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Application of an intelligent electrical fire monitoring system based on the EC-IOT framework in high-rise residential buildings

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ABSTRACT

In recent years, the rapid modernization and increasing adoption of smart homes have disrupted the traditional balance between electrical design standards, power line systems, and fire monitoring frameworks. This disruption has heightened electrical safety risks in residential buildings, endangering both lives and property. This study introduces an edge response delay calculation model using the Modbus protocol and a fine-grained distributed edge node networking architecture to enhance system efficiency. This research examines the platform's effectiveness in improving electrical safety and accident prevention in civil buildings, focusing on three key aspects: design concept, system architecture, and implementation. The platform seamlessly integrates electrical fire monitoring, IoT technology, and digital building simulation, enabling an intelligent early warning system for pre-disaster detection and an automated post-disaster response mechanism. The results show that the system enhances the pre-disaster early warning capability in the electrical fire business scenario, and provides efficient decision-making support for personnel escape evacuation and fire rescue in the post-disaster stage, which has important practical application value.

1. Introduction

General Secretary Xi Jinping pointed out in the report of the 20th National Congress of the Communist Party: "We must enhance our capacity for disaster prevention, mitigation, and relief, as well as our ability to handle major sudden public emergencies, and strengthen the construction of national and regional emergency response forces" [1]. According to statistics from the National Fire Rescue Administration [2], between 2012 and 2021, electrical fires accounted for 42.7 % of all residential fires nationwide, which is the highest proportion of all kinds of fires. In the first eight months of 2024, fires caused by electrical failures rose 14.4 % from the same period last year. In the nationwide fire data for the first half of 2023, residential fires represented 30.3 % of the total number of fires, yet these incidents accounted for 69 % of the total fatalities. In the first quarter of 2022, of 29 significant fire incidents, 34.5 % were attributed to electrical causes, also is the highest proportion. And in the 2021 fire data showed that the number of deaths in high-rise building fires increased by 22.6 % compared to the previous year, predominantly occurring in residential settings, which accounted for 84.7 % of high-rise fire incidents and 92.3 % of related fatalities. These statistics reveal that the proportion of the number of electrical fires remains significant. Electrical fire is characterized by universality, lethality and severity. And high-rise residential fires are characterized by a high density of occupants, complex ignition causes, rapid fire spread, difficult evacuation, intricate escape routes, significant firefighting challenges, and substantial losses in lives and property, making electrical fire safety a paramount issue. Therefore, monitoring electrical fires in high-rise residential buildings is the key focus of this study.

Among the causes of electrical fires, short circuits and poor contact between live wires and grounding bodies, which generate electrical sparks and arcs, are the main culprits. These electrical phenomena are difficult to capture using traditional electrical power models, making them some of the hardest signals to monitor in electrical fire management. At the same time, in recent years, with the widespread adoption of smart homes, various smart appliances and high-power electrical devices have entered households, bringing convenience to residents. At the same time also brings a lot of electrical safety risks. For example, high power equipment causes circuit overload, the continuous power supply demand of intelligent equipment may lead to overheating. In addition, the threshold of the power load specification for each house in the

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existing residential buildings [3] is already far lower than the load of modern electrical appliances in an ordinary family, which poses a hidden danger to power load. Although the recently updated electrical design standards GB51348–2019 for civil buildings have introduced several clauses aimed at enhancing electrical safety [4], for example, the improvement of the grounding system, the increase of the leakage protection device, etc. However, existing old buildings still have problems such as aging old lines and insufficient load capacity. The main research object of this article is the optimization and renovation of electrical fire monitoring in existing old high-rise residential buildings.

Based on the above problems, the author combined in the field of electric digital science and technology innovation and research and development strength of Fengji Intelligence Technology Research Institute, put forward a kind of application in existing old high-rise residential building new electrical fire monitoring scheme. This EC-IoT (Edge Computing Internet of Things) solution employs a "cloud + edge + terminal" Internet of Things architecture. It incorporates arc detectors and smart circuit breakers at the terminal level, while edge computing devices are placed at the edge layer. At the cloud level, power data is mathematically modeled to deploy intelligent analysis warnings and line fire location services, while the edge layer enables localized data analysis to assist in smart decision-making, achieving cloud-edge collaboration. EC-IoT system can optimize data processing, improve response speed and enhance system agility and reliability. Finally, for post-disaster evacuation, the system utilizes BIM (Building Information Modeling) digital information models to help firefighters understand the spatial information inside the building, and use the data of the monitoring system to update the location of the fire point and the spread of fire in real time, so as to help households to escape and assist firefighters to deploy rescue routes. Realize real-time monitoring, pre-disaster warning, automatic decision-making and post-disaster escape business linkage. Aiming to effectively reduce the occurrence and spread of electrical fires in high-rise residential buildings and reduce the loss of life and safety of people in residential buildings through technical means such as early warning and digital model evacuation simulation.

2. Current research status

Since the United States developed the world's first fire alarm device in 1847, developed countries have never stopped exploring electrical fire monitoring technology. At present, the latest international research directions are mainly concentrated in the following aspects: First, explore fire detection system models based on different technologies. For example, Alam, M.M [5] proposed a hybrid model based on multi-class support vector machine (MSVM) combined with rule-based classifier (RBC) for diagnosing constructed equipment faults and overcurrent faults and detecting leakage current faults. Madan Lal Saini [6] proposed a smart fire detection monitoring system that uses temperature, smoke, flame, LDR and MQ2 sensors to determine the speed and intensity of the fire, and uses the NodeMCU board fire alarm system building block to transmit the information to the fire control center and send a notification to the fire control center through the Blynk cloud to trigger the alarm according to the fire intensity. In addition, the introduction of big data AI algorithms, such as P. Dileep Kumar Reddy [7] introduced the recurrent neural network (AI-RNN-WO) with the whale optimization algorithm framework to optimize the analysis of real-time detection data parameters, so that the established new smart city model can improve the accuracy and reduce the false alarm rate. In terms of combining monitoring systems with spatial models, the latest research dynamically couples the edge computing Internet of Things (EC-IoT) system with the building information model (BIM), such as Hyeon-Cheol Kim [8] using a space-based digital twin model and using real particle-based image fire data. Combine the existing fire detection model with the spatial model to reduce the false detection rate. These studies have promoted the development of intelligent electrical fire monitoring technology and provided a more reliable solution for future building city safety.

The research in China has made significant progress in the field of intelligent fire monitoring. In early studies, Jiang Jianfeng and others [9] designed a combined electrical fire detector based on single-chip microcomputer and Internet of Things technology. They monitored multiple indicators of the detection circuit and realized remote monitoring of alarm information push by combining the Internet of Things platform. Men Maochen and colleagues [10] have developed a fire monitoring system based on the waveform characteristics of residual current, employing data analysis of waveform signals and utilizing BP neural networks through intelligent algorithms to recognize alarm faults, thereby improving the accuracy of early warnings for residual current-driven fires. In the field of fire monitoring in high-rise buildings, Jin Shan [11] has addressed detection needs by proposing a three-layer distributed Wireless Sensor Network (WSN) architecture for fire monitoring in high-rise buildings, effectively controlling congestion, optimizing routing, and prioritizing the reception and transmission of fire data to provide real-time reliable data transmission support for detection. Peng Tianhai and others [12] have utilized sensors and IoT technology to collect terminal data from high-rise buildings, enhancing location information logical nodes and employing terminal information models for monitoring and control.

