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Multi-level Fire Alarming System for Urban High-Voltage Cable Tunnel

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Abstract:

At present, the research and applications about fire alarming of high-voltage cables tunnel focus on measuring various characteristics of fires through sensors such as smoke, various characteristic gases of fire, videos, etc., so that fire can be detected as soon as possible to avoid greater losses. In order to detect the fire as early as possible, it proposed to build a multi-level early alarm system. Firstly, it established an experimental platform, and found that the cable and it would emit particles with nanometer size during overheating and discharging, so, it presented a method for detecting hidden cable tunnel fire hazards based on thermal-released-particle detection, which can alarm several hours or several days before the fire occurs. Additionally, the CO sensor and other conventional sensors were also used, then a multi-level fire alarming system for high-voltage cable tunnel was introduced, by which the fire can be effectively alarmed in the whole process of fire development.

Keywords: high-voltage cables tunnel, multi-level fire alarming, hazards, gas sensor.

INTRODUCTION

With the advancement of urban modernization, the scarcity of construction land and the need for urban aesthetics and safety have necessitated the gradual transition of existing 220/110kV overhead high-voltage lines into underground tunnels. This transition effectively mitigates the impact of sudden severe weather and extreme climate conditions, thereby reducing the risk of natural disasters triggering secondary disasters within the power grid. The main causes of tunnel cable fires are as follows: local high temperatures caused by overcurrent or overload in the line, local discharge caused by overvoltage, insulation damage, long-term low-current partial discharge, and cable grounding system failure [1-3].

Unlike the previously utilized overhead high-voltage power lines which primarily consisted of metal cables, the power cables in tunnels have insulation and sheath layers containing significant amounts of combustible polymeric materials, and the tunnel space is limited, so the fire develops rapidly. Especially, the high-voltage short circuits may cause explosions. Despite the implementation of various fire-fighting measures within the tunnel, the fire is difficult to extinguish. The narrow and enclosed tunnel space make it impossible for firefighters and fire trucks to enter in case of a fire. The 220/110kV cable channels are the main lines of the urban power grid, the fire in high-voltage tunnels often results in large economic losses. Consequently, fire alarming in high-voltage power cable tunnels is a crucial aspect of ensuring the safe and reliable operation of the entire power grid system, and its importance in power transmission safety has garnered widespread attention.

At present, the commonly used alarm sensors in the cable high-voltage tunnel are temperature sensors, image sensors and smoke sensors, but these sensors can only be triggered when the fire occurs to a certain extent. Each fire warning method has its own advantages and disadvantages, Zhu et al. [4] used smoke detectors, point type temperature detectors, and cable type linear temperature detectors to monitor the fire by utilizing D-S evidence theory to fuse and analyze these multi-sensor data. Guo et al. [5] pointed out that the alarm by temperature sensor in the utility tunnel relatively low, and the fire detection response time would be long, but the contact-type linear temperature sensor has the fastest responsibility rate. Li et al. [3] simulated fire development under different fire locations and fire source power according to the typical high-voltage cable tunnel structure, and established a fire early warning model based on support vector machine (SVM). Liu et al. [6] presented an intelligent cable tunnel fire detection method using particle swarm optimization algorithm including the fire source location, the maximum temperature value, and the temperature attenuation coefficient. and given a corresponding sensor optimization strategy.

In recent years, the early warning of cable fire based on gas sensor has been studied [7]. Some studies divide the period of cable fires into two stages: the early fire stage and the flame fire stage. The early warning of high-voltage power cable fires is an important part of the high-voltage tunnel fire alarm system, its purpose is to detect fires in the early or even latent stages of the fire and alarm in time.

Xie et al. [8] used temperature sensing optical fiber to monitor the surface temperature of the cable and deduce the temperature of the internal core of the cable, thereby providing early warning. During the initial stages of a tunnel high-voltage cable fire, PVC cable will release CO gas under pyrolysis at high temperature, so CO concentration may be used as one of the criteria for early fire. Zheng et al. [7] and Geng et al. [9] studied the early fire warning of cables and found that gas sensors had excellent response speed and response intensity to early fire response and the carbon monoxide could be selected as the characteristic gas for early fire detection. but Courty et al. [10] pointed out that CO emitted at the beginning of combustion was with low amount by which CO sensors could not accurately detect electrical fires in the early stages. In conclusion, the research on early warning of high-voltage cable fire needs to be further deepened.

