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Aging Life Evaluation of Coal Mining Flexible EPR Cables Under Multi-Stresses

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ABSTRACT As important power cables for the mining mobile equipment, such as mining shearers, ethylene propylene rubber (EPR) cables often suffer from the combining effect of various stresses on site. In order to evaluate the aging state of EPR insulation, the paper carried out the multi-stress accelerated aging test on the insulation of coal mining flexible EPR cables. The infrared spectrum, elongation at break and polarization and depolarization current of cable insulation samples were measured. The insulation state of EPR cable was evaluated by using the aging factor obtained from isothermal relaxation current. Based on the failure standard of 50% elongation at break, the life formula of EPR insulation was deduced. The experimental and analytical results show that the tiny air gap was torn to the larger air gap under the mechanical stress, which leads to the increase of oxygen infiltration and promotes the thermo-oxygen reaction. The fracture energy of EPR decreases, and mechanical aging is accelerated. Aging factor and elongation at break can indicates the deterioration degree of EPR insulation. Based on the least square method and Arrhenius equation, the service life of the insulation of coal mining flexible EPR cables is deduced.

INDEX TERMS Ethylene propylene rubber, cables, thermal aging, mechanical aging, life evaluation.

I. INTRODUCTION

Ethylene Propylene Rubber (EPR) is synthesized by ethylene, propylene and non-conjugated dienes. Because of its excellent corona resistance, moisture resistance, corrosion resistance and flexibility [1], [2], EPR has been the unique insulation of high voltage power cables for the coal mine mobile equipment [3], [4]. However, coal mining EPR cables are often subjected to mechanical stress such as extrusion and tensile stresses, as well as thermal stress caused by the frequent start and stop of motors with the heavy load, so EPR insulation is always aged and deteriorated rapidly. Finally, the service life of EPR cable is significantly shortened.

Lots of researchers focus on the life evaluation of power cables. G. C. Montanari studied the aging and breakdown characteristics of EPR under the combination of thermal and electrical stress, and established aging life model [5], [6]. T. W. Dakin evaluated the aging state of insulating materials under thermal aging based on Arrhenius equation, and predicted the aging degree of insulating materials [7]. X. Meng conducted the accelerating thermal aging test on EPR cables for the ship at different temperatures. Based on the failure criterion of 50% elongation at break, they deduced the endpoint judgment index of dielectric dissipation factor [8]. D. Fabiani studied XLPE cables aged under high temperature and different dose rates and evaluated the electrical properties of insulation. They found that the degradation of a polymer irradiated could saturate even though the higher irradiation was applied [9], [10].

In addition, more attention is paid on the application of Polarization and Depolarization Current (PDC) method to evaluate the insulation state. J. Hao evaluated the natural ester-paper insulation and mineral oil-paper insulation and concluded that an exponential relation between the stable depolarization charge quantity of both kinds of oil-paper insulation sample and the degree of polymerization of paper could be obtained [11]. Based on PDC, G. Ye analyzed the aging degree of XLPE cables with water trees. The results shown that the product of the depolarization current and time t of cables shown a relationship with the aging time [12].

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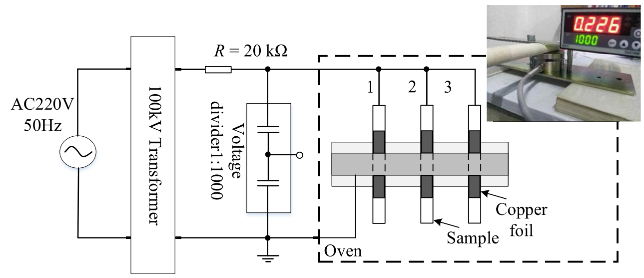

FIGURE 1. Diagram of the aging test system.

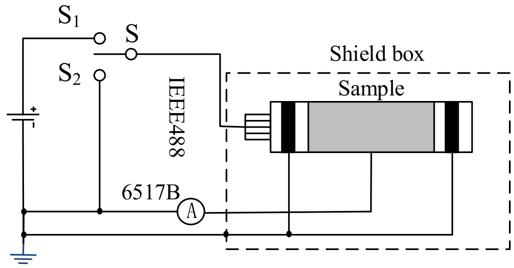

FIGURE 2. Diagram of the PDC current measurement.

