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Review

The Evolving Technological Framework and Emerging Trends in Electrical Intelligence within Nuclear Power Facilities

Yao Sun [1], Zhijian Wang [1], Yao Huang [1], Jie Zhao [2,*], Bo Wang [2], Xuzhu Dong [2] and Chenhao Wang [2]

1 China Nuclear Power Engineering Co., Ltd., Beijing 100840, China; syao758811@163.com (Y.S.); xtzhaojie@163.com (Z.W.); fradi_ssu@163.com (Y.H.)
2 School of Electrical Engineering and Automation, Wuhan University, Wuhan 430072, China; whwdwb@whu.edu.cn (B.W.); dongxz@whu.edu.cn (X.D.); 2023282070175@whu.edu.cn (C.W.)
* Correspondence: jiez_whu@whu.edu.cn

Abstract: This paper thoroughly explores the feasibility of integrating a variety of intelligent electrical equipment and smart maintenance technologies within nuclear power plants to enhance the currently limited level of intelligence of these systems and better support operational and maintenance tasks. Initially, this paper outlines the demands and challenges of intelligent electrical systems in nuclear power plants, highlighting the current state of development of intelligent electrical systems, including new applications of artificial intelligence and big data technologies in power grid companies, such as intelligent defect recognition through image recognition, intelligence-assisted inspections, and intelligent production commands. This paper then provides a detailed introduction to the architecture of intelligent electrical equipment, encompassing the smart electrical equipment layer, the smart control system layer, and the cloud platform layer. It discusses the intelligentization of medium- and low-voltage electrical equipment, such as smart circuit breakers, smart switchgear, and low-voltage distribution systems, emphasizing the importance of intelligentization in improving the safety, reliability, and maintenance efficiency of medium- and low-voltage distribution equipment in nuclear power plants. Furthermore, this paper addresses issues in the intelligentization of nuclear power plant electrical systems, such as information silos, the inefficiency of traditional manual inspection processes, and the lack of comprehensive intelligent design and evaluation standards, proposing corresponding solutions. Additionally, this paper presents the trends in intelligent operation and maintenance technology and applications, including primary and secondary fusion technology, intelligent patrol system architecture, intelligent inspection based on non-destructive testing, and a comprehensive solution based on inspection robots. The application of these technologies aids in achieving automated inspection, real-time monitoring, and the intelligent diagnosis of electrical equipment in nuclear power plants. Finally, this paper proposes basic principles for the development of intelligent electrical systems in nuclear power plants, including intelligent architecture, the evolutionary path, and phased goals and key technologies. It emphasizes the gradual transition from automation to digitization and then to intelligentization and presents a specific implementation plan for the intelligentization of the electrical systems in nuclear power plants. This paper concludes with a summary of short-term and long-term goals for improving the performance of nuclear power plant electrical systems through intelligent technologies and prospects for the application of intelligent technologies in the operation and maintenance of nuclear power plants in the future.

Keywords: nuclear power plant; electrical system; intelligence; intelligent electrical equipment; intelligent inspection

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1. Introduction

Intelligence has emerged as a pivotal topic across diverse industries, and nuclear power, being a cornerstone for national security and economic growth, has responded promptly to national initiatives [1–3]. Endeavors have been directed towards advancements in digital nuclear power, industry databases, and the evolution of smart power plants. Nonetheless, in the realm of electrical intelligence in nuclear power plants, we are still navigating the initial stages of exploration. A comprehensive framework for intelligent operation and maintenance technologies in nuclear power plants is yet to be formulated, pivotal technologies for intelligent electrical operations and maintenance remain unsystematically identified, and in-depth research into preliminary solutions for key technological breakthroughs is still lacking [4–6].

Currently, both domestically and internationally, there exists practical experience in the application of electrical intelligence in industrial sectors, thermal power plants, and nuclear power plant design [7]. By drawing insights from our peers, we can enhance our comprehension and technological proficiency, formulate scientific research and development plans, and expedite the design process for intelligent electrical systems in new nuclear power R&D projects. In the nuclear power field, there has been a surge in intelligence-related work, with several institutions dedicated to the research and development of infrastructure platforms and information resources [8]. For instance, the real-time monitoring of primary systems and crucial equipment in operating units has been implemented, and equipment fault data models have been established leveraging deep learning to provide early warnings for potential defects, yielding notable outcomes [9]. Additionally, some units have pioneered research in equipment health management, encompassing the wireless network-based video monitoring of key equipment and remote inspections, thereby reducing the need for on-site inspections [10–12].

At present, intelligent applications are primarily localized, leaving room for enhancements in both depth and precision. Additional research is imperative to boost the effectiveness of these applications and foster their broader adoption. As digital modeling and intelligent applications evolve further, nuclear power plants' industrial systems and equipment control are poised to evolve from automation to comprehensive intelligent control [13].

The structure of this paper is as follows: Section 2 provides a detailed discussion on the intelligence requirements and challenges faced by the electrical systems of nuclear power plants, including the current state of intelligence levels and existing issues. Section 3 introduces smart electrical equipment and its application in nuclear power plants, covering the architecture of smart devices and the intelligentization of medium- and low-voltage electrical equipment. Section 4 explores the intelligent operation and maintenance technologies and application trends of the electrical systems in nuclear power plants, involving the transition from automation to digitization, and then to intelligent development. Section 5 presents the development trends, basic principles, intelligent architecture, and development planning of the intelligentization of the electrical systems in nuclear power plants. Finally, in Section 6, we summarize the entire paper and provide an outlook for the future, emphasizing the potential of intelligent technology in enhancing the operational efficiency and safety of nuclear power plants.

2. Nuclear Power Plant Electrical System Intelligence Demands and Challenges

2.1. Current Status of Electrical System Intelligence

1. The rapid progression of artificial intelligence and big data technologies is fostering novel applications in power grid companies. These include intelligent defect recognition leveraging image recognition, intelligence-assisted inspections, and intelligent production commands, all of which offer valuable insights for the intelligent operation and maintenance of nuclear power plant electrical systems [14]. Initial successes have been achieved in areas such as computer vision, natural language processing with knowledge graphs, intelligent voice and speech recognition, and data intelligence technologies. The swift development of AI technology is poised to become a pivotal force in the realm of intelligent electrical equipment operation and maintenance [15,16];

2. The research and application of intelligent equipment are currently in the nascent stages of exploration. There exists a solid foundation in the integrated design and manufacturing of conventional sensing components and equipment bodies, encompassing examples like transformer top-oil temperature monitoring and cable joint humidity monitoring [17]. However, the concept of comprehensive equipment integration design grounded in the self-awareness of states is still in its infancy, and research into sensing components and methods is in its early stages. While traditional designs for nuclear power plant construction have gained widespread adoption, there remains significant room for exploration in the standardization and modularization of equipment related to the manufacturing, operation, and maintenance professions [18];
3. By enhancing the intelligence level of distribution equipment, it gains the ability to precisely perceive its actual operational status. This enables users to detect equipment defects proactively, thereby significantly improving safety, reliability, and maintenance efficiency [19]. Given the stringent reliability requirements for medium- and low-voltage distribution equipment in nuclear power plants, the application of intelligent non-safety-grade distribution equipment holds immense significance in reducing the risk of equipment failures in these facilities [20];
4. Intelligent inspection technology enables the automatic transportation of inspection objects and real-time monitoring of detection data through predefined inspection methods. This facilitates the prompt resolution of issues [21]. Nuclear power plants can adopt a management model for intelligent inspection equipment, collecting data information on crucial equipment and facilities across varying environments, thus laying the groundwork for achieving their management goals [22];
5. The intelligent operation and maintenance of distribution systems leverage advanced management systems to enable the real-time monitoring of diverse distribution data [23]. Operation and maintenance companies can keep a watchful eye on distribution operational data and warning notifications via a web client, seamlessly managing and dispatching personnel using mobile app platforms. Furthermore, maintenance personnel can offer timely feedback to the company through multimedia channels on the app, thereby enhancing the efficiency of electrical system management, eliminating traditional manual maintenance blind spots, and significantly reducing personnel and maintenance costs [24–26].