In order to find the fire in the period of potential fire hazard, some scholars have done exploratory research. Yao et al. [11] found that the WO3 thick films can as a significant volatile when the cable temperature raised in the early stage, and they were the criterion for conducting early fire warning. Yi et al. [12] analyzed the thermal pyrolysis gases of 9 commonly used XLPE cables, and found that DOP (Dioctyl Phthalate) and 2- ethyl hexanol (2-EH) were existed in the volatile gases of all tested cable, the corresponding commercial metal oxide semiconductor (MOS) gas sensors needs to be further developed.

The early definition of cable fire is not unified at present. Ye et al. [13] pointed out that the whole burning process of tunnel cable could be divided into five phases: the sheath fire, slow spread, rapid spread, full developed fire and decay. For the convenience of research, we propose to divide the cable fire period into three stages: the fire hazard stage, the early fire stage, and the flame fire stage.

Specifically, a method of using thermal-released-particle concentration monitoring to determine overheating and discharge of cables has been proposed for detecting the hidden fire, which is in addition to the existing high-voltage cable tunnel fire detection methods. A multi-level fire alarm system for high cable tunnels based on this has been established and applied.

MULTI-LEVEL ALARMING SYSTEM FOR HIGH VOLTAGE CABLE TUNNEL

Fire Stage

The progression of a high-voltage tunnel fire is a gradual and incremental process. According to our study, it is proposed that tunnel fires can be categorized into three distinct stages: the fire hazard period, the early fire stage, and the open flame stage, shown as Figure 1.

Figure 1. Different stages of tunnel fire

(1) Fire hazard stage

The high voltage tunnel cable fire is mainly caused by prolonged full-load or overload operation of cables, excessively high resistance at cable joints, and line short-circuit faults. Due to factors such as poor contact and partial discharge, the local temperature of the cable abnormally rises. If this issue remains unresolved for a long time, it will gradually damage the insulation layer and eventually causes a fire. At this stage, combustion has not yet occurred and there are no smoke, flames, etc.

(2) Early fire

Combustion has occurred, some smoke is beginning to appear inside the tunnel or called smoldering, but no distinct flames are observable.

(3) Flame fire

The fire is obvious, with visible flames and thick smoke.

Early fire Warning Based on Thermal-Released-Particle Detection

The structure of high-voltage XLPE cable is composed of conductor, inner semiconductor shielding layer, insulating layer, outer semiconductor, shielding layer, metal shield, metal armor, and outer sheath from inside to outside. Although the material of the outer sheath is usually flaming retardant, it will still burn under the cable tunnel fire. The insulating material XLPE is prone to expansion, melting, and dripping at high temperatures, which can easily lead to thermal diffusion, cause insulation breakdown and short circuits, and ultimately lead to fires or explosions. In the cable fire, both the inner insulation material and the outer sheath will be ignited [3].

The fire process of cables can be divided into thermal pyrolysis and combustion processes chemically. A large number of particles can be produced in both stages. The products of combustion usually appear as smoke particles, while the products of pyrolysis are usually tiny charged particles, which called " thermal-released-particle ". The pyrolysis reaction rate can be expressed by the following formula [3]:

$$\frac{da}{dt} = A\exp(-\frac{E}{RT}) f(a) \tag{1}$$

where A is the pre-exponential factor; E is the activation energy of the reaction; R is the gas molecular constant. T is the reaction temperature. a is the degree of pyrolysis. f () is the reaction mechanism function. From (1), it can be seen that the thermal pyrolysis of XLPE cable is also exponentially accelerated with the increase of temperature in the overheated state.

