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Study on the Formation and Propagation Mechanism of Electrical Fires in Distribution Systems

Yu Miao[1,*], Fei Tian[2], Rong Hu[3], Junshan Ge[2] and Tiansong Hu[1]

[1] Electric Power Research Institute of Guizhou Power Grid Co., Ltd., Guiyang, Guizhou, 550002, China
[2] Zunyi Power Supply Bureauof Guizhou Power Grid Co., Ltd., Zunyi, Guizhou, 563000, China
[3] Duyun Power Supply Bureauof Guizhou Power Grid Co., Ltd., Duyun, Guizhou, 558099, China

Corresponding authors: (e-mail: 13984030299@163.com).

Abstract Due to prolonged operation, aging of electrical insulation components, and improper use of electricity, the risk of electrical fires and their incidence rate have been steadily increasing, leading to frequent major and catastrophic electrical fire incidents. To address this issue, a research proposal has been developed to investigate the formation and spread mechanisms of electrical fires in distribution scenarios. Matlab/PSB software and PyroSim software are utilized as simulation and analysis tools. Under the guidance of simulation models and control equation theory, simulations are conducted to analyze the formation and spread mechanisms of electrical fires in distribution scenarios. When the operating current of electrical equipment exceeds 1.732 times the rated current, it can cause the coil to overheat and trigger a fire. To prevent further spread of the electrical fire, the simulation analysis of the fire spread mechanism was expanded. At t=2400s, the temperature reached 1560°C. Additionally, water mist fire extinguishing was employed, and the presence of water droplets was considered to avoid exacerbating the spread of the electrical fire in the distribution scenario. This fully elucidates the formation and spread mechanisms of electrical fires, providing important guidance for user electrical safety and fire protection.

Index Terms distribution scenario, simulation model, control equations, propagation mechanism

I. Introduction

In modern buildings, electrical systems are an indispensable and critical component, providing convenience for people's daily lives and work [1]. However, as building functions become increasingly complex and the number of electrical devices continues to grow, the risk of electrical fires in buildings has also risen [2]. Relevant statistical data indicates that in recent years, the situation regarding low-voltage electrical fires in buildings in China has been severe and shows an upward trend, resulting in significant loss of life and property damage. Currently, the implementation of corresponding preventive measures remains relatively weak, and research on the prevention and control of building electrical fires requires further exploration [3], [4]. Additionally, there is insufficient emphasis on the analysis of the causes of building electrical fires and the identification of their spread mechanisms. The results of such identifications often lack integration with relevant information about electrical faults in accidents, necessitating further research to enhance the accuracy of such identifications [5]-[8].

Electrical fires typically refer to fires caused by the release of thermal energy from faulty electrical circuits, electrical appliances, or power distribution equipment, which ignite the equipment itself or other combustible materials under combustible conditions [9]. From the perspective of fire incidents, the primary electrical cause of electrical fires in distribution scenarios is electrical circuit faults, which are also the main cause of electrical fires [10]-[12]. The first type of fault is caused by parallel contact between conductors. If the short circuit is a metallic short circuit, the large short-circuit current can cause traditional circuit breakers to effectively trip and instantly cut off the power supply, thereby effectively preventing electrical fires [13]-[16]. The second type of fault is a series arc fault caused by loose terminals, damaged conductors, or aged and damaged insulation in the distribution lines. The fault current is similar in magnitude to the load current, insufficient to trigger traditional circuit breakers [17]-[20]. Although its instantaneous hazard is less severe than that of a parallel arc fault, this fault has the characteristics of persistent existence and a long latent period [21]. If not promptly addressed, the prolonged high temperatures generated can ignite flammable materials near the fault arc, potentially triggering an electrical fire [22], [23]. Therefore, it is imperative to enhance the scientific rigor and effectiveness of electrical fire prevention measures to reduce the incidence of electrical fires and ensure the safety of people's lives and property.

The primary technical identification methods widely applied include metallographic analysis and residual magnetism analysis. Among these, metallographic analysis utilizes the internal microstructural characteristics of fire melt marks to qualitatively identify the nature of the melt traces. Zhang, J., et al. investigated the microstructure of luminous contact in electrical fires and compared it with the microstructural features and oxidation products of short-circuit melt marks, aiding in determining whether luminous contact caused by poor electrical contact was present in the fire accident [24]. Deng, J., et al. demonstrated that electrical faults of varying severity produce distinct arc melt droplets. By leveraging microscopic structural characteristics and metallurgical knowledge, this approach provides theoretical support for the extraction of fire-related material evidence and cause determination [25]. Khafagy, S. M., et al. similarly used quantitative carbon analysis and metallographic analysis methods to identify arc beads on the cross-section of wires. Since arc beads may be caused by either short-circuit faults or fire-induced thermal energy, their analysis results can provide valuable information for determining the cause and development process of fires [26]. Xu, N, et al. analyzed the effects of different overload currents and heating temperatures on the microstructure of copper wire melt marks. They simulated copper wires in fires using a test preparation method, and the results play an important role in determining the cause of fires [27].

