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[1] Zhi Tan
*, [1] Yu Chen
[1] Wei Fei
[1] Ningyi Zhou
[2] Yueping Yang
[2] Xiaomin Shen

Multi-Function Collaborative Flexible Source-Load Intelligent Interactive Operation Control Technology for Industrial Communities

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Abstract: - Different from the traditional power supply mode of only distribution network, the new energy distribution network gradually presents a strong coupling and strong correlation between the "source - network - load - energy storage" multi-energy system structure. Its various types of resources have the characteristics of wide regional distribution of "multiple points and wide areas". According to the characteristics of distribution network, this project studies the voltage self-optimizing control strategy in a wide range of distribution network with multi-source coordination. Through the coordinated regulation of multiple decentralized systems such as new energy power generation, energy storage and flexible load, the voltage quality in a large range is improved under the premise of guaranteeing energy storage capacity. Through the analysis of an urban distribution network, the results show that the proposed algorithm is feasible and advanced. Compared with the conventional regulation mode, this mode is more suitable for the regulation requirements of distribution network.

Keywords: New Distribution System; Wide Area Voltage Control; Distributed Source Network Load and Storage Resources; Deep Reinforcement Learning.

I. INTRODUCTION

As global energy trends lean towards a "low-carbon" paradigm, there's a growing presence of distributed power sources within the distribution grid, encompassing elements like wind power, distributed energy storage, and flexible demand response. The challenge lies in harnessing the regulatory capabilities of these diverse, decentralized energy entities—ranging from generation to storage and network infrastructure—to ensure the reliability and stability of the modern distribution system. Flexible source-load intelligent interaction refers to the effective coordination between the power side (such as renewable energy power generation facilities) and the load side (such as residences, commercial buildings and industrial facilities) in the smart grid system through highly intelligent and automated communication technologies. a pattern [1]. This interactive model allows the grid system to respond more flexibly to changes in energy supply and demand, improving system stability and efficiency.

In flexible source-load interaction, renewable energy generation facilities on the power side can adjust their output based on real-time demand and forecast data, while the load side can adjust its power consumption pattern through mechanisms such as demand response. For example, when solar power generation is sufficient, flexible loads on the load side (such as energy storage equipment, adjustable industrial production lines, or smart home systems) can increase the load to absorb excess power; and when power generation is insufficient, flexible loads can reduce the load. Or switch to other energy sources to reduce pressure on the grid. To accomplish this objective, various technological assistance is necessary, encompassing advanced metering infrastructure (AMI), intelligent electricity meters, load-adjusting mechanisms, energy oversight platforms (EMS), distributed energy oversight systems (DERMS), and robust data transmission networks, among others. Together, these technologies form the infrastructure of the smart grid, allowing the grid to monitor and predict energy supply and demand in real time and respond quickly. In addition, flexible source-load intelligent interaction also involves the reform of the power market, allowing load-side users to participate in the power market and obtain economic incentives by providing demand response services, further promoting the flexibility and efficiency of the power system. Flexible source-load intelligent interaction is one of the key ways to modernize the energy system, improve energy utilization efficiency, and ensure the security and stability of the power grid. As technology progresses and market mechanisms evolve, this framework will assume an ever more significant position within the forthcoming electrical grid.

[1] Zhejiang Electric (Ningbo Beilun) Smart Energy Co., Ltd, China
[2] Zhejiang Electric Power Co., Ltd. Ningbo Power Supply Company, China
*Corresponding Author: Ningyi Zhou

In terms of regulating devices, the conventional voltage adjustment method is to adjust the on-load transformer, shunt capacitor and static reactive power. This mechanism can control the power supply side by adjusting the energy distribution in the distribution network, but it is difficult to adjust the voltage at the end of the power supply side effectively because of the close relationship between its geographical position and its geographical position [2]. In addition, in the distribution network, because of its long operation period and slow action, it cannot meet the characteristics of rapid changes in the power grid and load. The new technology provides fast and flexible reactive power support for large capacity wind turbines [3]. At the same time, due to the existence of large R/X ratio, it has the same advantage as reactive power, so the energy storage system can make up for its indirect impact on the power output by adjusting charging, discharging and other ways, so as to improve the voltage quality of the system. Most of the existing power control models are hybrid integer nonlinear optimization problems based on optimal power flow, and their mathematical modeling is usually a non-convex, NP-- hard problem [4]. However, such algorithms not only have high requirements on the model.