When the cable and its protective layer are heated beyond their limit tolerance, the particles released by the material under this heating state are usually unstable microscopic particles, known as thermal-released-particle. Experiments have shown that as the temperature of combustible materials increases, they release a large amount of particle before reaching their ignition point. As the temperature continues to rise, it reaches the ignition point and begins to enter the smoke and fire stage. Figure 2 is showing the particle concentration during the combustion process of a material. As can be seen from it, when the temperature of the combustible reaches a certain release point, a large number of heat-releasing particles are released. When the temperature of the combustible material exceeds the ignition point, phenomena such as smoldering smoke will occur. After this point, smoke particles will appear.

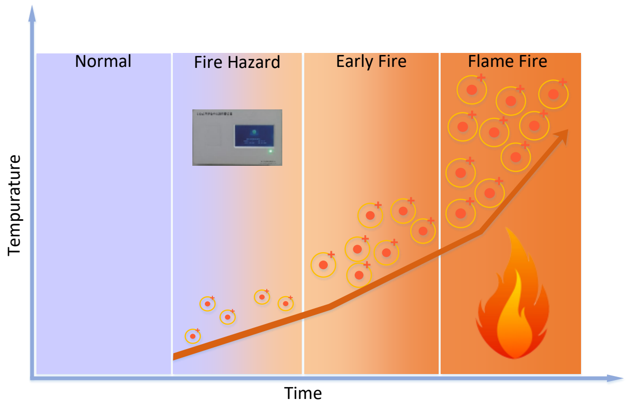


Figure 2. Particles count during the combustion process

Particles have the following characteristics:

(1) Particles are generated throughout the entire process of material combustion, as materials undergo pyrolysis and combustion under high temperatures, which can be divided thermal-released-particles and smoke particles.

(2) The diameter of thermal-released-particle is relatively small, mostly ranging from 1nm to 20 nm, while the diameter of common smoke particles is mostly between 400nm and 1200nm.

The cables in high-voltage tunnels are affected by partial discharge, leakage current, overload, and other factors. The combustible materials at the ignition point are heated from a stable state to an ionic state, releasing nanoscale thermal particles. As the temperature steadily rises, the concentration of thermal-released-particles continues to increase, even though no visible smoke particles have yet formed. The process from overheating to smoldering of the cable material can last for several hours at most. Therefore, at the initial stage of high-voltage cable fire in the tunnel, it is possible to determine the potential fire hazard by collecting the concentration of thermal-released-particles in the tunnel environment, which can eliminate the fire several hours before it occurs.

Multi-level Alarming System for High-Voltage Cable Tunnel

Based on the previously proposed fire classification principles and the technology about using thermally released ions for fire hazard detection, a multi-level fire alarming system for high-voltage cable tunnel fire prevention is proposed here, as shown in Table 1.

Table 1. Multi-level fire alarming system

Alarm Level	Sensors
Flame fire alarm	ambient temperature sensors, optical cameras
Early fire alarm	smoke sensors, CO sensers, CO_2 sensors, optical fiber temperature sensors
Fire hazard alarm	thermal-released-particle sensors

For the fire hazard alarm, the thermal-released-particle sensors are installed the wall of the tunnel. Through thermal-released-particle concentration monitoring, it can effectively identify the cable discharge and overheating status, so we can discovery the fire hazards and identify the cable fire early in the tunnel, which can give early warning hours or dozens of hours before the fire.

For the early fire alarm, the smoke sensors, CO sensers, CO_2 sensors, optical fiber temperature sensors and IR Cameras are used. It can give an alarm a few minutes or dozens of minutes before the fire develops. In the early fire stage, the smoke has appeared and is gradually obvious, so the smoke sensor can be triggered and alarm. During the combustion process of cables, a large amount of CO and CO_2 gases are released due to chemical reactions. Even though the tunnel has an exhaust system, it is a relatively enclosed space, so CO and CO_2 sensors can trigger alarms during this stage. Fu et al. [14] pointed out that CO sensors and smoking sensors can achieve relatively reliable early warning in high voltage power cable tunnels among gas sensors. Cable temperature monitoring is also an important way in the early cable fire alarm which can be achieved by two methods, one is to indirectly monitor the overheating of the cable's internal core through temperature-sensing optical fibers wrapped around the cable surface, the other is installing IR Cameras in the top of tunnel.