The residual magnetism analysis method utilizes the influence of electrical circuit short circuits on surrounding ferromagnetic materials to determine whether a short circuit fault has occurred in the circuit. Gurusamy, V., et al. demonstrated that flux component monitoring can be used to detect and locate early-stage rotor-to-rotor short circuit (ITSC) faults in permanent magnet synchronous motors, thereby reducing the probability of operational accidents [28]. Wei, D et al. proposed a method for extracting current second harmonics based on short-time Adaline, which can describe the severity of rotor-to-rotor short circuits by measuring the residual insulation capacity of the circuit system, and performs well in quickly tracking and detecting electrical faults at various stages [29]. Zamudio-Ramirez, I designed a sensor monitoring system based on flux analysis, which diagnoses different types of electrical faults by acquiring and analyzing magnetic flux signals in the motor [30]. Turvani, G et al. utilized nano-magnetic logic analysis technology to achieve accurate analysis of complex circuit faults. This tool can simulate the specific behavior of circuit fault defects under both ideal conditions and defective conditions [31].

Additionally, some scholars have introduced intelligent systems to simulate electrical fires, aiming to explore more feasible mechanisms for electrical fire induction. Thai, H. D., et al. investigated an information technology-based method for assessing the causes of electrical fires, using intelligent technology and programs to simulate electrical fire scenes, providing a comprehensive review of information to enhance the efficiency and accuracy of fire cause determination [32]. Xie, Z., et al. developed an arc fault simulation model, elucidating the temperature characteristics and ignition mechanisms of arc faults in distribution systems, thereby providing a good explanation for the rise time of arc temperature and the distribution characteristics of arc distance in electrical fires [33]. Of course, technical appraisal is only one important aspect of the process of identifying the causes of electrical fires and cannot replace the identification of fire causes. Technical appraisal should not be absolutized; it must be organically combined with on-site accident analysis to make the identification of electrical fire causes more accurate, scientific, and credible.

Based on the four stages of electrical fires in distribution scenarios, this paper categorizes the formation mechanisms of electrical fires into arc discharge mechanisms, electrical contact mechanisms, and electrical heating mechanisms. Additionally, it expands on three common types of electrical fires: short-circuit fires, overload fires, and leakage fires. Based on this, to prevent the further spread of electrical fires, the electrical fire control equation is determined, and with the technical support of Matlab/PSB simulation software and PyroSim simulation software, the task of constructing a simulation model is completed. Using the simulation model, the formation and spread mechanisms of electrical fires in distribution scenarios are analyzed through simulation.

II. Investigation into the Formation of Electrical Fires in Power Distribution Scenarios

II. A. Mechanism of Electrical Fire Formation

Electrical fires in distribution scenarios primarily occur in four stages: the initial incubation stage, the smoke stage, the intense fire stage, and the intense flame stage [34]. When users engage in improper operations, such as overloading electrical systems, violating installation regulations, or other non-compliant practices, it can lead to faults such as short circuits, electrical leaks, overcurrent, undervoltage, poor connections, and electrical heating, thereby causing electrical fires to form. Under normal conditions, electrical energy is transmitted to users through power transmission lines and step-up/step-down transformers from power plants. When an electrical fault occurs, electrical energy will not be transmitted along the original normal circuit. Instead, it will be redistributed and transmitted through the fault circuit, leading to overheating of the fault circuit and equipment, circuit short circuits, overcurrent, and leakage, thereby triggering an electrical fire. Research indicates that the formation mechanism of electrical fires can be explained by the following three theories:

II. A. 1) Arc discharge mechanism

An arc fault refers to the phenomenon where surrounding gases are ionized by voltage, resulting in arc heating, characterized by extremely high temperatures and intense light, posing a significant risk of electrical fires. The causes of such faults can be categorized into the following four aspects: (1) When a fault occurs in a circuit, electrical energy is generated. When this energy is converted into thermal energy, combustible materials can be instantly ignited, leading to an electrical fire. (2)

Electrical metals can melt under the extremely high temperatures generated by an arc, leading to spatter and subsequent fires. (3) With the increasing use of high-power electrical appliances in households, overloading the electrical system can cause arcs. These arcs can carbonize the insulation between phases, causing them to short-circuit. (4) Excessive electrical usage can lead to overvoltage, which is a key factor in arc discharge.

II. A. 2) Electrical contact mechanism

Electrical contact faults refer to abnormal voltage, current, or resistance caused by faults in the contact between lines or equipment. The causes of such faults can be categorized into three main aspects: (1) Overheating at the contact points can directly ignite the insulation layers of the lines or equipment, leading to fires. (2) Melting at the contact points can cause dripping, which may ignite flammable materials and result in fires. (3) Severe contact issues in power transmission lines can lead to sparks and arc discharges, potentially causing fires.

II. A. 3) Mechanism of electrical heating

Electrical heating faults refer to abnormal temperature conditions in circuits or equipment caused by abnormal voltage, current, or resistance in an electrical system. The causes of such faults can be categorized into the following four aspects: (1) Excessive current flow within conductors can cause a sharp increase in temperature at circuit connection points, leading to insulation layer combustion, connection point melting, and other faults. (2) In the event of a short circuit, temperatures can rise sharply, causing metal melting. Once metal melting occurs, it can result in electrical fires. (3) Electromagnetic electrical equipment such as motors and transformers, when used for extended periods, may experience core overheating, winding burnout, and reduced insulation performance, leading to equipment overheating and subsequent fires. (4) Heating electrical equipment such as household microwave ovens and incandescent lamps, when severely lacking in heat dissipation performance, may cause sustained overheating, leading to spontaneous combustion and ultimately electrical fires.

