Research on the Application of Infrared Thermal Imaging and WAPI Fusion Communication in Power Inspection

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Abstract: As the demand for operational efficiency and information security in smart grids continues to grow, traditional power inspection methods are no longer sufficient to meet the high standards required by modern power systems. This paper proposes a design scheme for an intelligent inspection system that integrates infrared thermal imaging and WAPI (Wireless LAN Authentication and Privacy Infrastructure) communication technology, aiming to enhance the security and real-time performance of power equipment condition monitoring and data transmission. Through a systematic analysis of the fault detection principles of infrared thermal imaging and the communication security characteristics of the WAPI protocol, the study designed a system architecture comprising front-end data collection, edge processing, encrypted transmission, and back-end analysis, and explored its application potential in substations and transmission lines. The results indicate that the system can effectively identify equipment thermal defects, ensure data transmission security, and improve inspection efficiency. The low latency and high security of WAPI are particularly suitable for high-demand scenarios. The inspection system integrating infrared thermal imaging and WAPI communication provides an efficient, secure, and scalable solution for smart power maintenance.

Keywords: Infrared Thermal Imaging; WAPI Communication; Power Inspection; Smart Grid; Data Security; Fault Detection

1. Introduction

As smart grids and power automation continue to advance, power systems are facing increasingly stringent requirements for operational efficiency, real-time data, and information security. Traditional manual inspection methods, which are inefficient, have limited coverage, and pose safety risks, are no longer sufficient to meet the high standards of modern power systems. In this context, infrared thermography (IRT), as a non-contact, high-sensitivity method for detecting thermal anomalies, has seen increasing adoption in the monitoring of power equipment status and fault prediction. Extensive research has demonstrated that this technology can accurately identify various thermal defects, including poor electrical contacts, line overloads, and equipment aging, thereby enhancing fault detection efficiency [1]. Existing reviews have summarized the typical application scenarios and technical challenges of IRT in transmission lines, substations, and distribution systems, concluding that it plays a significant role in enhancing the intelligence level of patrol inspections [2]. Additionally, with the development of deep learning and computer vision, the automatic recognition and fault classification capabilities of infrared images have continuously improved, significantly enhancing the accuracy and stability of image diagnosis [3,4].

WAPI (Wireless LAN Authentication and Privacy Infrastructure), as China's domestically developed wireless local area network communication security protocol, has demonstrated excellent applicability in power systems. WAPI employs domestic cryptographic algorithms (such as SM4), dynamic key negotiation mechanisms, and a two-way authentication system, effectively addressing common network attacks, data tampering, and unauthorized access issues [5]. Existing studies have deployed the WAPI communication architecture in substations, verifying its performance advantages in terminal mobile access, stable data transmission, and roaming handover, particularly suitable for power inspection scenarios with high network security requirements [6]. Some pilot projects have even applied WAPI to intelligent inspection robots in 500 kV substations, achieving encrypted transmission and real-time synchronization of inspection data, effectively improving the overall communication security level of the system [5]. Additionally, recent research has combined 5G with the WAPI protocol to explore multi-hop transmission optimization and energy consumption control issues in complex power scenarios, providing a theoretical foundation for its engineering applications [7].

Based on the above analysis, this paper proposes a design scheme for a power inspection system integrating infrared thermal imaging and WAPI communication technology, aiming to establish an intelligent inspection framework with the capabilities of "efficient thermal image acquisition—edge preprocessing—encrypted wireless transmission—remote secure reception." The research objectives of this paper primarily include: systematically reviewing the key principles and development trends of infrared thermal imaging and WAPI technology in power systems; proposing a structural model and functional module division for an integrated inspection system; and exploring the application potential and optimization directions of this system in typical scenarios such as substations and high-voltage transmission lines. The innovation of this paper lies in deeply integrating imaging recognition and secure communication, filling the current gap in communication security for infrared inspection systems, and providing new ideas and technical support for constructing a secure, efficient, and scalable intelligent power operation and maintenance platform.

2. Principles and Applications of Infrared Thermography Technology in Power Line Inspection

2.1 Overview of Infrared Thermography Principles

IRT is a non-contact temperature measurement and fault detection technology based on the principle of infrared radiation. All objects with temperatures above absolute zero emit infrared radiation in different wavelengths. Thermal imaging equipment detects this infrared radiation and converts it into thermal images, thereby visualizing the temperature distribution of the target. This technology is particularly suitable for online monitoring and fault diagnosis of high-voltage power equipment, enabling the acquisition of surface temperature information without interrupting normal operation and facilitating rapid identification of potential hotspots [1].

