A Novel Electrical Life Model of Crosslinked Polyethylene Based on AC Breakdown Time Statistical Analysis

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Abstract. To propose a more accurate electrical life model of crosslinked polyethylene (XLPE) under AC voltage, breakdown experiments of XLPE samples were carried out. The distribution of breakdown time varied with electric field strength within the sample were statistically analyzed, based on which the traditional inverse-power-law related electrical life model was thoroughly improved. The results showed that, under the same electric field strength, the breakdown time of XLPE could still be very dispersive, which mainly distributed in three time intervals. Different time intervals corresponded to different insulation failure processes, where the dominant failure process was determined by the electric field strength. By replacing the whole electrical life of the XLPE samples with only the breakdown time component of the dominant failure process, an improved electrical life model of XLPE was obtained. Compared with the traditional life model, the lifetime index n obtained by the improved model was more precise to evaluate the aging time of XLPE samples, especially those under long electrical aging process.

Keywords: Cross-linked Polyethylene · Failure time · Weibull Distribution · Statistic Characteristics · Inverse Power Law

1 Introduction

Cross-linked polyethylene (XLPE) is a semi-crystalline polymer formed by physical or chemical cross-linking of polyethylene (PE), and is widely used as an insulating material for power cables due to its outstanding electrical, thermal and mechanical properties [1]. XLPE cable has been applied in urban power systems in China for more than 40 years since the 1980s [2]. However, concerning problem rises as the insulation performance of XLPE cable decreases gradually due to the influence of electrical, thermal, moisture and other factors in long-term operation, which threatens the stability of power system [3]. According to statistics, cable failures due to insulation aging account for 21.1% of transmission line failures, ranking second among all other factors. With the further increase of cable service life, insulation aging of cables tends to be more serious, which will inevitably increase the frequency of cable transmission failure [4]. Therefore, it is

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of great significance to analyze the failure characteristics of XLPE, and make intensive studies of XLPE life assessment to improve the reliability of power grid operation.

For cables that are put into operation at early years, or those operates under low voltage levels, thermal aging is the main form of the insulating aging. However, with the continuous increase of cable transmission voltage level, electrical aging begins to play an increasingly important role in the failure process of XLPE insulation. Therefore, attention has been drawn to the electrical aging process of XLPE [5]. Due to the difference between the external environment and the internal structure of materials, there are different forms of electrical aging in insulating materials. For different aging forms, scholars have proposed different electrical aging theories, including charge injection and extraction theory, photodegradation theory, hot electron theory, and partial discharge theory, etc. [8, 9]. Under long-term electric stress, the molecular structure of XLPE is destroyed, and its insulation performance is gradually reduced. If there are defects such as air gaps or micropores in the insulation, the electric field distortion will also occur at the defects, thus accelerating the electrical aging process. To evaluate the electrical life of XLPE, scholars have conducted further researches. Liu carried out the AC withstand test and DC withstand test on XLPE cable slices respectively, and found that the AC breakdown field strength of XLPE decreases, whereas the DC breakdown field strength of XLPE increases, with the increase of voltage application time. Wang studied the DC electrical life of XLPE under different temperature, and adopted the traditional inverse power law model to quantify results. Conclusion indicates that the life exponent n of XLPE decreases with the increase of temperature. Yang obtained the XLPE insulation aging life index by changing the test parameters in the step-boost withstand test, and proved that the life model accuracy can be improved by prolonging the voltage duration. Despite of all the above researches, the electrical life model of XLPE is still within laboratory and being not adopted to industry. The reason is that the effect of electric stress on the performance of insulation material is of probability distribution. Even under the same experimental conditions, the insulation failure time of the sample also has a large dispersion [6–9]. However, the existed researches often ignore the statistical characteristics of the electrical life of XLPE.

In order to improve the accuracy of electrical life assessment of cable insulation materials, it is necessary to strengthen the research on the statistical characteristics of failure time of XLPE materials, but little attention has been paid to this point. In this paper, the voltage withstand test of XLPE samples is carried out; the distribution characteristics of XLPE failure time under different field strengths are counted; and the traditional XLPE electrical life model based on the inverse power law is modified based on statistical characteristics of failure time accordingly.

