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Deep Application of Communication Technology in the SMART GRID

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Abstract. Nowadays, the global energy supply is insufficient and environmental problems are becoming increasingly serious. The traditional power grid definitely needs to be transformed into an intelligent grid, which is an inevitable trend. This article today will clearly explain the three-layer communication architecture of the intelligent grid: The topmost wide area network is the backbone, which must ensure that measurements and controls over a large area can respond within milliseconds; the intermediate neighborhood network is responsible for the "last mile" from substations to users, and it needs to efficiently aggregate the data from a large number of terminals; the bottommost home or industrial local area network (LAN) is used for precise energy management for users. Based on this framework, the article also delves deeply into several key technologies - such as 5G network slicing, narrowband IoT, and long-range radio - explaining clearly how 5G's ultra-reliable and low-latency communication is practical in distribution differential protection; and the low-power wide-area network technology, and its advantages in deploying in large-scale IoT scenarios. Then, by combining several practical application examples such as advanced measurement systems, automatic fault recovery in power distribution, and microgrid coordination, we also discussed the core problems currently faced: threats to network security and potential incompatibility between different devices. For these issues, solutions were provided as well, such as using blockchain for authentication and relying on machine learning to detect risks. Finally, we also looked into the future, stating the future development directions of 6G perception integration and native AI networks.

Keywords: smart grid, 5G network slicing, Internet of Things, cybersecurity, edge computing

1. Introduction

Traditional power systems are typically designed as unidirectional energy transmission systems, flowing from large power plants to end-users through transmission and distribution networks. However, with the increasing penetration rate of renewable energy and the integration of high-power dynamic loads such as electric vehicles, the topology and operation mode of the power grid are undergoing fundamental changes. The concept of smart grid has emerged, and its essence is the high integration of power flow and information flow. In the smart grid, communication technology serves as its "nervous system" - not only does it need to process the data from numerous smart meters, but

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it also has to complete relay protection and fault isolation within milliseconds. However, the current communication infrastructure is somewhat lagging: the bandwidth is insufficient, the latency is too high, and there are often conflicts and incompatibilities among different devices. Therefore, both the academic and industrial communities are working hard to research and develop the next-generation communication technologies to be applied in the power sector to address these issues.

The purpose of this article is to thoroughly explain how these technologies can address the pain points of the smart grid - such as how to make the grid more visible (observability), more controllable (controllability), and more resilient (resilience). It also provides a theoretical foundation for future research.

2. Hierarchical architecture of smart grid communication

Grid communication can transform power lines into "information channels" for two-way transmission, enabling the integration and sharing of power information and communication information [1,2]. With power communication technology, the efficiency of power signal transmission in smart grids is higher, ensuring normal operation and meeting the demands of various terminal devices for power signals [1]. It can be said that communication technology is the key to making the grid "intelligent" - smart grids rely on integrating information technology and communication technology to achieve intelligent operation and management of the grid. For example, upgrading and modifying the power communication network can enable remote monitoring of the grid, fault analysis, real-time monitoring, and control [3]. As the core technology of the grid information platform, power communication is the "accelerator" that drives the grid towards intelligence.

In simple terms, power communication is the key to making the power grid more information-based, automated, and intelligent. It is responsible for transmitting and processing information such as the operating status of the power system and control instructions, ensuring the safe operation of the power grid [2]. In the construction of the infrastructure and system architecture of the smart grid, power communication technology plays a core role: communication equipment is the "source" of information, the communication network is the "channel" of information, and communication technology directly determines whether information can be transmitted quickly and control instructions can be timely feedback in the smart grid [4]. The current power communication technology integrates various methods such as optical fiber, wireless, and power line communication, building a comprehensive information exchange network covering all aspects of power generation, transmission, distribution, and consumption, laying the foundation for real-time monitoring, fault diagnosis, and optimal scheduling of the smart grid [5].

The communication network of the smart grid is large and complex. It is generally divided into three main levels to manage data transmission. Let's talk about the first level:

2.1. Wide area network

The wide area network is the "backbone" of the smart grid, and it needs to connect power plants, substations and control centers. It needs to transmit key control instructions and high-frequency data sent by the wide area phasor measurement units, so it has extremely high requirements for bandwidth and reliability [3]. Currently, the wide area network mainly uses optical fiber communication, but in remote areas, satellite communication has also become an important supplementary method.