In terms of combining fire prevention and control with the establishment of digital twin technology, Cao Lei and colleagues [13] have designed and constructed a lifecycle digital twin distribution simulation platform based on digital twin technology. This platform integrates basic data and functions and explores capabilities such as load diagnostics and load access planning, promoting the in-depth application of digital twin technology in the field of electrical intelligence. Digital twin technology can also enhance building fire escape and evacuation strategies. Song Yang and others [14] have constructed a three-dimensional digital twin model of complex high-rise buildings based on digital twin technology and simulation software, analyzing safety and firefighting evacuation issues through combining factors like fire source points, smoke exhaust, and sprinklers. They have built a rich experimental environment using fire simulation software to conduct dynamic evacuation studies based on digital twins, offering escape guidance for on-site personnel. Luo Xin [15] has designed a fire detection and escape rescue system, leveraging IoT and three-dimensional visualization technology to achieve functions including environmental parameter collection, storage, analysis, early warning, and visualization, providing escape plans for trapped individuals and reference for rescue personnel in formulating rescue strategies.

In summary, research at home and abroad has made significant progress in the field of intelligent electrical fire monitoring, promoted theoretical research and technical application of electrical fire prevention, and made important breakthroughs in combining with artificial intelligence, reducing false alarm rates, and integrating with digital twin technology. However, most of the existing research relies on platforms and big data training to obtain models and simulation analysis, ignoring the "edge" intelligent research that is closer to users, especially the low-latency performance of early warning response and the lack of practical cases in post-disaster escape and evacuation guidance. This paper proposes a cloud-edge collaborative Internet of Things framework based on fine-grained distributed edge nodes, combined with a digital building model platform, focusing on the platform's low-latency performance research in early warning response and post-disaster escape and evacuation guidance research, improving the response capabilities of disaster prevention and relief, and supplementing the shortage of research and practical cases in this area.

3. System design plan

The system's encompass technology frameworks from multiple fields, including Internet of Things (IoT) technology, electrical fire monitoring technology, and digital architectural simulation technology.

Therefore, the design plan for the system will be described and defined from three different perspectives, creating a new type of intelligent electrical fire monitoring system, as shown in the Fig. 1.

The application IoT technology enables the interconnectivity of devices and electrical monitoring equipment within buildings, allowing for the analysis and storage of business data through network communication technology, as well as platform-based management, which serves as a crucial support for system implementation. The system architecture is based on the mature EC-IOT framework within the IoT domain, adopting a layered design of "cloud, edge, and terminal".

Electrical early warning has business requirements with low latency. In order to realize electrical monitoring with low delay, the edge nodes need to be as close to the sensing data source as possible. Therefore, a fine-grained distributed edge node deployment scheme based on floor edge distribution calculation is proposed. The edge side deploys an edge node for each floor distribution domain, narrowing the service scope of the node to match the capabilities of the hardware, ensuring that the edge focuses more on nearby operations and is closer to the data source. This approach minimizes latency caused by network transmission and multi-level forwarding, enabling direct local computation and analysis. The highest level of alerts has execution authority, allowing for immediate local decision-making upon triggering the top warning level. When the highest alarm level is triggered, the edge node service can directly make local decisions and then report the notification to the cloud. Based on the fine-grained distributed edge node deployment scheme, the management scope of each edge node can be more clearly defined, which is easy to manage electrical parameter data, and can remove the limit of access to terminal devices. Theoretically, the problem of excessive access to terminal devices can be solved by increasing edge devices. In the deployment of the scheme, the key factors considered include: 1) the matching relationship between the power sensor load and the edge nodes; 2) the integrated network cabling should be able to meet the network communication of the edge nodes; if the Ethernet communication environment is not available, the edge nodes need to support the switching of 2 G / 4 G to meet the network coverage in the power distribution cabinet.

Electric fire monitoring technology primarily utilizes advanced sensor technology to capture and collect electrical signals related to electrical systems, enabling comprehensive monitoring of the health status of electrical circuits, which forms the foundation of the system's implementation. The system's electrical sensors mainly include temperature sensors, smoke detectors, fire source detectors, current and voltage sensors, residual current detectors, and electric arc sensors. Through the collaborative work of the sensor layer, the system can detect the potential electrical danger in time and provide effective early warning.

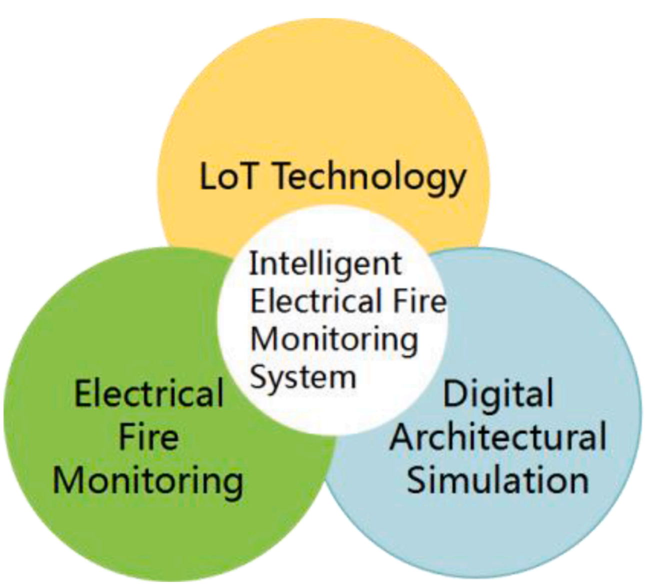

Fig. 1. Intelligent electrical fire monitoring system.

Digital building simulation will focus on the fire-fighting service linkage technology for disaster situations, providing important guidance for fire-fighting business operations and safe escapes. In view of the structure, layout and functional characteristics of relevant building entities, the system first conducts a thorough investigation of the building's plane layout, spatial structure and other conditions at the initial stage of deployment, and performs 3D digital modeling to mark existing fire hazards in daily management. Secondly, based on real-time information such as fire monitoring, early warning and fire location, combined with digital space models, it assists in judging escape routes and provides important command for disaster relief operations.

The design plan for the EC-IOT platform primarily considers three aspects: the building environment of civilian architecture, the electrical design standards for residential buildings, and user requirements. The guiding principles for the design are practicality, inheritability, and maintainability. Practicality is the main focus of the platform, aimed at addressing the challenges and pain points of early warning in electrical monitoring. This requires advanced research in power technology and a significant amount of electrical data to support energy modeling. Inheritability influences the construction costs of the platform; for community buildings, the number of endpoint devices tends to be high, leading to elevated hardware and manpower deployment costs. Therefore, it is preferable for the new sensors to be expandable in modular form on conventional devices, reducing labor costs related to rewiring and equipment replacement. Additionally, the hardware interfaces and structural standards of new devices should be compatible with traditional equipment. Finally, maintainability refers to the ability to assess the overall condition of the system through network and digital technologies within a certain maintenance cycle after the project is completed and the platform is online. Maintenance personnel should be able to repair fault points to ensure the platform's availability.

3.1. System architecture design based on EC-IOT

The electrical fire monitoring and early warning system is designed based on the EC-IOT (Edge Computing Internet of Things) framework [16]. The architecture is primarily divided into four levels: edge, border, management, and cloud. Compared with the traditional "cloud, terminal" integrated architecture, the layered design reflects the scalability of the system and the efficiency of interconnection between devices. Scalability is reflected in business scalability and resource scalability. Due to the independence of modules between layers, the degree of coupling is reduced. New functional modules or business scenarios can be added on the basis of maintaining the existing system business functions unchanged, which is convenient for horizontal business expansion; the access restriction of terminal devices can be achieved by adding edge devices. The cloud deployment based on cloud native sound can realize elastic expansion of resources according to the number of access devices and computing needs; the efficiency of interconnection between devices is reflected in the shortening of communication distance and delay from perception to business decision-making. The terminal devices of the perception layer no longer need to reach the cloud to execute business. Some business execution can be directly implemented at the edge layer. On the other hand, local communication links are more stable and efficient than external network links. Combined with the business division and design logic of the electrical monitoring system, they correspond to the field perception layer, edge computing layer, communication pipeline layer and platform application layer respectively, as illustrated in Fig. 2.

