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Digital Twin Structure Monitoring System and Key Technologies of Distribution Network Based on Intelligent Communication Network

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ABSTRACT
The continuous development of power market puts forward new requirements for power grid operation and power supply quality. Under this background, if electric power enterprises want to achieve sustainable development, they must strengthen management and technological innovation to improve their competitiveness. Currently, the distribution network construction is still dominated by the traditional cable transmission method, which has many drawbacks and can hardly meet the requirements of modern power production for communication capability. Digital twin technology is an advanced intelligent control method, which can effectively integrate information in complex systems. It can use data-driven to achieve real-time monitoring, fault detection and analysis functions, which can better help users improve the efficiency and security of power use. The intelligent communication network has the characteristics of good real-time, strong scalability and can quickly adapt to different environments, different devices and application scenarios. By building a complete set of distributed automatic control system, the goal of stable, reliable, efficient and energy-saving power system can be achieved. This paper presented the relevant calculation formulas of energy consumption and time delay in smart grid, and the effectiveness of the formula was verified through simulation. By combining the principle of heterogeneous sensors, a new intelligent integrated management system for remote monitoring of distribution lines was designed to realize a series of functions such as centralized meter reading, load forecasting, inspector positioning, online diagnosis, etc. of the intelligent dispatching center, which provided a theoretical basis for the optimal dispatching of the smart grid. This paper compared the traditional distribution network monitoring system with the distribution network digital twin monitoring system based on intelligent communication network. The results showed that the time delay and bit error rate of the optimized detection system had been significantly reduced, and the success rate of packet reception had increased by 10.4%; in addition, it could achieve higher accuracy and security and reduce operation

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and maintenance costs. Physical communication network is an important part of modern communication network, which can provide users with high-speed and reliable data transmission and exchange services, and plays an important role in the digital twin system of distribution network. It is of great significance to the safe and stable operation of the entire power system.

Keywords: Intelligent Communication Network, Distribution Networks, Digital Twins, Physical communication

1. Introduction

With the continuous penetration of information technology into various industries and the emergence of new products and applications, the traditional power generation methods are becoming increasingly difficult to adapt to the changes in modern society. In particular, the power industry has changed from a single energy form in the past to a new energy development and utilization mode featuring multi energy complementation, clean and efficient, low-carbon and environmental protection, which has brought unprecedented development opportunities to power enterprises.

Distribution network digitalization is one of the important directions of smart grid construction and development, which has been studied by many scholars. Song Xinya proposed using neural network method to establish the digital twin model of inverter model, and established the digital twin model of inverter based on system identification and parameter estimation, which is helpful to explain the effectiveness of neural network identifier in establishing decision table [1]. Zhou Mike introduced the basic framework of digital twins. During the development of the new power grid real-time online analysis system, he realized online analysis of digital twins to achieve a new online analysis architecture [2]. Jiang Zongmin provided a new method for the unified description and standardization of digital twins, which is conducive to the hierarchical creation of complex systems. It can more comprehensively represent complex physical entities, and can quickly realize the reuse of knowledge and the duplication of similar cell level twins [3]. Moutis Panayiotis found some fault features from the digital twin monitoring system for real-time monitoring of medium voltage distribution transformers with low-voltage measured values. Through status identification and rapid positioning of high-voltage circuit breaker fault points and low-voltage bus switch fault points, online monitoring of equipment was realized [4]. Brosinsky Christoph discussed the dynamic digital twin of power system as the basis of the new generation power transmission grid management system, and introduced a digital dynamic mirror simulation environment to reproduce the status of the reference network in real time, which paved the way for automatic grid control [5]. Nguyen Van Hoa proposed a digital dual integrated power hardware method for distributed renewable energy evaluation, which created a distributed smart grid based on multi-sensor information through synchronization between real-time simulator and supervision, control and data acquisition systems, and improved the operation efficiency of distribution network [6]. Distribution network digital twin is a comprehensive platform composed of multiple subsystems. It can simultaneously consider the resource constraints and demand management requirements required in the three links of power generation, transmission and distribution, thus making the whole system more flexible and efficient, which is of great significance for improving the reliability of power supply.