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The wide-area protection facilities are fully automated protection systems designed to handle sudden situations such as large-scale power transmission disruptions and congestion. Since they need to process urgent and unanticipated information, they must have extremely short response times in order to prevent widespread power outages. The wide-area control system has an automatic self-healing function, which is much more effective than the repair methods of local control centers, and its response speed is also faster than manual control. By integrating the automated self-healing system and the control center well, a flexible platform can be established for the wide-area control system. Through this platform, real-time stable control can be achieved and some faults can be prevented in advance.

The wide-area control facilities will utilize equipment such as high-voltage power transmission systems that are quick to react and controllable. They have higher requirements for data resolution and response time than ordinary monitoring, data response facilities, or energy management systems. For example, the response time required by wide-area protection and control facilities needs to be within the range of milliseconds to seconds, and the reliability of the communication system should reach around 99% or even higher. Wide-area measurement facilities are used to provide real-time data. They need to transmit the measurement data from intelligent measurement devices and also record the status of power grid equipment. This part also requires millisecond-level response time and extremely high reliability.

Overall, wide-area networks have functions such as wide-area control, measurement, and security protection. They require a large amount of high-speed data transmission, as well as fast response time and high reliability [6].

2.2. Neighborhood network

The network in this area mainly serves as a bridge connecting smart meters, data concentrators, and the control center over the last section from the substation to the user's home [1]. At this level, the main issue to be addressed is the excessive number and density of equipment, along with the particularly complex on-site environment. Wireless mesh networks and power line communication are commonly used technologies at this level. The domain network mainly realizes the distribution part of the power grid, including modules such as intelligent measurement, demand response, distributed automation, advanced payment, transmission, firmware upgrade, configuration update, interruption supply, and reconstruction management. It involves the processing and application of a large amount of data, with a large amount of data transmitted from user measurement terminals to data concentrators in its network. The intelligent measurement system in the regional network enables communication between the instruments and the control center, which not only ensures more accurate meter reading but also reduces operational costs. Depending on the type of service, the network requirements for measurement and reading devices are divided into several categories: measurement and reading on demand, reading at fixed intervals, and batch transmission reading. The response time ranges from a few seconds to several minutes, and even several hours.

Price-related application devices broadcast the price information of measurement devices and terminals. The general data volume is approximately 100 bytes, and the data delay should be less than 1 minute.

For prepaid services, the system will open an account for the user, who can deposit money in advance. The equipment control center can send corresponding reminder messages to the user based on the data in the account and can disconnect or reconnect the connection. The data volume is approximately 50–150 bytes, and the data delay should be less than 30 seconds.

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Distributed automation provides real-time operation information, automatic control, and data communication for information management functions for the power grid structure, used for monitoring and controlling the power grid. The data volume is between 25 and 1000 bytes, the data delay should be less than 4 to 5 seconds, and the reliability requirements are particularly high, generally above 99.5%.

Power outage and power restoration management can promptly detect where the network or equipment is disconnected and then quickly take measures to restore the network connection. The data volume is generally 25 bytes, and the data delay should be less than 20 seconds.

The data volume of demand response devices is approximately 100 bytes, and the data delay should be less than 1 minute.

The data volume of firmware upgrade and software update functions is approximately 400,000 to 2,000,000 bytes, and the data delay can be relaxed to several days.. In summary, the communication technology used in the neighborhood network should have a high transmission rate and a large coverage area [6].

2.3. Home/industrial LAN

The home/industrial LAN is located on the user side and is responsible for connecting smart meters, smart home appliances, electric vehicle charging stations, and rooftop photovoltaic inverters. With the popularization of demand side response, home/industrial LANs are no longer just data collection points, but also end control nodes for energy management. Wi Fi and Bluetooth are the dominant technologies at this level. A home local area network is a network architecture that involves home automation and building automation, and can transmit electronic measurement data or related information between devices and controllers. This part does not require high-speed data transmission and has a small coverage area.