Although lots of researches have paid attention on the insulation life evaluation, the aging evaluation of EPR cable used in coal mine is unavailable, especially under the multi stresses, such as electrical, thermal and mechanical stresses [13].

In order to evaluate the insulation aging state of EPR cables for mining under multi-stresses, the accelerated aging test was carried out in the lab. Infrared spectrum, polarization and depolarization current and elongation at break were measured. According to the characteristic parameter including carbonyl index, aging factor and the attenuation of breaking elongation, the aging state of cable insulation was evaluated. Based on the failure criterion of 50% elongation at break, the life evaluation equation of EPR cables used in coal mine was given.

II. SAMPLE AND EXPERIMENTAL SETUP

A. SAMPLE PREPARATION

Samples used in this paper were cut from MYPT-6/10kV coal mining flexible cables with the EPR insulation. The sectional area of the cable conductor was 25 mm^2, and the insulation thickness was 5 mm. The samples' length was about 300 mm. All layers except from the conductor and insulation layer were removed. The 20 mm of insulation layer at one side of sample was removed. The exposed conductor was connected with high-voltage wirings. The opposite side of samples was sealed with the silicone rubber for avoiding corona. Before the aging, the insulation surface was carefully cleaned with the anhydrous alcohol. Finally, the copper foil as the grounding electrode was tight wrapped round the insulation surface. The distance between the copper foil and two sides of conductor was more than 40 mm.

B. AGEING TEST

Firstly, the multi-stress aging test was carried out for 600 hours. The applied electrical, thermal and mechanical stresses were 15 kV, 100 °C and 1 kN, respectively. For analyzing the effect of temperature on aging, new samples were aged at the temperature of 120 °C, 135 °C, 150 °C and 165 °C for 200 hours, respectively. In this case, the applied voltage and mechanical stresses were the same as aging test at 100 °C.

Fig. 1 shows the aging test system in which electrical, thermal and mechanical stresses can be applied to three samples together. In order to prevent partial discharge between the high-voltage wires and the metal shell of oven, the samples were placed in an insulation box made from the epoxy resin insulating board. The sample was clamped by two steel plates whose distance could be adjusted by two screws for controlling the pressure applied on the sample. A pressure sensor was inserted between the sample and one steel plate.

C. MEASUREMENT SYSTEM

1) PDC TEST

PDC was measured by Keithley 6517B as shown in Figure 2. During test, a positive DC voltage of 400 V was applied to the sample. The polarization measurement time was about 600 s, and the depolarization measurement time was more than 1200 s. During the constant temperature aging, PDC was measured after samples were aged per 200 hours.

2) CARBONYL INDEX

According to Fourier-transform infrared spectroscopy (FTIR) results, the carbonyl index can be expressed as [14]–[16]

$$\text{carbonyl index} = \frac{A_{\text{C=O}}}{A_{\text{C-H}}} = \frac{A_{1710\text{cm}^{-1}}}{A_{2916\text{cm}^{-1}}} \quad (1)$$

where, $A_{\text{C=O}}$ and $A_{\text{C-H}}$ is the light absorption intensity of carbonyl group and methylene. The wave number 2916 cm^{-1} represents the stretching vibration peak of methylene and is used as a reference peak because it hardly changes with thermal aging. The stretching vibration peak of C = O group is at 1710 cm^{-1} [17], [18].

FTIR was tested by Nicolet IS50. Every samples were scanned 10 times, and the range of wave number was from 400 to 4000 cm^{-1}. Before the test, the sample was peeled off aged cables, cleaned and dried about half an hour at 80 °C.

3) ELONGATION AT BREAK

Elongation at break was measured by INSTRON 3344 electronic universal material testing machine with a maximum load of 2 kN. The dumbbell type sample was made in accordance to the Chinese national standard, GB/T 528-2009.

