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Approach for Reliability Evaluation of Cross-Linked Polyethylene Under Combined Thermal and Vibration Stresses

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Abstract: Based on Wiener process model, a new approach for reliability evaluation of cross-linked polyethylene (XLPE) is proposed to improve the lifetime evaluation reliability of XLPE under multi-stressing conditions and study the failure probability distribution. In this paper, two accelerated aging tests are carried out under combined thermal and vibration conditions. The volume resistance degradation data of XLPE samples are tested with a 24 h interval under the accelerated stressing conditions at (130 °C, $12\,\mathrm{m/s^2}$) and (150 °C, $8.5\,\mathrm{m/s^2}$), respectively. Nonlinear degradation data obtained from the experiment are transformed to linear intermediate-variable values using time scaling function, and then linearized degradation data are calculated and evaluated on the basis of linear Wiener process model. Considering traditional Arrhenius equation and inverse power criterion, parameters of the linear Wiener model are estimated according to the maximum likelihood function. The relationship curves on probability density and reliability are given, and the lifetime distribution of XLPE under different stressing conditions is also obtained for evaluating the reliability of XLPE insulation. Finally, the life expectancy of XLPE is 17.9 a under an allowance temperature of 90 °C and an actual vibration acceleration of $0.5\,\mathrm{m/s^2}$. The approach and results in this paper may be used for reliability assessment of high-voltage multiple samples or apparatuses.

Key words: accelerated multifactor aging, lifetime evaluation, reliability distribution, degradation test, cross-linked polyethylene (XLPE)
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0 Introduction

Cross-linked polyethylene (XLPE) is widely used as electrical insulation of high-voltage power cables due to its excellent thermal resistance, good electric properties and mechanical strength. With the changes of various cables' laying conditions, reliable life estimation of XLPE insulation under complicated conditions becomes more and more important[1-3].

XLPE insulation aging is not a single electrical stress result, but the cause under multiple factors including electrical, thermal and mechanical stresses[4-9]. Usually, the Arrhenius equation and inverse power criterion are used to assess residual life of XLPE insulation under thermal and mechanical stresses. The estimated lifetime can be extrapolated from test data. Because of the single testing environment and larger dispersion of test data, the life evaluation reliability is so lower that the multiple test results are not consistent.

In most cases, the major stresses that aging cable insulation endures are often electrical stress, thermal stress, dielectric losses and mechanical stress. Tzimas et al.[10] proposed Zhurkov model for charactering thermal stress of solids. However, this model parameters need to be extrapolated to power cables with respect to full-size insulation. Tzimas et al.[10] also put forward Arrhenius model and the inverse power model for the thermal and electrical life. However, research on thermal and vibration stresses is relatively scarce. The Weibull distribution is commonly used for statistical processing of breakdown data of electrical insulation. The two-parameter Weibull distribution has been critically examined and assessed insulation condition in service. Fabiani and Simoni[11] gave a simple review of current Bayesian reliability demonstration methods, and focused on the effect of different types of prior information. This method needs a large sample size or substantive prior information. The Weibull distribution is also used to investigate the electrical breakdown of insulation materials[12]. However, it is difficult to obtain enough breakdown failure data in a short time because of high reliability and long lifetime for cable

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insulation material. The degradation failure data are required more impactful work. In order to avoid unnecessary search, the searching solution utilizes some rules and reduces complexity, and optimal solution should be found with reasonable computation cost.

Considering that degradation data of dielectric parameters are usually scattered with nonlinear variation during the aging tests, several performance degradation models have been proposed, such as degradation path model[13-15], degradation amount distribution model[16-18], Wiener model[19] and Gamma model[20]. Among these stochastic process models, Wiener process model can be used for smooth independent Gaussian incremental-performance degradation process and is widely applied in engineering field because of its excellent calculating and analytical abilities. The degradation based reliability demonstration test (RDT) plan design problems are studied by Wiener model for long life products under a small sample circumstance[21]. The Wiener model can transform the problem from calculating the first hitting time distribution of the diffusion process crossing a constant threshold into a standard Brownian motion crossing a time space transformation. It develops a degradation model using a nonlinear diffusion process and provides an approximation of the probability density function[22-23].