3. In-depth analysis of key communication technologies

3.1. 5G and its network slicing technology

With the continuous advancement of smart grid construction, it has put forward diversified demands for communication technology, such as high-speed transmission, low latency response, high reliability guarantee, and large-scale equipment access [7]. 5G technology is considered a game-changer for smart grids, especially for distribution network automation. Compared with 4G, 5G has three core application scenarios: enhanced mobile broadband, massive IoT connections, and ultra-high reliability and low-latency communication.

The application of ultra-high reliability and low-latency communication in differential protection: Differential protection in the distribution network requires an end-to-end communication delay of less than 10 milliseconds and a reliability of 99.999%. The characteristics of high reliability and low latency of 5G can exactly meet this requirement, so there is no need to spend a lot of money laying fiber optics, and wireless communication can be used directly.

Network slicing: This is the key to enabling the power grid to utilize 5G capabilities. Through network slicing, operators can virtualize several independent logical networks on the same set of physical equipment. For example, priority can be given to allocating a slice with high priority and low latency to precise load control, and a slice with small bandwidth and the ability to connect many devices can be allocated for smart electricity meters for reading. This way of isolating resources has greatly improved the safety and service quality of power grid operation [7]. In the Jeju Island smart

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grid demonstration project, engineers created three independent 5G network slices, one ultra-high reliability low latency communication slice for connecting the monitoring and control system of the wind farm to ensure real-time control of wind turbine attitude; A massive machine class communication slice is used to connect tens of thousands of smart meters and sensors on the island; An enhanced mobile broadband slice is used for maintenance personnel's augmented reality remote assistance and high-definition video inspection. This system achieves precise satisfaction of different business needs and is a typical practice of the network slicing concept.

3.2. Low-power wide-area network

A low-power wide area network is a long-distance, low-power wireless communication network. Due to its wide network coverage and low terminal power consumption, it is very suitable for large-scale deployment of IoT applications. Compared to traditional Bluetooth and WiFi, Wireless connection technologies such as Zifeng and low-power wide area network technology have longer transmission distances; Compared to cellular technology, their power consumption is lower [8].

3.2.1. Long-distance radio

Long-range radio is a proprietary physical layer technology of Shengte Technology Company, which has not yet been publicly disclosed. It mainly uses narrowband spread spectrum technology, with a sensitivity of up to -148 decibel milliwatts and a frequency below 1 GHz, laying the foundation for the long-range and low-power performance of later long-range radio technologies [9,10]. Long-distance radio is a wireless technology based on the frequency band below 1 GHz, which makes it easier to communicate over long distances with lower power consumption. Currently, it is mainly used in fields such as the Internet of Things, device-to-device, and smart cities.

3.2.2. Power line carrier communication technology

Power line carrier communication, also known as PLC technology, has made a very ingenious improvement - it directly uses existing wires as the transmission channels instead of laying separate communication lines. This is cost-effective, has a wide coverage area, and has particularly obvious advantages. When building smart grids, this technology has been used very maturely. For example, in common scenarios such as automatic data collection by smart meters and remote centralized meter reading, it helps a lot and effectively promotes the upgrading of the power information collection system towards an intelligent direction.

However, PLC technology still has some shortcomings in terms of transmission speed and anti-interference ability. Its transmission speed is relatively slow, and it is also easily affected by interference such as wire noise. Therefore, when actually using it, some targeted optimizations need to be made to improve its transmission effect and stability [11].

3.2.3. Narrowband Internet of Things

Narrowband IoT is a licensed spectrum cellular communication technology, which is a new generation of cellular IoT technology defined by the Third Generation Partnership Program for low-power wide area networks. Narrowband IoT operators can directly reuse existing base station equipment and deploy it directly on global mobile communication networks and general mobile communication networks, greatly reducing deployment costs and achieving smooth upgrades [12,13].

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Low power consumption is one of the most critical features of narrowband IoT. Narrowband IoT terminals are in sleep mode 99% of the time and integrate multiple power-saving technologies. The standby time of narrowband IoT terminal modules can reach up to 10 years.

In the same frequency band, narrowband IoT has a gain of 20 dB greater than existing networks and a coverage capacity that is 100 times larger, even in basements, underground pipelines, and other places [8]. Next is the ability to support massive connections, with one sector of narrowband IoT capable of supporting 100000 connections.

