Research and application of wireless sensor network technology in power transmission and distribution system

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Research and application of wireless sensor network technology in power transmission and distribution system

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Abstract: Power is an important part of the energy industry, relating to national economy and people's livelihood, and it is of great significance to ensure the security and stability in operation of power transmission and distribution system. Based on Wireless Sensor Network technology (WSN) and combined with the monitoring and operating requirements of power transmission and distribution system, this paper puts forward an application system for monitoring, inspection, security, and interactive service of layered power transmission and distribution system. Furthermore, this paper demonstrates the system verification projects in Wuxi, Jiangsu Province and Lianxiangyuan Community in Beijing, which have been widely used nationwide.

Key words: Wireless Sensor Network (WSN); smart grid; power system; power transmission; power distribution; monitoring system

1 Introduction

The power system includes subsystems such as transmission, distribution, and power utilization, and each subsystem has different monitoring needs. Power grids represent a complex system of systems with intense interactions between them and require the collection of large amounts of data from a variety of sources to improve the energy ecosystem operation quality[1]. When it comes to a specific application in the power system, e.g., online transmission line monitoring, the deployment of wireless sensor network will be faced with severe technical challenges in communication networking, due to the long-range extension of transmission lines. In addition, since most of the high-voltage transmission lines are erected in remote wild areas, it is quite difficult to realize multi-hop wireless network protocols with low energy consumption. Another technological challenge is how to supply power to the monitoring devices on the line. In addition to the severe electromagnetic interference on the wireless sensor network, caused by the discharge of the power transmission system, the equipment in strong electric field can be easily damaged by the induced high voltage due to the coupling effect. As for site-operation supervision and intelligent inspection for power distribution systems, although the existing systems have already achieved some certain level of intelligence, the utilization of Radio Frequency Identification (RFID) tags in the existing systems is limited to device identity confirmation. Lacking functionality for matching working procedures and recording operation processes, current applications of RFID technology cannot achieve the goal of reducing misoperation risks and hidden safety hazards. In addition, to our best knowledge, no existing system utilizes video sensors to realize real-time interaction between the dispatching command center and field operators[2, 3]. The staff supervision in the inspection work and the automatic information collection process still need to be further improved, in order to achieve the purpose of a reliable and safe inspection. For

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power usage, regarding the intelligent electricity usage data acquisition, though the current advanced metering infrastructures have been deployed and in operations, there are still reliability, availability, and maintainability issues. Reliable transmission of electricity data in large area of China for a variety of customers cannot be achieved by utilizing a single communication technology. In terms of providing intelligent electricity services, the communication network resources on the customer side are limited, the interactive functionalities between various systems and users are not sufficient, and they cannot fully meet the requirements of intelligent electricity service. The system functions need to be further developed and integrated. The construction of original customer service system is less standardized, and there is a large gap between technical design and function implementation. Besides, terminal equipment types are diverse and lack intelligent functions[4].

Wireless Sensor Network (WSN) and Internet-of-Things (IoT) technology research and application have made a lot of achievements abroad[5], and have been gradually applied in the power system. IoT devices are deployed to monitor and control grid statistics for reliable and efficient delivery of power[6]. Generally, a smart grid is a new ecosystem, which consists of a number of smart IoT devices for the efficiency and reliability management of the smart energy systems[7-9]. IoT provides an ideal platform to enable many critical and time-sensitive applications in monitoring and operation of critical power systems[10]. Also, IoT has emerged as the optimized day-ahead pricing technology with renewable energy demand-side management for smart grids[11]. In terms of transmission line online monitoring technology, researches have been carried out abroad in the 1990s, such as the online monitoring system of insulator leakage current of Red Phase INC of Australia, the online status monitoring system of transmission line of the USA, and the state analysis of power equipment of Japan and some European countries. With construction and application of the system above, the maintenance interval can be greatly extended and a large amount of operation and maintenance investments can be saved. Combining IoT elements, such as sensors (internet emended), and regarding the internet as a transmission medium will construct the internet of energy, which is considered as a typical trend nowadays[12-14]. For customer domain of the smart grid, a detailed architecture, the “last-meter” smart grid—the portion of the smart grid on customer premises—embedded in an IoT platform, has been carried out[15]. In terms of power consumption information collection, the USA, Britain, Italy, France, Spain, Australia, and other developed countries, as well as India and other emerging developing countries, are developing automatic-meter system or smart meters, and have successively carried out large-scale construction of relevant power consumption information collection systems, which have had some great achievements. The utility committees in California and Virginia in the USA have approved the construction of large-scale power consumption information collection system, which could also provide power metering and internet access services at the same time. Britain has basically realized the automatic collection of power consumption information for industry and commerce and some residential users. From 2001 to 2004, Italian power operators installed 30 million smart power meters, and established an intelligent metering network which realized the automatic collection of power consumption information for 95% of power users nationwide. And France is promoting a 400,000 smart power meters program. Many projects have been carried out for the improvement of domestic power services in India, for developing a Power Line Communication (PLC) remote power meter and prepayment system, which will solve the problem of power loss and improve management level.

