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Development of Fire Risk Reliability Model for Distribution Systems Based on RBI Technology

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Abstract This paper improves the fire detection method for distribution systems based on RBI theory, establishes a reliability model for fire risk in distribution systems, and uses the risk assessment results to formulate a fire detection plan suitable for the evaluation object. The probability of a fire accident occurring in a distribution system line is expressed using five parameters. Based on the classification standards for failure probability levels, the probability level of a fire occurring in a distribution system line is determined. The severity of fire consequences in distribution system lines is summarized using six parameters. Based on the classification criteria for consequence levels, the consequence level of fire accidents in distribution system lines is determined. Finally, the fire risk reliability of the distribution system is assessed using the fire risk matrix. Taking a certain substation as an example, an RBI assessment of its fire risk was conducted, identifying three high-risk projects. Corresponding fire prevention and control measures were proposed for rectification.

Index Terms RBI, distribution system, risk matrix, reliability model

I. Introduction

With the advancement of technology, an increasing number of electrical devices are being used in daily production and life. As a result, electricity has gradually become the most important energy source in human production and life [1], [2]. While electricity is widely applied in production and daily life, bringing greater convenience to humanity, it also poses potential hazards. In recent years, electrical fires have accounted for the highest number of fire incidents in China's fire accident statistics. Electrical fires are primarily caused by issues such as electrical leakage, short circuits, and overloading [3]-[5]. Areas with high rates of electrical fires are primarily concentrated in large and medium-sized cities and economically developed regions, and the incidence of electrical fires has been increasing annually [6], [7]. Locations with frequent electrical fires are primarily densely populated areas, such as farmers' markets, large shopping centers, cinemas, and other cultural and entertainment venues [8], [9]. As such, electrical fires have had adverse negative impacts on economic construction and development, and these impacts are becoming increasingly severe [10].

Given the severe trend of electrical fires, the current focus of fire safety work lies in preventive measures such as predicting, warning, and forecasting electrical fire accidents, thereby eliminating the root causes of electrical fires [11]-[14]. Currently, electrical fire safety inspections are one of the most effective methods for preventing electrical fire accidents. By identifying fire hazards and assessing risks, such inspections help prevent fire accidents from occurring [15], [16]. Therefore, in preventing electrical fire accidents, it is essential to adhere to the principle of "safety first, prevention foremost." Reliability models should be used to conduct comprehensive fire safety inspections of electrical equipment, promptly eliminating safety hazards to prevent electrical fire accidents [17]-[20].

In the face of increasingly severe electrical fire accidents, many scholars have developed safety inspection methods to prevent electrical fire accidents. Literature [21] proposes a real-time deep learning algorithm to classify and locate faults in large-scale power distribution networks. By extracting feature vectors from distribution line measurement values, it can not only identify locations with fire risks but also accurately determine the type of system fault. Literature [22] designed an intelligent electrical fire detection technology for green buildings. By extracting multi-information fusion data, it detects arc faults in building distribution systems and further validates the reliability of detection results through simulation, effectively preventing electrical fires within buildings. Reference [23] combines intelligent electronic device relays with controllable solid-state circuit breakers to form an effective detection scheme for DC faults in distribution systems. It can characterize the transient behavior of various fault conditions and locations, thereby achieving fault protection for distribution systems. Reference [24] introduces a power line communication method for detecting real-time fault types and locations in power lines. By using a zero-crossing detector to determine the sequence of the R, Y, and B phases, it achieves accurate indication of fault conditions. Reference [25] explores detection and isolation methods for series DC arc faults in distribution systems. It employs an integrated machine learning (EML) algorithm to train on different arc fault behavior indicator data, enabling accurate identification of arc faults under varying load conditions and reducing fire hazards. Reference [26] indicates that the operational characteristics and fault characteristics of photovoltaic distribution systems under partial shading conditions are similar. Therefore, by utilizing wavelet packet analysis of voltage and current data from photovoltaic arrays for fault detection, the system's tripping function under fault conditions can be significantly ensured, thereby improving system protection efficiency. Literature [27] highlights the importance of early simulation and detection of DC arc faults in photovoltaic systems. By comparing DC arc fault models suitable for different conditions, the detection rate of arc faults in distribution systems is improved, thereby preventing severe fire hazards caused by photovoltaic systems. The methods proposed in the aforementioned studies effectively ensure the safe and reliable operation of distribution systems. However, they do not consider the workload and cost of system detection, which to some extent reduces the efficiency of risk management in distribution systems. The essence of RBI (Risk-Based Inspection) technology lies in analyzing and prioritizing the likelihood of hazardous events occurring and the severity of their consequences, enabling targeted and scientific detection. This ensures the safe and reliable operation of the detection system while also improving safety performance, making it particularly effective in electrical fire prevention detection.