Compared to traditional 3G/4G networks, narrowband IoT has a 50-100 times increase in uplink capacity, and a single base station cell with a bandwidth of 200 kHz can support 50000 users [14]. Compared with existing wireless technologies, narrowband IoT can increase the number of accesses by 50-100 times under the same base station, while optimizing massive storage and access control, making it suitable for scenarios with massive access

4. Typical applications of narrowband Internet of Things

With the further acceleration of urbanization, the construction of municipal public facilities has developed rapidly, and the increase in manhole covers is inevitable. However, many of the manhole covers outside the cities lack reliable real-time monitoring and management systems. Illegal incidents, such as manhole covers being moved or stolen, occur frequently. Currently, most cities rely on manual inspections, which are extremely inefficient.

Using narrowband Internet of Things to monitor and manage manhole covers is quite different. It can monitor the status of the manhole covers in real time. If a manhole cover is moved or damaged, an alarm will be triggered immediately, thus minimizing the harm and losses to the greatest extent.

The benefits of using narrowband Internet of Things technology to monitor manhole covers are numerous: it eliminates the need for manual inspections, automatically transmits all data to the monitoring center, and saves a lot of manpower and resources. In addition, it can accommodate ten times the user capacity of general group wireless services, fully meeting the needs of so many manhole covers in the city; the normal communication and backup currents are at the milliampere level, and the standby time of the narrowband Internet of Things terminal module can reach 10 years, greatly simplifying the manhole cover monitoring work and making it convenient for later maintenance [15].

5. Application scenarios driven by communication technology

5.1. Advanced measurement system

The advanced metering system is not merely an automatic meter reading system; it is also the foundation for two-way interaction. This system can support the formulation of real-time electricity prices and enable remote load control [5]. By collecting electricity usage data at high frequencies, power grid companies can establish detailed usage profiles for users. This way, they can optimize the grid's operation and provide users with energy-saving suggestions to help them save on electricity costs.

5.2. Distribution automation and fault self-healing

In traditional power distribution networks, dealing with faults requires manual inspection of the lines, which takes several hours.

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However, with 5G technology connecting intelligent pole-type switches and fault indicators, things are different. Once a fault occurs, this system can automatically identify the faulty area within just a few hundred milliseconds and isolate the fault through logical control. As a result, the power supply in non-fault areas can be restored promptly [7]. This secondary self-repair capability significantly reduces the average time of power outages for users.

Singapore's national power distribution network has been highly automated - if a cable fails, the sensors and intelligent switches installed in each distribution station will quickly transmit the fault information via fiber-optic Ethernet back to the control center. The system can automatically plan the path for restoring power supply within a few seconds, switch the load to other normally powered feeders, and restore power quickly. This system has reduced the average power outage time in Singapore to one of the lowest levels in the world, only about 0.3 minutes per year. Photovoltaic and wind power have intermittency and volatility. To maintain the frequency and voltage stability of microgrids, extremely high-frequency state synchronization is required between inverters, energy storage systems, and diesel generators. The communication network must support distributed control algorithms based on multi-agent systems to ensure plug-and-play and coordinated operation of various distributed power sources.

5.3. Advanced energy management with home/industrial LAN and emerging technologies

In 2021, a distribution automation project in a coastal city adopted a communication network architecture mainly based on fiber optic communication and supplemented by wireless communication. The project covers the main 10 kV distribution network in the urban area and deploys over 1000 distribution automation terminals. The system has achieved real-time monitoring of the distribution network, automatic fault location and isolation, network reconstruction, and other functions. After the implementation of the project, the power supply reliability rate of the distribution network in the region increased from 99.85% to 99.98%, and the average annual power outage time decreased from 13.14 hours to 1.75 hours. In 2023, the city constructed a power communication system specifically designed to serve the consumption of new energy. The system is based on the synchronous digital system fiber optic transmission network as the backbone, combined with the fourth-generation mobile communication technology wireless access network, to achieve real-time monitoring and control of more than 200 wind farms and photovoltaic power stations in the province. The system supports functions such as new energy power prediction and automatic power generation control, reducing the province's new energy abandonment rate from 12% to below 5%, and increasing the annual consumption of new energy by more than 3×109 kW·h [16].