2.2. Problems with the Intelligentization of Nuclear Power Plant Electrical Systems

1. The fragmented information repositories of nuclear power plant equipment constrain the degree of intelligence and impede the later-stage tracking, servicing, and design optimization of unit equipment [27];
2. The traditional manual inspection process at nuclear power plants suffers from low efficiency, inconsistent detection quality, incomplete data, and a lack of real-time monitoring and accessibility [28]. This necessitates the adoption of a more scientific, comprehensive, and real-time inspection methodology;
3. The absence of comprehensive intelligent design and evaluation standards for nuclear power plant electrical systems necessitates the development of reasonable designs and the establishment of robust evaluation criteria [29];
4. The lack of a top-level design for information security protection in nuclear power plant electrical systems demands the exploration and implementation of a comprehensive information security system [30];
5. The safety protection measures of the electrical systems in nuclear power plants need to be enhanced. The electrical systems of nuclear power plants lack effective safety strategies in "lateral isolation, vertical encryption, and comprehensive protection", and are facing issues such as insufficient anti-virus systems, weak host security, and the absence of data encryption and authentication mechanisms, necessitating targeted measures to enhance safety protection.

3. Intelligent Electrical Equipment and Its Application in Nuclear Power Plants

3.1. Architecture of Intelligent Electrical Equipment Technology

The architecture of smart electrical equipment comprises three distinct layers, namely the smart electrical equipment layer, the smart control system layer, and the cloud platform layer, as depicted in Figure 1 [31–33].

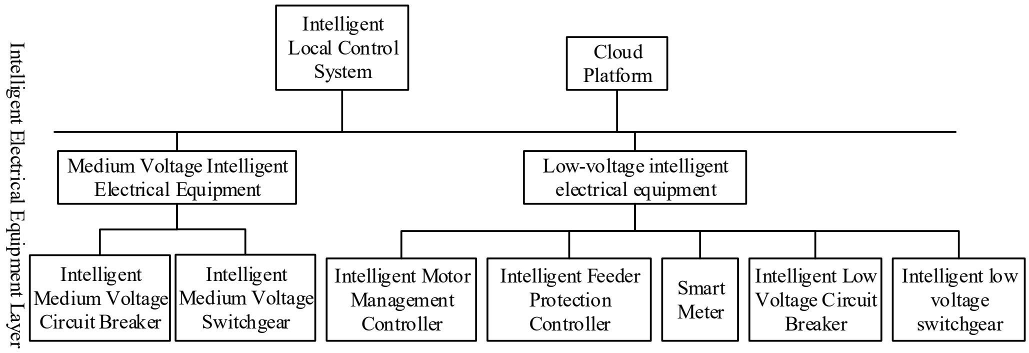

Figure 1. Intelligent electrical equipment system architecture.

3.2. Smartification of Medium- and Low-Voltage Electrical Equipment

1. Medium-voltage intelligent circuit breaker: Incorporating embedded temperature sensors, it gathers temperature data and facilitates the online intelligent monitoring of the opening/closing coils and energy storage motor. This expedited, visual understanding of the circuit breaker's health status enables the dynamic diagnosis of its health trends [34];
2. Medium-voltage smart switchgear: This system enables the continuous online monitoring of busbar, cable temperatures, and the coordination status between circuit breakers and switchgear [35]. It supports remote or local control of circuit breaker operations, monitors the remaining electrical life, and incorporates individual arc protection, integrated protection, and the online monitoring of leakage currents and discharge counts for surge arresters [36];
3. Low-voltage distribution system: Leveraging smart motor management controllers, it controls, protects, and monitors low-voltage motors. Smart feeder protection controllers oversee feeder circuit monitoring, protection, and alarms. Smart meters measure, display, and store incoming circuit electrical parameters [37];
4. Intelligent low-voltage circuit breaker: Embedded temperature sensors enable temperature collection and online monitoring of the circuit breaker, with a real-time local display, providing a quick, visual understanding of its health status [38–40];
5. Low-voltage intelligent switchgear: An integrated temperature control system within the cabinet continuously monitors the environment and temperatures of drawers and electrical equipment. It offers over-temperature warnings, the timely detection of potential fault points, and allows for drawer replacement without power interruption, enhancing operational continuity and reliability. Additionally, energy consumption data analysis aids in improving energy efficiency [41].

3.3. Intelligent Local Control System

An autonomous and intelligent localized control system is being formulated with the capability to:

1. Optimize energy efficiency: Through a visual platform, it analyzes energy usage based on various load types, metering zones, and operational modes, facilitating comprehension of the system's energy flow and pinpointing avenues for enhanced efficiency [42];
2. Facilitate operation and maintenance: By showcasing system diagrams, cabinet configurations, and communication network blueprints via a maintenance management in-

terface, it enables oversight of the electrical system's operational standing, equipment status and parameters, and communication statuses [43]. Smart monitoring mitigates the need for manual periodic inspections, thus lessening operational manpower and time expenditure, and offering pre-emptive warnings for equipment failures, enabling proactive maintenance and minimizing unscheduled downtimes [44];

3. Manage power quality: It conducts real-time surveillance of power quality parameters, governance apparatus, and electronic devices, capturing and documenting event occurrences and types, and generating comprehensive reports. This enables the remote execution of effective power management strategies [45];
4. Oversee electrical equipment: It compiles and displays the operational health status, vital equipment information, and operational metrics of electrical equipment. It also assesses the condition and aging of medium-voltage switchgear, medium-voltage circuit breakers, low-voltage distribution cabinets, and low-voltage circuit breakers [46–48].

3.4. Cloud Platform

Given the paramount importance of nuclear power data security, a dedicated cloud platform is employed to consolidate data gathered from smart devices. This platform serves as a repository and analysis hub, with core capabilities encompassing monitoring, optimization, management, and prediction. It conducts a comprehensive, intelligent analysis and evaluation of electrical systems and equipment, accurately assessing their current status and intelligently forecasting future trends. Furthermore, it calculates and assesses potential risks, thereby establishing a dynamic risk management and early warning system to ensure the safe and efficient operation of nuclear power facilities [49,50].

3.5. Electrical Main Equipment Intelligent Integration of Primary and Secondary Fusion

Primary and secondary fusion technology enhances the intelligence of electrical systems by integrating intelligent components of secondary equipment into primary electrical equipment, such as column switches, ring main units, and transformers. This integration enables state visualization, grid networking, and automation control, laying the foundation for the overall intelligence of the electrical system [51].

To facilitate automatic identification and plug-and-play capabilities in electrical system equipment, integrated devices adhere to standardized interfaces, communication protocols, and data models [52]. Analyzing and adhering to these standardized components allows for software-defined implementation, enabling plug-and-play functionality in fusion terminals, intelligent ring main units, and distribution transformers. This ultimately leads to the visualization of feeder areas [53–55].