This paper comprehensively compares the magnitude of risk from two dimensions: the probability of an accident occurring and the severity of its consequences, thereby establishing a reliability model for fire risks in distribution systems. The formula $F=((1-F1)\times(1-F2)\times(1-F3)\times(1-F4)\times(1-F5)$ is used to calculate the probability of a fire accident occurring in a distribution system. The formula $C=C1+C2+C3+C4+C5+C6$ is used to calculate the severity of the consequences of a fire accident in the distribution system. Through case analysis, the reliability of fire risk in the distribution system is assessed, and fire prevention measures are proposed.

II. Risk-based inspection (RBI) technology

RBI stands for "risk-based inspection." It is an optimized inspection strategy method established on the basis of the concept of pursuing the unity of system safety and economic efficiency. Its essence is a management method that aims to ensure intrinsic safety and reduce operating costs by scientifically analyzing the probability and consequences of inherent or potential dangerous events in a system, ranking risks, and identifying major problems and weak links [28].

II. A. Basic Principles of RBI

RBI links the risks that may occur during equipment use with in-service inspections. By applying risk analysis, all equipment in the process, including pipelines, is ranked according to risk. Based on this, only high-risk equipment is inspected using effective inspection methods tailored to the characteristics of the damage, significantly reducing the risk. This ensures that the risk level of all equipment in the process remains at a low or acceptable level during the next operational period. Inspection plans developed using the RBI method do not require inspections for medium- and low-risk equipment. This is an advanced method for developing inspection plans, which can reduce equipment risks and production costs.

When conducting RBI analysis, risk is defined as the probability of failure within a certain period of time multiplied by the consequences of failure, i.e., the potential losses to personnel, the environment, and economic property caused by failure. Risk can be expressed by the following formula:

$$Risk = F\text{ailure probability} \times F\text{ailure} \tag{1}$$

From the definition of risk, it can be seen that risk management can be considered from two aspects: reducing the probability of failure and minimizing losses. Based on an understanding of the two-dimensional nature of risk, RBI achieves equipment integrity management through more targeted risk management measures.

In quantitative RBI analysis, the probability of failure is considered to be composed of three factors: general failure frequency (GFF), equipment correction factor (FE), and management system evaluation factor (FM), namely:

$$F\text{ailure probability} = GFF \times F\text{E} \times FM \tag{2}$$

II. B. RBI's analytical approach

RBI identifies the failure mechanisms and modes of all equipment, analyzes the probability and consequences of failure, and calculates the risk level of each piece of equipment, ranking them accordingly. Based on this, effective inspection methods are applied to high-risk equipment to reduce risk, while medium- or low-risk equipment may require fewer inspections or none at all.

RBI analysis methods are categorized into three types: qualitative, quantitative, and semi-quantitative. These three methods complement each other, forming a continuous unified system rather than distinct, separate approaches. A typical RBI project typically integrates the use of qualitative, semi-quantitative, and quantitative methods. The selection of these methods can be tailored to the specific needs of different stages in the development of equipment inspection plans.

Qualitative RBI methods are simplified analytical approaches that rely on engineering experience for judgment, requiring only a small amount of data input and applying simple algorithms to assess the likelihood and consequences of equipment failure. This method can quickly and roughly rank equipment risks, distinguishing low-risk equipment (or areas) from high-risk equipment (or areas). Using this method to develop an equipment inspection plan is relatively conservative. Qualitative RBI methods require implementation by experienced personnel.

Quantitative RBI methods are precise but labor-intensive. This method requires detailed analysis of a large amount of data, enabling risk ranking for all equipment. It can identify whether current inspection procedures result in over-inspection or under-inspection, and allow effective inspection of high-risk equipment based on risk ranking and damage mechanisms. Additionally, it can calculate inspection costs and the benefits derived from applying RBI methods.