Intelligent communication can realize two-way interaction during the operation of power system, which has been discussed by many scholars. Dehghanpour Kaveh discussed the placement of metering instruments, network topology, the impact of renewable energy penetration and network security for distribution system state estimation. Both traditional and modern data-driven and probabilistic technologies had been reviewed, which provided researchers and utility engineers with insights on the technical achievements, obstacles and future research directions of intelligent communication in distribution networks [7]. Dutta Soham proposed a real-time intelligent communication islanding detection method for distribution network, which could extract the target point location information from the obtained voltage and current vector data through discrete Fourier transform, so as to achieve the purpose of fault location for the entire distribution network [8]. Bidgoli Hamid Soleimani proposed a two-level real-time voltage control scheme, which was used to maintain the voltage within the specified range in the distribution network using distributed generation units, so as to improve the power quality and stabilize the grid operation [9]. Koutsoukis Nikolaos C introduced a multi-stage coordinated planning method for active distribution networks. On the premise of meeting the requirements of power grid security, economy and sustainable development, the load characteristics undertaken by each node in the system and its interaction with other lines and other factors were comprehensively considered, and the whole network was predicted according to the relevant power flow changes in different periods [10]. Mishra Sivkumar tried to use various technologies to solve the problem of distribution network reconfiguration. Based on the analysis of traditional distribution network modeling methods and grid planning models, he proposed a cloud computing based distributed power supply simulation platform to achieve intelligent protection and positioning under fault conditions [11]. Khalid Mehmood Khawaja used the optimal location and size of the battery energy storage system for voltage regulation in the power distribution system, while increasing the life of the battery, thus improving the efficiency of the entire power distribution system [12]. Intelligent communication network plays an increasingly important role in the process of distribution network management, which can effectively reduce the waste of power resources and save costs.

The existing distribution network has strong network capacity and can meet the basic power supply demand. However, its reliability is poor, and there are a lot of hidden troubles, which leads to the increase in the probability of power grid accidents. Therefore, it is urgent to study a technology that can improve the operation efficiency and security level of distribution system. As one of the most advanced information communication methods, intelligent communication and control technology is an important means to realize intelligent power system. The application of this technology in power distribution system can achieve the purpose of protecting equipment and improving power quality.

2. Distribution Network Digital Twin Structure Monitoring System Based On Intelligent Communication

2.1. *Intelligent communication network structure*

With the continuous development and maturity of mobile communication technology, wireless communication has been widely used in enterprise management. More and more mobile terminals can access the Internet for data exchange through wireless network communication technology, which plays a very important role in improving enterprise office efficiency and employee enthusiasm, Therefore, machine learning and intelligent communication have gradually become an indispensable part of enterprise informatization construction [13]. As one of the current popular network architectures, it can provide users with more efficient and convenient data transmission methods and more diversified application service functions, thus greatly promoting the improvement of people's living standards in the information age. The network structure of the intelligent communication network is shown in Figure 1.