First of all, it expands the "diversified" information collection, "source" refers to traditional power, pumped storage, nuclear power, etc., and adds a variety of new energy sources including centralized and distributed wind power generation, photovoltaic power generation and virtual power stations. "Network" in addition to the conventional transmission grid, heat network and other physical forms, but also add wireless private network, optical fiber private network and other Internet of Things access; "Load" refers to the power grid and residential electricity load, but also includes electric vehicles, load integrators, intelligent buildings, air conditioners, industrial customers and other load resources, and monitoring and summary; "Storage" refers to a variety of stored or stored energy, such as energy stored on the grid side and energy stored on the user side, and the collection of monitoring [5]. In addition, it can also help the panoramic perception of the entire power grid through a variety of universal information, such as weather, fires, typhoons, dense channels, geographic information, etc. Secondly, in terms of the depth of data collection, it breaks the previous centralized scheduling mode, improves the global perception of the power grid to a high level, collects static and dynamic data, uses the idea of network and the method of big data to clean up the data, dig the value of the data, and analyze various data, so as to expand the application range of data [6]. Integrating the attributes of energy storage, electric vehicles, and integrated energy resources into the power grid's frequency regulation capabilities can enhance new energy utilization. Expanding the "smart" grid and creating a multi-variable cooperative regulation and dispatch system based on intelligent interactions between generation, network, load, and storage is essential. This initiative aims to address the issue of curtailed new energy consumption due to global negative contingencies by achieving a spatial and temporal distribution of new energy use across daily, intra-daily, and sub-hourly timescales, day after day and real time based on the four-level power supply planning, load forecasting, new energy generation forecasting and unit adjustment based on "net-province-land-county", and discover the consumption of new energy in time [7]. The adjustment demand of new energy is published online, and the active participation of ubiquitous adjustable resources is guided by the declaration and linkage response based on the consumption gap of new energy. The flexible consumption of new energy is promoted. Some researchers at home and abroad have applied deep neural networks to the optimal power flow calculation of power distribution systems. Some researchers have modeled it using a heuristic segmented agent algorithm based on Markov games [8]. At present, the Markov decision model has been used to optimize it, and it is found that the energy storage can adjust the active power balance in the distribution network, thus improving the voltage quality of the distribution network. Although the above research adopts data-based analysis methods, it has not yet carried out large-scale voltage regulation for a large-scale power network under the synergistic interaction of multiple and dispersed energy sources in the distribution network. This project intends to study a "data-driven" based "source-network-charge-storage" integrated coordinated control strategy for distribution network, so as to meet the requirements of multi-source integrated charge scheduling in a large range. Firstly, a large-scale voltage control mode of "source-charge-energy storage" based on regional power grid is established to ensure storage capacity, reduce network loss and improve voltage quality [9]. The non-central local observation Markov decision problem is modeled, and the multi-agent depth-determined gradient optimization method is used to optimize the problem. Through a medium-sized urban distribution network example.

II. TECHNICAL FRAMEWORK FOR INTEGRATED MANAGEMENT OF LOAD AND STORAGE RESOURCES OF THE SOURCE NETWORK

The ubiquitous resource integration management Architecture of source network coexistence is shown in Figure 1 (image cited in Edge Computing Application, Architecture, and Challenges in Ubiquitous Power Internet of Things).