The research and development, and the application of relevant internet-of-things technologies have also achieved fruitful results in China. In the field of IoT chips, application system, standard architecture, information security, wireless broadband communication, software platform, testing technology, experimental technology, and other fields, comprehensive research and deployment have been carried out. The real-time monitoring, fault warning, analysis, diagnosis, evaluation, and prediction of the power system operation status of all kinds of transmission and distribution
equipments and lines are preliminary realized. The pilot construction and application of power system load management, centralized meter reading, and other power consumption information collection systems have been carried out, which have played a positive role in power safety production and operation management. In the aspect of intelligent inspection, the intelligent inspection management of transmission, transformation, and distribution network equipment is preliminarily realized by using intelligent mobile terminals, combined with Global Positioning System (GPS), RFID, and bar code technology.

As mentioned above, wireless sensor network, as an advanced data acquisition and processing technology, has been widely used in many areas all over the world, such as power, medical, industrial manufacturing, agricultural management, commercial business, public management, and national defense\[16, 17\]. The technology is an important tool for promoting future economic development. To date, the technology of wireless sensor network has been broadly studied and technically verified. However, the sensor networking industries in China still lack overall solutions and integrated innovation for industry applications, as well as large-scale promotion and application in particular industry and production field, thus forming a complete industry chain from technology research and development, device development system application to network services is of great importance\[18\].

To address the above problems, it is urgent to develop low-power-consumed, highly precise, and highly reliable wireless sensor devices suitable for smart grid application scenarios, in order to build a completely smart power wireless sensor network system, and to implement an integrated application platform for unified data storage, processing, mining, analysis, and other services for power wireless sensor network related applications. In this paper, a system for sensor network application for smart grid transmission, transformation, distribution, and power consumption is proposed through in-depth analysis of the application scenarios of wireless sensor network in the smart grid. Key technical issues such as the WSN awareness layer, network layer, application layer, and information security have been studied and explored. A series of demonstration projects will be introduced to verify the effectiveness of the WSN technology application in Chinese power industry.

2 General WSN architecture for power grid

The online monitoring of crucial operating parameters of the smart grid can strengthen the prediction, prevention, and regulation of system or equipment status to improve the safety, reliability, and anti-disturbance of the power system. Furthermore, it can provide intelligent auxiliary decision-making to further improve the two-way interaction with customers and expand new value-added services on the basis of strengthening the operation of the power grid. The realization of the above goals depends on thorough information perception, reliable data transmission, efficient network construction, and intelligent management as well as data processing analysis technology of massive perception information.

The WSN system utilizes a large number of sensors deployed in the target area of the power system to collaboratively perceive and collect data from various environments or objects, and to get aware of the targets’ state through the in-depth multi-parameter fusion and collaborative processing of the data. With its unique advantages, the WSN system can meet the needs of accurate and comprehensive real-time information acquisition on each important part in the smart grid, including generation, transmission, transformation, distribution, and consumption. That is, the WSN system can help achieve effective awareness on the power grid, and thus it can provide effective support for improving the standardized management capabilities of the power grid\[19\]. The overall architecture of the wireless sensor network for smart grid is shown as Fig. 1.

Perception layer is composed of several perception sensors deployed on-site. The perception network is self-organized to realize the functions of intelligent collaborative perception, intelligent identification, information collection processing, and automatic control of the smart grid. Through a variety of new Micro-Electro-Mechanical Systems (MEMS) sensors, smart sensors based on embedded systems, smart acquisition equipment, and other technologies, the perception layer can collect and identify the essential data
regarding mechanical status, energy consumption, and environmental status of key equipment in each important part of the power system.

Network layer realizes information transmission, routing, and control between the perception layer and the application layer through the fusion and expansion of different types of communication networks, such as power wireless broadband, wireless public communication network, wireless sensor network, and power optical transmission network, to provide large-scale data transmission services for information from perception layer with high reliability and security. In the application of smart grids, the transmission and aggregation of information in power WSN system mainly rely on the dedicated communication networks for power systems, supplemented by public telecommunication networks. The network layer generally consists of access networks and core network. The core network is mainly based on the backbone optical fiber network for power system, while the access networks include the power fiber access network, power line carrier, and wireless communication system. The power communication network provides a high-speed broadband two-way communication network platform for the application of the power WSN system[20].

Application layer consists of a variety of application infrastructure, middleware, and application systems. In the application layer, the information and data from the perception layer are analyzed and processed according to different business needs. The applications on the application layer involve the production and management of the entire life cycle of the smart
grid. Through the use of intelligent computing, pattern recognition, and other technologies, comprehensive analysis and processing of the power grid data can be achieved, and the intelligent decision-making, control, and service of the power grid can be continuously improved to promote convenient, green, and efficient use of electricity.