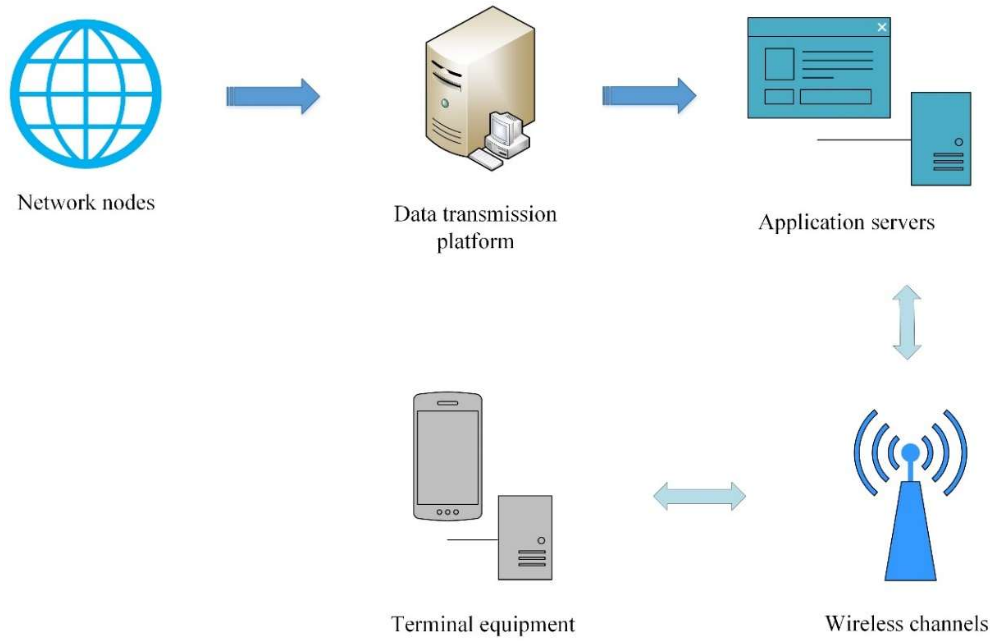

Fig. 1. Network structure of intelligent communication network

The intelligent communication network structure is generally composed of wireless channel, network node, data transmission platform, application server and terminal equipment. Among them, wireless communication is the most critical link to realize the interconnection between various components. The module is mainly used to convert wireless signals into electrical signals. The transmission modes are mainly divided into wired transmission and wireless transmission. Among them, wireless transmission can be divided into two forms: wired transmission and wireless transmission. The former is suitable for mass production environment, while the latter is suitable for small manufacturing environment. Both of them are flexible. Network node is the core of intelligent communication network architecture. It completes various communication functions by collecting and processing external information and providing corresponding services. Its performance directly affects whether the overall structure can operate normally and whether the application range can meet the requirements. The data transmission platform can be regarded as a physical unit, which can process the information received from the terminal and provide corresponding services to users, but it may also lead to data loss or leakage, or even system paralysis. Therefore, the entire system needs to be monitored and managed. As the most important part of the whole network system, the server undertakes the functions of transmission, storage, retrieval, analysis, calculation and other basic information processing when performing tasks. At the same time, it also has certain management features, such as support for remote access, automatic backup, etc. Terminal equipment is the link between subsystems in intelligent communication. It usually includes hardware equipment and software. Hardware equipment includes gateway, router and switch. In terms of software, it mainly includes two levels: operating system and application software, which are respectively responsible for connecting and controlling different intelligent devices.

2.2 Problems in distribution network industry

In recent years, the socio-economic structure has undergone profound changes. New technologies based on the Internet are constantly emerging, which makes the power consumption mode more complex and changeable, and the user demand is higher and higher. The traditional operation mode of transmission and distribution lines can no longer meet the growing service demand of modern power system. However, because the power market system is not sound enough, there are certain difficulties in the operation and maintenance of the distribution network. At the same time, there are also many weak links in information acquisition, communication transmission and control management, which lead to increasingly prominent power quality problems. This requires strengthening the intelligent transformation of the power grid to improve the reliability of power supply and service quality. The main problems faced in the construction of intelligent distribution network are shown in Figure 2.

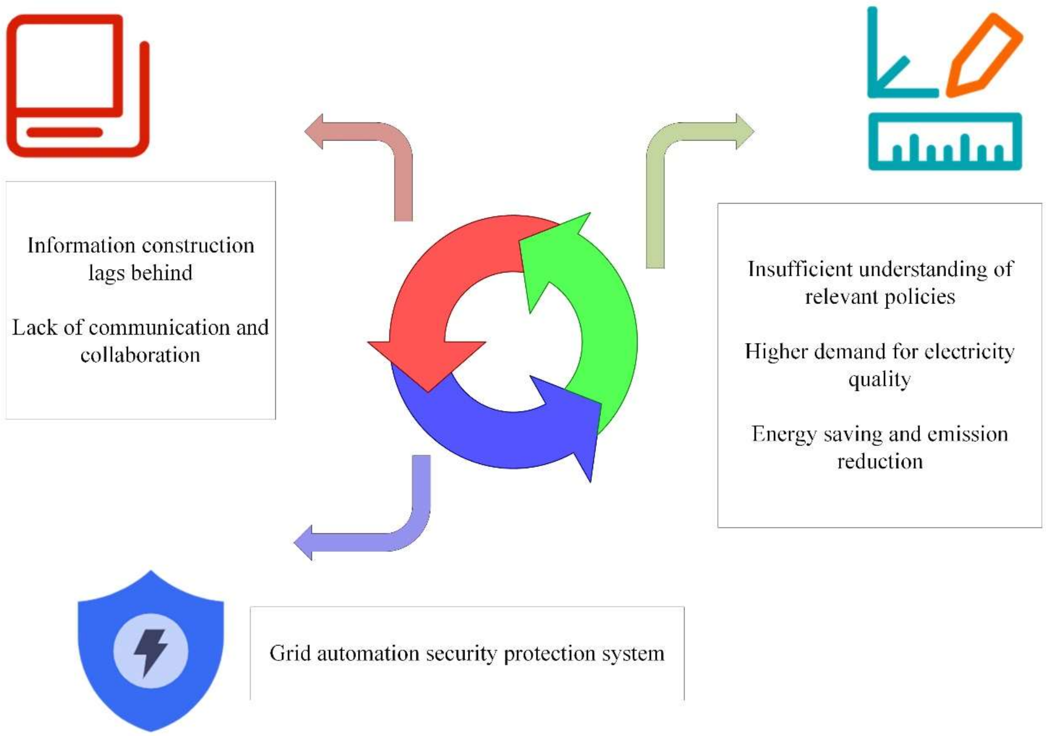

Fig. 2. The main problems faced during the construction of smart distribution network

It can be seen from Figure 2 that there are three main problems in the current power grid industry: insufficient theoretical support, inadequate system planning and high technical risks. Among them, the lack of theoretical support and the lag of information construction are the most important factors. The direct reason is that the isolated information island leads to the lack of communication and cooperation between various systems, and there is no effective management in the actual operation process, which makes the power grid enterprises unable to provide users with the required power in a timely and accurate manner. The main manifestation of the lack of system planning is the insufficient understanding of the direction of power market development and power system reform and other related policies, which has caused the power demand-side response mechanism to fail to be well implemented. In addition, with the rapid development of social economy, people put forward higher requirements for the quality of electricity, which makes electricity equipment need more advanced and reliable power supply to meet the needs of production and life. Moreover, in order to achieve better energy conservation and emission reduction, a series of policies to promote the development of energy conservation and environmental protection industries have been introduced, which means that the power system would face greater challenges and pressure. The high technical risk refers to the fact that a comprehensive security protection system has not yet been fully established in the field of grid automation, which therefore to a certain extent affects the normal operation and business development of grid enterprises in a highly competitive environment.