Employing electronic transformers, as opposed to traditional electromagnetic transformers, eliminates errors during voltage and current signal transmission and processing to secondary equipment. This results in a significant improvement in the accuracy of protection, measurement, and metering devices, bolstering the performance of the electric measurement subsystem. This approach fulfills the technical requirements of primary and secondary fusion [56].

The key to primary and secondary fusion lies in standardized connections between primary and secondary components, enabling comprehensive state perception, functional alignment, and efficient operation and maintenance. This significantly enhances the operational reliability of the entire electrical system [57]. The key challenges we face include the following [58–62]:

1. Enhancing the coherence and compatibility of primary and secondary components in terms of both fundamental and intelligent functionalities;
2. Establishing standardized connection protocols for primary and secondary interfaces on the grid system level to guarantee the seamless replacement and plug-and-play compatibility of equipment from diverse manufacturers;

3. Boosting functional integration by incorporating capabilities like line loss management, fault distance determination, and single-phase grounding fault mitigation into primary and secondary systems, aligning with the automation demands of modern electrical systems;
4. Elevating the reliability of electronic transformer and sensor devices by thoroughly investigating and addressing issues such as electromagnetic interference and life cycle matching in secondary equipment.

4. Intelligent Operation and Maintenance Technology and Application Trends in Nuclear Power Plants

Drawing from the operational and maintenance challenges encountered in nuclear power plant electrical systems, we have referenced the recent trends towards intelligent electrical operation and maintenance technology as well as the practical experience gained from the operation and maintenance of intelligent substations [62].

4.1. Electrical Main Equipment Intelligent Integration of Primary and Secondary Fusion

By leveraging high-definition video surveillance, infrared thermal imaging, intelligent inspection robots, and other techniques, we automate the inspection process within the station, enabling the real-time display of inspection images and progress. Utilizing artificial intelligence algorithms for advanced image recognition and analysis, the inspection results are presented in various formats, including visible light images and infrared thermal imaging, allowing for customized report generation that meets industry standards, as depicted in Figure 2 [63,64].

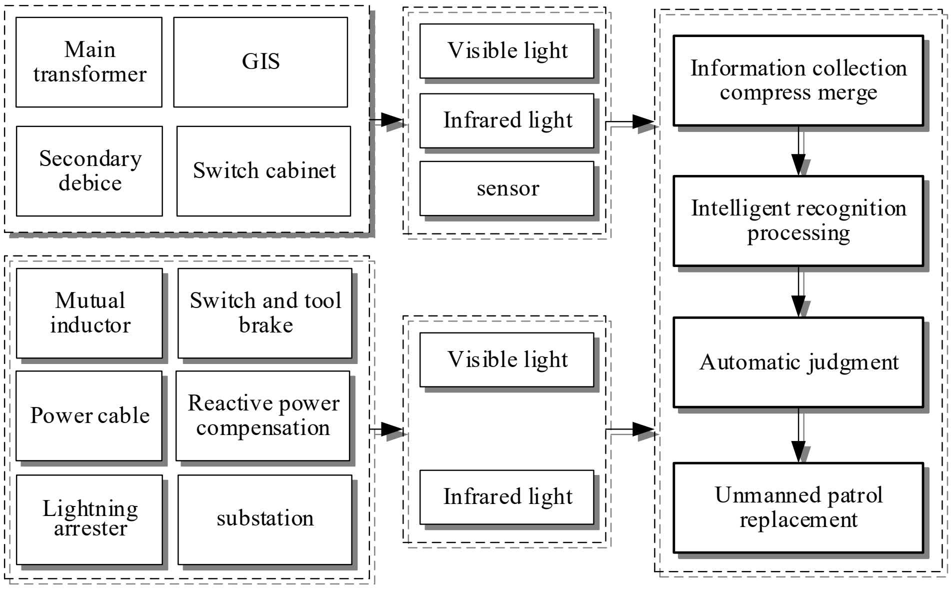

Figure 2. Intelligent patrol system architecture.

The intelligent inspection service encompasses two key areas: equipment appearance inspection and equipment status monitoring. For equipment appearance inspection, we utilize robots, wired/wireless cameras, drones, handheld terminals, and other innovative methods. On the other hand, equipment status monitoring is achieved through advanced techniques such as infrared cameras, temperature/humidity sensors, and equipment meter collection. In terms of on-site safety control, we adhere to the strict requirements of safety work procedures. This involves conducting standardized safety inspections of construction and maintenance operation sites, both on-site and remotely, to ensure the safety of personnel, the electrical system, and equipment. Research into intelligent inspection necessitates the support of power sensors, as depicted in Figure 3 [65–67].

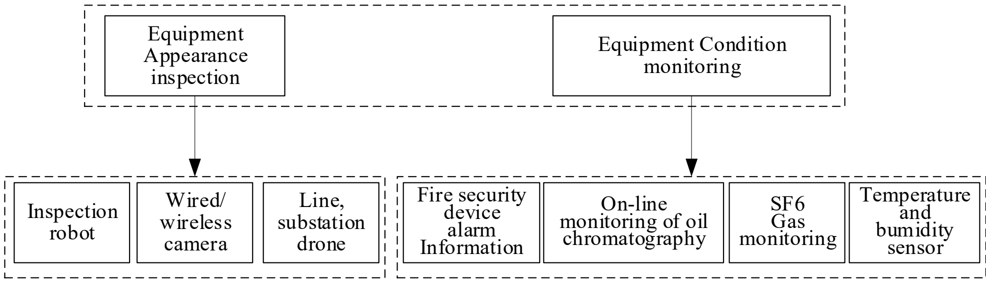

Figure 3. Intelligent patrol business.

1. Application of power sensors in power supply scenarios: The monitoring of generator set parameters, including power, wind speed, rotation speed, vibration, angle, pressure, and temperature, alongside non-destructive testing data such as gearbox oil analysis and blade structure analysis, enables fault diagnosis and the comprehensive health monitoring of the crucial components in wind turbine transmission chains: blades, gearboxes, and generators [68];
2. Application of power sensors in transmission, transformation, and distribution networks: Leveraging power optical fibers, we achieve the precise monitoring of transmission line characteristics like temperature, stress, and vibration. The optical fiber doubles as a sensing medium and communication channel, boasting an optical detection signal sampling rate of over hundreds of MHz. This allows for meter-level accuracy in localizing events on transmission lines spanning hundreds of kilometers. Integrated with sensors for video, imagery, and micro-meteorological data, we effectively monitor and pre-empt risks associated with icing, wind-induced vibrations, oscillations, and external damage [69]. Additionally, techniques and devices such as ultrahigh frequency, ultrasonic, oil chromatography, infrared detection, and optical fiber winding temperature measurement are extensively utilized in power transformers for real-time monitoring and fault diagnosis. This ensures the timely and accurate detection of latent faults, preventing their deterioration and escalation;
3. Typical application scenarios on the user side: In industrial parks, sensors for environmental and energy consumption monitoring, along with intelligent devices like inverters and smart circuit breakers, gather crucial data pertaining to water, electricity, natural gas, steam, and the environment for enterprises. These data points are seamlessly integrated with production and management systems like MES and ERP, enabling efficient distributed new energy operations, maintenance, energy conservation measures, emission reduction strategies, and other business-enhancing services that ultimately boost energy utilization efficiency [70–73].