2 Experimental Setup

The setup of voltage withstand test platform is shown in Fig. 1. The platform mainly consists of a transformer, a voltage regulator, a water resistor and a high voltage oil cup. The transformer and the voltage regulator provide the high voltage required for the test. The water resistor has a resistance value of 30 kΩ, which limits the short-circuit current once the sample is broken down. High voltage generated by the transformer is applied to the XLPE sheet sample through the oil cup. Inside the oil cup are two disc-shaped copper electrodes with a diameter of 25 mm and a thickness of 4 mm, the edges of which are rounded into a semicircle with a radius of 2.5 mm. Place the XLPE sheet between the two electrodes and rotate the adjusting nut on the oil cup to clamp the sample, then measure the thickness of the three-layer structure of "electrode-XLPE sample-electrode" with a vernier caliper. The thickness should be within 9 ± 0.01 mm to ensure that each sample bears the same pressure during the test. In order to avoid surface flashover and partial discharge during the experiment, the electrodes and samples were immersed in Kunlun 25 transformer oil. The experimental temperature was controlled between 15 °C and 20 °C.

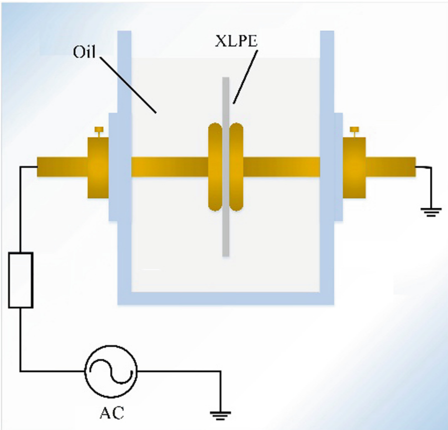

Fig. 1. Voltage withstand test platform for XLPE sheet samples

XLPE samples used in the study were 200 mm × 200 mm × 1 mm sheets provided by Sunway Co., Ltd. The thickness of different samples and different parts of the same sample is measured by a thickness meter, the results show that the thickness of the sample is 1 ± 0.01 mm. Before the experiment, the sample was cut into 55 mm × 55 mm × 1 mm. The surface of each sample was wiped with absolute ethanol to eliminate the influence of surface impurities on the experimental results.

To determine the testing voltage of the voltage withstand test, the breakdown strength of 10 XLPE samples were first measured based on GB/T 1408.1. The test was carried out with an equal diameter electrode with a diameter of 25 mm and the edges rounded to an arc with a radius of 2.5 mm. The size of the tested sample was 55 mm × 55 mm × 1 mm. During the test, the voltage was continuously increased at a rate of 0.5 kV/s until the breakdown. To avoid flashover, the sample and electrodes were immersed in Kunlun 25 transformer oil.

According to the test results, the breakdown strength E_0 of the XLPE sheet sample is 42.49 kV/mm, which meets the specified value of JB/T 10437 on XLPE insulation breakdown strength. Referring to GB/T 29311, the initial field strength applied on the XLPE samples during the voltage withstand test should be between $0.8E_0$ and $0.9E_0$, therefore, $E = 36$ kV/mm is selected as the initial field strength of the test. The field strengths of the other four groups were set to 28 kV/mm, 30 kV/mm, 32 kV/mm and 33 kV/mm. The thickness of the XLPE samples is 1 mm, therefore, voltages applied on the samples are 28 kV, 30 kV, 32 kV, 33kV and 36 kV, respectively.

In order to study the effect of the internal structure of XLPE on its electrical life, the microstructure of the cross section of XLPE sheet sample was observed by JSM7500F scanning electron microscopy (SEM). The magnification was 2000 times. Before the test, the XLPE was cooled in liquid nitrogen for 30 min for brittle fracture, and the fracture surface was treated by metal spraying.

3 Experimental Results

3.1 Breakdown Strength Rest Results

The breakdown strength test results of the XLPE sheet samples are shown in Fig. 2. According to the standard GB/T 29310, the sample breakdown data can be analyzed by using the two-parameter Weibull distribution.

