Research on the thermal aging life prediction of XLPE cable

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Abstract. Crosslinked polyethylene(XLPE) cable is one of the most important tools to transmit electric energy and electrical signals, but its insulation material is vulnerable to damage due to the complex working environment. If the aging cable is not replaced in time, it will easily cause fire and threaten the safety of life and property. Life prediction of cables is essential to ensure reliable operation. Hence, the objective of this study is to provide a theoretical basis for cable replacement. This paper, firstly, focuses on the thermal aging mechanism of cable. Based on Arrhenius Model, multivariate nonlinear regression method was used to process the data and the thermal aging life prediction model of cable had been derived. From the real operation perspective, the reliability of the model was analyzed. 50% of retention of elongation at break was measured as an indicator of the failure point, the life evaluations of cable was carried out. The result indicates that the service life of cable at 90 °C is 32.2 a.

1. Introduction
The degree of cable insulation determines the safety of its operation[1]. Thermal aging will lead to an irreversible decrease in mechanical properties[2]. In recent years, the importance of electric energy is increasing, and the application of cable in various fields has increased. However, because cable is buried underground or mounted in the air, it is highly susceptible to the influence of external natural environment and its own operation environment such as temperature, humidity and chemical effects that could affect insulation life[3], which causes the gradual aging and failure of insulation material. If the cable is not replaced in time, the overload operation, such as excessive current and high ambient temperature in the cable, will cause fire easily, leading to major power grid accidents directly.

Therefore, from the perspective of the potential threat of aging cable, the service life of cable under real operation conditions was calculated by analyzing the aging condition of cable in operation and predicting its lifetime. At present, researchers in various countries have little research on cables in operation, so people can only judge the running time of cables by experience, and there is a lack of convincing data to predict the cable life. R Stephanie et al. discussed the XLPE cable life evaluation method based on Weibull Model and obtained its lifetime[4]. Z Cibulkova et al.[5] and P Marko et al.[3] used DSC method to study the influence of temperature on cable. Crine, Jean-Pierre predicted the aging characteristics of cable at constant temperature by Breakdown and Accelerated aging Tests under different voltage raise ramps[6].

In order to avoid potential problems caused by aging and provide basis for cable replacement time, Arrhenius model was combined with second-order dynamic model to apply to the real life model. The data from the Cable Testing Center were fitted and the cable lifetime was analyzed. From the goodness of fit and the real situation perspective, it was proved that this model is reliable and can predict the service life of the cable in real operation well.
2. Aging mechanism of cable insulation

The degree of insulation performance change can determine the aging level of insulation materials. If the material’s insulation performance reaches a certain value, the degree of insulation aging is serious. The value that the insulation cannot be used safely is called the end of insulation life[7]. This paper also takes the value as the end of cable life. The common factors causing insulation aging are thermal aging, electrical aging, chemical aging, mechanical aging, etc., but more than 80% of cable failure is caused by heat, and the key to shortening cable’s service life is thermal aging with temperature as the main factor[8]. Therefore, the influence of thermal aging on cable life is mainly studied in this paper.

The essence of thermal aging is the complicated chemical and physical changes caused by the high ambient temperature or the long-term current-carrying heat during the operation of cable, which causes the insulation temperature to rise and the performance of the insulation layer to decline.

3. Methodology

3.1 Establishment of prediction model

The common methods for cable thermal aging life prediction include conventional assessment and accelerated assessment[9]. The former is an internationally recognized life test method with high reliability, but the test period is too long. The latter is a fast method to simulate the aging mechanism of cable. Its principle is to speed up the physical and chemical reaction of materials by increasing the insulation aging temperature to simulate the aging process. By testing the characteristic value of cable life, the function is established among cable life, aging time and aging temperature. The test data are analyzed to obtain the prediction model of thermal aging life, so cable’s service life under the normal operation of insulation can be calculated. Weibull Model and Arrhenius Model are often used to analyze the aging life of cable[10].

In 1889, Arrhenius summarized many experimental results and proposed the following empirical formula:

$$\frac{d\ln K}{dT} = \frac{E_a}{RT^2}$$  \hspace{1cm} (1)

Where, $K$ is the reaction speed constant at temperature $T$; $E_a$ is the active energy, which is generally a constant independent of temperature; $T$ is absolute temperature; $R$ is the molar gas constant which is $8.314 \text{ J} / (\text{K} \cdot \text{mol})$.

Emsley et al. determined the aging rate is not a constant, but a variable which will change continuously with the aging time—the second-order dynamic model[11]:

$$K = \frac{\partial M}{\partial t}$$  \hspace{1cm} (2)

Where $M$ is the degradation of elongation at break retention.

The cable’s elongation at break retention at the initial time $t_0$ is $M_0$, and at the end time $t_1$, that is, the end of cable life, elongation at break retention of cable is $M_1$. From equations (1) and (2), $M$ is described as:

$$M = \exp \left\{ \ln A + \ln t - \frac{a}{T} \right\}$$  \hspace{1cm} (3)

Where $t = t_1 - t_0$, $M = |M_2 - M_1|$, $a = \frac{E_a}{R}$, $\ln A = C$, $A$ is known as Arrhenius constant.

