Renewable Energy and Power Quality Journal
https://repqj.com/index.php/repqj/index
RE&PQJ, Vol. 23, No. 4, 2025

Construction of Provincial Dispatching Automation System for Power Grids Assisted by Homogeneous and Heterogeneous Modes

Chenhui Hang, Zhihao Yang*, Fuhe Wang, Dong Han, Xiaoguang Wang, Xingyu Qiao

Inner Mongolia POWER (GROUP) CO., LTD. Power Dispatching Control Branch, Hohhot, Inner Mongolia, China
*Correspondence author email: m19969012490@163.com

Abstract. The traditional provincial power grid dispatching automation system faces many challenges, among which information islands and poor data interoperability are the key issues that restrict dispatching efficiency and system stability. In actual engineering applications, due to differences in technical standards and protocols, it is difficult for power grid dispatching systems in different regions to achieve efficient data sharing and collaborative dispatching. For example, there are significant differences in data interaction and dispatching strategies between regions with a high proportion of new energy access and regions dominated by traditional thermal power, resulting in delayed cross-regional dispatching response and difficulty in effectively responding to new energy output fluctuations and sudden failures. In addition, the widespread access of distributed energy has further aggravated the complexity of data integration, limiting the flexibility and intelligence level of traditional dispatching systems. To solve these practical engineering challenges, this paper proposes an optimized dispatching architecture based on homogeneous and heterogeneous modes, integrating the characteristics of different regions, achieving efficient data sharing and resource optimization dispatching, and improving the intelligence level of the system. A multi-region collaborative optimization dispatching model is constructed, which comprehensively considers factors such as load characteristics, power structure, power grid topology, and cross-regional information interaction, covering multiple goals such as economic optimization, new energy consumption, and dispatching response speed, and imposes relevant constraints to ensure the safe operation of the power grid. Through multi-source data fusion technology, combined with long short-term memory (LSTM) network for load forecasting, genetic algorithm (GA) optimization of power flow distribution, deep reinforcement learning (DRL) dynamic adjustment of scheduling strategy, we further designed a fast load adjustment mechanism, fault tolerance mechanism and intelligent emergency plan recommendation system. Experimental results show that the system is superior to existing methods in data sharing efficiency, scheduling response time, load forecasting accuracy, system stability, etc., providing technical support for efficient and intelligent scheduling of provincial power grids.

Key words. Homogeneous and heterogeneous modes, Provincial power grid dispatching, Automation system, Multi-regional collaborative optimization, Intelligent dispatching algorithm

1. Introduction

The provincial dispatching automation system for power grids is vital in ensuring power safety and optimizing resource allocation [1,2]. With the large-scale access of new energy and the advancement of power market reform, the challenges faced by power grid dispatching are becoming increasingly complex, and traditional dispatching methods are challenging to meet the requirements of modern power systems. At present, the provincial dispatching system of power grids generally has the problem of information silos [3]. The dispatching system architectures in different regions may be not unified [4], and data interoperability is poor [5], limiting the ability of information sharing and collaborative optimization. In addition, the traditional centralized dispatching mode lacks flexibility when facing the high penetration rate of renewable energy, and it is difficult to effectively deal with problems such as fluctuation in renewable energy output, cross-regional energy dispatching needs, and sudden faults [6-8]. The inefficiency of emergency response further restricts the safe and stable operation of the power grid. Therefore, studying breaking through the existing dispatching system's limitations and improving the intelligence, flexibility, and collaboration of the dispatching system has become an important direction for the current power grid dispatching optimization [9,10].

To this end, a power grid dispatching optimization architecture based on homogeneous and heterogeneous modes is studied in this paper to improve data sharing and resource dispatching efficiency. On the basis of keeping the core architecture of the dispatching system consistent, this method allows different regions to adopt an adaptive architecture according to their characteristics, thereby considering the advantages of unified management and flexible dispatching. By building an optimized dispatching mechanism, the data interaction capability is improved, and the efficiency and stability of cross-regional collaborative dispatching are enhanced. This paper further combines simulation experiments to verify the dispatching optimization effect of the proposed method and evaluates it from the aspects of data sharing efficiency, dispatching response speed, system stability, etc. The research results show that this method can effectively improve the operating efficiency and intelligence level of the provincial dispatching system of the power grid, providing new optimization ideas for developing smart grids.

Main contributions: (1) Multi-region collaborative optimization scheduling model: A multi-region collaborative optimization scheduling model based on homogeneous and heterogeneous modes was constructed. Through standardized data interfaces and communication protocols, the problems of inconsistent data formats and differences in communication protocols between regions were solved, and efficient cross-regional data sharing and collaborative scheduling were achieved, significantly improving the interoperability of inter-regional scheduling; (2) Data fusion and intelligent scheduling algorithm: Multi-source data fusion technology was adopted to integrate data from different regions, combined with LSTM load forecasting, GA optimization of flow distribution and DRL dynamic adjustment of scheduling strategies, which improved the accuracy and flexibility of scheduling decisions and effectively solved the difficulties in scheduling strategy formulation caused by poor data interoperability; (3) Emergency scheduling and stability optimization: A rapid load adjustment mechanism, fault-tolerant mechanism and intelligent emergency recommendation system were designed to ensure that the system can still operate stably in the event of delays or failures in data interaction between regions, thereby enhancing the reliability and interoperability of inter-regional scheduling.

2. Current Status and Challenges of Traditional Power Grid Provincial Dispatching Automation System

The development of the provincial power grid dispatching automation system has experienced an evolution from traditional manual dispatching to modern intelligent dispatching, and people have carried out in-depth research in this field [11,12]. Currently, the mainstream dispatching methods mainly include centralized dispatching and regional dispatching [13,14]. The centralized dispatching mode relies on the provincial dispatching center for unified management and has strong global control capabilities, but it relies heavily on data calculation and transmission. When faced with the high penetration rate of new energy and the complexity of the power grid structure, the dispatching efficiency and flexibility are subject to certain restrictions. The regional dispatching model can improve the autonomy of local dispatching by dividing independent regions for distributed management, but the cross-regional coordination ability is weak, which easily leads to a decrease in the overall resource allocation efficiency. In recent years, technologies such as artificial intelligence (AI) [15], big data analysis [16], and cloud computing have been gradually applied to the research on power grid dispatching optimization [17]. Methods such as intelligent prediction and machine learning-assisted decision-making have shown certain advantages in load prediction and fault diagnosis [18,19]. However, the existing intelligent means are still mainly limited to local optimization, and it is difficult to break through the bottleneck of data sharing and collaborative dispatching, resulting in limited improvement in the overall system's intelligence level.

The traditional provincial dispatching automation system of power grids mainly relies on the dispatching center to perform key functions such as real-time power monitoring [20], load prediction [21], and fault response [22]. Its workflow usually includes information collection, data calculation, dispatching decision-making, and command execution. In the information collection stage, various sensors and measuring equipment are responsible for collecting power grid operation status data and uploading it to the dispatching center for processing. The data calculation link relies on the dispatching system to perform calculation tasks such as load prediction, flow calculation, and short-term optimization dispatching to provide a reasonable dispatching solution. In the dispatching decision-making process, the dispatching center controls the power grids in each region according to the established dispatching strategy. It sends specific instructions to the power generation, transmission, and distribution sides to ensure the safety and economy of the power grid operation. However, the traditional system emphasizes centralized management in its architectural design, resulting in a relatively fixed dispatching mode that is difficult to adapt to complex and changing power demands. In addition, the interoperability of data across regions is poor, which affects the ability of the dispatching system to collaborate [23,24].

From the perspective of the limitations of the system architecture, the traditional provincial dispatching automation system faces many challenges. First, the data integration capability is insufficient. Due to differences in technical standards and protocols, dispatching systems in different regions are difficult to achieve efficient data sharing, resulting in information silo problems [25]. Second, the dispatching system has low flexibility. Traditional rule-driven dispatching methods cannot quickly respond to the fluctuation and load changes of new energy, resulting in a lack of adaptability of the dispatching strategy [26,27]. Furthermore, the emergency dispatching capacity is limited. When an emergency occurs, the cross-regional coordination and rapid response capabilities are weak, which affects the safety and stability of the power grid [28]. In addition, the traditional dispatching model is difficult to fully utilize technologies such as AI and big data when facing the needs of intelligent development, resulting in limited depth and breadth of dispatching optimization [29,30]. In general, breaking through the limitations of traditional architecture, improving data sharing efficiency, and enhancing dispatching flexibility and collaboration capabilities have become key issues in the current power grid dispatching optimization.

