of the objectives considered in real production. Experiments in real production have shown that the model and algorithm are effective [52]. A dynamic planning method was proposed to determine the optimal charging and discharging time of a rechargeable battery by analyzing several special cases of this model. A polynomial time algorithm for solving the special case of a single operation with uniform capacity is also proposed [53]. A Lagrangian relaxation method based on equipment capacity relaxation and operation-first relaxation is proposed for the flexible job shop scheduling problem of steelmaking-refining-continuous casting process. Unlike the full optimization of the LR problem in traditional LR methods, computational results and comparisons show that the proposed method significantly improves the efficiency of the LR method, while the DCASLA method with capacity relaxation strategy performs the best of eight methods in terms of solution quality and running time [54]. SCC scheduling is a complex hybrid flow-shop (HFS) scheduling problem. In the reference [55], the scheduling problem is modeled as a mixed integer programming (MIP) problem with the objective of minimizing the total weighted advance/delay penalty and job waiting. A Lagrangian relaxation (LR) method is proposed to decompose the relaxed problem into two tractable subproblems by separating continuous and integer variables. An improved sub-gradient layer algorithm with global convergence is proposed to solve the Lagrangian pairwise problem. Computational results and comparisons show that the proposed LR method outperforms the traditional LR method in terms of solution quality and has significantly shorter running time [55]. Bo et al. [56] propose a new hierarchical architecture to coordinate demand-responsive industrial loads in industrial parks with secondary frequency control in thermal power plants. This framework coordinates demand-responsive loads and generation resources for optimal dispatch on two time scales. The strategy is proven practically to be able to maintain the economic and safe operation of industrial parks while meeting realistic market regulation requirements. Literature [57] proposes a resource task network (RTN)-based scheduling model that incorporates the flexibility of EAF to reduce power costs. The effectiveness of the model is verified by several examples.

5. Energy Internet and Industrial Internet

5.1. Energy Internet

The idea of the Energy Internet was first proposed in the book *The Third Industrial Revolution* written by American scholar Jeremy Rifkin in 2011. He believes that a new energy utilization system combining new energy technology and information technology is about to emerge [58]. It is mentioned in the book that the Energy Internet should have the following four major characteristics: (1) renewable energy is the main primary energy; (2) supporting the access of ultra-large-scale distributed power generation systems and distributed energy storage systems; (3) realizing wide-area energy sharing based on internet technology; (4) supporting the electrification of the transportation system (that is, the transformation from fuel vehicles to electric vehicles). Chinese scholars generally believe that Energy Internet is centered on the existing power system with the utilization of Internet technology. It will ultimately achieve a high degree of coordination between renewable energy and other energy systems, forming a two-way interactive energy service network for production and consumption. It has the characteristics of high penetration rate of renewable energy, nonlinear randomness with multi-source big data and multi-scale dynamics.

The development trend of the Energy Internet can be summarized into the following three points. (1) Energy marketization. As a starting point, Energy Internet breaks the industry barriers and promotes and reshape the energy industry with marketization and innovation. Based on the Information Internet, the Energy Internet can provide an open platform for various participants and a large number of users. It reduces entry costs and facilitates the connection between supply and demand. It also makes the transaction of equipment, energy and services more convenient and efficient. A win-win situation is achieved for multiple parties and the public's entrepreneurial enthusiasm is activated. These result in continuous impetus for the energy revolution. (2) Energy efficiency. Energy Internet realizes the open interconnection and scheduling optimization of multiple types of energy. It provides conditions for the comprehensive development, cascade utilization and sharing of energy, largely improving the comprehensive efficiency of energy consumption. (3) Green energy. Energy Internet can support the access and consumption of high-penetration renewable energy through the coupling and complementation of multiple energy sources, applications of various energy storage and demand-side response [59]. Energy Internet will help to form a huge "market place" for energy assets and realize the full life cycle management of energy assets. Through this market, the upstream and downstream parties in the industrial chain can be effectively integrated to form interaction and transactions between supply and demand. It also allows more low-risk capital to enter the field of energy investment and development, which effectively controls the risks of investment.