For the flame fire alarm, the ambient temperature sensors and optical cameras have been equipped. The above sensors used for early fire detection will continue worked. During the flame fire stage, due to the spread of combustion, the ambient temperature in the tunnel increases significantly, and flame and smoke are more obvious. The fire image recognition algorithms based on deep learning can be used and detect flame and smoke in surveillance videos of optical cameras, thus achieving intelligent alarming [15-17].

Through the above designed multi-level fire alarm system, it is possible to achieve comprehensive and multi-level alarming for high-voltage tunnel cable fires, maximizing the possibility of early detection of fire hazards and extinguishing fires before they ignite or in the early stages.

EXPERIMENT AND APPLICATION

In order to measure the whole process of cable fire, we built an experimental platform. It is 600 cm long, 140cm wide, and 150cm high, with the top, bottom, and one side equipped fire-resistant panels. On the other side is a tempered glass wall, which can observe the whole combustion process in real-time. The Gas sensors (CO and H2), particle sensor, and temperature sensor have been installed. One vent hole is on the upper right side, shown as Figure 3[14].

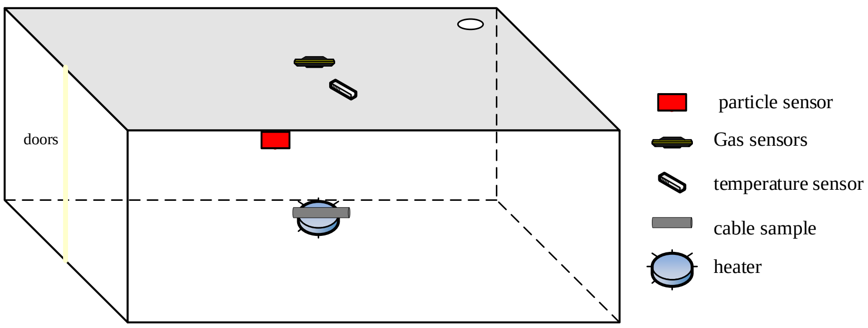
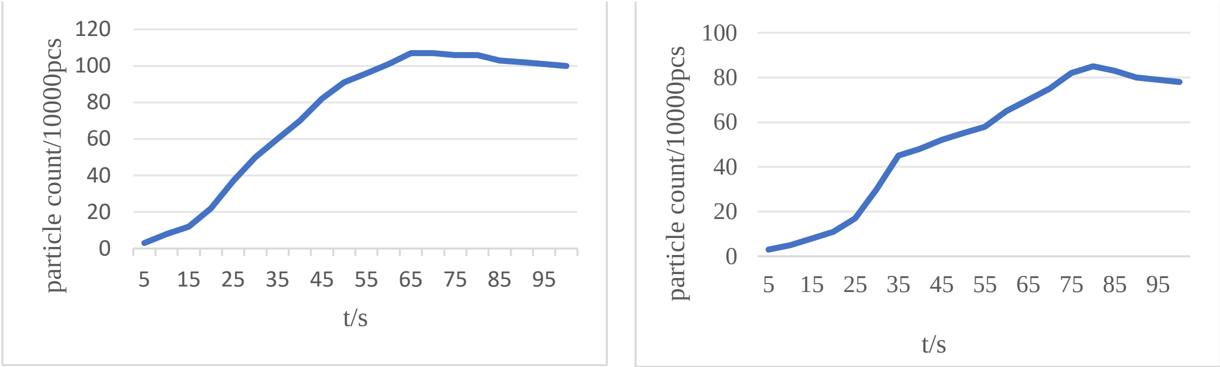


Figure 2. Experimental platform

Based on the experimental platform, the high voltage power cable (ZRC-YJLW03-127/220kV) is taken as the experimental sample, which generally used in high-voltage power cable tunnel.