Thermal imaging systems typically include infrared detectors, optical systems, signal processing modules, and image processing software. In power inspection applications, equipment such as transformers, circuit breakers, surge arresters, busbars, and connectors are typical inspection targets. Through infrared images, abnormal phenomena such as poor contact, overloading, aging, or localized heating can be clearly identified [2].

2.2 Typical Applications of Infrared Thermal Imaging in Power Systems

In the power industry, infrared thermal imaging technology has been widely applied in scenarios such as transmission and transformation equipment, distribution systems, photovoltaic power stations, and wind farms.

(1) Substation Equipment Inspection: Infrared thermal imagers can identify localized heating caused by loose connections or aged insulation, particularly common at cable joints, circuit breakers, and transformer leads. Some power companies have incorporated this technology into their regular inspection processes, enhancing equipment early warning capabilities [8].

(2) Transmission line inspection: In high-voltage transmission lines, conductor connection points and surge arresters are prone to overheating hazards after prolonged operation. Using drones equipped with infrared imaging systems enables rapid large-scale, long-distance inspections, reducing labor costs and improving inspection efficiency.

(3) Photovoltaic module inspection: In photovoltaic power plants, issues such as micro-cracks, hot spots, and junction box failures in modules can be quickly identified using infrared imaging. Research shows that hotspot effects can be detected at an extremely early stage through thermal imaging, effectively preventing efficiency declines and safety hazards [3].

(4) Cable and low-voltage distribution box inspection: Cable overloading or short circuits often cause overheating. Infrared detection, as an

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accurate and efficient supplementary method, is replacing traditional manual box inspections.

2.3 Advantages of Infrared Thermal Imaging Technology

Infrared thermal imaging technology has rapidly expanded its applications in the power industry due to its multiple advantages:

• Non-contact and live-line detection capabilities: Inspections can be conducted while equipment is in operation, ensuring operator safety and minimizing the impact of maintenance on the power supply system;

• Efficient visualization: Real-time output of intuitive images helps maintenance personnel quickly identify abnormal locations;

• High potential for integration with AI: By integrating with image recognition and deep learning algorithms (such as YOLOv5 and CNN), it can achieve automatic defect identification and intelligent classification, improving the efficiency of large-scale data processing [9].

In addition, infrared thermal images are intuitive and easy to understand for front-line workers, facilitating rapid on-site judgment and helping to form standardized intelligent inspection processes.

2.4 Technical Challenges and Development Trends

Although infrared thermal imaging technology shows great potential in power inspection, it still faces some challenges:

• Environmental interference: External environmental factors (such as wind speed, sunlight intensity, and humidity) can affect image clarity and temperature measurement accuracy. Research suggests conducting measurements in the early morning or on cloudy days and combining multispectral imaging to improve stability [10].

• High Dependence on Image Processing: Traditional infrared images have low contrast and unclear target edges, necessitating the use of image enhancement and deep learning models for identification and classification.

• Equipment Cost Issues: High-resolution thermal imagers are expensive, limiting their adoption in small and medium-sized enterprises. There is an urgent need for solutions that balance cost and performance.

In the future, infrared thermal imaging will continue to integrate deeply with AI, IoT, 5G, and other technologies to achieve intelligent inspections, real-time data uploads, and automatic diagnostics. By integrating thermal imaging data with equipment history.

3. Adaptability Analysis of WAPI Communication Technology in Power Systems

3.1 Introduction to the WAPI Protocol

WAPI is a domestically developed wireless security communication protocol defined by the national standard GB 15629.11 2003, aimed at addressing the shortcomings of WEP and traditional Wi-Fi security mechanisms. The protocol consists of two main sub-frameworks: WAI (Authentication Infrastructure) and WPI (Privacy Infrastructure). WAI is responsible for device authentication and key negotiation processes, while WPI implements data encryption, integrity protection, and replay attack prevention. This security system employs SM4 symmetric encryption and ECC elliptic curve signature technology to establish mutual trust among certificates for terminals (STA), access points (AP), and authentication servers (AS), as well as dynamic session key management. Through mutual authentication, it ensures the authenticity of both communication parties [11].