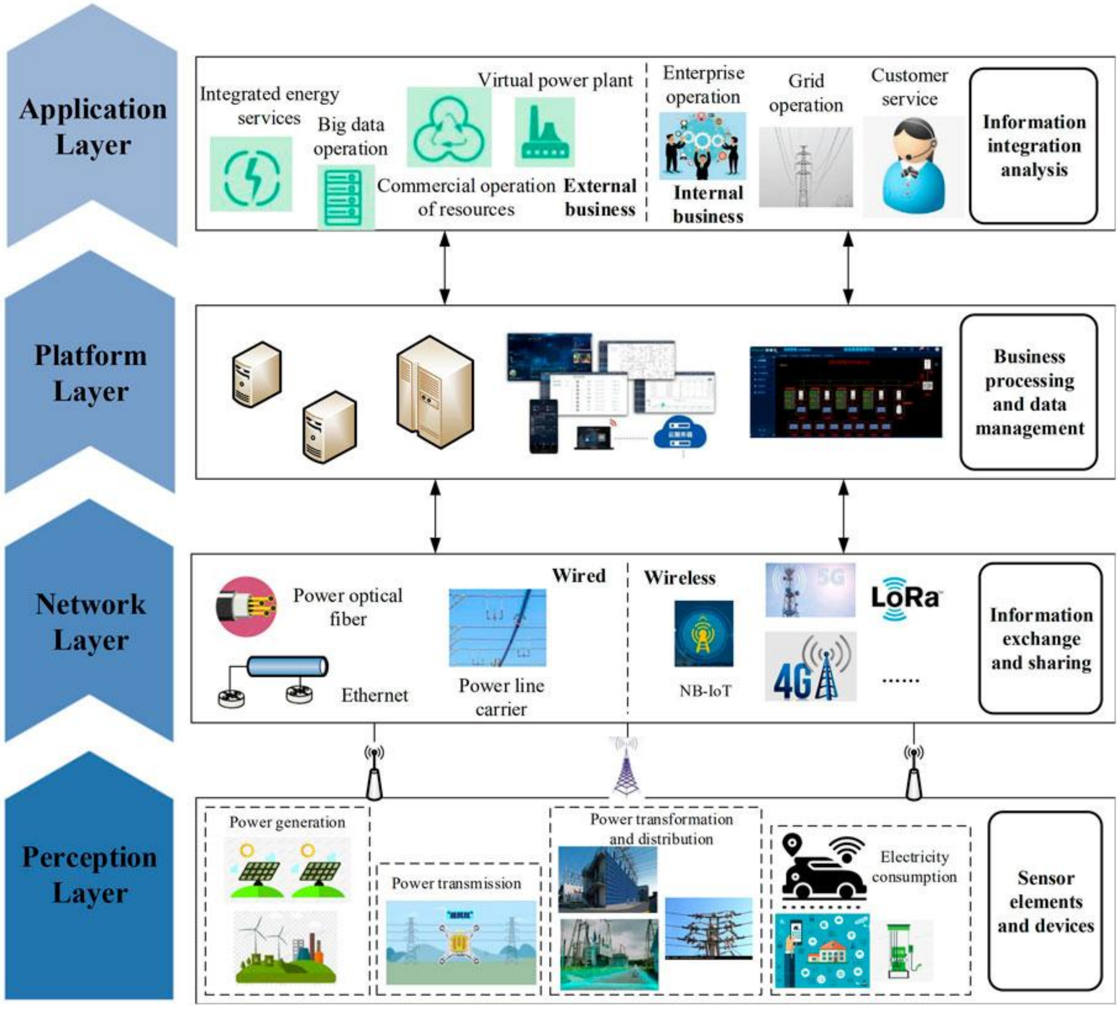

Fig.1 Architecture diagram of the integrated resource management system of source network load and storage

1) At the access level, through network interconnection, new energy plants, distributed power supplies, energy storage equipment, electric vehicles, load integrators, intelligent buildings, air conditioning equipment, industrial customers, virtual power plants and other new energy and energy use equipment are interconnected to obtain the overall working status of "source-net-charge-storage links", and boundary calculation methods are used. Real-time, efficient and optimal service.

2) The network layer uses various types of network resources, such as local area network, secure access network, resource high-speed synchronization network.

3) At the platform level, according to different sources, types, structural differences and other characteristics, the use of data platform access specifications, break through the data barriers caused by differences, build a unified platform specifications, and use big data and data cleaning and other means to improve the quality of data and instant sharing ability. Through the standardization and opening of the platform, the unified management of high-level applications is realized.

4) At the application level, the layered data sharing mode among various programs, efficient longitudinal data flow. The utilization of global information awareness facilitates the optimization of interactions between the generation, grid, loads, and storage systems throughout the day. Additionally, it enables the planning optimization of these systems, considering the constraints related to peak shaving and frequency regulation. According to the control principle of stratification, segmentation and segmentation, it can realize the correction and coordination control of various controllable resources of the power grid, automatic generation control AGC,

and evaluation and evaluation of the implementation effect of electricity consumption, so as to improve the timeliness, convenience and rapidity of dispatching work.

III. CORE ISSUES OF INTEGRATED SOURCE NETWORK RESOURCE COOPERATIVE SCHEDULING

A. *Integrated processing method of large-capacity data*

This project researches the joint access and data mining method of "source-net" according to the outstanding characteristics of "source-net load", such as diverse data types, large spatio-temporal scale, fast generation speed, strong timeliness and large difference in accuracy [10]. Firstly, the universal source-network-load storage and universal data access mode are studied. Some researchers have proposed the architecture of regulated cloud computing and the general data structure of power scheduling under regulated cloud computing. Other external environments, such as weather, fire, typhoon, dense channel, geographic information, etc., provide support for the integration of global information. The single modeling and integrated modeling are organically integrated to form a complete system to realize the comprehensive display and analysis of all levels. Figure 2 Multi-source collaborative ubiquitous resource modeling process (image cited in BPMN in healthcare: Challenges and best practices).