Discharge Stage

We adjust the discharge device to make surface discharge occurs. The discharge duration is 1 minute. During the experiment, the total number of particles with diameters of 0.3um (less than 0.3um), 0.5um (0.3-0.5um) and 1um (0.5-1um) in the air was counted by a laser particle counter. Discharge experiments were conducted for epoxy resin and XLPE cable respectively to plot the cumulative number of particles of each size (the sum of the number of particles of each size). Figure 3 (a) shows a particle count curve for the epoxy resin surface discharge experiment, and Figure 3 (b) shows a particle count curve for the XLPE cable surface discharge experiment.



(a) Epoxy resin (b) XLPE Cable

Figure 3. Curves of particles count during surface discharge

As shown in Figure 3, the total number of particles with four different diameters generally exhibits an exponential increase with the increase of discharge time, and the curve tends to stabilize after reaching a certain value. The statistical results are shown in Table.2. The experimental data shows that with the increase of discharge intensity, the number of particles produced by discharge also increases. It can be seen from the table that the number of particles with a diameter of less than 0.3um is dominant in the discharge test, which is called thermal-released-particles.

Table 2. Particle data in surface discharge

		Count of particles (10000pcs)	
		Epoxy resin	XLPE
<0.3μm	Average (Normal)	0.7823	0.8825
	Peak (Discharge)	109.63	92.3581
0.3-0.5μm	Average (Normal)	0.0303	0.0372
	Peak (Discharge)	0.1101	0.0954
0.5-1μm	Average (Normal)	0.0098	0.0241
	Peak (Discharge)	0.0823	0.0497

Overheating Stage

In the overheating experiment, the heating temperature is 150 ℃, and the heating duration is 10 minutes. We have conducted four overheating experiments on the cable samples, and selected one of the four groups of sample data to draw the change curve of the particles count with different particle sizes, as shown in Figure 4.

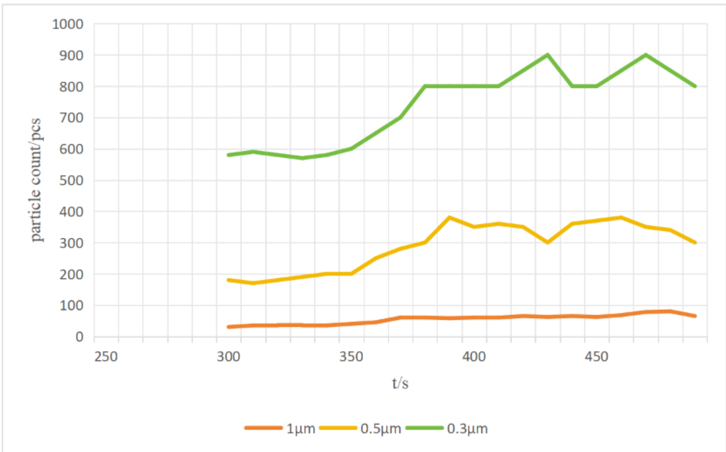


Figure 4. Curves of count of particles with different diameters

The experimental data show that the overheated cable will pyrolyze and release nano-sized solid particles, of which the particles with diameter less than 0.3um is the most significant. The number of particles with diameter greater than 1um changes little in the overheated state and normal state.

Fire Budding Stage

When the temperature rises to the ignition point of the tunnel cable, a large amount of CO begins to be produced due to the initial stage of combustion. It can be seen from Figure 5 that after about 1000 seconds of heating the cable, the CO concentration begins to increase obviously. After a certain stage of increase, it undergoes a period of slow fluctuation and then rapidly increases at a higher rate. Due to the fact that the CO background concentration in the normal power cable tunnel space is basically 0, the CO concentration changes significantly in the cable smoldering stage under heating conditions, so it can be used as one of the typical early fire warning criterions [14].