6. Challenges and countermeasures

6.1. Cybersecurity threats

The deep integration of communication technology has expanded the attack surface of the power grid. The smart grid is facing unprecedented network security threats. Attackers of false data injection attacks manipulate the measurement data of smart meters or power management units, mislead the state estimation of the control center, and may lead to incorrect scheduling instructions or even large-scale power outages. Denial of service attacks block communication channels, causing the control center to lose its monitoring capability over substations [4]. The countermeasure is to introduce a distributed authentication mechanism based on blockchain to ensure the authenticity of

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data sources; Using machine learning algorithms such as deep autoencoders to detect traffic anomalies and identify false data attack features [4]. Implement strict physical layer key generation technology.

6.2. Standardization and interoperability

The devices in the smart grid are produced by different manufacturers and follow different standards, such as IEC 61850 and IEEE 2030, etc. Due to the lack of a unified interoperability standard, system integration becomes particularly troublesome.

The IEC 61850 standard was originally designed for substation automation, and now it has gradually expanded to areas such as distribution networks and distributed energy. Promoting the data exchange format based on the common information model is the key to solving the mutual connection between different systems [3].

7. Exploration of the application of artificial intelligence in electrical engineering and automation

At present, the development of artificial intelligence technology is extremely rapid, and its applications in the fields of electrical engineering and automation are also increasing. In this section, we will elaborate on the specific applications of artificial intelligence in smart grids, optimization of automatic control systems, equipment maintenance and fault diagnosis, energy management and optimization, as well as electrical engineering design and simulation. The purpose is to help you clearly understand the new opportunities that artificial intelligence brings to the field of electrical engineering.

Let's start with the applications of artificial intelligence in grid scheduling, fault prediction and diagnosis. Smart grids are an important development direction in electrical engineering, and to truly realize smart grids, artificial intelligence technology must be relied upon. In the area of grid scheduling, artificial intelligence can analyze a large amount of power data in real time, accurately predict electricity demand, and optimize the allocation and scheduling of power resources. As a result, the operational efficiency of the grid has increased significantly, and the risks of insufficient or excessive power supply have been greatly reduced.

At the same time, artificial intelligence can also help the grid perform fault prediction and diagnosis. By using deep learning on historical fault data, it can identify patterns of potential problems in the grid and give early warnings before faults occur, leaving sufficient time for maintenance personnel to handle the situation. This significantly reduces the impact of grid faults on normal power supply.

Let's talk about how to use artificial intelligence to optimize automatic control systems and make the control more accurate and efficient. In the past, traditional automatic control systems usually used fixed control methods and parameters, which were difficult to adapt to the complex and constantly changing operation of the power system. Now, with the use of artificial intelligence, new methods for optimizing automatic control systems have been provided.

Using machine learning algorithms, the automatic control system can continuously learn from operational data and improve control strategies on its own, making the control more accurate and efficient. In addition, artificial intelligence can also enable the control system to adapt to changes by itself and automatically adjust according to the current actual situation of the power system, ensuring that the power system can operate stably and safely [17].

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8. Conclusion

Communication technology is the key foundation for building a strong, smart, and green smart grid, helping traditional power systems gradually evolve into the Energy Internet; this paper systematically analyzes the smart grid's three-layer communication architecture, explaining the technical needs and matching solutions for each layer—wide area networks support core grid scheduling with high reliability and low latency, neighborhood networks collect terminal device data, and home/industrial local area networks enable flexible user-side interaction. 5G network slicing meets the grid's diverse business needs through logical isolation, while low-power wide-area network technologies like NB-IoT and LoRa provide low-cost, wide-range access for large-scale IoT devices, and together these two types of technologies support key scenarios such as distribution automation and microgrid coordination, greatly improving the grid's monitoring, control, and stability. However, their deep integration also brings challenges like false data injection attacks and inconsistent device standards, which can be solved by methods including blockchain authentication, machine learning anomaly detection, and common information model standardization; in the future, combining 6G sensing with AI-powered self-healing networks will be an important trend, and further research should focus on building secure, ubiquitous, and computing-network integrated communication systems to better support global carbon neutrality goals.

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