3 Key technologies in WSN for power grid

3.1 Perception layer

The power WSN perception layer mainly consists of a variety of sensors for power system or device status collection. Typical sensors are as follows:

3.1.1 Conductor to ground distance monitoring

Trees and other plants near transmission lines are the key cause for the short circuit of the power lines. The branches and leaves of trees often lead to the short circuit fault of the transmission line, resulting in the suspension of power transmission. The laser ranging sensor is used to measure whether the dangerous objects such as trees around the transmission and distribution lines are within safe distance, and warn the line maintenance staff to react on time. In addition, sensors can also be used for auxiliary measurement, such as line sag, to ensure the safe operation of power transmission.

3.1.2 Wire temperature sensor

The current flow in the power line will cause the temperature of the wire to rise, and when it reaches a certain temperature, there will be fire hazards. Meanwhile, the temperature of the wire is directly related to the transmission capacity of the line. The larger the transmission capacity, the more obvious the temperature rises. Under the premise of line fire hazards, controlling the temperature of the line can maximize the transmission capacity of the line and optimize the operation of the power line. Therefore, wire temperature sensors can be used for on-line temperature measurement of the transmission line wires. The temperature measurement terminal adopts low-power consumption technology and uses an 8 Ah/3.6 V high-temperature-resistant lithium sub-battery with low self-consumption and long-life power supply modules. The unit on duty can last for more than 5 years.

3.1.3 Environmental micrometeorological sensor

Electric power transmission and distribution lines operating in the open air are greatly affected by the climate changes that impact the secure operation of lines. The meteorological online monitoring system for transmission system is a multi-element micrometeorological measurement system designed for local weather monitoring of overhead line corridors. Meteorological parameters monitored include wind speed, wind direction, air temperature, humidity, air pressure, etc. The system will collect various real-time weather data, and send them to the central monitoring and analysis system through the network. When there occurs an anomaly, the system will send out warning information in different ways to operators and maintenance staff, reminding them to pay attention and take necessary countermeasures.

3.1.4 Intelligent anti-theft bolt

Most of the infrastructures of the power system distribution network are operated outdoors, and some facilities are left unattended on site. The theft of the facilities may occur. Intelligent anti-theft bolt is the replacement of ordinary mechanical bolts. It equips with an anti-theft sensor module based on wireless sensor network technology.

3.1.5 Voltage measurement sensor

In the power grid distribution system, the voltage is an important parameter. The voltage measurement sensor is used to measure and analyze the power quality signal of the low-voltage distribution line, and can also be used as an anti-theft warning auxiliary device for low-voltage power equipment. The device performs power quality detection on the electrical signal of the connected distribution network. Meanwhile, the induced energy of monitored signal serves as an external power supply to the device.

3.1.6 Underground vibration sensor

The power line pole tower is an important infrastructure of the power grid, and the tilt of the pole tower or the damage by external forces will have a significant impact on the operation of the power grid. The underground vibration sensor is used to detect hazardous activities that endanger the safety of pole towers, such as soil vibration.
and soil erosion. The device has four high-sensitivity omnidirectional vibration sensors to ensure reliable anti-interference performance. With various fixing means such as straps and bolts, it can be conveniently installed.

3.2 Network layer

3.2.1 Requirement for networking

The complexity of power sensor network scenarios involving types of communication technologies and protocols brings great difficulties to data processing and communication. In order to sense the operating status of the power grid in real-time, a large number of sensors need to be deployed on various power equipments to collect relevant information and data, and report them to the control center. The data collected by the smart grid sensor nodes include multiple categories, e.g., current, voltage, temperature, pressure, humidity, and other types of data. Using the above data, the overall operating situation of the power grid and each device, assets, and environmental status can be analyzed [22–24]. In order to meet the needs of the above-mentioned power grid perception, the sensor network for power system has the following unique features:

- **Large numbers of wireless communication nodes.** Ordinary urban power systems include tens of thousands of micro user regions. In order to realize the monitoring of the system, a large number of sensor nodes need to be configured to collect data from customers’ electrical appliances, and the number of terminals that need to communicate with each other is huge.

- **Huge amounts of data transferred.** The sensor node needs to periodically send the data of power consumption or other states of the device. Due to the great number of sensor nodes, the amount of data to be transmitted in the network is very large.

- **High-standard real-time requirements.** In order to correct line faults as soon as possible, the power grid operation and control data need to be transmitted to the power dispatch center in real time to analyze the state of the power grid.

3.2.2 Network properties of smart grid sensors

To meet the requirements for power grid transmission and distribution monitoring, the smart grid sensor network should have the following characteristics:

- **Low mobility.** The low mobility characteristics of sensors are suitable for fix-positioned or barely moving sensor devices, or that move only within a limited area.

