Architecture, Key Technologies and Applications of Load Dispatching in China Power Grid

Yu Dong, Xin Shan, Yaqin Yan, Xiwu Leng, and Yi Wang

Abstract—**With the development of renewable energy and the changes in the characteristics of power grid, it is becoming increasingly difficult to balance power supply and demand in space and time. In addition, the requirement for improved dispatching capability of power grid is increasing. Therefore, the potential of flexible load dispatching should be realized, which can promote the large-scale consumption of renewable energy and the construction of new power grid. Based on the analysis of existing load dispatching studies and the differences in the characteristics of domestic and foreign load dispatchings, a technical architecture and several key technologies are proposed for load resources to participate in power grid dispatching under the new situation, i.e., the autonomous collaborative control system of load dispatching. This system implements the multi-layer coordinated control of main, distribution and micro grids (load aggregators). Adjustable load resources are aggregated through an aggregator operation platform and connected with a dispatcher load regulator platform to realize real-time data interaction with dispatching agencies as well as the monitoring, control, and marketing of aggregators. It supports the load resources to participate in network-wide dispatching optimization via continuous power adjustment. Several key technologies such as the control mode, load modeling, dispatching strategy, and safety protection are also elaborated. Through the closed-loop control of orderly charging piles and energy storage clusters in the North China Power Grid, the feasibility of the proposed architecture and key technologies is verified. This route has successively supported multiple adjustable load aggregators to participate in the ancillary services market of North China Power Grid for peak-shaving. Finally, the technical challenges of load resources participating in power grid dispatching under the dual carbon goals are discussed and prospected.**

Index Terms—**Automatic power control (APC), load modeling, load dispatching, renewable energy accommodation, situation awareness.**

I. Introduction

In 2021, China clearly stated to make every effort to reach the peak of carbon emissions by 2030 and strive to achieve carbon neutrality by 2060. This is named the China dual-carbon goals. Besides, non-fossil energy will account for approximately 25% of primary energy consumption in 2030 and the total installed capacity of wind power and solar power will reach 1.2 GW or more [1]-[3]. However, the randomness and fluctuation of wind power and photovoltaic power generation are evident, and the increasing generation of renewable energy improves the requirements for their large-scale optimization configuration and the safe operation of power grid [4]. In the next decade, the daily fluctuation of newly-added power caused by renewable energy will exceed 500 GW. To balance power supply and demand in space and time will become increasingly difficult. The requirements of the dispatching capabilities of power grid will become higher [5]. Therefore, in the context of dual-carbon goals, the development situation of renewable energy should be considered, the potential of flexible load dispatching should be utilized, and the large-scale and efficient consumption of renewable energy should be promoted.

In order to achieve the balance between power generation and consumption, traditional dispatching and control are achieved by adjusting generator sets. However, when there is a large proportion of grid-connected capacity of intermittent energy such as wind power, the traditional dispatching mode, which relies solely on the adjustments achieved by the conventional generators to balance wind power fluctuations, fails to utilize the full dispatching and control capabilities of the power grid. In the future, demand-side controllable resources will be incorporated into the dispatching plan and real-time control system of the power grid. The transformation from the traditional model of "source adjusting with load" to the collaborative model of "source-load interaction" is promoted [6]. Several load resources have the potential of dispatching on the distribution network, which exhibit the characteristics of multiple points with large quantity, small capacity, low voltage level, and diverse subjects. These include various loads such as electric vehicles, distributed energy storage, air conditioning and electric heating of smart building, and industrial parks [7]. According to statistics, approximately 400000 electric vehicles were recorded at the end of 2018, among which approximately 230000 were in Beijing. The capacity of these energy storage resources exceeded 200 MW. The air conditioning ownership was approximately 80 million units, and the number of electric heating households reached 1.63 million. Guiding these resources to be included in the optimization control of the

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Y. Dong, Y. Yan, and X. Leng are with State Grid Corporation of China, Beijing 100031, China (e-mail: dong-yu@sgcc.com.cn; yan-yaqin@sgcc.com.cn; xiwu-leng@sgcc.com.cn).

X. Shan (corresponding author) and Y. Wang are with NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing 211000, China (e-mail: shanxin@sgepri.sgcc.com.cn; wang-yi2@sgepri.sgcc.com.cn).

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power grid, will increase the regulation resources of the Beijing – Tianjin – Tangshan power grid by a maximum of approximately 4 GW. Additionally, the power marketing and dispatching departments in various regions have established marketing demand response systems or interruptible precise load shedding systems of various degrees, which gather a considerable amount of load resources to cope with the extreme conditions of the power grid, such as the tension of peak summer balance or DC high-power lockout. If these are included in the routine dispatching of the power grid, the dispatching capability of the power grid will be considerably improved and the level of clean energy consumption will be increased [8], [9].

The rapid development in 5G communication and the Internet of Things have led to significant increases in the technical level of various load terminal devices such as electric vehicles and distributed energy storage, interconnect implementation, perceive, measure, and control terminal loads [10]. If adjustable load resources are guided by efficient technical support and innovation combined with market-based incentives to respond to power grid dispatching through continuous power dispatching, the dispatching potential and flexibility of load-side resources will be completely realized, and a win-win situation for the power grid and users can be achieved [11].

Therefore, the operation form of the power grid in China is changing with the rapid development of ultra-high-voltage (UHV) power grid and renewable energy, gradual improvement in the electricity market, continuous advancement of two-way interactive power consumption of users, and diversified and multi-directional flow of electric energy and information. In order to adapt to this situation, the dispatching and control modes of the power grid will also undergo major changes, presenting new requirements for the business support of dispatching systems in the future [12]-[14]. Reference [15] models load communication delay and packet loss, and proposes a new aggregation control strategy considering the number of users being controlled. The control strategy has the characteristics of low delay and high accuracy to control the load group, which can ensure the timeliness of the control action, so as to suppress the depth of the system frequency drop, reduce the frequency adjustment error, and reduce the risk of system instability. Reference [16] carries out global unified planning for power dispatching information from the aspects of object identification coding rules, model rules, modeling methods, and global sharing. It proposes a structured design scheme of general data object for power dispatching oriented to regulatory cloud. The scheme will lay a solid foundation for business cooperation and data exchange and sharing among professionals and institutions, and strengthen the centralized decision-making of power grid operation. Reference [17] proposes a hierarchical and partitioned emergency load cutting system architecture, which divides the load distribution network into several regions. For each region, the model parameters of the external network equivalent are identified by local measurement, and the load cutting optimization model considering the external network equivalent is established. This model is transformed into a second-order cone programming model, which can be solved effectively by using the second-order cone relaxation technique. Reference [18] establishes a multi-level power dispatching model of flexible load taking into account the predicted mean vote (PMV), and proposes a consumption allocation strategy taking into account the PMV of multi-region users. Based on the power state queue, a joint dispatching strategy is carried out for the flexible load groups with single and multiple power levels, and the load power is dynamically adjusted according to the variation of consumption. It will realize accurate consumption, improve the users' comfort, and make the multi-level power loads run smoothly.