5.2. Industrial Internet

Industrial Internet is a result of the integration of global industrial systems with advanced computing, analysis, sensing technology and Internet connectivity [60]. Its essence is to connect and integrate equipment, production lines, factories, suppliers, products and customers closely through an open and global industrial network platform, so as to efficiently share all kinds of factor resources in the industrial economy, reducing costs, increasing efficiency and helping the manufacturing industry extend the industrial chain and promote the transformation and development of the manufacturing industry through automated and intelligent production mode. Industrial Internet will improve the operation performance of all levels of industrial systems, the reliability of assets and the operation efficiency of units and industrial networks, thus bringing great benefits to business and the global economy [61].

Industry 4.0 is an era in which information technology is used to promote industrial transformation—that is, the era of intelligence. It includes the basic mode change from centralized control to decentralized enhanced control. The goal is to establish a highly flexible production mode of personalized and digital products and services. Industry 4.0 projects are mainly divided into three main themes. The first is the "smart factory", which focuses on the study of intelligent production systems and processes, and the realization of networked distributed production facilities. The second is "intelligent production", which mainly involves the entire enterprise's production logistics management, human–computer interaction and the application of 3D technology in industrial production processes. The plan will pay special attention to attracting the participation of small and medium-sized enterprises and strive to make them become users and beneficiaries of a new generation of intelligent production technology, as well as creators and suppliers of advanced industrial production technology. The third is "smart logistics", which mainly integrates logistics resources through the Internet, the Internet of Things and logistics networks to give full play to the efficiency of the existing logistics resource suppliers, while the demand-side can quickly obtain service matching and logistics support.

6. Planning and Scheduling for Industrial Demand-Side Management under Environment of Energy Internet and Industrial Internet

6.1. Challenges for Industrial DR

(1) Industrial load adjustable characteristics analysis and screening methods

In the adjustable load screening method, the adjustable industrial load resources need to be evaluated from multiple dimensions. Each type of industrial load has its own advantages and disadvantages in dimensional indexes. Thus, it involves multi-objective optimization or comprehensive evaluation. Secondly, the adjustable characteristics of the industrial load are characterized by complex categories and large amounts of data, and different types of load resources have different characteristics and are affected by various factors to different degrees. Therefore, it is necessary to screen the key factors affecting various types of adjustable load resources in the construction of participation and satisfaction indexes. In addition, the value assessment of adjustable load resources is also a challenge, which requires a comprehensive quantitative assessment of the benefits of adjustable resources. Considering the above key information, it will be important to construct a load screening method that considers multidimensional assessments.

(2) DSM and industrial production integrated scheduling

As the proportion of new energy access increases, the adjustment of generating units alone can no longer meet the absorption of large-scale renewable energy. High energy-consuming loads can play their energy storage characteristics within a certain adjustment range to smooth out the fluctuations of new energy and provide power support for the grid. Realization of industrial demand-side response means that the original controller of the industrial load needs to be modified to upload the key production status information of the industrial load to the grid dispatch and to accept the power regulation instruction of the grid dispatch. The modification of the industrial load controller is a difficult point. Secondly, whether the uploading of key production information of industrial load causing the production information leakage or not is also a problem. In short, the realization of integrated scheduling of DSM and industrial production is a hardware and software prerequisite for industrial demand response.

(3) Modeling of industrial load multi-objective multi-constraint problems

In the process of industrial load regulable resource aggregating participating in system operation, there are different requirements for the regulation performance of regulable resources at the system level for different operation scenarios such as peak regulation, frequency regulation and standby. Different types of industrial load regulation resources have different regulation performance, production processes, production boundary constraints, regulation costs and comfort sensitivity. Making full use of the adjustable characteristics of industrial loads in different scenarios such as peaking and frequency regulation of power system involves full consumption of renewable energy. At the same time, the best overall regulation characteristics of adjustable resources, the minimum regulation cost and the maximum overall comfort of users are taken into account to achieve the synergistic operation of network-source-load in a power system.