In this paper, an accelerated aging test with combined thermal and vibration stresses is designed and the degradation data of XLPE samples are obtained. Nonlinear Wiener process model and time scale transformation function are used, and model parameters are determined by the maximum likelihood estimation. The probability density function and reliability function are derived to assess the lifetime of XLPE samples. The approach and results may be used for reliability assessment of high-voltage multiple samples or apparatuses.

1 Model Establishment

1.1 Wiener Model

Assumption 1 During random process, product performance parameter $X(t)$ meets the following properties at time t. Therefore, linear Wiener process model can represent degradation parameters with smooth and independent Gaussian performance degradation process.

Feature 1 $\Delta X(t)$ is degradation increment from t to $t+\Delta t$, and let $\Delta X(t)$ be a normal distribution, i.e., $\Delta X(t) = X(t+\Delta t) - X(t) \sim \mathcal{N}(\mu\Delta t,\ \sigma^2\Delta t)$, where $X(t)$ is linear Wiener process, μ is drift parameter and σ is diffusion coefficient.

Feature 2 For two arbitrary non-intersecting periods $[t_1, t_2]$ and $[t_3, t_4]$, the incremental $X(t_2) - X(t_1)$ and the incremental $X(t_3) - X(t_4)$ are independent with $t_1 < t_2 \leqslant t_3 < t_4$.

Feature 3 $X(0) = 0$, $X(t)$ is continuous at $t = 0$.

Here, Wiener degradation model can be described as

$$X(t) = \mu t + \sigma w(t), \tag{1}$$

where $w(t)$ is Brownian motion.

Assumption 2 Equation (1) only applies to the degradation performance which is a linear degradation process. However, a lot of product degradation processes are nonlinear; time power conversion method is put forward in the approach presented in this paper. Nonnegative monotonically-increasing function $\gamma(t)$ which has variable t is constructed. Equation (1) can be rewritten as

$$X(t) = \mu\gamma(t) + \sigma w(\gamma(t)), \tag{2}$$

where

$$\tau = \gamma(t) = t^{\lambda},$$

λ is conversion coefficient. By the time t scale transformation, we can transform a nonlinear degradation progress into a linear process:

$$Y(\tau) = \mu\tau + \sigma w(\tau). \tag{3}$$

Assumption 3 The failure threshold l of the samples is a constant ($l > 0$). The lifetime L is the first time to reach the failure threshold:

$$L = \inf\,(Y(\tau) \geqslant l), \tag{4}$$

where $Y(\tau)$ is degenerate process after linearization of time scale, and inf $(Y(\tau) \geqslant l)$ is failure threshold.

Through the theoretical derivation, the time distribution of life L, in addition to linear Wiener process life, follows inverse Gaussian distribution. The life distribution function $F(\tau)$ and the probability density function $f(\tau)$ are

$$F(\tau) = \varphi\left(\frac{l-\mu\tau}{\sigma\sqrt{\tau}}\right) + \varphi\left(\frac{-l-\mu\tau}{\sigma\sqrt{\tau}}\right)\exp\left(\frac{2\mu l}{\sigma^2}\right), \tag{5}$$

$$f(\tau) = \frac{\mathrm{d}F(\tau)}{\mathrm{d}t} = \frac{1}{\sqrt{2\pi\sigma^2\tau^3}}\exp\left[-\frac{(l-\mu\tau)^2}{2\sigma^2\tau}\right], \tag{6}$$

where $\varphi(x)$ is standard normal distribution function. Therefore, the reliability function can be concluded as

$$R(\tau) = 1 - F(\tau) = \varphi\left(\frac{l-\mu\tau}{\sigma\sqrt{\tau}}\right) - \varphi\left(\frac{-l-\mu\tau}{\sigma\sqrt{\tau}}\right)\exp\left(\frac{2\mu l}{\sigma^2}\right). \tag{7}$$

1.2 Accelerated Aging Model

In general, the life of products or samples will change according to some rules under different stresses. Accelerated aging model is mathematically modeled by the product life varying under different stress levels, and it represents the relationship between products life and stress level. At present, accelerated factors in aging tests contain temperature, mechanical vibration, electrical stress (voltage, current, electric power, electric field strength), light intensity, humidity, and so on. The usual accelerated aging models are Arrhenius model, inverse power criterion, single stress Eyring model, generalized Eyring model, and so on.

