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Distributed energy storage node controller and control strategy based on energy storage cloud platform architecture

Tao Yan[1], Jialiang Liu[1], Qianqian Niu[1,2], Jizhong Chen[1], Shaohua Xu[1], Meng Niu[1], Jerry Y.S. Lin[3]

1. China Electric Power Research Institute, Haidian District, Beijing 100192, P.R.China
2. Beijing Jiaotong University, Haidian District, Beijing 100044, P.R.China
3. Arizona State University, 336E Orange ST Tempe, AZ 85281, Arizona, U.S.A

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Abstract: Based on the energy storage cloud platform architecture, this study considers the extensive configuration of energy storage devices and the future large-scale application of electric vehicles at the customer side to build a new mode of smart power consumption with a flexible interaction, smooth the peak/valley difference of the load side power, and improve energy efficiency. A plug and play device for customer-side energy storage and an internet-based energy storage cloud platform are developed herein to build a new intelligent power consumption mode with a flexible interaction suitable for ordinary customers. Based on the load perception of the power grid, this study aims to investigate the operating state and service life of distributed energy storage devices. By selecting an integrated optimal control scheme, this study designs a kind of energy optimization and deployment strategy for stratified partition to reduce the operating cost of the energy storage device on the client side. The effectiveness of the system and the control strategy is verified through the Suzhou client-side distributed energy storage demonstration project.

Keywords: Distributed energy storage, Optimum control, Plug and play, Energy storage cloud platform.

1 Introduction

With the development of the smart grid, client-side distributed energy storage has become one of the important power consumption businesses. The energy storage system has the advantages of cutting peak and filling valley, reducing the fluctuation of new energy, and improving energy efficiency and power quality. Furthermore, the energy storage system is an important measure for building modern services, an important way for the whole society to consume clean energy, and an important support for the new generation of power systems. Most especially in the past two years, a series of national policies in the field of energy

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Qianqian Niu
18126130@bjtu.edu.cn

Tao Yan
yantao@epri.sgcc.com.cn

Jialiang Liu
jialiangl@epri.sgcc.com.cn

Jizhong Chen
chenjz@epri.sgcc.com.cn

Shaohua Xu
xushaohua@epri.sgcc.com.cn

Meng Niu
niumeng@epri.sgcc.com.cn

Jerry Y.S. Lin
jerry.lin@asu.edu

storage have created opportunities for the future large-scale application of the customer-side distributed energy storage technology in China. However, some problems still exist, such as strong decentralization, difficult control, inconsistent aggregation parameters of the distributed system, and high overall operation cost.

Scholars at home and abroad have performed much research and practice on distributed energy storage resource management. For the coordinated control of energy storage and distributed power, electric vehicles, and other controllable resources, Ref. [1] proposed a "source network coordination" scheduling method using energy storage to reduce the wind power dispatching risk and constructed an economic evaluation of the energy storage system. The model, which is divided into different probability interval prediction scenarios, evaluates the feasibility of using energy storage systems to increase the scale of wind power acceptance. According to Ref. [2], the coordinated operation strategy considering the photovoltaic active power output, charging and discharging requirements of electric vehicles, and energy storage state was proposed considering the coordinated operation of electric vehicles and the photovoltaic energy storage in the grid-connected mode. Based on the hybrid energy storage system, Ref. [3] adopted the fuzzy control method to perform adaptive control on the energy storage state to realize optimal power distribution and stabilize the photovoltaic power fluctuation. In terms of research on the real-time distributed adaptive control of the client-side distributed energy storage terminal, Ref. [4] proposed a completely distributed method of arranging the operation plan and obtained the optimal strategy of each device only through the iterative coordination between adjacent energy storage devices. Ref. [5] studied the arbitrage problem of the distributed battery energy storage system under dynamic electricity price and obtained the Pareto optimal arbitrage strategy weighing economic value and battery life cycle.