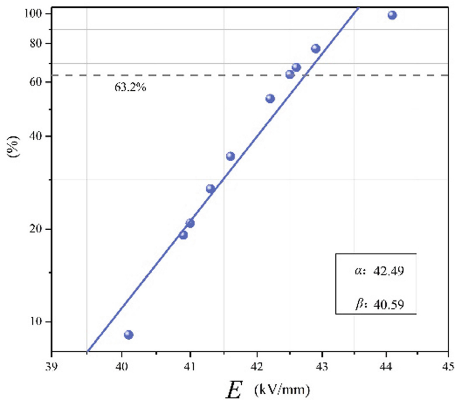

Fig. 2. The breakdown strength test result of samples

The Weibull distribution can be expressed as following:

$$F(x) = 1 - \exp(-(\frac{x}{\alpha})^{\beta}) \tag{1}$$

In formula (1), $F(x)$ is the cumulative failure probability of the sample; x is the independent variable, which can represent the breakdown time or breakdown field strength of the sample in this paper; β is the shape parameter, and the larger the value of β, the smaller the data dispersion is; α is the scale parameter. When x represents the failure time of the sample under constant electrical stress, α represents the failure time corresponding to the cumulative failure probability of 63.2% of the sample. When x represents the short-term breakdown strength of the sample, α represents the electric field strength corresponding to the cumulative failure probability of 63.2% of the samples. Generally,

α is used to represent the characteristic failure time or breakdown strength of the sampled
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It can be seen from Fig. 2 that the characteristic breakdown strength of the XLPE sheet sample is $E_0 = 42.49$ kV/mm. The shape parameter $\beta = 40.59$, which indicates that the dispersion of the breakdown strength of XLPE is small.

3.2 Voltage Withstand Test Results

5 set of experiments were conducted to investigate the *E*-*t* characteristics of XLPE samples at different electric field strengths, with 12 sample in each set.

Figure 3 is the schematic diagram of the distribution of breakdown points of the sample, in which the "pressurized area" is the part of the sample in close contact with the electrode. In order to avoid the influence of the edge effect on the experimental results, the failure time of the samples whose breakdown points are located in the edge area is not included in the statistics.

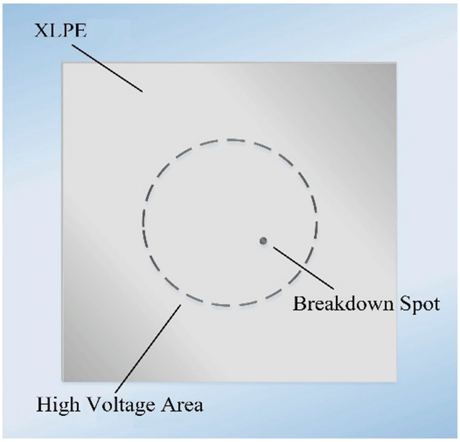


Fig. 3. Breakdown point distribution diagram

The Weibull distribution of the failure time of samples under different electric field strengths is shown in Fig. 4. According to the results, failure time of the XLPE sample increase with the decrease of the applied field strength. At the same time, it can be found that the shape parameter β is always lower than 1 regardless of the field strength, which indicates that the failure time dispersion of the samples is large.

4 Electrical Life Model and Its Modification

4.1 XLPE Electrical Life Model Based on Statistical Characteristics of Failure Time

The relationship between the electrical lifetime of XLPE and the applied electric field follows the inverse power law:

$$t = CE^{-n} \tag{2}$$

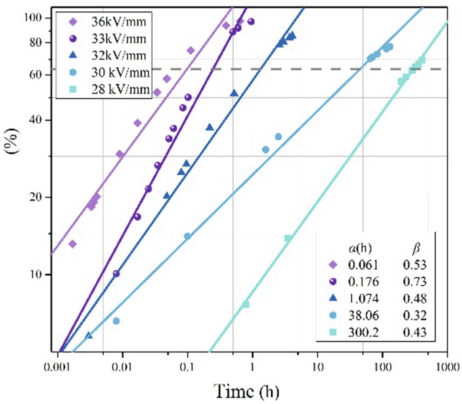


Fig. 4. Weibull distribution of failure time of XLPE samples under different electric field intensities

In formula (2), t represents the sample failure time; E represents the electric field strength, and C is a constant. When the life index n is a constant, the E-t characteristic curve of the material is a straight line on the log-log coordinate axis. The E-t characteristic curve of XLPE sheet samples can be drawn from the voltage withstand test results, and then the XLPE electrical life model can be established.

In the course of the study, it was found that some samples were not broken down in the limited experimental time, although the electrical life of the samples should be prolonged with the decrease of electric field strength according to the inverse power law, the proportion of the number of samples that were not broken down to the total number of samples in the same group was still increasing. On the other hand, through the statistics of the breakdown time of the breakdown samples, it is known that the failure time of XLPE sheet samples has a large dispersion, even under the same field strength. The maximum failure time of the samples is more than a hundred times of the minimum failure time. Therefore, it is not appropriate to draw the E-t characteristic curve of XLPE sheet samples directly according to the statistical results of failure time.