(4) The dynamics and complexity of industrial load

The output and quality of industrial products are closely related to the production state. Industrial enterprises have strict requirements for production conditions. The study of controllable characteristics of industrial loads and the mining of the regulation capacity of industrial loads must be based on the industrial production process and load production constraints. In practice, the industrial production process may be very complex. The industrial load production constraints are often displayed as non-electrical variables, so it is necessary to consider the industrial load production stage characteristics and link such production characteristics with the industrial load electrical regulation variables to establish a model that meets the actual controllable characteristics of production.

(5) The load active response mechanism of multi participation of a grid company, power selling company and an industrial park

At present, the main profit mode of China's power selling companies is still making difference for "low buy and high sales". It does not involve peak adjustment or frequency regulation services, the fluctuation of renewable energy power and other value-added services. It is important to consider how to establish a reasonable load active response mechanism involving multiple parties of power grid company, power selling company and industrial park to realize the reasonable management and distribution of load control capability of load users. It can not only provide new peak regulation and frequency regulation manual for grid companies, but also smooth the power fluctuation of the agreement wind farm and photovoltaic power station to make sure all sides finally acquire profit.

6.2. Integrated Demand Response

Integrated demand response is an important manifestation of the convergence of energy, information and value on the demand-side in the Energy Internet. It provides an important opportunity for the demand-side users to achieve deep participation in power system regulation, transmission of energy market price signals and participation in the energy market.

With the further development of the Energy Internet, the demand-side integrated energy system (IDR) breaks down the traditional model of the independent operation of different energy systems. Deep integration and complementation of multiple energies such as electricity, thermal energy and natural gas on the demand-side can be achieved. It provides a new demand response path for the demand-side. Aras Sheikhi defines IDR as the derivation and expansion of the traditional power demand response in the integrated energy system. IDR enables the demand-side load regulation, energy storage and distributed system optimized operation via utilizing the coupling and complementation characteristics of different energies. Both energy transformation and load transition can be applied in IDR program. Energy users can not only shift their energy consumption, but also change the source of the consumed energy. Thus, IDR further taps the demand response potential and improves the flexibility of both the energy system and load, which is conducive to improving energy efficiency and reducing energy supply and energy costs.

The industrial load is stable and highly automated. It possesses great IDR potential. On the one hand, IDR can reduce congestion of energy pipelines in industrial parks, strengthen the balance of supply and demand, improve market liquidity and guide customers to change energy demand. On the other hand, IDR can improve the energy efficiency and reliability of the energy supply. However, there are great challenges in bringing industrial IDR into effect. The energy utilization system in industrial parks is complex, coupling multiple energy forms and involving multiple segments such as energy production, transmission and utilization. Furthermore, the load characteristics are strongly related to production processes and schedule. With the development of the Industrial Internet, industrial parks have realized the close integration of equipment, production lines, factories, suppliers, products and customers, bringing new challenges and opportunities to the development of industrial IDR.

In terms of modeling, there are various types of energy-consuming equipment, distinct energy utilization characteristics, multiple energy complementation and high uncertainties derived from renewable energy and industrial production schedule. The establishment of a reasonable and reliable load model and its response characteristics for demand-side devices is the foundation and keystone of industrial IDR. Existing studies mainly focus on steady-state modeling of the integrated energy system. For example, energy hub is used as an overall modeling method, which establishes a multi-energy flow coupling model using the input and output relationships of the external ports of the integrated energy system. Energy bus architecture is used as a local detail modeling method, which establishes a detailed analysis model using a multi-energy bus equation.