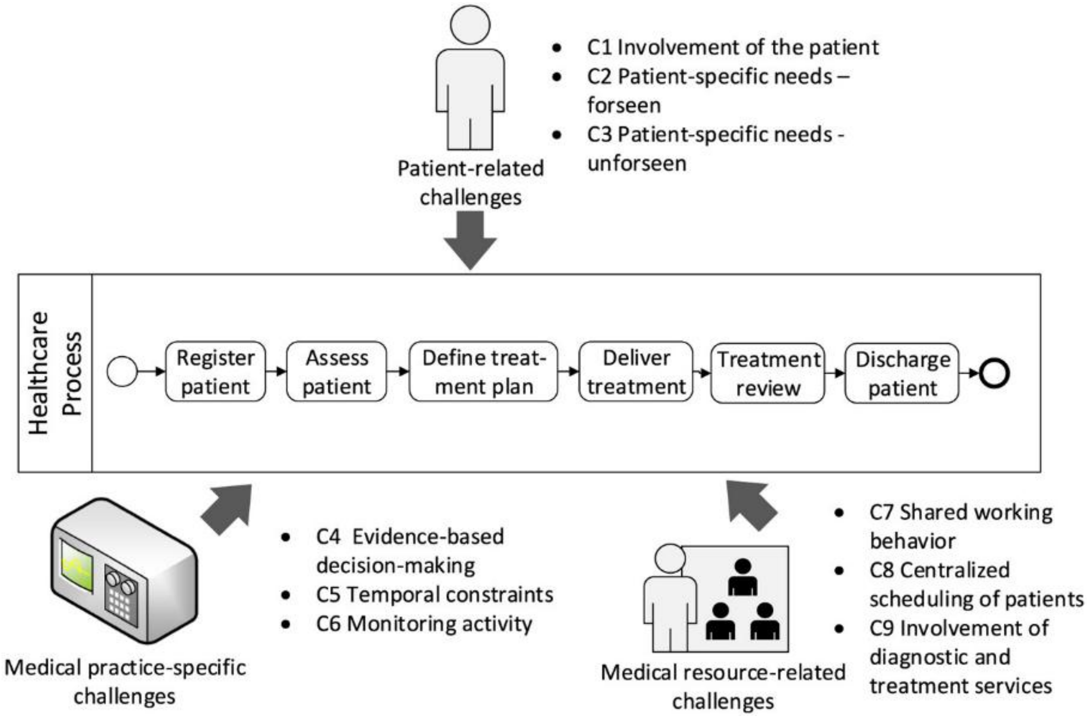

Fig.2 Ubiquitous resource modeling

According to the general metadata object modeling method, set a unique ID code rule, and complete the standards and specifications of various models according to the needs of the application and the common specifications of the common pattern [11]. Through the integration of distributed photovoltaic information at the market end, distributed power supply information of wireless public network private network and other channels, various cross-departmental and cross-domain of the Internet Department, and various cross-domain and cross-domain data a platform-type shared Internet of Things platform is built.

B. *Integrated processing of multi-source information*

Pervasive computing based on the Internet of Things connects terminals of different types and Spaces to the network, and stores, shares and manages them. With the development and application of machine learning, artificial intelligence and other fields, it will provide important theoretical support for universal perceptual data processing in perceptual environment. Some scholars have introduced data-based flow processing and batch processing methods into the collection, processing and application of collocation data [12]. The project plans to adopt the "data-pattern-application" method to standardize data access and process the entire process, so as to complete the analysis and modeling of big data and shift from the traditional driving model to the intelligent model based on the needs of monitoring system operation data, forecasting data analysis and analysis processing. This project aims to explore multi-level scheduling collaborative management and optimal allocation of computing resources based on the idea of "hierarchical management of resource scheduling and global sharing of computing services". In order to achieve the "source - network - load - storage of all links" comprehensive and efficient integration [13]. Therefore, this project intends to study the multi-source information integration method suitable for ubiquitous environment. Through the real-time integration and integration of various basic data collected, the abnormal cleaning and correction of data and the adaptive restoration of time and space are realized, which makes the intelligent panoramic situation sensing analysis more accurate.

This project proposes a cross-scale integration Method based on Multi-Source information (Figure 3 is quoted in Frontiers in Energy Research, 2022, 10: 891867.): (1) cross-scale information matching, association and filtering; (2) Cross-scale coordination of cross-scale measurement information; (3) Cross-scale cross-scale modeling of cross-scale information. Intelligent data cleaning refers to other methods for intelligent cleaning and screening of massive data. The outliers are corrected according to certain rules to increase the credibility of the original data [14]. Aiming at the integrated distributed storage and real-time extraction method of multi-source spatial information, a set of complete, accurate and general data structure form is proposed for various scenarios and algorithms, which lays a foundation for the application research of various applications in intelligent power system.