The on-site perception layer is situated in the physical wiring of building floors or residences and comprises various electrical terminal devices and sensors. This mainly includes smart circuit breakers, smoke

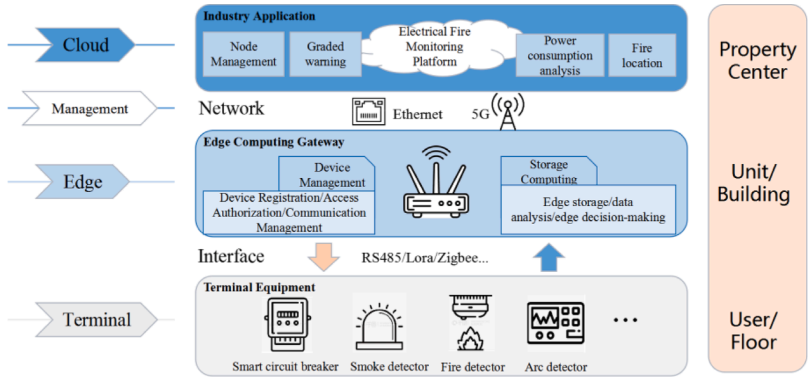

Fig. 2. Architecture diagram of electrical fire monitoring and early warning system.

detectors, fire source detectors, and arc detectors. The temperature sensor is used to monitor the temperature of the electrical circuits of each household's fire line. The current sensor can detect the current in the electrical circuit and detect abnormal conditions such as current overload, short circuit or overcurrent. The voltage sensor can detect abnormal voltage in the electrical circuit. When the voltage is unstable or rises suddenly, it may cause damage to electrical equipment and cause a fire. The residual current detector mainly monitors the residual current. When the residual current exceeds the safe value, it will quickly issue an alarm, handle the fault in time, and prevent further fire arcs or short circuits. The smoke sensor can detect the smoke generated before the fire occurs and provide auxiliary early warning signals. The fire source detector can identify the generation of flames and determine the relevant information of the fire.The electric arc sensor can identify abnormal arcs in the circuit. The arc caused by aging, loose or damaged wires in the circuit is a common cause of electrical fires. The actual deployment uses the FJB3–63 leakage protection circuit breaker [17] independently developed by Fengji Intelligent Technology Research Institute, which has a leakage protection device with temperature compensation and built-in temperature sensors, current sensors, voltage sensors and other sensor modules, with overload protection (power detection), leakage protection (residual current detection), short circuit protection (current detection) and other functions; the detection cost of electric arc is relatively high, and the arc light detector independently developed by Fengji Intelligent is used. The device uses ultraviolet sensors that detect the unique wavelength of arc light and infrared sensors with unique infrared wavelengths to effectively monitor electric arcs. It provides the system with parameters such as voltage, current, residual current protection value, leakage current, three-phase power, etc., and can also remotely control the line switch. It is a key component in the perception layer. This layer provides the system with the key electrical parameters and sensor parameters necessary for electrical fire monitoring, which is the basis for the system to correctly warn or perceive fire [18].

The edge computing layer is located on physical wiring within units or buildings and can be divided into edge nodes based on actual needs, with the option to deploy them at the floor level. The edge nodes are important units for achieving efficient system monitoring, local computing, and local decision-making. This layer primarily utilizes edge computing gateways that possess local real-time processing and computing capabilities. Its main functions include device management and storage computing. Device management is mainly divided into device registration, access authorization, and communication management. Storage computing employs time-series database technology to persistently store local metadata over time, perform real-time analysis, and facilitate local decision-making. The edge layer has a certain degree of autonomy; even in the event of a communication failure with the cloud, it can still manage metadata, conduct computational analysis, and execute control actions based on decision trees [19]. Additionally, this layer serves as a bridge between the on-site sensing layer and the cloud platform. It connects southward to the sensing devices via industrial buses like RS485/CAN or wireless connections such as Lora and Zigbee to gather metadata, while northward it connects to the internet platform through Ethernet and 5 G channels for information reporting and command issuance.

The communication pipeline layer mainly facilitates network communication between the platform application layer and the edge computing layer, with network designers creating network topology designs based on the site environment. In new buildings, the integrated wiring systems are relatively advanced, where vertical subsystems typically use fiber optics or Ethernet cables to connect different floors, thus primarily relying on wired communication. In older residential areas, the wiring systems are already established and difficult to modify, so wireless communication is generally predominant.

The application layer of the platform can be deployed on physical servers at property management centers or in public/private cloud computing environments, utilizing cloud-native technologies for the construction, deployment, and management of microservices. These microservices are related to user business applications, such as node management, tiered early warning, electricity usage analysis, and fire incident location. Additionally, since this layer is closest to the user, its business functions are deeply integrated with fire response, emergency rescue, and other operational segments to achieve automation and intelligence in business processes. Meanwhile, the cloud platform offers backend management features such as global data analysis, intelligent decision-making, and data visualization. Both the platform and applications can scale horizontally based on business size, allowing the development of distributed platforms or applications.

4. System implementation plan

4.1. Hardware environment deployment plan

The deployment of the system's hardware environment is an important stage of system implementation. The principle of hardware environment deployment is to minimize the cost of wiring changes or new additions in the old buildings, while satisfying the data collection function. The main principle is that edge nodes should be deployed in the form of "plug-ins" to the distribution cabinet as much as possible to draw power locally. If the distribution cabinet is too far away from the network wiring, 5 G edge computing equipment should be used to achieve data communication to avoid long-line network cable laying and manpower investment. Since the building's integrated wiring system is modular and hierarchical, this design features provide engineering experience for the deployment of hardware environments for electrical fire systems. Therefore, the system's hardware environment can be integrated and deployed into the wiring subsystem according to business needs, and the mapping relationship between building wiring and system wiring can be established. According to this idea, the deployment plan is designed and implemented on the vertical subsystem, management subsystem, horizontal subsystem and workspace subsystem. The specific plan is shown in Fig.3.

The vertical subsystem is the routing of building trunk cables to realize the connection of various management subsystems. It mainly deploys switches to aggregate data information on each floor. The management subsystem is generally located in the electric well room. Since the distribution box centrally manages the floors at the electricity entrance of each household, a safe power monitoring box is added at the outlet of the distribution box to deliver electricity to the household, and a circuit breaker is used for separate control of each household's line to realize the power consumption of each household on the floor. monitor [20]. The safe power monitoring box is composed of main intelligent circuit breaker FJB3–63, arc detector, residual current detector and other sensors. In order to reduce line transmission delay and wiring complexity and enable edge nodes to focus on adjacent services, the service granularity of edge nodes is reduced to the floor, and a chip with hardware computing power that matches the demand is selected as the main control SOC of the edge node to control Hardware costs. The sensor is connected to the edge node through the 485 bus to monitor the total voltage, current, residual current, arc fault and other sensing data of each household in real time. In addition, the southbound channel of the edge node also has NB-IoT and PLC (power carrier communication) protocols. The NB-IoT protocol is a cellular communication technology used for low-power IoT devices. It has strong penetration and is the communication protocol between edge nodes and smoke sensors in the system. The PLC protocol is a protocol for data transmission in power lines. It is the communication protocol between edge nodes and temperature and humidity sensors in the system.