3. Application of Homogeneous and Heterogeneous Modes in Provincial Power Grid Dispatching System

A. Definition and Characteristics of Homogeneous and Heterogeneous Modes

In the construction of provincial power grid dispatching automation system, the optimized dispatching architecture based on homogeneous and heterogeneous modes provides a solution that takes into account both uniformity and flexibility, aiming to break through the limitations of traditional centralized dispatching systems in data interoperability, dispatching optimization, regional adaptability, etc. [31-33]. By building a unified core dispatching platform and multiple flexible regional dispatching units, this architecture can not only meet the dispatching coordination needs of the whole province, but also customize and optimize the grid characteristics of each region.

In this architecture, the provincial dispatching center serves as the core platform, and realizes data sharing, load forecasting, dispatching optimization and cross-regional resource dispatching across the province through a unified architecture design. The core platform includes key modules such as the dispatching command center, the global load forecasting system and the optimized dispatching calculation engine. The dispatching command center is responsible for formulating the global dispatching strategy and coordinating the dispatching instructions. The global load forecasting system combines long-term and short-term load forecasting technologies to provide accurate power demand forecasts. The optimized dispatching calculation engine calculates the optimal power dispatching plan based on optimization algorithms such as mixed integer linear programming (MILP) [34] and deep reinforcement learning (DRL) [35]. The MILP algorithm minimizes the dispatch cost or other optimization objectives under all power dispatch constraints by adjusting decision variables.

The core platform adopts standardized data interfaces, unified computing models, and global optimization algorithms to ensure the coordination and consistency of the province's power grid operation, thereby improving the overall dispatch efficiency and system stability.

The innovation of this architecture is that it supports regional dispatch units to adopt flexible technical architectures and optimization algorithms according to the specific needs and characteristics of their respective power grids to adapt to the energy structure, load characteristics, and dispatch needs of different regions. For example, in areas with high penetration of new energy, dispatch units can focus on new energy power forecasting, real-time optimization dispatching, and energy storage coordination strategies to improve new energy absorption capacity and cope with power fluctuations. In areas dominated by traditional thermal power, they rely more on economic dispatch strategies and unit optimization dispatching to reduce operating costs.

For areas with a high proportion of distributed energy, the architecture supports distributed collaborative dispatching technology based on edge computing to achieve local autonomous optimization while maintaining efficient collaboration with the core platform. Through this architecture design that combines isomorphism and heterogeneity, the system enhances the adaptability of each region to new energy fluctuations, load changes, and emergencies on the basis of ensuring province-wide coordination, thereby improving the flexibility, stability, and intelligence of power grid operation.

B. Systematic Integration Mechanism of Homogeneous And Heterogeneous Architectures

In the provincial power grid dispatching system, the design of homogeneous and heterogeneous modes is not only an innovation at the architectural level, but also the underlying logic throughout the realization of system functions. In order to ensure the seamless integration of the architectural framework with the multi-region collaborative optimization model, intelligent dispatching algorithm and emergency strategy proposed later, this paper designs a systematic integration mechanism. The core dispatching platform establishes a global data model through the CIM standard and the IEC 61850 protocol to provide standardized data input for subsequent LSTM load forecasting, GA flow optimization and DRL strategy adjustment. At the same time, the regional dispatching unit converts local heterogeneous data (such as new energy power forecast, energy storage status, etc.) into a globally available format through the adapter module to ensure the compatibility of data sharing and model training. The homogeneous architecture achieves global optimization through mixed integer linear programming (MILP), while the heterogeneous regions deploy differentiated algorithms according to the differences in energy structure (such as XGBoost prediction in new energy areas and economic dispatch optimization in traditional thermal power areas). The two achieve parameter synchronization through the federated learning framework to ensure that the local optimization results can be dynamically fed back to the global dispatching model. During normal operation, regional dispatch units independently perform local optimization (such as energy storage charging and discharging strategies, load adjustment) based on heterogeneous characteristics; when cross-regional power flow fluctuations or emergencies occur, the core platform dynamically takes over part of the dispatching authority through the DRL model and triggers the emergency load adjustment mechanism. This hierarchical response design not only retains the flexibility of heterogeneous regions, but also ensures the consistency of global dispatch. In addition, the intelligent agent mechanism of heterogeneous regions complements the global optimization of the core platform: when a regional dispatch unit fails, the adjacent regions automatically adjust the strategy through the pre-trained DRL model, and the core platform reallocates spare resources based on real-time data to ensure the overall stability of the system. Through this systematic integration mechanism, homogeneous and heterogeneous architectures not only provide an operating environment for intelligent algorithms, but also achieve overall optimization goals through data interfaces, algorithm collaboration, and functional layering.

C. Applicability of Homogeneous and Heterogeneous Modes in Power Grid Dispatching

The advantages of the homogeneous and heterogeneous modes in power grid dispatching are mainly reflected in the following aspects:

First, in terms of multi-regional coordinated dispatching optimization, this method effectively breaks through the incompatibility of data formats, communication protocols, and system architectures faced by the traditional provincial dispatching system of the power grid when coordinating different regions. It avoids delays in dispatching responses. By maintaining consistency at the core level, a unified dispatching framework for the entire province is achieved while allowing each region to adopt adaptive technologies and improve the autonomy and flexibility of regional dispatching, thus enhancing the cross-regional resource optimization dispatching capability.

Second, in terms of the compatibility of distributed energy and energy storage systems, with the widespread access of distributed photovoltaic, wind power, and energy storage systems, the grid operation mode is gradually evolving from traditional centralized to distributed. Heterogeneous dispatching units can optimize the dispatching strategy of distributed power sources and energy storage equipment according to the different penetration rates of new energy. For example, in regions where renewable energy output is unstable, the XGBoost prediction model can be used to improve the precision of wind and solar power output predictions. Combined with the optimal charging and discharging strategies of the energy storage system, precise renewable energy consumption can be achieved, thereby improving the stability of the power grid and the utilization rate of renewable energy.

In addition, in terms of intelligent dispatching optimization, this method can adapt to the operating characteristics of power grids in different regions and support regional dispatching units to use different intelligent optimization algorithms. For example, in the regulation of new energy fluctuation, reinforcement learning methods can be used to optimize the regulation strategy of energy storage and adjustable loads. In the optimization of transmission line flow, GA can be combined for intelligent dispatching optimization. By adopting regional adaptive intelligent optimization algorithms, the precision and intelligence level of power grid dispatching decisions can be improved.

D. Construction of Dispatching Automation System Based on Homogeneous and Heterogeneous Modes

1) Data Sharing Mechanism and Information Fusion Strategy

In the grid dispatch optimization architecture of this study, homogeneous and heterogeneous modes refer to the flexible application of different technical standards and communication protocols based on the characteristics of each regional power grid on the basis of ensuring uniformity and interoperability, so as to form a dispatch system that is both coordinated and adaptable. Homogeneity ensures data compatibility and information sharing between systems through unified data interfaces and standardized communication protocols. Heterogeneity is reflected in the fact that different regions adopt flexible localized dispatch strategies, optimization algorithms and communication protocols according to their differences in grid structure, energy distribution, load characteristics, etc., to achieve precise dispatch.

To ensure the coordination and efficiency of cross-regional dispatch, the system adopts standards such as the Common Information Model (CIM) and IEC 61850 to ensure the consistency of data formats between dispatch units in different regions, and enhance the overall coordination ability of the system through data interoperability. At the same time, by using IEC 61970 and IEC 61968 standards, the data exchange between the energy management system (EMS) and the distribution management system (DMS) is seamlessly connected, thereby promoting information sharing between regions.

In terms of data transmission, the IEC 104 standard is used to transmit real-time measurement and control data. At the same time, the MQTT and DDS protocols are combined to reduce data transmission delays through the publish-subscribe mechanism to ensure fast and accurate information transmission. Based on this data transmission model, the system can efficiently realize the coordination and linkage of regional dispatch units. The evaluation formula for data transmission delay is as follows:

$$\Delta t = \frac{1}{f} \cdot \log\left(\frac{P_{\text{current}}}{P_{\text{initial}}}\right) \quad (1)$$

Among them, Δt is the data transmission delay time. f is the system processing frequency. P_{current} and P_{initial} are the power values of the current and initial data, respectively. This formula can effectively evaluate the delay with different data transmission protocols and help the dispatching platform optimize the data transmission strategy.