II. B. Common types of electrical fires in power distribution scenarios

Based on the theoretical analysis of the formation mechanisms of electrical fires, it can be concluded that the formation mechanisms of electrical fires include arc discharge mechanisms, electrical contact mechanisms, and electrical heating mechanisms. Based on the formation mechanisms of electrical fires, three common types of electrical fires in distribution scenarios have been identified, namely short-circuit fires, overload fires, and leakage fires. The specific descriptions are as follows:

II. B. 1) Short circuit fire

Short-circuit fires are a common type of electrical fire in distribution scenarios. They typically occur when conductive parts at different potentials in an electrical circuit are directly connected or connected via a low-impedance path, causing a sudden increase in current and the instantaneous generation of a large amount of heat, thereby leading to a fire. When a short circuit occurs, resistance decreases sharply, causing a surge in current that far exceeds the safe current-carrying capacity of the conductors. This causes the conductors to heat up rapidly and may even melt, while also generating sparks and arcs that can ignite nearby flammable materials. Based on their causes, short circuits are primarily due to electrical circuits being in use for an extended period, causing insulation layers to age, crack, or peel off, thereby losing their insulating properties and resulting in short circuits between exposed conductors or between conductors and the ground. Alternatively, during the construction and installation of electrical circuits, improper operations such as loose conductor connections or inadequate insulation treatment may also leave potential short circuit hazards. Short circuit fires are characterized by their sudden onset and rapid spread. Once they occur, the current increases sharply, generating sufficient heat and sparks to ignite surrounding flammable materials, quickly forming a fire. They may also trigger other electrical faults, such as equipment damage or system failures, further exacerbating the severity of the fire.

II. B. 2) Overload fire

Overload fires refer to situations where the current in an electrical circuit exceeds the safe current-carrying capacity of the conductors, causing the conductors to overheat, accelerate the aging of the insulation layer, and ultimately lead to a fire. When an overload occurs, the heat generated increases sharply, causing the temperature of the insulation layer to rise continuously. When the temperature exceeds the ignition point of the insulation material, the insulation layer will catch fire and ignite surrounding flammable materials [35]. From the perspective of its causes, the primary factors include the increasing number of electrical devices within the distribution system, which leads to an increase in electrical load. If the electrical circuit design is unreasonable or the equipment configuration is inappropriate, it is easy to cause circuit overloading. Additionally, improper use of high-power appliances or unauthorized wiring connections may also lead to circuit overloading. The hazards of overloading fires are characterized by concealment and persistence. Overloading is a gradual accumulation process, and initial signs are often difficult to detect. However, as time progresses, the temperature of the conductors continues to rise, the insulation layer gradually deteriorates, and eventually a fire is triggered. Overloading may also cause other electrical faults, such as equipment damage or system failure, further exacerbating the severity of the fire.

II. B. 3) Electrical leakage fires

An electrical leakage fire refers to a fire caused by electrical circuits or equipment with degraded or damaged insulation, resulting in current flowing through the insulation layer to the ground or other non-conductive parts. The heat and sparks generated can ignite surrounding flammable materials, leading to a fire. During an electrical leakage, current generates heat and sparks at the leakage point, and the heat and sparks are sufficient to ignite surrounding flammable materials. The occurrence of electrical leakage fires is primarily due to prolonged use of electrical circuits and equipment or exposure to external environmental factors, which can cause the insulation layer to age, crack, or peel off, resulting in degraded or damaged insulation performance. External environmental factors such as moisture and corrosion can also accelerate the aging and damage of the insulation layer, leading to electrical leakage. Since leakage currents are typically small and difficult to detect, prolonged leakage can cause the insulation layer to gradually age, generating heat and sparks, which may ultimately lead to a fire. Additionally, electrical leakage can easily cause electric shock accidents, posing a threat to personnel safety.

II. C. Simulation Analysis

II. C. 1) Simulation Tools

MATLAB is a numerical computing environment with advanced graphics and visualization capabilities, integrating a high-level language for scientific computing. Simulink is a platform based on MATLAB for modeling dynamic systems. The Graphical Editor (PSB) in the Simulink environment allows users to create schemes and simulate power systems using oscilloscopes provided by Simulink models, and the simulation results can be displayed at observation points on the waveforms.

II. C. 2) Simulation Model

A typical low-voltage distribution system primarily consists of a step-down substation, low-voltage distribution lines, and electrical equipment. Figure 1 shows the schematic diagram of a typical low-voltage distribution system. To analyze the fault mechanisms and propagation patterns of electrical fires in distribution scenarios, Matlab/PSB software was used to simulate and model the formation mechanisms of electrical fires in distribution scenarios. The main components used in the simulation model include display components, three-phase transformers, three-phase circuit breakers, three-phase power meters, current measurement devices, three-phase faults, three-phase series RLC loads, three-phase power sources, and transmission lines. Table 1 shows the parameter settings for the transmission line, with system parameters matched to each other, a frequency of 100 Hz, and a simulation time set to 0.1 s. The variable step size algorithm ode25tb was selected, with a relative error of 1e-8. The fault duration ranges from 0.02 seconds to 0.1 seconds. By configuring the parameters of the three-phase fault simulation module, a single-phase short circuit is simulated, with two shorting phases: a short circuit and a three-phase two-phase short circuit to ground, while another short circuit fault occurs in the circuit. Each oscilloscope waveform (Scopel~Scope6) displays current and voltage waveforms, and these waveforms are saved in the .mat file format on the computer.