Semi-quantitative RBI methods require the same data as quantitative methods but do not need to be as precise, allowing for simplified approaches such as estimating fluid volumes within equipment. This significantly reduces the time required compared to quantitative methods while yielding most of the results obtained by quantitative RBI methods.

In most cases, a qualitative or semi-quantitative RBI method can first be used to analyze the entire facility, followed by a detailed analysis of equipment in high-risk areas using a quantitative RBI method.

The RBI plan process is shown in Figure 1. It describes the key elements of a risk-based inspection plan. These key elements are essential for any comprehensive plan, regardless of the method used (qualitative, semi-quantitative, or quantitative).

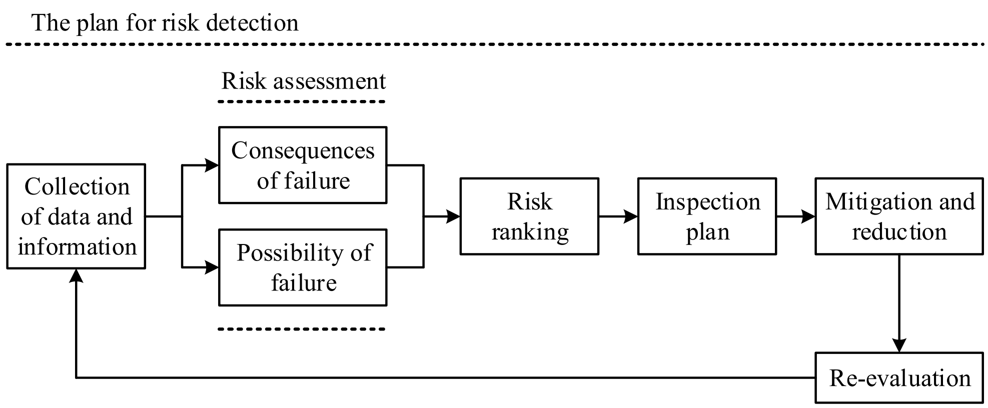

Figure 1: The process of RBI

II. C. *Application of RBI Technology in Distribution Systems*

In power distribution systems, the concept of risk was first introduced in the nuclear power industry and has since been extended to grid systems such as thermal power generation. Risk-based maintenance (RBM) technology applied to thermal power plants is primarily implemented through two methods: risk-based inspection (RBI) technology and risk-based maintenance (RBM) technology. The main implementation steps are as follows: system segmentation, identification of critical components, data organization for assessment, establishment of damage mechanisms, identification of high-risk components, risk rating, and risk management.

In recent years, the application of risk inspection and risk management in distribution systems has provided an additional safety assurance scheme for power plant equipment. In the future, combining risk inspection with remaining life calculation in asset integrity management methods within distribution systems will be a more effective approach [29].

III. Establishment of a reliability model for fire risks in power distribution systems

III. A. *Prerequisites for Model Establishment*

The fire risk assessment of the power distribution system established in this paper covers the general requirements for fire safety inspections of low-voltage power distribution lines, lighting devices, and general low-voltage electrical equipment, visual inspections, instrument inspections, and methods for identifying fire hazards in power distribution systems and handling the results. Assumptions for establishing the model:

(1) The electrical equipment at the terminals of the power distribution system is reliable and safe.

(2) The primary and secondary power distribution devices are reliable and safe.

III. B. *Risk Reliability Model*

According to the definition of risk: risk is expressed in terms of the severity and probability of potential accidents, reflecting the impact and likelihood of accidents. Therefore, risk is expressed using equation (3):

$$R = F \times C \tag{3}$$

Among them, R ——electrical wiring fire accident risk, F ——probability or possibility of electrical wiring fire accidents, C ——severity of electrical wiring fire accidents.

The concept of accident risk indicates that risk is determined by two factors: consequences and probability of occurrence. The magnitude of risk must be comprehensively compared from these two dimensions.

III. B. 1) Possibility of fire accidents

Analyzing a complete power distribution system circuit can be viewed as a loop, which consists of load terminals (electrical equipment), wires, switches, circuit breakers, power sources, and other components. The structure diagram of this power distribution system circuit is shown in Figure 2.