4.2. Intelligent Inspection Based on Non-Destructive Testing

Intelligent inspection employs non-destructive testing methods, which preserve the integrity of the components being tested, to identify anomalies or flaws within the material's internal structure. These flaws induce reactions like heat, sound, light, electricity, and magnetism, which are detected using advanced technology and equipment. Key detection techniques encompass infrared thermography, ultrasonic inspection, eddy current testing, magnetic particle/flux leakage testing, and radiographic testing [74].

The distinctive characteristics of electromagnetic non-destructive testing are its non-destructiveness, non-invasiveness, real-time capability, speed, high sensitivity, and reliability. These features have led to its widespread application in defect detection in the power industry. Given the unique requirements of nuclear energy, the safety inspection of nuclear power plant equipment is subject to stringent demands. Non-destructive testing plays a pivotal and indispensable role in nuclear power, ensuring safe operation, cost-saving preventive maintenance, and providing crucial data support [75]. To address the challenge of precisely detecting micron-level heterogeneous membrane layers on nuclear fuel component cladding, a multi-parameter electromagnetic testing technology utilizing phased array eddy current has been proposed. This innovative technology enables the detection and identification of oxide film thickness, fouling layer thickness, and hydrogen absorption layer thickness on the cladding surface [76].

4.3. Comprehensive Solution Based on Inspection Robots

1. Inspection Robot Products and Capabilities

Inspection robots offer comprehensive, round-the-clock, fully autonomous, and intelligent inspection and monitoring capabilities for power plants. They significantly reduce labor demands and operational costs, thereby enhancing the automation and intelligence of routine inspection operations and management [77].

Leveraging technologies such as intelligent robot design, artificial intelligence, image recognition, and big data analysis and alert systems, a comprehensive system for intelligent inspection robots has been established for power transmission and transformation equipment.

This inspection robot system comprises three distinct layers: the equipment layer, the communication layer, and the station control layer. The equipment layer encompasses robots, charging stations, micro-weather stations, environmental monitoring devices, security systems, fixed video surveillance equipment, and the equipment under inspection. The communication layer consists of wireless base stations, switches, and other communication components. Finally, the station control layer comprises servers, operation terminals, time synchronization equipment, and other control components [78].

The backend software platform includes databases, database middleware, and data buses, while the backend software applications encompass system management, debugging tools, model configuration, data acquisition, data analysis, and advanced functionalities such as electronic mapping, video surveillance, voice intercom, pattern recognition, intelligent integration, automated reporting, historical queries, and curve analysis [79,80], as depicted in Figure 4.

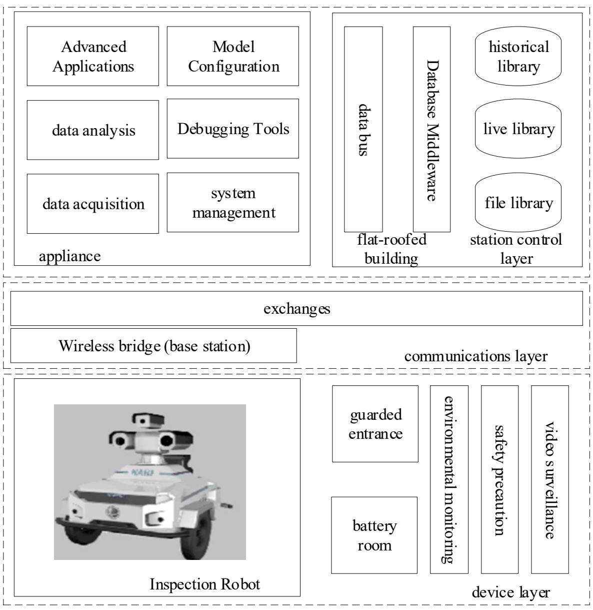

Figure 4. Overall architecture of the inspection robot system.

The inspection capabilities encompass a range of functions, such as automated routine inspections, manual remote inspections, targeted fixed-point inspections, two-way communication, noise detection, and infrared temperature readings [81].

The image recognition feature employs visible light cameras to capture images, utilizing advanced image matching and pattern recognition techniques. This allows for the detection of external equipment and foreign objects, recognition of knife switch/switch states, and accurate reading of equipment instrument values. Among the outdoor images recognized are breathing apparatus, casing oil level gauges, oil temperature gauges, circuit breakers, isolating switches, opening and closing indicators, lightning arresters, and more. While indoors, it can recognize hydraulic gauges, SF6 pressure gauges, leakage current meters, opening and closing switches, voltage meters, indicator lights, cabinet panels, and various other components [82].

2. Essential Technologies Underpinning Intelligent Inspection Robots

Intelligent inspection robots are cutting-edge products that incorporate a diverse array of technologies, including electromagnetic compatibility, motor drive control, multi-sensor fusion, navigation and behavior planning algorithms, wireless transmission protocols, advanced image recognition, and sophisticated visual technology. The fundamental technologies that drive these robots are outlined below [83,84].

a. Positioning and Navigation Technologies: GPS positioning excels in accuracy and adaptability to diverse environments, yet its precision comes at a premium cost and reliance on external satellites and base stations, rendering it unsuitable for indoor applications. Magnetic track and QR code positioning methods offer precision but require significant modifications to the surroundings, thereby restricting their extensive outdoor usage. Inertial navigation provides autonomous positioning independent of the environment, yet it faces challenges due to accumulating errors and the high cost of high-precision inertial devices [85]. Laser positioning achieves high accuracy without external dependencies but relies on sophisticated algorithms. However, its reliability diminishes in dynamic environments, and multi-line laser sensors add to the overall cost. Multi-data fusion navigation positioning incorporates environmental modeling, laser radar scanning, odometer data recording, and environmental map creation. Autonomous positioning then marries real-time odometer data with pre-existing environmental maps, aligning lidar data with the maps through feature matching [86].
b. The main body platforms encompass: wheeled robots, leveraging laser-based trackless navigation for flexible path configurations and robust adaptability; track robots, operating on magnetic tracks, offering broad coverage and rapid inspection capabilities; and tracked robots, boasting excellent off-road performance and smooth operation [87];
c. The automatic charging system comprises the robot body and the charging module. It determines the necessity of charging by assessing the battery level and whether the robot has completed its current inspection task;
d. Control system: The centralized control framework oversees a diverse array of robots, facilitating their remote management through standardized interfaces. This allows for data collection, the issuance of control commands, and a range of functionalities, including remote control, inspection task scheduling, real-time monitoring, data analysis, and historical query capabilities [88];
e. Technology outlook: We aim to comprehensively promote the standardization system for inspection robots, fostering the transition towards intelligent operation and maintenance modes. This includes strengthening technological research and development, deepening our research into the robot's key technologies to enhance inspection effectiveness, and exploring information exchange between the robot's backend monitoring system and production management systems to expedite system integration and interconnectivity [89].

4.4. Key Technologies of Intelligent Inspection

1. Artificial Intelligence Platform

An artificial intelligence platform was constructed, as depicted in Figure 5, encompassing three distinct layers: the basic layer, the functional layer, and the application service layer. This platform is designed to achieve standardized service delivery, customized solution generation, and microservice API outputs [90].