3.2 Communication Requirements for Power Inspection

In modern power system inspections, especially when using unmanned inspection robots, terminal temperature measurement devices, smart cameras, and other mobile terminals, the communication system must meet the following key requirements:

• Real-time: Data such as images and heat maps must be transmitted in real time with low latency to enable rapid response to abnormal events.

• Security: Inspection data is sensitive and confidential information, so confidentiality and integrity must be ensured during transmission;

• Stability: Communication coverage must achieve seamless coverage both inside and outside facilities, rapid roaming handover, and consistent stability;

• Multi-terminal integration: The system must support simultaneous access by multiple terminal devices (robots, tablets, sensors) and reliably handle data transmission tasks.

Traditional Wi-Fi has limitations in these areas, such as prolonged roaming handover, poor security due to open authentication, and chaotic key management, making it difficult to meet the dual requirements of security and real-time performance for power inspection operations [12].

3.3 Comparison between WAPI and Traditional Wi-Fi (WPA2/WPA3)

As a critical national infrastructure, the power system has significantly higher cybersecurity requirements for its communication networks compared to general commercial environments. While Wi-Fi technology is widely adopted in substations and patrol terminals, traditional Wi-Fi (especially the WPA2 protocol) is increasingly unable to meet the actual needs of the power industry in terms of encryption mechanisms, identity authentication, and interference resistance as wireless attack methods become more sophisticated. In contrast, the WAPI protocol, with its domestically developed and controllable encryption mechanisms, national cryptographic standards, and bidirectional authentication design, demonstrates superior performance in communication security and trust control, as shown in Table 1.

Table 1. Comparison of Key Technical Parameters between WAPI and Traditional Wi-Fi Protocols

Comparison Dimensions	WAPI Protocol	WPA2 / WPA3 Protocol (IEEE 802.11i)
Identity authentication mechanism	Uses ECC digital certificates to achieve two-way authentication between STA, AP, and authentication server	WPA2 mostly uses PSK (pre-shared key) for one-way authentication; WPA3 introduces SAE and EAP-TLS
Encryption algorithms	National encryption SM4 encryption algorithm	Supports block chain encryption and message integrity verification AES-CCMP (WPA2), GCMP-256 + PMF (WPA3)
Key negotiation method	Dynamic key negotiation based on asymmetric encryption ECC, supporting periodic automatic key replacement	Static key (PSK) or EAP dynamic negotiation, with higher complexity
Anti-attack capability	Capable of resisting replay attacks, man-in-the-middle attacks, and spoofing attacks	WPA3 has many improvements over WPA2, but poor compatibility with older devices
Roaming Switching Performance	Supports AP fast switching protocol, with an internal communication delay of ≤ 20ms, suitable for frequent roaming environments	Roaming latency depends on device and protocol support, with WPA2 performing worse than WPA3
Network management mechanism	Unified key control and centralized management of authentication servers to enhance security policy consistency	WPA2/WPA3 multi dependent device settings, poor consistency of distributed policies
Compliance and controllability	Meet national level protection and critical infrastructure security compliance requirements, with controllable and auditable algorithms	International general agreement, insufficient compatibility with national secrets, limited compliance
Deployment compatibility	Adapt to domestic chips and embedded terminal devices, compatible with deployment requirements in the power industry	International agreements generally have strong support, but domestic platforms need to be compatible with the adaptation layer

WAPI offers advantages such as strong identity authentication, security and controllability, and fast switching in critical infrastructure scenarios (such as substation inspection systems), making it a suitable protocol choice for power inspection.

3.4 Analysis of the Applicability of WAPI in Power Systems

3.4.1 Engineering case support

Guangxi Power Grid Company deployed the WAPI network for the first time at the 220 kV Langdong substation, enabling secure wireless access between the internal network and inspection terminals, and supporting business scenarios such as inspection robots, smart cameras, and environmental monitoring. During the six-month trial operation period, robot video and sensor data were transmitted stably, eliminating the security risks associated with traditional Wi-Fi. Additionally, State Grid Jiangsu Electric Power Company completed WAPI network coverage across the entire station at the Suzhou Guoxiang Substation and conducted a 100-day trial operation, significantly improving terminal access flexibility and communication stability, with an average latency below 100ms, fully supporting intelligent inspection and other business operations. Ningxia Ultra-High Voltage Company deployed a WAPI network at the 750 kV Shahu Substation, enabling the secure access of patrol robots and monitoring terminals to the internal network, significantly improving the deployment accuracy of monitoring equipment and data transmission efficiency.