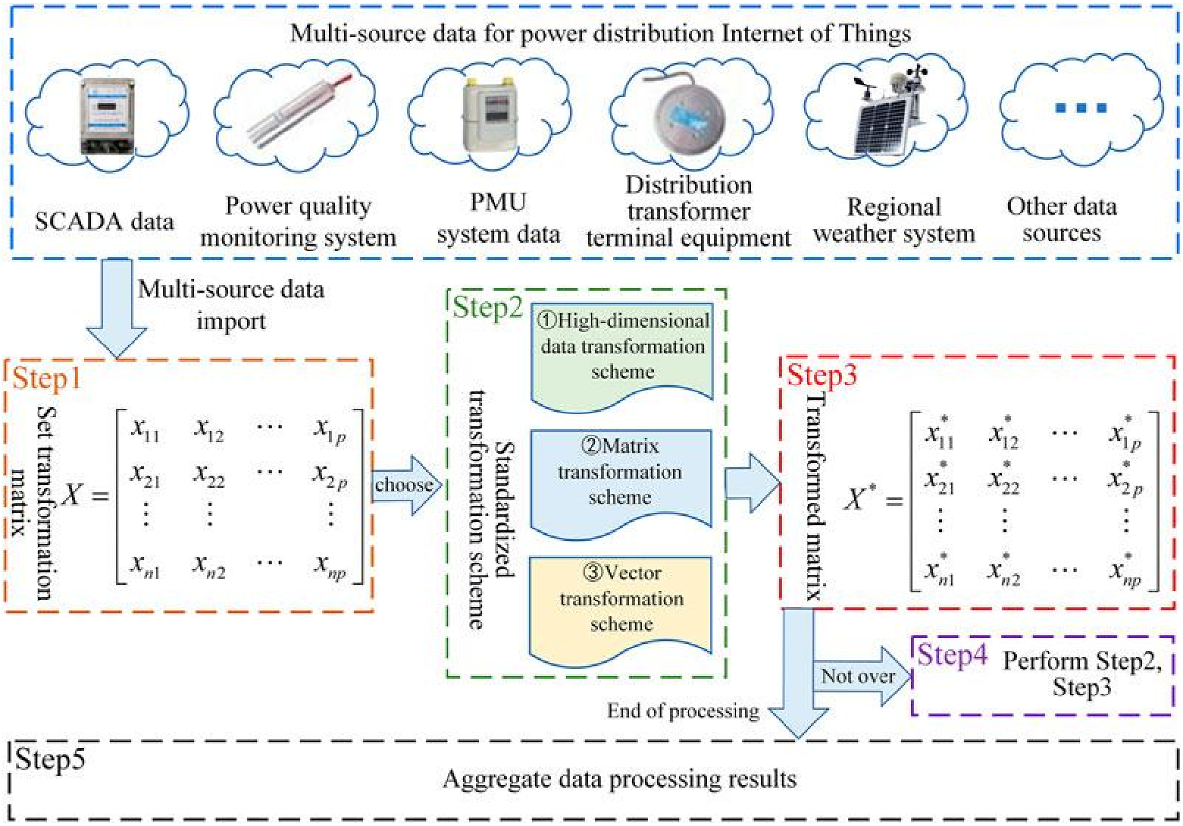

Fig.3 Unified fusion process of ubiquitous multi-source data

C. Unified Service Technology for multi-source data

The source network uses the above two core technologies to gather data resources at various levels and provide basic data and technical support for power grid operation, market transaction, scheduling management, planning and maintenance, etc. At the same time, it also provides relevant information about power grid operation for enterprises in other industries and power consumers [15]. It provides help for the government's macro-control and other aspects of work. The traditional real-time data service based on section type or document type has high technical barriers, which restricts the development of ubiquitous technology and limits the popularization of ubiquitous technology. Use the integrated service of multi-source data, use the service bus of wide area service Agent to discover, locate and access remote services, and use the message bus as the information transmission channel for data transmission, and use standardized data structure to describe the flow mode of data. Among them, the domain of receiving data, the identification of data structure and the data to be transmitted are important interface parameters [16]. Transmit message The service transmits a message after it is generated. Receiving Packets After receiving a packet, the service sends the packet according to the packet requirements. The integrated service process of universal multi-source data is presented. The service isolates multi-dimensional data repositories, enabling consistent access to various types of data. This method gives full play to the function of the service and makes it have a higher degree of openness, so as to achieve the purpose of instant sharing of services according to needs.

D. Resource holographic perception and decision

Through real-time monitoring of the status of each node of power generation, transmission, distribution, electricity consumption, energy storage and the working status of the monitoring system, combined with the dynamic monitoring of meteorological, forest fires, dense transmission channels and other control systems closely related to the power grid [17]. Specifically, geographic GIS maps are used to display typhoon names, wind circle size and intensity, predicted paths and possible equipment, and to present the dynamics of typhoon evolution based on typhoon forecast data; By integrating the forecast data such as typhoon path, typhoon grade and typhoon radius with the relevant data of transmission lines, intelligent identification based on multiple fault sets such as typhoon path, typhoon grade and typhoon radius can be realized and incorporated into the static security analysis of the power system to evaluate the potential damage of typhoon to the power system and put forward the prediction of typhoon damage level [18]. Power supply planning, load forecasting, new energy generation forecasting and unit control space data of "net-provincial-land-county" level are proposed based on the traditional track model algorithm. Finally, it can achieve large-scale coordination and control of accurate power grids, and improve the overall safety, economy and disaster resistance of large power grids.

IV. POWER SYSTEM CONTROL MODE WITH SOURCE-NETWORK-CHARGE-STORAGE INTEGRATION

In a distribution network with multiple decentralized energy sources, such as flexible load and flexible load, reactive power support is provided to the distribution network inverter power supply of the transmission line, and the demand side of the load is actively adjusted by adjusting the storage charge discharge and flexible load, so as to realize the load-storage synergistic linkage of the source network and ensure that the voltage level of each node is in a reasonable safe range. A wide-area voltage management and control model of distributed source network load and storage is constructed to retain storage backup capacity, reduce network loss and keep the voltage of each node in the safe range [19]. The objective functions and constraints contained in the proposed model are shown as follows. Figure 4 shows the Power system control mode of source-network-charge-storage integration (the picture is quoted in Dispatchable Power from Energy Storage Systems Help Maintain Grid Stability).