Based on the goal of dual-carbon, this paper proposes a technical architecture and several key technologies required to incorporate adjustable load resources such as electric vehicles, distributed energy storage, air conditioning, and electric heating of smart buildings into the scope of power grid load dispatching. After converging through aggregators, adjustable load achieves interconnection and awareness on the dispatching side. Through automatic power control (APC), the continuous power dispatching of the load resource cluster can be achieved. Furthermore, the power and time flexibility of the load will be completely utilized, increasing the power grid dispatching resources and helping to reduce peaks and troughs and clean energy consumption. Through the practical cases in North China Power Grid, the coordinated control function of the source, network load, and storage is expanded, and the proposed load dispatching architecture and key technologies are validated. Finally, the technical challenges of large-scale adjustable load resources participating in power grid dispatching are discussed and prospected.

II. Overall Structure of Load Dispatching

A. Characteristics of Power Grid Load Dispatching in China

The situation and characteristics of load dispatching in China and other countries are not the same. Other countries generally operate within a power grid area. The electrical distances between the power source and the load are relatively short. The transmission and the distribution can operate in a decoupled manner. The load dispatching is realized on the distribution level. In Maryland, USA, as for measures and managements after power accidents, load dispatching is not directly conducted by dispatching operators but by the regional dispatching agency [19]. A new power system focusing on renewable energy is being built in China. The power generation centers of renewable energy are primarily located in the west of China. Power will be transmitted to the eastern load centers thousands of kilometers away through UHV AC/DC transmission. The transmission and distribution have a strong interaction. Load dispatching should be achieved through the framework of centralized coordination of transmission and distribution and regional autonomy within the distribution network. The current dispatching system in China has a five-level dispatching architecture, i.e., national dispatching – regional dispatching – provincial dispatching – local dispatching – power distribution [20]. The objects of load dispatching are distributed with a considerable amount in the latter three levels. Therefore, resources need to be aggregated from the power distributors and aggregators, and then flexibly connected to the regional, provincial, and local levels for different needs [21]. For example, to solve the problems of cross-regional renewable energy consumption and high-power loss, regional dispatching needs to be connected; to solve the problem of renewable energy consumption within the province and the power problem of internal divisions, the participation of regional dispatching is also needed; to solve the problems of distributed renewable energy consumption, local congestion, voltage, and other issues within an urban power grid, it is necessary to connect to the local dispatching.

Differences can also be observed in the incentive mechanism of load dispatching in China and other countries. Several developed countries have relatively advanced experience in the development and research of responses to user demands [22]. The United States and the European Union have gained rich practical experiences in demand response. Their technology and market mechanisms are also relatively mature and complete. The United States has quit from some demand response projects such as the capacity markets, electricity markets, and ancillary service markets. The European Union has launched a pilot project for the automatic demand response to industrial and commercial equipment, which guides users to actively participate in services such as demand response, peak-shaving, and frequency modulation through market means such as electricity price incentives and demand-side bidding. The Singapore Wholesales Electricity Spot Market is a single electric energy market. To encourage the demand response to participate in the market, the subsidy is not based on marginal pricing but is calculated based on one-third of the increase in consumer surplus. Furthermore, its penalty mechanism is relatively strict [23]. The Electric Reliability Council of Texas in the United States operates the day-ahead and real-time electric energy markets, with a "price cap" reaching 9000 $/MWh (approximately 62 yuan/kWh). Furthermore, it allows load projects to participate in the ancillary service market. The upper limit of the load items that provides the spinning reserve services for the Texas wholesale market was initially set to be 25% of the total spinning reserve service demand, which was increased to 50% in 2006. At present, China has a two-level spot market that comprises inter- and intra-provincial spots. Some provinces and regions in China are promoting the construction of electricity market, but its development is still in its infancy; further, compared with the electricity markets in foreign countries, the market in China is just in the beginning [24]. In this market environment, it is difficult to regulate the grid by adjusting the dynamic demand response in real time based on prices or incentive signals.

Therefore, the load dispatching system in China needs to: ① consider the characteristics of large-scale UHV long-distance transmission, super-massive load dispatching objects, inconsistent levels of development of power grid in various provinces, and inconsistent development stages of the electricity market in various provinces; ② be integrated with the existing five-level dispatching framework and two-level spot market; ③ be consistent with the current statuses of power grid and market development to achieve the goals of step-by-step implementation and coordinated development in different regions.

B. Overall Framework

Demand-side resources are complex and exhibit some characteristics such as small capacities, massive quantities, and wide distribution [25]. In the future, in each region, the cost of demand-side response, power response characteristics of adjustable resources, etc., will be different. The demand-side resources themselves exhibit the problem of coordinated dispatching and control in a wide area [26]. In particular, the distributions of wind power (and other renewable resources) and loads in China are in reverse. Therefore, the dispatching technology support system needs to achieve not only the wide-area coordinated control of the demand-side resources themselves, but also the cross-regional coordinated dispatching of renewable energy power generation and demand-side resources from the level of the entire interconnected power grid.

According to the existing supervision rules in China and the principles on management and division of labor for load aggregators of State Grid Corporation of China, there are currently four main types of load resource aggregators [27], including Internet of Vehicles platforms (electric vehicles), smart energy service platforms (user-side energy collection, hosting and demand response), third-party independent entity (virtual power plants) aggregators, and large users (self-provided power plants, large industrial users). Based on the dispatching characteristics of various load resources and the differentiated dispatching requirements, load dispatching for multiple scenarios is formed to support the efficient consumption of clean energy and the safe and reliable operation of the power grid. The scenarios and goals of load dispatching are shown in Fig. 1.

Based on the current status of the dispatching system and electricity market, as well as the load characteristics in China, this paper proposes an architecture of an autonomous collaborative control system for load dispatching, as shown in Fig. 2 [28]. The characteristics of the architecture are as follows.