III. RESULTS

A. POLARIZATION AND DEPOLARIZATION CURRENT

In multi-stress aging test at the constant temperature, the polarization current, I_p, and depolarization current, I_d, of samples at different aging stages are shown in Fig. 3. The

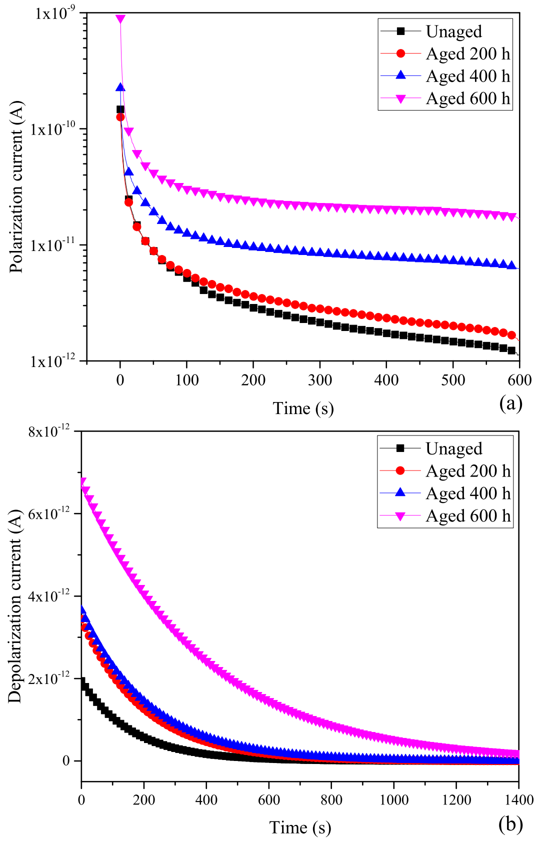

FIGURE 3. PDC of samples with different aging degree: (a) polarization current; (b) depolarization current.

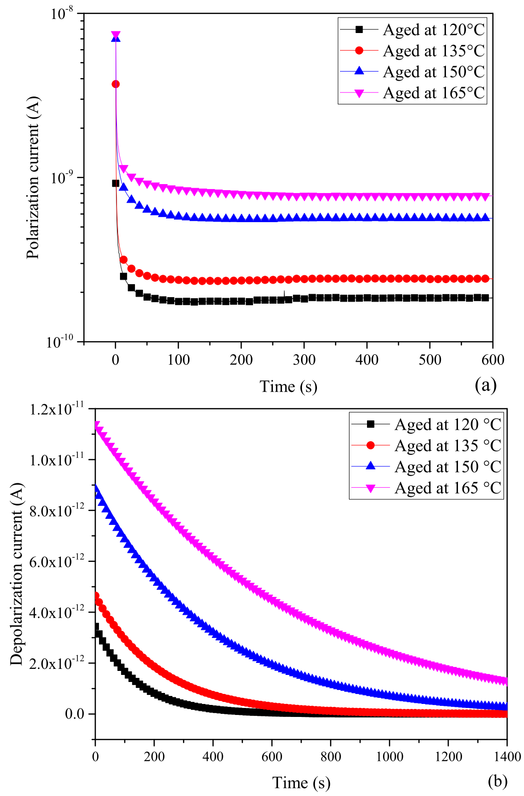

FIGURE 4. PDC of samples aged at different aging temperature: (a) polarization current; (b) depolarization current.

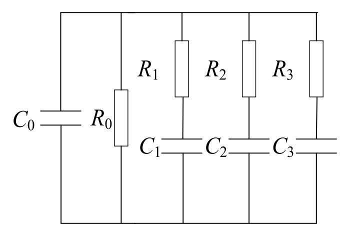

FIGURE 5. Extension Debye model of cable.

polarization current can be divided by two stages. At the beginning of about 100 s, it decreases fast. Then, it spends a long time to a steady value. The polarization current of samples unaged and aged 200, 400 and 600 hours stabilizes to steady state values, about 1 pA, 2 pA, 10 pA and 20 pA, respectively. It means that the conductivity gradually increases with aging. After voltage is removed, the time of depolarization current reaching the steady state value depends on the aging degree. The longer aging time, the slower depolarization current decreases. In particular, the depolarization current of samples aged 600 hours shows a slowest decreasing trend. Therefore, PDC can be used as an index to evaluate the aging degree of EPR cables.