3.4.2 Meeting the communication requirements of the patrol system

The protocol design and deployment of WAPI demonstrate that it fully meets the real-time, security, and stability requirements of the power patrol system:

• Low latency: After deployment, the real-time feedback capability of terminal video and thermal map data has been significantly enhanced, with an average latency maintained below 100 ms;

• Global coverage: By forming a wireless coverage network using multiple access points (APs) and outdoor bridges, seamless communication is achieved in substation environments with no dead zones;

• Security and stability: Bidirectional certificate authentication and a key management system effectively defend against security threats such as man-in-the-middle attacks, spoofed APs, and data tampering;

• Business integration capability: It can simultaneously support high-definition video, infrared images, sensor data, and mobile office terminals, with high concurrent access capacity.

3.5 Summary of Applicability

The WAPI protocol is based on domestically developed security standards, combining SM4 encryption and ECC authentication mechanisms to provide communication security that meets the requirements of the State Grid's graded protection and information security regulations. Its dynamic key negotiation design, low-latency roaming support, and wide-area wireless deployment capabilities give it significant advantages in business scenarios such as unmanned inspections, remote monitoring, real-time infrared thermal imaging transmission, and security alerts. For power inspection scenarios with extremely high communication security requirements, such as substations, transmission towers, and distribution rooms, the applicability and application value of WAPI are undeniable. Additionally, its localized controllability facilitates rapid promotion in key domestic infrastructure.

4. Design Concept for Inspection Systems Integrating Infrared Thermal Imaging and WAPI Communication

4.1 Overall Architecture Concept

This system adopts an overall architecture consisting of “front-end infrared data acquisition devices + edge processing modules + WAPI wireless transmission + back-end control center,” as shown in Figure 1.

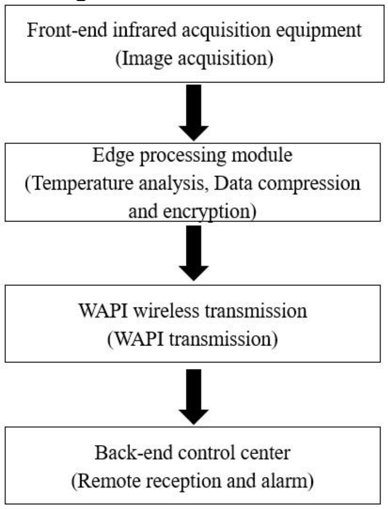

Figure 1. Structural Diagram of the Power Inspection System Integrating Infrared Thermal Imaging and WAPI Communication

• Front-end infrared data acquisition devices: Deployed on patrol robots or fixed structures, these devices use high-resolution infrared thermal imaging cameras to collect real-time thermal images of power equipment, detecting abnormal conditions such as hot spots, poor electrical contacts, and aging.

• Edge processing module: Located near the collection end, it uses an embedded computing platform (such as a single-board computer or FPGA) to preprocess infrared images, including image denoising, feature extraction, preliminary temperature measurement, and anomaly identification, while compressing and encrypting the images.

• WAPI Wireless Transmission: Utilizing the WAPI protocol architecture, encrypted transmission of processed thermal images and analysis results to the backend control center via a wireless local area network security structure (including WAI and WPI) ensures data integrity, confidentiality, and identity authentication.

• Backend Control Center: Deployed at the dispatch center or backend server, it securely receives WAPI-transmitted data, stores inspection results, performs further analysis, visualizes the data, and integrates with the dispatch system to enable alarm notifications and decision support.

4.2 Functional Module Division

The efficient operation of the infrared thermal imaging and WAPI communication system relies on the coordinated cooperation of multiple functional modules. The system is divided according to the standard information chain model of collection-processing-transmission-reception to ensure the integrity and timeliness of data flow at each stage.