1) The architecture entails a "three-level connection to control, two-level market" model based on "sub-center – provincial dispatching – local dispatching/aggregator" which is compatible with the existing five-level dispatching framework and two-level spot market to adapt to the existing control architecture and market model. Meanwhile, it also considers the development trend of regulating cloud and aggregators in the future. It can achieve a seamless connection of the system and the phased development of functions. The significance of classification modeling and partition monitoring in regional scheduling is as follows. Classification modeling is to model different types of loads. Partition monitoring is based on topology analysis to divide the power grid into hierarchical power supply areas which can monitor the power generation, load and other information of the respective areas.

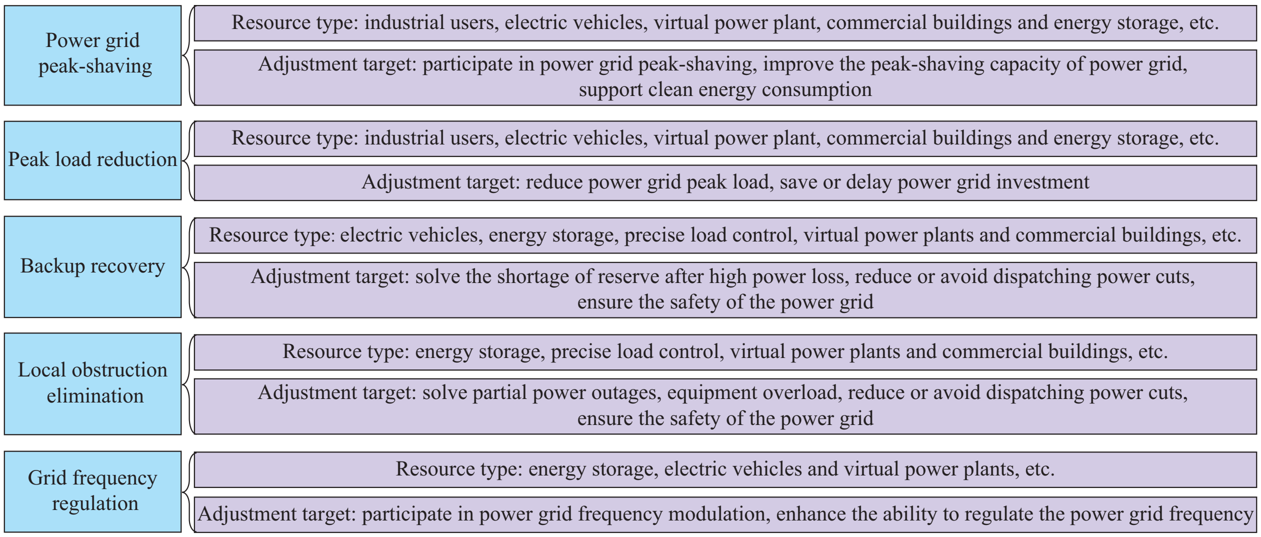

Fig. 1. Scenarios and goals of load dispatching.

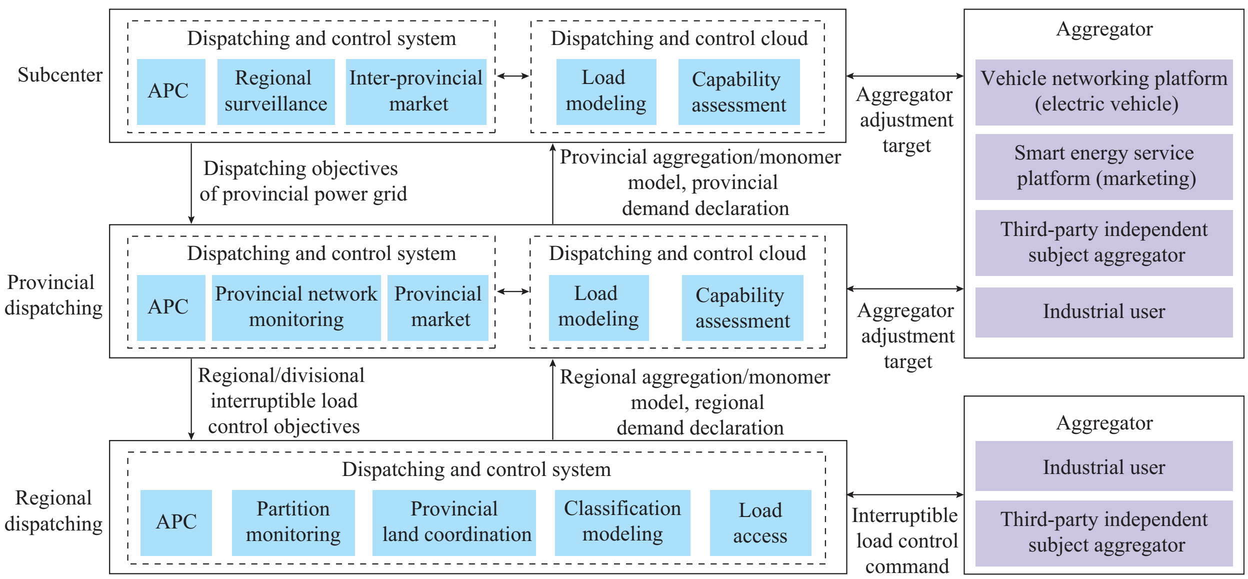

Fig. 2. Framework of autonomous collaborative control system for load dispatching.

2) This architecture adopts a multi-layer autonomous collaborative control mode, which can effectively solve the problems of various load types, small capacities, and complex characteristics, and reduce the impact of the uncertainty of a single load on the power grid through multi-level aggregation and control. The architecture satisfies the requirements for the large-scale participation of adjustable loads in real-time dispatching and control in the new situation. It not only inherits the traditional merits of distributed control system such as reliability and flexibility, but also strengthens the comprehensive application of system-wide information.

3) This architecture adopts the coordination method with a dispatching system and cloud. It deploys adjustable load access, monitoring, control, and other functions on the smart grid dispatching and control system (i.e., the D5000 system). It also deploys full-path modeling and sharing of adjustable loads, reference power prediction, load characteristic analysis, adjustment performance evaluation, and other functions in the control cloud, with a focus on analysis.

This architecture supports multi-level access of aggregators to the spot market. Four types of aggregators can perform market declaration, clearing, and settlement through sub-center/provincial dispatching to solve the problems pertaining to the transmission grid level, and have consistent access methods with the current Internet of Vehicles platforms and smart energy service platforms. Industrial users and aggregators can also avail access through local dispatching to solve the problems pertaining to the transmission and distribution coordination levels. This method is consistent with the current access methods for industrial users.

C. Main Innovations and Key Technologies

This load dispatching framework can realize the new power grid scheduling mode of generation, load, and storage, improve the flexible dispatching capacity and operation efficiency dramatically, and support the safe and reliable operation of the power grid and the efficient consumption of clean energy. The main innovations and key technologies of this paper are shown in Fig. 3.