2) Core Dispatching Platform

As the decision-making center of the provincial power grid dispatching system, the core dispatching platform is responsible for dispatching optimization calculations, real-time monitoring, intelligent prediction, and dispatching decision execution across the province. Figure 1 shows its functional architecture:

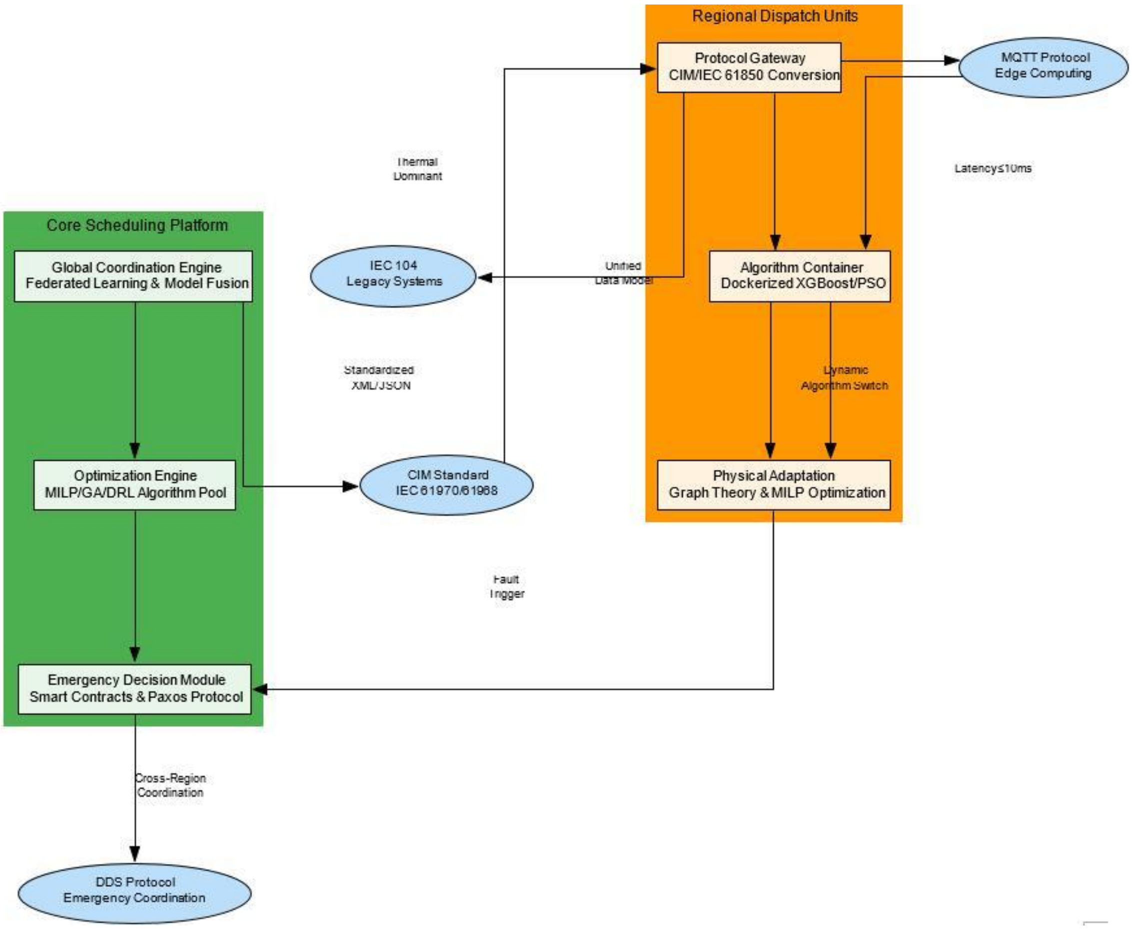

Figure 1. Architecture diagram of the core dispatching platform functions

The core platform uses the LSTM model combined with homogeneous and heterogeneous modes to process the grid load time series data, predict future load demand, and adjust the dispatch strategy based on the prediction results. The specific prediction model is as follows:

$$h_t = \sigma\left(W_h \cdot h_{t-1} + W_x \cdot x_t + b\right) \quad (2)$$

Among them, h_t is the hidden state at the current moment. h_{t-1} is the hidden state at the previous moment. x_t is the current input data. W_h and W_x are weight matrices, respectively. b is the bias term. σ is the activation function. Through LSTM, the core platform can predict future load demand and adjust the dispatching strategy based on the prediction results.

In terms of scheduling optimization, the deep reinforcement learning (DRL) model is used to optimize scheduling decisions and dynamically adjust system behavior by maximizing the reward function. The specific reward calculation formula is:

$$R_t = \gamma \cdot R_{t+1} + \rho \cdot \delta_t \quad (3)$$

Among them, R_t is the reward at the current moment. γ is the discount factor. R_{t+1} is the reward at the next moment. δ_t is the improvement of the dispatching decision. Through DRL, the system can dynamically adjust the dispatching strategy based on real-time data, thereby improving the efficiency and stability of power grid operation.

3) Regional Dispatching Unit

The regional dispatch unit adopts customized dispatch strategies based on the characteristics of the regional power grid, load characteristics, energy structure and regional demand. In areas with high penetration of new energy, the regional dispatch unit combines the XGBoost prediction model with the energy storage optimization dispatch strategy to improve the new energy consumption capacity and reduce the impact of power fluctuations on the system. The formula of the XGBoost prediction model is:

$$y_t = \sum_{i=1}^{N} \beta_i \cdot f_i(x_t) \quad (4)$$

y_t is the predicted load value. β_i is the weight of each base learner. $f_i(x_t)$ is the output of the i -th base learner for the input data x_t. N is the number of base learners. By combining XGBoost, the regional dispatching unit can effectively respond to the fluctuation of new energy and make timely dispatching decisions.

In areas where traditional energy is the main source, the dispatch unit focuses on applying economic dispatch strategies to optimize unit output and reduce operating costs. The objective function of economic dispatch is:

$$\min \sum_{i=1}^{m} (C_i \cdot P_i) \quad (5)$$

Through this optimization objective, the dispatching unit can effectively reduce costs while meeting the supply and demand balance of the power grid and equipment safety constraints.

4) Hierarchical Dispatching Mode

The provincial dispatching system of the power grid proposed in this study combines homogeneous and heterogeneous modes, and adopts a hierarchical dispatching mode that combines centralized dispatching with distributed collaborative dispatching. Under normal operating mode, the core dispatching platform is responsible for the overall dispatching optimization of the province, and the regional dispatching unit performs adaptive dispatching according to the load characteristics and energy structure of the local power grid to ensure the stability of the local power grid. The core platform and the regional units improve the coordination and dispatching efficiency of the power grid through a unified data interface and real-time information sharing.

In the event of an emergency or system anomaly, the core platform can quickly take over some regional dispatching tasks and adjust strategies to ensure the safe and stable operation of the power grid. The emergency dispatching strategy is adjusted through the following optimization goals to take into account both economy and emergency response capabilities:

$$\min \sum_{i=1}^{n} (C_i \cdot P_i + \lambda_i \cdot d_i) \quad (6)$$

Among them, λ_i is the emergency dispatching coefficient, and d_i is the dispatching deviation caused by the emergency. This optimization goal balances grid stability and economy while enhancing emergency response capabilities and ensuring rapid recovery of normal operations.

This model flexibly adjusts dispatch strategies in emergencies through the collaboration between the core platform and regional dispatch units, improving the adaptability and stability of the grid to emergencies.

4. Dispatching Optimization Implementation

A. Multi-regional Collaborative Optimization Dispatching Model Based on Homogeneous and Heterogeneous Modes

1) Model Construction

This study aims to build a multi-regional collaborative optimization dispatching model based on homogeneous and heterogeneous modes to improve the overall dispatching capability of the provincial dispatching automation system of the power grid. The construction of the model covers load characteristics, power structure, power grid topology, and cross-regional information interaction, with a special focus on improving the collaboration capability and resource allocation efficiency of regional power grids through optimizing dispatching strategies.

In the grid topology modeling, based on the topological structure of each regional power grid, this study applies a power flow optimization model. The cross-regional power transmission path and transmission capacity are analyzed through network graph theory, and the power flow direction and transmission capacity are optimized. This study combines intelligent optimization algorithms, especially GA, to optimize the grid topology and power flow to further improve the optimization effect. GA is used to simulate the natural selection process and evaluate the power flow distribution of the power grid. Through operations such as crossover and mutation, the power transmission path and distribution method are optimized to improve the efficiency and stability of cross-regional power transmission. Figure 2 shows the specific topology and optimization of power flow:

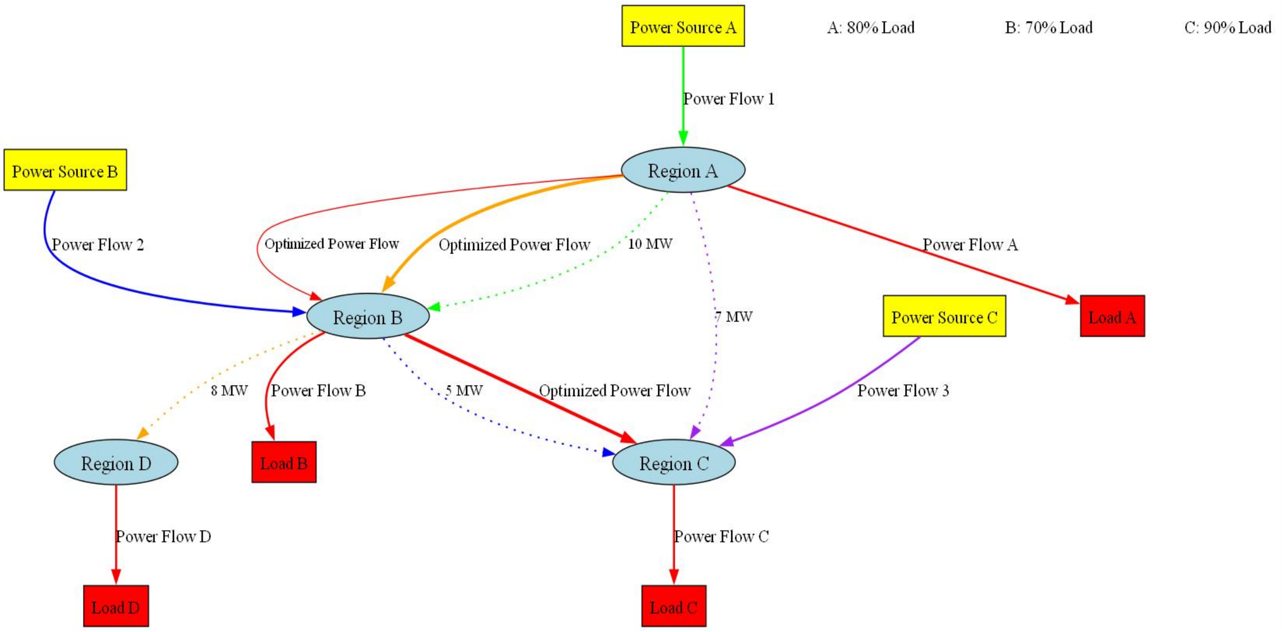

Figure 2. Power flow and topology optimization diagram

Through this optimization model, the system can calculate the power flow distribution in real time, ensure the efficient transmission of electricity between regions, and consider the safety and stability of the lines to avoid problems such as overload, excessive load on generator sets, and unstable voltage. The combination of GA and power flow analysis models enables the system to adapt to complex grid topology changes and ensure the optimization of power flow paths.

2) Objective Function Design

In the multi-regional collaborative optimization dispatching model based on homogeneous and heterogeneous modes, the objective function design needs to fully consider the heterogeneity between regions and the demands of dispatching optimization. The core objective of the model is to minimize the overall operating cost of the system while improving the collaboration ability and resource allocation efficiency between regional power grids.

The economic optimization objective is:

$$\min \sum_{r=1}^{R} \left(C_{\text{fuel}} \left(P_r \right) + C_{\text{transmission}} \left(P_r, P_{\text{network}} \right) \right) \quad (7)$$

Among them, R is the number of regions. $C_{\text{fuel}}(P_r)$ is the fuel consumption cost function of region r. P_r is the power generation of region r. $C_{\text{transmission}}(P_r, P_{\text{network}})$ is the transmission loss cost function. P_{network} is the power flow between regions in the network.

The new energy consumption optimization objective is:

$$\max \sum_{r=1}^{R} \left(\eta_{\text{solar}} P_{\text{solar},r} + \eta_{\text{wind}} P_{\text{wind},r} \right) - \sum_{r=1}^{R} \left(C_{\text{storage}} \left(E_r \right) \right) \quad (8)$$

Among them, η_{solar} and η_{wind} are the power generation efficiency of solar energy and wind energy, respectively. $P_{\text{solar},r}$ and $P_{\text{wind},r}$ are the solar energy and wind energy power in region r. $C_{\text{storage}}(E_r)$ is the dispatching cost of the energy storage system in region r. E_r is the capacity of the energy storage system.

The dispatching response speed optimization objective is:

$$\min \sum_{r=1}^{R} \left(T_{\text{response}} \left(P_r, P_{\text{forecast}} \right) + \lambda_{\text{adjust}} \Delta P_r \right) \quad (9)$$

Among them, $T_{\text{response}}(P_r, P_{\text{forecast}})$ represents the response time of the region r after receiving the new predicted load information P_{forecast}. ΔP_r is the dispatching adjustment amount of region r. λ_{adjust} is the weight factor of the dispatching adjustment.

3) Constraints

The constraints in this study are designed to ensure the feasibility of dispatching optimization and the safe operation of the power grid. Firstly, the power balance constraint requires that the power generation in each region be balanced with the load demand, especially when the power generation of renewable energy fluctuates greatly. To this end, the energy storage system and demand-side response regulation are used to effectively maintain the stable operation of the power grid and avoid system faults caused by power imbalance.

Secondly, the transmission capacity constraint takes into account the capacity limitations of the transmission lines in each region to ensure that the flow of power does not exceed the carrying capacity of the line, avoid problems such as overload or voltage drop, and ensure the stability and safety of the power grid. The dispatching execution constraint limits the adjustment frequency of the dispatching instruction to ensure the rationality of the dispatching response time and avoid frequent dispatching adjustments that lead to instability or excessive oscillation of the power grid. Finally, the equipment safety constraint follows the N-1 safety criterion, that is, the system can still maintain stable operation in the event of a fault in any single equipment or line. This constraint helps to improve the power grid's reliability and emergency response capabilities, ensuring that the power grid can recover quickly and maintain a stable power supply when a fault occurs.

B. Data Fusion and Intelligent Dispatching Algorithm Based on Homogeneous and Heterogeneous Modes

1) Multi-Source Data Fusion

The dispatching platform collects real-time operating data such as power, frequency, and voltage through the monitoring and data acquisition system. It obtains high-precision phasor data through the synchronous phasor measurement unit. These data significantly improve the dynamic monitoring capability of the power grid. The user load data provided by the power metering system is used to optimize load prediction and demand-side management. Meteorological data helps improve the power prediction precision of new energy. In addition, integrating market transaction data optimizes economic dispatching, thereby enhancing the economy of the dispatching scheme.

In the process of data fusion, these heterogeneous data are first standardized to ensure that the data between different systems are compatible and can be smoothly connected. The data cleaning link is particularly important. Methods such as outlier detection and feature extraction are used to improve data quality. Outlier detection is processed using the density-based local outlier factor (LOF) algorithm and density-based spatial clustering of applications with noise (DBSCAN). Specifically, the LOF algorithm detects abnormal data points by calculating the ratio of the local density of the data point to the density of its neighborhood. The formula is:

$$\mathrm{LOF}(p)=\frac{\sum_{o\in N_k(p)}\frac{\mathrm{lrd}(o)}{\mathrm{lrd}(p)}}{\left|N_k(p)\right|} \quad (10)$$

Among them, p is the data point. $N_k(p)$ is the k nearest neighbor of point p. $\mathrm{lrd}(p)$ is the local outlier factor of data point p. Data points with large LOF values are represented as outliers. For DBSCAN, the density-based clustering process determines the core points through the following formula:

$$\left|N_\epsilon(p)\right|\geq \mathrm{MinPts} \quad (11)$$

$N_\epsilon(p)$ is the neighborhood point set of point p within radius ϵ. MinPts is the minimum point number threshold. If the neighborhood of a data point contains at least MinPts points, the point is a core point.

In terms of feature extraction, this study uses wavelet transform and principal component analysis (PCA) methods. Wavelet transform can decompose time series data into different frequency components at multiple scales and extract important patterns in the signal. The specific discrete wavelet transform (DWT) formula is as follows:

$$y(t)=\sum_n \alpha_n\cdot\psi(t-n) \quad (12)$$

Among them, $y(t)$ is the representation of the signal in the time domain. α_n is the wavelet coefficient. $\psi(t)$ is the mother wavelet function. n is the scale and position parameter. Through wavelet transform, the change patterns of different time scales in the power grid operation data are extracted. The PCA method extracts the most representative principal components in the data by reducing the dimension, which reduces redundant data while retaining most of the information. The key step of PCA is to solve the covariance matrix of the data matrix and obtain its eigenvalues and eigenvectors.

This paper applies the MQTT and DDS protocols to support the rapid sharing and efficient collaboration of cross-regional data, which are based on the publish-subscribe mechanism and can ensure low-latency and efficient data transmission between regions. In addition, this study uses federated learning technology, which allows each region to train and optimize models based on local data without centrally storing data. In federated learning, the model update process of each region is synchronized through Formula (13):

$$w_t=\sum_{i=1}^{N}\frac{n_i}{n}\cdot w_{t,i} \quad (13)$$

Among them, w_t is the update of the global model. $w_{t,i}$ is the local model of the i-th region. n_i is the data volume of the i-th region.