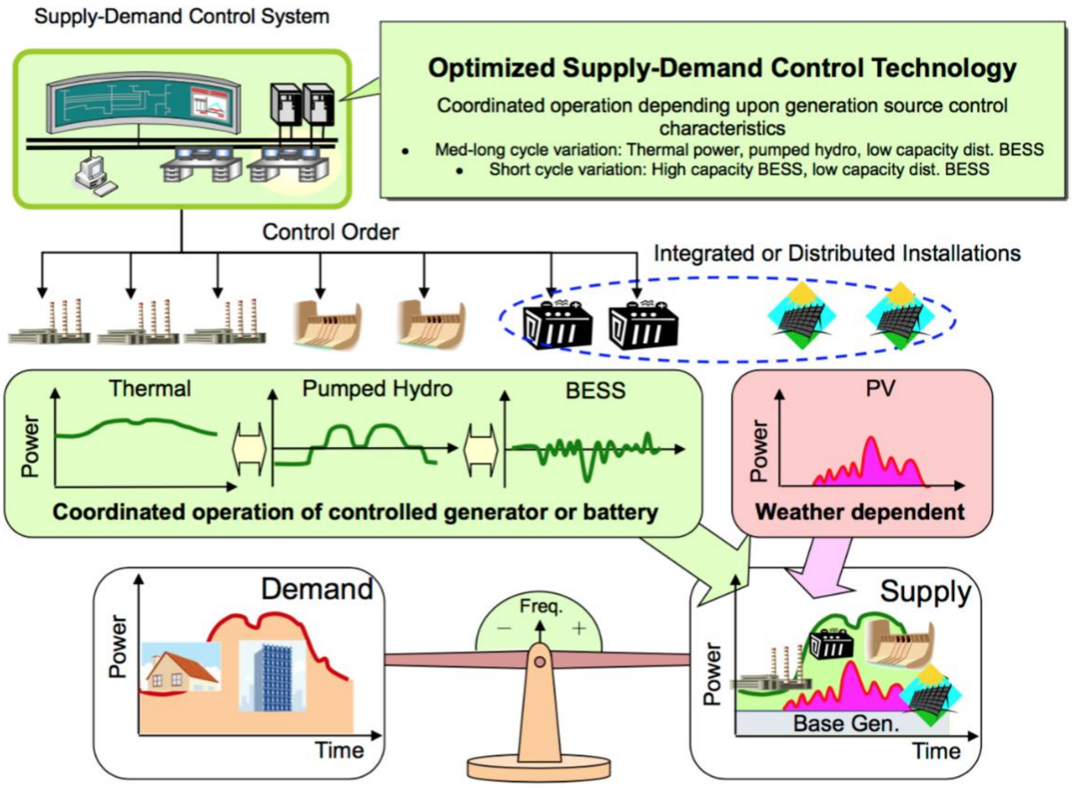

Fig.4 Control flow of source-network-charge-storage integrated power system

A. Objective function

The objective function of wide area voltage management and control is to ensure the storage reserve capacity and minimize the network reactive power loss, while keeping the voltage of each node within the safe range.

$$\min G(X(i,t),Y(i,t)) = \partial_1 G_\alpha + \partial_2 G_{ESS} + \partial_3 G_\delta \tag{1}$$

$$G_\alpha = \sum_{t\in T} \frac{1}{M} [\sum_{i\in M} 2(\alpha(i,t) - \alpha_{ref})^2] \tag{2}$$

$$G_{ESS} = \sum_{i\in A_{ESS}} | R_\gamma(i,t) - R_\gamma(i,0) | \tag{3}$$

$$G_\delta = \sum_{t\in T} \frac{X_{loss}(t)}{R_M} = \sum_{t\in T} \frac{|W_{ij}(t)|^2 h_{ij}}{R_M} \tag{4}$$

$$\partial_1 + \partial_2 + \partial_3 = 1 \tag{5}$$

$R_\gamma(i,t)$ and $R_\gamma(i,0)$ are respectively the charged state of ESS installed on node i at time t and the initial state. M, T, A_{ESS} is the distribution node set, voltage regulation period and ESS installation node set respectively. $W_{ij}(t)$ and h_{ij} are the current amplitude and branch resistance at time t on branch (i, j); R_M is the network reference apparent power.

B. Constraints

The constraint conditions include distribution topology constraint, distribution power flow constraint, reactive power constraint of distributed RDG, charge and discharge power and capacity constraint of ESS, and power constraint of flexible load participating in demand response.

a. Topology constraints of distribution network

$$T = (A, Z) \tag{6}$$

Distribution network topology constraints include all node A and branch Z sets in distribution network topology T.

b. Power flow constraint of distribution network

$$\begin{gathered} X_R(t) + X_{PV}(i,t) + X_{WT}(i,t) + X_{ESS}(i,t) - \\ X_{FL}^{after}(i,t) - X_{Load}(i,t) = \alpha^2(i,t) \sum_{j\in A_i} f_{ij} - \\ \alpha(i,t) \sum_{j\in A_i} \alpha(j,t)(f_{ij}\cos\xi_{ij} + \varepsilon_{ij}\sin\xi_{ij}) \end{gathered} \tag{7}$$

$$\begin{gathered} Y_R(t) + Y_{PV}(i,t) + Y_{WT}(i,t) - Y_{Load}(i,t) = \\ -\alpha^2(i,t) \sum_{j\in A_i} \varepsilon_{ij} + \alpha(i,t) \sum_{j\in A_i} \alpha(j,i)(f_{ij}\cos\xi_{ij} + \varepsilon_{ij}\sin\xi_{ij}) \end{gathered} \tag{8}$$

$X_{FL}^{after}(i,t)$ is the active power after the flexible load on node i participates in the demand-side response. $X_{Load}(i,t), Y_{Load}(i,t)$ is the active and reactive power demand of load on node i at time t. j is the set of nodes connected to node i, and $j \in A_i; f_{ij}, \varepsilon_{ij}$ is the conductance and susceptance on branch i, j respectively. ξ_{ij} is the phase difference between nodes i, j.

c. Reactive power constraint of distributed RDG

$$Y_{PV}^{\min}(i,t) \le Y_{PV}(i,t) \le Y_{PV}^{\max}(i,t) \tag{9}$$

$$Y_{WT}^{\min}(i,t) \le Y_{WT}(i,t) \le Y_{WT}^{\max}(i,t) \tag{10}$$

$Y_{WT}^{\max}(i,t), Y_{WT}^{\min}(i,t)$ is the upper and lower limit of reactive power output of WT on node i at time t.

d. ESS *Constraints on charging and discharging power and capacity*

$$X_{dc}^{\max} \le X_{ESS}(i,t) \le X_{c}^{\max} \tag{11}$$

$$Z_{ESS}^{\min} \le Z_{ESS}(i,t) \le Z_{ESS}^{\max} \tag{12}$$

e. *Power constraints of flexible load participating in demand response*

$$X_{FL}^{\min} \le X_{FL}^{after} \le X_{FL}^{\max} \tag{13}$$

V. Example analysis

A. Scenario and Parameter Settings

An example analysis is made of a medium-sized town (Figure 5). The system uses a 110 kV substation to connect to a higher level of power grid, with a total capacity of 79 square kilometers, and three voltage levels are connected by transformers [20]. There are 6 transformers, 5 photovoltaics, 5 energy storage devices, and 2 flexible loads in the system.