This method is accurate, but the process of fitting calculation is troublesome and inconvenient to use. In this paper, based on equation (3), the correction coefficient $c_1$ was added to $\ln t$ in Arrhenius Model, and the auxiliary constant $c_2$ was added to obtain a simpler result:

$$\ln t = b + \frac{c}{T}$$  \hspace{1cm} (4)
Where \( b = \frac{1}{c_1} \ln \frac{M - c_2}{A}, c = \frac{a}{c_1} \), both of them are constants related to cable aging performance, and \( t \) and \( T \) is the cable aging life and aging temperature, respectively. Equation (4) shows that the logarithm of cable aging life is linear with the reciprocal of aging temperature, and the slope is \( c \). Thus, the prediction of cable service life is transformed into the calculation of undetermined coefficient of life prediction model. Therefore, \( b \) and \( c \) can be obtained by measuring the degradation of elongation at break retention of cable at different temperatures.

3.2 Sample preparation

According to cable test specifications and standards, all samples were cut into dumbbell size shown in Figure 1, and were aged at 135(408.15), 150(423.15), 165(438.15) and 180 °C(453.15 K), respectively. All samples must be cooled at room temperature for 24 h after the aging test, and then the tension test was conducted to measure elongation at break and calculate elongation at break retention. The end of cable life was selected as 50 % of elongation at break retention.

3.3 parameter calculation

Based to equation (4), the coefficients \( b \) and \( c \) can be calculated by least square method. \( \ln t \) and \( 1/T \) can be assumed as \( y \) and \( x \), the result is:

\[
\begin{bmatrix}
    b \\
    c
\end{bmatrix} = Q \begin{bmatrix}
    M \\
    -x
\end{bmatrix} \left( \begin{array}{c}
y \\
N
\end{array} \right)
\]

(5)

Where \( Q = \frac{1}{M - nx} \), \( M = \sum_{i=1}^{n} x_i^2 \), \( N = \sum_{i=1}^{n} x_i y_i \), \( \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i \), \( \bar{y} = \frac{1}{n} \sum_{i=1}^{n} y_i \)

4. Results and discussion

One drawing of the relationship between elongation at break retention \( M \) and aging time \( t \) at different aging temperatures \( T \) is shown in Figure 2. It can be seen from Figure 2 that \( M \) is related to \( t \) and \( T \). By regression analysis, the relation among them is calculated as:

\[
M = -0.018t - 0.924T + 477.495
\]

(6)

According to equation (7), the complex correlation coefficient \( R \) is 0.562, which shows a nonlinearity between \( T \) and \( t \) and the retention rate of elongation at break. The degradation of elongation at break retention is not a constant, but positively correlated with \( T \) and \( t \).

\[
R = \frac{\sum (M - \bar{M})(M - \bar{M})}{\sqrt{\sum (M - \bar{M})^2 (M - \bar{M})^2}}
\]

(7)

The fitting curves of elongation at break retention of cable under different aging temperatures and aging times are shown in Figure 3. The results are as follows:

\[
M_t = -3.737\ln t^3 + 69.578\ln t^2 t - 437.571\ln t + 1023.506
\]

(8)
\[ M_2 = -10.975 \ln t + 183.518 \ln^2 t - 1033.622 \ln t + 2049 \quad (9) \]
\[ M_3 = -9.193 \ln^3 t + 124.398 \ln^2 t - 568.248 \ln t + 963.467 \quad (10) \]
\[ M_4 = -10.344 \ln^3 t + 106.988 \ln^2 t - 380.707 \ln t + 551.67 \quad (11) \]

Where, \( M_i (i = 1, 2, 3, 4) \) is elongation at break retention of cable at temperatures 453.15, 438.15, 423.15 and 408.15 K, respectively. Table 1 shows the nonlinear regression effect of the logarithm of elongation at break retention and aging time. Results indicate that equations (8) to (11) agree well with real aging process. According to equations (8) to (11), when elongation at break retention is 50%, aging times at different aging temperatures are 3885.4, 976.5, 383.8, 113.3 h, respectively. The result is shown in Figure 4, which indicates relationship between logarithm of aging time and reciprocal of aging temperature is linear and agrees with equations (4).

Hence, from equations (4) and (5),
\[ \begin{bmatrix} b \\ c \end{bmatrix} = \begin{bmatrix} -26.657 \\ 14238.776 \end{bmatrix} \].

The prediction model of cable life with 50% elongation at break retention is described as:
\[ \ln t = -26.657 + \frac{14238.776}{T} \quad (12) \]

The real operation temperature of cable is 90°C, and cable’s service life from equation (12) is 32.2 a, which is in accordance with the service life of cable in real operation. Hence, the life prediction model of cable is reliable.

**Table 1. Regression effect.**

| Sl.no. | Temperature(K) | \( R^2 \) | S.E. |
|-------|----------------|----------|------|
| 1     | 453.15         | 0.999    | 0.88 |
| 2     | 438.15         | 0.9998   | 1.066|
| 3     | 423.15         | 0.995    | 4.49 |
| 4     | 408.15         | 0.9997   | 0.635|

5. Conclusion

Taking XLPE cable as the research object, this paper analyzes the data obtained from the Cable Testing Center by multivariate nonlinear regression analysis. The model of its lifetime has been proposed by considering thermal aging as the main reason of cable aging. The life prediction of XLPE cable in real operation is completed. When the operation temperature of cable was 90 °C, the service life was 32.2 a. It is clear that the proposed model based on second-order dynamic model and Arrhenius Model can predict the service life of cable better, which was of great significance to reduce the fire caused by cable aging.

From the current research perspective, XLPE cable service life prediction is not perfect. Through this paper, XLPE cable service life prediction should be further studied.

In fact, the aging of cable is caused by many factors. The accelerated aging experiment based on
Arrhenius Model only considers the thermal aging factor, but ignores the influence of other aging factors such as electrical and mechanical forces on cable aging, which needs further study.

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