However, in terms of policy, Refs. [6,10,14] pointed out that China's client-side distributed energy storage technology started late and is still in the early stage of industrial development. Relevant technologies, applications, policies, standards, and financial support are not perfect and still in the development stage of the "technology pushing application, application pushing policy." In terms of technology, such a distributed energy storage with "wide area layout, large number, and small individual capacity" still faces many problems in practical promotion. Refs. [7-9] pointed out that the current distributed energy storage output and access have the characteristics of decentralization and poor controllability, and the wide-area distributed energy storage lacks effective scheduling means at the present, which will cause a great waste of energy storage resources. Unlike the large-scale centralized storage installed on the power side, the distributed storage is usually installed on the customer side. Refs. [11-13] only studied the distributed energy storage architecture. How to realize the coordinated operation of various resources on the client side and the win–win cooperation among different stakeholders is the focus and challenge of future research.

In view of the abovementioned problems, this study selects the comprehensive optimal control scheme based on the energy storage cloud platform architecture [15-18]. By making use of the peak-valley price difference, the operating cost of the client-side energy storage device can be reduced, and the distributed client-side energy storage can be encouraged to actively participate in the interactive load regulation of the power grid. The information bridge between the distributed energy storage device and the power grid is established through the plug and play device for energy storage, which realizes the access authentication of the energy storage cloud network on the top, obtains the information of the comprehensive platform of the power grid, and realizes the control of the distributed energy storage device on the bottom [24, 25]. In this way, the information of the distributed energy storage device can be mastered in real time; the safety and the reliability of charging and discharging the energy storage battery can be improved; and the operating cost of the energy storage device can be reduced. Finally, the effectiveness of the proposed device and control strategy is verified by the customer-side energy storage demonstration in Suzhou [26-29].

2 Storage cloud and distributed storage node controller

2.1 Storage cloud

Fig. 1 shows the architecture diagram of the client-side energy storage system based on the energy storage cloud.

The client-side energy storage system based on the energy storage cloud mainly consisted of the following parts: client-side energy storage equipment layer; transmission layer; energy storage cloud application management layer; and customer service layer.

The client-side energy storage equipment layer consists of the client-side energy storage equipment, plug and play device, and communication equipment. The client-side energy storage equipment mainly includes a mobile energy storage for electric vehicles and a fixed-energy storage for industrial/commercial/residential users, mainly completing the storage and release of electric energy. Plug and play

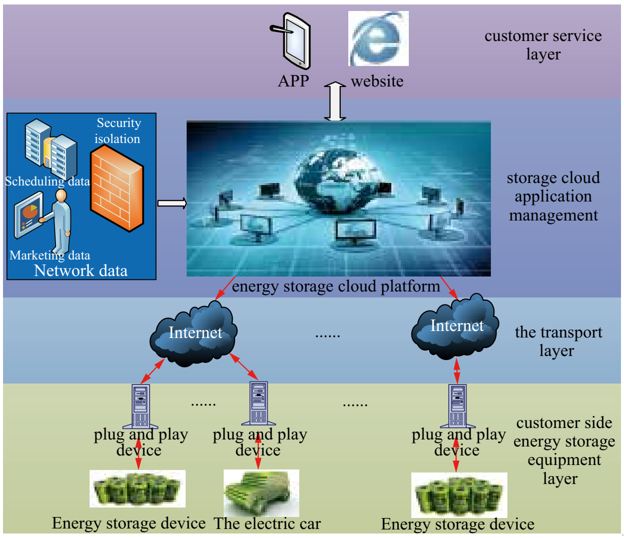

Fig. 1 Schematic of the energy storage cloud platform architecture

devices are the bridge between energy storage devices and the power grid. The communication equipment realizes the connection between the upwardly facing and bottom plug and play devices of the energy storage equipment on the client side.

The transmission layer guarantees the completion of the communication between the client-side energy storage device layer and the energy storage cloud. It can be realized by many kinds of schemes, including wired and wireless communication. At present, the platform mainly uses an optical 5G/4G/GPRS network and an energy storage cloud to achieve a two-way connection of information and data. The transmission performance is stable, maintenance is simple, and cost is low.