With regard to temperature and vibration stress accelerated aging tests, Arrhenius model and inverse power criterion can be used to describe the relationship between life and multi-stress:

$$L = L_{\mathrm{T}} L_{\mathrm{S}} = AS^{-m} \exp(U_0/RT) \tag{8}$$

where S is the material stress, R is gas molecules constant, T is the aging temperature, A is the pre-exponential factor in multi-factor aging, m is the inverse power coefficient which is related to vibration stress, U_0 is the activation energy of the sample, L_{T} is the material lifetime under combined thermal stress, and L_{S} is the material lifetime under combined vibration stress.

For the multi-factor accelerated aging test of electric field strength, temperature and vibration stress, the electric stress aging of XLPE is also in accordance with the inverse power criterion.

Based on Eq. (8) and superposition theorem, the relationship between multi-stress and model life expectancy is expressed as

$$L = L_{\mathrm{T}} L_{\mathrm{S}} L_E = AS^{-m} E^{-n} \exp(U_0/RT), \tag{9}$$

where E is the electric field strength, and n is the inverse power coefficient which is related to the electric field strength.

1.3 Model Parameter Estimation

As we have seen from Eq. (5) to Eq. (7), the drift parameter μ and the diffusion coefficient σ should be solved before evaluating the reliability of XLPE. Let Y_{ijk} be the ith measurement result for the jth sample under the kth accelerated aging stress. In addition, τ_{ijk} is the ith measurement time for the jth sample under the kth accelerated aging stress; $\Delta Y_{ijk} = Y_{ijk} - Y_{(i-1)jk}$ is increment of performance degradation; $\Delta\tau_{ijk} = \tau_{ijk} - \tau_{(i-1)jk}$ is time increment. According to the Wiener process model, there is

$$\Delta Y_{ijk} \sim \mathcal{N}(\mu \Delta\tau_{ijk}, \sigma^2 \Delta\tau_{ijk}). \tag{10}$$

From performance degradation data, maximum likelihood estimation can be concluded as

$$L(\mu, \sigma^2) = \prod_{i=1}^{n_1} \prod_{j=1}^{n_2} \prod_{k=1}^{n_3} \left\{ \frac{1}{\sqrt{2\pi\sigma^2 \Delta\tau_{ijk}}} \times \exp\left[-\frac{(\Delta Y_{ijk} - \mu\Delta\tau_{ijk})^2}{2\sigma^2 \Delta\tau_{ijk}} \right] \right\}, \tag{11}$$

where n_1 is the test time of the sample, n_2 is the number of samples and n_3 is the number of test stresses.

Considering double factor accelerated aging model under combined temperature and vibration stresses, the expressions on μ and σ^2 can be deduced from Eq. (8) according to the constant failure mechanism principle:

$$\mu = K_1 S_k^m \exp(-B/T_k), \tag{12}$$

$$\sigma^2 = K_2 S_k^m \exp(-B/T_k), \tag{13}$$

where, B is the correlation coefficient; K_1 and K_2 are the test coefficients of μ and σ^2, respectively; T_k and S_k represent the material stress and aging temperature under the kth accelerated aging stress, respectively. Substituting Eqs. (12) and (13) into Eq. (11) yields a new expression from multi-factor life model and maximum likelihood function:

$$L(K_1, K_2, m, B) = \prod_{i=1}^{n_1} \prod_{j=1}^{n_2} \prod_{k=1}^{n_3} \left\{ \frac{1}{\sqrt{2\pi K_2 S_k^m \Delta\tau_{ijk} \exp(-B/T_k)}} \times \exp\left[-\frac{(\Delta Y_{ijk} - K_1 S_k^m \Delta\tau_{ijk} \exp(-B/T_k))^2}{2K_2 S_k^m \Delta\tau_{ijk} \exp(-B/T_k)} \right] \right\}. \tag{14}$$

By Eq. (14) and the extreme condition of maximum likelihood function, equations of model parameter estimation can be obtained as

$$\frac{\partial \tilde{L}}{\partial K_1} = 0, \quad \frac{\partial \tilde{L}}{\partial K_2} = 0, \quad \frac{\partial \tilde{L}}{\partial m} = 0, \quad \frac{\partial \tilde{L}}{\partial B} = 0, \tag{15}$$

where

$$\tilde{L} = \ln L(K_1, K_2, m, B).$$

Parameter estimations of K_1, K_2, m and B can be calculated by substituting ΔY_{ijk}, Δt_{ijk}, T_k and S_k into Eq. (15). For the accelerated aging test of electric field strength, temperature and vibration stress, the analytical procedure of maximum likelihood parameters is the same as the above analysis process.