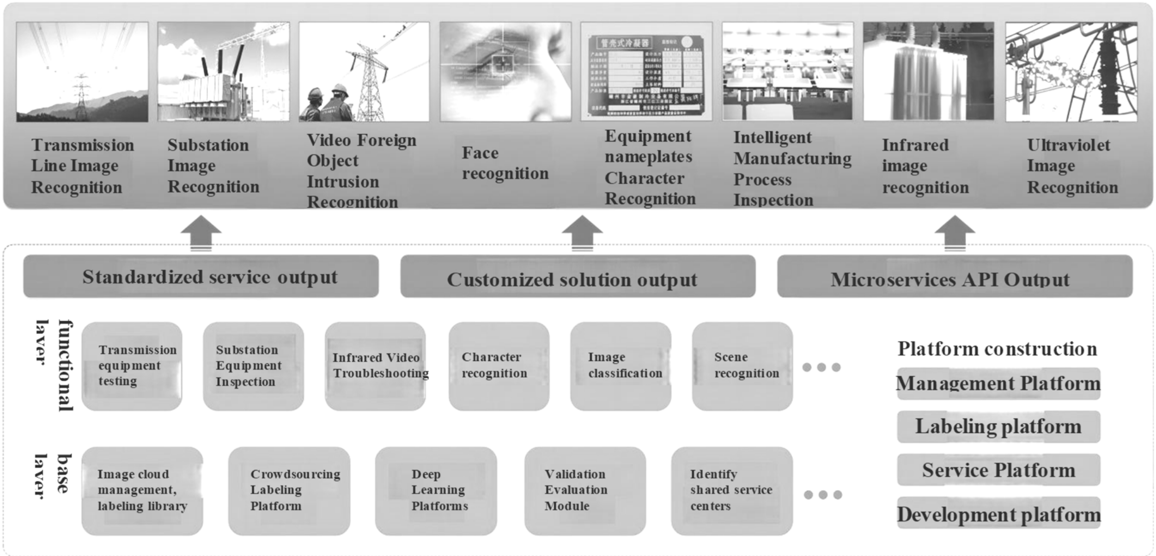

Figure 5. Artificial intelligence platform.

2. Image recognition capabilities

Utilizing the image recognition research application platform depicted in Figure 6, it possesses capabilities in device recognition, facial recognition, object recognition, and character recognition. These technical functionalities can be effectively applied across various scenarios such as transmission systems, substations, distribution networks, and intelligent manufacturing environments [91].

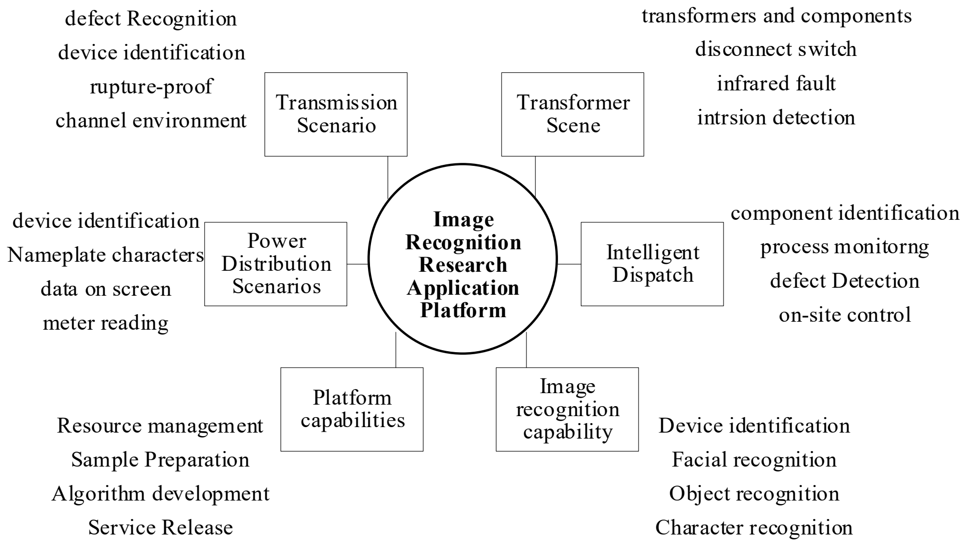

Figure 6. Image recognition capabilities.

3. Rapid iteration of vision applications

Leveraging the Internet of Things and artificial intelligence, a technology application ecosystem can be established for the rapid iteration of visual applications. This ecosystem encompasses the cloud, edge, and terminal layers, enabling adaptability to diverse application scenarios [92], as depicted in Figure 7.

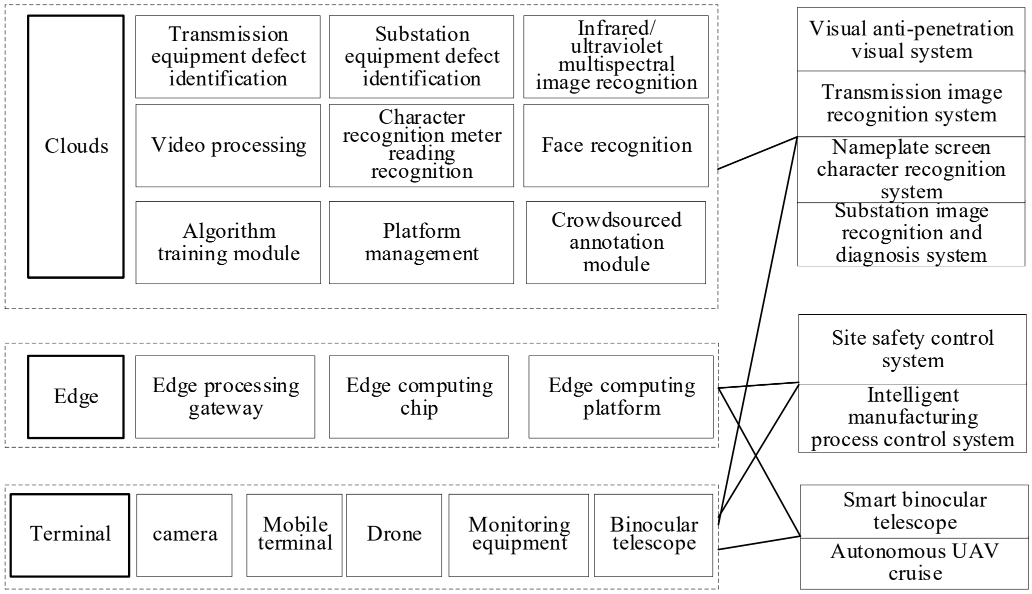

Figure 7. Visual applications.

4. Power Station Image Recognition

Infrared temperature measurement and differential Analysis: By utilizing a high-sensitivity infrared thermal imager mounted on the inspection robot, we can precisely compare and analyze temperature variations across various device components or between distinct devices, thereby identifying thermal irregularities and defects with accuracy.

External equipment visual inspection technology: Leveraging a high-definition video camera, the robot captures detailed images of equipment's exterior and critical components. Through image analysis, it detects defects such as damage, oil leaks, rust, and foreign objects, supporting concurrent assessments of multiple targets with a recognition accuracy of 90% or higher.

Intelligent meter recognition: Our inspection robot incorporates a high-definition camera, along with algorithms for pan-tilt control, image recognition, and shot compensation. This enables the robot to accurately identify meter readings and the positions of switch knives, enhancing operational efficiency and precision.

Additional detection capabilities: Our system offers additional detection options such as noise detection and weather monitoring. Additionally, it can be equipped with ultraviolet and partial discharge detection devices to further enhance its overall detection capabilities.