The storage energy cloud application management layer is composed of a data collection area, an exchange area, a data storage area, a platform service area, and an inner network area. The data acquisition area reads the data transmitted by the transport layer and arrives at the data storage area through the exchange area for storage. The internal network area sends the internal dispatching and marketing data of the power grid to the management of the energy storage cloud application through the security isolation device. The platform service area integrates the underlying and intranet data to implement the corresponding platform services.

The customer service layer is the terminal that realizes the customer-side energy storage service. Panoramic display user interface and client-side applications mainly support various forms of terminal access, such as computers and mobile phones. Customers can choose the corresponding energy storage services according to their needs, but they are also managed by the energy storage cloud platform.

2.2 Distributed storage node controller

The distributed energy storage node controller is used to connect the customer energy storage equipment and the public network. This study designs a distributed energy storage node controller–plug and play device. The plug and play device collects the operation data of the distributed energy storage device and sends the relevant information of the distributed energy storage device. At the same time, it is also the carrier of the energy storage device to obtain grid-related information, implement grid-related control, and participate in demand-side response interaction and other functions. Fig. 2 shows the functional architecture of the plug and play device.

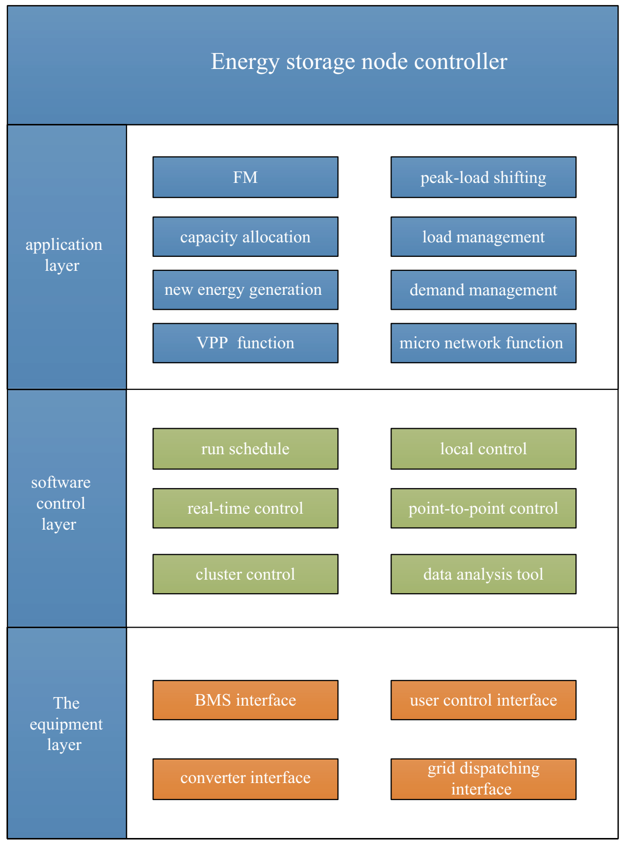

Fig. 2 Plug and play device functional structure diagram

The energy storage cloud platform generates control strategies by collecting the internal and external data of the power grid. By accessing the web-based monitoring interface, users can realize the functions of distributed energy storage device monitoring, control strategy formulation, power grid interaction, analysis and statistics, income query, and so on. Fig. 3 illustrates the plug and play device architecture.

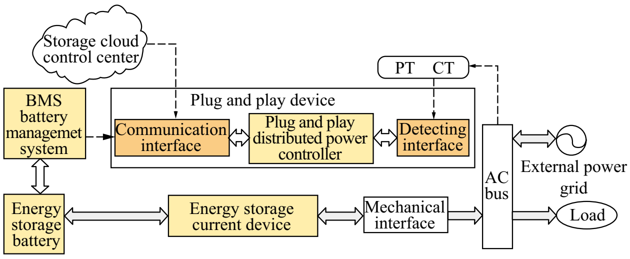

Fig. 3 Plug and play device architecture

3 Distributed energy storage network operation architecture

3.1 Functional architecture

Fig. 4 shows the functional architecture of the distributed energy storage network operation platform. The system realizes the functions of acquisition, monitoring, protection, and control of the energy storage equipment based on the play device. At the same time, the user energy storage equipment connected to the system has authentication encryption, local energy management and mode setting, and other functions. The whole system completes the perfect combination of front-end data, intermediate intelligent cloud computing, and back-end application.

