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Breakdown Characteristics and Lifetime Estimation of Rubber Insulating Gloves Using Statistical Models

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Abstract: This paper is aimed at predicting the life of rubber insulating gloves under normal operating stresses from relatively rapid test performed at higher stresses. Specimens of rubber insulating gloves are subject to multiple stress conditions, i.e. combined electrical and thermal stresses. Two modes of electrical stress, step voltage stress and constant voltage stress are used in specimen aging. There are two types of test for electrical stress in this experiment: the one is Breakdown Voltage (BDV) test under step voltage stress and thermal stress and the other is lifetime test under constant voltage stress and temperature stress. The ac breakdown voltage defined as the breakdown point of insulation that leakage current excesses a limit value, 10 mA in this experiment, is determined. Because the very high variability of aging data requires the application of statistical model, Weibull distribution is used to represent the failure times as the straight line on Weibull probability paper. Weibull parameters are determined by three statistical methods i.e. maximum likelihood method, graphical method and least squares method, which employ SAS package, Weibull probability paper and FORTRAN, respectively. Two chosen models for predicting the life under simultaneous electrical and thermal stresses are inverse power model and exponential model. And the constants of life equation for multistress aging are calculated using numerical method, such as Gauss Jordan method etc.. The completion of life equation enables to estimate the life at normal stress based on the data collected from accelerated aging test. Also the comparison of the calculated lifetimes between the inverse power model and the exponential model is carried out. And the lifetimes calculated by three statistical methods with lower voltage than test voltage are compared. The results obtained from the suggested experimental method are presented and discussed.

Key words: rubber insulating gloves, multistress, breakdown voltage (BDV), life estimation

1. Introduction

Rubber insulating gloves used in HV working areas are deteriorated with time by multiple stresses, such as electrical, thermal and mechanical stresses. So, the degree of deterioration of their electrical characteristics, which can be expressed in terms of the withstand voltage, is regarded as an important parameter from the viewpoint of electrical safety engineering. The multiple stresses may act together to accelerate degradation and ultimately cause failure of the insulation. Additionally, simultaneous application of stresses is important because the results are quite different from those obtained when the stresses are applied singly or sequentially. In particular, simultaneous electrical and thermal stresses have been commonly investigated since the presence of these two stresses is almost unavoidable [1-3].

In this paper, the specimens of rubber insulating gloves are subject to electrical stress such as 29~34 kV combined with thermal stress, 23, 50 and 90°C. The results of experiment are divided into two groups: the one that has the results of BDV test and the other that has the results of failure time test. The life of gloves is estimated by data obtained from the experiment. To calculate some parameters which can evaluate all the failure times for the particular aging test conditions, an assumption on Weibull distribution, a kind of statistical model, is required. Weibull parameters and constants of life equation are determined by using Weibull Probability Paper (WPP) and numerical methods (Gauss Jordan method, Gaussian elimination method, etc.).

The results of the BDV test are plotted on the WPP.

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Also the results of the failure time test plotted on the WPP are used for estimating the Weibull parameters. The calculated lifetimes determined by the three statistical methods at test temperature are compared with each other. The completion of the life equation enables accelerated aging test data to be extrapolated to normal stress levels, thus it is possible to predict the life of specimen during normal operation.

2. Breakdown in Solid Dielectrics

Electrical breakdown and aging start from points of local field enhancement. Under the action of a high electric field, a solid dielectric may either globally or locally loose its mechanical stability which leads to complete or partial disintegration. This phenomenon is known as dielectric breakdown. The breakdown can either be due directly to a field-induced mechanical instability or it can be the indirect result of local or global instabilities in the electric current distribution [4]. And all breakdown in solid dielectrics is ultimately thermal in the sense that the discharge track involves at least the melting and probably the vaporization of the dielectric.

Most dielectrics show increasing electrical conductivity and decreasing thermal coductivity as the temperature increases. For this reason, breakdown at high temperatures tends to be thermal in nature. The basic equation for thermal breakdown is [5]:

$$C\frac{\partial T}{\partial t} - div(K\ grad\ T) = \sigma E^2 \tag{1}$$

where K is thermal coductivity and σ is electrical coductivity. C is specific heat per unit volume of solid and the other symbols have their usual meaning.

