Research on Aging and Burning Performance of AC 380V ZR-YJV Cable Insulation Sheath

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Abstract. Carrying out research on the aging and burning performance of cable insulation sheath is an important means to prevent cable fires. The thermal aging test box, cone calorimeter and synchronous thermal analyzer were used to study the effect of thermal aging on the combustion performance of AC 380V ZR-YJV cable insulation sheath. The results show that in the early stage of thermal aging of the cable, the ignition time of the YJV cable insulation sheath material gradually increases; compared with unaged cables, the ignition time of cables being aged for 15 days has increased from 8 seconds to 57 seconds while the initial peak value of the heat release rate of the cable decreased from 123 kW/m² to 22 kW/m². A large amount of easily decomposable additives in the early stage of thermal volatilized from aging cable sheath may be responsible for the reduction trend of the ignition and fire occurrence of the cable insulation sheath. And for the condition of the aging time increasing, the ignition time decreases from 57s to 32s, and the heat release rate will increase from 22 kW/m² to 85 kW/m² in which the ignition and fire trend of the cable insulation sheath increase.

1. Introduction

The power cables used in 380V substations are mainly Cross-linked polyethylene (XLPE) insulated Polyvinyl chloride (PVC) sheathed cables (hereinafter referred to as YJV cables). The cable is often affected by the high temperature environment or heating inside the cable core due to overload, which increases the temperature of the cable insulation sheath and accelerates its aging. As the degree of aging deepens, the insulation performance of YJV cables decreases significantly, increasing the possibility of cable short circuit and fire disaster. Therefore, studying the aging and burning performance of the cable insulation sheath is essential to prevent cable short circuit, fire disaster and ensure the safe and stable operation of substations.

Concerning the aging problem of cables, researchers have done various cable performance studies. Li Xiaokang et al. [1] tested with a cone calorimeter to study the influence of fire-retardant coatings on the combustion performance of cables and found that although the fire retardant coating increases the thermal inertia of the cable insulation surface, reduces the amount of smoke produced by the cable,
and increases the difficulty of ignition, but the CO yield during the combustion process is relatively high which raises the toxicity of the smoke. Ouyang Benhong et al [2] used different aging methods to study the space charge distribution law of XLPE cables in order to evaluate the aging state of XLPE cables. Liu Gang et al [3] analyzed the aging mechanism of the cable by the isothermal relaxation current method (IRC). In order to study the influence of different aging time on the insulation performance of the cable, Yang Fan et al [4] accelerated the aging of the cable at a high temperature of 140°C.

In this paper, the aging and burning performance of AC 380V ZR-YJV cable insulation sheath was studied. The thermal aging treatment of the ZR-YJV cable is investigated via the accelerated thermal aging box. The ignitability and heat release rate of the thermally aging treatment cable are studied by a cone calorimeter. And a synchronous thermal analyzer is used to study the pyrolysis characteristics of aging cables.

2. Experiment setup

2.1 Experimental materials
ZR-YJV is a four-core cable with three cores of 185 square millimeters and one core of 95 square millimeters by Foshan Zhongbao Cable Factory Co., Ltd.. The rated phase voltage is 0.6kV and the rated line voltage is 1kV. From inside to outside, there are three layers including polyethylene layer, flame retardant PVC layer and semi conductive material outer sheath. The insulation layer adopts three-layer extrusion structure. The inner insulation of the conductor surface is the conductor shielding layer, the middle is cross-linked polyethylene, and the outer insulation is the insulation shielding layer.

2.2 The main equipment and instruments of the experiment
The RLH-100 thermal oxygen aging box made by Nanjing Huanke Experimental Equipment Co., Ltd. has a temperature range of 20~200 ℃, a heating rate of 1.0~3.0 ℃/min, and a time setting range of 0~9999 h. The S001 cone calorimeter adopted are made by the British FTT Company. The STA449C synchronous thermal analyzer of Netzsch Scientific Instruments Trading Co., Ltd. has the highest resolution TG / DSC and incomparable long-term stability. Sta 449C has high accuracy, μg resolution and excellent stability, and can test 5g samples.

2.3 Experimental method
The heat aging experiment refers to the method specified in GB/T 2951.2-1997 and GB/T12706.1-2002, and the cable sample is placed in a natural ventilated aging box, and the aging temperature is set to 135±0.5℃. Then, The aged samples are cooled down at ambient temperature for 24 hours.