2) Intelligent Dispatching Algorithm

This study uses various intelligent dispatching algorithms to optimize the dispatching process of the power grid. Figure 3 shows the optimization process:

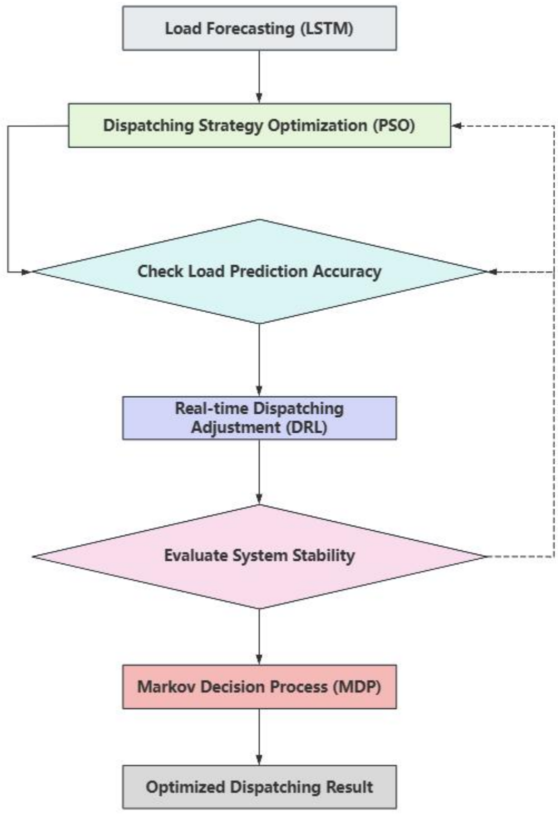

Figure 3. Process of optimizing power grid dispatching using intelligent dispatching algorithm

First, LSTM is used to predict the load and demand of the power grid so as to accurately predict future load demand and dynamically dispatch it according to the prediction results. This study combines the particle swarm optimization (PSO) algorithm to optimize the dispatching strategy to improve the real-time response speed of the dispatching instruction. The PSO algorithm can find the global optimal solution in the multi-dimensional search space, ensuring that the power grid can respond quickly under various complex operating conditions.

3) Dynamic Optimization Mechanism

This study improves the adaptability and robustness of the power grid system by dynamically adjusting the dispatching strategy at different time scales. In terms of short-term dispatching optimization (hour), the time series analysis method is used to optimize the day-ahead dispatching plan, focusing on improving economic efficiency and maximizing the utilization of new energy. Through the analysis of historical load and power generation data, future power demand and power generation capacity are predicted, and the power generation plan is adjusted to ensure supply and demand balance and cost-effectiveness.

In ultra-short-term dispatching optimization (minute), the study adopts a rolling optimization mechanism to dynamically adjust the dispatching strategy based on real-time monitoring data. Whenever the system status changes, the dispatching platform recalculates the power distribution based on the latest data to ensure the stable operation of the power grid under rapid fluctuation or emergencies.

For real-time dispatching optimization (second), edge computing technology is combined with the deployment of local computing units at power grid nodes to achieve fast data processing and optimization decisions, cope with rapid changes in power grid load and equipment status, and improve the real-time performance and accuracy of dispatching.

When responding to emergencies, this study combines distributed optimization with the centralized decision-making mechanism of the core dispatching platform. This hybrid mode ensures that adaptive optimization can be quickly performed when a local fault occurs. At the same time, the core platform makes unified decisions based on global information, improves emergency response efficiency, and ensures the stability and safety of the power grid.

C. Emergency Dispatching Strategy Optimization Based on Homogeneous and Heterogeneous Modes

During the operation of the power grid, the ability to respond to emergencies is one of the key indicators for measuring the performance of the dispatching system. Although intelligent dispatching algorithms can improve the efficiency and stability of daily operations, in the face of emergencies such as natural disasters and equipment faults, special emergency dispatching strategies are still required to ensure the rapid recovery and stable operation of the power grid. Therefore, this study further designs an emergency dispatching strategy optimization scheme based on homogeneous and heterogeneous modes to enhance the emergency response capability and system stability of the power grid in emergencies. Figure 4 shows its execution mechanism:

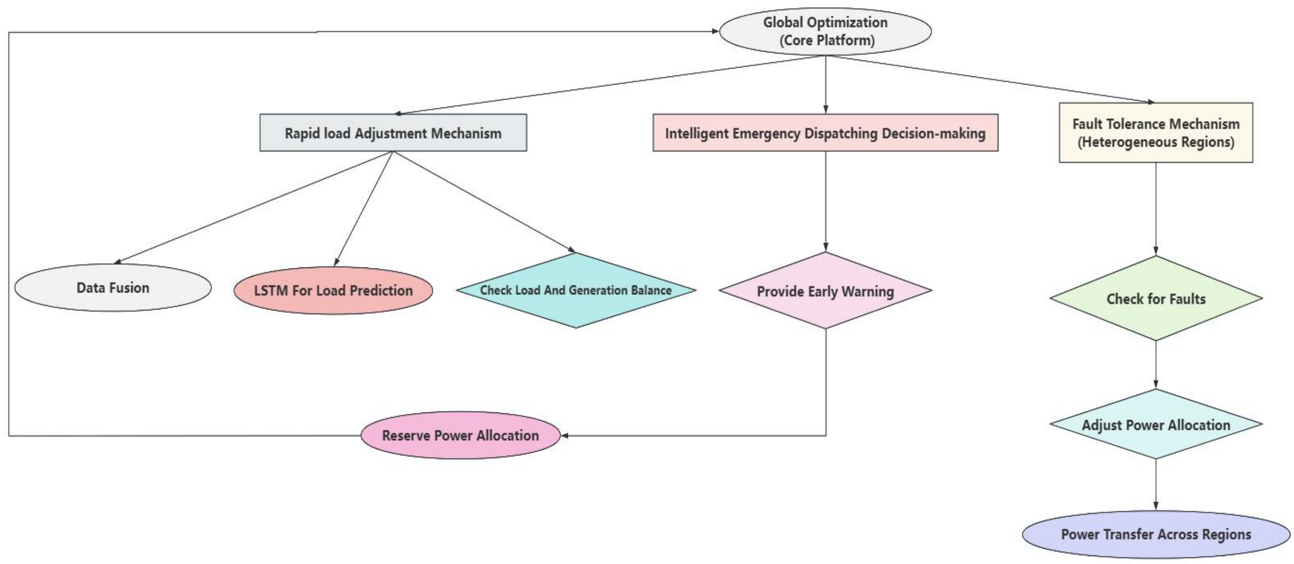

Figure 4. Flowchart of emergency dispatching strategy execution based on homogeneous and heterogeneous modes

1) Rapid Load Adjustment Mechanism

When an emergency occurs, rapid adjustment of load allocation is the key to ensuring stable operation of the power grid. To this end, this study designs a multi-level load adjustment mechanism and combines it with advanced monitoring and prediction technologies to achieve timely response to emergencies. The system monitors key parameters such as power, frequency, and voltage of the power grid in real time through the collaborative work of synchronized phasor measurement units and data acquisition and monitoring control systems. Combining data fusion with LSTM deep learning algorithms based on historical power fluctuation trends and real-time data, the model can effectively predict abnormal load fluctuation and warn of possible faults in advance, thereby providing dispatchers with sufficient reaction time and reducing the impact of emergencies.

When an overload or equipment fault occurs, the core dispatching platform initiates a hierarchical load reduction strategy. Specifically, the first-level response prioritizes the reduction of adjustable loads to quickly reduce load pressure; the second-level response coordinates the energy storage system to adjust power and enhance the flexibility and stability of the system; the third-level response reduces the load pressure in local areas through cross-regional load transfer to ensure the stability of the entire network. The MQTT/DDS communication mechanism ensures fast and low-latency data transmission between different regions. Through a flexible power allocation mechanism, each regional dispatching unit can adjust its strategy in a timely manner when the load of the entire network fluctuates, reduce the impact of sudden accidents on the local power grid, and thus ensure the overall stability and reliability of the power grid.

2) Fault Tolerance Mechanism for Heterogeneous Regional Collaborative Dispatching

During the operation of the power grid, sudden faults may cause a dispatching unit to fail, thus affecting the stability of the system. To improve the fault tolerance of the system, this study proposes a fault tolerance mechanism for heterogeneous regional collaborative dispatching based on intelligent agents to ensure the high reliability and stability of the power grid. This mechanism uses intelligent agent technology to enable each regional dispatching unit to have adaptive capabilities. When a regional dispatching system fails, the dispatching units in the adjacent areas can automatically adjust the dispatching strategy according to their heterogeneous characteristics, reduce the impact of the fault on the power grid, ensure that the power grid can recover quickly in the event of a local fault, and prevent the fault from spreading.