Video surveillance cameras are deployed on the horizontal subsystem. The integration of cameras in electrical fires plays an important role in improving fire warning and prevention. The original video image frames are used, and the edge node service obtains the image frames regularly. Through the deep learning algorithm model based on YOLOv5 (A visual object detection algorithm) target detection [21], the inference judgment of the fire source status and the opening and closing status of the fire door is realized, and the system's electrical safety monitoring of the corridor is enhanced.

The workspace subsystem is the subsystem closest to the residents. Monitoring equipment needs to pay attention to protecting user privacy. The system mainly deploys smoke and temperature and humidity sensors for real-time monitoring. Because the amount of data on smoke sensor status and temperature and humidity status is very small, in order to reduce wiring costs, NB-IoT wireless communication technology is used to report smoke sensor status to edge nodes. the temperature and humidity sensor can choose PLC to realize data transmission.

4.2. Software implementation plan

The software implementation work of the system is mainly to build hierarchical early warning module, power consumption analysis module, node management module and fire positioning module, as shown in the Fig. 4. The hierarchical early warning module mainly implements the electrical fire early warning function. The module divides various parameter indicators into different levels of thresholds, and through the power consumption analysis module, it analyzes the data obtained from the monitoring module such as residual current, temperature, humidity, arc, fire source status, The smoke status is analyzed, and the warning levels are divided into three levels: yellow warning (level three warning), orange warning (level two warning), and red warning (level one warning). The first-level early warning is the highest, the third-level early warning is the lowest. When the early warning reaches the first level, the edge node has the authority to execute the power-off decision to prevent problems before they occur. And the second-and third-level early warning reports are presented in the form of text messages and system event columns for users. The relevant definitions and descriptions of the warning levels in the system are shown in the Table 1.

The monitoring module and intelligent decision-making module programs mainly run on edge nodes and execute low-level decisions; the power consumption analysis module in the cloud mainly analyzes and calculates historical data and executes high-level decisions.

The power consumption analysis module mainly implements early warning notifications for the auxiliary hierarchical early warning module, analyzes residents' electricity usage habits and behavior, and can also link the intelligent decision-making module and the node management module based on the analysis results to implement certain decisions; the node management module Mainly through cloud-edge collaboration, the platform manages edge nodes and edge devices, including remote control of edge devices, health detection of edge nodes, and remote version upgrades of edge nodes; the fire positioning module mainly implements post-disaster fire protection business processing. This includes locating the fire situation and planning firefighting and escape routes to guide fire operations, which is mainly achieved through the 3D modeling module. The 3D modeling module can provide route guidance to nearby residents and provide support for fire rescue plans based on information such as fire conditions, fire door status, and fire location.

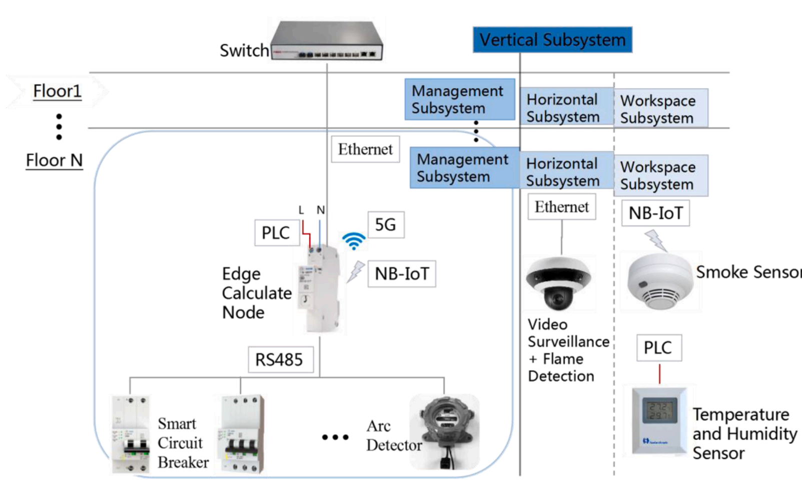

Fig. 3. System hardware deployment plan.

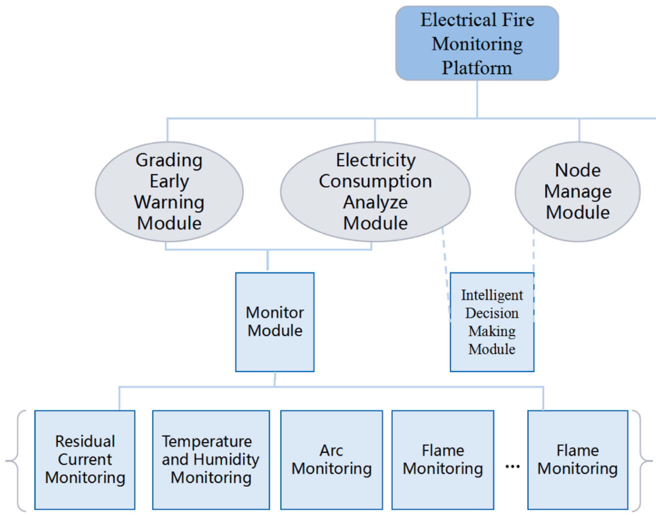

Fig. 4. Structure of electrical fire monitoring platform.

Table 1
Warning levels and implementation definitions.

Warning Level	Event Type	Trigger conditions	Early warning module measures
Yellow Warning	Overvoltage	The voltage parameter exceeds the alarm threshold by 5~10 %	Generate alarm log;
	Overcurrent	The current parameter exceeds the alarm threshold by 5~10 %	SMS notifies users of warning levels;
	Over temperature	The temperature parameter exceeds the alarm threshold by 5~10 %	Generate low-risk events in the monitoring system event column.
	Leakage current	The leakage parameter exceeds the alarm threshold by 5~10 %	
Orange Warning	Overvoltage	The voltage parameter exceeds the alarm threshold by 10~20 %	Generate alarm log;
	Overcurrent	The current parameter exceeds the alarm threshold by 10~20 %	SMS notifies users of warning levels;
	Over temperature	The temperature parameter exceeds the alarm threshold by 10~20 %	Generate high-risk events in the monitoring system event colum.
	Leakage current	The leakage parameter exceeds the alarm threshold by 10~20 %	
Red Warning	Overvoltage	The voltage parameter exceeds the alarm threshold by 20 %	Generate alarm log;
	Overcurrent	The current parameter exceeds the alarm threshold by 20 %	SMS notifies users of warning levels;
	Over temperature	The temperature parameter exceeds the alarm threshold by 20 %	The monitoring system pop-up window displays high-risk events;
	Leakage current	The leakage parameter exceeds the alarm threshold by 20 %	The edge node performs a circuit breaker trip operation on the user;
	Smoke alarm	Receive smoke alarm events twice in a row	Notify the administrator to initiate the emergency plan.
	Flame alarm	Receive flame alarm events twice in a row	

Note: 1. The threshold here is generally higher than the standard deviation of the rated value of the parameter in the national civil power grid. For example, under the deviation of the rated voltage range of 220 $V \pm 7$ %, the threshold will be greater than 235.4 V, and so on.
2. Excluding false alarms in data collection, the condition for each event type to be formed is that the values of three points continuously meet the trigger condition.