However, the steady-state model uses a specified conversion coefficient, which cannot reflect the dynamic characteristics of equipment operation. The nonlinearity and dynamic characteristics of the coupling equipment cannot be adequately described by the steady-state model. The industrial IDR deals with the production load, which requires high load control accuracy and safety criterion. Therefore, the dynamic modeling of IDR based on equipment operation mechanism is the future research direction. The use of a dynamic model based on physical mechanism modeling can accurately descript the equipment operating characteristics. The different load response time scale can be captured. However, the operation optimization using a dynamic model requires a large amount of calculation. Thus, it is difficult to meet the timeliness requirement of demand response.

Artificial intelligence-assisted load modeling is developing quickly. This data-driven modeling method shows low dependence on mathematical models and strong applicability to complex systems, but its simulation results lack verification and cannot be explained with clear mechanisms. Improving the interpretability of the data-driven model is the key to promoting its application.

Hybrid data-driven and mechanism-driven modeling is the future development direction. This modeling method can not only improve the accuracy and interpretability via mechanism-driven part, but also improve the calculation speed using data-driven results. Thus, a multi-level load model using this hybrid modeling method can be built and meet the multi-scale requirements of demand response businesses.

In terms of scheduling strategy, it often derived from solving the demand-side energy system operation optimization problems. Due to the different network characteristics of multiple energies, there remains a number of research highlights to be addressed in solving operation optimization problems with multi-level architecture and multi-agent participation.

One is how to optimize and solve the complex and non-linear problems caused by the coupling of multiple energy sources in the integrated energy system. The current research mainly focuses on two directions. The first is to convert non-linear problems into linear problems using piecewise linear approximation, branch and bound methods. Then, the approximately linear problems can be solved using linear methods such as mixed integer linear programming. Heuristic algorithms, such as particle swarm optimization algorithm, adaptively improved firefly algorithm, bacterial foraging optimization algorithm, etc., are also used to solve nonlinear and even non-convex optimization problems.

Another one is how to improve the optimization solving speed to meet the multi-time scale demand response with acceptable accuracy of the solution, such as day-ahead, intraday and real-time DR. The current main research directions include two parts. The first is to reduce the complexity of solving problems by optimizing mathematical algorithms. Sparse matrix dimensionality reduction technology and optimizing the model network equations are used to reduce the number of calculations. Adaptive damping factors and simultaneously changing the search direction and calculation step are used to improve the optimization algorithm applicability to large-scale energy network optimization problems. Second, increase the computer calculation and solving speed. Parallel iterative algorithms are used to accelerate the calculation speed. A serial solving calculation program is split into multiple parts on different cores according to the data transfer and control relationship in the energy network equations. By applying multi-threading technology to reduce the communication consumption in the parallel calculation, high performance, high precision and real-time simulation method can be formed.

In terms of market operation and mechanism design, current electricity DR is mainly achieved through the mechanism of government issuing demand and user bidding participation. However, due to the characteristics of multi-energy complementation and substitution, the IDR market mechanism needs further study in areas such as different energy prices, multi-agent information asymmetric trading behavior, etc. For IDR price receivers, how to optimize bidding strategies based on the service prices of various energy markets and their own response capabilities is the key to increasing the benefits of participating in demand response. For IDR price makers, how to consider the impact of multi-agent bidding strategies and the dynamic balance of multiple energy sources on clearing prices is the key to establishing a healthy and sustainable integrated demand response market environment. In addition, considering factors such as time dimension, regional span, energy type, etc., the establishment of a multi-level and multi-dimensional IDR evaluation method is the foundation to promote the IDR market.

7. Policy Guarantee and Market Mechanism

7.1. Current Status of Policy Mechanisms

The policy is the basic guarantee for the development of demand response, clarifying the legal status of demand response, the source of subsidies, and the rules of participation. From the evolution of demand response policies in Western countries, it can be seen that in the early stage of demand response, legislation was used to establish market status of demand response. The legislation provided a legal basis for the development of demand response and promoted the development of demand response through government subsidies.