1. Infrared image recognition: We possess a comprehensive fault database for substation equipment, encompassing over 200 instances of typical infrared image defects spanning 11 equipment categories and 55 fault types. This database is scalable and designed to accommodate future additions. The intelligent analysis of transformer status was shown in Table 1;
2. Edge intelligence analysis technology: The edge intelligent box, integrated into the robot platform, offers miniaturized and agile computing. It enables functions such as model distribution, computational offloading, on-site analysis, and general computing capabilities, fostering a seamless collaboration between cloud and edge computing;
3. External state visual perception: Leveraging deep feature learning, we have created and trained a comprehensive sample library for substation equipment. This library powers intelligent recognition and analysis of various equipment targets and faults, including transformer oil leaks, surface oil contamination, breathing apparatus defects, metal corrosion, bushing and meter damage, foreign object intrusions, and more. It further localizes, classifies, and annotates abnormalities, enhancing the accuracy of transformer status assessment and fault diagnosis to over 95%. Our recognition model boasts the capability to identify 10 subclasses within 5 major defect categories,

characterized by low miss rates, high reliability, speed, and practicality, demonstrating its effectiveness in engineering applications;

4. Visual multi-alignment technology: Prior to each magnification level, it precisely locates the meter position and calibrates the visible light camera's angle to ensure the meter is centered in the frame. Leveraging high dynamic range imaging technology, it enhances crucial image features, effectively mitigates the impact of varying lighting conditions on meter readings, and ultimately elevates the accuracy of readings.

Table 1. Intelligent analysis of transformer status.

Serial Number	Transformer Location	Type of Exception
1	High-pressure side casing	Cracks and discoloration on casing surface, metal corrosion
2	Low-voltage side casing	Cracked and discolored casing, rusted metal
3	Oil pillow	Component surface oil, metal corrosion
4	Oil temperature	Meter identification, meter breakage
5	Oil level	Meter identification, meter breakage
6	Operational data	Meter identification, meter breakage
7	All sides	Rusting
8	Top of transformer	Component surface oil, metal corrosion
9	Transformer perimeter	Foreign object
10	Surrounding ground	Ground oil stains
11	Ventilator	Discoloration of silicone, damage to oil seal

5. Nuclear Power Plant Electrical System Intelligent Development Trends

5.1. Basic Principles

The integration and interconnection of various components within the nuclear power plant's electrical system should be orchestrated to foster collaborative development, mutual sharing, and efficient utilization. Through the integration of digital system computing analysis, the system's observability, descriptiveness, and controllability [29–31] will be enhanced, thereby advancing the intelligent construction of nuclear power plants with exceptional quality [93]. The basic principles therefore are as follows:

1. Business imperative: Maintain a focus on problem-solving, value creation, and result-driven objectives. Conduct a scientific analysis to assess the necessity of digitization requirements for various stages, targets, and operational links;
2. Technical viability: Evaluate the novelty, efficacy, robustness, and universality of technologies based on factors such as application maturity, applicability, implementation ease, and problem-solving capability. Determine the optimal technical approach and implementation roadmap;
3. Safety and dependability: Develop comprehensive plans for perception capture, connectivity, data storage, and shared applications across the nuclear power plant's electrical system to guarantee utmost safety and reliability;
4. Economic prudence: Strike a balance between cost and efficiency, considering benefits and adhering to a global perspective and systematic approach. Select strategies and models that are economically rational and globally optimized, tailored to local conditions.

5.2. Intelligent Architecture

1. The intelligent information architecture encompasses four key layers: production control, information processing, information acquisition, and digital intelligent electrical equipment. This architecture unfolds into four distinct stages of data management: acquisition, transmission, storage, and utilization. It harmonizes the perception and interconnectivity of various components within the intelligent electrical system, enabling shared perception devices. This fosters seamless integration and adaptive construction of diverse business applications, ultimately achieving equipment transparency, data transparency, and application transparency [94], as depicted in Figure 8.

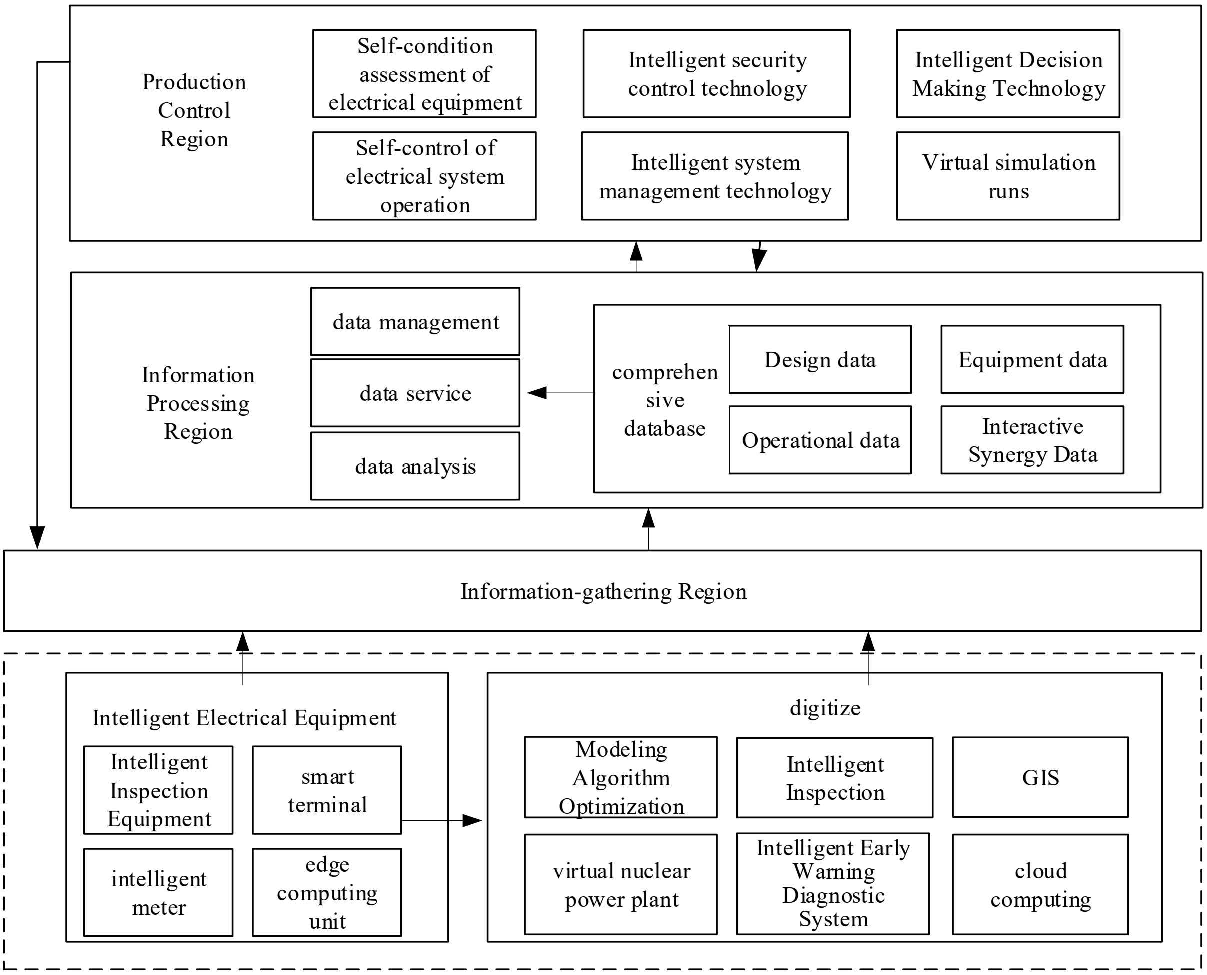

Figure 8. Overall framework for electrical intelligence in nuclear power plants.