In addition, this study designs a dynamic allocation mechanism for backup power sources, which flexibly dispatches backup power sources according to the actual needs of the power grid to ensure the continuity of power supply. Combined with the demand side management (DSM) technology, the large user load is dynamically adjusted to reduce the pressure on the local power grid, thereby further improving the overall fault tolerance of the power grid. To enhance fault tolerance, this study also designs a three-layer fault tolerance mechanism: local level (within the region), cross-regional level (between regions), and global level (provincial level). At the local level, the regional dispatching unit automatically performs dispatching corrections through local optimization algorithms to ensure rapid recovery of the power supply. At the cross-regional level, the core dispatching platform coordinates multiple heterogeneous regions, optimizes the dispatching scheme, and performs flexible dispatching. At the global level, the core dispatching platform takes over the dispatching tasks of the entire province, improves system stability through global optimization, and ensures the reliable operation of the power grid.

3) Intelligent Emergency Dispatching Decision-Making

This study applies an intelligent dispatching decision-making mechanism based on AI to improve the intelligence and automation level of emergency dispatching response, which can quickly provide the optimal dispatching scheme when an emergency occurs to ensure the stability and safety of the power grid. First, through an in-depth analysis of historical fault data and combined with machine learning models, a fault prediction system is built to calculate the probability of emergency events in real time and provide early warning information to dispatchers. This system can identify equipment fault risks promptly through online status monitoring, enhancing the foresight and accuracy of emergency schemes.

In addition, this study develops an intelligent emergency scheme recommendation system that combines knowledge graphs and expert systems to automatically generate emergency dispatching schemes based on the actual operation of the power grid. The system uses federated learning technology to ensure cross-regional dispatching optimization while protecting data privacy. Through this intelligent recommendation system, the power grid can respond quickly when an emergency occurs and adjust the power grid operation strategy promptly, thereby significantly improving the power grid's emergency dispatching capability.

5. Simulation Experiment and Result Analysis

A. Simulation Experiment Design

1) Data Source and Experimental Environment

Most of the experimental data for this study are from the historical operation data of a provincial power grid, including real-time dispatching data, load prediction data, power trading data, etc. The data spans nearly three years, and the data sampling frequency is 15 minutes, with more than 520,000 data records in total. In addition, some data come from the public IEEE118-node power system intelligent power flow adjustment training public dataset. In the process of data preprocessing, the missing data are first supplemented by linear interpolation to ensure the continuity of the data. Second, box plot analysis and the 3σ principle are used to detect and remove outliers to improve data quality. Finally, the Min-Max standardization method is used to normalize the data and convert the data to the [0,1] interval to improve the model training efficiency. The processed data together constitute the experimental dataset of this study.

In terms of the experimental environment, this study is conducted on an Ubuntu 22.04 server equipped with an Intel Xeon Platinum 8375C CPU, an NVIDIA A100 40GB GPU, and 256GB RAM to meet large-scale computing requirements. The experiment uses PyTorch 2.0 and TensorFlow 2.9 as deep learning frameworks. MATPOWER 7.1 and PSS/E are used for power grid dispatching simulation to ensure the precision and reliability of the experiment.

2) Experimental Design

This experiment aims to evaluate the performance of the provincial dispatching automation system of the power grid based on the homogeneous and heterogeneous modes, focusing on its advantages in data sharing efficiency, dispatching response time, load prediction precision, and system stability. It is compared with the existing dispatching systems. Four systems are set up in the experiment, including the experimental group (homogeneous and heterogeneous dispatching system) and three control systems: traditional centralized dispatching (control group 1), distributed dispatching (control group 2), and LSTM-based intelligent dispatching system (control group 3). Through multi-dimensional comparison, the proposed method's effectiveness and adaptability are fully verified.

The experiment involves multiple subtasks. The constructed experimental dataset is used in the load prediction experiment to perform prediction modeling and precision evaluation in each system. In the dispatching optimization experiment, 1,000 typical dispatching tasks are simulated to examine the data sharing efficiency and dispatching response time of different systems. In the system stability test, load fluctuation and sudden fault conditions are simulated to evaluate the stability and adaptability of each system in a complex operating environment. All experiments are conducted in the same computing environment to ensure the fairness and comparability of the test results.

The core indicators of the experimental record include four aspects. First, the data sharing efficiency is measured by the average data update rate (%) and the average data transmission rate (Mbps) of each system to evaluate the data interaction capabilities of different systems. Second, the dispatching response time is measured in milliseconds (ms) to measure the time required for each system to compute the dispatching scheme, thereby evaluating its real-time performance. Third, the load prediction precision is measured using indicators such as MAE, RMSE, and mean absolute percentage error (MAPE) to quantify the accuracy of the prediction model. Finally, the system stability mainly examines key parameters such as voltage deviation, frequency fluctuation, and line loss rate to evaluate the impact of the dispatching strategy on the stability of the power grid.

B. Experimental Results Analysis

1) Data Sharing Efficiency

Figure 5 presents the average data transmission rate and average data update rate of each system after 1,000 simulation experiments are conducted on each system.

Figure 5 shows that the power grid dispatching system based on homogeneous and heterogeneous modes proposed in this paper performs well in data sharing efficiency, with an average data transmission rate of 5.23Mbps, significantly higher than other systems; the average data update rate is also 92.4%, significantly better than the control group. This improvement is mainly attributed to the system's use of the Common Information Model (CIM) and IEC 61850 protocol, which unifies the data format and improves interoperability; at the same time, with the help of the publish-subscribe mechanism of the MQTT and DDS protocols, the data transmission delay is reduced and the rapid transmission of data is guaranteed. In addition, the architecture combining homogeneous and heterogeneous modes not only achieves global optimization, but also takes into account regional flexibility, further enhancing data sharing efficiency. These optimization measures jointly improve the system's data interaction capabilities and provide strong support for the high precision and rapid response of power grid dispatching.

2) Dispatching Response Time

Table 1 lists the average response time and the longest and shortest response time records of each system in 1,000 simulation experiments:

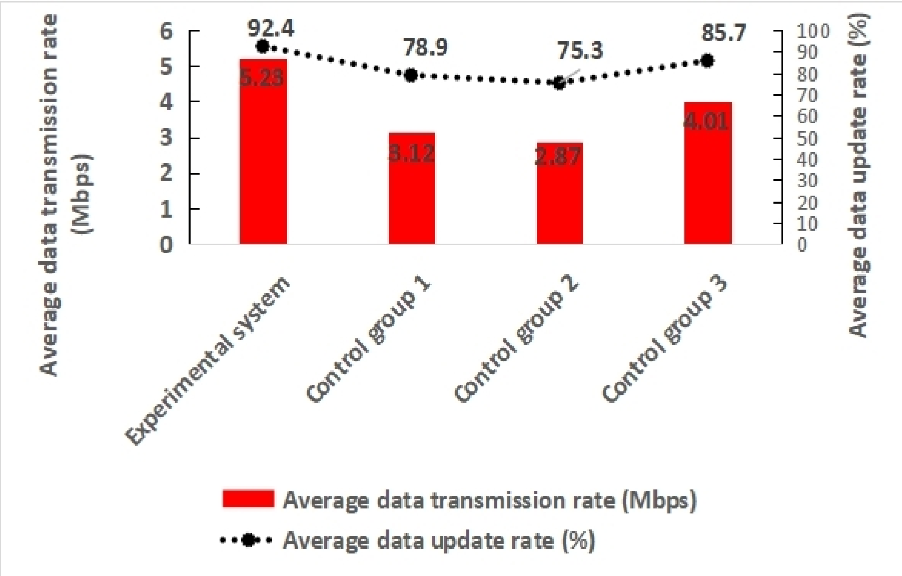

Figure 5. Experimental results of data sharing efficiency of each system

Table 1. Dispatching response time

Dispatching system	Average response time (ms)	Maximum response time (ms)	Minimum response time (ms)
Experimental system	312	489	135
Control group 1	486	672	300
Control group 2	532	748	316
Control group 3	398	574	222

Table 1 shows that the power grid dispatching system based on homogeneous and heterogeneous modes is significantly better than the control group in terms of dispatching response time. The average response time of the experimental group is 312ms, which is much lower than the 486ms of the centralized dispatching system, 532ms of the distributed dispatching system, and 398ms of the LSTM-based intelligent dispatching system. The maximum response time of the experimental group is 489ms, which is significantly lower than other control groups, and the minimum response time is 135ms, which is better than other systems. This shows that the system can respond quickly under different load conditions.

This advantage stems from the multi-faceted optimization of the system. The architecture of the system combining homogeneous and heterogeneous modes not only achieves global optimization, but also takes into account regional flexibility and reduces the delay of dispatching decisions. The application of multi-source data fusion technology and efficient communication protocols further accelerates the speed of data transmission and processing. In addition, the synergy of intelligent optimization algorithms (such as

LSTM, GA, and DRL) enables the system to dynamically adjust the dispatching strategy according to real-time data, so as to respond quickly under different load conditions. These optimization measures jointly improve the dispatching response speed of the system, meet the needs of real-time dispatching of the power grid, and improve operation efficiency and stability.