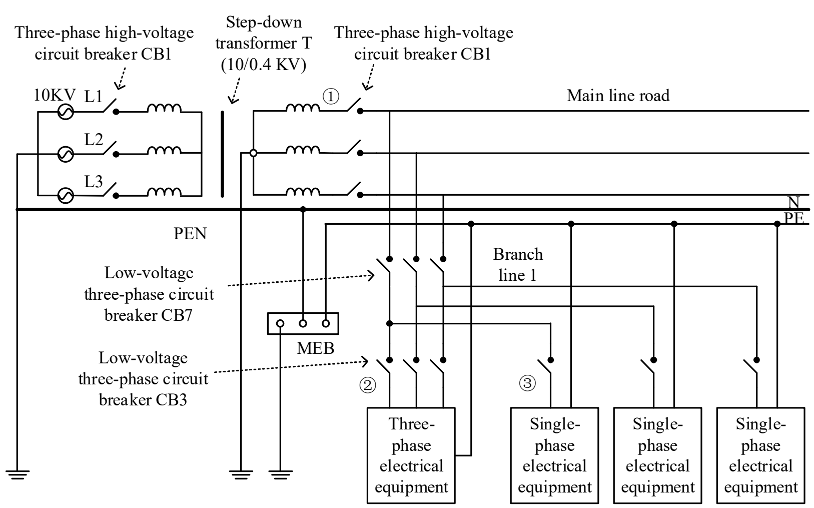


Figure 1: Schematic diagram of a typical low-voltage distribution system

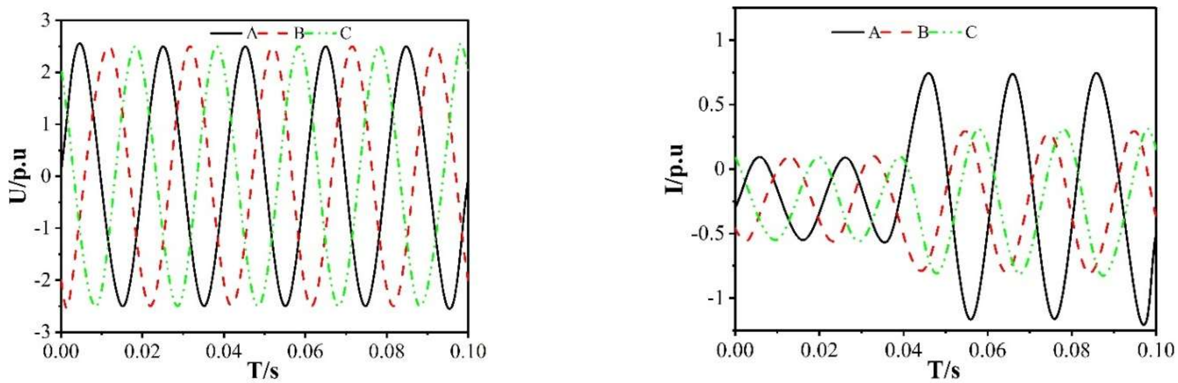
Table 1: Parameters of power transmission lines

Component	R_1/Ω/km	L_1/mH/km	C_1/uF/km	R_0/Ω/km	L_0/mH/km	C_0/uF/km
Parameters	0.0126	0.1018	0.00108	0.0226	0.5037	0.00029

II. C. 3) Simulation Results

Currently, we are analyzing the simulation and simulation results of various short-circuit faults on the main transmission lines ①②③ and the main line (single-phase ground fault, two-phase phase loss short circuit, two-phase ground circuit short circuit between phases), poor contact, and overload at the location shown in Figure 1, Line 1, and drawing conclusions. Here, the high-voltage circuit breakers CB1 and CB2 are shown, with CB3 representing the three-phase motor protection circuit breaker, and CB4 and CB6 representing the A, B, and C phase circuit breaker protections.