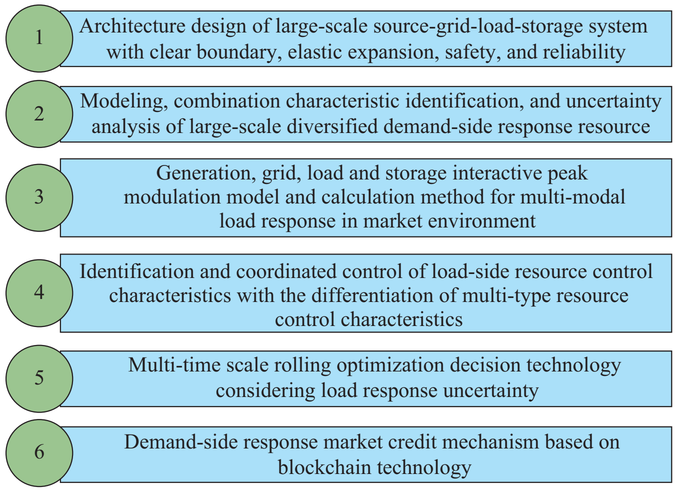

Fig. 3. Main innovations and key technologies.

III. Key Technologies for Load Dispatching

A. Control Mode

As the scale of renewable energy power generation continues to increase, the uncertainty of load changes, and restrictions such as backup and network security constraints are affected, local power grid cannot easily achieve power balance by coordinating the output of conventional units within the region [29]. The current power balance mode of "balance in province" should be broken and expanded to the regional and even national power grid. Large-scale unified centralized coordinated control decisions should be made for the entire network, and the unit status, load changes, and generation of renewable energy from each regional power grid should be integrated to maximize the optimization and dispatching of resources. This paper proposes to build a control system with "centralized coordination and regional autonomy" based on the safe operation of the power grid and with the goal of maximizing the consumption of renewable energy.

1) Core Reflection of Centralized Collaboration

The four types of load aggregators send load models and real-time data to the dispatching agencies and participate in the load service market through market declarations. The dispatching agency reasonably sets its target values of control or operation based on global calculations and completes the joint clearing of resources on both the power generation side and the load side of forming an adjustment curve that guides load aggregators. During the day, the APC module generates global optimization instructions in real time according to the load dispatching curve and sends them to load aggregators, who will decompose the instructions and send them to the load terminals for execution. Through global coordination, the global optimality of control is achieved to optimize the overall goal.

2) Core Reflection of Regional Autonomy

The objects of autonomous control consist of a sub-control area in space, such as a certain local dispatching area or load aggregator. Using fast adjustable resources in the area, the changes in the state quantity caused by the fluctuation of the injection quantity within the area are controlled within a certain target value or a given range, which was set in a centralized and coordinated manner, making the control area more friendly and easier to interact with outer areas in the overall global system. This will help reduce the complexity of the problem through distributed autonomy, to obtain control agility, reliability, and operability. The distributed algorithm of regional autonomy refers to the method of APC module adjustment curve according to the load. It generates the whole network optimization instruction in real time, and sends the regional adjustment instruction to the regional load aggregator at the same time. The specific process is shown in Fig. 4.

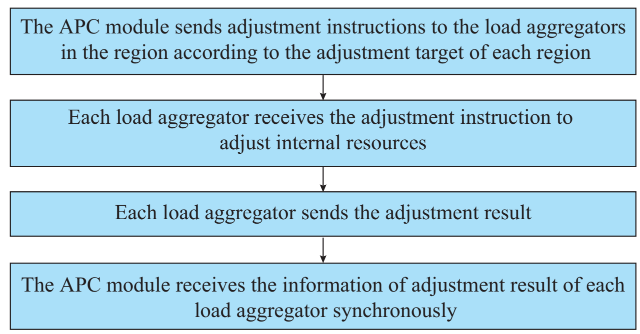

Fig. 4. Specific process of regional autonomy distributed algorithm.

3) Control Goal of Sub-centers: Regional Coordination

Each sub-center uses the D5000 system to perform APC, regional monitoring, acquisition of inter-provincial spot market data, and distribution of the province-level power grid control targets to the provincial dispatching. Further, it deploys the four types of load modeling and capability assessment functions on the control cloud. The sub-centers interact with the operation platform of aggregators through the communication interface. The operation platform uploads data such as the real-time power of the adjustable load resources and the adjustment target to the load dispatching platform. The data is not only shared with the control cloud or ancillary service market system, but also sent to the data collection and monitoring module after the data text is generated on the load dispatching platform. To decompose the control targets, the adjustable capacity data of load need to be obtained to establish and update the basic model of single resource and adjustable capacity database. Using the basic model of single resource, adjustable capacity database, hierarchical partition and multi-level aggregation object, the adjustable capacity of aggregation object under different dimensions is analyzed and derived. According to the adjustable ability, the power grid control targets are decomposed and sent to individual resources. As for the modeling and control of individual load, the work is conducted by the load aggregators in the lower layer.

After receiving the control instructions from the sub-center, the provincial dispatching uploads the demand and load aggregation model at its level and sends control instructions to the local dispatching. The local dispatching implements basic functions such as operation monitoring and operation control of the power grid in various areas, and provides information support such as accurate and reliable power grid operation status to the dispatching and analysis level. Other than APC and regional monitoring, provincial-local coordination, classification modeling, and load access should also be implemented. Further, the ability to directly upload the regional requirements and models without going through the control cloud should be realized. For large-scale users and third-party independent aggregators, the load interruption control instruction can be executed through local dispatching under certain conditions.

In order to adapt to the development of power grid and electricity market in China, load dispatching includes the following two modes. One is the market-oriented adjustment mode, where the central or provincial dispatching sends the overall adjustment targets to the aggregators, which are decomposed and issued to the terminals for being executed by aggregators. This mode considers safety and economic coordination. Another is the interruptible load control mode. From provincial to local dispatching, the control targets are issued according to the regional division. The local dispatching performs the strategic decomposition and execution. This mode primarily considers safety.

B. Load Modeling

The load modeling in the proposed framework refers to the dispatching capability modeling including two aspects. One is the dispatching capability modeling of load aggregators for the dispatching and operation of power grid; the other is individual load modeling for aggregators. The load models are established to accurately describe the relationships between environmental variables, equipment parameters, and power changes. The current mainstream research method is the construction of precise physical models. Equations are used to reflect the correlation between variables, such as thermodynamic models of water heaters and air conditioners [30]. The modeling problem on the load side is different from that on the power generation side, where the control characteristics are relatively consistent. In practical applications, the actual load operation model is affected by unstructured influences in several aspects, such as by the subjectivity of users' behaviors, differences in manufacturer parameters, and non-deterministic influence parameters of the environment. The model cannot be easily described in detail. Most of the current solutions are focused on a relatively ideal setting in one or several situations [31].

