Influence of Arc Size on the Ignition and Flame Propagation of Cable Fire

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Abstract: Cable fire caused by arc faults is one of the essential factors threatening the safe operation of a power system. The ignition and flame propagation of cable fire dependent on the characteristics of the arc discharge is lacking in-depth understanding at present. In this work, with the constant electric power deposited into the arc discharge, the effects of arc size on the ignition and flame propagation of 110 kV XLPE cable fire are investigated for the first time. The arc size is changed by varying the gap distance of electrodes from 1.5 cm to 2.5 cm. It is interesting to find that the larger the arc size is, the faster the cable fire is ignited and propagates, and the larger the damaged area of the sheath of the cable is. Therein, when the gap distance increases from 1.3 cm to 3.1 cm, the equivalent impedance and the length of the arc discharge increase nearly seven times and three times, respectively. However, the gas temperature of the arc decreases slightly from 2280 K to 2100 K. In addition, a 3D model of the cable fire ignited by arc discharge is computed by Pyrosim software with fire dynamic simulation (FDS) module. Simulated results show that as the arc size increases, the cable fire is ignited faster, the flame propagates both vertically and horizontally increasing significantly, which is agreed well with the experimental results. This study deepens the understanding of the cable fire ignited by arc discharge and therefore it is useful for the evaluation and prevention of cable fire.

Keywords: arc discharge; high-voltage cable; fire simulation; fire ignition; flame propagation

1. Introduction

Power cable is important electrical equipment to ensure the safe operation of an urban power system. Cable fire is usually caused by cable faults including short circuits, electric leakage, and overload, which could result in frequent power failure and therefore serious economic losses and safety problems of the power system. According to the statistical report from China, the proportion of fires caused by electrical faults is 72% among the large-scale electrical fires from 2006 to 2015 [1]. Therein, more than two thirds of urban fires are caused by cable burning [2]. Arc discharge from the cable faults is one of the important factors that should be responsible for the cable fire. The ignition of an arc discharge in the cable system is due to the breakdown of the insulation layer or the abnormal floating high voltage of the cable sheath.

Experimental simulation of cable fire provides a direct and effective scientific basis for the evaluation of cable burning characteristics and methods of the prevention of cable fires. A fire source is essential in experimental simulation. As far as we know, there are mainly four types of fire sources, including gas burner [3–10], heat radiation fire source [11–21], Electric heating fire source [22], and Oil pan fire source [23,24]. Although these fire sources could ignite the power cable, they could not simulate the ignition of cable fire by arc discharge. This is because the temperature of the arc discharge reaches thousands of
degrees Celsius, which is much higher than the temperature of the above-mentioned fire sources. In addition, the arc discharge has a small cross-section and high energy density. Therefore, it is very desirable to study the fire source based on arc discharge for cable fire.

To understand the ignition of the cable fire by arc discharge, several research groups have made a great effort. He Jingyu et al. established a test platform for the ignition of cable fire by arc discharge. An arc discharge is generated along with the knife scratch of the sheath of the cable, but the cable cannot be successfully ignited [25]. By use of FDS software, Liu Surong et al. simulated the ignition of the 10 kV cable tunnel by arc discharge in a single-phase grounding fault. The simulated results show that the power cable could be ignited at 14.4 s after the start of the fire source [26]. However, the cable fire could not be ignited in their experiment. Recently, Wu Shuqun et al. proposed a fire source based on Jacob’s ladder arc, which is used to simulate the arc discharge caused by the abnormal floating voltage of the cable sheath. Experimental results show that as the fire source is applied to the outer sheath of the cable, a 110 kV cable fire can be successfully ignited and propagates forward a few minutes later [27]. Nevertheless, the previous works mainly focus on the development of a fire source for the ignition of power cable; little attentions is paid to the effects of the parameters of arc discharge on the ignition of the cable fire and flame propagation. Therefore, this study is aimed to investigate the effects of the size of the arc discharge on the ignition and flame propagation of the cable fire. A Jacob’s ladder arc is served as the fire source. The experimental setup of the 110 kV cable fire ignited by arc discharge is introduced in Section 2. The electric characteristics and gas temperature of the arc discharge, the experimental ignition of cable fire, and the simulation of the ignition of the cable fire and flame propagation by Pyrosim software are presented in Section 3.