3) Load Prediction Precision

Table 2 shows the results of load prediction experiments for each system:

Table 2. MAE, RMSE, and MAPE of load prediction of each system

Dispatching system	MAE (MW)	RMSE (MW)	MAPE (%)
Experimental system	4.82	7.21	1.82
Control group 1	6.13	9.47	2.31
Control group 2	6.92	10.32	2.54
Control group 3	5.34	8.12	2.07

The data in Table 2 show that the power grid dispatching system based on homogeneous and heterogeneous modes performs best in terms of load forecasting accuracy. The MAE, RMSE and MAPE of the system in this study are 4.82MW, 7.21MW and 1.82%, which are significantly better than other control systems. The MAE and RMSE of the traditional centralized dispatching system are 6.13MW and 9.47MW respectively, with large errors, reflecting its inadequacy in adapting to complex power grid load changes. The MAE and RMSE of the traditional distributed dispatching system further increased to 6.92MW and 10.32MW, indicating that its prediction accuracy has decreased due to the lack of data integration capabilities. Although the LSTM-based intelligent dispatching system is better than the traditional system, the MAE and RMSE are still 5.34MW and 8.12MW, and the MAPE is 2.07%, indicating that there is still room for improvement in load forecasting accuracy.

The advantage of the system in this study in load forecasting accuracy comes from its comprehensive integration of multi-source data and optimized prediction algorithms. By integrating real-time operation data, meteorological data and market transaction data from different regions, the system can capture load change trends more accurately. At the same time, the prediction model of long short-term memory (LSTM) network combined with deep reinforcement learning (DRL) has further improved the accuracy and adaptability of the prediction. This combination of data fusion and intelligent algorithm enables the system to more effectively cope with complex and changeable power grid loads, thereby significantly improving the load prediction accuracy and providing strong support for the accuracy and reliability of power grid dispatching.

4) System Stability

Figure 6 presents the results of the stability test of each system:

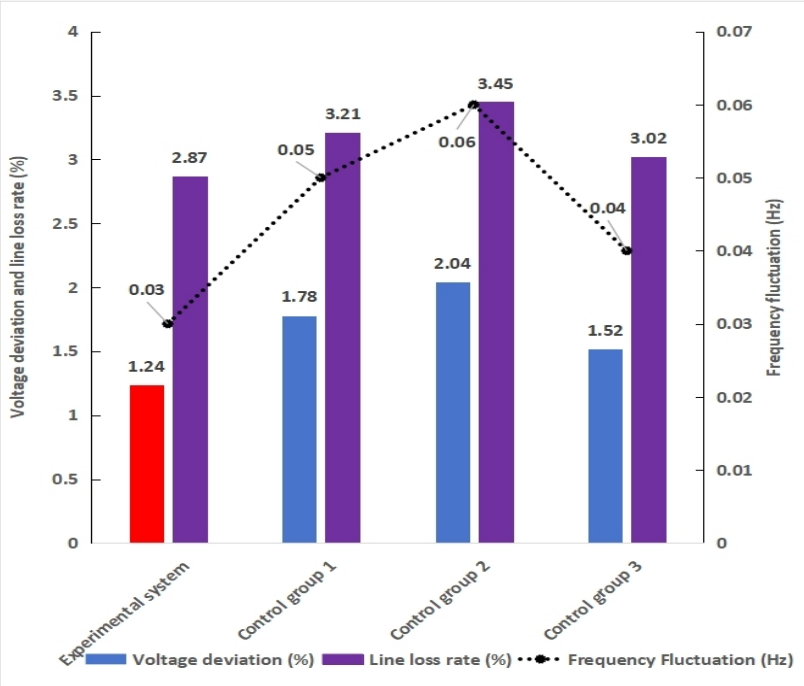

Figure 6. Experimental results of stability test of each system

In Figure 6, the grid dispatching system based on homogeneous and heterogeneous modes constructed in this study performs best in key indicators such as voltage deviation, frequency fluctuation, and line loss rate, effectively improving the stability of grid operation. Experimental data show that the voltage deviation of the system in this study is 1.24%, which is much lower than the 1.78% of the traditional centralized dispatching system and the 2.04% of the traditional distributed dispatching system, indicating that the dispatching strategy can maintain the voltage level more precisely and reduce grid fluctuations. The frequency fluctuation of the system is only 0.03Hz, significantly better than that of the traditional centralized dispatching system and the traditional distributed dispatching system, reflecting its stronger dynamic adjustment capability when dealing with load disturbances. In addition, the system has the lowest line loss rate of only 2.87%, which is significantly lower than both the traditional centralized dispatching system and traditional distributed dispatching system, indicating that its optimized dispatching strategy helps reduce power loss while improving energy efficiency. Although the LSTM-based intelligent dispatching system is superior to the traditional dispatching system in terms of stability, its voltage deviation, frequency fluctuation, and line loss rate are still inferior to those of the system in this study. In general, the power grid dispatching system based on homogeneous and heterogeneous modes demonstrates significant advantages in improving the stability of the power grid due to its precise dispatching optimization and more efficient resource coordination capabilities.

6. Conclusion

This paper studies the application of the homogeneous and heterogeneous modes in the provincial dispatching system of the power grid. An optimized dispatching architecture based on this approach is proposed. By building a unified core dispatching platform and a collaborative working model for multiple heterogeneous regional dispatching units, the limitations of traditional dispatching systems in cross-regional collaboration, regional adaptability, and dispatching optimization are addressed. The core dispatching platform is responsible for global dispatching optimization and resource coordination. The regional dispatching unit flexibly adjusts dispatching strategies according to the characteristics of their respective power grids to give full play to the advantages of different regional power grids. In addition, this paper also applies data sharing mechanism, intelligent dispatching algorithm, and emergency dispatching strategy, which effectively improves the system's prediction precision, real-time response capability, and emergency handling capability, providing a strong guarantee for the efficient and stable operation of the power grid.

As the level of grid intelligence continues to improve, future research should explore the application of homogeneous and heterogeneous modes in a broader range of smart grid environments, especially in dealing with complex power system dynamics, cross-regional resource coordination, and other issues. Meanwhile, combined with advanced technologies such as blockchain and cloud computing, the system's transparency, data security, and decision-making efficiency can be further improved. The dispatching system can be promoted to develop in a more intelligent and autonomous direction. As the proportion of renewable energy continues to grow, the challenges the grid dispatching faces may become more complex. Therefore, fully responding to problems such as new energy fluctuation, load prediction errors, and emergencies within a multi-regional collaboration framework becomes an important research direction for future power grid dispatching systems. Through continuous technological innovation and system optimization, future power grids are expected to better adapt to the ever-changing energy structure and increasingly complex operating environment.

Acknowledgment

None

Consent to Publish

The manuscript has neither been previously published nor is under consideration by any other journal. The authors have all approved the content of the paper.

Funding

None

Author Contribution

[Chenhui Hang, Zhihao Yang]: Developed and planned the study, performed experiments, and interpreted results. Edited and refined the manuscript with a focus on critical intellectual contributions.

[Fuhe Wang, Dong Han]: Participated in collecting, assessing, and interpreting the date. Made significant contributions to date interpretation and manuscript preparation.

[Xiaoguang Wang, Xingyu Qiao]: Provided substantial intellectual input during the drafting and revision of the manuscript.

Conflicts of Interest

The authors declare that they have no financial conflicts of interest.

References

[1] V. Kulkarni, S.K. Sahoo, S.B. Thanikanti, S. Velpula, D.I.