2.2. Digital twin monitoring system model of distribution network based on intelligent communication

With the rapid spread of new generation information technology such as Internet of Things, cloud computing, big data, artificial intelligence and continuous improvement of network infrastructure, traditional distribution network business would face the challenge of digital transformation. Intelligent communication protocol (In Signal Network) is a key technology to realize information exchange on the basis of Internet and mobile communication network. It not only solves the traditional communication network interconnection problem, but also makes the wireless network more flexible and efficient to adapt to the development requirements of new services, thus effectively improving the level of enterprise informationization and promoting the coordinated development of social economy. The digital twin system of distribution network based on intelligent communication technology has the advantages of high real-time and good scalability, and its application in the field of distribution automation can further improve the efficiency and safety performance of power grid operation. The model is shown in Figure 3.

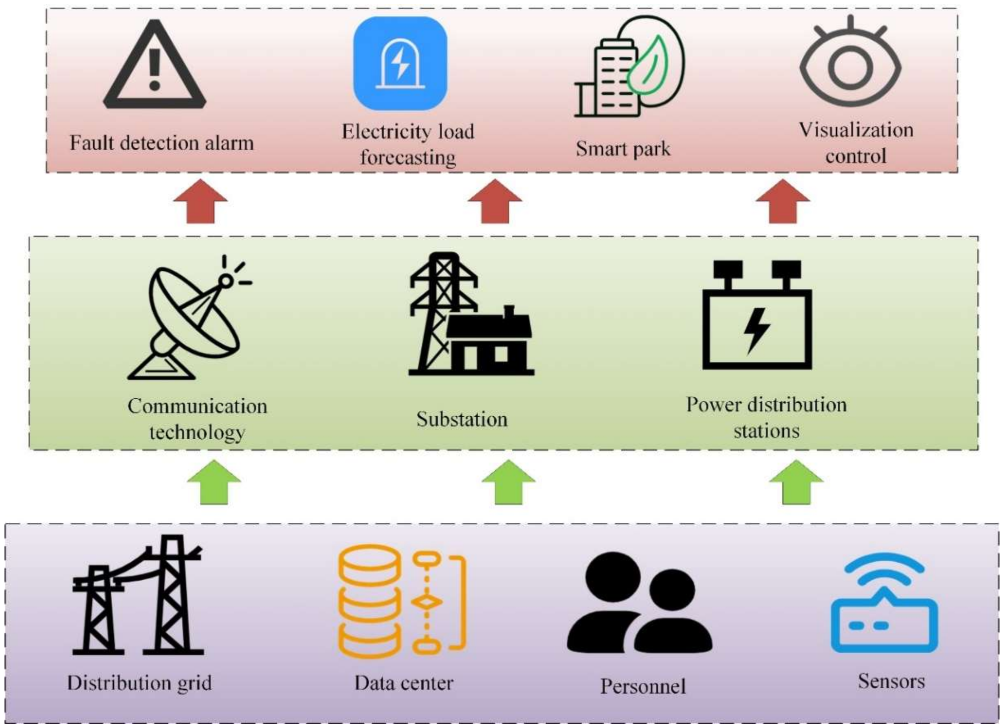

Fig. 3. Model of digital twin monitoring system for distribution network based on intelligent communication

In Figure 3, the distribution network digital twin system integrates the physical world with the digital virtual space, which realizes the full life cycle management of the distributed distribution network and covers all distribution lines and equipment from the substation to the end of the user metering box. The IoT sensing terminal is used to carry the front-end sensing network and aggregate all sensing data and operating data through intelligent fusion terminal and intelligent gateway, so as to finally realize the visual control of distribution network. It provides power supply enterprises with online operation and maintenance services based on blockchain, Internet of Things and other technologies, and promotes the improvement of operation and maintenance efficiency and management level of smart grid [14]. Due to the high nonlinearity and uncertainty of the electric power industry, how to accurately predict the probability of various faults and their distribution is very important to ensure the smooth operation of the entire system. Real time monitoring and early warning of the distribution network would help enterprises find and eliminate potential faults and reduce the occurrence of grid accidents. The emergence of smart parks has greatly promoted the electric power automation industry to move towards the direction of intelligence. It can effectively improve the accuracy and reliability of various indicators in the production process, and plays a very important role in maintaining social security and the safety of people's lives and property. The digital twin system of distribution network with intelligent communication as the core can also realize intelligent forecasting of power load, and can prevent the blackout time in advance or reduce the harm caused by peak power consumption, thus avoiding serious casualties and economic losses caused by blackout. Relevant industries should be guided to improve the power consumption structure and promote the large-scale promotion and application of new energy. Therefore, it can be predicted that the digital twin of distribution network based on intelligent communication would become a new trend in the development of power system in the future, and also an inevitable requirement for the transformation and upgrading of traditional power industry [15].