4.3. Pilot application of intelligent monitoring system in high-rise residential communities

At present, the system has been tested and operated as a pilot in many old residential areas in Chongqing. Through the large-scale deployment of sensors and intelligent equipment, it has initially realized functions such as community environment perception, abnormal event warning, and personnel and vehicle management. During the pilot

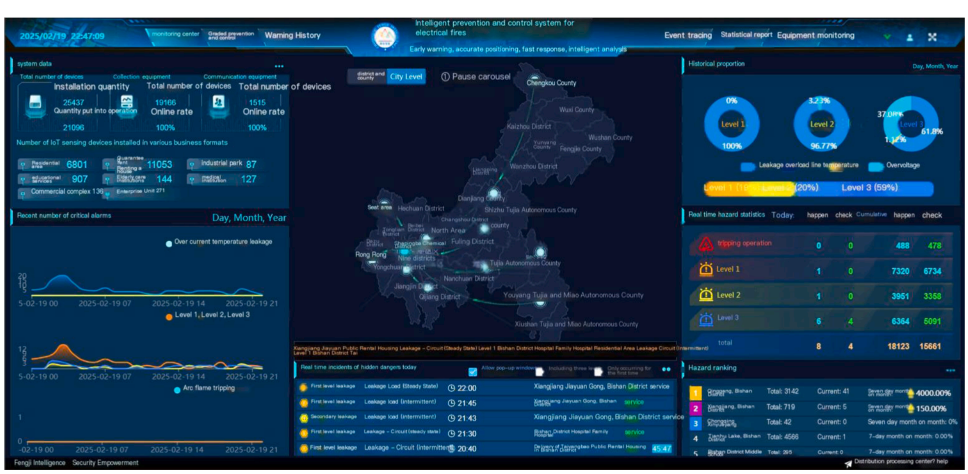

Fig. 5. Electrical fire monitoring system interface diagram.

process, a total of 25,473 related sensors and sensing devices were installed, and 1515 edge communication gateway devices were installed, as is shown in Fig. 5. Through the coordinated operation of these devices, the intelligent monitoring system can monitor the key areas of the community in real time, respond quickly to emergencies, and significantly improve management efficiency and safety protection capabilities. This section describes in detail the operating mechanism and actual application effect of the intelligent monitoring system from the perspective of system performance analysis and fire linkage business functions.

Each edge node uses the Modbus protocol to obtain data from the terminal data acquisition device. The protocol instructions are as shown in Table 2:

In the deployed intelligent circuit breakers, the number of registers that need to be collected is 40, and each register occupies 2 bytes. The edge node collects data at a frequency of 15 s/time, and the metadata is stored in the time series database of the edge node; the reporting platform frequency is 1 min/time, and the analysis data is stored in the distributed cloud database. The analysis data is mainly information with business value, which does not require high real-time performance and is used by applications on the common platform. According to the above collection frequency, the total amount of data stored on the edge side of the pilot is 2.70GB/month. It can be seen that the amount of metadata is huge, so the storage capacity of the edge node needs to be reasonably designed, at least 1.5 times the monthly storage amount when the data collection frequency is the highest; on the other hand, the time series database should have efficient life cycle management capabilities, including rolling storage and timely automatic cleanup of historical data design mechanisms.

4.3.1. *Intelligent monitoring system performance testing and analysis*

Alarm response capability is one of the important performance indicators of electrical fire systems. According to the different alarm triggering mechanisms, they can be divided into two types: passive alarm and active alarm [22].

Passive Alarm: When an abnormality or fault occurs in the electrical circuit, the built-in circuit breaker or protection device of the system will directly perform overload or short-circuit protection action, automatically cut off the circuit, and trigger an alarm in this way. This method relies on the self-protection function of the on-site equipment and usually responds after a fault occurs. According to the latest specifications for electrical fire monitoring systems [23], the short-circuit protection time of the circuit breaker should not be greater than 5 ms.

Active Alarm: The system collects electrical parameters (such as leakage, temperature, current, voltage, etc.) in real time, and based on intelligent analysis algorithms or preset alarm thresholds, provides early warning of potential electrical safety hazards. When an abnormal trend is detected, the system actively sends an alarm signal to remind users to take corresponding measures to reduce the risk of fire. The response time of active alarms has not yet been clearly regulated. The active alarm response time of traditional electrical fire systems should not be higher than 5 s.

Passive alarms are usually responses after a fault occurs. The FJB3–63 leakage protection circuit breaker deployed in this system has passed 3C certification and meets national standards. In contrast, active alarms make decisions based on comprehensive electrical parameters, have early warning capabilities, and can provide preventive measures before an accident occurs, which is the focus of this chapter.

The system will test the three key electrical parameters of current, voltage and temperature as monitoring objects. This section first proposes a Modbus-based edge response delay calculation model. The theoretical response value range is obtained through calculation and analysis of this model. Based on this, the topology structure is optimized so that the theoretical value is within the active alarm response time specification. secondly, a pilot application is carried out based on the topology structure, and test cases are created and executed for the three electrical parameters respectively to obtain the actual response value of the electrical parameter alarm; finally, the comprehensive response capability of the system is verified by determining whether the actual response value of the system falls within the theoretical response value range.

Data collection of electrical parameters. Current, voltage and temperature parameter sampling are all performed in the intelligent circuit breaker, and Modbus protocol based on the serial bus is used for communication. Modbus communication is divided into RTU(Remote Terminal Unit) mode and ASCII(American Standard Code for Information Interchange) mode. At the same rate, RTU mode allows a higher character density, so it has a higher throughput [24] and is more suitable for scenarios with high real-time requirements.

Calculation and derivation of edge response delay calculation model [25]. According to the Modbus RTU mode, the edge node and the device node transmit data in an 11-bit frame format with 1 start bit, 8 data bits, 1 stop bit, and 1 end bit. Combined with the transmission rate, the time it takes for the Modbus protocol to access a resource once can be calculated, and then the polling time after the master station traverses and accesses the resources of all nodes can be calculated [26]. Under the network topology of Fig. 3, the theoretical response value interval RT under a node computing domain can be calculated as RT = all request time + all response time + network access time + scanning cycle. RT can represent the time interval for the system to perceive any monitoring sensor parameter, reflecting the comprehensive response capability of the monitoring system, and is of great significance in the real-time performance of the fire monitoring system. The calculation method of the edge response delay calculation model RT is as follows:

$$\mathrm{R}\boldsymbol{T} = \sum_{i=1}^{\boldsymbol{NN}} \left(\frac{11 * (8 + (2 * \boldsymbol{NR_i} + 5))}{\boldsymbol{BR}} + \frac{\boldsymbol{DT_i}}{1000} \right) + \mathrm{NAT} + \mathrm{SP} \tag{1}$$

DT represents the device node response time, NR represents the number of resources of the device node, and SP represents the scanning period of the edge node to the device node. The formula $11 * (8 + (2 * \mathbf{NR_i} + 5))$ represents the total number of bits required to transmit to access NR 2-Byte resources in Modbus master-slave mode (sending 8-Byte request frames and receiving Byte response frames). It can be seen that in addition to constant parameters, RT is mainly affected by variable parameters NR and NN. Therefore, it is the key to balance the system perception capability and response performance to reasonably control the number of device nodes that represent the user and the number of resources that represent the number of sensor features to be monitored.

In the pilot residential area tested, the characteristics of the constant parameters are: device node response time DT = 200 ms; network access time public network NAT = 100 ms; baud rate BR = 115200bit/s; generally, the number of device node resources NR of the same category

Table 2
Edge node protocol instruction table.

Byte sequence number	Byte segment name	Byte length	Illustrate
1	Slave Address	1	Indicates the address of the target device (slave station), ranging from 1 to 247 (0 is the broadcast address)
2	Function code	1	0 × 03, read register instruction
3~4	Starting address	2	The register start addresses to be read, ranging from 0 × 0000 to 0xFFFF (high byte first, low byte last)
5~6	Number of registers	2	The number of registers to read, ranging from 1 to 125 (high byte first, low byte last)
$N+1$~$N+2$	CRC Check	2	Cyclic redundancy check (CRC-16) to ensure data integrity

is the same, and it is assumed that the device response time DT of the same edge node is the same. The pilot residential area structure is 11 households/floor, NN = 11, the number of necessary sensor data collected by the device node is 40, NR = 40, and the formula can be obtained:

$$RT = (2.39s + SP) \quad (2)$$

It is calculated that when a certain parameter of a household reaches the threshold, the system will theoretically receive an alarm notification between 2.39 s (optimal case) and (2.39+SP)s (worst case). The size of the interval depends on the value of SP in the edge node for the scanning cycle. If the actual response value of the system falls within the theoretical interval (2.39, 2.39+SP), it means that the system response capability has reached the index. The following analyzes the response capability of some key electrical parameters of the system under the pretest conditions of SP = 15 s and SP = 60 s.