According to Fig. 4, failure time of samples under same electric field strength has a large dispersion, and can be divided into several time intervals, each of which may correspond to different failure processes of XLPE. Therefore, it is necessary to classify and discuss different failure processes when establishing a new electrical life model.

In order to reduce the influence of subjective factors on the classification results, a noisy spatial clustering method based on Density (Density-Based Spatial Clustering of Applications with Noise) is used. The DBSCAN algorithm divides the failure time of the broken down samples according to the distribution concentration of data points. Firstly, the algorithm traverses each data point, calculates the local density of each point and the distance between each data point, and then finds out the point with the maximum local density as the clustering center, and completes the data clustering analysis according to the distance between each point and the clustering center. The clustering results are shown in Fig. 5.

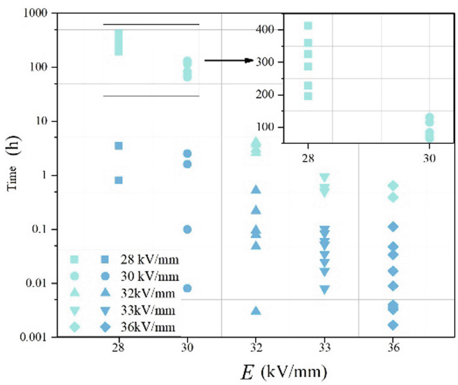


Fig. 5. Clustering result of failure time of the breakdown samples

According to Fig. 6, the failure time of the punctured samples can also be divided into two categories. Considering the availability of unbroken samples, the failure time of XLPE insulation is distributed in three time intervals.

According to the classification results of DBSCAN algorithm, the XLPE insulation failure is divided into three failure processes: failure process 1 (samples with short time breakdown), failure process 2 (samples with long time breakdown) and failure process 3 (samples without breakdown in the experiment). The failure time of samples in different failure processes is processed by Weber distribution, and the statistical results are shown in Table 2.

Table 2. Statistical results of failure time of different failure processes of XLPE samples

E (kV/mm)	Scale parameter α/H		The shape parameter β	
	Failure process 1	Failure process 2	Failure process 1	Failure process 2
36	0.022	0.609	0.74	2.87
33	0.056	0.790	1.35	3.01
32	0.174	3.674	0.63	5.21
30	0.958	104.8	0.40	3.46
28	2.941	335.8	0.96	3.98

In the experiment, it is found that the number of unbroken samples (corresponding to failure process 3) increases with the decrease of applied field strength, and the number of samples in failure process 1 and failure process 2 also changes with the change of field strength by analyzing the breakdown time data of broken samples. In order to study the relationship between XLPE failure process and electric field strength, the proportion of samples in each failure process to the total number of samples in the same group under different field intensities is calculated, and the calculation results are shown in Fig. 6.

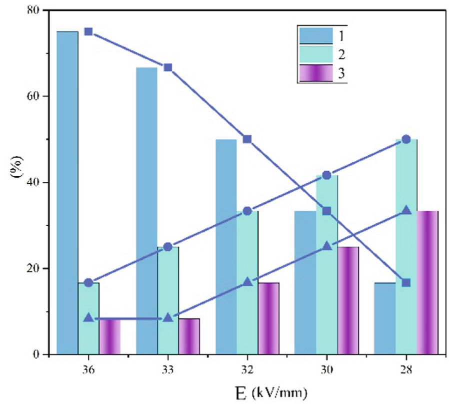


Fig. 6. The relationship between the proportion of different failure processes and the electric field strength

It can be seen from Fig. 6 that when the electric field strength is high, the failure process 1 accounts for the highest proportion, followed by the failure process 2, and the failure process 3 accounts for the lowest proportion. With the decrease of electric field strength, the proportion of failure process 1 decreases, while the proportion of failure process 2 and failure process 3 increases. When the electric field strength $E = 30$ kV/mm, the proportion of failure process 2 exceeds that of failure process 1, which is the highest among the three failure processes. When the field strength E = 28 kV/mm, the proportion of failure process 1 decreases further, and it is the lowest among the three failure processes. The above results show that different failure processes are affected by different electric field strengths, and the three failure processes may correspond to different insulation failure mechanisms.