2.4 Application of physical communication principle in smart grid

The Open System Interconnect (OSI) model establishes a unified specification for the entire communication network system, and has a standard basis of good universality and scalability. The model includes seven layers. The physical layer is the lowest layer in all layers of network communication, which supports the implementation of other layer functions, such as data transmission and information processing, network transmission protocols, etc., and plays a vital role in the security and reliability of data transmission in various application environments. As the most basic and widely used part of the network communication system, the physical layer protocol can meet the requirements of different users for data transmission quality and speed by providing flexible and secure communication interfaces. Table 1 describes the OSI model.

Table 1. Introduction to the OSI model hierarchy

	Description
Physical layer	Determine network status, manage routing, and develop interfaces for applications
Data link layer	Determine network status, manage routing, and develop interfaces for applications
Network layer	Information exchange to improve system transmission speed and reliability
Transport layer.	Data transfer and error detection
Session layer	Communication links between users
Representation layer	Communication methods between devices or applications
Application layer	Interfaces between network services and end users

In Table 1, the main task of the physical layer in the OSI model is to provide network connection, data forwarding, message sending and other services, while ensuring the quality of service between nodes. The data link layer is responsible for maintaining the protocol stack, which includes determining the network state, managing routing, and developing interfaces for applications. In the whole process, the physical layer and the data link layer operate independently, but they depend on each other and work together. The network layer is the basis for realizing data transmission and application environment functions. There are many businesses to be handled in this part, among which the most important is information exchange. The purpose is to enable the transmission system to adapt to various communication requirements and improve transmission speed and reliability. The transport layer can provide connection oriented or non connection oriented data transmission and error detection, so it is an open and flexible architecture with high flexibility and scalability. Session layer and presentation layer are two relatively independent and non-interference entities. The former is mainly used to represent the communication between users, while the latter is mainly used to describe the communication mode between devices or applications, namely the so-called "session". The application layer is the interface between network services and end users, through which the increasing requirements of end users can be met.

At present, the power grid industry is in the stage of transformation and upgrading, and with the rapid development of information technology and automation level, the connection between its internal subsystems has become closer. In order to better realize system functions, reduce energy consumption and improve equipment utilization, it is necessary to effectively optimize scheduling strategies to meet the requirements of different levels of business under the current situation. Physical communication is the most commonly used method in modern power communication network, which can provide real-time information services and ensure stable and reliable network performance. Its specific application is shown in Figure 4.