(1) Image Acquisition Module

The image acquisition module primarily consists of an infrared thermal imaging camera, which operates based on the principle of imaging using an object's infrared radiation characteristics. According to the Stefan-Boltzmann law:

$$E = \varepsilon \sigma T^4 \quad (1)$$

Among them: E is the radiant energy per unit area (W/m²); ε is the emissivity of the target surface (generally 0.85~0.98); σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \mathrm{W/m^2 \cdot K^4}$); T is the absolute temperature of the target (K).

(2) Temperature Analysis Module

The temperature analysis module performs structured processing on thermal images, including target identification, image segmentation, temperature extraction, and region annotation. Hotspot analysis relies on regional temperature differences, which can be expressed as:

$$\Delta T = T_{\text{hot}} - T_{\text{ref}} \geq \delta \quad (2)$$

Where: T_{hot} is the temperature of the high-temperature target area in the heat map; T_{ref} is the reference temperature (which can be the average temperature of the surrounding area); δ is the temperature rise criterion (threshold, typically 5–10°C).

To prevent occasional noise from interfering with the results, the system uses a time series smoothing algorithm, namely:

$$T_i^{\text{avg}} = \frac{1}{N} \sum_{j=i-N+1}^{i} T_j \quad (3)$$

Where: T_i^{avg} is the average temperature of the current frame; N is the sliding window size.

In addition, a temperature gradient factor can be introduced to reflect the degree of thermal anomaly:

$$G = \frac{T_{i+1} - T_i}{d} \quad (4)$$

Where d is the pixel spatial distance, which is used to determine the heat source diffusion rate and helps assess the severity of the hazard.

(3) Data compression and encryption module

Infrared thermal image data is large in size and needs to be compressed before transmission. The compression ratio formula for JPEG2000 or H.265 encoding is

$$R = \frac{S_{\text{original}}}{S_{\text{compressed}}} \quad (5)$$

Among them: R is the compression ratio (typical value 10~30); S_{original} is the original image data size (KB); $S_{\text{compressed}}$ is the compressed image size (KB)

The security of compressed image transmission relies on the SMS4 encryption algorithm, which is a Chinese national commercial cryptographic algorithm supporting 128-bit block encryption, combined with hash verification to ensure data integrity.

For each frame of image data, let the pre-encryption information be M. The encryption process is as follows:

$$C = \mathrm{Enc}_k(M) \quad M = \mathrm{Dec}_k(C) \quad (6)$$

Where: Enc_k is the SMS4 encryption function; key k is 128 bits long; C is the ciphertext, and M is the plaintext.

Message integrity authentication is achieved through MAC (Message Authentication Code), defined as:

$$\mathrm{MAC} = \mathrm{HMAC}(k, M) \quad (7)$$

Among them, HMAC can be constructed using the SHA-256 algorithm.

(4) WAPI Wireless Transmission Module

The WAPI module supports wireless identity authentication and secure data transmission. The transmission process includes the following key stages:

• Authentication and key negotiation: Uses ECC asymmetric encryption algorithms for digital signature exchange;

• Data encapsulation: Encapsulates compressed and encrypted data packets into WAPI message structures, adding AKM and MIC fields;

• Channel switching and power control: Supports automatic switching between the 2.4GHz and 5GHz frequency bands to ensure transmission stability.

Data transmission performance can be approximately described by the following formula:

$$D = \frac{n \cdot s}{t} \quad (8)$$

Where: D is the transmission rate (KB/s); n is the number of frames; s is the size of a single compressed image frame (KB); t is the transmission time (seconds).

In typical scenarios, WAPI communication rates can reach 10 to 54 Mbps, meeting the requirements for reporting images from power equipment at a rate of once per second.

(5) Remote reception and alarm module

The back-end control platform deploys data reception and alarm judgment functions. This includes the following steps:

• Data decryption and verification: Decrypt data using a shared key and verify MAC value consistency.

• Image restoration and visualization analysis: Restore different pseudo-color standard heat maps according to device type.

• Alarm strategy triggering:

$$\text{If} \Delta T \geq \delta \Rightarrow \text{trigger}_{\text{alert}} \quad (9)$$

The system can be linked to the SCADA platform to generate fault reports and automatically upload them to the operation and maintenance platform. At the same time, it supports real-time alarm push notifications via the web front end or app.