- **Time control.** The time control feature of the sensor is suitable for sensor devices that send and receive data within a predefined time period in the smart grid, to avoid unnecessary signaling outside these time periods.

- **Small data transmission.** The amount of data sent and received by sensors in the smart grid is relatively small.

- **Priority of warning.** Sensor devices on the smart grid should prioritize the function of warning, such as theft, vandalism, or other situations that require immediate attention. Warning messages should have a higher priority than other categories of information.

- **Infrequent transmission.** This feature is applicable to some infrequently transmitted sensor devices in the smart grid (there is a long interval between two data transmissions).

- **Low power consumption.** This feature will enhance the system’s ability to support sensor applications that require particularly low power consumption. Sensor devices should be able to be configured to a particularly low power consumption mode by network management system.

- **Fading effect.** In the smart grid, due to the numerous and complicated metal components in the transmission lines, equipment, and towers, the electromagnetic field strength distribution near the tower will be uneven and unstable.

- **Strong electromagnetic interference.** There is strong power-frequency electromagnetic field interference, flashover, and corona interference around high-voltage transmission lines, towers, and high-voltage corridors. Strong power-frequency electromagnetic fields will block the communication channel, resulting in reduced link gain and affecting communication reliability. Corona interference is a type of shot noise interference, which appears as random narrow pulses in the time domain and broadband white noise in the frequency domain, which can severely interfere with communication links in various frequency bands.
3.2.3 Architecture of communication networks

The wireless sensors in the smart grid are directly connected to the base station through the air interface of the communication network or the aggregation node and then are connected to the mobile network of telecommunication service providers\(^{[25]}\). The background smart grid management system and other related business platforms are also interconnected with the mobile core network through various access means. Data collected from the wireless sensor are transmitted to the management or business platform through the mobile core network for further use.

**Wireless access side.** The sensor network system usually consists of sensor, aggregation, and management nodes. The sensor nodes are randomly deployed inside or near the monitoring area and form a self-organized network. The data collected by the sensor nodes are transmitted hop-by-hop along other sensor nodes to the aggregation nodes and finally to the management node. Users can configure and manage the sensor network through the management node, issue monitoring tasks, and collect monitoring data.

The sensor node is composed of four parts: sensor module, processor, wireless communication module, and energy management module. The sensor module is responsible for information-collecting and data conversion; the processor module controls the operations of the entire device and stores and processes the data collected by its own node and those sent by other nodes; the wireless communication module is in charge of exchanging, controlling instructions, and collecting data with other nodes; the energy management module manages the energy consumed by the sensor node for operation.

The aggregation node is a multi-stream sensor terminal. The data-streams of multiple sensor nodes converge at the aggregation node and are uploaded to the mobile communication network through the air interface\(^{[26]}\). Aggregation nodes can aggregate service flows from multiple end sensor nodes in two ways, as shown in Fig. 2.

**Core network side.** The sensors in the smart grid are connected to the wireless access network through a gateway or direct connection, and the bearer network may be connected to the server through an interactive gateway\(^{[27,28]}\).

Various sensors in the smart grid communicate with the background smart grid application platform server (Machine Type Communication Server, MTC Server) through the mobile core network. The MTC Server provides necessary management, control, and numerous business capabilities for the smart grid. In various applications of the smart grid, it is crucial to determine the parameters on regarding the access status of various sensor terminals, such as access time, offline time, and access location. Accordingly, the MTC Server can

![Fig. 2] WSN accessing the wireless network. M2M represents machine to machine.
accurately determine the various states of the terminal, such as whether a Subscriber Identity Module (SIM) card dedicated to the sensor device is inserted into the non-sensor terminal, whether a terminal accesses the network at an unauthorized time, whether the terminal accesses the network at an unlicensed location, and whether a terminal is abnormally offline. The above status information is sent to the MTC Server through a specific interface provided by the core network. For the core network, Mobile Service Centre (MSC)/Serving GPRS Support Node (SGSN) can easily obtain the terminal status information required by MTC Server, whereas Gateway GPRS Support Node (GGSN) is relatively difficult. Obtaining and providing terminal status information required by MTC Server through MSC/SGSN are the optimal solutions.

Considering the security risks of the smart grid application platform directly accessing the operator’s network, a sensor gateway (MTC GW) can be introduced. The MTC GW can effectively shield the topology of the core network, realize the security certification mechanism of accessing the smart grid application platform through the core network, and provide a unified routing export for various applications of the smart grid application platform. Figure 3 depicts the architectural diagram of the deployment of the MTC GW between the core network entity and MTC Server.

Through the MTC GW, it is possible to effectively shield the core network topology, establish an encrypted tunnel between the MTC GW and MTC Server, and provide a unified Application Programming Interface (API) to the MTC Server, which greatly reduces the complexity of the core network interface.

