Research on Defect Diagnosis of High-voltage Cables in Power Grid Based on Statistical Theory

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Abstract. In this paper, the ZR-YJV223-15kV cable is selected as the experimental sample, and the focus is on the change of the two insulation characteristic quantities, the dielectric loss factor and the polarization index. The insulation characteristic quantities of cables with different types of defects is tested and analysed during the combined electric and heating aging process. To obtain the differences in the evolution of the characteristic quantities affected by different types of defects, statistical analysis and OriginPro8 software scientific methods are used to systematically analyse and process experimental data, at the same time the correlation between each characteristic quantity is found out. It proves that the dielectric loss factor and polarization index can be used to screen out the types of cable defects in the aging stage. The research results will provide technical support to ensure the safe and reliable operation of the power system.

1. Introduction

As an important equipment for power transmission, power cables are increasing in application and demand, especially cross-linked polyethylene (XLPE) cables. The special molecular structure and cross-linked structure make it have good electrical properties. Characteristics, insulation properties, heat resistance and mechanical properties¹ are widely used in high-voltage and ultra-high-voltage lines.

In the process of cable installation and laying, the insulation defects of the cable accessories will be caused by improper installation technology or external force damage. The concentrated distribution of electric fields at the concentrated defects will lead to the accumulation of space charges and leakage currents. Increase will lead to further deepening of defects, there by shortening the operating life of the cable²⁴. In order to avoid these problems, it is necessary to use methods such as data monitoring or experimental analysis to ensure that the cable is repaired and replaced before the end of life to prevent occurrence. The aging of the insulation leads to problems such as cable breakdown, which affects the safe and effective transmission and operation of electric energy.

Studying the insulation aging problem of XLPE cable during operation, analyzing the characteristic quantity change trend and data characteristics of different insulation defect types of cables from the
mechanism, and timely positioning the defect location according to the test results is of great help to the maintenance of the cable.

2. Sample preparation and experiment

The object of this research is the ZR-YJV223 95 mm8.7/15kV type cable. The XLPE main insulation thickness is 3.4 mm, the sheath thickness is 2.8 mm, and the approximate outer diameter of the cable is 58.2 mm. The basic structure is shown in Figure 1. The meaning of each symbol is shown in Table 1.

| Symbol | Representation |
|--------|----------------|
| ZR     | Flame retardant cable |
| YJ     | XLPE insulation |
| V      | Polyethylene sheath |
| 22     | Steel tape armor |
| 3×95mm | Three conductors, each conductor has a cross-sectional area of 95 square millimeters |
| 8.7/15 kV | Rated working voltage 8.7/15kV (available voltage range 0.6/1kV~26/35kV) |

2.1. Sample preparation

The four experimental sample processing methods are shown in the Figure 2 to Figure 5. The reason for the failure of cable joints is mostly due to the improper installation process during the cable laying process, external force damage and then the joint defects. At present, there are many kinds of cable defects found, and the reasons for the defects are various, but domestic researchers will study this problem. There are three main types of cable joint defects involved, which are also the defects with the highest failure rate, which are air gap defects, spike defects and scratch defects [5-7]. This article also focuses on these three typical defects in order to achieve the purpose of making the research results more popular.
2.2. Experiment procedure

The model of the thermal aging test equipment is M/TC300 (Shanghai Muuni Test Equipment Co., Ltd.). In order to achieve the synergistic aging effect of electrical stress and thermal stress, the thermal aging box needs to be modified. The modified sample aging diagram is shown in Figure 6 Shown. This time the dielectric loss factor test equipment uses the HTJSY anti-interference dielectric loss measuring instrument.

![Figure 6 Photo of cable ageing and wiring](image)

The polarization index test experiment adopts the weak signal test system independently developed by the special power supply team of Dalian University of Technology, which can accurately measure the leakage current of the sample to nanoamp.

Refer to the GB-T12972 standard. This time the aging voltage is 21kV, and the aging temperature is 135°C. Take 3 samples of A, B, C, and D cables and put them into the combined electric heating system for aging, and put the cable samples of the same category into an aging system to prevent the 3 samples from affecting each other during the aging process. A short circuit was formed, and the 3 samples were separated by 15cm and separated by insulating paperboard. The aging cycle was 5 days, and a total of 10 cycles were processed, and the aging time was 1200h.

At the end of each aging cycle, take A1, B, C and D cable samples from the aging system, cool to room temperature, remove surface dirt, and short-circuit both ends of the cable for 24 hours to release the internal Residual charge. Press 1kV for testing. The experimental voltage of 1kV is lower than the rated voltage of the cable, which will not affect the cable. Take the average of multiple measurements.