The load modeling methods mainly include statistical comprehensive modeling, measurement-based method, and fault-based simulation method. The inputs of these methods are load types, voltage grades, and electrical data, and the outputs are the load model and its parameters. The aggregation model is mainly a classification model of automatic aggregation of individual regulated resources from three dimensions of space, time, and object based on the individual model. The time scales include second level and minute level. The resource types include industrial users, non-industrial air conditioners, energy storage, load aggregators (including smart parks, commercial buildings, integrated energy bodies, etc.), electric vehicles and group control load collection quantity, predicted value, response rate and control effect, etc. It supports business scenarios such as blockage elimination, backup control, and power balancing. Obviously, the modeling method varies with load types to make the model more accurate. Different methods are suitable for different scenes and load types to meet the requirements of strategy optimization and cluster control.

The load modeling from the view of load aggregators is used for balancing power and load dispatching. For multiple types of devices, it is difficult to accurately describe all physical models due to the heterogeneity of device types and factory parameters [32]. From the view of aggregators, the physical load models mainly include two types: electrovalence-response model and excitation-response model [30]. The detailed models are presented as follows [33].

1) Electrovalence-response Model

Electricity price is a flexible response mechanism. Through economic leverage, various types of flexible loads are urged to change their electricity consumption behavior so as to participate in the interaction. With the change of electricity price, the change of electricity demand can be in the following two ways. Part of the load cannot be transferred to other time periods (for example, lighting load), and this part of the load can only be "yes" or "no". Therefore, this type of load is only sensitive in a single period, called "self-elastic demand" and its elasticity value is negative. Part of the load can be transferred from the peak period to the off-peak period or the trough period. This kind of load has multi-period sensitivity, which is called "cross elastic demand", and its elasticity value is positive.

To simplify the calculation, the electricity-price-type loads in this paper all refer to the electricity-price-type loads with self-elastic demand.

The response model of electricity-price-type-load $P_{i,1}$ can be characterized as:

$$P_{i,1} = P_{i,0} + \varepsilon_{i,i}(c_i - c_{i,0}) \tag{1}$$

where i is the flexible load type; $P_{i,0}$ is the initial power; $\varepsilon_{i,i}$ is the self-elasticity coefficient; c_i is the actual electricity price; and $c_{i,0}$ is the initial electricity price.

The interaction cost of invoking electricity-price-type loads λ_1 can be characterized by the change of electricity sales revenue on the grid side as:

$$\lambda_1 = \frac{1}{\varepsilon_{i,i}} P_{i,1}^2 - P_{i,1}\left(\frac{1}{\varepsilon_{i,i}} P_{i,0} - c_{i,0}\right) - P_{i,0} c_{i,0} \tag{2}$$

2) Excitation-response Model

Excitation is also a flexible response mechanism. Typical excitation loads include interruptible loads and direct loads. Taking interruptible loads as an example, they participate in power grid dispatching operation by signing contracts. The content of the contract includes advance notice time, duration, load dispatching capacity, discount rate, compensation rate, etc.

The response model of the excitation load $P_{i,2}$ can be characterized as:

$$P_{i,2} = P_{i,0} + \Delta P_i \tag{3}$$

where ΔP_i is the load dispatching capacity.

When the user reduces or increases the load in response to the incentive contract, the interaction cost of invoking the incentive load can be represented by the change in the electricity sales revenue on the grid side as:

$$\lambda_2 = \alpha c_{i,0} \Delta P_i \tag{4}$$

$$\lambda_3 = (1-\beta) c_{i,0} \Delta P_i \tag{5}$$

where α is the discount rate; and β is the compensation rate.

On this basis, some data-driven technologies such as neural network and support vector machine (SVM) are applied to conduct the parameter updating and model correction. In order to improve the accuracy and actual fit of the model, the parameters of the generalized model are time-varying. Based on historical data, key features are extracted to establish standardized models and obtain the corresponding parameters. With data accumulation, the load model and parameters keep updating to finally meet the accuracy requirements. The schematic diagram is presented in Fig. 5 [30].

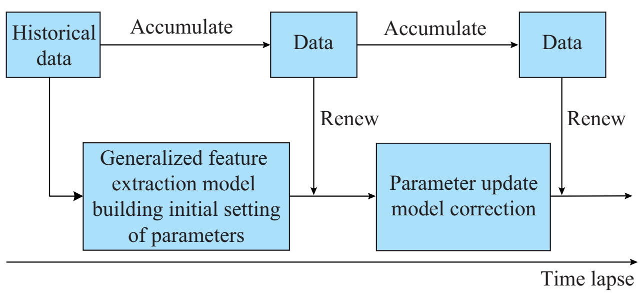

Fig. 5. Schematic diagram of load modeling correction and parameter updating based on data-driven technologies.

Therefore, load dispatching needs to solve the basic modeling problems caused by the integration of massive flexible resources, e.g., how to model massive heterogeneous resources for dispatching behaviors, how to consider the decision-making behaviors and dynamic processes of the responding subjects with limited rationality and limited information to effectively perceive the multi-dimensional response potential, and how to protect the users' privacy.

According to the information agreement between individual load users and load aggregators, the bidirectional data transmission is carried out through bidirectional identification authentication policy. The whole process of data transmission is monitored through the active tracking and confirmation strategy of information interaction state. The information of individual load users does not interact with the power grid directly instead of the load aggregators. Load aggregators interact with load individuals according to power grid instructions to ensure the privacy of load personal information.

The multi-dimensional load response potential with multiple goals of voltage dispatching, blockage elimination (such as the surface and equipment overloads), peak dispatching, and frequency modulation is dynamic. The users' response behaviors are affected by the response goals, response time, response decision, and group behavior. They often exhibit spatial heterogeneity and dynamic changes in time, which gradually help attain the balance. To perceive the response situation and accurately obtain the multi-dimensional response potential holographically for total information, it is necessary to start from the dynamic response, aim at different response goals, analyze the continuous changes in response groups during different time periods, and continuously adjust the model for response strategies.