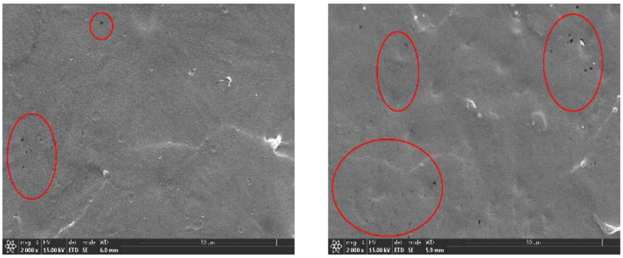
The relationship between failure probability and time of power equipment meets the "bathtub curve", that is, the failure rate of equipment is higher in the early stage of operation, and the "early failure" of equipment often occurs at this time. When the equipment runs stably, the failure probability decreases and tends to be stable, and the failure of the equipment is mostly "random failure". With the increase of the operation life of the equipment, the failure probability of the equipment also increases. At this time, the failure of the equipment is mostly caused by "aging failure", and the failure time of different failure processes is quite different.

In the manufacturing process, there are inevitably defects such as cracks or micropores in XLPE. Due to the distortion of the electric field near the cracks or micropores, the defects bear higher electric stress, which further develops the defects in the material and eventually leads to insulation failure [6].

Figure 7 is the microtopography of two different XLPE sheet samples, in which the convex part is the brittle fracture crack generated in the brittle fracture process. It can be seen that the internal structure of XLPE is not exactly the same even if it is produced by the same manufacturer in the same batch. There are micropore defects in the samples shown in Fig. (A) and Fig. (B), in which the micropores in sample 1# are small and the defects are sparsely distributed, and there are more micropores in sample 2# and the defects are densely distributed. Under electric field, the internal defects of XLPE develop gradually. When the internal defects of XLPE are densely distributed, the fine defects close to each other are easy to merge into larger defects in the development process, and the size of the merged defects is higher than that of the original defects, which leads to more serious electric field distortion at the defects and accelerates the material deterioration rate until breakdown. This process takes less time and corresponds to the "early failure" process described above.

When the internal defects of the material are sparsely distributed, due to the long distance, the defects are not easy to merge into larger defects in the growth process, but keep relatively independent development, eventually leading to the insulation failure of the sample, which takes a long time, corresponding to the above "random failure" process.

The above analysis shows the influence of the sparseness of defects in the material on its electrical life. When there are no obvious defects, the internal electric field is more uniform. Under the action of electrical stress, the material is gradually aged and the insulation performance is continuously decreased.When the breakdown strength of the sample is lower than the applied field strength, the sample will be broken down under the action of high field strength, and this process takes the longest time, which corresponds to the "aging failure" process mentioned above.



(A) 1 # sample (B) 2 # sample

Fig. 7. SEM images of XLPE samples

Figure 8 is an *E-t* characteristic curve for different failure processes of XLPE sheet samples plotted from the data in Table 2. Because that failure time of the sample in the aging failure process is not observed in the experiment, only the *E-t* characteristics of the samples in the early failure and random failure processes are analyzed. It can be seen from Fig. 8 that the early failure process life index n_1 of XLPE is 20.73, and the random failure process life index n_2 is 28.45. Observing Fig. 6, when the electric field strength $E \geq 32$ kV/mm, the early failure (failure process 1) accounts for the highest proportion among the three failure processes, and the breakdown time of the sample in the early failure process represents the electrical life of the XLPE sheet sample; When the field strength $E \leq 32$ kV/mm, the random failure (failure process 2) dominates the three failure processes, and the breakdown time of the sample in the random failure process is used to represent the electrical life of the XLPE sheet sample, so the modified

XLPE electrical life model is obtained as follows:

$$\lg t = \begin{cases} 30.46 - 20.73 \times \lg E & E \in [32, 42.49) \\ 43.65 - 28.45 \times \lg E & E \in (0, 32) \end{cases} \tag{3}$$

where $E = 42.49$ kV/mm is the power frequency breakdown strength of the XLPE sheet sample. When the electric field strength exceeds this value, the *E-t* characteristic of XLPE will no longer satisfy the relationship described in formula (3).