2 Acquisition and Statistical Analysis of Degradation Data

2.1 Accelerated Aging Test

The main XLPE failures result from thermal aging, electric aging and mechanical aging. In order to simulate ultrahigh-voltage cable insulation aging under vibration condition, temperature and vibration strength (accelerated velocity) are selected as accelerated aging condition. Experiment is carried out using many groups of XLPE samples under the condition of constant stress accelerated degradation test. A simplified schematic diagram of the vibration clamp and electrode is shown in Fig. 1. As shown in Fig. 1, the vertical vibration produced by vibration table is passed onto the fixed clamp by transmission rod. Due to the adjusted vibration frequency and amplitude, the vibration accelerated aging is generated on the XLPE samples.

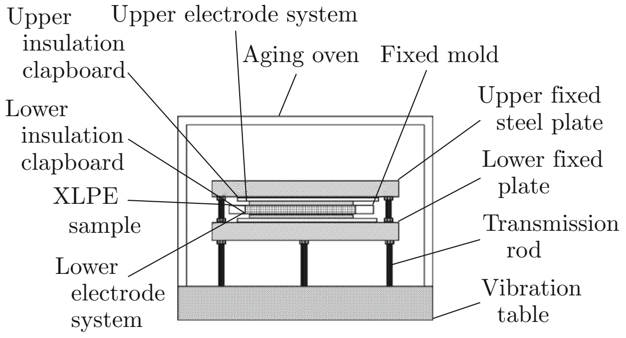

Fig. 1 Schematic diagram of aging equipment

XLPE samples are made by silane crosslinking technology.

(1) 16 pieces of 80 mm×80 mm×1.0 mm XLPE samples are prepared for aging test. 8 pieces of XLPE samples of the first group are put into aging test oven under the aging condition of combined stress S_1 (130 °C and 12 m/s^2 accelerated velocity). The second group sets 8 pieces of XLPE samples in aging test oven under the aging condition of combined stress S_2 (150 °C and 8.5 m/s^2 accelerated velocity).

(2) The samples at S_1 are tested 25 times with a measuring interval of about 24 h. The first test result is set as initial resistance value. The residual tests are based on the first test result to calculate current resistance degradation. The results are shown in Fig. 2.

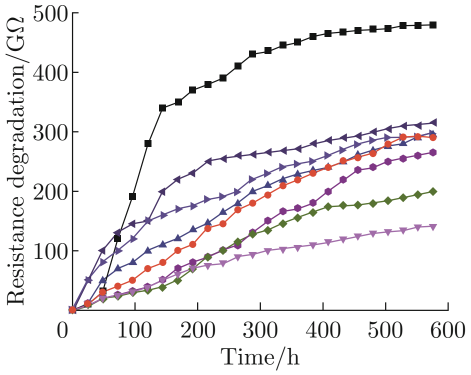

Fig. 2 Resistance degradation for 8 pieces of XLPE samples at S_1

(3) The samples at S_2 are tested 19 times. The samples' preparation process is the same as above. The results are shown in Fig. 3.

(4) A commercial high-resistance meter is used to measure each XLPE sample and record the current insulating resistance. That the insulating resistance of XLPE samples decreases more than two orders of the initial value is regarded as the end criterion of XLPE life. After testing, the average initial insulation resistance of 16 XLPE samples is 500 GΩ, therefore 5 GΩ is set as the failure threshold of XLPE samples, and the degenerate resistance failure threshold is about 500 GΩ.