2. The equipment management layer architecture comprehensively encompasses several key aspects such as intelligent video management, three-dimensional scene management, equipment status monitoring, equipment analysis, operational and maintenance business administration, as well as specialized technical management. A detailed breakdown of these components is presented in Figure 9.
3. Data Layer Model Architecture: Figure 10 illustrates the model architecture of the data layer that underpins the intelligence of the electrical system in nuclear power plants. This architecture comprises primary and secondary equipment models, data models, equipment analysis models, operational and maintenance business models, as well as professional management models, drawing from references [95].

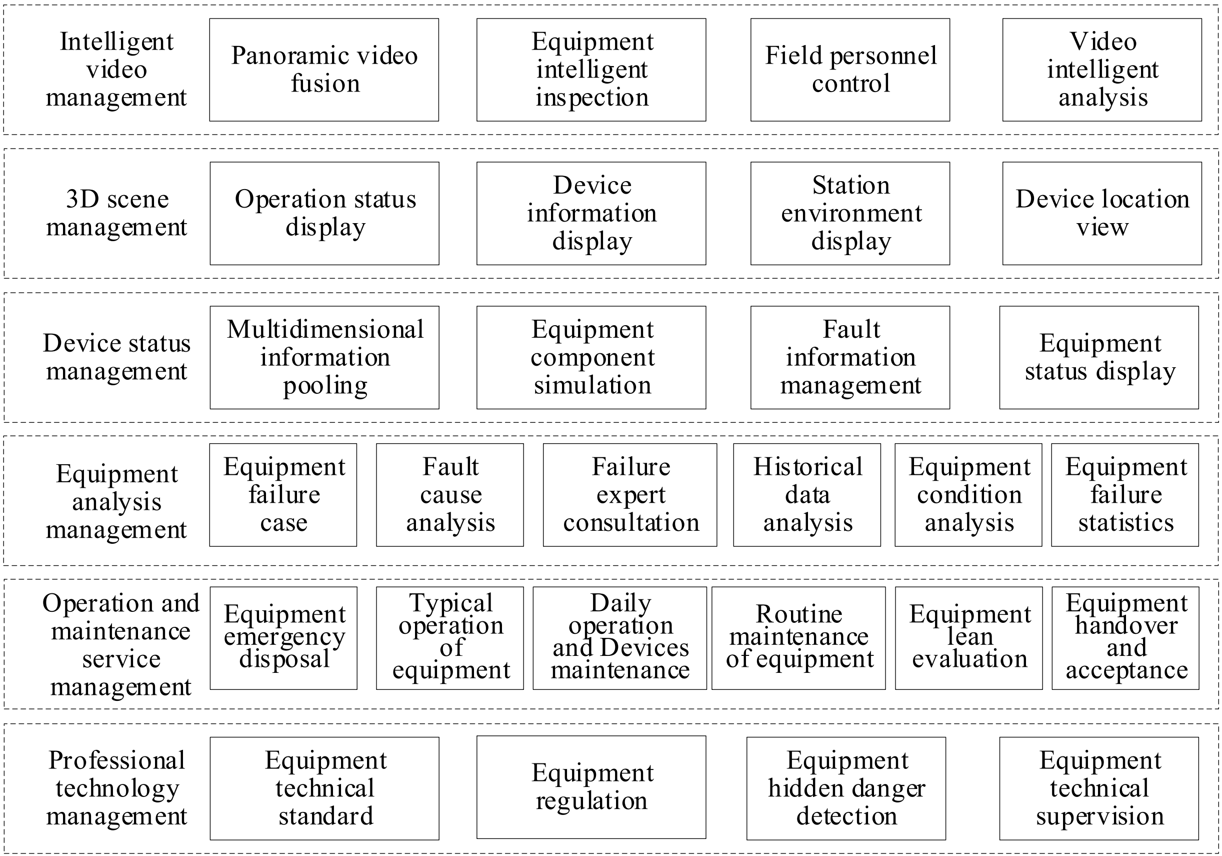

Figure 9. Functional framework for the intelligent application of nuclear power plant electrical systems.

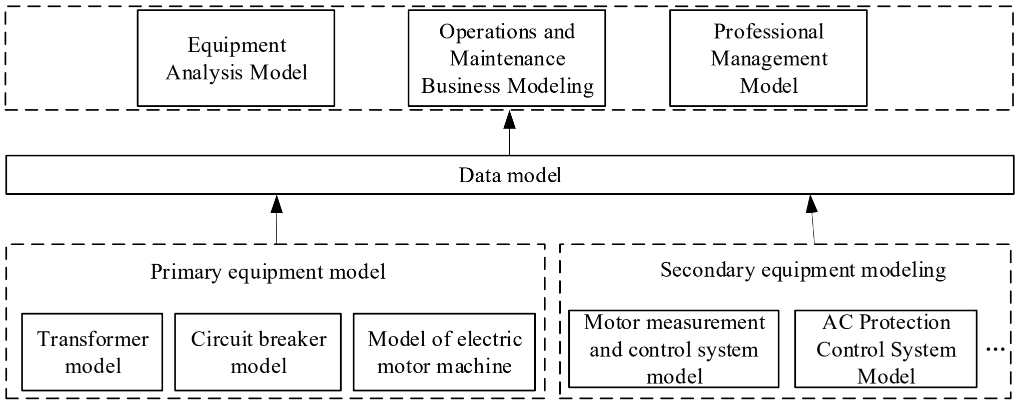

Figure 10. Nuclear power plant electrical intelligence data model architecture diagram.

5.3. Evolutionary Path of Development

The evolutionary roadmap for the intelligentization of the electrical system in nuclear power plants, as presented in Table 2, depicts a journey commencing with automation and culminating in full intelligentization. This journey progresses from the automation of electrical equipment and systems, through digitization enabled by data collection, analysis, and modeling with integrated software and hardware, to the establishment of cross-disciplinary, cross-domain, and cross-regional data platforms that enrich digital applications and services in the nuclear power industry. Subsequently, intelligentization technology is harnessed to empower the electrical system with self-learning, self-organization, and self-management capabilities, assisting in critical operational decision-making. Ultimately, leveraging advancements in comprehensive situational awareness and other digitization initiatives, the roadmap aims to achieve networked and intelligent adaptability of nuclear power electrical systems to cyclic processes, while providing tailored intelligent recommendations to support individual users' decision-making needs [96].

Table 2. Nuclear power plant electrical intelligence evolutionary route.