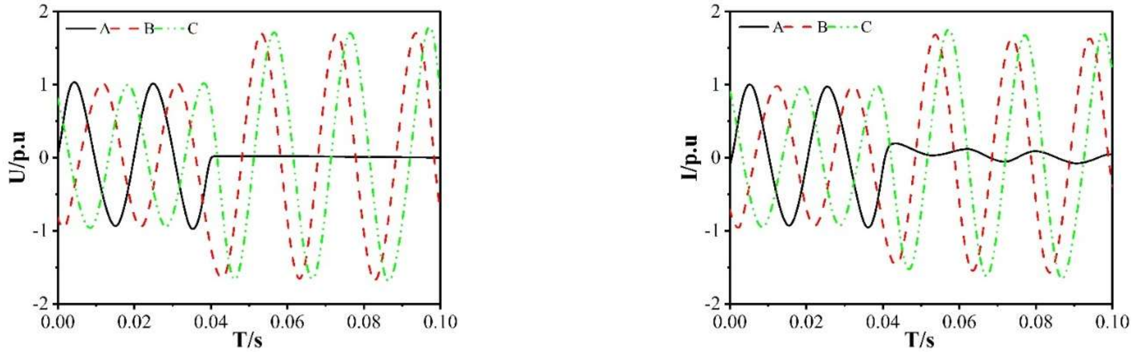
Figure 2 shows the output waveforms of the transformer's high-voltage side, where (a) and (b) represent the voltage waveform and current waveform, respectively. The single-phase current waveform on the low-voltage side of the transformer (point ① in Figure 1) becomes the original fault current due to the high-voltage phase fault, while the fault current caused by the transformer ground fault becomes 1.39 times the original current. This will exert a strong electromagnetic force on the transformer windings. Since the electromagnetic force is proportional to the square of the current, the fault short-circuit electromagnetic force is approximately 9.87 times the rated operating current, which can easily cause the transformer windings to deform and damage the insulation. It also causes the transformer winding overheat protection device to trip. If the device is faulty, it may cause the transformer windings to burn. At this point, all electronic equipment will cease to function.



(a)Voltage waveform (b)Current waveform

Figure 2: The output waveform of the high-voltage side line of the transformer

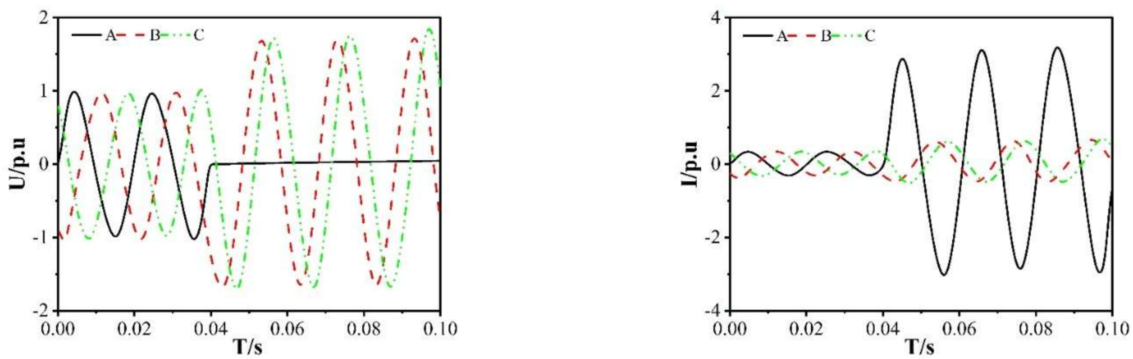
If CB1 is not tripped, the voltage and current waveforms in the main circuit are as shown in Figure 3. The voltage fault phase is close to 0, the current is too small, and the voltage and current of the non-fault phase are both 1.732 times those before the fault. The residual current operated circuit breaker CB2 can provide effective protection against ground faults. However, if it malfunctions, and if the three-phase circuit breaker used in the three-phase power supply main circuit has phase loss or three-phase imbalance protection functionality, it will disconnect the faulty circuit. Otherwise, the three-phase power supply circuit will operate in a phase-loss state. At this point, although the current of the non-fault phase is 1.732 times that before the fault, if the circuit was originally operating under light load or no load conditions, the current may not reach the trip value of the overcurrent protection device. Whether it is a power line or various electrical equipment, the voltage of the non-fault phase is 1.732 times that before the fault, and the probability of insulation breakdown increases. If the three-phase power supply of CB3, which serves as the operating device, is in operation, and the motor has a certain speed and direction, as long as the resistance of the load torque is not too large, the motor will continue to run. However, at this stage, the motor generates significant heat, and the windings may be damaged due to high-temperature combustion. For single-phase electrical equipment, where the phase voltage of the faulty phase is zero, a short circuit may occur. If the fault current reaches the overcurrent protection threshold of CB5 and triggers the action value of CB6, it can activate the electrical protection mechanism. Otherwise, the single-phase electrical equipment will continue to operate under single-phase power supply. For example, for various lighting fixtures, when the current through them reaches 1.732 times the rated current, the circuit breaker will trip to provide protection. If it does not trip, it will reduce its service life. For household appliances such as washing machines and air conditioners, excessive voltage and current may cause the motor coils to overheat and potentially lead to fires.