Rathod. Power systems automation, communication, and information technologies for smart grid: A technical aspects review. TELKOMNIKA (Telecommunication Computing Electronics and Control), 2021, 19(3), 1017-1029. DOI: 10.12928/telkomnika.v19i3.16428
[2] T.L. Zang, S.J. Wang, Z.A. Wang, C.Z. Li, Y.F. Liu, et al. Integrated planning and operation dispatching of source–grid–load–storage in a new power system: A coupled socio–cyber–physical perspective. Energies, 2024, 17(12), 3013-3056. DOI: 10.3390/en17123013
[3] X. Yang, K. Jia, Z.R. Peng. Construction of integrated network order system of main distribution network based on power grid operation control platform. Energy Informatics, 2024, 7(1), 70-97. DOI: 10.1186/s42162-024-00368-6
[4] Y. Dong, X. Shan, Y.Q. Yan, X.W. Leng, Y. Wang, et al. Architecture, key technologies and applications of load dispatching in China power grid. Journal of Modern Power Systems and Clean Energy, 2022, 10(2), 316-327. DOI: 10.35833/MPCE.2021.000685
[5] K. Jia, X. Yang, Z.R. Peng. Design of an integrated network order system for main distribution network considering power dispatch efficiency. Energy Informatics, 2024, 7(1), 69-96. DOI: 10.1186/s42162-024-00369-5
[6] W. Dai, Y. Gao, H.H. Goh, J.Y. Jian, Z.H. Zeng, et al. A Non-Iterative Coordinated Scheduling Method for a AC-DC Hybrid Distribution Network Based on a Projection of the Feasible Region of Tie Line Transmission Power. Energies, 2024, 17(6), 1462-1482. DOI: 10.3390/en17061462
[7] H. Tang, K. Lv, B. Bak-Jensen, J.R. Pillai, Z.F. Wang. Deep neural network-based hierarchical learning method for dispatch control of multi-regional power grid. Neural Computing and Applications, 2022, 34(7), 5063-5079. DOI: 10.1007/s00521-021-06008-4
[8] G.H. Wen, X.H. Yu, Z.W. Liu. Recent progress on the study of distributed economic dispatch in smart grid: an overview. Frontiers of Information Technology & Electronic Engineering, 2021, 22(1), 25-39. DOI: 10.1631/FITEE.2000205
[9] F. Marzbani, A. Abdelfatah. Economic dispatch optimization strategies and problem formulation: A comprehensive review. Energies, 2024, 17(3), 550-581. DOI: 10.3390/en17030550
[10] P. Arevalo, F. Jurado. Impact of artificial intelligence on the planning and operation of distributed energy systems in smart grids. Energies, 2024, 17(17), 4501-4523. DOI: 10.3390/en17174501
[11] Z.X. Ji, X.H. Wang, J. Zhang, D. Wu. Construction and application of knowledge graph for grid dispatch fault handling based on pre-trained model. Global Energy Interconnection, 2023, 6(4), 493-504. DOI: 10.1016/j.gloei.2023.08.009
[12] C. Deming, P. Pasam, A.R. Allam, R. Mohammed, S.G.N. Venkata, et al. Real-Time Scheduling for Energy Optimization: Smart Grid Integration with Renewable Energy. Asia Pacific Journal of Energy and Environment, 2021, 8(2), 77-88. DOI: 10.18034/apjee.v8i2.762
[13] S. Feng, D.S. Yang, B.W. Zhou, Y.H. Luo, G.D. Li. Real-time active power dispatch of virtual power plant based on distributed model predictive control. Electronics Letters, 2022, 58(23), 872-875. DOI: 10.1049/ell2.12640
[14] Z. Cai, G.F. Zhang, D. Xu, Q. Ding, X.M. Guo, et al. Multi-area joint scheduling model considering peak load regulating of nuclear power. Energy Reports, 2021, 7, 1-9. DOI: 10.1016/j.egyr.2021.02.069
[15] W.L. Shi, X. Han, X.Y. Wang, T.J. Pu, D.X. Zhang. Intelligent reinforcement training optimisation of dispatch strategy for provincial power grids with multi-agent systems: Considering operational risks and backup availability. IET Energy Systems Integration, 2024, 6(2), 129-143. DOI: 10.1049/esi2.12131
[16] B.B. Guo, F.L. Li, J. Yang, W. Yang, B.Y. Sun. The application effect of the optimized scheduling model of virtual power plant participation in the new electric power system. Heliyon, 2024, 10(11), e31748-e31763. DOI: 10.1016/j.heliyon.2024.e31748
[17] K. Wang, J. Wu, X. Zheng, J.H. Li, W. Yang, et al. Cloud-edge orchestrated power dispatching for smart grid with distributed energy resources. IEEE Transactions on Cloud Computing, 2022, 11(2), 1194-1203. DOI: 10.1109/TCC.2022.3185170
[18] S.M. Sharifhosseini, T. Niknam, M.H. Taabodi, H.A. Aghajari, E. Sheybani, et al. Investigating Intelligent Forecasting and Optimization in Electrical Power Systems: A Comprehensive Review of Techniques and Applications. Energies, 2024, 17(21), 5385-5420. DOI: 10.3390/en17215385
[19] L.Y. Lv, X. Fang, S. Zhang, X. Ma, Y. Liu. Optimization of grid-connected voltage support technology and intelligent control strategies for new energy stations based on deep learning. Energy Informatics, 2024, 7(1), 73-92. DOI: 10.1186/s42162-024-00382-8
[20] C.L. Tai, Y.B. Sun, S.M. Sun, Z.X. Sun, X. Chen, et al. Investigating Intelligent Call Technology for Dispatching Telephones Towards System Integration. Electronics, 2025, 14(1), 179-198. DOI: 10.3390/electronics14010179
[21] S.Z. Sun, C.X. Wang, Y. Wang, X.H. Zhu, H.C. Lu. Multi-objective optimization dispatching of a micro-grid considering uncertainty in wind power forecasting. Energy Reports, 2022, 8(6), 2859-2874. DOI: 10.1016/j.egyr.2022.01.175
[22] R. Zhang, J.L. Yu. New urban power grid flexible load dispatching architecture and key technologies. Frontiers in Energy Research, 2023, 11, 1168768-1168783. DOI: 10.3389/fenrg.2023.1168768
[23] Z.F. Yang, P. Yong, M.X. Xiang. Revisit power system dispatch: Concepts, models, and solutions. iEnergy, 2023, 2(1), 43-62. DOI: 10.23919/IEN.2023.0010
[24] C.D. Iweh, S. Gyamfi, E. Tanyi, E. Effah-Donyina. Distributed generation and renewable energy integration into the grid: Prerequisites, push factors, practical options, issues and merits. Energies, 2021, 14(17), 5375-5409. DOI: 10.3390/en14175375
[25] X. He, H. Dong, W.L. Yang, W. Li. Multi-source information fusion technology and its application in smart distribution power system. Sustainability, 2023, 15(7), 6170-6186. DOI: 10.3390/su15076170
[26] M.L. Li, B.X. Hou, Z.Y. Zhang. The enhancement of power system stability with large-scale renewable energy integration: Collaborative application research on big data, artificial intelligence, energy storage, and intelligent control technology. Advances in Resources Research, 2025, 5(1), 79-102. DOI: 10.50908/arr.5.1_79
[27] Q.W. Xu, Y.J. Cao, H.X. Zhang, W. Zhang, V. Terzija. Bi-level dispatch and control architecture for power system in China based on grid-friendly virtual power plant. Applied Sciences, 2021, 11(3), 1282-1301. DOI: 10.3390/app11031282
[28] D. Shi, R.Y. Hu, Y.H. Wu, H.D. Qiu, C. Yang, et al. Toward Artificial-Intelligence-Empowered Smarter Power Grid: Forecasting, Dispatch, and Control. IEEE Power and Energy Magazine, 2024, 22(6), 54-65. DOI: 10.1109/MPE.2024.3408111
[29] J. Yu, J.C. Liu, Y.J. Wen, X. Yu. Economic optimal coordinated dispatch of power for community users considering shared energy storage and demand response under blockchain. Sustainability, 2023, 15(8), 6620-6646. DOI: 10.3390/su15086620

[30] Z.Y. Tong, Y.Y. Zhou, K. Xu. An intelligent scheduling control method for smart grid based on deep learning. Mathematical Biosciences and Engineering, 2023, 20(5), 7679-7695. DOI: 10.3934/mbe.2023331

[31] T.M. Yang, S.H. Lou, M. Zhang, Y.C. Li, W. Feng, et al. Research on a Two-Layer Optimal Dispatching Method Considering the Mutual Aid of Peak Regulating Resources among Regional Power Grids. Energies, 2024, 17(3), 667-681. DOI: 10.3390/en17030667

[32] N.Y. Wu, F.Z. Zhang, J.J. Wang, X.N. Wang, J.Z. Wu, et al. A review on modelling methods, tools and service of integrated energy systems in China. Progress in Energy, 2023, 5(3), 032003-032037. DOI: 10.1088/2516-1083/acef9e

[33] Y. Zahraoui, T. Korõtko, A. Rosin, H. Agabus. Market mechanisms and trading in microgrid local electricity markets: A comprehensive review. Energies, 2023, 16(5), 2145-2197. DOI: 10.3390/en16052145

[34] Y. Li, B. Wang, Z. Yang, J.Z. Li, G.Q. Li. Optimal scheduling of integrated demand response-enabled community-integrated energy systems in uncertain environments. IEEE Transactions on Industry Applications, 2021, 58(2), 2640-2651. DOI: 10.1109/TIA.2021.3106573

[35] H. Tang, S.P. Wang, K.J. Chang, J.Y. Guan. Intra-day dynamic optimal dispatch for power system based on deep Q-learning. IEEJ Transactions on Electrical and Electronic Engineering, 2021, 16(7), 954-964. DOI: 10.1002/tee.23379