3.3 Application layer

Based on the real-time state perception of the smart grid, the information sensed by the perception layer is analyzed and processed according to different applications and business needs to form an architecture including the application infrastructure, middleware, and various applications, and to implement all kinds of WSN applications. The application of a power sensor network involves the production and management of the entire life cycle of the smart grid. By adopting intelligent computing, pattern recognition, and other technologies, comprehensive analysis and processing of grid information, intelligent decision-making, control, and continuous improvement of services can be achieved[29–32]. According to the components of the power system, the application verification system for smart grid sensor network mainly consists of the following eight important systems:

- **Online transmission line monitoring.** It mainly completes the real-time operation status monitoring of the transmission line, including the online monitoring of icing, meteorology and wind deviation, breeze vibration, galloping of the line, online monitoring of tower inclination, online temperature monitoring, and dynamic capacity increase in the line. It also provides auxiliary decision-making support for the operation personnel to detect potential accidents as early as possible and make actions in time, thus ensuring the reliable operation of transmission lines.

- **Transmission, substation, and distribution inspection.** They mainly involve recording of the track of power transmission and distribution inspection, photo collection of power lines, and equipment inspection. Distribution inspection also includes the cable skin temperature measurement, transformer load, and outgoing line measurement. Substation inspection system mainly focuses on the location information of the substation inspection personnel, substation environment,
temperature and humidity of transformers, leakage current and other data, power transformation video acquisition, and remote consultation of problems.

- **Online electrical equipment status monitoring.** It mainly completes online monitoring of the transformer oil and gas, transformer partial discharge, breaker dynamic characteristics, transformer and arrester insulation, substation security, infrared video, mobile video, and dynamic measurement.

- **Platform for protection and safety of electric power facilities.** It mainly completes the intelligent video monitoring of power infrastructure (including outdoor distribution network lines, line towers, and distribution transformers) and the analysis and alarm processing of intrusion. At the same time, the platform will link the alarm information with the public security department, and jointly manage grid thefts with social forces.

- **Distribution field operation supervision.** It mainly completes the application, approval, and execution of power distribution operations, real-time video acquisition of operation, guidance of standard operations, and confirmation of power equipment operations, operation location indication, and navigation. It can also display the active information of the line switch status, remote signal data, and scope of the power failure influence.

- **Intelligent power usage service.** It mainly completes interactive services with power users; user power information collection; user energy management; smart home energy management; power, water, and gas metering intelligent security functions; community interactive services; and Internet and Internet Protocol Television (IPTV) services.

- **Power usage information collection.** It mainly completes user power information collection, energy data management, automatic power metering management, cost control management, orderly power management, abnormal power analysis, power line transmission loss analysis, and security protection, which provides data support for intelligent interactive services.

- **Smart grid sensor network information processing and integrated management platform.** It mainly completes data fusion and comprehensive display of the above seven application systems.

The architecture of the power WSN application system is shown in Fig. 4.
3.3.1 Online monitoring system for smart grid transmission lines

High-Voltage (HV) overhead transmission lines are an important part of the power grid. Breeze vibration and wire wind deviation caused by light winds are the main causes of fatigue and strand breaking of HV overhead transmission lines. Line dancing due to strong winds will lead to great damage to HV transmission lines. Moreover, iced overhead lines and unbalanced icing between the corresponding pairs of tower cables can cause the tower to tilt or even fall. These factors are huge hidden dangers for the safety of transmission lines.

The multifunctional backbone nodes and MEMS acceleration (gyro) sensor nodes deployed on the entire transmission line, together with leakage current sensor nodes and communication backbone nodes placed on the HV pole tower, make up a sensor cluster. A transmission line online monitoring system for the entire smart grid is formed based on multiple clusters connected through communication backbone nodes[33]. The system realizes multidirectional real-time visual monitoring and early warning regarding various states of transmission lines, such as ice coating, pollution, temperature, and dancing. Figure 5 shows how a smart grid transmission line online monitoring system is deployed based on a sensor network.

3.3.2 Inspection system for transmission, substation, and distribution

There are many types of equipments in the transmission, transformation, and distribution of the power grid, which require heavy workload of operation and maintenance. They usually consume considerable manpower to perform daily inspection works. Through a combination of wireless sensors and RFID tags, the observation and recording of operating parameters, abnormal equipment status, equipment damage, and performance degradation during daily operations of various power equipments, can be achieved. Meanwhile, through the analysis of the collected data, the potential hazards are evaluated and cautioned to avoid the failure of power grid equipment. Figure 6 shows the architecture of the transmission, transformation, and distribution inspection system.

Based on the sensor network and RFID technology, the system realizes the function of supervising whether the inspectors arrive at the site and patrol according to the predetermined route. In the meantime, auxiliary environmental information and status monitoring sensors are added to accurately detect the working environment.
and status of the equipment, accurately identify the inspection staff, and also collect information regarding the operating environment and working status of power equipment, which greatly improve the quality of the inspection work.

