Research on thermal aging life of cable based on second-order dynamics modification equation

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Abstract: With the increasing application of cable in various fields, more and more attention has been paid to the aging of cable. In order to ensure the operation safety of instruments and all kinds of equipment, it is urgent to find a fast and accurate method to evaluate the residual life of cable. In this paper, a second-order kinetic model is adopted and the Arrhenius thermal aging equation is improved. In view of the working environment with relatively high temperature, the thermal aging life prediction model for cable is obtained to calculate the residual life rapidly. It provides theoretical support for timely detection of risks and elimination of potential accidents.

1. Introduction
A cable is usually made of one or more mutually insulated conductors and a protective outer layer of insulation that carries electricity or information from one place to another. With the continuous development of China's economy and science and technology, the popularity of electricity has been quite high, which makes the production and manufacturing of all walks of life are inseparable from the cable, then the service life of the cable directly affects the safety of production, the service life of the cable is determined by the oxide induction period of sheath material. The most direct cause of cable aging fault is insulation reduction and breakdown. Once the insulation fails, there will be a short circuit between the wires, causing damage to the entire electrical equipment and system, resulting in a variety of accidents. Especially for bullet train and locomotive equipment, the working temperature of traction motor is higher, and the cable has to bear higher temperature, so the thermal aging of cable insulation material has become one of the main reasons affecting the service life of the cable. In order to ensure the running safety of bullet trains and locomotives, a quick and simple method to evaluate the residual life of cables is urgently needed.

2. Thermal life prediction model

2.1 Cable life prediction theory
In the research field of thermal aging of cable insulation layer materials, Montsinger proposed that thermal aging life is affected by temperature, and the thermal aging life of cable insulation layer will be reduced by half for every 10°C increase of temperature. In the mid-20th century, Dakin proposed that insulation aging is caused by its internal chemical reaction and proposed dake-Arrhenius law[1-2]. Domestic research on thermal aging life prediction also did a lot of, a surplus in the conventional and rapid thermal aging experiments of the insulating material aspects to do a lot of research, Li Yongjing[3-5] today in rubber material such as storage and use, to the environment factors and different forecast model carried out extensive research, Jiang Peina[6] introduce the method of
mathematical statistics cable life prediction, and made a great contribution in this direction, Zhang Tieyan[7] introduced the probability theory into the cable life prediction and used the improved Weibull distribution model to predict the cable life. In addition, researchers from North China Electric Power University, Shanghai Jiaotong University, Naval Engineering University and other universities have also done a lot of work on cable life prediction, and put forward many improvement and optimization schemes for the prediction model, making outstanding contributions to this field.

2.2 Model building
In this paper, the fracture elongation at break retention rate $M$ was used as the characteristic of aging. In the early 20th century, Kuhn and Ekenstam proposed a first-order kinetic model for the degradation reaction of polymers under the action of heat. The model regarded aging rate $K$ as a constant, and the formula was as follows:

$$\Delta M = K t$$

Since then, scientists have found that when the fiber aging characteristic quantity drops to a certain value, the relationship between elongation at break and time no longer satisfies the first-order kinetic formula[8]. For this reason, Emsley et al. regarded aging rate as a quantity changing with time and proposed a second-order kinetic equation, namely:

$$\frac{dM}{dt} = K$$

The exponential form of Arrhenius empirical formula is as follows:

$$K = A \exp \left(\frac{-E_a}{RT}\right)$$

A is called the prefactor, also known as Arrhenius constant, $E_a$ is the experimental activation energy, $T$ is the absolute temperature, and $R$ is the molar gas constant.

In order to adapt to a larger temperature range, the following broad index formula can be used for correction:

$$K = A \exp \left(\frac{-E_a}{RT}\right)^\beta$$

Where $\beta$ is a dimensionless quantity.