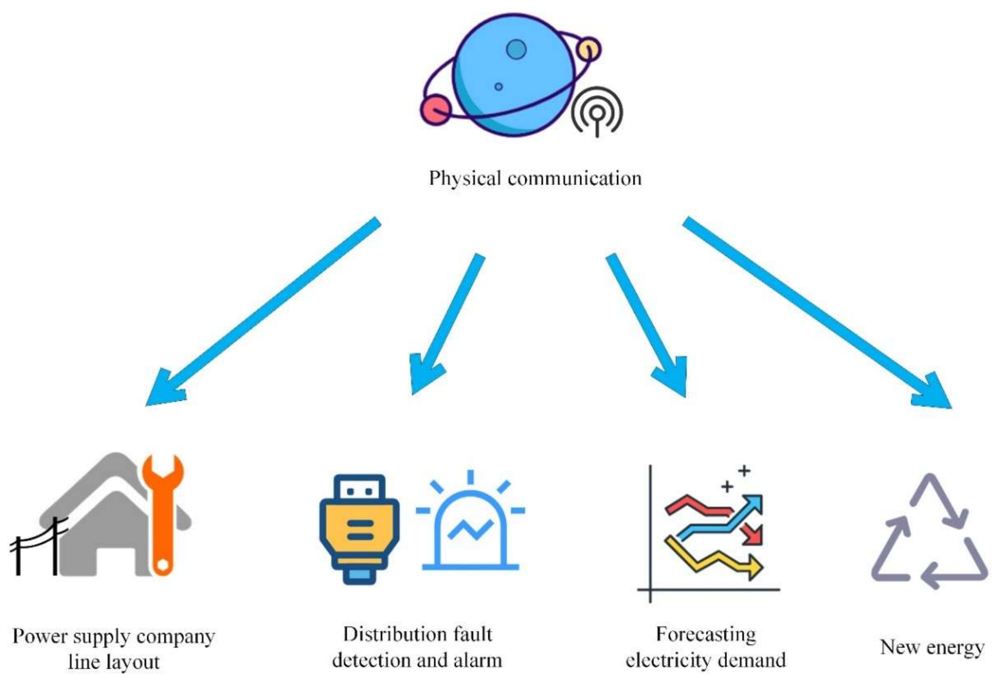

Fig. 4. Physical communication in the smart grid

First of all, power supply enterprises can reasonably plan the distribution line layout and construction according to their own actual conditions to avoid unnecessary investment waste and resource waste. At the same time, it can make the power grid more flexible to adapt to various changes, which is conducive to improving the economic benefits of the entire power system. Secondly, users can timely alarm or deal with power distribution faults to reduce losses. For example, in case of power failure, relevant staff would be notified by telephone, fax or other means, and remote meter reading function can also be realized to transmit data to the server of the local power supply bureau, which effectively solves the problem of manual meter reading and facilitates management and maintenance. Thirdly, distribution network operators can use this approach to understand the status of the whole network and make corresponding adjustments, so as to accurately predict future power demand and ensure safe production. In the actual power supply process, it can give full play to the role of smart grid, and also provide technical support and services for power dispatching. Finally, the intelligent substation based on physical communication means not only has strong practicability and economy, but also can promote the transformation of traditional energy industry to new energy and promote the healthy and orderly development of social economy. Therefore, it is widely used at this stage. However, due to its relatively low safety and reliability, many new energy industries are still in the exploration stage.

3. Smart Grid Digital Twin Structure Monitoring System and Key Technologies

3.1. Network energy consumption and delay

It is supposed that the average energy consumption for sending a data packet is Q_t, and the average energy consumption for receiving a data packet is Q_r. There are *N* sensor nodes, of which *n* nodes can directly communicate with the target node, and the data of other nodes should be forwarded to the target node through these *n* nodes. Every time all nodes in the network send packets, the average energy consumption of these *n* nodes is:

$$Q_{\text{average}} = \frac{N}{n} Q_{\text{t}} + (\frac{N}{n} - 1) Q_{\text{r}} \tag{1}$$

Among all the *N* nodes, those nodes consume the most energy.

When all nodes send packets once, the average energy consumption in the network is:

$$Q_{\text{v}} = Q_{\text{t}} \tag{2}$$

According to Formula (2), it can be obtained:

$$Q_{\text{v}} \le Q_{\text{average}} \tag{3}$$

When $N = n$, there are:

$$Q_{\text{v}} = Q_{\text{average}} \tag{4}$$

It is assumed that the time delay for a data transmission is T_1, and the time delay for a data transmission is T_2. At this time, the average time delay for data transmission from the terminal node to the target node is:

$$T_{\text{average}} = (G_h + 1) \times T_1 + G_f \times T_2 \tag{5}$$

In Formula (5), G_h is the average number of times the terminal node sends data to the target node, and G_f is the average number of times the terminal node sends data to the nearest heterogeneous node.

3.2. Simulation analysis of communication performance in intelligent distribution network

The node sends data as *M*, and the transmission distance is *l*; the energy consumed for sending data is E_1, and the energy consumed for receiving data is E_2, so there are:

$$E_1(M, l) = \begin{cases} ME_s + M\lambda_1 l^2 & l < l_0 \\ ME_s + M\lambda_2 l^4 & l \ge l_0 \end{cases} \tag{6}$$

$$E_2(M) = ME_s \tag{7}$$

Among them, E_s represents the circuit loss during signal transmission; λ_1 and λ_2 represent the energy consumed by power amplification, and l_0 represent the reference distance of sensor nodes in the circuit.

It is assumed that the two-dimensional coordinate of the node in the connected circuit is (a, b). Since nodes are also affected by various environmental factors during communication, the environmental factor between nodes is defined as σ, and its definition formula is:

$$\sigma = \frac{e_i - e_r}{10 \times \log \frac{l_{ij}}{l_0}} \tag{8}$$

$$l_{ij} = \sqrt{(a_i - a_j)^2 + (b_i - b_j)^2} \tag{9}$$

Among them, e_i is the path loss in the area where node *i* is located, and e_r is the path loss when the reference distance is l_0 under ideal environment.

4. Simulation Comparison Experiment of Digital Twin Structure Monitoring System of Distribution Network

4.1. Experimental methods

In order to verify and evaluate the effectiveness, advantages and disadvantages of the research on intelligent grid digital twin online monitoring system based on intelligent communication network, the traditional distribution network detection system was compared with the improved system. The traditional monitoring system was defined as Group A, and the improved monitoring system was defined as Group B. By setting different parameters, the voltage data of smart grid transmission lines were simulated from four aspects: success rate of packet reception, delay, normalized routing overhead and routing initiation frequency, and the experimental data were recorded and analyzed.

4.2. Data analysis

1) Packet receiving success rate. It was known that the two systems have the same number of nodes and the same speed. The number of data packets obtained by the two systems when the pause time was 0 seconds, 30 seconds, 60 seconds, 120 seconds and 200 seconds were analyzed. The results are shown in Figure 5.