Early scientific work on the breakdown of thin single crystal dielectrics gave rise to the impression that breakdown field strength depended only on the dielectric substance and the temperature - hence the concept of "intrinsic breakdown". Frohlich gave a formula for a critical field at which collision recombination no longer balances collision ionization:

$$E_c = E_o\left(1 + \frac{2}{\exp(k\omega/kT) - 1}\right)^{0.5} \tag{2}$$

In this formula E_0 is a field strength determined by crystal parameters, and ω is the angular frequency of the longitudinal polarization waves. Also k is Boltzmann's constant.

The breakdown process was divided into four stages by Budenstein

1) A formative stage in which energy is deposited in preferred sites in the dielectric; there may be many mechanisms, and collision ionization could be of primary importance.

2) A tree initiation stage in which concentrations of ions in the gaseous phase are formed at places of high field concentration and deposition of energy.

3) A tree growth stage in which energy is supplied from the field to the gases which then further erode the solid.

4) A return streamer which occurs when a tree extends from one electrode to the other; current through the highly conducting streamer forms the breakdown channel.

3. Life Models for Multistress Aging

The ultimate goal of lifetime studies is to develop a reliable mathematical model for the aging process relating the test stress to time to failure. A number of models for multistress aging have already been proposed. Most of these models are extensions of models developed under single stresses, for example, for thermal stress, the Arrhenius relationship [6]

$$L = A\exp\left[\frac{B}{T}\right] \tag{3}$$

and for the voltage stress, the inverse power model [7]

$$L = KV^{(-N)} \tag{4}$$

or the exponential law.

$$L = C\ \exp\ (-nV) \tag{5}$$

where L is the life of the insulation. The term 'life' means the time-to-failure of the insulation system under aging stresses. Life is thus determined by measuring the time to puncture (or breakdown) of the insulation. The multistress models that have been proposed can be divided into two broad groups; the one that has an inverse power law type of dependence for the electrical stress and the other that has an exponential relationship. The models of both types have been widely used by Simoni and by Ramu et al. in fitting their data.

A general equation for predicting the life under simultaneous electric and thermal stresses with the inverse power term for electrical aging is

$$L = k(T)\exp(-B\Delta T)V^{-n(T)} \tag{6}$$

where V is the voltage stress above V_0, the threshold voltage below which electrical aging is assumed to be negligible, B is the thermal constant, $k(T)=\exp(k_1-k_2\Delta T)$ is a temperature- dependent constant, $n(T)=n_1-n_2\Delta T$ is the exponent which is temperature-dependent where n_1 and n_2 are constants and $\Delta T=1/T_0-1/T$, with T being absolute temperature.

An example of a model with an exponential dependence for the electrical stress is

$$K = \exp\left[A(V) + \frac{B(V)}{T}\right] \tag{7}$$

where $A(V)=A_1+A_2V$ and $B(V)=B_1+B_2V$. The factors A_1, A_2, B_1 and B_2 are constants.

4. Experimental Set Up and Procedure

The aging test set up is presented in Fig. 1. Standard cylindrical brass electrodes (A), 2.54 cm in diameter with rounded edges in accordance with ASTM-D149-81 specifications [8], were used in stressing the specimens of rubber insulating gloves. Transformer oil (B) in the test cell was heated to the test temperature by means of a heating coil (C). The type of rubber insulating gloves for protection of workers from electrical shock in accordance with ASTM-D120-87 specifications [9] is class1 in five classes. The specimens (D) for testing were cut to squares of approximately 6 cm and inserted into the test cell filled with transformer oil at the test temperatures, 23, 50 and 90°C. And the supplementary experiment at 120°C was performed to know the tendency of lifetimes under voltage stress. To maintain the constant test temperature, a temperature controller (E) was used. The output voltage of ac-proof tester (high voltage generator (F)) is from zero to 50 kV. The electrical stress such as 29~34 kV was applied to the specimens. The representative value of the experimental result uses the mean of a ten-time test under each multistress. In this test two modes of electrical stress were used in insulation aging: step stress and continuous stress. The step stress was used in the BDV test and the continuous stress was used in the failure time test.