Fig. 4 shows the polarization current and depolarization current of the sample aged 200 hours at different temperatures. It can be seen that the steady state value of PDC increases with the aging temperature rising. The application of multi-stresses can evidently deteriorated samples and enhances insulation conductivity. Therefore, both thermal stress and mechanical stress can accelerate the deterioration of EPR. It can be explained by the EPR decomposition as aging time increases. During multi-stresses aging, thermal oxidation breaks the molecular chain, and leads to the formation of impurity ions such as the polar oxide and small polar molecules. During polarization phase, the impurity ions move along the direction of the electric field and cause the increase of polarization current. In addition, the previous studies have shown that small physical defects will gradually form in EPR such as the air gap in the order of micrometer [19]. Moreover, the thermal aging accelerates the fracture of EPR molecular chain, resulting in the increase of defects, as well as the trap energy level and trap density. In this case, the number of carriers in bulk increases and further affects the charge distribution and poling process.

Generally, the polarization types of cables insulation can be divided as bulk polarization, interfacial polarization between crystalline and amorphous region, and interfacial polarization between impurities. Therefore, the extended Debye model shown in Fig. 5 is often used to describe the polarization of cable insulation. In Fig. 5, C_0 is the capacitance of insulation layer, R_0 is the leakage resistance; R_1 and C_1 are the branch parameters characterizing the polarization of cable

TABLE 1. Aging factor A of unaged and aged samples.

Aging time/ hour	0	200	400	600
Aging factor A	1.65	1.78	2.69	5.43

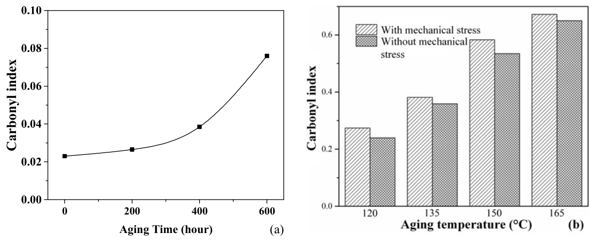

FIGURE 6. Carbonyl index of samples: (a) aged at same temperature; (b) aged at different temperature.

insulation, R_2 and C_2 are the branch parameters representing the interface polarization between the crystalline and amorphous region, and R_3 and C_3 are the branch parameters of interface polarization between impurities when the insulation is degraded.

The polarization current and depolarization current can be expressed as

$$I_q = I_0 + \sum_{i=1}^{3} \alpha_i e^{-t/\tau_i} \tag{2}$$

$$I_d = \sum_{i=1}^{3} \alpha_i e^{-t/\tau_i} \tag{3}$$

where i is 1, 2 and 3, representing three polarization types respectively, α_i is the fitting coefficient, t is the measurement time, and τ_i is the time constant. According to the isothermal relaxation theory, the aging factor A value can be calculated and reported in Table. 1 [20]. It can be concluded that the aging factor A rises with the aging time. The aging factor A can be used to estimate the aging degree of EPR.

B. CARBONYL INDEX

Fig. 6 shows the carbonyl index of cable samples at different aging stages. It can be seen from Fig. 6a that with the increase of aging time, the carbonyl index shows the evident change. At the early aging stage, 0∼400 hour, the rising rate of carbonyl index is slow, which indicates that EPR does not get worse. At end of aging, i.e. about 600 hours, the carbonyl index approaches 4 times larger than the value of unaged EPR. Therefore, the aging rate of EPR accelerates with multi-stresses aging, especially near the end of life.