With the gradual increase in the scale of demand response, the single source of subsidy funds can no longer maintain the sustainable development of DR. By establishing a system benefit charging system, a certain percentage of fees will be added to the electricity price (18 U.S. states add 1–3%), dedicated to demand-side management to provide a stable source of funds for demand response implementation. In contrast, China's demand response policy system has been initially established. At the national level, a number of policies clearly encouraged the development of demand response. However, none of them established the legal status of demand response in national regulations. At the provincial and municipal levels, there are 10 provinces that have issued special policies for demand response, which are mainly based on fixed-rate compensation. The sources of demand response subsidies are mainly from the peak electricity price premium funds and the surplus part of the power purchase price difference in the cross-provincial renewable energy power spot transaction. From a national perspective, the source of subsidy funds is relatively single.

The market mechanism is a strong guarantee for the sustainable development of demand response. In the early stage of the development of demand response, a subsidy mechanism with fixed rate compensation as the mainstay and market bidding mechanism as a supplement was mainly established. With the continuous development of DR, the market-oriented transaction mechanism has been gradually enriched from the initial emergency demand response projects. Economic demand response projects regard demand response as "negative watt generators" to participate in energy trading in the power spot market (SM). The UK has allowed large power users and load aggregators to participate in the ancillary service market (ASM) and shares the cost of ancillary services with the beneficiary market entities. France has established a capacity market in which demand response could participate, and introduced a "red, white and blue time-of-use electricity price" policy. Germany, the Netherlands and Belgium have adopted the incentive demand response of electricity price packages, which were represented by electricity sales companies to adapt to the decentralized electricity market transaction mode. In contrast, China's demand response mechanism is still in the pilot exploration stage. In northern China, it has been explored that demand response resources are packed to participate in the ASM. In Shandong, it has been explored that demand response resources and generating resources are joint clearing of the SM. The market mechanism of China needs to be further enriched and improved.

7.2. Market Insights for Industry Demand Response

In the future, the long-term development of industrial demand response will first be deeply integrated into the construction of the demand response market (DRM). Then, the operation of the DRM will be fully coordinated with ASM and SM. On the one hand, DRM will aggregate and participate in ASM transactions in the form of virtual power plants. On the other hand, it will be effectively connected with the SM, with the guarantee of capacity market (CM).

(1) Construction of DRM

The DRM is a market established for all customer-side adjustable power load resources with power control capabilities to participate in the demand response business fairly. In the DRM, industrial enterprises generally reach the response threshold (generally 500 kW) and can directly participate in the transaction. Users who have not reached the response threshold can participate in the transaction after aggregation through the load aggregator. The traded varieties are grid peak shaving, valley filling and their derivatives. The peak shaving varieties are mainly traded when the grid has peak load or the local transformer is overloaded, while the users take the initiative to reduce power. The valley filling varieties are mainly traded during heating seasons, holidays or time when electricity generated by clean energy is booming. The negative reserve of the grid is insufficient, while users take the initiative to increase the power. The automation level of industrial enterprises is high. Meanwhile, there are many types of loads, which therefore bring about many types of transactions that can be participated in DRM. The cost-grooming mechanism in the

DRM will adopt the principle of “who benefits, who bears”. First, the terminal electricity price should reflect the services brought by the reliable power supply for the users under extreme conditions. Secondly, the service for generators who benefit from the increase in electricity consumption and the mitigation service of deep peak shaving must be paid, as well. The income in the DRM will be shared by the users who provide the response of decreasing/increasing the power.

(2) Participation in ASM transactions

The DRM needs to coordinate with the ASM, because the ASM can provide more abundant application scenarios for demand-side resources. It is worth noting that the best way for adjustable loads to participate in the ASM is through virtual power plant aggregation. From the perspective of response volume, response speed and response cost, the adjustable load of industrial enterprises has the highest comprehensive value among the many resources of virtual power plants. Among them, there are both user-side energy storage and distributed power (even captive power plant) that can provide fast frequency modulation services, as well as industrial impact loads and non-industrial air-conditioning loads that can provide peak-shaving services when the response time is above several minutes. Compared with newly-built pumped storage, small hydropower and small centralized energy storage power stations, they are obviously economical. The virtual power plant aggregator will provide platform-based aggregation services for industrial enterprises. The ASM transaction signals above the virtual power plant aggregator platform do not need to be received by industrial enterprises. They only need to receive the regulatory signals sent by the platform. The income from the ASM will be distributed to the industrial enterprises according to their contribution degree.