The cone calorimetry experiment is in accordance with international standards specified in ISO 5660:2002. A cone calorimeter is used to test the ignition time and heat release rate of YJV cables with different aging degrees.

In the thermogravimetric experiment, the heating rate is set to 10°C/min, the temperature range is 25~600℃, the gas flow is 30 mL/min in a nitrogen atmosphere, and the cable sample mass is about 10 mg for thermogravimetric analysis.

3. Results and analysis

3.1 The ignition characteristics of thermal aging on the cable insulation sheath
The cone calorimetry is to measure the ignition time of the test object under a given heat radiation intensity, that is, the time when the surface of the test object ignited by an electric spark. The shorter the ignition time, the greater the ignition risk of the test object [5]. Table 1 shows the ignition time required for the YJV cable insulation sheath with different aging time. Fig. 1 shows the influence trend of the ignition time of the YJV cable insulation sheath with the degree of aging.
Table 1 The ignition time required for the YJV cable insulation sheath with different aging time

| Aging time / day | 0  | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|-----------------|----|----|----|----|----|----|----|----|----|----|
| Ignition time / s | 8.3| 18.7| 22.1| 57.6| 39.3| 36.6| 34.3| 34.1| 33.8| 32.7|

As shown in the Fig. 1 under a given heat radiation intensity of 75kW/m², the ignition time of the YJV cable insulation sheath dependence on the increase of the aging time shows one peak file with the trend of rising and then falling corresponding the aging time from 0-15 days and 15-45 days, respectively. In the cone calorimetry experiment, the length of ignition time mainly depends on the concentration of combustible gas on the surface of the sample. Fig. 1 shows the aging time has a great influence on the ignition time, indicating that the aging time has an obvious effect on the release of combustible gas on the surface of the sample when heated. When the aging time increases from 0-15 day, the corresponding ignition time gradually increased. The main reason is that the lubricant (such as paraffin) on the surface of the YJV cable insulation sheath, the plasticizer, anti-oxidant and other flammable components in the sheath are heated and volatilized, resulting in prolonged ignition time. In the later stage of aging (15-45 day), as the aging effect continues to deepen, the thermal stability of the insulating sheath material decreases, and the performance decreases, causing the shorten of the ignition time.

![Fig. 1 The influence of aging time on the ignition time of YJV cable insulation sheath](image)

3.2 The influence of heat release rate of thermal aging

The heat release rate is one of the most important parameters to judge the combustion performance of cable insulation. In general, the heat release rate’s peak is considered to study the combustion characteristics of the YJV cable insulation sheath. However, due to the particularity of the material structure of the YJV cable sample, in the cone calorimetry test, the dependence of the heat release rate on time is often more complicated, and there exists multiple peaks in the heat release rate curve. But for the fire warning situation, the initial peak of the curve expressing dependence of the heat release rate on time is the most meaningful value. Generally, as the ignition time is prolonged, the heat release rate’s initial peak decreases, which means that the ignition risk of the cable insulation material and the risk of flame spread will be reduced [5-7]. In fact, the ignition time of the cable and the initial peak value of the heat release rate mainly depend on the properties of the cable insulation sheath material. As far as YJV cables are concerned, these high temperature characters mainly depend on PVC. Table 2 shows the initial peak value of heat release rate of YJV cable insulation sheath with different aging time. Fig. 2 shows the influence of aging time on the initial peak value of heat release rate of YJV...
cable insulation sheath. It can be seen from that the entire curve is roughly like a valley. In the early stage, as the aging time increases from 0-15 days, the initial peak value of the heat release rate of the YJV cable samples gradually decreases; in the later stage, as the aging time increases from 15-45 days, the initial peak value of the heat release rate of the YJV cable sample gradually rises, which is just the opposite of the trend of the early stage above. The main reason is: in the early stage of accelerated thermal aging of the cable, a large amount of additives easily decomposed and volatilized are lost in the insulating sheath.