(1) Current testing case analysis of current under SP = 15s

In the test condition, the system sets the current threshold of a household to 45A, and gradually starts high-power electrical appliances, so that the current rises from 11.4A at point A in normal conditions to 52A at point C within 69 s, exceeding the threshold. Since the collected values are discrete values with an interval of 15 s, the theoretical time of the threshold at point B is obtained through analysis and calculation, and the system response accuracy $\Delta T = T$(C)-T(B) is obtained. In this test, a total of 4 sample points that meet the alarm characteristics are generated, as shown in Fig. 5. The response accuracy (from left to right) calculated by the same method is shown in Table 3. The short transient value cannot represent the real situation, so the first transient situation is excluded and a total of 3 observation sample points are obtained (Fig. 6).

Therefore, under the test condition of SP = 15 s, the current alarm response accuracy of the three observation sample points is within Tth (2.39, 17.39), and the current response capability reaches the theoretical index.

(2) Analysis of voltage, temperature and residual current test cases under SP = 60s

In actual working conditions, the types of overvoltage are divided into operating overvoltage, resonant overvoltage and transient overvoltage [27]. In the test condition, the operating overvoltage is constructed for testing, the system voltage threshold is set to 275 V, and the overvoltage situation is simulated by performing multiple circuit break operations on the no-load line. This time, a point where the voltage value of a sample point has a positive correlation with the apparent power of phase A is captured as a test sample point. Based on the analysis, the theoretical time of point B threshold is calculated, and the system response accuracy $\Delta_T = T$(C)-T(B) = 14.74 s is obtained. In the same way, the system response time Δ_T for temperature and residual current can be obtained, as shown in the Figs. 7–9.

Therefore, under the test condition of SP = 60 s, the system response accuracy of voltage, current and residual current all fall within the Tth interval (2.39, 62.39), and the system response capability reaches the theoretical index.

In summary, in the delay range (2.39, 2.39+SP) that characterizes the system's active alarm response capability, the smaller the SP value, the better the system's response capability. In particular, when SP is less than 2.61 s, the system's active alarm delay requirement of <5 s can be met. In order to achieve a balance between network resources and response performance, the engineering value of SP = 2 s is the best.

Table 3
System current response accuracy.

Observation points	Response accuracy ΔT (seconds)
1	11.7
2	6.9
3	6.9

4.3.2. Disaster evacuation linkage services

Evacuation linkage service is one of the important functional indicators of the electrical fire system. When a fire occurs, due to the complex internal conditions of high-rise buildings and the large number of residents, there are often complex routes and unclear fire conditions when escaping and evacuating. Fire rescue personnel do not understand the complex internal conditions of the building, and the fire information is not specific enough. Digital building simulation technology plays an auxiliary role in improving fire safety management and emergency response to fire accidents [28]. When a fire occurs, it helps firefighters quickly understand the internal information of the building. The monitoring system can provide fire information and assist in making rescue plan layouts more quickly. However, there are still limitations, such as the inability to integrate data with the sensor system in real time, insufficient simulation of fire dynamic changes, and insufficient accuracy of personnel evacuation simulation [29]. This system attempts to establish a digital information model library for the building, import basic building physical structure, standard floor plan, number of building floors, number of households and other information, and use the data of the monitoring system to update the location of the fire point and the spread of the fire in real time, help residents make escape judgments, and assist firefighters in deploying rescue routes [30].

When an electrical fire occurs, for example, during the system test, there is a level 1 warning of a leakage alarm, the system will automatically power off. The system will immediately notify relevant staff members. In the test case, the system notified the property manager, support experts, electricians and other relevant personnel via SMS within 4 s, and automatically cut off the power. If the system's smoke detectors and flame detectors detect abnormal fire conditions, the location of the abnormality will be displayed in the building model. At this time, real-time data will continue to be transmitted to the platform to help staff determine the real-time situation of the fire.

Among the four sample groups, Community-J was selected as a case study for disaster escape and evacuation business linkage. The community has two 31-story high-rise residential buildings, each 3 elevators and 11 households, with a total of 710 households. Taking one of the high-rise residences as an example, based on the relevant information of the fire hydrant, equipment pipe well, building elevator and escape exit of the building standard floor, a BIM digital model was established, to simulate the analysis and recommendation of building fire escape path, fire safety passage and escape route, as shown in the Fig. 10.

In the fire disaster situation simulation test, assuming that the fire point is the user $\alpha-1$ on the α floor, when an electrical fire is detected, the fire alarm will be activated, the terminal will automatically carry out power off processing, and quickly notify the staff and all the users of this building through SMS to report the fire location. When no smoke or flames are detected in all the core tubes, users on all floors can evacuate via the stairs in coordination with the elevator [31]. Users on high floors ($x \geq \alpha$) are given priority to evacuate using the elevator, while users on low floors ($x < \alpha$) are given priority to evacuate using the stairs. When smoke and flame diffusion are detected in the front room of the α floor, the same floor and upper users will be notified through SMS. At this time, the fire control center will stop all elevators and only stair evacuation will be allowed. At the same time, the video terminal will also detect the opening of the roof safety channel. If it is open, the high-level users ($x > \alpha$) will be informed at the same time. In this case, the more high-level users can still choose to evacuate upward to the roof. If the roof safety channel is not opened, users (none No.1 users) above can choose temporarily hide in the safety place in their room. Due to the fire combustion direction is upward, and the speed is fast, located in the x-1 ($x > \alpha$) vertical direction of each layer of users cannot hide in their own

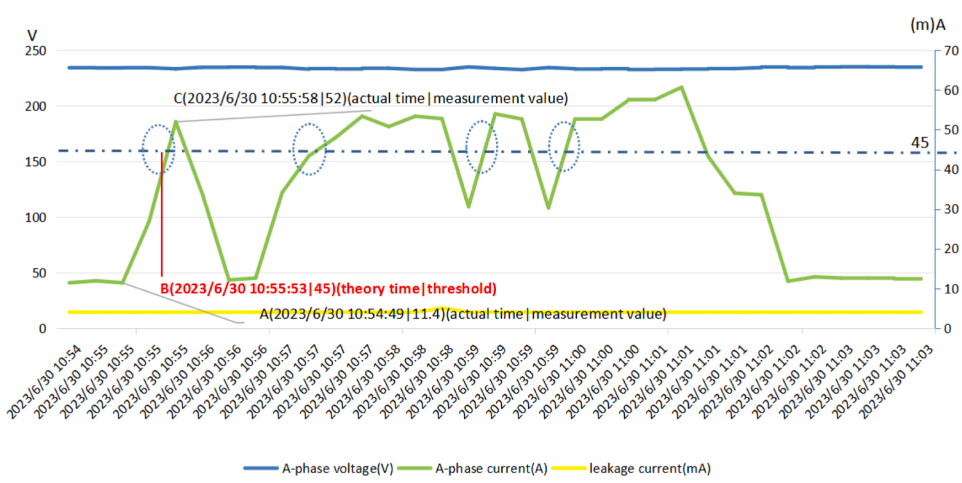

Fig. 6. Overcurrent test monitoring chart.