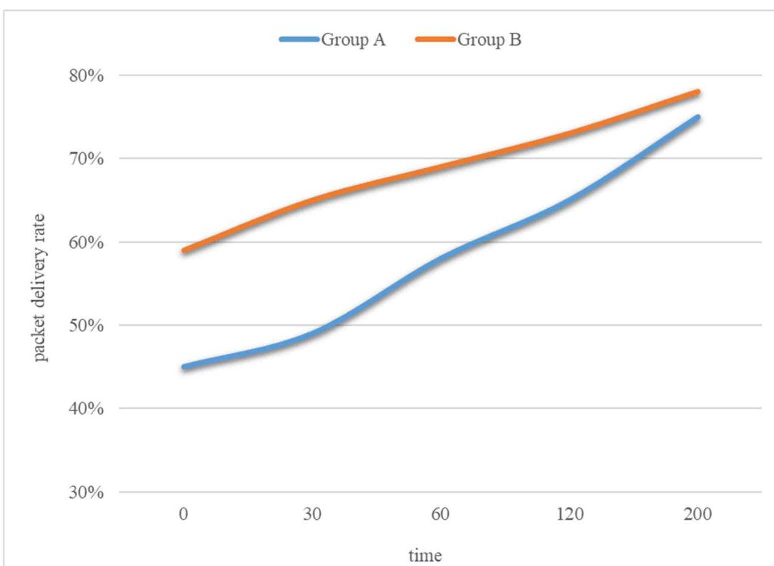

Fig. 5. Comparison of the success rate of packet reception between the two groups

It can be clearly seen from Figure 5 that Group B had a high success rate; when the pause time was longer, the success rate of Group A was greatly improved. It can be concluded that the longer the node pause time in the network, the greater the packet delivery rate, and the greater the success rate of packet reception. After calculation, the average success rate of Group A was about 58.4%, and that of Group B was about 68.8%, which was about 10.4% higher than that of Group A. Therefore, the optimized digital twin detection system of distribution network has higher execution efficiency, and can transmit more data packets that accurately reach the destination node. It can not only reduce the error rate and loss probability, but also reduce the equipment cost and enhance the network connectivity.

2) Delay. The time delay effect under different pause times was compared. The results are shown in Figure 6.

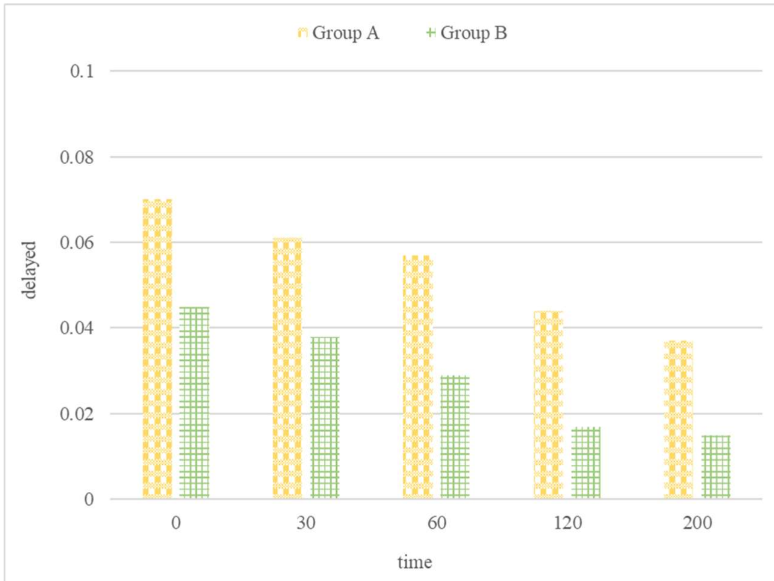

Fig. 6. Comparison of latency time of the system before and after optimization

In Figure 6, Group A network delay time was longer than Group B network delay time in each pause time, and the delay was shorter when the network node pause time was longer. When the pause time was 0 seconds, the connectivity between nodes was strong, which indicated that there was a maximum delay. When the node paused for 200 seconds, the connection between nodes was stable and the delay was reduced. Compared with Group A, Group B effectively reduced the average delay of the distribution network monitoring system because the original link fracture would cause the node to restart the routing request, which increased the time consumption and caused the delay to increase. However, the improved system has the function of backup routing, which reduced the number of route starts and network delay to a certain extent. It also increased the flexibility of network operation.

3) Normalized routing overhead. The normalized routing overhead under different pause times was compared. The results are shown in Figure 7.