With extensive studies conducted on the application of big data technology, it is possible to directly analyze the target association relationships using the large amount of result data to obtain a generalized model, avoiding the deviation of the physical model caused by the diversity of equipment and users' behaviors. Meanwhile, according to the data analysis results, the users' categorical characteristics can be traced in a reversed manner, the load situation can be further analyzed, and the generalization model can be revised. Therefore, the establishment of load models and user-behavior analyses based on data-driven technologies are critical for the load dispatching of the power grid in the new situation. Therefore, the adaptive multi-scale generalization modeling and the response potential evaluation of massive flexible heterogeneous resources are the key modeling techniques.

C. Dispatching Framework

With the continuous increase in the generation of renewable energy, the uncertain factors brought by intermittent energies, represented by wind power and solar energy, have increased. Furthermore, the load exhibits random fluctuations. These increase the uncertainty of the operation status of the power grid [34]. More importantly, the capability of massive dispatching resources is a more complex random variable. Its response time, location, capability, and decision-making are all random. Therefore, it is of great significance to consider the coordinated dispatching problem of controlling resources with multiple types and loads with multiple time sequences, while utilizing the rapid response capabilities of various loads, to formulate effective dispatching strategies to satisfy the requirements of the safe operation of the power grid.

In scenarios such as power grid peak-shaving, frequency modulation, renewable energy consumption, and ancillary services, power grid dispatching has different goals and constraints on the dispatching speed, capacity, duration, and even dispatching costs based on different scenarios. In response to the dispatching requirements in multiple scenarios, the loads need to have a strong time domain and functional complementarity and need to provide continuous dispatching capabilities and demand matching groups that adapt to multiple scenarios, forming a navigational match between load characteristics and power grid dispatching requirements. These practical demands of load dispatching aim to participate in balancing and adjusting supply and demand of power grid and to create interactive and intelligent power grid.

In recent years, with the gradually mature technologies such as big data analysis and mining, situational awareness, and artificial intelligence, an increasing number of effective processing methods have been provided for the collection, perception, and control of large amounts of interactive information required for load dispatching. Among them, data mining and artificial intelligence can mine and extract the effective feature information in the load data, providing a reference for the determination of important parameters of the generalization model and avoiding the redundant impacts of a large amount of data. In addition, situational awareness, analyses, and deduction technology can deeply analyze the potential coupling relationships and usage correlation characteristics between multiple users and devices [35]-[37]. Quantified loads can control the potential space, which lays the foundation for the development direction of precise, intelligent, and practical load control.

D. Communication Protection

The load dispatching platform is a supporting platform deployed to adapt to the participation of adjustable load resources in the control business. It is a part of the D5000 system, through which it extends to the Internet. It is mainly positioned as a gathering and processing center for load resource information. It undertakes and analyzes information using traditional automation systems, along with on-demand interaction among monitoring, control, and market data in various systems. It supports the adjustable load resources to participate in the control business, without affecting the traditional business structure of the existing production control. It includes the functions such as basic platform, data collection, processing and verification, model data storage, ancillary analysis and decision-making, instruction forwarding, control performance evaluation, and visual display.

In the new scenario, the network used by the load dispatching platform is extended from the original dispatching data network to the Internet, which is from point-to-point control to multi-level collaborative control. The transparent sharing of power grid information is achieved, making the information security issues faced by the technical support system of the power grid dispatching more complicated and severe. There are illegal visits from both outside the system and legitimate users in the system. During the process, communication delays, packet loss, and other situations may also occur. The network and response characteristics are inconsistent, and the differences are relatively large [31]. Ensuring the effectiveness and safety of control has recently become a topic of interest.

The first problem is the communication network architecture. Since the nodes of the system need to cooperate closely and collaborate to complete the users' tasks, the communication overhead between nodes is high. Higher requirements are placed on the load-carrying capacity of the communication network. Secondly, it is necessary to establish an efficient, safe, and reliable communication mechanism for the dispatching system platform. High-speed data transmission in wide-area network (WAN) broadband is susceptible to interference, which has a high bit error rate and reduces the utilization of bandwidth resources. Therefore, it is necessary to investigate the reliable high-speed data transmission technologies. Thirdly, on the basis of reliable communication, it is necessary to ensure real-time data communication between the dispatching system platform and the applications, and among applications themselves. Therefore, it is necessary to study the protocols and models of message bus and service bus suitable for the environment for a wide area, to meet the real-time and security requirements of the system.

As for the cyber-security issue, there are two methods to solve the problem of network security. In terms of load resource access, the hardware can guarantee the system security to use special firewall, physical isolation device, logical isolation device, and other physical network isolation hardware, and realize one-way data access among the production control area, management information area, and Internet area. For software, it ensures the security of information network by means of user authority control, digital certificate authentication, data encryption, and other technical methods. When load aggregator is connected, two-way identity authentication is required first. The data exchange channel can be established only when the identities of both parties are authenticated. During data interaction, secure socket layer (SSL)/transport layer security (TLS) protocols based on asymmetric encryption algorithms are used to encrypt data. The encrypted data are sent separately from the key, preventing the transmission from being eavesdropped or tampered. Therefore, it ensures the integrity and security of the transmitted content. In terms of load dispatching instructions, blockchain technology is introduced into the control of load-side resources. The non-modifiable and non-replicable characteristics of blockchain are combined with the high security and reliability requirements of load dispatching instructions. It prevents the issuing of untrusted source dispatching instructions or the tampering by unauthorized users to ensure the safe transmission of load dispatching instructions and information confidentiality.

IV. Practical Application of Load Dispatching

A. Practice Scheme

Under the strategic guidance of "reaching carbon emission peak and carbon neutrality", the proportion of installed capacity of renewable energy continues to increase. The total installed capacity of heating machines in the North China Power Grid during the heating period of 2019-2020 was 182.89 GW, accounting for 73% of the installed capacity of thermal power, an increase of approximately 2%. The total installed capacity of heating machines in the Beijing－Tianjin－Tangshan power grid was 51.37 GW, accounting for 77% of the installed capacity of thermal power, an increase of approximately 2%. The increase in the proportion of heating units reduces the peak-shaving capacity of the units and compresses the space for renewable energy consumption. During the difficult period of renewable energy consumption, the minimum average power generation load rate of the Beijing－Tianjin－Tangshan power grid reached 50.92%, the average power generation load rate during the night trough period reached 59.99%, and that in the afternoon trough period reached 60.93%. Peak-shaving resources are clearly insufficient. There is an urgent need to find out various adjustable resources for peak-shaving.

By taking advantage of and guiding the characteristics of "flexible time of electricity consumption, guidable electricity usage behavior, predictable electricity usage patterns, and intelligent electricity usage methods" of these resources and incorporating them into power grid optimization control, up to 4 GW of dispatching resources will be added to the Beijing - Tianjin - Tangshan power grid.