Fig. 6b is a carbonyl index of samples aged at different temperature. With the increase of aging temperature, carbonyl index gradually increases, which can be explained by the thermal degradation mechanism of EPR. In the process of thermal oxygen degradation, the molecular bond of EPR is broken, and the oxidation reaction leads to the formation of carbonyl group [4], [21]. At the same aging temperature, the carbonyl index of samples subjected to the mechanical stress is higher than that of normal samples. It indicates that the mechanical stress can enhance the thermal degradation process. It can be explained that the tiny air gaps form inside the insulation due to thermal aging. Under the mechanical stress, these gaps gradually develop to larger gaps, and become local weak points which further accelerates the thermal oxygen reaction of EPR. Thermal-oxidative degradation of EPR can produce polar oxides containing carbonyl groups. Polar oxides can be decomposed to free radicals, resulting in the increase of free radicals. At the same time, under the long-term effect of the electric field, the antioxidants in the insulating gradually migrate to the outer layer, and the thermal-oxidative degradation of EPR becomes a positive reaction process of automatic catalysis and the macro-molecule bond continuously breaks [22].

TABLE 2. Elongation at-break of EPR under different aging degree.

Aging time / hour	0	200	400	600
EAB%	423%	405%	364%	343%

C. ELONGATION AT BREAK

The value of elongation at break (EAB%) which decreases to 50% of the original value is taken as the sign of life end of insulation material. The initial value of elongation at break of new EPR is about 423%, so the standard value of insulation failure evaluation, namely 50% elongation at break, is about 212%. Table. 2 shows the elongation at break of samples after multi-stress aging at 15 kV, 100 °C and 1 kN. The elongation at break of EPR decreases gradually as the aging time increases. The longer the aging time is, the higher the attenuation of elongation at break is. The elongation at break depends on the aging time, which shows a good monotonic increasing relationship.

In the paper, an exponential function is used to fit the elongation at break of EPR with different aging time, and the relationship between EAB% and aging time H is obtained as

$$EAB\% = 4.26 - 8.15 \times 10^{-4} \exp(\lg H/0.40) \tag{4}$$

where, H is larger than 0 h.

Fig. 7 shows the change curve of EAB% with aging time H. It can be seen that the elongation at break has little change at the early stage of aging, and decreases rapidly after aging for 200 h, but the attenuation of elongation at break is still higher than 50% of the initial value. It indicates that the test sample still maintains a relative well insulation performance. Based on the functional relationship between aging factor A and aging time H shown in the following equation 8, the corresponding relationship between EAB% and aging factor A can be deduced as follows

$$EAB\% = -642(\frac{A - 1.51}{0.016})^{0.013} + 1068 \tag{5}$$

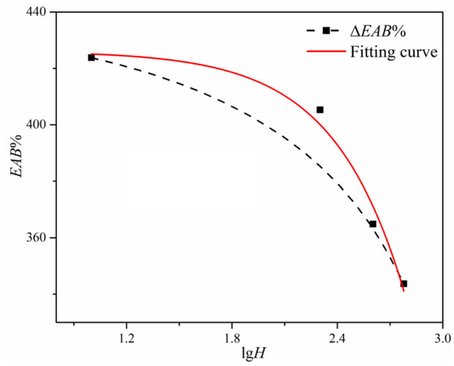

FIGURE 7. Relationship between elongation at break and aging time.

TABLE 3. Elongation at-break of EPR under different aging degree.

Temperature/°C	120	135	150	165
Elongation at break	401%	354%	282%	194%

In order to further analyze the relationship between elongation at break and aging time, multi-stress aging tests are carried out at different temperatures. Table. 3 shows the measurement results of elongation at break of samples after multi-stress aging at different temperatures. It can be seen that elongation at break decreases gradually with the increase of aging temperature. At a higher temperature, the rate of chemical reaction of EPR increases, the molecular weight drops rapidly, the intermolecular force is weakened, which results in a decrease in the fracture energy of EPR and the elongation at break, so the temperature will significantly affect the elongation at break of EPR. According to Table. 3, after aging at 150 °C for 200 h, the elongation at break is about 282%, which is significantly lower than the value after aging at 100 °C for 600 h, about 343.71%. The attenuation of elongation at break after aging at 165 °C for 200 h has exceeded the evaluation standard value of insulation failure.