The distributed energy storage network operation architecture adopts the system layout mode of "local and remote two-level deployment and multi-system integration application."

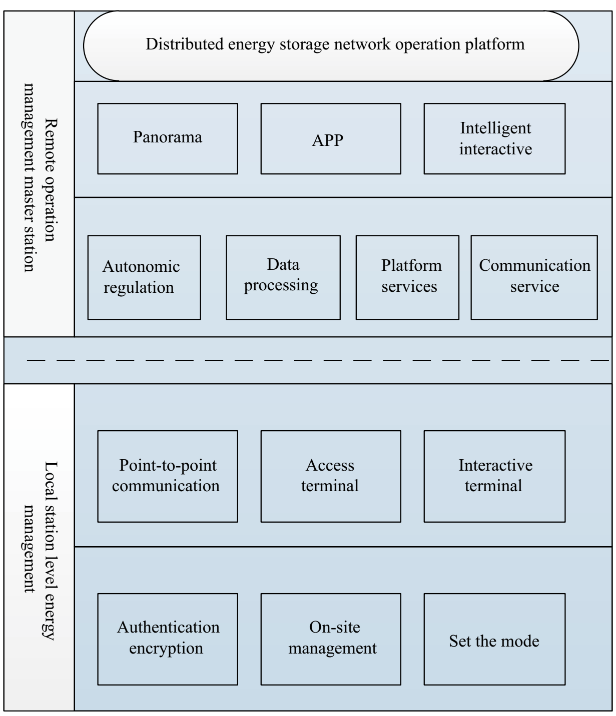

Fig. 4 Functional architecture of the distributed energy storage network operating platform

The local station-level energy management system layout application site and the real-time monitoring of the field energy storage system and related auxiliary equipment are realized. A local autonomous operation can be realized according to the user power plan and load curve. The local station-level energy management system completes the real-time collection and temporary storage of the equipment operation data. According to certain communication protocols, the local station-level energy management system realizes the two-way connection of information and data with the remote operation management master station through a fiber 5G/4G/GPRS network. Meanwhile, the operation data of the power battery of the electric vehicle mobile energy storage system installed with a vehicle terminal can be directly uploaded to the remote operation management master station through the 5G/4G/GPRS network in accordance with the specified communication protocol.

The remote operation management master station provides advanced application services to platform users and optimized control strategy support for the local station-level energy management system on the basis of a data analysis. The remote operation management master station also realizes business association with the power grid dispatching automation system, power demand side management platform, power market trading system, and so on through the data interface, thereby expanding the new mode and the new format of distributed energy storage applications and giving full play to the diversified value of distributed energy storage resources.

3.2 Communication system deployment plan

The distributed energy storage network operation platform creates a perfect security protection system and realizes the unified application of the internal and external networks of the platform based on the mixed application mode of the 5G/4G network. Fig. 5 shows the 5G schematic deployment plan.

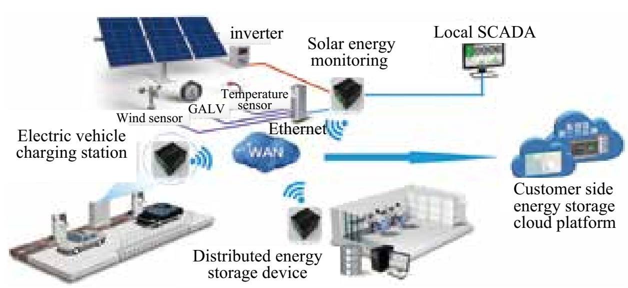

Fig. 5 5G schematic of the deployment plan

Aiming at the problems of long data collection cycles, large amounts of distributed energy storage data, and small data collection dimensions faced by the current smart energy storage 4G data terminals, the 5G communication core network can implement 5G technology information security and interaction of wide-area distributed energy storage systems, which are solutions to achieving a cloud-based coordinated control architecture for distributed energy storage clusters. For the continuous transmission of large-scale intelligent energy storage operation and maintenance big data scenarios, specific “high-performance” network slices can be generated to make up for the limitations of the existing distributed energy storage devices. The lack of real-time communication channels has a negative impact on the safe operation of energy storage systems. A new form of energy internet based on the 5G customer-side source-network-load-storage is constructed.