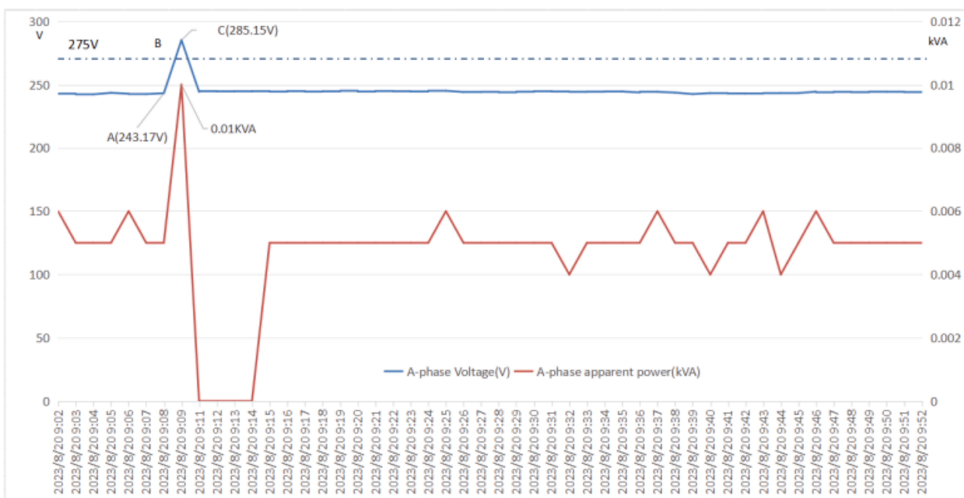

Fig. 7. Voltage response curve ($\Delta_T = 14.74$ s).

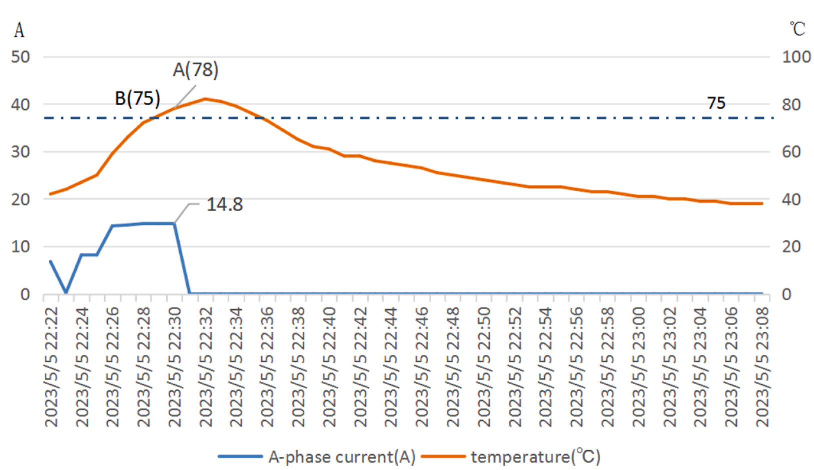

Fig. 8. Temperature response curve ($\Delta_T = 60$ s).

house. And if the escape route is blocked, they can give priority to find the users of $\alpha+$ 4 floor and above in the farthest end to the No.1 room for emergency temporary shelter, and waiting for rescue. The fire analysis and route recommendation schematic diagram is shown in Fig. 11.

Through the disaster rapid response and user warning notice, can effectively improve the response speed, especially to prevent the delay of night fire response. Through digital simulation and fire positioning, it can help users to judge the development of fire, and help to reduce the

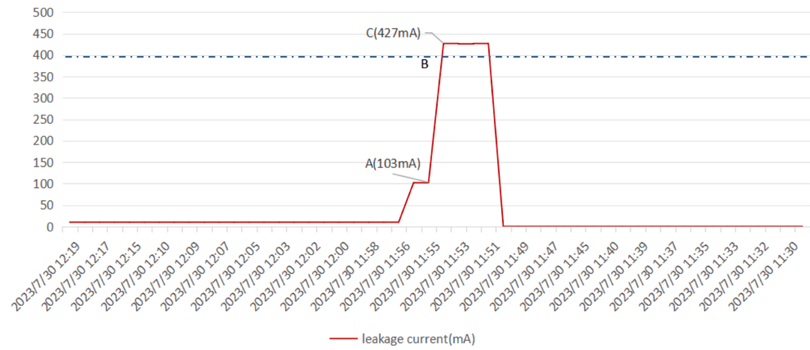

Fig. 9. Residual current response curve ($\Delta_T = 4.42$ s).

Fig. 10. Standard floor information analysis diagram and BIM model.

loss of personnel life safety caused by unimpeded evacuation path, smoke diffusion, safe channel blockage and so on, in the case of fire. At the same time, help firefighters to accurately locate the fire situation, and provide timely rescue guidance for the building.

5. Conclusion

The intelligent electrical fire monitoring system is based on the mature EC-IOT technical architecture system, adopts the design concept of cloud-edge-end collaboration, and has good horizontal business expansion capabilities. In view of the early warning decision of the system, the paper proposes an edge response delay calculation model based on the Modbus protocol, and designs a fine-grained distributed edge node networking architecture based on the model. On the edge node, the computing domain of the edge node is adjusted through model calculation to match the service scope of the node with the hardware computing power and communication delay requirements. This enables the edge node to focus more on adjacent businesses, perform local calculations and analysis close to the data source, and effectively reduce the delay caused by network transmission and multi-level forwarding. In the hierarchical early warning mechanism, edge nodes have local decision-making authority and can directly execute emergency operations and report them simultaneously, realizing an efficient response mechanism of "act first and report later".

For the business linkage of the system, the system innovatively realizes the deep integration of electrical fire technology, Internet of Things technology and digital building simulation technology, forming a pre-disaster intelligent early warning and post-disaster business intelligent linkage technology system. Electrical fire technology and specifications ensure the safe and stable operation of the power system. Internet of Things technology realizes pre-disaster intelligent analysis and monitoring and early warning through advanced sensors and network equipment, while digital building simulation technology

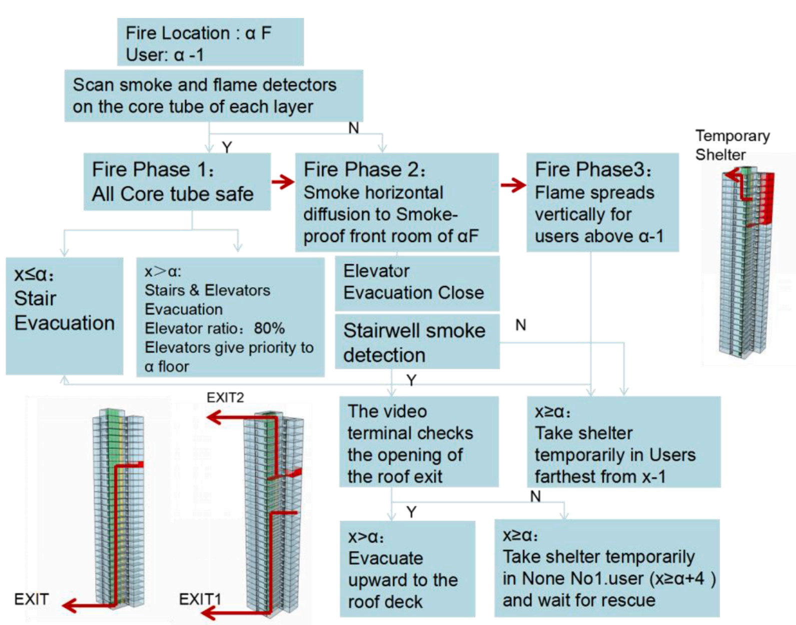

Fig. 11. Analysis and recommendation of the system escape route.

provides a constraint framework for the structure, layout and functional characteristics of physical buildings, enabling users to monitor and analyze more timely and conveniently. Results indicate that the system significantly improves early warning capabilities for electrical fires and enhances decision-making support for evacuation and fire rescue, demonstrating strong practical application value.