2. The Experimental Setup

When the grounding wire is stolen or the cable system is poorly grounded, high suspension voltage of several kilovolts on the metal sheath of the power cable is presented, which leads to the arc faults and therefore the possibility of cable fire. In previous work [27], the equivalence between a Jacob’s ladder arc and the arc fault is analyzed, which shows that the Jacob’s ladder arc can serve as a fire source for the ignition of cable fire. Figure 1 shows the experimental setup of the ignition of the power cable by Jacob’s ladder arc. The arc discharge is driven by an ac power supply with voltage amplitude up to 20 kV and a frequency of 20 kHz. The arc power supply consists of two parts: the first-stage low-voltage conversion module and the second-stage high-voltage boost module. The output power of the arc power supply varies from 0 to 300 W. A pair of copper electrodes serves as the high-voltage electrode and the ground electrode. When high voltage is applied to the electrodes, the arc discharge is ignited at the narrow gap between the electrodes. Due to the buoyant force and the electromagnetic force, the arc climbs up along the electrodes and becomes a stable arc at the tips of the electrode, which is referred to Jacob’s ladder arc. The photo of Jacob’s ladder arc is shown in the dotted box on the right side of Figure 1. The diameter of both electrodes is about 2 mm and the inclination angle in the vertical direction of these electrodes is 15°. The distance between the tips of the electrodes is 2 cm. The distance is marked with a yellow dashed line in Figure 1. A cross-linked polyethylene (XLPE) cable (model YJLW02-64/110 kV) is used. The outer sheath material of the cable is polyvinyl chloride (PVC). The diameter and the length of the cable are about 9 cm and 60 cm, respectively. The distance between the electrode tip and the surface of the cable is about 3 cm.

A voltage probe (Tektronix P6015A) is used to measure the voltage waveform of the arc. The current probe (Pearson 6585) is used to measure the current signal of the arc. The oscilloscope Tektronix MDO3034 is used to record the voltage and current signals for further analysis and processing. A spectrometer Andor SR-500i with an ICCD detector is used to collect the emission spectrum of the arc. The slit width and the grating of the spectrometer are 50 µm and 3600 g/mm, respectively. The exposure time of the ICCD camera is 0.5 s. The image accumulation is 100. The gate width and gain are 50 µs and 1500,
respectively. The optical lens (f = 7.5 cm) is installed between the arc and the slit of the spectrometer, which leads to the arc imaging onto the slit entrance with a projection ratio of 1:1. The collected emission spectrum comes from the position of the arc that is 2.5 mm away from the tip of the electrode.

![Figure 1. The schematic of the experimental setup.](image)

3. Experimental Results

3.1. The Electric Characteristics of Jacob’s Ladder Arc

By changing the distance between the tips of the electrodes, arcs with different sizes are obtained, while the power deposited into the arc keeps at a constant of 200 W. The power is calculated by integrating the current and voltage waveforms of the arc discharge. Figure 2 shows the photos of the arc discharge with different gap distances. The Jacob’s ladder arc has a white inner flame surrounded by a typical yellow outer flame, resulting in an inverted V shape. This is due to the buoyant force and the electromagnetic force. When the gap distance increases from 1.3 cm to 3.1 cm, the length and height of the arc increase significantly.

![Figure 2. The photos of arc discharge with different gap distances.](image)

Typical voltage and current waveforms of the arc are shown in Figure 3. The gap distance between the tips of the electrodes is 2.3 cm. The power deposited into the arc is 200 W. The amplitude of the sustained voltage of arc discharge is 2.9 kV. The amplitude of the arc current is 150 mA. The current and voltage waveforms are almost the same phase. In other words, the inductance of the wire is negligible and therefore the arc discharge could be regarded as an equivalent resistive load. The arc resistance is estimated at 20.7 kΩ. A typical “zero break” phenomenon of arc current is observed [28–33].