The 5G large-bandwidth communication capabilities and a combination of 4G/5G and other wireless APN/VPN private networks, R485, power carrier, CAN bus, Bluetooth, etc. are utilized to achieve an efficient collection of various energy storage operation and maintenance data. Combined with battery health status perception and function, the energy storage system integrated the sensing technology through the smart energy storage 5G data terminal to achieve the cumulative charge and discharge times, battery capacity (SOC), cell balance, battery internal resistance, worst single node and battery health index, integrated sensing functions (e.g., automatic collection of key battery parameters and data encryption transmission). The effectiveness and convenience of the health state perception in energy internet operation are realized by sensing the health status of the distributed energy storage equipment, grasping the health indicators of the wide-area distributed energy storage, realizing the early warning of potential problems, and improving distributed energy storage batteries.

As regards network deployment, the distributed energy storage network operating platform is deployed in the electric power security Ⅲ area. It includes a database server, an application server, a file server, an interface server, and so on. The distributed energy storage network operation platform establishes a data interface with the other business systems of the internal network through the power security III area-integrated data network. Other business systems include a power dispatch automation system, a power demand-side management platform, a power market trading system, etc.

In terms of the external network interaction, the service of the interaction between the distributed energy storage network operation platform and the internet is deployed in the demilitarized zone of the power grid company. It includes a collection server, a web application server, a file server, an external interface server, a security server, and so on. The energy storage devices in the equipment layer of the operating platform are arranged as follows:

(1) Industrial/commercial/resident user fixed-energy storage devices are connected to a 380 V or 10 kV distribution network in accordance with the relevant provisions of the Technical Regulations for Electrochemical Energy Storage Systems Access to Distribution Network. Direct access is adopted when the fixed-energy storage device is connected to the 380 V distribution network. In contrast, when the fixed-energy storage device is connected to the 10 kV distribution network, the output is directly connected to the metering cabinet or via the booster transformer. The metering cabinet shall be equipped with intelligent electricity meters, current transformers, voltage transformers, and other equipment. The metering cabinet is connected to the grid-connected cabinet through the bus. The grid-connected cabinet is equipped with a relay protection device and a load switch and connected with the 10 kV distribution network. The energy management system of the fixed-energy storage device establishes a communication channel with the remote energy management master station via a fiber 5G/4G/GPRS network. The fixed-energy storage device and the remote energy management master station realize information and data exchange.

(2) The mobile energy storage device of the electric vehicle is connected with the distribution network through the charging and discharging facilities of the electric vehicle. The remote energy management master station for the mobile energy storage of electric vehicles installed with on-board terminals can directly connect to the 5G/4G/GPRS network to realize data collection and status monitoring of battery charging and discharging. The distributed energy storage network operation platform can realize the monitoring control and operation management of EV charging stations, centralized installation charging piles, and decentralized installation charging piles. Meanwhile, when the EV mobile energy storage without a vehicle terminal is connected with the charging and discharging facilities, the remote energy management master station can monitor its charging and discharging status through a fiber 5G/4G/GPRS network.

4 Control strategy

The distributed energy storage network operation platform realizes a real-time status monitoring of the industrial/commercial/residential user fixed-energy storage device, electric vehicle mobile energy storage device, charging pile, and other facilities on the equipment layer through a system communication network and manages the operational data of the access platform. According to the real-time operation and historical data of the distributed energy storage system, the network operation platform of the energy storage can predict the charging and discharging plans of the distributed energy storage device. The dispatchable potential of the distributed energy storage resources at the station, regional, and provincial levels is evaluated through a data analysis. The strategy of the distributed energy storage system participating in a market transaction is formulated by combining the market price and demand information. Each distributed energy storage device is assisted to optimize the operation strategy to consequently optimize the comprehensive benefit. Fig. 6 presents the optimal power allocation strategy.