By deploying a load dispatching platform and expanding the multi-coordinated control function of the source network load and storage, North China Power Grid has successively achieved the resource access of a total of six load subjects (electric vehicles, distributed energy storage, virtual power plants, electric heating, vehicle-to-grid (V2G), etc.) in three aggregators. The network access of load dispatching platform is shown in Fig. 6. Resource access with companies such as State Grid Comprehensive Energy Service Group Co., Ltd. and China Tower Co., Ltd. is underway.

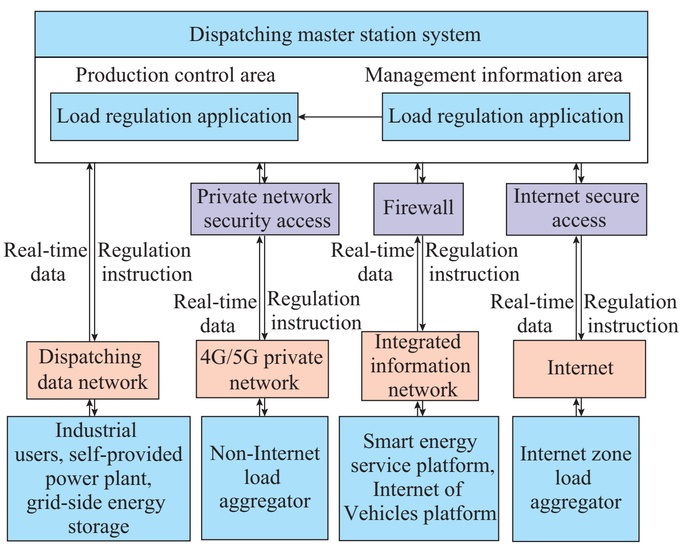

Fig. 6. Network access of load dispatching platform.

On May 21, 2019, the D5000 system of North China Power Grid firstly achieved interconnection with the operation platform of the State Grid Electric Vehicle Company. On May 31, 2019, through AGC, the charging power of a single electric vehicle was adjusted. On June 18, 2019, 168 hours of joint real-time control of charging and discharging power of electric vehicles and distributed energy storage clusters were achieved. On November 23, 2019, the continuous adjustment of the thermal load power of the Zhangjiakou Dongyuan Thermal Power Plant Boiler of China was achieved under the management and control platform of the North Hebei Virtual Power Plant of China. On April 14, 2020, the two-way power AGC control of electric vehicles was achieved for the first time through V2G charging piles.

The peak-shaving auxiliary service market in North China Power Grid has access to 2651 charging/changing stations independently operated by the third parties and a total of 27006 charging piles through the multi-coordinated scheduling and control platform of generation, network, load, and storage. In April, the number of modified V2G charging piles made the breakthrough from 0 to 1. There are 6 distributed energy storage power stations and 5 types of loads, such as large industrial load and regenerative electric heating, with a total resource of 266 MW and peak-regulating power of about 40 MW. Taking the 168-hour test on June 18, 2019 as an example, the North China Power Grid performed power optimization and closed-loop control on electric vehicle clusters and distributed energy storage clusters for seven consecutive days. Before optimization, electric vehicle clusters had the smallest charging load at the most difficult peak-shaving time at night. The load trend was opposite to the demand for peak-shaving by the power grid. Although distributed energy storage is charged during the low trough at night and discharges in the morning and evening during the peak, there is still a large room for optimization in terms of charging and discharging periods and power targets. During the closed-loop period, the two types of aggregated resources were put into the controlled mode by AGC in North China Power Grid. During the control period, the command tracking situation was relatively good, reflecting the high-quality adjustment performance of load resources, as shown in Appendix A Fig. A1.

B. Application Effectiveness

Through the implementation of the proposed technical framework for adjustable load resources to participate in power grid dispatching control, the aggregator declared information such as the capacity of the aggregated resources, actual controllable upper and lower limits, and state of charge of battery. Two new control objects, electric vehicles and distributed energy storage, were added to the D5000 system of North China Power Grid. Combining with the day-ahead load prediction and peak-trough characteristics of the Beijing - Tianjin - Tangshan power grid, the load resources were included in the conventional dispatching resource pool for the optimization and formulation of ideal charging-discharging curves. For the first time in China, North China Power Grid achieved continuous power adjustment of load resources through AGC at the dispatching end. A continuous increase in the charging power of electric vehicles and distributed energy storage during the load trough period in the early morning was achieved. Furthermore, the discharging power of distributed energy storage increased continuously and dynamically during morning and evening peak hours (see Appendix A Fig. A2). On the premise of equipment safety and meeting the users' experience, power adjustment synchronized with the day-ahead predicted peak-shaving demand was achieved.

The practice projects also have great effects in partial-area power grid. ① Electric vehicles can participate in the peak-shaving. The bus station in Tianjin Dongli Development Zone is taken as an example. From 01:00-04:00 am on December 18, 2019, the average power during peak load was around 1400 kW, while the historical average power was basically 0. ② The target output of State Grid Electric Vehicle Company charging pile was 46.97 MW, while the actual output was 41.32 MW. The target output of controllable load of Northern Hebei was 7 MW and the actual output was 7.1

MW. The tracking errors were within the acceptable tolerance. ③ During the pilot period, from December 12, 2019 to April 30, 2019, the system run smoothly, the network was safe and reliable, the market operated well, the settlement was timely and accurate, and the information release was open and transparent, which has been fully recognized by all market entities. The third independent entity received 2.68 million yuan in peak-adjustment revenue, promoting new energy consumption of 19.53 GWh.

This practice has achieved real-time connection and data sharing between the dispatching automation system and the operation system of load aggregators for the first time in China, breaking through barriers on multiple levels and achieving the power aggregation perception and monitoring of electric vehicles and distributed energy storage. By incorporating adjustable load resources into the AGC scope, power optimization and closed-loop response based on the day-ahead load prediction have been achieved, showing that it is technically feasible for various adjustable load resources to participate in power grid dispatching. Based on the 168-hour test, the technical architecture and key technologies have successively supported multiple third-party load subjects for participating in the peak-shaving ancillary service market in North China Power Grid.

V. Future Prospect and Conclusion

At present, the number of electric vehicles in China exceeds 2 million and it will reach 80 million in 2030. It is estimated that by 2025 and 2030, the installed capacity of user-side energy storage will reach 8 GW and 15 GW, respectively. The technical framework and several technologies mentioned in this paper can be extended to the scenarios where electric vehicles, distributed energy storage, air conditioning, and electric heating in buildings, industrial parks and other adjustable loads participate in business dispatching in the form of aggregation. More high-quality load-side dispatching resources can be gathered for the power grid.