![Figure 4 shows the sustained voltage, discharge current, and the arc resistance of Jacob’s ladder arc as a function of the gap distance between electrodes.](image)
channel, the lower the arc equivalent resistance, and the lower the arc voltage because of the fixed arc power.

![Voltage and current waveforms of Jacob's ladder arc.](image)

Figure 3. The voltage and current waveforms of Jacob's ladder arc.

![Sustained voltage, discharge current, and arc resistance as a function of gap distance.](image)

Figure 4. The sustained voltage, discharge current, and arc resistance as a function of gap distance.

3.2. Ignition of Cable Fire

A 110 kV XLPE cable is used for fire ignition. The outer sheath of the XLPE cable is made of PVC. PVC materials contain halogen elements, which are flame retardants. The fire source is Jacob’s ladder arc, which is placed right below the cable. The distance between the tips of the electrodes is 1.5 cm. The distance between the tips of the electrodes and the surface of the cable is about 3 cm. The cable is arranged horizontally. The XPLE cable is ignited by Jacob’s ladder arc with a power of 200 W, as shown in Figure 5. As the arc is generated between the two electrodes, the middle part of the arc contacts the surface of the cable bottom, as shown in Figure 5a. At 60 s later, the contact area of the arc or flame with the cable surface becomes larger, as shown in Figure 5b. However, the cable has not been fully ignited, which means that the flame will be extinguished if the fire source is moved away. At 240 s, the size of the flame grows significantly, where a small part of the outer sheath of the cable melts obviously. The cable is ignited, and the flame starts propagating along the surface of the cable, as shown in Figure 5c. At 300 s, the flame propagates vertically and spreads along both sides to the top of the cable, as shown in Figure 5d. The bottom part of the sheath of the cable begins to fall off. At 335 s, the arc power supply is turned off and therefore the arc discharge disappears immediately, but the cable is still burning. A fire extinguisher is used to put out the cable fire. Overall, the ignition of cable fire by arc discharge can be divided into the three stages. Firstly, when arc discharge appears and the cable fire is not ignited, the surface temperature of the PVC sheath of cable rises. Secondly, as the temperature increases up to over the pyrolysis.
temperature of PVC, the PVC material near the arc discharge starts pyrolyzing, generating various olefin fragments, and releasing a large amount of black smoke. Finally, the area of the sheath near the ignition source is burning up, and the pyrolysis region moves upward. When the flame on the upper part of the cable mainly comes from the burning of the cable sheath material rather than the fire source, the cable is ignited successfully.

![Figure 5](image_url). The ignition of the cable fire.

To compare the ignition and flame propagation of the cable fire with different arc sizes, the distances between the tips of the electrodes are set at 1.5 cm and 2.5 cm, while the arc power is fixed at 200 W. The experiment of the ignition of the 110 kV cable is the same as that in Figure 5. It is found that the cable fire is successfully ignited in both cases. Figure 6a,b show the photos of the cable fire at the 320 s after the start of the arc discharge in both cases. It seems that the flame size around the cable for the distance of 2.5 cm is larger than that for the distance of 1.5 cm. Figure 6c,d show the photos of the damaged surface of the cable after flame burning. A red circle is used to mark the significantly damaged part of the cable sheath. The radius and the area of the damaged surface for the distance of 1.5 cm are 2.3 cm and 16.6 cm², respectively. The radius and the area of the damaged surface for the distance of 2.5 cm are 4 cm and 50.2 cm², respectively. In addition, the metal armor layer is exposed in the case of 2.5 cm, which is not observed in the case of 1.5 cm. Therefore, it is concluded that serious damage of the cable is caused by the arc discharge with a larger gap distance and same arc power.