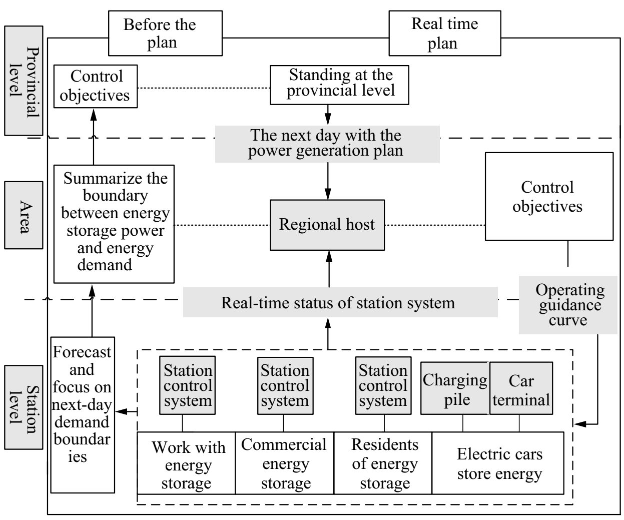

Fig. 6 Power optimization and deployment strategy

4.1 Control objectives

In the market environment, as the owner of the distributed energy storage, the market participants aim to maximize the benefits of the distributed energy storage system. By contrast, the market operators aim to maximize social welfare. In other words, when a power grid company is a platform operator, it should not only consider the optimal benefit of each independent distributed energy storage system, but also maximize the diversified value of the distributed energy storage system resources from a global perspective. Therefore, the control strategy proposes a layered and partitioned power optimal allocation strategy, which comprehensively considers the operators and the distributed energy storage owners to optimize the control benefits. The platform operators are described below from the two aspects of the objective function of the global and independent distributed energy storage.

The network operation platform for energy storage needs to integrate supply and demand signals, such as regional power grid power supply, load level, demand response, demand for auxiliary services, and operation status of the energy storage system. Considering physical constraints, this study provides auxiliary optimal operation decision signals for various distributed energy storage systems. The objective function is as follows:

$$Min\sum_{t=1}^{N_t}\begin{bmatrix}\sum_{g=1}^{N_g}\lambda_{g,t}\cdot P_{g,t}+\sum_{s=1}^{N_s}\lambda_{s,t}^{dis}\cdot P_{s,t}^{dis}\\ -\sum_{s=1}^{N_s}\lambda_{s,t}^{ch}\cdot P_{s,t}^{ch}-\sum_{d=1}^{N_d}\lambda_{d,t}\cdot P_{d,t}\end{bmatrix} \tag{1}$$

where g, s, and d denote the number of power generation units, distributed energy storage systems, and loads, respectively. $\lambda_{g,t}$, $\lambda_{s,t}^{dis}$, $\lambda_{s,t}^{ch}$, and $\lambda_{d,t}$ are biddings for the power generation unit at time t, distributed energy storage system in the discharge mode, distributed energy storage system in the charging mode, and load, respectively. $P_{g,t}$, $P_{s,t}^{dis}$, $P_{s,t}^{ch}$, and $P_{d,t}$ are denote the real-time power of the power generation unit at t, distributed energy storage system in the discharge mode, distributed energy storage system in the charging mode, and load, respectively. The objective function cost is set to minimum to maximize the value of the energy storage network operation platform from the overall perspective.

On the basis of meeting the travel needs of electric vehicle users, the mobile energy storage of electric vehicles can minimize the daily charging cost and generate hidden economic benefits for the distribution network by participating in the one- or two-way exchange of power grid energy and information. Its objective function is expressed as

$$Min\sum_{t=1}^{N_t}\left[\lambda_t^{ch}\cdot P_t^{ch}-\lambda_t^{dis}\cdot\left(P_t^{dis}-P_t^{use}\right)\right] \tag{2}$$

where λ_t^{ch} and λ_t^{dis} are the charging and discharging prices of the electric vehicle, respectively. P_t^{ch}, P_t^{dis}, and P_t^{use} are the electric vehicle charging power, discharge power, and normal driving discharge power, respectively. The electric vehicle mobile energy storage rationally plans the charging behavior. The saved charging electricity fee is directly reflected in the time-sharing charging price λ_t^{ch}.