Step	Evolutionary Path	Time Series	Objectives and Performance Content
1	Automatization	Recent past	Utilizing advanced sensing technology, we aim to elevate the automation level of the electrical equipment system, enabling the miniaturization and integration of equipment. This involves the profound integration of diverse sensing units, intelligent self-testing of equipment health status, electromagnetic compatibility, and data transmission anti-interference measures. Furthermore, we leverage computer network technology to effectively manage and monitor the electrical system, ensuring its optimal performance and reliability.
2	Digitalization 1.0	Recent past	While still relatively basic in terms of software application, the system is capable of achieving data acquisition, structured processing, and analysis for a single electrical component. This functionality provides foundational support for professional data handling and feedback mechanisms.
3	Digitalization 2.0	Mid-term	The implementation of data acquisition, structured processing, and analysis for small electrical systems has been achieved, accompanied by significant advancements and improvements in the hardware platform and model level.
4	Meshing	Mid-term	From the perspective of the local plant electrical system, we aim to accomplish the mining and interfacing of data beyond the local area, gradually exploring the establishment of cross-disciplinary, cross-field, and cross-regional data flow within our platform. By connecting structured data, upgrading our hardware platform and modeling capabilities, we comprehensively enrich nuclear power-related applications and services.
5	Intelligent 1.0	Forwards	From the perspective of the electrical system spanning the entire plant, we can leverage intelligent technology to construct a smart brain within the new frontier. This brain will enable self-learning and self-optimization capabilities, thereby assisting in decision-making processes.
6	Intelligent 2.0	Forwards	We have achieved breakthroughs in the development of complex integrated models and nuclear power global situational awareness and perception models, addressing challenging issues. This enables nuclear power systems to achieve networked and intelligent self-adaptation to cyclic processes, allowing for customized intelligent recommendations to assist in decision-making.

5.4. Stage Goals and Key Technologies

Taking into account the maturity of electrical intelligentization technology and the evolution of intelligent equipment, in tandem with the safety, reliability, and economic demands of nuclear power plant electrical systems, we have formulated stage-specific objectives as depicted in Figure 11.

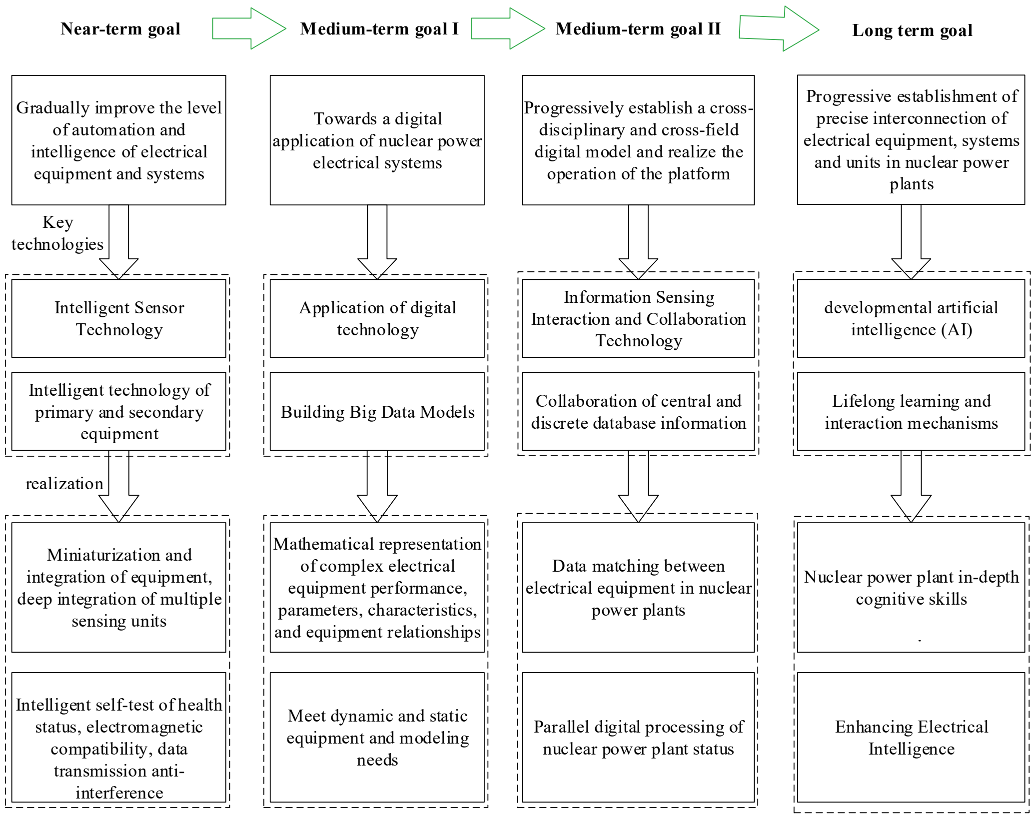

Figure 11. Nuclear power plant electrical system intelligence milestones.

1. Recent past: For operational nuclear power plants, cost-effective and reliable upgrades and transformations are carried out on electrical system equipment, encompassing the renewal of sensors, primary and secondary fusion switchgear, ring main units, and distribution transformers. This involves implementing intelligent system modifications or constructions at the operational and maintenance levels to enhance the electrical system's intelligence level. By advancing the digitization of the electrical system's foundation through smart sensing, data collection technology, and primary and secondary fusion intelligentization, we empower primary equipment with greater intelligence, enabling status visualization, networked control, and automation. This serves as the fundamental functional backbone for the electrical system's intelligentization [97].
2. Mid-term: For newly built or refurbished nuclear power plants, a holistic approach to electrical intelligentization is implemented. This methodology involves the design of multifaceted applications and platform systems encompassing intelligent operation, inspection, communication, monitoring, information security, and electrical system protection. This approach systematically elevates the level of electrical intelligence. By leveraging secure and efficient computing platforms, along with robust foundational data, advanced numerical algorithms, benchmark modeling, 3D simulation models, and visualization techniques, we gradually establish digital and intelligent applications tailored specifically for nuclear power plant electrical systems. This allows for a comprehensive, accurate, and intuitive representation, calculation, and prediction of the primary performance, parameters, and behaviors of real-world electrical system components within nuclear power plants. Additionally, through the efficient iteration and precise restoration of production data, we achieve comprehensive optimization and enhancement of nuclear power plant electrical system performance, providing valuable feedback and assistance [98].
3. Forwards:We aim to establish interdisciplinary, cross-domain, and cross-regional data information platforms that facilitate intelligent development practices spanning

the entire plant and across all specialties. Leveraging existing industrial internet or Internet of Things (IoT) frameworks, our efforts within the nuclear power plant's internal electrical systems focus on exploring and accessing data beyond local constraints. Through collaborative exploration and practice, we gradually establish cross-disciplinary, cross-domain, and cross-regional digital models and operational platforms. Ultimately, within this digital platform, a collaborative comprehensive application system and its corresponding development improvement mechanism are forged.

6. Summary and Outlook

In recent years, the evolving trends in intelligent electrical maintenance technology and the operational insights gained from smart substations provide valuable references for boosting the electrical intelligence of nuclear power plants in the near future.

We have outlined a roadmap for the intelligent evolution of nuclear power plant electrical systems, aiming to transform electrical equipment and systems from automation to digitization, ultimately attaining intelligent development milestones. Technically speaking, this journey entails a shift from perception to cognition in terms of intelligence.

In the immediate term, our priority is on deploying intelligent equipment in operational nuclear power plants. However, as we look towards the medium- to long-term, we will redirect our focus to enhancing the overall intelligence level from a systemic perspective for newly planned nuclear power plants.

We have also crafted implementation plans for the intelligentization of electrical equipment in nuclear power plants. A key component of these plans is primary and secondary fusion technology, which seamlessly integrates intelligent units into primary equipment, thereby enhancing its overall intelligence.

With the rapid development of intelligent technology, the intelligent development of the electrical systems in nuclear power plants will continue to deepen and is expected to achieve significant leaps in the next few years.

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