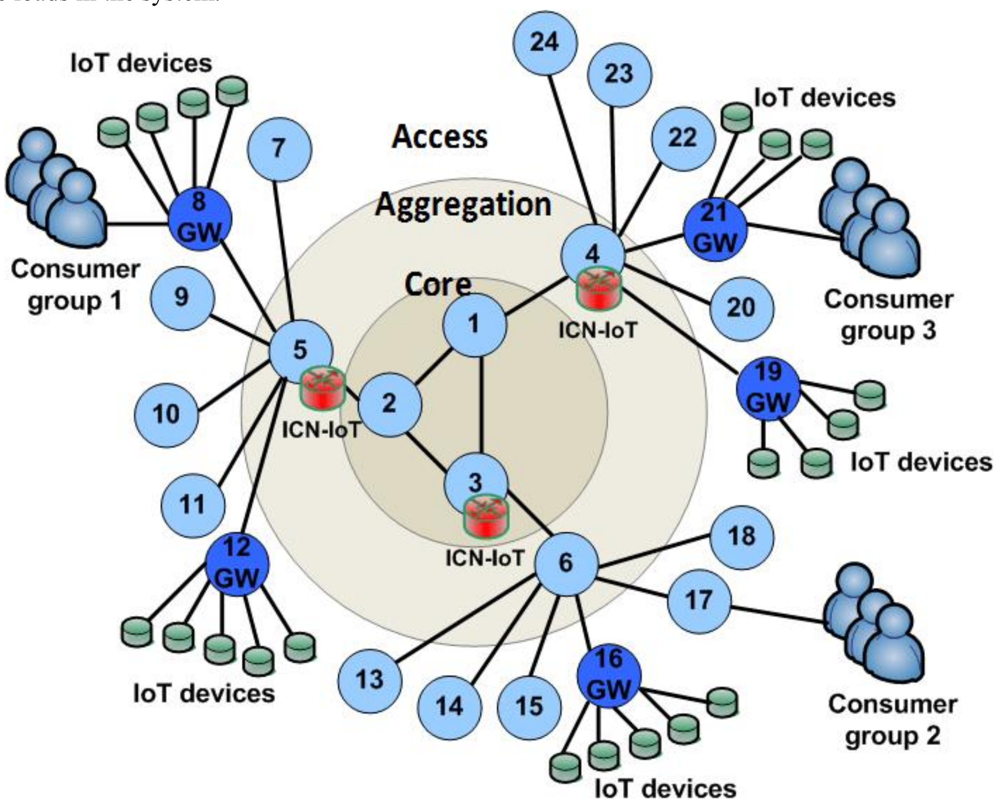

Fig.5 Topology of distribution network for example

The load data of 152 power customers in the past 3 years is selected as a sample, and real-time reactive power loss is generated under 5% random interference according to the preset power factor, and it is interpolated at a spatial resolution of 3 minutes. In the data of three years, the data of two years are selected as samples, and the data of one year is tested. Each subject adopts the Actor network structure consistent with the Critic structure, that is, one input layer, two hidden layers and one output layer [21]. The input layer of the actor network is a state vector of 1x114 dimensions, a hidden layer of 128 nodes, and an output layer of 1x23 behavior vectors. The input layer of the Critic network is a 1x137 dimensional state-behavior vector. In each round, 5 random seeds are used and 240 random selections are made in each round.

B. Analysis of training results

Figure 6 shows the average cumulative return for each round over 10,000 exercises. In the early stage, the individual income is very low, which indicates that the individual is still in a state of "exploration" as a whole, and has not learned an effective behavior strategy. After 1000-3500 cycles, the returns gradually increased and leveled off, indicating that the individual's performance gradually improved with the passage of time and had the ability to adapt to external conditions; After more than 4000 times, the benefit of the system tends to be stable, which shows that the method has a good control performance, and proves that the method is feasible to solve a wide range of distributed voltage regulation problems.