3.3. Gas Temperature and Size of Arc Discharge

To better understand the effects of the gap distance of arc discharge on the ignition and flame propagation of the cable fire, the heat conduction from the arc discharge to the cable is analyzed, which is dependent on the gas temperature and the size of the arc discharge. Firstly, the arc size is derived from the calibrated pixels of discharge photos in Figure 2. Figure 7 shows the relationship between the length of the arc discharge and the gap distance. When the gap distance between the tips of the electrodes increases from 1.3 cm to 3.1 cm, the length of arc discharge increases from 28 mm to 79 mm, the height of arc discharge increases from 20 mm to 38 mm, the overall surface area of the arc discharge increases from 672 mm² to 1098 mm². Therefore, with a constant of arc power, as the gap distance increases, the arc size increases significantly. Since the distance between the tips of
the electrodes and the bottom of the cable is 3 cm, as the arc height and length increase, most of the arc will gather at the bottom of the cable, which results in the growth of the contact area of arc discharge with the bottom surface of the cable. This leads to the cable sheath possibly receiving more heat from the arc discharge and therefore larger damage area in Figure 6.

![Figure 6. The photos of the cable burning and cable damage with different arc sizes. The distances between the tips of electrodes are 1.5 cm for (a,c) and 2.5 cm for (b,d).](image)

![Figure 7. The length of arc discharge as a function of the gap distance.](image)

During the ignition process of the cable fire, the heat conduction from the arc discharge to the cable also relies on the gas temperature of the arc discharge. In this work, the gas temperature of the arc discharge is obtained by fitting the emission spectrum of the second positive band system of nitrogen molecules ($C^3Π_u$-$B^3Π_g$). The radiation spectrum of arc discharge in the wavelength range of 200–800 nm is collected by an optical spectrometer with an ICCD detector. Figure 8 shows a typical $N_2$ emission spectrum at the center wavelength of 337 nm. According to the reference [34], when the simulated spectral line fits well with the experimental spectral line, the $N_2$ rotation temperature can be obtained. Due to the high frequency of particle collisions at atmospheric pressure, the rotation temperature of gas molecules is very close to the gas temperature. Therefore, the gas temperature of arc discharge with a power of 200 W is about 2100 K near the electrode. This is much lower than the gas temperature of the arc in high-voltage circuit breakers. This is due to the high arc current of several kA in these breakers.
Figure 8. The experimental and simulated emission spectrum of N\textsubscript{2} in arc discharge with a gap distance of 2 cm.

Figure 9 shows the gas temperature of the arc discharge for different gap distances with fixed arc power. As the gap distance between the tips of the electrodes increases from 1.3 cm to 2 cm, the gas temperature of the arc discharge drops slightly from 2280 K to 2100 K. When the gap distance further increases, the gas temperature of the arc discharge remains almost unchanged. It clearly shows that the gas temperature difference of the arc discharge between the two cases of the gap distance of 1.5 cm and 2.5 cm is only 100 K. This means that the gas temperature of arc discharge is expected to play a minor role in the ignition of cable fire with different arc size.

![Graph showing gas temperature of arc discharge vs gap distance](image)

**Figure 9.** The gas temperature of the arc discharge as a function of the gap distance between the tips of the electrodes.

From the point of view of energy balance, the input power of arc discharge is dominated by Joule heating, which derives from the arc power supply. The electric power deposited into arc discharge (arc power) is mainly transferred to the air through thermal...
convection, the photons through atoms or molecules radiation, electrodes, and cables through thermal conduction. The power balance equation is given by

$$P' = P'_Q + P'_T + P'_r$$  \(1\)

where \(P'\) is the arc power, \(P'_Q\) is the thermal convection power, \(P'_T\) is the thermal conduction power, and \(P'_r\) is the thermal radiation power. According to Fourier’s law, the thermal conduction power transferred to the cable is expressed as