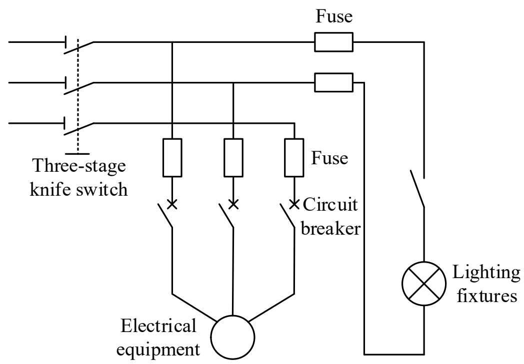

Figure 2: Construction chart of distribution line

The reliability diagram of the power distribution system circuit is shown in Figure 3. It can be seen that in this large circuit of the power distribution system, all components are connected in series. When all components are functioning normally, the system can operate normally. In other words, when any component in the power distribution system circuit fails, it will cause the system to fail.

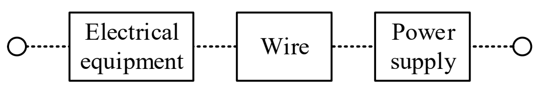

Figure 3: Reliability block diagram of distribution line

Based on the assumptions established by the model, this paper concludes that primary and secondary power distribution equipment is reliable and safe.

Based on the structure of the power distribution system lines and the mechanism of power distribution system fires, an accident tree for power distribution system fire accidents can be drawn, as shown in Figure 4.

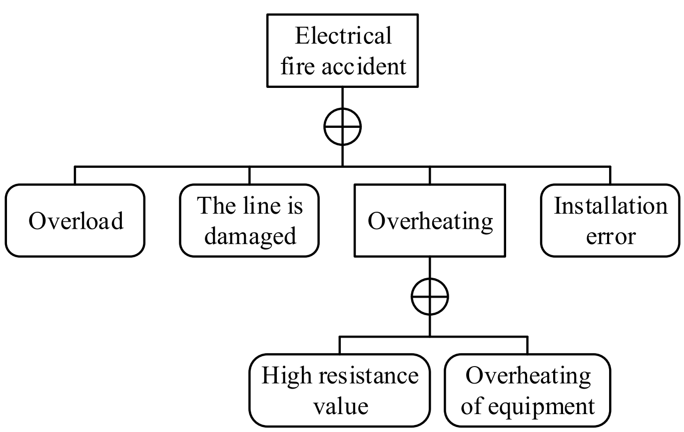

Figure 4: Distribution circuit fire accident tree

In this paper, the load factor $F1$ is used to evaluate the failure rate of electrical equipment, mainly considering whether there is overload in the distribution system lines, that is:

$$F1 = P(X1) \tag{4}$$

The failure rate of electrical wires is evaluated using the damage coefficient $F2$, which mainly considers the damage to the wiring, i.e.:

$$F2 = P(X2) \tag{5}$$

A complete power distribution system circuit necessarily has connection points (commonly known as wire ends). The handling of each wire end also affects the reliability of the power distribution system circuit. Poor contact at the connection points will increase the resistance value. Once the power is turned on, the connection point with high resistance will become a hot spot, which may lead to a fire. Therefore, this paper uses the resistance coefficient $F3$ to evaluate the resistance problem of the circuit, mainly considering whether the installation of the connection points in the power distribution system circuit complies with regulations, that is:

$$F3 = P(X3) \tag{6}$$

There is a special type of electrical equipment known as high-temperature heating equipment. This type of electrical equipment can quickly convert electrical energy into thermal energy. If such equipment is placed too close to combustible materials, it can easily cause a fire. Therefore, this paper considers it separately and uses the equipment coefficient $F4$ to evaluate equipment overheating issues, i.e.:

$$F4 = P(X4) \tag{7}$$

A key factor in distribution system fires is combustible materials. Here, combustible materials refer to materials that are installed too close to the various components of the distribution system during the installation process. This is related to the installation of the distribution system. Therefore, this paper uses the process coefficient $F5$ to evaluate the installation of the distribution system, mainly considering whether the entire distribution system installation meets the requirements, i.e.:

$$F5 = P(X5) \tag{8}$$

By calculating the probability of occurrence of each basic event in a power distribution system fire accident, we can calculate the probability of occurrence of the top event, a power distribution system fire accident, F, that is:

$$F = P(T) \tag{9}$$

The likelihood of a fire accident occurring in a power distribution system is determined by the following five parameters: $F1$、$F2$、$F3$、$F4$、$F5$:

$$F = ((1-F1)\times(1-F2)\times(1-F3)\times(1-F4)\times(1-F5)) \tag{10}$$

The classification of failure probability levels is shown in Table 1:

Table 1: Failure probability level

Failure probability coefficient	Feature	Failure probability level
0~0.2	rarely	1
0.2~0.4	chance	2
0.4~0.6	sometimes	3
0.6~0.8	It's likely to happen	4
>0.8	Occur often	5

III. B. 2) Consequence Analysis

Based on the factors influencing the consequences of fire accidents in distribution system lines, the severity of fire consequences in distribution system lines is summarized using the following six parameters: fire load coefficient $C1$, firefighting coefficient $C2$, environmental coefficient $C3$, personnel coefficient $C4$, protection coefficient $C5$, and toxicity coefficient $C6$.

Since these six severity levels are independent of each other, they do not influence one another, and their effects are additive, this paper uses a simple summation method to calculate the severity of consequences of distribution system line fires:

$$C = C1 + C2 + C3 + C4 + C5 + C6 \quad (11)$$

The classification of consequence levels is shown in Table 2.

Table 2: Consequence grade

Damage factor	Grade	Damage level
0~20	Ignorable	A
21~40	Medium	B
41~60	Severe	C
61~80	Hazardous	D
>81	Catastrophic	E

III. C. Risk Level Classification

This paper divides the assessment of research subjects into four levels, with the risk matrix shown in Figure 5.

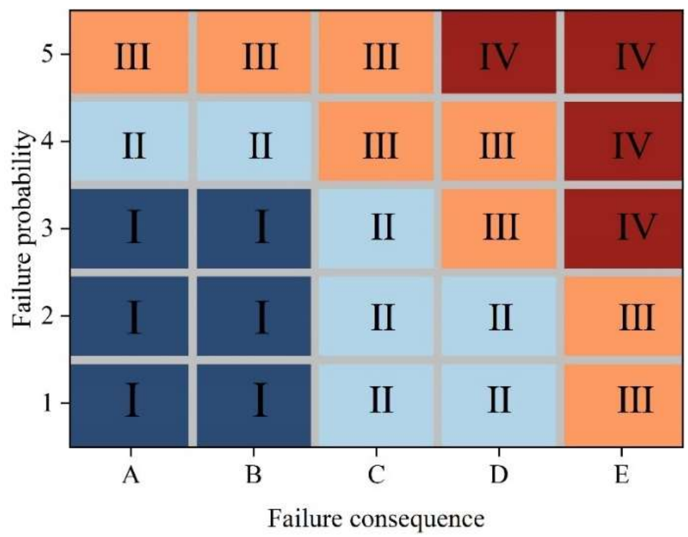

Figure 5: Risk matrix

In the RBI application process, different countermeasures are taken for different risk levels, as shown in Table 3. There are four levels in total: high risk, medium-high risk, medium risk, and low risk.

Table 3: Risk hierarchy

Grade	Area of danger	Countermeasures
I	Low risk area	Reduce inspection and maintenance as appropriate (extend the inspection cycle)
II	Medium risk area	Regular maintenance and inspection shall be carried out
III	Medium-high risk area	Conduct online monitoring and nondestructive testing (shorten the inspection cycle)
IV	High risk area	We will strengthen management and rectify the problems and eliminate the problems of accidents