The benefits for the industrial/commercial/residential fixed-energy storage systems can be maximized in two aspects. First, the control strategy of the energy storage system is optimized to minimize the user's electricity cost. Second, the changes in market demand can be closely tracked, and greater benefits can be obtained through active market participation. The objective function for this is expressed as

$$Min\sum_{t=1}^{N_t}\left[\lambda_t^{ch}\cdot(P_t^c+P_t^{ch})-\lambda_t^{dis}\cdot(P_t^{dis}-P_t^{use})\right] \quad (3)$$

where P_t^c is the user load power; P_t^{ch} is a fixed-energy storage charging power; P_t^{dis} is a fixed-energy storage discharge power; and P_t^{use} is the power allocated to the user load in the discharge mode of the energy storage system.

4.2 Constraint condition

The network operation control of the distributed energy storage system must consider the constraints of power grid, battery, and user behavior.

(1) In terms of the grid constraints, the following must be met under the premise of not considering transmission and distribution congestion and meeting the load safety margin of the regional distribution network:

$$\sum_{g=1}^{N_g}P_{g,t}+\sum_{s-1}^{s}(P_{s,t}^{dis}-P_{s,t}^{ch})-\sum_{d=1}^{N_d}P_{d,t}=0,\forall t \quad (4)$$

The instantaneous power value of each unit cannot exceed its power limit.

(2) In terms of the battery constraint, the charging and discharging powers of the distributed energy storage system cannot exceed their limit. The real-time SOC cannot exceed the maximum and minimum available capacity limits of the energy storage system.

$$P_s^{dis,\min}\leqslant P_{s,t}^{dis}\leqslant P_s^{dis,\max},\forall t,\forall s \quad (5)$$

$$P_s^{ch,\min}\leqslant P_{s,t}^{ch}\leqslant P_s^{ch,\max},\forall t,\forall s \quad (6)$$

$$SOE_s^{\min}\leqslant SOE_{s,t}\leqslant SOE_s^{\max},\forall t,\forall s \quad (7)$$

(3) In terms of the user behavior, for the mobile energy storage system of an electric vehicle, its vehicle attributes require that it must first meet user needs. This is generally done by setting the available time and terminating the SOC.

$$\begin{cases}SOE_s^{set}\leqslant SOE_{s,ti}^{end}\leqslant SOE_s^{\max},\forall s\\ ti_{begin}\leqslant ti\leqslant ti_{end}\end{cases} \quad (8)$$

For the industrial/commercial/residential fixed-energy storage systems, the sum of the charging and user load powers of the energy storage system shall not be greater than the set maximum demand value.

$$P_{demand}\leqslant P_{s,t}^{ch}+P_{s,t}^{c},\forall t,\forall s \quad (9)$$

5 Model validation

The project was demonstrated and verified by the Suzhou Langqinwan community. This study mainly analyzed the effect of the peak load reduction and residents' economy before and after the distributed energy storage system installation. The community has 212 residents, and 40 residents installed energy storage. The cell distribution capacity was 1260 kVA. The maximum load was approximately 250 kW. The total charging and discharging powers of the energy storage equipment were approximately 90 kW. The permeability of the energy storage installation was 36%.

5.1 Peak storage and valley filling effect of energy storage

The distributed energy storage aims to participate in peak load cutting and valley filling. Only two charging and discharging processes were considered. The power diagram was drawn at 15 min intervals. Fig. 7 shows the load power curves before and after the energy storage installation. Table 1 lists the peak–load ratio of each period.