Due to space limitations, this article mainly focuses on the analysis of electrical parameters. However, the electrical fire monitoring system itself involves a variety of complex factors. In the future, we can further explore the deep integration of multi-source heterogeneous data, combine electrical fire monitoring data with environmental monitoring data, user behavior data, etc., and use big data analysis and artificial intelligence technology to improve the system's intelligent warning and decision-making capabilities. In addition, with the help of AI technology development, knowledge graph technology can be introduced to build a knowledge base in the field of electrical fires. Combined with a large language model, it will help enhance the system's cognitive reasoning ability, enabling it to more accurately identify fire risks and provide more scientific and efficient warning information, thereby improving the level of intelligence in electrical fire prevention and control.

CRediT authorship contribution statement

Mengying Ma: Writing – review & editing, Writing – original draft, Visualization. **Chengdi Xu:** Writing – original draft, Visualization, Validation. **Junfeng Han:** Visualization, Validation.

Declaration of competing interest

The author declares that there is no conflict of interest in this article.

References

[1] Xi Jinping, in: Report of the 20th National Congress of the Communist Party of China, 2022.
[2] National Fire, Rescue Administration Statistics. https://www.119.gov.cn/qmxfgk/sjtj/index.shtml.
[3] Residential building electrical design code, 2011. JGJ 242-2011, Section 3.3.
[4] National standard of the People's Republic of China, 2022. Civil Building Electrical, Design Standard.
[5] M.M. Alam, M. Shahjalal, M.H. Rahman, et al., An energy and leakage current monitoring system for abnormality detection in electrical appliances, Sci. Rep. 12 (2022) 18520.
[6] M.L. Saini, R. Kumar, D.C. Sati, T. Bharti, Fire monitoring and prevention system based on the severity of fire using NodeMCU and Cloud, in: 2024 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics (IITCEE), 2024. Bangalore, India.
[7] P. Dileep Kumar Reddy, Martin Margala, S. Siva Shankar, Prasun Chakrabarti, Early fire danger monitoring system in smart cities using optimization-based deep learning techniques with artificial Intelligence[J], J. Reliab. Intell. Environ. 10 (2024) 197–210.
[8] C.H. Kim, K.H. Lam, H.S. Lee, et al., Early fire detection system by using automatic synthetic dataset generation model based on digital twins[J], Appl. Sci. 14 (5) (2024).
[9] Jiang Jianfeng, Yang Liufang, Cao Weijia, Liao Youwei, Design and implementation of combined electrical fire detector based on NB-IoT and single-chip microcomputer[J], Fire Sci. Technol. 39 (08) (2020) 1142–1144.
[10] Men Maochen, Du Yujia, Xu Mingming, Wu Huanzhao, Research on intelligent electrical fire monitoring based on residual current waveform characteristics[J], Fire Sci. Technol. 42 (04) (2023) 549–554.
[11] Jin Shan, Jin Zhigang, High-rise building fire monitoring system architecture based on distributed WSNs[J], Comput. Eng. Technol. 40 (8) (2019) 2167–2173.
[12] Peng Tianhai, Chen Yu, Yang Fan, Su Lei, Information model of electrical fire monitoring terminal in high-rise buildings[J], J. Shandong Univ. (Eng. Sci. Ed.) 52 (10) (2022) 132–140.
[13] Cao Lei, Wang Yun, Xu Shihua. Load sensing and diagnosis based on digital twin technology distribution simulation[J], Intell. Build. Electr. Technol. 18 (3) (2024) 39–42.
[14] Song Yang, Wang Jing, Dynamic analysis of fire safety evacuation in complex buildings based on digital twin concept[J], Sci. Technol. Eng. 23 (24) (2023) 10596–10603.
[15] Luo Xin, Visual fire monitoring and escape rescue system based on the internet of Things[D], Chongqing Univ. 6 (2020).
[16] Edge Computing Reference Architecture 3.0 White Paper, Edge Computing Industry Alliance (ECC) and Industrial Internet Industry Alliance (AII), 2018, p. 11.
[17] https://www.cqfjzn.cn/?yinjian/, 2022.
[18] N.B. Mohamadwasel, A. Ma'arif, NB theory with bargaining problem: a new theory [J], Int. J. Robot. Control Syst. 2 (3) (2022) 606–609.
[19] Y.R. Mohammed, N. Basil, O. Bayat, et al., A new novel optimization techniques implemented on the AVR control system using MATLAB-SIMULINK[J], Int. J. Adv. Sci. Technol. 29 (5) (2020) 4515–4521.
[20] N. Basil, B.M. Sabbar, H.M. Marhoon, et al., Systematic review of unmanned aerial vehicles control: challenges, solutions, and meta-heuristic optimization[J], Int. J. Robot. Control Syst. 4 (4) (2024).
[21] Wang Yixu, Xiao Xiaoling, Wang Pengfei, et al., Improved YOLOv5s algorithm for small target smoke and flame detection[J], J. Comput. Eng. Appl. 59 (1) (2023).
[22] N.B. Mohamadwasel, S. Kurnaz, Implementation of the parallel robot using FOPID with fuzzy type-2 in use social spider optimization algorithm[J], Appl. Nanosci. (2021) 1–11.
[23] GB 14287.6-2020, Electrical Fire Monitoring System - Part 6: Electrical Fire Prevention Current-limiting Protector for electric fire prevention, Standardization Administration of China (SAC), 2020.
[24] V.G. Găitan, I. Zagan, N.C. Găitan, Modbus RTU protocol timing evaluation for scattered holding register read and modbuse-related implementation, Processes 13 (2) (2025) 367.
[25] N. Basil, H.M. Marhoon, Selection and evaluation of FOPID criteria for the X-15 adaptive flight control system (AFCS) via Lyapunov candidates: optimizing trade-offs and critical values using optimization algorithms[J], e-Prime-adv. Electr. Eng. Electr. Energy 6 (2023) 100305.
[26] VasileGheorghiță Găitan, Ionel Zagan, Modbus protocol performance analysis in a variable configuration of the physical fieldbus architecture, IEEE Access 10 (2022) 123942–123955.
[27] A.F. Mohammed, H.M. Marhoon, N. Basil, et al., A new hybrid intelligent fractional order proportional double derivative+ integral (FOPDD+ I) controller with ANFIS simulated on automatic voltage regulator system[J], Int. J. Robot. Control Syst. 4 (2) (2024).
[28] H.M. Marhoon, N. Basil, A. Ma'arif, Exploring blockchain data analysis and its communications architecture: achievements, challenges, and future directions: a review article[J], Int. J. Robot. Control Syst. 3 (3) (2023) 609–626.
[29] N. Basil, H.M. Marhoon, A.F Mohammed, Evaluation of a 3-DOF helicopter dynamic control model using FOPID controller-based three optimization algorithms[J], Int. J. Inf. Technol. (2024) 1–10.
[30] N. Basil, A.F. Mohammed, B.M. Sabbar, et al., Performance analysis of hybrid optimization approach for UAV path planning control using FOPID-TID controller and HAOAROA algorithm[J], Sci. Rep. 15 (1) (2025) 4840.
[31] Liu Zhaofeng, Xu Qiang, Qi Qin, Research on simulation and strategy of emergency evacuation in high-rise residential building fire[J], J. Catastrophol. 37 (2) (2022) 174–181.