Furthermore, the attenuation of elongation at break, $\Delta EAB\%$, of EPR at different aging temperatures is defined as:

$$\Delta EAB\% = EAB_0\% - EAB_T\% \tag{6}$$

where, $EAB_0\%$ is the elongation at break of the unaged sample, and $EAB_T\%$ is the elongation at break at a certain aging temperature T.

The relationship between $\Delta EAB\%$ and T follows the exponential function and is expressed as

$$\Delta EAB\% = 0.282 \exp(T/24.54) \tag{7}$$

Fig. 8 shows the relationship between $\Delta EAB\%$ and T. After aging at 165 °C for 200 h, $EAB\%$ is lower than 50% of the initial value. $\Delta EAB\%$ rises to more than 200%. It is assumed that $\Delta EAB\%$ of EPR aged for 200 h and 165 °C is the reference value during the whole aging process. The aging life of EPR insulation aged at 100 °C, 120 °C and 135 °C can be estimated as about 1496 h, 650 h and 353 h, respectively. Therefore, under the constant mechanical stress and electric field, the service life of EPR cables will decrease rapidly with the operating temperature.

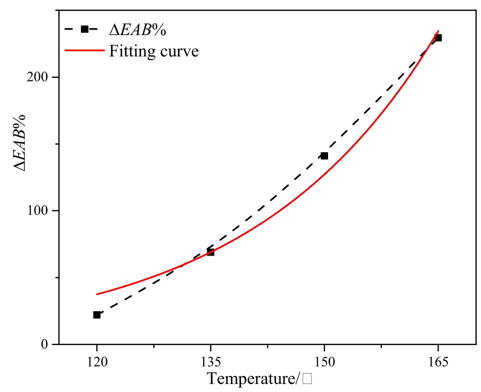

FIGURE 8. Relationship between the attenuation of elongation at break and temperature.

TABLE 4. Estimating standard of aging factor A.

Insulation condition	Residual breakdown voltage	A
Very good	$11U_0$~$25U_0$	0~1.75
Middle life	$8U_0$~$11U_0$	1.75~1.90
old	$7U_0$~$8U_0$	1.90~2.10
Serious aging	$3U_0$~$7U_0$	>2.10

IV. LIFE EVALUATION

A. EVALUATION ACCORDING TO AGING FACTOR A

Table. 4 is the common evaluation criteria of power cables according to aging factor A [20]. By comparing Table. 1 and 4, it can be seen that the value of A for the new sample is 1.65, which is within the normal range, namely the cable is in very good condition. Aging factors of samples aged 200 h, 400 h and 600 h are 1.78, 2.69 and 5.43, respectively. According to the standards in Table. 4, the tested cable after 200 h of aging is in the middle age, and the cable aged 400 h shows the serious deterioration, which should be replaced.

However, this conclusion is not consistent with the variation of PDC and carbonyl index of EPR cable. The criteria of aging factor A given in Table. 4 is slightly strict. The reason for this phenomenon is that material selection, processing and manufacturing process for different cables are different. Therefore, the test results on site should be compared with the evaluation database of historical isothermal relaxation current of cables with the same type and dimension when the life evaluation of cable insulation is carried out.

In addition, by exponential fitting of aging factor A after different aging time, the relationship between multi-stress aging factor A and aging time H for insulation of coal mining

TABLE 5. Parameters x and y.

i	1	2	3
x	1/373	1/393	1/408
y	3.174946	2.813087	2.547614

flexible EPR cables can be expressed as

$$A = 1.51 + 0.016\exp(H/163.28) \tag{8}$$

B. EQUATION OF LIFE EVALUATION

In this paper, elongation at break reaching the half of initial value is used as the characteristic quantity to describe the insulation life of EPR cables. Combined with Arrhenius formula, which is the empirical formula describing the dependence of reaction rate constant on temperature [23], the insulation life of EPR at different temperatures is studied when the electrical stress and mechanical stress is constant. The relationship between logarithmic of aging time, lg$H$, and the reciprocal temperature of EPR can be given as

$$\lg H = E/RT + B \tag{9}$$

where H is the aging life of EPR, E is the activation energy of insulating materials, R is the molar gas constant, T is thermodynamic temperature, and B is the relevant constant.