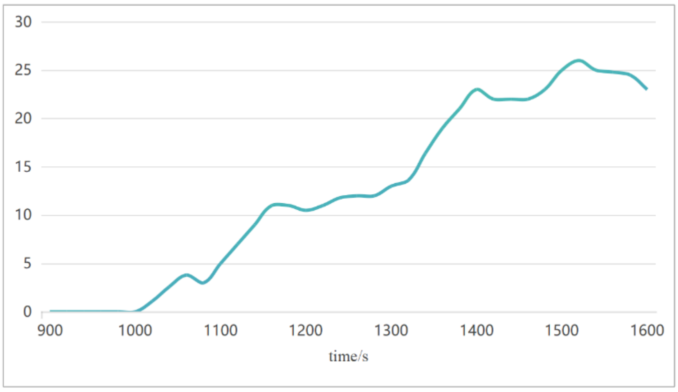


Figure 5. Change of CO concentration in fire budding stage [14]

Multi-Level Fire Alarm and its Application

The designed multi-level cable fire alarm system has been applied to a high-voltage cable tunnel in a large city. The particle detectors, CO sensors, CO_2 sensors, optical fiber temperature sensors, ambient temperature sensors, optical cameras were installed in the tunnel. The instrument with screen installed on the left in the Figure 6 was our designed particle detector, which used to detect the thermal-released-particles and alarm in case of cable fire hazard. The diameter range of particles collected by the instrument is from 2 nm to 20 μm.

The alarm logic is shown in Figure 7. The whole system is logically divided into three levels of alarm, namely, fire hazard alarm, early fire alarm and fire alarm. All alarms adopt the threshold method, and the alarm will be generated when the collection amount of each sensor exceeds the set threshold. The alarm threshold values could be adjusted according to the actual situation.

Figure 6. Multi-level fire alarm system installed in high-voltage tunnel

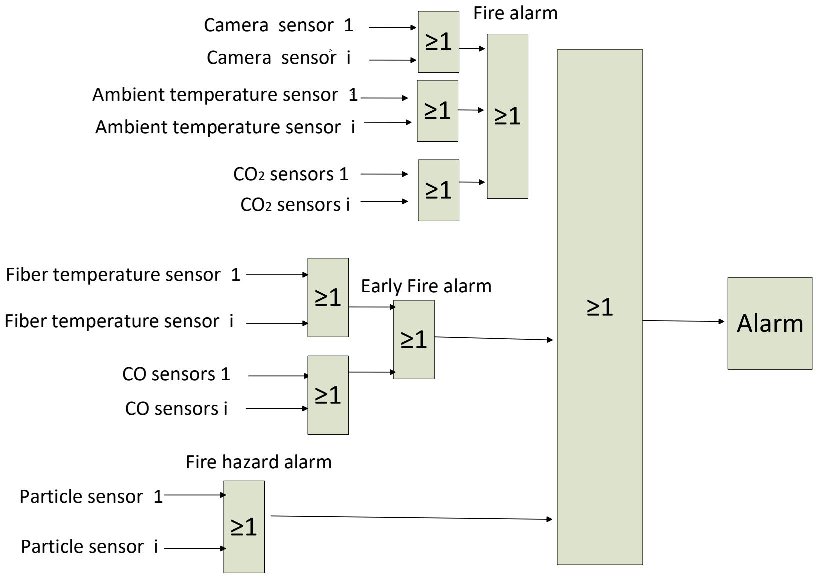


Figure 7. Multi-level fire alarm logic

CONCLUSION

The fire development of high-voltage cable tunnel is a gradual process, in which the overheating of cable is the main cause of tunnel fire. The overheating ais mainly caused by partial discharge, poor contact, aging connector, current overload and other reasons. When the temperature rises to the ignition point of the cable material, it will be in the budding state of fire (or smoldering state). In order to detect the tunnel cable fire earlier, it is proposed to divide the cable fire into three stages, namely, overheat stage, budding stage and lame stage according to the our research needs. For the very earlier warning of cable fire, a two-level early fire alarm method based on concentration of nanoparticles and CO detecting is proposed.

The experiments show that with the time going on, the cables will emit a large number nanoparticles during the overheating stage, most of which are particles with diameter less than 0.3 um. At this stage, the concentration of CO changes little. When the ignition point of the cable material is reached, that is, the budding stage of the fire, the concentration of CO begins to rise significantly.

The proposed multi-level fire alarm system and the designed nanoparticle detectors have been applied to a high-voltage cable tunnel in a city, which has achieved good effect for fire prevention. In the further research, the characteristic gas in the cable overheating stage will be included in the early warning system to further improve the fire alarm effect.

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