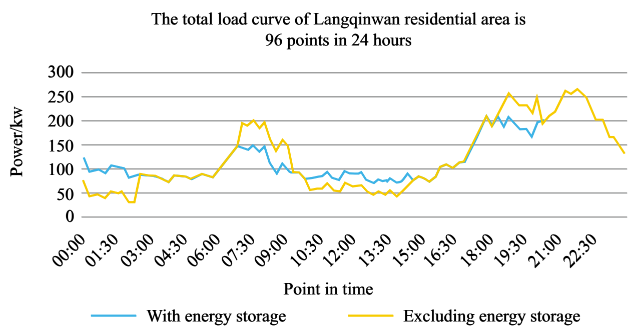

Fig. 7 Typical load curve of Langqinwan area

Table 1 Peak and valley filling rate of the energy storage at each period

Work condition \ peak valley	In valley 1 00:00-02:15	Peak clipping 1 07:00-09:00	In valley 2 10:00-14:00	Peak clipping 2 18:30-20:00
Cut peak fill rate (actual)	119%	29.8%	49.3%	21.5%
Cut peak fill rate (full power)	180.4%	44.7%	73.8%	32.3%

The results showed that the average peak and the valley differential rate before and after the energy storage installation were approximately 89.5% and 61.9%, respectively. Moreover, the overall peak and valley differential rate of the energy storage weakening was approximately 27.6%. The energy storage installation will significantly reduce the grid load peak and valley rate and play a role in load smoothing.

5.2 Consumer tariff analysis

The energy storage system performs a charge and discharge cycle every day (charge: 0:00–02:30; discharge: 18:00–20:30) with maximum user benefit as the goal. Fig. 8 shows the load curves before and after the energy storage installation in the cell. The electricity charges of the users were calculated according to the current peak and valley electricity prices of Suzhou residents. The results showed that after the energy storage equipment installation, the user can save approximately 5.8% of the electricity bill every day. Company electricity bills were also reduced.

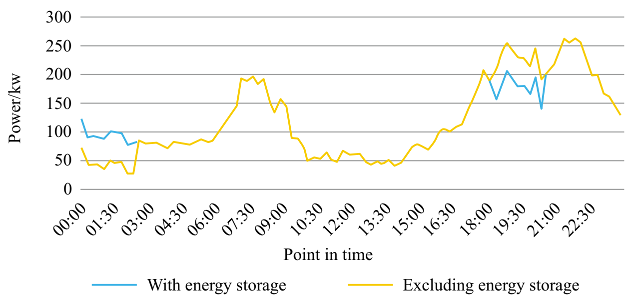

Fig. 8 Typical load curve of Langqinwan area

6 Conclusion

Energy storage is expanding its resource scale as an important supporting technology for the development of energy internet. Starting from the promotion of open sharing and the efficient utilization of energy storage resources, this study proposed an architecture of the "local and remote deployment and multi-system integration application" of the energy storage network operation platform. In addition, a method for the optimal allocation of multiple energy storage application powers considering spatial and temporal distribution characteristics was proposed to realize the optimal regulation of distributed energy storage resources. The platform operators and owners of the distributed energy storage system can achieve benefit optimization by establishing a provincial–region–station-level three-layer regulation model. This model provides technical means for widely mobilizing user-side distributed energy storage resources to participate in the power grid interaction and for improving the low utilization rate of user-side distributed energy storage resources.

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Biographies

Tao Yan received his Ph.D. degree in 2007 from Beijing University of Technology, China. He works at the China electric power research institute. He mainly studies the power electronics technology and the access technology of the energy storage system.

Jialiang Liu received his master degree from Huazhong University of Science and Technology (HUST), China. He works at the China electric power research institute. He mainly studies energy storage systems.

Qianqian Niu received her bachelor degree in 2018 from Shanxi University of Engineering. Her major field of interest includes power electronics.

Jizhong Chen received his Ph.D. degree from Institute of Electrical Engineering of the Chinese Academy of Sciences in 2007. He works at China Electric Power Research Institute. He mainly studies the integration, application and evaluation of large-scale energy storage technology.

Shaohua Xu received his Ph.D. degree from China Electric Power Research Institute. He works at the China Electric Power Research Institute. He mainly studies microgrid inverter control.

Meng Niu received her master degree from Beijing Jiaotong University in 2010. She is a senior engineer at China Electric Power Research Institute. She is working on configuration and integration of large scale energy storage system in power system.

Jerry Y.S. Lin is an expert of the China electric power research institute and a distinguished professor for life at Arizona state university. He provided technical support for battery modeling in this project.

(Editor Chenyang Liu)