Table 2 The initial peak value of heat release rate of YJV cable insulation sheath with different aging time

| Aging time / day | 0  | 5  | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 |
|------------------|----|----|----|----|----|----|----|----|----|----|
| Initial peak heat release rate / s | 123.7 | 62.2 | 38.8 | 21.9 | 39.3 | 39.8 | 99.3 | 106.1 | 84.1 | 85.6 |

Fig. 2 The influence of aging time on the initial peak value of heat release rate of YJV cable insulation sheath

3.3 Influence of thermal aging on thermal decomposition of sheath insulation

Thermal decomposition experiments were performed on YJV cable sheath materials and insulation materials with different aging degrees through a synchronous thermal analyzer. Table 3 shows the thermogravimetric relationship of YJV cable sheath materials with different aging time. In the thermal decomposition experiment, it can be observed that there are two obvious stages in the thermal decomposition of the PVC sheath under the protection of nitrogen. From room temperature (about 24 °C) to 250 °C, the sheath sharp and the quality hardly changes. After the temperature passing 250 °C, the thermal decomposition of the sheath changes tremendous. Overall, as the aging time increases, the quality loss of the sheath in the first stage is significantly reduced. The quality loss of the sheath material without aging and aging for 10 days, 20 days, and 30 days to accelerate thermal aging respectively accounts for 43%, 36%, 32% and 28% compared with the total mass of the sample. This also confirms the reason why thermal aging affects the ignition time of the sheath material and the initial peak of the heat release rate.

Table 3 The thermogravimetric relationship of YJV cable sheath materials with different aging time

| temperature / °C | 24 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Aging time / day | 0  | 5   | 10  | 15  | 20  | 25  | 30  | 35  | 40  | 45  |
Table 4 shows the thermogravimetric relationship of YJV cable insulation materials with different aging time. In the decomposition experiments of YJV cable insulation materials, it can be observed that the pyrolysis of the unaged cross-linked polyethylene insulation material has only one stage and is relatively stable. The thermal decomposition only occurs after the temperature above 400 °C, and the mass loss fraction is about 94%. The thermal decomposition of the sample after thermal aging is divided into two stages, the first stage starts at 250°C, the mass loss of the sample with accelerated thermal aging time of 10 days, 20 days and 30 days is 9%, 14%, 22%. During the process of heat aging, small molecules such as anti-oxidants and stabilizers are decomposed by heat effect, which reduces the thermal stability of cross-linked polyethylene. At the same time, anti-oxidants have the effect of protecting plasticizers from oxidation. The more antioxidants escape from the cable insulation materials, the easier the plasticizers will be oxidized; The second stage of significant decomposition occurs between 400 °C and 500 °C. The total mass loss of cross-linked polyethylene insulation material is 83%, 82%, and 80%, respectively. The pyrolysis reaction has occurred during the thermal aging process and some decomposition products have been released which causes the total mass loss of cross-linked polyethylene insulation. It can be seen that the main reaction occurring during the thermal aging process is the thermal decomposition of the additives, which leads to the reduction of the thermal stability of the cross-linked polyethylene.

| temperature / °C | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|------------------|---|---|---|---|---|---|---|---|---|----|
| mass retention rate(0-day)/% | 100 | 101 | 101 | 100 | 57 | 57 | 56 | 55 | 50 | 47 |
| mass retention rate(10-day)/% | 100 | 101 | 102 | 101 | 64 | 63 | 62 | 61 | 58 | 55 |
| mass retention rate(20-day)/% | 100 | 101 | 101 | 100 | 68 | 62 | 61 | 60 | 56 | 52 |
| mass retention rate(30-day)/% | 100 | 100 | 100 | 99 | 72 | 70 | 69 | 68 | 63 | 59 |

4 Conclusion
In this paper, the thermal aging combustion performance of the AC 380V ZR-YJV cable insulation sheath is investigated. The ignitability, heat release rate and pyrolysis characteristics of the cable are analyzed, and the following conclusions are drawn:

(1) The ignition time of YJV cable gradually increases with the growth of aging time, and then gradually decreases which shows an overall trend of prolongation; on the contrary, the initial peak value of the heat release rate firstly decreases with aging time, then gradually increases, and the overall trend is downward;

(2) In the early stage of cable thermal aging, its ignition time is prolonged and the initial peak value of heat release rate decreases. The main reason is that plasticizers, anti-oxidants and other additives in the cable sheath material gradually decompose and volatilize in the early stage of the accelerated thermal aging;

(3) Thermal aging can accelerate the degradation of the insulation and mechanical properties of the cable insulation and sheath material, and increase the risk of current leakage and short circuit. In the early stage of cable aging, the probability of ignition and fire occurrence of sheath material does not increase but decrease; in the later stage of cable aging, the risk of ignition and flame spread of the sheath material increased.
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