(a)Voltage waveform (b)Current waveform

Figure 3: The voltage and current waveforms of the main line

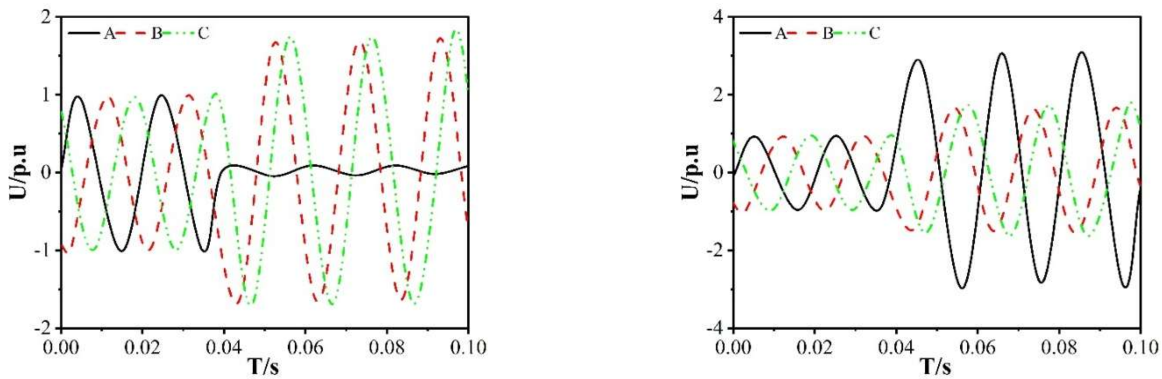
Figure 4 shows a single-phase (three-phase) ground fault in a three-phase electrical device (point ② in Figure 1), along with the voltage and current waveforms of the three-phase device's power supply lines. During the fault-free phase of the three-phase voltage electrical equipment, the voltages UB and Uc and currents Ib and Ic represent the current values before the fault. The voltage UA of the faulty phase is 0, and the current Ia is 5.96 times the value of Ic before the fault. Since the current in phase A is 5.96 times the fault current, even when the motor is running under no load, the fault current typically reaches a value that triggers the overcurrent protection device, thereby reducing the likelihood of burning out the three-phase motor.



(a)Voltage waveform (b)Current waveform

Figure 4: Voltage and current waveforms of Line ② equipment

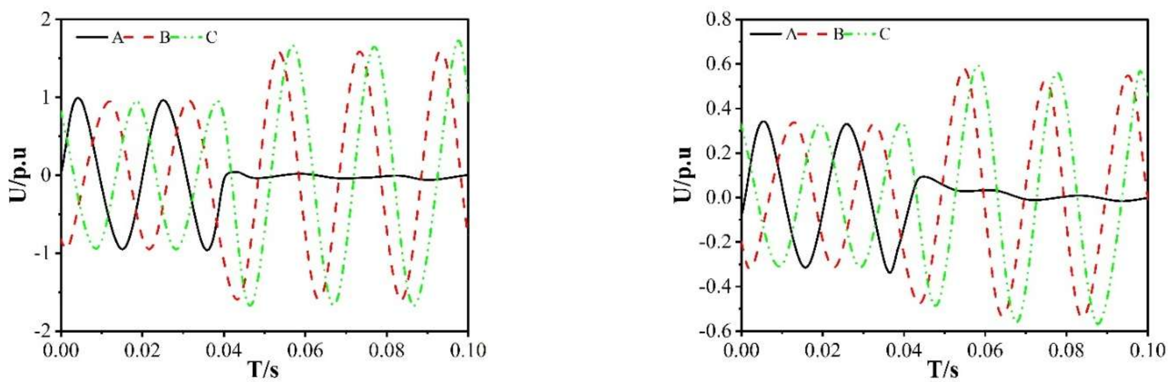
If there is no action from CB3, the main line voltage and current waveforms are as shown in Figure 5. The fault phase voltage is close to 0, and the fault current is 3 times that of the normal phase voltage and current before the fault, which is 1.732 times the normal value. Residual current protection circuit breakers can reduce such faults, but they are not reliable if the power lines are equipped with phase circuit breakers that fail to trip during a phase failure or phase imbalance, resulting in three-phase current imbalance. In such cases, the circuit breaker will trip the fault, otherwise the power lines will operate in a phase-failure state. At this point, if the line is in the open direction or in a no-load state, the fault current cannot reach the overcurrent protection trip value, and the three-phase power lines will continue to operate. The medium voltage in the non-fault phase will increase by 1.732 times compared to before the fault, increasing the likelihood of insulation breakdown and discharge.



(a)Voltage waveform (b)Current waveform

Figure 5: Main line voltage and current waveforms

The voltage and current waveforms of single-phase electrical equipment are shown in Figure 6. CB2, CB5, and CB6 do not operate. The electrical equipment, circuit, and structure are subjected to tension and waveform currents on the main phase. Faults in voltage phase and convergence of current zero-phase result in an increase in voltage and current again. This is similar to the case of a single-phase low-voltage side short circuit in a transformer. For this reason, the probability of a fire caused by single-phase three-phase electrical equipment is very small.



(a)Voltage waveform (b)Current waveform

Figure 6: Voltage and current waveforms of single-phase electrical equipment lines

III. Investigation into the spread mechanism of electrical fires in power distribution scenarios

Through simulation and analysis of the formation of electrical fires in the distribution scenario described in Chapter 2, we gained a deep understanding of the mechanisms and causes of electrical fires. On this basis, in order to further understand the patterns and mechanisms of electrical fire spread in distribution scenarios, we designed a simulation and analysis plan for the spread of electrical fires in distribution scenarios using PyroSim software as a research tool.

III. A. Software Introduction and Control Equations

III. A. 1) Software Introduction

PyroSim is a software program specifically designed for dynamic fire simulation. It provides users with a graphical user interface that is easy and convenient to use. Based on fluid dynamics, it can numerically calculate the changes and movement patterns of various substances such as temperature, smoke, and CO_2 during a fire. It can also simulate fire simulation results for the same model under different operating conditions, providing possibilities for fire research and prediction under various conditions.