IV. Application examples

IV. A. Overview of the power distribution system

A certain 330 kV unmanned substation has a station area measuring 120 m east-west and 95 m north-south. The average temperature at the site is 15.4°C, with an extreme maximum temperature of 38.5°C, and an average wind speed of 2.5 m/s. The substation entrance is located on the west side. The main control and communication room is oriented north-south in a linear layout. The 330kV structure, GIS foundation, and 330kV relay room are arranged on the north side of the station area. The 110kV structure, GIS foundation, 330kV relay room, and 35kV No. 2 distribution room are arranged between the 110kV distribution area and the 330kV distribution area. Capacitors and reactors are arranged on both sides of the main transformer. The substation has 3 × 240 MVA transformers, 4 × 30 MVA oil-filled capacitors, and 4 × 30 MVA reactors. The walls of the outdoor cable trench are constructed using reinforced concrete, cast in one piece, with drainage channels at the bottom of the trench. The trench covers are made of prefabricated composite high-strength cable trench covers. The clear width of the main circular fire lane within the station is 4.0m, with a turning radius of 9m. The slope of the fire lane is 0.5%. The circular fire lane connects to other lanes at two points.

(1) Building Structural Fire Protection Design

The fire resistance rating of internal structural columns is 2.4 hours, structural beams have a fire resistance rating of 1.4 hours, load-bearing walls are 250 mm thick with a fire resistance rating of 2.4 hours, and non-load-bearing walls are 115 mm thick with a fire resistance rating of 0.4 hours.

(2) Fire Protection Power Supply and Fire Protection Distribution System Equipment

The fire control room serves as the main control room. Fire protection electrical equipment: The fire alarm control panel is powered by a dual power supply, including an UPS power supply and a battery power supply. Except for the main control communication room, no fire protection equipment is installed in the equipment rooms.

(3) Fire Emergency Lighting and Evacuation Guidance System

Emergency lighting provides 10% illuminance. Evacuation signs are installed at exit locations and personnel passageways. The emergency lighting load is supplied by the accident lighting power distribution panel, which has one AC input and one DC input. The DC circuit is equipped with an inverter transformer. Under normal conditions, AC power is supplied; in case of a fault, DC power is converted to AC power. The system provides continuous power supply for 2 hours.

(4) Fire Alarm System

(5) Fire Water Supply and Fire Extinguishing Facilities

The main transformer fixed fire extinguishing system uses an oil drainage and nitrogen injection fire extinguishing device. The system's nitrogen cylinders are configured with a capacity of 45L, and the oil drainage pipe has a diameter of DN150. The main transformer, secondary equipment room, monitoring room, battery room, and other areas are equipped with different quantities and models of ammonium phosphate dry powder fire extinguishers.

IV. B. RBI Risk Assessment

IV. B. 1) RBI Risk Testing Preparation

Based on the scope of work already determined and the division of districts, the status of projects within each district is shown in Table 4.

Table 4: List of district projects

Partition	Item name	Quantity
Zone 1	Coal pipe	1
	Provincial coal holder suspension tube	1
	Provincial coal entry box	3
	Economizer outlet header	2
	Water wall internal thread	1
	Water cooler	5
Zone 2	Upper wall	3
	Water-cooled wall drain	2
	Horizontal flue wall	1
	Upper wall	1
	Ceiling superheater tube	2
	underpass	3
	Wall tube	5
Zone 3	Screen tube	1
	Screen overboard	3
	End superheater inlet tube	2
	End superheater outlet tube	2
Zone 4	Reheater cold section inlet tube	5
	Reheater cold segment outlet pipe	1
	Reheater heat segment inlet tube	3
	Reheater heat segment outlet pipe	2
	Reheater entry header	1
	Reheater outlet small header	3
	Reheater outlet catheter	4

IV. B. 2) RBI Risk Matrix and Analysis

After completing the statistical analysis of project data across the four zones, calculate the failure probabilities for each zone and determine the distribution of risk levels.

(1) The analysis results for Zone 1 are shown in Figure 6. From the matrix diagram, it can be seen that there are no high-risk projects, 1 medium-high risk project, 8 medium-risk projects, and 8 low-risk projects. The economizer suspension pipe is a project with relatively high risk, and its primary damage mechanism is fly ash wear. The effective inspection strategy for it is to strengthen macro-level inspection measurements during maintenance periods.