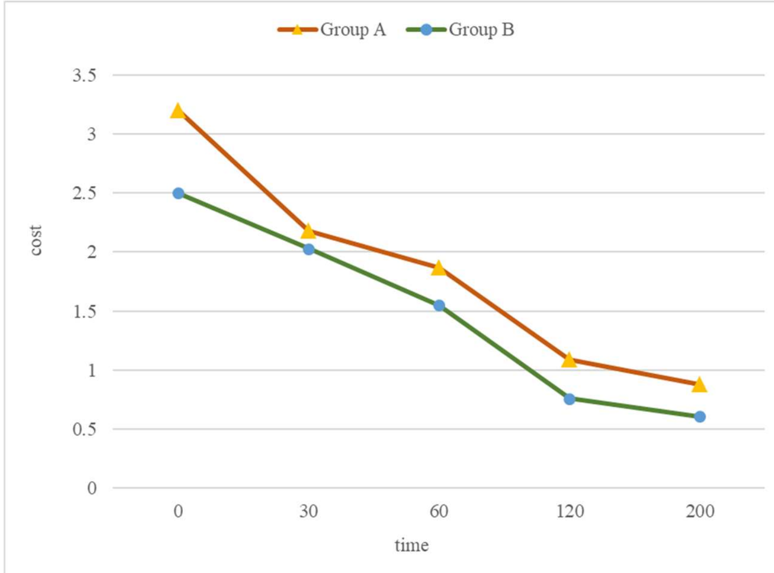

Fig. 7. Comparison of normalized routing overhead for the two groups

It can be seen from Figure 7 that the curve of Group B was distributed below Group A and showed a steady downward trend. When the pause time was less than 30 seconds, the decrease of group A was greater than that of group B. This was because during continuous waiting, all nodes would choose an optimal path for transmission, which reduced the number of route discovery to a certain extent. At the same time, it also reduced the number of control packets and the network running cost. According to the above analysis, it can be concluded that with the increase of node residence time in the network, the moving range of nodes becomes smaller and smaller, which greatly reduces the routing overhead.

4) Route initiation frequency. The change of route initiation frequency under different pause times was compared. The results are shown in Figure 8.

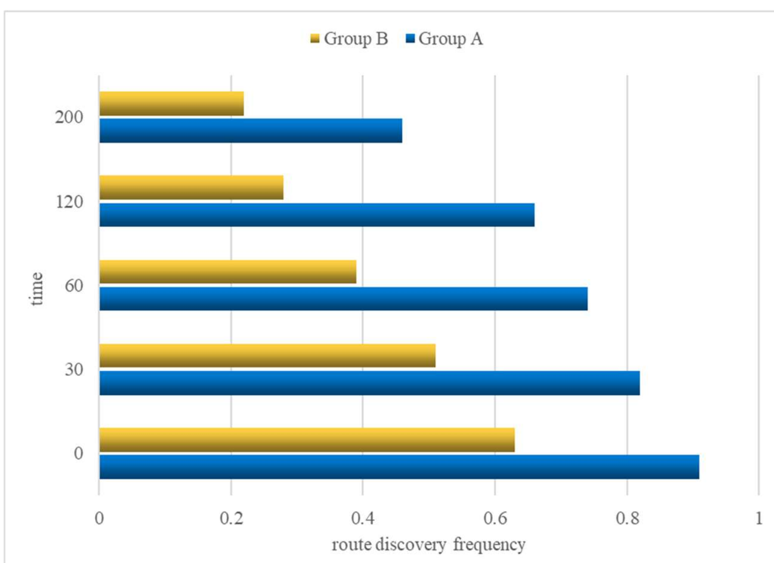

Fig. 8. Comparison of the frequency of route initiation between the two groups

In Figure 8, the frequency of Group B was far lower than that of Group A in terms of route initiation frequency; with the increase of time, the route initiation frequency of both groups showed a decreasing trend. Although the original system has high performance, when the network fails, the traditional router based forwarding protocol would cause a lot of information loss or data misreading, which seriously affects the network bandwidth utilization and quality of service. The improved smart grid digital twin distributed monitoring system can improve the communication efficiency between nodes through real-time detection of wireless links.

5. Conclusions

Distribution network plays a key role in the operation of urban power grid, which is the most basic and core part to ensure the reliability and security of power supply. The operation of power grid is directly related to the security, stability and economic operation of power grid. The integration of intelligent communication network into the digital twin structure monitoring system of distribution network can improve the level of distribution automation, and realize the collection, analysis and processing of the status information of distribution network equipment. This paper introduced the basic architecture of digital twin technology in the field of distribution network, and analyzed its specific applications in state assessment, real-time monitoring and load forecasting, which prospected the future development trend of digital twin technology in the field of distribution network. A smart distributed substation model based on cloud computing and big data technology was built by combining modern information technologies such as intelligent communication, which provided support for improving the operation and maintenance capacity of distribution network, and can promote the transformation and development of traditional power system to digital. As one of the most important information transmission channels in the current distribution automation system, physical communication can realize bidirectional data transmission between various data channels. Through the power line communication network, various terminal equipment and terminal equipment can be accessed to complete power resource allocation.

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