(3) SM guidance and CM compensation

When the industrial virtual power plant has the same regulation attributes and market position as the power generation resources, it can further participate in the SM. The industrial virtual power plant will act as a real power plant node, essentially changing the physical model (power flow model) of the power grid. Under the premise of complying with safety-constrained unit combination (SCUC) and safety-constrained economic dispatch (SCED), the electricity price is quoted at marginal cost. At this time, virtual power plants that alleviate grid congestion and the impact of renewable energy volatility will be incentivized to participate in the linkage with other real power plants. Consequently, joint clearing of marginal electricity prices is realized. It will greatly improve the economics of power system operation. At the same time, the industrial virtual power plant will be used as a backup resource that can be met at all times in the power capacity compensation mechanism, in order to cope with the challenges brought by the high proportion of new energy generator assembly capacity and power generation. The stable operation of the power system can meet the peak load demand of users to ensure the reliable power supply. The power capacity can be auctioned. The auction time can be carried out several months or one year in advance, providing market members with multiple bidding opportunities and marginal clearing. The marginal cost of industrial virtual power plants is low, which attracts sufficient investment in industrial virtual power plants to participate in the CM.

The requirements of the external environment, the improvement of policy mechanisms in the energy and power industry and the advancement of technical means provide unprecedented opportunities for the development of demand response. Demand response will gradually develop in the direction of marketization and intelligence. However, demand response will also face some challenges in the future. First, when the power grid is under extreme circumstances in which market-oriented measures fail, how demand response continues to play a role is worthy of further discussion. The large blackouts in California and Texas in the United States in 2020 proved that under the influence of force majeure, demand response methods cannot meet the power system regulation requirements. In this case, relevant mandatory policies such as orderly use of electricity may be adopted to ensure the safe and stable operation of the power system and the reliable use of electricity for customers. The second challenge is how to achieve fair access and universal service. In rural or some remote areas, the penetration rate of demand response services is extremely low. It is necessary to lower the entry barrier for demand response so that more people can participate in demand response market transactions. Thirdly, there are some key technologies to be solved. For example, how to maximize the efficiency of system operation with the participation of demand-side resources needs to be further studied. Moreover, accurate and real-time forecasts of adjustable load resources at different time scales and efficient aggregation of demand-side resources at different levels in different regions must be achieved. Furthermore, how the emerging technologies such as big data, 5G and blockchain can be deeply integrated with demand response to facilitate the rapid development of demand response is quite a challenge.

8. Conclusions

This paper introduced the typical demand response and characteristic of industrial demand-side management. A review of the most important features of the industrial demand-side management has been presented. Planning and scheduling for industrial demand-side management under the environment of Energy Internet and Industrial Internet has been described in detail. Finally, the policy guarantee and market mechanism of industrial demand-side management has been designed in this paper. The construction of DRM is the basic of market design. The DR market will be operated greatly with the coordination of the ASM, SM and CM.

All in all, in the background of deep integration of Energy Internet and Industrial Internet, facing the existing challenges in demand response of power system, the authors of this paper believe in the following solutions. Firstly, we must research the production data-driven industrial load controllable characteristic modeling method, explore the coordination mechanism of multiple types of industrial loads that adapt to multiple regulation scenarios of the power grid, propose real-time industrial load control methods for real-time regulation needs of the power grid, and develop new low-cost technologies to realize the cooperative and interactive response of source-grid- load and storage. Secondly, we must develop multi-type demand response resources combined with cross-disciplinary deep integration means such as artificial intelligence, build a data-driven industry-wide demand-side adjustable resource pool, and realize accurate two-way sensing and interaction between power grid and load. This paper can guide a promising path for the vigorous development of industrial demand-side management in the future.

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