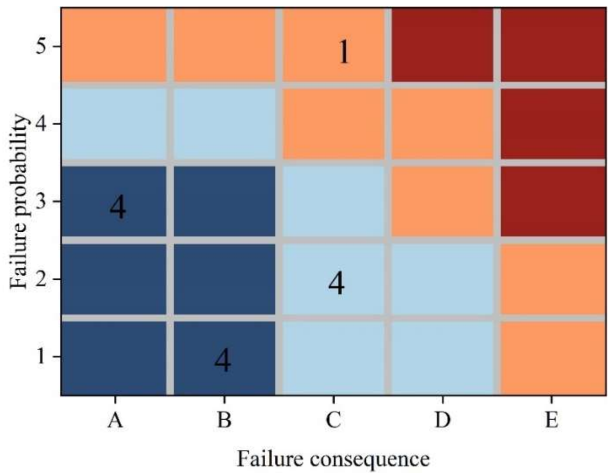

Figure 6: Analysis results of Zone 1

(2) The analysis results for Zone 2 are shown in Figure 7. From the matrix diagram, it can be seen that there is one high-risk project, one medium-high risk project, four medium-risk projects, and the rest are low-risk projects. The high-risk project is the water-cooled wall internal threaded pipe, whose primary damage mechanism is H2S corrosion, and the effective strategy is process data adjustment.

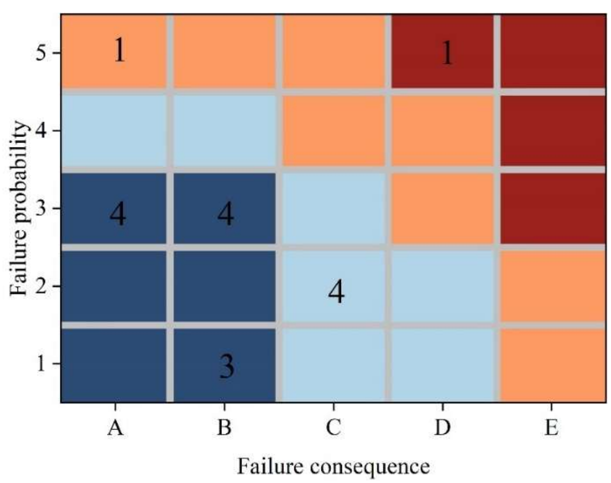

Figure 7: Analysis results of Zone 2

(3) The analysis results for Zone 3 are shown in Figure 8. From the matrix diagram, it can be seen that there are 2 high-risk projects, 2 medium-high-risk projects, 4 medium-risk projects, and 11 low-risk projects. One of the high-risk projects is the screen inlet pipe, whose damage mechanism is mainly high-temperature overheating, and the effective strategy is creep measurement. The other project is the screen outlet pipe, whose damage mechanism is mainly spheroidization, and the effective strategy is metallographic analysis and hardness testing.

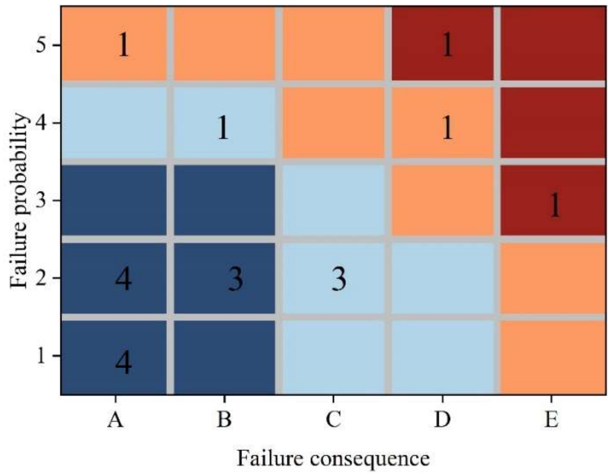

Figure 8: Analysis results of Zone 3

(4) The analysis results for Zone 4 are shown in Figure 9. From the matrix diagram, it can be seen that there are no high-risk projects, with 2 medium-high risk projects, 4 medium risk projects, and 2 low risk projects. The higher-risk projects are the inlet of the cold section and the outlet of the hot section of the reheater. The primary damage mechanism is water-vapor erosion, and the effective strategy is to adjust the operation mode of the soot blower.