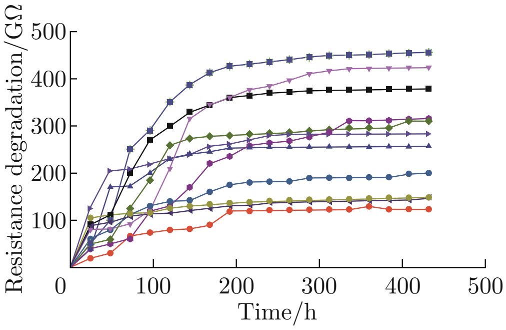

Fig. 3 Resistance degradation for 8 pieces of XLPE samples at S_2

2.2 Time Scale Transformation of the Performance Degradation data

Two groups of degradation resistance of XLPE samples are shown in Figs. 2 and 3. It can be observed clearly that resistance degradation data of XLPE samples change with significant dispersion at the same aging condition. Moreover, linear Wiener model is not applied due to nonlinear resistance degradation curve. It is necessary to linearize the resistance degradation curve by time scale transformation.

As shown in the diagrams, the degradation of resistance and time can be expressed as

$$X(t) = t^{\alpha} \exp(a + b/T), \tag{16}$$

where a and b are constants, and α is the time conversion factor.

Each degenerate curve is fitted, and the maximum likelihood function is applied to obtain the optimal time conversion factor. Data analysis verifies that the relationship between XLPE resistance degradation and time meets time scale transformation function. The time scale transformation function is $\tau = t^{0.436}$.

2.3 Reliability Assessment and Life Prediction

Completing the time scale transformation yields resistance degradation test results, and the transformed data are put into Eq. (14). According to the maximum likelihood function, the results are obtained as

$$\begin{aligned} K_1 &= 83\,040.47, & K_2 &= 18\,493.51, \\ B &= 5\,411.75, & m &= 0.0409\,84. \end{aligned}$$

Under an allowable temperature of 90 °C and an external vibration acceleration of 0.5 m/s^2 (general accelerated velocity in the actual laying condition), from Eqs. (12) and (13), the drift parameter and the diffusion coefficient can be obtained as

$$\mu = 0.027\,15, \quad \sigma^2 = 0.006\,047\,3.$$

After substituting $\tau = t^{0.436}$ into Eq. (6), the failure probability density function of XLPE samples can be also solved under an allowable temperature of 90 °C and an external vibration acceleration of $0.5\,\mathrm{m/s^2}$. That is

$$f(t) = \frac{l}{\sqrt{2\pi\sigma^2\tau^3}} \exp\left[-\frac{(l-\mu\tau)^2}{2\sigma^2\tau}\right] = \frac{5}{\sqrt{2\pi \times 0.006\,047\,3 t^{1.308}}} \times \exp\left[-\frac{(5-0.027\,15 t^{0.436})^2}{0.006\,047\,3 t^{0.436}}\right]. \tag{17}$$

According to Eq. (7), the reliability function is

$$R(t) = \varphi\left(\frac{l-\mu\tau}{\sigma\sqrt{\tau}}\right) - \varphi\left(-\frac{l+\mu\tau}{\sigma\sqrt{\tau}}\right)\exp\left(\frac{2\mu l}{\sigma^2}\right) = \varphi\left(\frac{5-0.027\,15t^{0.436}}{0.077\,765t^{0.218}}\right) - \varphi\left(-\frac{5+0.027\,15t^{0.436}}{0.077\,765t^{0.218}}\right) \times \exp\left(\frac{2\times 0.027\,15\times 5}{0.006\,047\,3}\right). \tag{18}$$

Figures 4 and 5 show the failure probability density function and reliability function of XLPE samples, respectively, under an allowable temperature of 90 °C and an external vibration acceleration of $0.5\,\mathrm{m/s^2}$.