However, it is necessary to note that there are still many technical problems that need to be addressed to fully achieve the real-time responses to power grid instructions. This can be achieved by using adjustable load resources and including them in flexible adjustments to achieve the real load dispatching control with multiple coordinated source network loads and storage. Through continuous research and exploration, large-scale real-time measurable and controllable adjustable load resources can be achieved.

1) In terms of device performance, the precision and real-time performance of the current power data collection of adjustable load resources are still far from meeting the requirements of dispatching services. It is necessary to continue to improve the technical levels of load terminal equipment, increase the transformation of the collection and control performance of the devices, increase the real-time data upload frequency and response following capability, expand the number of load resources that can participate in real-time control, and increase the investment and construction of load terminals with strong adjustment capabilities such as V2G and orderly charging piles.

2) As for the dispatching level, the coordination of the control strategies of adjustable load resources and traditional dispatching resources for participating in power grid peak-shaving, frequency modulation, and event handling scenarios in a day or a day ahead need to be further studied to find reasonable methods for evaluating whether the overall adjustable load resources respond to the dispatching command, evaluate their true contributions to the dispatching of the power grid, and eliminate the vacant individuals hidden in the load group. Moreover, the applications of the load dispatching platform must be further improved, perfected, and enriched.

3) As for the aggregator level, the issue is to investigate the accurate rolling calculation of the security domain of controllable power for a large number of load users and the statuses of equipment within the operation platform. Further, different optimal strategies should be adopted to maximize the adjustment space of distributed load resources according to the characteristics of different resources. Compared with the data in the main grid, it is difficult to distinguish the deviation of load-side power data. It is necessary to further study the audit technology for the load-side data to avoid the interference of unintentional or malicious false and wrong data on the dispatching and market operations. The data connection between dispatching and marketing agencies should be expanded. The data fraud and distortion problems should be identified by comparing the power integral amount and marketing power amount data.

4) In terms of interruptible loads, it needs further research to optimize and transform the current demand response and dispatching precision load-shedding systems (for example, in Shandong and Jiangsu provinces). In addition, the resource advantages of the existing systems should be exploited and the management and control capabilities of the system platform should be expanded to incorporate it into the overall technical architecture in this paper. The "interruptible" attribute of a large number of loads gathered in this part of the system should be transformed into an "adjustable" attribute and upgraded from "precise shedding" to "precise adjustment". In this way, the full potential of load-side dispatching can be realized.

It is important to establish a load dispatching control model that serves the multi-coordination of source, grid, load, and storage for fully utilizing the role of the service hub of the energy network, expanding the global perception and the control capabilities of power grid dispatching, and improving the level of clean energy consumption. Improving the load control capacity can fully drive the joint development of the entire industrial chain from dispatching to the load sides and promote the "new infrastructure" related business development and model innovation such as charging piles of electric vehicles.

This architecture will promote the dispatching model transformation from the traditional model of "source moves with load" to "source-grid-load-storage coordinated interaction", facilitate the development of the integrated energy industrial chain and fully serve the national strategy of "reaching carbon emission peak and carbon neutrality" and the construction of new power systems.

Appendix A

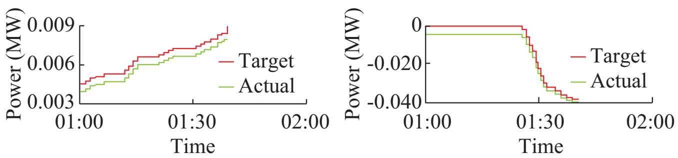

Fig. A1. AGC responses of electric vehicles and distributed energy storage control test. (a) Electric vehicles. (b) Distributed energy storage.

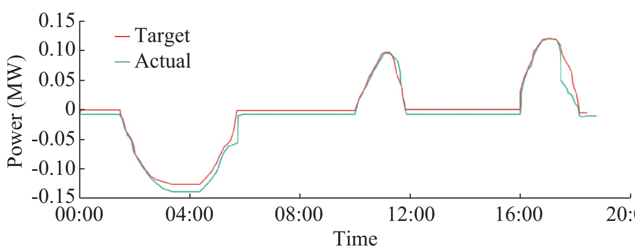

Fig. A2. All-day power optimization curve of distributed energy storage.

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Dong Yu received bachelor's degree in electrical engineering and automation, and master's degree in electrical engineering, both from Tsinghua University, Beijing China, in 1998 and 2017, respectively. He is currently the Party Secretary and Deputy Director of the National Power Dispatching & Control Center, State Grid Corporation, Beijing, China. He has long been engaged in power grid dispatching, operation, and control. He has presided over the work of many national and industrial standards, owned 5 national invention patents, compiled and published 9 professional books such as Operation and Control of Large-scale Wind Power Storage Combined System, and published 7 professional papers in Ei-indexed journals and Chinese core journals. He is the Leader of the "Key Technology and Application of Asynchronous Networked Operation Control of High Proportion Hydropower Complex Power Grid" project, which won the first prize of Scientific and Technological Progress of State Grid Corporation. His research interests include power grid dispatching and operation.

Xin Shan received the B.S. degree in electrical engineering from Tianjin University, Tianjin, China, in 2003, and the M.S. degrees in electrical system automation from State Grid Electric Power Research Institute, Nanjing, China, in 2006. He is current a Professorate Senior Engineer of NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing, China. His research interests include smart dispatching and control technology of power grid.

Yaqin Yan received the B.S. and M.S. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2001 and 2004, respectively. He is currently a Senior Engineer of National Power Dispatching and Control Center, State Grid Corporation of China, Beijing, China. His research interests include energy management system (EMS) and data platform.

Xiwu Leng received the M. Eng. degree in electrical engineering from North China Electric Power University, Beijing, China, in 2001. He is a Professorate Senior Engineer with National Power Dispatching & Control Center, State Grid Corporation of China, Beijing, China. He assumed the post of Deputy Secretary General of National Grid Operation and Control Standardization Committee. His research interests include standardization of large-scale power grid operation and control, grid-connected operation for adjustable load, construction of network plant coordination mechanism, safety supervision system of dispatching and control institutions, and improvement of management capacity.

Yi Wang received B.S. and M.S. degrees from Hohai University, Nanjing, China, in 2002 and 2009, respectively. He is currently working in NARI Group Corporation (State Grid Electric Power Research Institute), Nanjing, China. His research interests include modeling, optimization, and control of load, and analysis and decision for smart grid.