III. A. 2) Control equations

PyroSim's numerical calculations use the Navier-Stokes equations, which are suitable for low-speed flow and heat-driven flow, and employ a large eddy simulation (LES) model to handle turbulent flow. The partial differential equations governing the energy, momentum, and mass of the fluid are as follows.

Energy conservation:

$$\frac{\partial}{\partial t}(\rho h)+\nabla phu=\frac{Dp}{Dt}+q^{'''}-\nabla q^{''}+\phi \tag{1}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho u)+\nabla \rho u+\nabla p=\rho g_n+f+\nabla \tau_{ij} \tag{2}$$

Conservation of mass:

$$\frac{\partial \rho}{\partial t}+Au=0 \tag{3}$$

In the equation, ρ — density of the gas, u — velocity vector, τ_{ij} — Newtonian fluid viscosity stress tensor, f — external vector, p — pressure, h — enthalpy, $q^{''}$ — heat flux vector, $q^{'''}$ — heat release rate per unit volume, ϕ — dissipation function.

III. B. Model Construction

III. B. 1) Electrical Fire Model

Due to the presence of electrical equipment in various workplaces within the power distribution scenario, and considering the complexity of the study, the number of electrical devices, and the distribution of personnel, the power distribution scenario is deemed to have a high level of danger due to the variety and quantity of electrical devices used in the tunneling tunnels, as well as the high density of personnel. Therefore, eight grids were established in the model, with four grids measuring 240m × 6m × 6m, the remaining 4 grids are 20m × 6m × 6m in size. Considering computational time and accuracy, each grid is set to 1m × 1m × 1m in size, resulting in a total of 18,360 grids.

III. B. 2) Boundary conditions, detectors, and fire source settings

Ten monitoring points are installed at positions 1 to 10 in the model, each equipped with temperature sensors and smoke detectors to monitor fire alarms and smoke propagation. A temperature slice is set at a height of 3.8m in the model to visually monitor the distribution pattern of temperature in the tunnel during a fire. At fire source positions 1, 2, and 3 in the model, numerical simulations are conducted for fire sources with areas of 2m² and with heat release rates of 541 kW and 1061 kW, respectively, are simulated. The air temperature is set to 40°C, and the simulation time is set to 3600 seconds.

III. B. 3) Patterns of fire source release

Most electrical fires in mines are caused by overheating, short circuits, and other factors, so the fires start small and gradually grow larger. This type of fire is classified as a T2 fire, with a heat release rate of:

$$Q=at^2 \tag{4}$$

In the equation, a — fire development coefficient, t — time.

The fire development speed is classified into four types: ultra-fast, fast, medium, and slow. The fire development coefficients corresponding to the four types of fire growth rates are 0.1869, 0.04684, 0.01119, and 0.002926, respectively. Some scholars believe that electrical fires belong to the medium-speed category. The two types of heat release rates of the fire sources set in this paper exhibit the growth pattern in a t^2 fire.

III. C. Analysis of simulation results

Figure 7 shows the simulated results of the heat release rate of a fire in a power distribution scenario over time. As can be seen from the figure, when a 1200.0°C ignition source is placed next to the equipment, the equipment catches fire after approximately t=360s. During the initial stage of the fire, the rate of fire intensity development is very rapid, and the fire heat release rate reaches 36 kW after only 200 seconds. Between t=600 and 1200 seconds, the rate of fire intensity increase slows slightly, and after 600 seconds, the fire heat release rate increases by an additional 36 kW. From t=1200 seconds until the ignition source disappears, the fire heat release rate remains relatively stable. After the ignition source disappeared at t=1200 seconds, the fire heat release rate rapidly decreased and then slowly diminished, with the fire naturally extinguishing by t=3600 seconds.

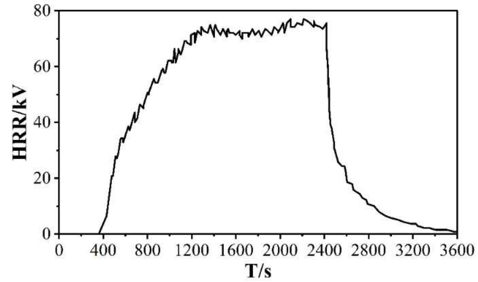
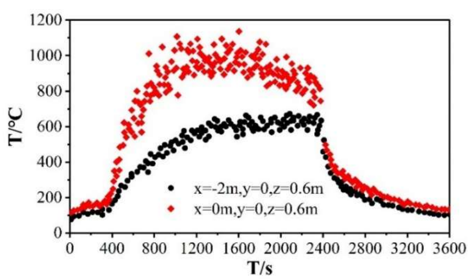
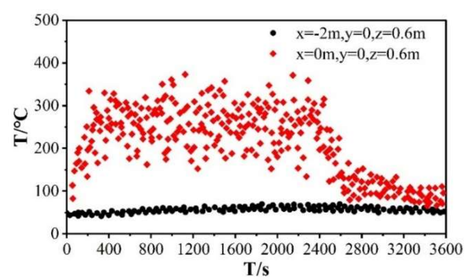