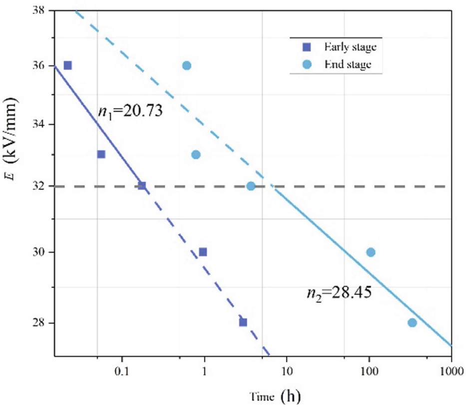


Fig. 8. *E-t* characteristic curve of different failure process of XLPE sheet sample

According to formula (3), when the electric field strength $E \geq 32$ kV/mm, the lifetime index n_1 of XLPE is 20.73, and when the electric field strength $E < 32$ kV/mm, the lifetime index n_2 of XLPE is 28.45. The point corresponding to $E = 32$ kV/mm is the "inflection point" in the *E-t* characteristic curve.

It should be pointed out that the proportion of samples in the aging failure process increases with the decrease of the applied field strength, so it can be determined that there is a certain field strength E_c, when the field strength $E < E_c$, the aging failure will occupy the dominant position in the XLPE failure process. The electrical life of XLPE will be much larger than that calculated by formula (3), that is, the electrical life model of XLPE obtained is conservative at lower field strength.

4.2 Traditional XLPE Electrical Life Model

The *E-t* characteristic curve of the XLPE sheet sample can be drawn from the data in Fig. 4, and then the traditional XLPE electrical life model based on the inverse power law is established as shown in Formula (4).

The slope of the *E-t* curve is related to the life index n. The failure process of XLPE under high and low electric field strength is different, and the corresponding life index n is also different. Generally, the E-t characteristic curve of XLPE can be approximately regarded as a broken line composed of different straight line segments, and the position of the inflection point of the curve determines the shape of the curve. At present, the selection of curve inflection point is mostly from the mathematical point of view. In the process of curve fitting, the appropriate inflection point is selected to make the fitting curve have the highest fitting degree. Compared with the traditional method, the method proposed in this paper gives more consideration to the physical meaning when determining the position of the inflection point of the curve, so that the modified model has more application value. The comparison between the traditional XLPE electrical life model and the modified model is shown in Fig. 9.

$$\lg t = \begin{cases} 32.47 - 21.69 \times \lg E & E \in [32, 42.49) \\ 63.44 - 42.04 \times \lg E & E \in (0, 32) \end{cases} \tag{4}$$

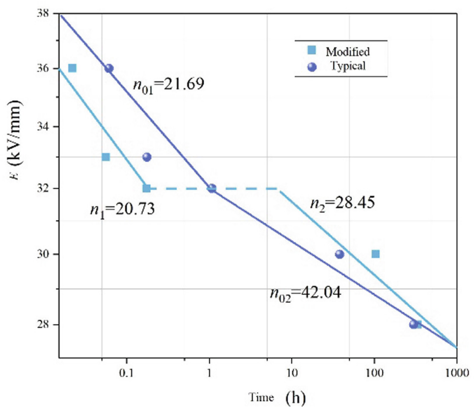


Fig. 9. Comparison of traditional XLPE electrical life model and modified model

5 Conclusion

In this paper, that statistical characteristics of XLPE failure time under different electric field strengths are studied by voltage endurance experiment on thin XLPE samples, and the traditional XLPE electrical life model base on inverse power law is improved. The following conclusions are drawn:

1) in this pap, that failure time of XLPE, which is in the dominant failure process, is use to express the electrical life of the material under the same field strength without waiting for the breakdown of all samples, which can improve the efficiency of voltage durability experiment.

   And 2) determine that position of an inflection point in an *E-t* characteristic curve of the XLPE through the statistical characteristics of the XLPE failure time under the action of different electric field strengths, and correcting a traditional XLPE electric life model based on an inverse pow law according to the position. According to the modified model, when the electric field strength $E \geq 32$ kV/mm, the lifetime index n_1 of XLPE is 20.73; When the electric field strength $E < 32$ kV/mm, the lifetime index of XLPE $n_2 = 28.45$.

3) The results show that the difference of breakdown strength between different XLPE samples is small, and the difference of failure time of XLPE under the same field strength is significant, so the voltage durability test can better reflect the insulation state of the material.

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