4.3 Key Advantages of Integrated System Design

4.3.1 Real-time efficiency

Compared to traditional manual inspections, the system enables real-time data collection and transmission without the need for on-site personnel, covering high-risk, high-pressure, or hard-to-reach areas, significantly improving inspection efficiency. Drones or robots can automatically perform inspection tasks on a regular or irregular basis and promptly upload images to the backend, eliminating delays associated with manual inspections.

4.3.2 Security and control

The WAPI protocol ensures data transmission security over communication links through two-way certificate authentication, SM4 encryption, and dynamic key negotiation mechanisms, and complies with national security standards. Data is encrypted throughout the entire transmission process from the collection endpoint to the receiving center, preventing man-in-the-middle attacks, data forgery, and unauthorized access.

4.3.3 Strong scalability

The system features a modular design, enabling expansion to integrate intelligent image analysis platforms, scheduling systems, or asset management systems as needed. The backend control center can be integrated with AI algorithm platforms to automatically classify faults and provide maintenance strategy feedback, and connect with scheduling systems to issue remote commands and arrange tasks, achieving a closed-loop inspection process.

4.4 Typical Application Scenarios

4.4.1 Remote inspection system for substations

Substations are generally located on the outskirts of cities or in mountainous areas, where operating environment requirements are high. The system can use high-magnification infrared thermal imaging cameras to regularly collect thermal images of key equipment such as main transformers, circuit breakers, and knife switches. After real-time processing by edge devices, the images are uploaded via WAPI to achieve unmanned intelligent inspection. Through temperature gradient analysis:

$$G = \frac{T_{i+1} - T_i}{d} \quad (10)$$

It can assess abnormal hair heating, insulation aging, etc., and assist in the formulation of maintenance strategies.

4.4.2 Unmanned inspection of high-voltage transmission lines

Drones equipped with infrared thermal imaging cameras fly regularly to high-voltage line corridors to perform remote thermal monitoring of suspension connection points, insulators, and anti-aging components. During flight, the drones compress and encrypt images via edge computing modules, establish communication links through ground-based WAPI base stations, and transmit image and temperature data to the control center. The backend system analyzes historical thermal map trends to pinpoint abnormal temperature points with geographic coordinates, trigger alarm notifications, and automatically generate inspection reports. This scenario eliminates the need for complex terrain and high-risk manual inspections, enabling long-term unmanned safe inspections.

4.5 System Implementation Recommendations and Future Expansion Directions

To ensure the effectiveness of the system's implementation, the following implementation recommendations should be considered:

• Equipment selection and compatibility: Infrared thermal imagers should have sufficient temperature accuracy and spatial resolution, edge processing units should support high-performance compression and encryption capabilities, and WAPI access points should support fast roaming and multiple access terminals.

• Network Coverage Planning: Plan a reasonable WAPI network coverage density within substations or at the ends of transmission lines to ensure “no blind spots and low latency.”

• Key and Certificate Management System: Establish a comprehensive authentication server, certificate authority, and key update mechanism to ensure the stability and controllability of the identity and encryption system during long-term operation.

• Data Interfaces and System Integration: The backend center should provide standard APIs to seamlessly integrate with dispatch systems, asset management systems, and AI platforms, enabling data sharing and collaborative applications.

• Long-Term Maintenance and Upgrade Path: It is recommended to leverage edge computing to upgrade AI models, promote drone and robot inspection systems, and continuously monitor the development of WAPI and domestic communication equipment ecosystems to enhance system universality.

5. Conclusion

This study proposes a power inspection system that integrates infrared thermal imaging and WAPI communication technology. By combining non-contact thermal defect detection with state-of-the-art encryption algorithms for secure data transmission, the system successfully achieves efficient, real-time, and secure data collection and transmission. The system demonstrates significant advantages in scenarios such as substations and high-voltage transmission lines, enabling rapid identification of equipment faults and ensuring communication security. Additionally, its modular design supports future scalability. However, the system still faces certain limitations, such as infrared thermal imaging being highly susceptible to environmental interference, high-resolution equipment being costly, and WAPI network deployment requiring further optimization to reduce power consumption and costs. In the future, system performance can be further enhanced by introducing multispectral imaging, optimizing edge computing algorithms, and integrating 5G and AI technologies. Additionally, promoting the adoption of WAPI within the domestic equipment ecosystem will provide technical support for building a full lifecycle digital twin power maintenance platform.

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