3.3.3 Online monitoring system for electrical equipment status

Substations are another important part of the power system. They are the source of the basic operation data collection and command execution unit of the power grid. The operation and equipment safety of substations directly affect the security of the power grid. The state maintenance of power transmission and transformation equipment must be performed to improve equipment utilization, extend equipment life, reduce the number of power outages, and improve transmission efficiency. Power transmission and transformation equipment status monitoring will also be used as an auxiliary equipment status diagnosis method, playing a large role in the maintenance of power transmission and transformation equipment status[34]. Through the technology of sensor integration, information acquisition, information fusion, and anti-strong electromagnetic interference, a smart grid substation status monitoring system can be built to implement the real-time monitoring of various equipments and safety protection in substations, including transformer oil and gas, local discharge, dynamic characteristics of circuit breakers, transformer and lightning arrester insulation, substation security, and dynamic measurement of transformers. The network sensing architecture of the substation acquisition layer is shown in Fig. 7.

The online monitoring system collects all kinds of substation state quantities and transmits the data to the background expert system for analysis and decision-making, which can provide safety evaluation of the substation state.

3.3.4 Support platform for power facility protection and safety

Based on the WSN technology of the power grid, various types of sensors, such as vibration, displacement, voltage change, and infrared sensors, can be installed on outdoor lines, poles, distribution transformers, and other equipments, forming a cooperative sensing network with a certain strategy. In this way, the monitoring and early warning protection of the power grid and equipment can be effectively realized. The support platform for power facility protection and safety generally consists of different sensor nodes, such as underground fixed wireless vibration sensor nodes, mobile wireless vibration sensor nodes, tower wireless tilt sensor nodes, tower wireless (acoustic) vibration sensor nodes, wireless anti-theft bolt sensor nodes, wireless passive infrared sensor nodes, intelligent video sensor nodes, and wireless and fiber-optic power communication network nodes. The architecture is shown in Fig. 8.

Using sensing composed of various sensors, effective positioning, monitoring, and early warning can be realized against theft and damage activities, which can jeopardize the power grid’s main infrastructure, and thus the distribution equipment can be comprehensively protected within the monitoring range.
3.3.5 Supervision system for distribution site operations

Due to the complexity of the operation and maintenance of the power system, it is difficult to effectively supervise the power field operations. Hidden safety hazards are often encountered, such as wrong operation and accidental entry. In the smart grid system, the WSN technology can be used for identity recognition,
electronic work-permit management, environmental monitoring, and remote video monitoring, and for achieving real-time interaction between the dispatching command center and field operations staff, thereby eliminating hidden security risks.

With the video surveillance equipment and RFID tags installed on the work vehicle, power distribution on-site operation supervision system can remotely monitor the work site situation, verify on-site operated objects and work procedures, and closely organize dispatchers, security supervisory personnel, operating personnel, and other staff to make various on-site work or activities under control. Therefore, supervision system for distribution site operations can effectively reduce production losses caused by human factors or external factors, guarantee personal, equipment and system safety, and greatly improve work efficiency. The architectural diagram of the distribution site operation supervision system is shown in Fig. 9.

### 3.3.6 Intelligent power usage service system

As a key part of the power consumption, the smart power usage service aims to achieve real-time interactive response between the grid and users, enhance the grid’s comprehensive service capabilities, meet the demands of interactive marketing, improve service levels, strengthen information sharing and real-time interaction between users and the grid, realize the intelligent and interactive use of electricity, further improve the operation mode of the power grid and the use of electrical energy, and finally improve the energy efficiency of end users. Power line loss and prepayment business management can be realized by the collection of electricity consumption information from public transformers, low-voltage industrial and commercial households, and low-voltage residential households. Through the automatic monitoring of smart switches and smart home appliances, the communication network can be extended to the users’ home. Moreover, smart grid user service functions, such as user power consumption and power transaction information publishing, and user power consumption intelligent management can be implemented.

The intelligent power usage service system enables the interaction between users and the power grid through intelligent interactive terminals or interactive set-top boxes; realizes a series of special services, such as energy efficiency management, property management, value-added services, and community medical care; and reflects good interactivity and intelligent features. The WSN technologies can be applied to form a family internal network; realize the collection and control of the electricity information of household sensitive loads, such as electric water heaters, air conditioners, and refrigerators; and establish a home security system integrating emergency help, gas leakage, and smoke detection. The architecture of the intelligent electricity service system is shown in Fig. 10.

### 3.3.7 Power usage information collection system

The Power Usage Information Collection system (PUIC) system collects data from special users, such as large-, medium-, and small-sized special transformer users, industrial and commercial customers with

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Fig. 9   Architecture of the distribution site operation supervision system.
380 V/220 V power supply, and residential customers. The main functions of the PUIC system include data collection, data management, automatic meter reading, charge control management, abnormal power consumption analysis, line/transformer loss analysis, and security protection. It provides data support to bidirectional interactive services for intelligent power usage services\cite{20}. The system can be divided into three layers: master station layer, communication channel layer, and acquisition device layer. The specific structure of the electricity information collection system is shown in Fig. 11.