Figure 7: Simulation results of the fire heat release rate varying with time

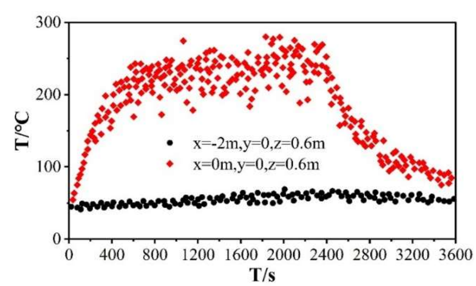
To reasonably arrange fire alarm sensors, the temperature changes over time were recorded at 12 locations on the inner walls and 6 locations on the surfaces of the equipment within the distribution scene. Due to the symmetrical structure of the equipment and the fire source location, Figure 8 shows the results for 6 locations on the inner walls of the equipment, where (a) to (c) represent the upper wall, lower wall, and side walls, respectively. As shown in Figure 8(a), the temperature change patterns at the two positions x = −2m and x = 0 on the centerline of the upper wall surface of the distribution equipment are consistent with the fire heat release rate change patterns. Before t = 360s, the temperatures at these two wall surfaces increase synchronously and slowly, with a small temperature difference between them. At t = 360s, the high temperature only reaches 160°C, while the low temperature is 140°C. This is primarily because the high-temperature gases around the ignition heat source rise to the upper wall surface due to buoyancy. However, since there is equipment horizontally arranged in the middle, it obstructs the upward movement of the hot gases, resulting in relatively low temperatures at these two points during the initial stage of the fire. As shown in Figures 8(b) and (c), the temperature change patterns at the positions x = −2m and x = 0 on the centerline of the lower and side walls of the cable channel do not fully align with the fire heat release rate change patterns. During the initial stage of the fire, there was no significant difference in wall surface temperature changes before and after equipment ignition at these two locations. Near the ignition source, i.e., at x=0, the wall temperature begins to increase with time, quickly reaching approximately 240°C, and then remains at this level for a long time until the ignition source disappears, after which the wall temperature gradually decreases with time. At x=−2m, the temperature change is minimal. Analysis indicates that the thermal decomposition temperature of the equipment's insulating rubber is relatively high (660°C), and the decomposition rate is slow. The resulting fire plume primarily concentrates above the cable tray, with only the wall surfaces near the fire source experiencing significant heating. Comparing Figures 8(b) and (c), it can also be observed that the temperature at the lower wall surface at x=0 reaches approximately 200°C after about 100 seconds, while the temperature at the side wall surface at x=0 takes 320 seconds to reach 200°C.



(a)Upper wall surface



(b)Lower wall surface



(c)Then the wall surface

Figure 8: Simulation results of temperature variation over time

Figure 9 shows the results at four locations on the surface of the equipment. The temperature change patterns at the two locations x = −2 m and x = 0 on the centerline of the upper and lower surfaces of the equipment are consistent with the fire heat release rate change patterns. Since the thermal decomposition temperature of the insulating rubber sheath selected in the calculation is 660°C, it can be seen from Figure 9 that, within this 3600-second time period, thermal decomposition only occurred on the lower surface of the equipment at the x = 0 location. Before t = 360 s, the temperature on the lower surface at x = 0 increases rapidly, reaching 660°C at t = 360 s, and then remains constant until t = 2100 s. Subsequently, the surface temperature increases rapidly again, reaching a maximum of 1560°C at t = 2400 s. This indicates that the rubber at this location began pyrolysis at t = 360 seconds and completed pyrolysis by t = 2100 seconds. The subsequent temperature values correspond to the copper core of the equipment's conductors. Clearly, if water mist fire suppression is employed at this point, it is essential to consider whether a large number of water droplets could fall onto this area, potentially causing a short circuit and further spreading the electrical fire in the distribution scenario. The PyroSim software comprehensively reveals the mechanisms of electrical fire spread in distribution scenarios.

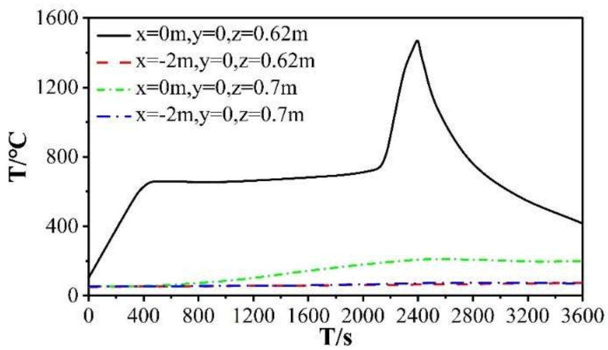


Figure 9: Simulation results of surface temperature varying with time

IV. Conclusion

This paper summarizes the common types of electrical fires in distribution scenarios based on the formation mechanism of electrical fires. Matlab/PSB software and PyroSim software are selected as the simulation analysis tools for this study. Under the influence of the simulation model and control equations, a simulation analysis of the formation and spread mechanism of electrical fires in distribution scenarios is conducted. As the number of electrical devices increases, when the actual operating current reaches 1.732 times the rated current, coil overheating can lead to electrical fires, effectively illustrating the formation mechanisms and principles of electrical fires in distribution scenarios. Additionally, the simulation results of electrical fire spread in distribution scenarios are supplemented. When the time reaches 2400 seconds, the temperature reaches its peak value of 1560°C. It is important to note whether a short circuit exists to prevent the spread of electrical fires in distribution scenarios, thereby intuitively demonstrating the mechanism of electrical fire spread in distribution scenarios.

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