$$P'_{Tc} = kA \frac{dT}{dn}$$  \(2\)

where \(k\) is the coefficients of the thermal conductivity of the sheath of the cable, \(A\) is the contact area between the arc discharge and the bottom surface of the cable. \(\frac{dT}{dn}\) is the temperature gradient along with the heat flow, which is dependent on the gas temperature at the center of the arc column and the radius of the arc column. Therefore, as the gap distance increases from 1.5 cm to 2.5 cm, the length and the surface area of the arc discharge increases significantly, the contact area between the arc discharge and the bottom surface of the cable increases, and while the gas temperature remains almost unchanged. This leads to the increase in the thermal conduction power transferred to the cable and therefore larger flame size and damaged area of the cable sheath.

3.4. Simulation of Cable Fire

To further understand the influence of arc size on the fire ignition and flame spread, a three-dimensional model of cable fire is computed by the Pyrosim software with the FDS module. Two intersecting rectangular fire sources are used to represent the “inverted V”-shaped Jacob’s ladder arc, as shown in Figure 10. The cross-section of the rectangular fire sources is square. The length and the surface area of the rectangular fire source are the same as that of the arc discharge in Figure 2. Figure 10 shows the simulated fire sources with different gap distances. According to the Stefan-Boltzmann law, the total power radiated by a unit area of a black body surface per unit time is proportional to the fourth power of the thermodynamic temperature of the black body. Because the gas temperature of the arc discharge for different electrode distances is the same, the heat release rate of the simulated fire source is set to 130 kW/m\(^2\), which is calculated from the arc power. The other parameters of the simulated fire source are the same as those in the experiment. It should be pointed out that the curved surface model of the cable is limited by the Pyrosim software. A rectangular parallelepiped model of the cable with a side length of 8.5 cm and a total length of 30 cm is built, which is automated equivalent to a cylinder model during the calculating process in the software. The ignition of the cable fire is operated in an open environment. The material of the outer sheath of the cable is polyvinyl chloride with a density of 1.25 g/cm\(^3\) and a thickness of 6.8 mm. The specific heat and thermal conductivity of the cable are set to 4.18 kJ/(kg·K) and 0.14 W/(m·K), respectively. The material of the insulating layer is XLPE with a density of 0.94 g/cm\(^3\) and a thickness of 3.7 mm. The conductor of the cable is copper. To monitor the flame propagation in the cable fire, five temperature sensors are set on the surface of the cable, as shown in Figure 11. The temperature sensor 1, sensor 2, and sensor 3 placed on the same side are lined vertically on the bottom, middle, and top of the cable, respectively. The temperature sensor 4 is placed onto the center of the top surface of the cable. They are on the same vertical plane as the fire source. The temperature sensor 1, sensor 2, sensor 3, and sensor 5 are on the same side plane. Sensor 5 is placed at the right hand of sensor 2 in the same horizontal line. The distance between sensor 2 and sensor 5 is 10 cm. The vertical distance between sensor 1 and sensor 2 is 4 cm. The vertical distance between sensor 2 and sensor 3 is 4 cm, too. The horizontal distance between sensor 3 and sensor 4 is 5 cm.
The simulated fire source is set to 130 kW/m², which is calculated from the arc power. The heat release rate of the arc discharge for different electrode distances is the same, the heat release rate of the cable fire is presented in Figure 12a. The gap distance between the tips of the electrodes is 2 cm. At 60 s after the flame appears at the bottom of the cable. At 120 s, the flame grows and propagates along the side of the cable, where the maximum temperature reaches as high as 900 °C. The flame caused by the arc has completely spread to the side of the cable, which is similar to the phenomenon obtained in the experiment in Figure 5. At 180 s, the flame reaches the top surface of the cable. At 335 s, the whole cable has been covered by flame. This is different from the experimental results, where the cable is not completely covered by the flame at 335 s. This is mainly because the flame-retardant cable of cross-linked polyethylene is used in the experiment but not taken into consideration in the simulation.