3. Analysis of results

3.1. Analysis of Test Results of Polarization Index

As shown in Figure 7, the polarization index of the C cable samples reached 12.992 after 1200h of aging, which has the greatest impact on the insulation performance of the cable, mainly because the cutting-edge metal in XLPE severely changes the electric field distribution in it, and the polar small molecules generated after the chemical reaction And the original charge inside the XLPE under the action of the concentrated electric field, the irregular collision movement is intensified, which makes the trap density increase, the trap energy level deepens, and the polarization index becomes obvious. The polarization index of the Class D cable samples reached 10.773 after 1200h of aging, which increased by 35.97% compared to the non-defective cable samples, mainly due to scratches in the XLPE. The scratches would penetrate into the air and change the scratches at the same time. The field intensity distribution around the mark causes the polarization of the molecules to participate in the air, and the direction of movement of the charge, electrons and polar molecules of the orientation polarization changes, which accelerates the aging effect and causes the polarization index to increase. The polarization index of the B-type cable samples reached 9.245 after aging for 1200h.
Compared with the above two types of defective cables, the existence of the air gap defect has relatively little effect on the polarization index, and the moisture and impurities in the air gap will participate in the aging. The chemical reaction leads to the generation of impurity ions, which accelerates the aging of the cable, reduces its insulation performance, and causes the polarization index to increase.

Take the polarization index test result of the last aging cycle as the data sample, and set the hypothesis test: the original hypothesis is "the sampled data is normally distributed", and the alternative hypothesis is "the sampled data is not normally distributed". Regard each group of data as a data subset, use OriginPro8 software to perform normal distribution test to obtain the P value of each group of data. Results are shown in the following table.

Table. 2 Normal distribution test result of polarization index

| Group | 1   | 2   | 3   | 4   | 5   | 6   | Average value | P value | Standard deviation |
|-------|-----|-----|-----|-----|-----|-----|---------------|---------|-------------------|
| A     | 8.140 | 7.471 | 7.916 | 8.257 | 7.806 | 7.948 | 7.923 | 0.8225 | 0.2747 |
| B     | 9.694 | 9.379 | 8.474 | 9.479 | 8.728 | 9.716 | 9.245 | 0.1781 | 0.5211 |
| C     | 12.268 | 14.461 | 13.916 | 11.755 | 13.870 | 11.682 | 12.992 | 0.1594 | 1.2291 |
| D     | 11.419 | 10.229 | 11.544 | 11.065 | 10.037 | 10.338 | 10.772 | 0.2693 | 0.6518 |

The results show that the P values of the four sets of sample data are all greater than 0.05, so it can be considered that the four sets of sample data subsets all obey the normal distribution. The analysis of variance can determine whether there are significant differences between the data subsets. The OriginPro8 software is also used to perform one-way ANOVA on the experimental results of different types of cable samples. The analysis results are shown in Table 3.

Table. 3 ANOVA analysis results of polarization index

| Source          | Degree of freedom | Sum of squares | Mean square error | F value | P value |
|-----------------|-------------------|----------------|-------------------|---------|---------|
| Factor level    | 3                 | 85.2891        | 28.4297           | 49.82362| 1.83197×10^-9 |
| Random error    | 20                | 11.4121        | 0.5706            |         |         |
| Total deviation | 23                | 96.7012        |                   |         |         |

It can be seen from the table that the mean square error between groups is 85.2891, the mean square error within the group is 11.4121, and the mean square error between groups is much larger than the mean square error within the group, indicating that the average values of each group of data subsets are basically unlikely to be equal. The calculated F value is 49.82362, assuming that the significance level of α=0.05 is considered, that is, the 95% confidence level, then F0.05(3,20)=3.10, F>F0.05(3,20). Therefore, it can be concluded that the average value of each group of cable data subsets after 1200h aging is different, and there is a significant difference between the polarization index data of each typical defective cable[8].
3.2. Analysis of Test Results of Dielectric Loss Factor

Figure 8 shows the relationship between the dielectric loss factor and the aging time of the four types of cable samples.

![Figure 8 Dielectric loss factor test results](image)

Take the dielectric loss factor test result of the last aging cycle as the data sample, and set up hypothesis testing: the original hypothesis is "the sampling data is normal distribution", and the alternative hypothesis is "the sampling data is not normal distribution". Regard each group of data as a data subset, use OriginPro software to perform normal distribution test to obtain the P value of each group of data.