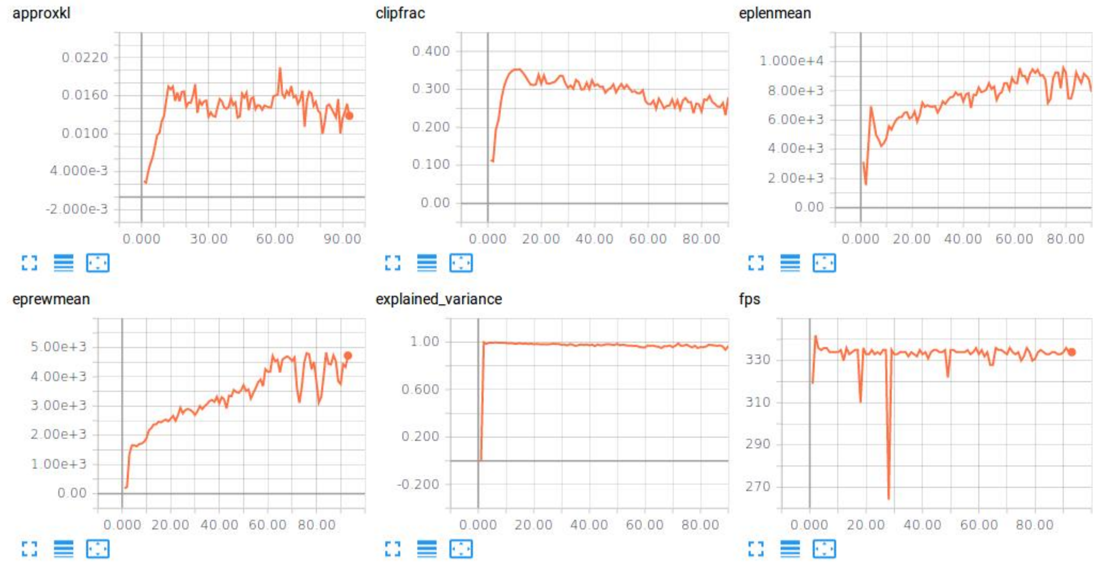

Fig.6 Average cumulative reward curve

C. Analysis of test results

In the test set, 3-day test data were extracted from the experimental group, a total of 1440 times, each test lasted 3 minutes, and the average test time was 2.65 seconds. The test results were shown in Figure 7. In order to facilitate the explanation, the active and reactive power of load, PV, WT and flexible load are calculated, and the active power output in each period is calculated.

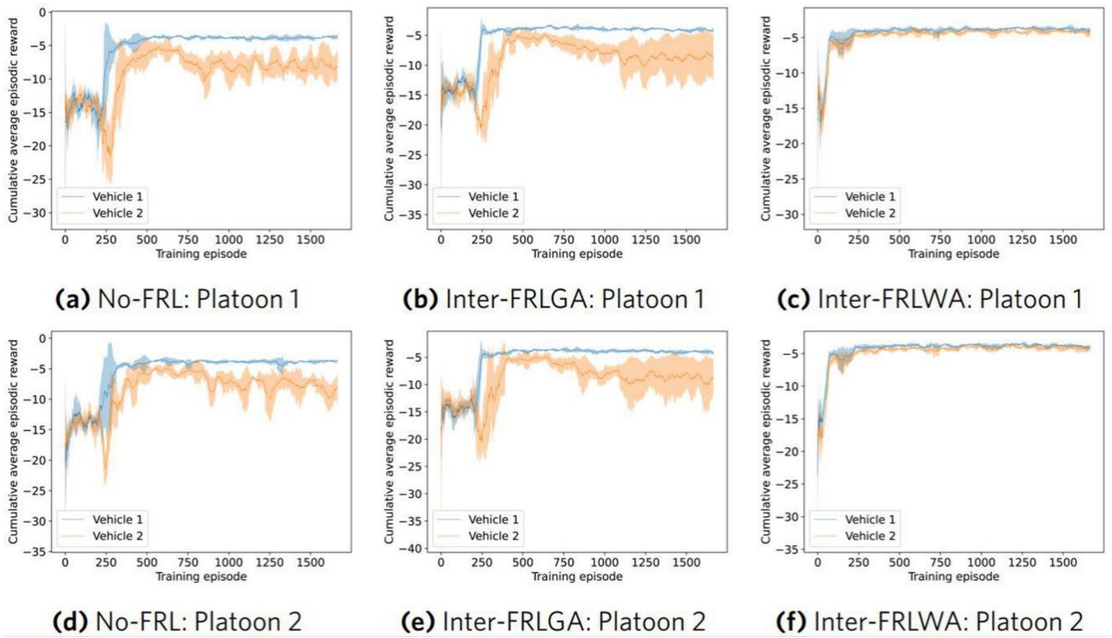

Fig.7 Online test results

PV and WT inverters can adjust the reactive power factor in time according to the reactive power requirements of the distribution network, so as to balance the reactive power of the whole network. The active energy storage system can adjust the AC power with the power grid in time according to the active load of the distribution network, so as to achieve the global active power balance. Flexible load reduces power consumption at peak and peak times, and increases power consumption at peak and valley times. At present, the SOC value of the system is in the range of (0.2,0.8), which indicates that the system can maintain a certain standby capacity, and the grid loss has been maintained in a small range, which indicates that different types of energy can be used to control the voltage while ensuring the grid loss. After three days, the average voltage of each contact was maintained between (0.98 and 1.01), where the maximum voltage at 95 was 1.034 and the minimum voltage at

1.002; The maximum voltages at node 105 are 1.007 and 0.977, which indicate that the stability of the system can be monitored and guaranteed by using a wide range of distributed source and network load distribution.

VI. CONCLUSION

This project intends to study a wide range voltage regulation strategy with multi-source cooperative interaction in distribution network. The MADDPG algorithm is used to solve it, so as to overcome the existing multi-objective optimization design too dependent on accurate mathematical models. Through simulation calculation, the control scheme proposed in this project can ensure that the voltage of each node is stable within a safe range on the premise of ensuring the stable operation of the power grid.

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