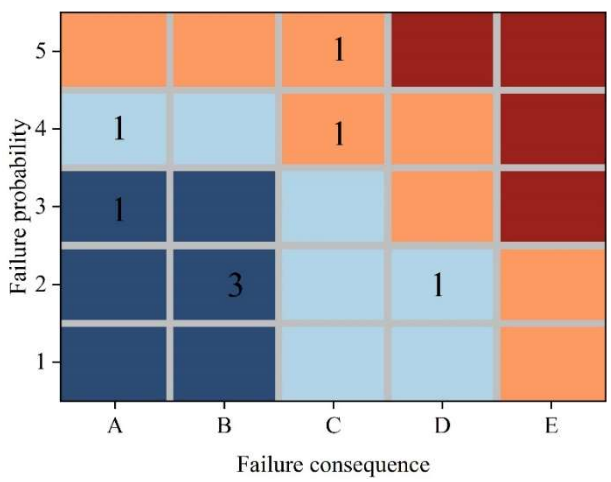

Figure 9: Analysis results of Zone 4

The number of devices with different risk levels in the four zones is shown in Figure 10. There are 3, 6, 14, and 34 items, respectively, from high-risk to low-risk items.

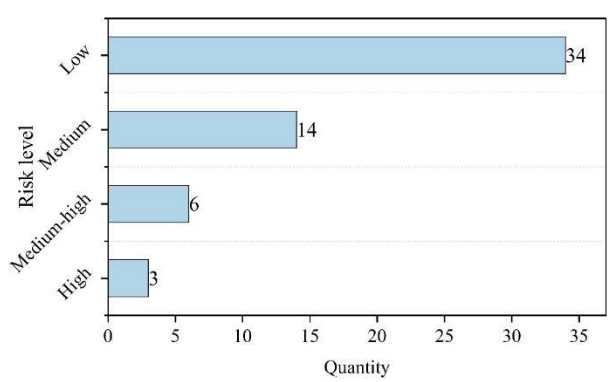

Figure 10: The number of devices at different risk levels in four partitions

In summary, based on the fire risk reliability model, it can be effectively analyzed that there are currently three high-risk projects in this substation, and fire prevention and control measures need to be implemented in a timely manner.

IV. C. Fire prevention and control measures for power systems

In order to effectively curb the occurrence of fire accidents in the long term, the key lies in implementing strict fire management strategies, including establishing clear operating procedures, conducting regular drills, and using information technology to enhance fire prevention awareness and emergency response capabilities. According to the "Fire Prevention Management Regulations for Power Systems," power companies should arrange at least four fire drills per year, and during seasons with high fire risk, such as summer, the number of drills should be doubled. The improvement of employees' emergency response capabilities hinges on the implementation of fire drills. Experimental results indicate that routine drills can reduce fire response times by over 20%. According to the "Electric Power Safety Training Standards," at least 24 hours of mandatory training per year is required for the popularization of firefighting knowledge and the improvement of skills, covering early fire alarms, emergency evacuation procedures, and the effective operation of firefighting equipment, so that every employee can demonstrate basic response skills in the event of a fire. The preparation of emergency plans and their application in fire accidents are key links in management strategies. This process should ensure key elements such as the cutting off of equipment power, the design of personnel evacuation routes, and the operation of fire extinguishing facilities. The "Electric Power Fire Emergency Plan Standards" clearly stipulate that the coverage of these elements must reach 100%. The use of advanced information management tools to monitor fire-related information in real time and achieve data sharing has become a key measure to strengthen fire safety management. According to the recommendations of the "Technical Specifications for Intelligent Fire Management," each fire drill and accident record should be entered into the system to enable real-time sharing and access to firefighting data, with the aim of improving the scientific nature of fire prevention work. The use of systematic and data-based fire management methods has significantly enhanced the fire prevention and control capabilities of the power system and ensured its stable operation in high-risk environments [30].

V. Conclusion

A fire risk reliability model for distribution systems was developed using RBI technology. Based on the criteria for classifying consequence levels, the consequence levels of fire accidents in distribution systems were determined. Taking a 330 kV unmanned substation as an example, the fire risk reliability model was applied to conduct a detailed analysis of each area and propose effective fire prevention and control measures. The substation has 3, 6, 14, and 34 high-risk, medium-high-risk, medium-risk, and low-risk projects across its four zones, respectively. The model ultimately identified the projects requiring priority fire prevention and control measures at the substation. This model can accurately analyze fire hazards in distribution systems, saving significant manpower and resources while reducing maintenance costs and complexity.

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