| Group | 1/% | 2/% | 3/% | 4/% | 5/% | 6/% | Average value/% | P value/% | standard deviation/% |
|-------|-----|-----|-----|-----|-----|-----|-----------------|-----------|----------------------|
| A     | 3.153 | 3.755 | 3.247 | 3.661 | 3.001 | 3.541 | 3.393          | 0.6061    | 0.3024               |
| B     | 4.325 | 4.000 | 4.431 | 4.264 | 3.818 | 4.074 | 4.152          | 0.8636    | 0.2285               |
| C     | 4.661 | 5.209 | 4.861 | 4.695 | 5.375 | 4.996 | 4.557          | 0.3789    | 0.2974               |
| D     | 4.426 | 4.635 | 4.602 | 4.347 | 4.660 | 4.672 | 4.557          | 0.1006    | 0.1365               |

According to statistical theory, if the P value is greater than 0.005, the null hypothesis cannot be rejected, that is, the four sets of sample data subsets are considered to be normally distributed. The analysis of variance can determine whether there are significant differences between the data subsets. The OriginPro8 software is also used to perform one way ANOVA on the experimental results of different types of cable samples. The analysis results are shown in Table 5.

| Source          | Degree of freedom | Sum of squares | Mean square error | F value | P value |
|-----------------|-------------------|----------------|--------------------|---------|---------|
| Factor level    | 3                 | 8.3545×10^-4 | 2.78483×10^-4      | 44.42528| 4.9700×10^-9|
| Random error    | 20                | 1.25372×10^-4| 6.26858×10^-6      |         |         |
| Total deviation | 23                | 9.60822×10^-4|                   |         |         |

It can be seen from the table that the mean square error between groups is 2.78483×10^-4, and the mean square error within the group is 6.26858×10^-6. The mean square error between the groups is much larger than the mean square error within the group, indicating that the average value of each data subset is basically not It is too likely to be equal. The calculated F value is 44.42528, assuming that the significance level of α=0.05 is considered, that is, the 95% confidence level, then F0.05(3,20)=3.10, F>F0.05(3,20). Therefore, it can be concluded that the average value of each group of cable data subsets after 1200h aging is different, and there is a significant difference between the dielectric loss factor data of each typical defective cable.
3.3. **Correlation between dielectric loss factor and polarization index**

It is observed from the experimental results that the existence of typical defects will affect the aging progress of the cable to varying degrees, making the dielectric loss factor and polarization index larger. Compared with the non-defective cable, with the change of aging time, the change trend of the curve is not the same. There is no obvious change, so the experimental results of the non-defective cables (group A) are used as reference data to explore the correlation between the dielectric loss factor and the polarization index of the cable. Figure 9 shows the regression fitting diagram of the dielectric loss factor and polarization index, Table 7 shows the fitting parameter results, and Table 8 shows the single-factor analysis of variance results of the linear regression significance test.

![Figure 9 Linear regression line of dielectric loss factor and polarization index](image)

It can be seen that the mean square error between the groups is 0.00823, the mean square error within the group is $1.44401 \times 10^{-5}$, and the mean square error between the groups is much larger than the mean square error within the group, indicating that the average values of the data in each group are basically impossible to be equal. The calculated $F$ value is 570.13318, assuming that the significance level of $\alpha=0.05$ is considered, that is, the 95% confidence level, then $F_{0.05}(1,64)=3.99$, $F>F_{0.05}(1,64)$. Therefore, it can be concluded that the average value between each set of data is different, the slope of the regression line $\beta_1$ is not 0, and the power frequency dielectric loss factor of the XLPE cable is positively correlated with the polarization index, which is reasonable. As the aging degree of XLPE deepens, its insulating ability decreases, and the characteristic quantity that characterizes the insulating ability, that is, the dielectric loss factor and the polarization index decrease simultaneously.

| Slope | Intercept | Statistics |
|-------|-----------|------------|
| Value | Error     | Value      | Error      | R-Sq(adj) |
| 0.00487 | 0.00101 | 0.00402 | $1.68314 \times 10^{-4}$ | 87.95% |

**Table. 6 Fitting parameter results**

| Source | Degree of freedom | Sum of squares | Mean square error | F value   | P value |
|--------|-------------------|----------------|-------------------|-----------|---------|
| Regression | 1                 | 0.00823        | 0.00823           | 570.13318 | 0.00    |
| Residual | 64                | $9.24165 \times 10^{-4}$ | $1.44401 \times 10^{-5}$ |           |         |
| Sum     | 65                | 0.00916        |                   |           |         |

4. **Conclusions**

The electrical parameters of the samples obtained by the combined electric and heat aging experiment is analyzed and processed, and the change law of the dielectric loss factor and polarization index of different types of cables with aging time is obtained. Among them, the cable with spiked defects is the fastest decrease the insulation performance with the increase of aging time. It can identify the
significant differences in the change of characteristic quantities caused by different defects by using statistical analysis and OriginPro8 software, and the type of defects in the degraded cable is identified by using the degree of change in dielectric loss factor or polarization index.

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