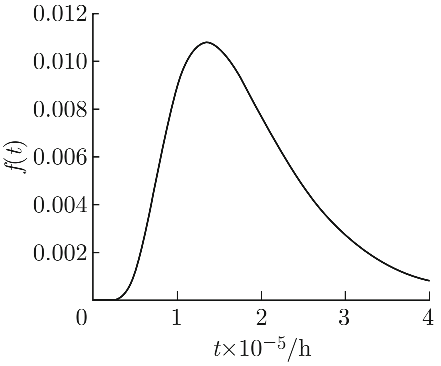

Fig. 4 Failure probability density function of XLPE samples

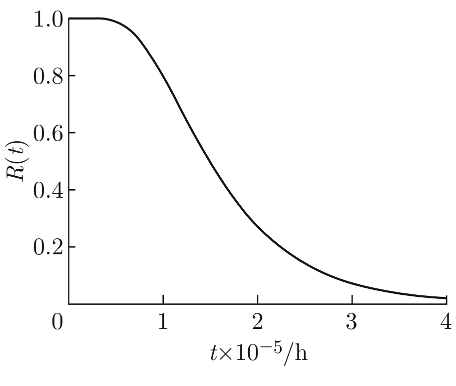

Fig. 5 Reliability function of XLPE samples

From the inverse Gaussian distribution, it can be indicated that the average lifetime is $\bar{L} = l/\mu$ under time scaling τ (linear). By the time scale transformation function $\tau = t^{0.436}$, the life expectancy is achieved as

$$\bar{L} = (l/\mu)^{\frac{1}{0.436}}. \tag{19}$$

Therefore, the life expectancy $\bar{L} = 157\,116.16\,\mathrm{h} \approx 17.9\,\mathrm{a}$ can be obtained under an allowable temperature of 90 °C and an external vibration acceleration of $0.5\,\mathrm{m/s^2}$. This value is corresponding to the peak of failure probability density curve, as shown in Fig. 6. At a low temperature of 90 °C, the effect of external vibration acceleration on XLPE life is greater than that at a high temperature of 150 °C.

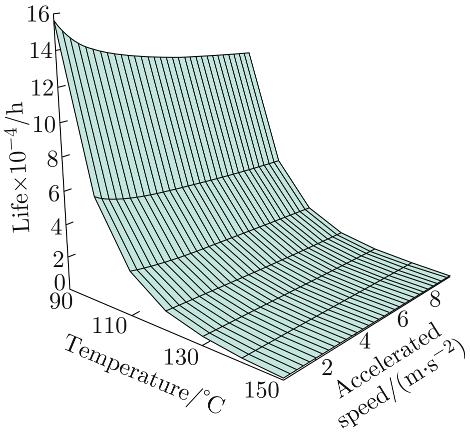

Fig. 6 Life distribution under different stress combinations

3 Conclusion

Degradation based on Wiener model provides an efficient way to estimate sample life reliability. In order to estimate life reliability of XLPE insulation under multi-stress aging conditions, this paper focuses on nonlinear Wiener process model and aging tests.

For aging test, the resistance data of XLPE samples are suitable for using as nonlinear degradation data. The important consideration in calculation is to linearize resistance degradation data of XLPE by the time scale transformation function. If in practice the degradation data do not follow linearity or normality, additional work will be necessary. It is necessary for time scale transformation through which the original nonlinear model can be transformed to a linear model.

A temperature and vibration stress accelerated aging life model can be built by combining Arrhenius equation with the inverse power criterion. Model parameters are estimated with the maximum likelihood function, and then the probability density, reliability and life distribution of XLPE are obtained at different stressing combinations. The results show that the effect of external vibration acceleration on the XLPE life is greater than that of high temperature.

According to theoretical calculation, the life expectancy of tested XLPE samples is 17.9 a at an allowance temperature of 90 °C and an external vibration acceleration of $0.5\,\mathrm{m/s^2}$.

References

[1] LEGUENZA E L, ROBERT R, MOURA W A, et al. Dielectric behavior of XLPE aged under multi-stressing conditions [C]//*12th International Symposium on Electrets*. [s.l.]: ISE, 2005: 254-257.

[2] ARAS F, ALEKPEROV V, CAN N, et al. Aging of 154 kV underground power cable insulation under combined thermal and electrical stresses [J]. *IEEE Electrical Insulation Magazine*, 2007, **23**(5): 25-33.

[3] MAZZANTI G. The combination of electro-thermal stress, load cycling and thermal transients and its effects on the life of high voltage ac cables [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2009, **16**(4): 1168-1179.

[4] DANG C, PARPAL J L, CRINE J P. Electrical aging of extruded dielectric cables review of existing theories and data [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 1996, **3**(2): 237-247.