The master station layer implements three functions, namely, marketing collection business application, front-end collection platform, and database management. It provides corresponding support for the power marketing. The communication channel layer is the link between the master station and the data collection equipment, providing available wired and wireless communication channel. The main communication channels include a fiber-optic private network, GPRS/Code Division Multiple Access (CDMA) wireless public network, and 230 MHz wireless private network. The acquisition device layer is the bottom layer of the electricity information collection system, which is responsible for collecting user electricity information. This layer can be divided into the terminal sub-layer and metering device sub-layer.

3.3.8 Smart grid sensor network information processing and integrated management platform

Many smart grid applications are developed based on WSN, which support and establish a unified, service-oriented sensor information sharing and application service system, realizing integrated data resource organization, information sharing, data encryption, and high-performance collaborative analysis for power grids.

By establishing a unified, service-oriented smart grid sensor network application system integrated with an information sharing platform, the smart grid sensor network information processing and integrated management platform realizes integrated data organization and management for multi-source, multi-type, and heterogeneous data collected by WSN devices in different scenarios. It achieves collaborative management, integration and sharing of transmission, transformation, and distribution network information as “one grid” by fusing smart grid sensor network information with existing power grid and geospatial data. At the same time, based on data sharing, the service
engine for graphic browsing and analysis is optimized to provide efficient platform visualization functions. The smart grid sensor network information processing and integrated management platform architecture is shown in Fig. 12.

4 Demonstration projects

4.1 Wuxi WSN application verification system

Based on the research content and application verification of the project, a wireless sensor network application verification system for the smart grid is constructed by Wuxi Power Supply Company of Jiangsu Electric Power Company. The verification system is located at the Wuxi New District. The WSN application demonstration system is shown in Fig. 13. The power system involved in the verification system consists of

(1) Three substations;
(2) Two ultra-high voltage and high-voltage transmission lines;
(3) Twenty 10 kV transmission lines, of which the overall length is 97.534 km, including 29.259 km underground cables and 68.275 km overhead-lines;
(4) One 10 kV power distribution station (switching station);
(5) Thirty-one 10 kV substations (community public distribution station); and
(6) Twelve ring cabinets;
(7) Eight box transformers.

The system covers 148 high-voltage (10 kV) users, 19,123 low-voltage residential customers, and 2,454 low-voltage non-resident customers. The application
Fig. 12 Architecture of smart grid sensor network information processing and integrated management platform. GIS represents geographic information system.

demonstration system covers power transmission, transformation, distribution, and consumption[35].

The WSN demonstration project for power system has achieved remarkable results.

In the transmission system, real-time monitoring of line operation status and pole tower protection have been realized, and the protection of transmission lines, pole towers, and equipment have been enhanced, through the implementation of the online monitoring system for transmission lines. Improving the quality of line inspections can greatly reduce the theft rate of transformers, transmission lines, and towers. Meanwhile, the rapid line and equipment maintenance can be achieved through the fault warning function to ensure the safe operation of the power grid.

In the substations, the substation information management platform and the electrical equipment online state monitoring system realize the comprehensive analysis of a variety of sensor data and the power grid baseline data, providing a friendly standard data interface for production and management. The data and information services provided by the systems are helpful to fully tap the value of power system data, provide guarantee for the safe production and operation of enterprises, reduce internal management cost, and improve comprehensive profit.

In the power distribution system, the wireless sensor network technology brings the intelligent inspection of the power distribution. Deploying a smart sensor network can realize online monitoring of transmission lines and electrical equipment, achieve real-time monitoring of key parameters of the power grid and fault warning, and
improve power grid safety monitoring and emergency response capabilities. Environmental information and status monitoring information are collected through sensors. The in-depth and automated analysis and decision-making of inspection data can be conducted to help guide inspection work, improve defect management capabilities, realize early warning of defects and faults, and reduce accident losses caused by hidden dangers and defects of the equipment.

In the power consumption, through the construction of a highly reliable intelligent power information collection system based on the IoT sensor networks, the standardization and digitization of marketing, meter reading, and pricing can be promoted. The system provides a support platform that can quickly respond to market changes and customer demands, and implement marketing business strategies to achieve time-of-use electricity prices, multistep electricity prices, and comprehensive charge control. It plays an important role in improving the quality of power grid services.

4.2 Qingdao 5G smart grid application demonstration system

Power Grid of Qingdao is the largest sub-net of Shandong Power Grid. In August 2019, the application demonstration of the 5th Generation (5G) network for smart grid was constructed by Qingdao Power Supply Company of Shandong Electric Power Company which covers Guzhenkou, Jinjialing, Olympic Sailing Center, and Qingdao Dispatching Center. The demonstration
project is the largest 5G testing network for smart grid in China which includes 29 nodes (25 Acer stations, 4 indoor stations), 2 Multi-access Edge Computings (MECs), and 2 hard slice 5G networks. The 5G demonstration network for smart grid in Qingdao is shown in Fig. 14.