Figure 10. Schematic of the equivalent fire source of arc discharge with different gap distances in the simulation.

Figure 11. The model of the cable fire.
To quantitatively study the effects of the arc size on the flame propagation, the horizontal speed of the flame propagation is obtained with the knowledge of the time delay between the temperature peaks of sensor 2 and sensor 5 and the distance between sensor 2 and the sensor 5. The temporal distribution of the temperature measured by the sensors is presented in Figure 12b. Generally, the temperature of the sensors increases slowly at first and then rises suddenly at a specific time. For example, the temperature of sensor 1 keeps almost constant at 50 °C at first and then increases sharply at 75 s, reaching a maximum of about 815 °C at 111 s. This is because the flame reaches the position around sensor 1 at 75 s. An obvious time delay of the temperature peaks among these temperature profiles of five sensors is observed. They are presented as sensor 1, sensor 2, sensor 3, sensor 5, and sensor 4 in ascending order of the appearance of the temperature peaks. It can be deduced that the flame firstly propagates from the bottom to the top along the side of the cable after the ignition of the cable fire by arc discharge, which is agreed well with the experimental results in Figure 5. Afterward, the fire spreads horizontally towards sensor 5. Finally, the flame reaches the top surface of the cable.

To analyze in detail the ignition and the flame propagation with different arc sizes, the time corresponding to the half maximum of the temperature curve of sensor 2 is referred to the ignition time of the cable fire, and the time corresponding to half maximum of the temperature curve of sensor 5 is referred to the averaged spread time of the cable fire. Figure 13 shows the ignition time and the spread time of the cable fire for different arc sizes. When the gap distance between the tips of the electrodes increases from 1.5 cm to 3.1 cm, the ignition time decreases from 98 s to 82 s, and the spread time decreases from 121 s to 92 s. In addition, as the electrode distance increases, the time difference between the ignition time and the spread time of the cable fire decreases.

Figure 12. (a) The temporal and spatial distribution of the temperature during the ignition and flame propagation of the cable fire. (b) The temporal distribution of the temperature measured by the sensors.

Figure 13. The ignition time and the spread time of cable fire with different gap distances.
and the sensor 5. The vertical speed of the flame propagation is obtained with the knowledge of the time delay between the temperature peaks of sensor 1 and sensor 3 and the distance between sensor 1 and sensor 3. Figure 14 shows the horizontal and vertical speeds of flame propagation with different gap distances. When the gap distance increases from 1.5 cm to 3.1 cm, the horizontal speed of the flame increases from 0.128 cm/s to 0.154 cm/s, the vertical speed of the flame increases from 0.356 cm/s to 0.9 cm/s. Obviously, the vertical speed of the flame is greater than the horizontal speed of the flame. This means that the flame propagates faster along the side of the cable. Therefore, as the arc size increases, the speed of the flame propagation increases, which leads to the observation of larger flame size of the cable fire and therefore more serious damage of the cable sheath.

Figure 14. The horizontal and vertical speed of the flame propagation with different gap distances.

4. Conclusions

To understand the cable fire caused by the arc discharge, the effects of arc size on the ignition and flame propagation of the 110 kV cable fire are investigated. When the gap distance between the tips of the electrodes increases from 1.3 cm to 3.1 cm with a constant of arc power, both the length and the surface area of the Jacob’s ladder arc increase significantly, and the gas temperature of the Jacob’s ladder arc decreases slightly. The experimental and simulation results of the ignition and flame propagation show that as the arc size increases, the ignition time of the cable fire becomes shorter, the speed of the flame propagation increases significantly, and both the flame size and the damaged area of cable sheath increase. This is mainly due to the significant increase in the contact area between the arc and the cable, instead of the small change of gas temperature of the arc discharge. The study contributes to the understanding of the ignition of the cable fire by arc discharge, which is in favor of the development of an electric fire source based on arc discharge and the assessment of the cable fire scale.

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