If $y = \lg H$ and $x = 1/T$, the above equation can be written as

$$y = a + bx \tag{10}$$

According to the least square method, when the aging temperature is 100 °C, 120 °C and 135 °C, a and b can be calculated as follow

$$b = \frac{\sum_{i=1}^{3} x_i y_i - \sum_{i=1}^{3} x_i \sum_{i=1}^{3} y_i/3}{\sum_{i=1}^{3} x_i^2 - (\sum_{i=1}^{3} x_i)^2/3}$$

$$a = \frac{\sum_{i=1}^{3} y_i - b\sum_{i=1}^{3} x_i}{3} \tag{11}$$

where x_i and y_i are reported in Table. 5.

It concludes that under 15 kV and 1 kN the life equation of the insulation of EPR mining cable can be written as

$$\lg H = -4.1191 + 2721.717/T \tag{12}$$

Generally, the aging temperature of operating cable is determined by two parts: ambient temperature of cable and conductor temperature.

1) AMBIENT TEMPERATURE OF CABLE

In Chinese coal mine, the average underground ambient temperature is not allowed to exceed 28 °C in common, so in this paper, the ambient temperature is assumed to be a constant temperature of 28 °C.

2) CONDUCTOR TEMPERATURE

The cable conductor temperature is related to the carrying capacity, the load factor and the ambient temperature. The temperature rise of conductor, ΔT, can be expressed as

$$\Delta T = T - T_0 = KI^2 \tag{13}$$

where T_0 is the ambient temperature, T is the normal operating temperature, K is the load factor, and I is the rated load current of the cable conductor.

Due to the frequent stop and start of mine mobile equipment, the actual current, I_R, flowing through the conductor during operation is different from the rated current I. Assuming that the actual current is K_R times of rated current, the actual temperature rise of the conductor is K_R^2 times of the temperature rise at rated current. When the cross-sectional area of conductor is 3×25 mm^2, a long-term load capacity is about 113 A at the temperature of 25 °C. The actual current I_R can be easily measured on site. Coefficient and the actual temperature of conductor is as follows

$$K_R = \frac{I_R}{I} \tag{14}$$

$$T_R = T_c + K_R^2 \Delta T \tag{15}$$

According to the equation 12∼15, the life of EPR cable under multi-stresses can be calculated. For example, assuming that the carrying capacity of cables during operation 54 A, the insulation life of the new EPR cable for mining is about 33210 h when the electrical stress, mechanical stress and thermal stress are 15 kV, 1 kN and 315 K respectively.

V. CONCLUSION

Based on the measuring results of EPR cable, including FTIR spectrum, polarization and depolarization current and elongation at break, the aging factor A, which is a non-destructive dielectric parameter, is given as the parameter of insulation evaluation of EPR cable. Based on Arrhenius equation and 50% elongation at break, the evaluation equation of insulation life for coal mining flexible EPR cables is derived. The following conclusions are obtained:

(1) Under mechanical stress, the tiny air gap is gradually torn to a larger air gap and becomes a local weak point, leading to the increase of oxygen infiltration and promoting thermo-oxygen reaction. As the temperature increases, the reaction rate of thermal oxygen increases, the molecular weight decreases rapidly, and the intermolecular force decreases, which leads to the decrease of fracture energy of EPR and accelerates mechanical aging.

(2) The aging factor A has a definite functional relationship with elongation at break and aging time, so the aging factor A as nondestructive parameter can be used to evaluate the insulation aging status of EPR cables.

(3) Under the constant electric stress and mechanical stress, the life evaluation equation of EPR cable is deduced based on the Arrhenius formula. Combining with the actual operating temperature of the cable, the method on the prediction for the service life of the new cable is given.

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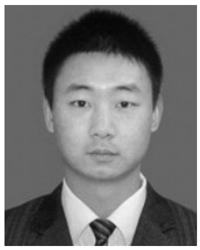

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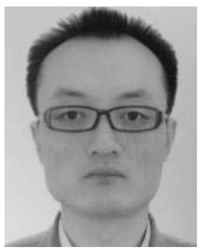

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