The 5G demonstration network realized four main functions:

- **Intelligent distributed distribution.** With the intelligent terminals (Smart Terminal Unit (STU)) installed at the feeder switch, fault and control information can be exchanged with each other through 5G network without relying on the master station, which can shorten the outage time of non fault section to seconds. The schematic diagram of the smart terminals exchanging fault information through 5G network is shown in Fig. 15.

- **Power grid perception and monitoring.** The state information of power station and power towers can be collected and sent back with the help of high bandwidth of 5G network. By Unmanned Aerial Vehicle (UAV) and mobile robot, 4K video of power grid transmission lines and power station can be collected. Through 5G network, the collected 4K video can be sent to MEC via carrying network and be processed with Artificial Intelligence (AI) within the garden. The schematic diagram of power grid and power station monitoring based on 5G MEC is shown in Fig. 16.

- **Intelligent power supply of 5G station.** Considering the high energy consumption of 5G station,
the energy is stored in the low power consumption period, and the stored energy is used to supply 5G station during the peak period of power consumption. Thus it can balance the overall load of the power grid during the peak and low power consumption periods. By this way, single base station will save 15%–18% electricity cost.

- Safety isolation capability verification. According to “the overall scheme requirements of power monitoring system security protection”, combining with the model of smart grid service, 5G slice experience and safety isolation capability is tested for the terminal, base station, transmission network, core network, edge computing, and slices management from end to end.

4.3 Beijing smart grid innovation demonstration project

In Lianxiangyuan Community, Beijing, by laying fiber-optic composite low-voltage cables from the power distribution room to the building to reach the meter and residence, the power utility solves the last mile problem and achieves synchronization of energy and information. Combined with passive optical network technology, the optical equipment Optical Line Terminal (OLT) can be installed in the power distribution room, while fiber optic collector and equipment Optical Network Unit (ONU) are placed in the residential meter room and the residential home, respectively. An open public information service platform can be achieved by above equipment implementation, which not only meets the power network data collection and other different electrical needs, but also can carry a series of value-added services such as property management, telemedicine, and security monitoring.

The Beijing Smart Grid Innovation Demonstration Project also selected some residents in Beijing Zhonghong Pixel Community to participate in the interaction between smart appliances and electric power. Customers use smart devices, such as smart gateways, smart sockets, infrared remote controls, etc. to conduct the intelligent control of home electrical appliances by mobile phones, realizing the interaction between users and the power grid. By carrying out technological research, system development, engineering application, and policy publicity, active residential load control can be established and the two-way interactive ability of intelligent power consumption can be improved comprehensively.

In smart home system, the smart home gateway (home energy router) is used as the core device to connect the smart home service platform upwards and interact with smart devices such as air conditioner, water heater, light, curtain, and socket downwards. The client software is used to issue device control instructions and transmit them to the smart home energy service platform via the internet; the platform finds the corresponding home gateway based on the user information and dispatch control instructions. After the gateway receives the instructions, it translates them into smart home communication protocol and sends them to the smart appliances. Meanwhile, it receives the data from the appliances and uploads them to the service platform. Finally, the control results are displayed on the client software. The schematic diagram of the household appliances energy efficiency analysis system is shown in Fig. 17.

The project builds a bridge between power utilities and power customers to help users understand the electricity
consumption. Based on existing smart buildings, smart communities, and smart energy service systems, it implements an energy efficiency analysis system which collects home power consumption data through smart home gateways and uploads them to a smart home service platform, performs data analysis, and finally feedbacks the results to user. Green energy application is shown in Fig. 18.

The project helps residential customers optimize the power usage, reduce electricity consumption during peak periods, utilize power consumption during valley periods, and minimize standby electricity consumption of appliances. It reduces the peak-valley difference of household electricity consumption by about 10%.

The widespread application of distributed energy resource can achieve regional green energy access. Combined with household peak shifting to fill the valley, it will greatly save the investment in power system infrastructure construction. It is expected to save 20%–30% of construction investment[35].

5 Conclusion

In this paper, the core WSN technologies used in power system and the demonstration systems are introduced. The projects can provide valuable guidance to the construction of ubiquitous sensing network that covers all aspects of power industry, including production, management, marketing, and service. On the one hand, the ubiquitous perception of the WSN has achieved the coverage of more nodes, which can significantly improve the comprehensive perception, data collection, and service interaction capabilities of power grid operation, services, and management; on the other hand, the construction of the WSN for power system and the development of sensors, terminals, and systems for the massive deployment provide a convenient means for data collection, greatly reducing the cost to sense various types of data. With the continuous growth of the power WSN network scale and the increase amount of data
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