[5] LUO P, XU Y, GU X, et al. Thermal and mechanical properties analysis for EHV XLPE cables with different operating years [C]//Annual Report *Conference on Electrical Insulation and Dielectrics Phenomena*. [s.l.]: IEEE, 2013: 47-51.

[6] MAZZANTI G. Analysis of the combined effects of load cycling, thermal transients, and electrothermal stress on life expectancy of high-voltage AC cables [J]. *IEEE Transaction on Power Delivery*, 2007, **22**(4): 2000-2009.

[7] FOTHERGILL J C, DODD S J, DISSADO L A, et al. The measurement of very low conductivity and dielectric loss in XLPE cables: A possible method to detect degradation due to thermal aging [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2011, **18**(5): 1544-1553.

[8] LALL P, LOWE R, GOEBEL K. Prognostication of accrued damage in board assemblies under thermal and mechanical stresses [C]//*IEEE 62nd Electronic Components and Technology Conference*. [s.l.]: IEEE, 2012: 1475-1487.

[9] AL-ARAINY A, MALIK N H, QURESHI M I, et al. The performance of strippable and bonded screened medium-voltage XLPE-insulation cables under long-term accelerated aging [J]. *IEEE Transactions on Power Delivery*, 2007, **22**(2): 744-751.

[10] TZIMAS A, ROWLAND S, DISSADO L A, et al. Effect of long-time electrical and thermal stresses upon the endurance capability of cable insulation material. [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2009, **16**(5): 1436-1443.

[11] FABIANI D, SIMONI L. Discussion on application of the Weibull distribution to electrical breakdown of insulating materials [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2005, **12**(1): 11-16.

[12] KORZHOVA M E, KORZHOV A V. Weibull distribution parameters in electrical insulation reliability assessment [C]//*2nd International Ural Conference on Measurement*. [s.l.]: IEEE, 2017: 409-414.

[13] GEBRAEEL N Z, LAWLEY M A, LI R, et al. Residual-life distributions from component degradation signals: A Bayesian approach [J]. *IIE Transactions*, 2007, **37**(6): 543-557.

[14] MAZZANTI G. The combination of electro-thermal stress, load cycling and thermal transient and its effects on the life of high voltage AC cables [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, 2009, **16**(4): 1168-1179.

[15] MUSALLAM M, JOHNSON C M. Monitoring through-life thermal path degradation using real time thermal models [C]//*IEEE Power Electronics Specialists Conference*. [s.l.]: IEEE, 2008: 738-743.

[16] SU C, JIANG Y H. Forecasting model for degradation path and parameter estimation based on neural network [C]//*2009 16th International Conference on Industrial Engineering and Engineering Management*. 2009: 1735-1738.

[17] ZUO M J, JIANG R Y, YAM R C M. Approaches for reliability modeling of continuous-state devices [J]. *IEEE Transactions on Reliability*, 1999, **48**(1): 9-18.

[18] HUANG W, DIETRICH D L. An alternative degradation reliability modeling approach using maximum likelihood estimation [J]. *IEEE Transactions on Reliability*, 2005, **54**(2): 310-317.

[19] PENG C Y, TSENG S T. Statistical lifetime inference with skew-Wiener linear degradation models [J]. *IEEE Transactions on Reliability*, 2013, **62**(2): 338-350.

[20] LING M H, BALAKRISHMAN N. Model misspecification analyses of Weibull and Gamma models based on one-shot device test data [J]. *IEEE Transactions on Reliability,* 2017, **66**(3): 641-650.

[21] TSAI C C, TSENG S T, BALAKRISHNAN N. Optimal design for degradation tests based on Gamma processes with random effects [J]. *IEEE Transactions on Reliability*, 2012, **61**(2): 604-613.

[22] JIN G, MATTHEWS D. Reliability demonstration for long-life products based on degradation testing and a Wiener process model [J]. *IEEE Transactions on Reliability*, 2014, **63**(3): 781-797.

[23] SI X S, WANG W B, HU C H, et al. Remaining useful life estimation based on a nonlinear diffusion degradation process [J]. *IEEE Transactions on Reliability*, 2012, **61**(1): 50-56.