Let $b = \frac{E_a}{R}$, the joint equation (2) and equation (4), we can get:

$$M = A \exp \left(-\left(\frac{E_a}{RT}\right)^\beta + \ln(t_1 - t_0)\right)$$

In order to make the fitting calculation more accurate, the correction coefficient $C$ is increased, and $M = |M_1 - M_0|, t = |t_1 - t_0|$ is obtained, the final formula is as follows:

$$M = A \exp \left(-\left(\frac{E_a}{RT}\right)^\beta + \ln(t)\right) + C$$

The corresponding life $T_1$ at the corresponding temperature is calculated by using the modified formula, and the relationship between the fracture elongation retention rate $M$ and the aging time is obtained when the temperature is unchanged. The fracture elongation retention rate was measured by tensile test, and the life $T_2$ was calculated according to the formula, then the remaining life was $T_1 - T_2$.

3. Conclusion
To visually represent the relationship between relevant parameters in the cable aging process, the aging time of rubber material was taken as the abscissa, and the average elongation at break was taken
as the ordinate for curve fitting. The final data fitting curve is shown in Figure 1

![Figure 1](image-url)  
**Figure 1.** The relation curve between elongation at break and thermal aging time at different temperatures.

By fitting equation (6) with experimental data, the results are as follows:

$$M = -58652948\exp \left(-\left(\frac{2276.36}{T} \right)^{1.75732} \right) + \ln t + 119.2432 \quad (7)$$

According to the formula, the aging life of cable rubber material under different working temperature is calculated at different end points of different elongation at break. The results are shown in Table 1.

| Operating temperature (℃) | Aging life under different elongation at break retention rates (h) |
|---------------------------|---------------------------------------------------------------|
| 90                        | 115147 100616 86085 71554                                     |
| 100                       | 35623   31127  26631  22137                                    |
| 110                       | 11981   10469  8957   7445                                      |

According to the results in Table 1, curve fitting was performed on the obtained data, and the resulting relationship was shown in Figure 2.
By fitting the functional relationship between $m$ and $t$ at different temperatures, we can obtain the relationship between the retention of elongation at break and the aging time, so that the elapsed aging time $t$ can be obtained from the real-time $M$.

Table 2. Prediction equations at different operating temperatures

| Operating temperature(℃) | Prediction equation |
|--------------------------|---------------------|
| 90                       | $t=1.576 \times 10^{-14} \cdot M^3 - 2.607 \times 10^{-12} \cdot M^2 - 1.453M + 1.733 \times 10^5$ |
| 100                      | $t=3.33 \times 10^{-4} \cdot M^3 - 0.05M^2 - 447.1M + 5.357 \times 10^4$ |
| 110                      | $t=1.825 \times 10^{-15} \cdot M^3 - 3.019 \times 10^{-13} \cdot M^2 - 151.2M + 1.803 \times 10^4$ |

When calculating the residual life of the old cable, the cable samples should be made into several standard dumbbell samples, and then the elongation at break of the samples should be measured. After taking the average value, the retention rate of the elongation at break can be calculated. According to the actual working temperature, the appropriate prediction equation is selected from Table 2, and the cable's actual service life is calculated by substituting the fracture elongation retention rate into the corresponding equation. Then, the cable's remaining life can be calculated by taking the fracture elongation retention rate of 50% as the end point.

For example, the elongation at break rate of the old styrene butadiene rubber cable measured in the tensile test is 77%, and the actual working temperature is about 90℃. Choose the following equation from table 2:

$$ t = 1.576 \times 10^{-14} - 2.607 \times 10^{-12}M^2 - 1453M + 1.733 \times 10^5 $$

If $M=77\%$, $t=61419$ (h) can be obtained.

It can be seen from Table 1 that, with the cable's elongation at break retention rate $M=50\%$ as the life end point, the aging life is 100616 h, and the remaining life of the cable is $100616-61419=39197$ h =4.4 a.

4. Conclusion

The temperature range of the cable thermal aging life prediction model is expanded by using the extensive exponential correction, and the fitting calculation difficulty of the prediction model is reduced by increasing the correction coefficient $C$. After the tensile test, the residual life of the cable can be calculated quickly according to the corresponding model.
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