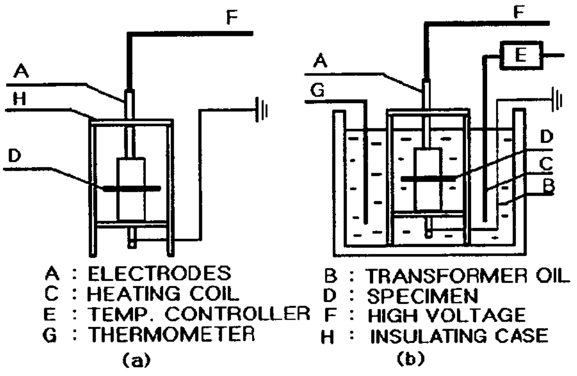

Fig. 1. Experimental set up for the test (a) in air (b) in Tr oil.

First, the test specimen was inserted into the BDV test cell. After 60 sec, the test voltage was raised at a rate of 1 kV/s. If the leakage current excesses 10 mA, the buzzer rings. The breakdown voltage under combined the step stress and the test temperature was checked. The data of test are sorted to the descending order. Also this data are plotted on the Weibull probability paper.

Second, in the failure time test the test voltage was fixed under the test temperature. The continuous voltage was applied for electrical stress. The time-to-failure was recorded until the insulation breakdown of the specimen. The next procedures are in accord with the BDV test procedures except for the failure time data. The failure times of the specimen under multistresses are used as the input data of the three statistical methods to determine the Weibull parameters.

That is, the parameters are determined by the graphical method, the maximum likelihood method (SAS package) and the least squares method (FORTRAN) [10, 11] to estimate the life time based on the time-to-failure data obtained from experiment. And then, the constants of life equation are calculated by the numerical method (Gauss Jordan method or Gaussian elimination method for simultaneous equation). Describing this method in detail, the lifetime L in equation (6) and (7) is substituted by the scale parameter (α) and so the constants of life equation are calculated by solving the linear simultaneous equations. Plotting the results of the life equation, the life of the specimen under combined electrical and thermal stresses can be estimated.

5. Results and Discussions

The results of the ac aging experiments to estimate the life of the specimen of rubber insulating gloves under combined electrical and thermal stresses are shown in Fig. 2 to Fig. 7. The results of the BDV test are plotted in Fig. 2 to Fig. 3. The results of the failure time test are plotted in Fig. 4 to Fig. 7.

The distribution of BDV in air and in transformer oil at room temperature is plotted in Fig. 2. The breakdown voltage of the specimen in the transformer oil is higher than that of the specimen in air. Fig. 3 shows the Weibull plots for ac breakdown voltage in transformer

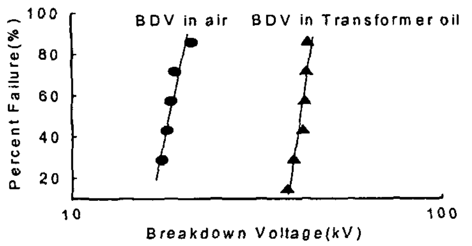

Fig. 2. Weibull plots for ac breakdown voltage in air and transformer oil at room temperature.

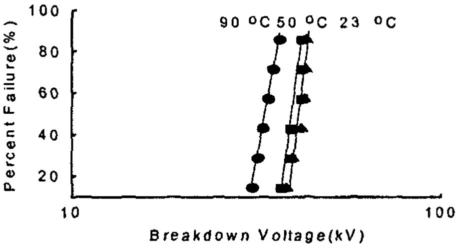

Fig. 3. Weibull plots for ac breakdown voltage in transformer oil at 23, 50 and 90°C.

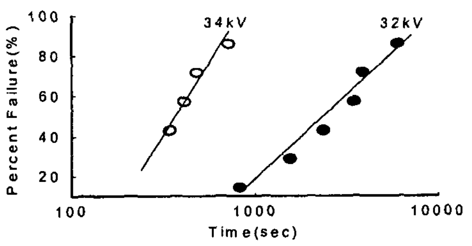

Fig. 4. Weibull plots for time to breakdown under voltage stresses at 23°C.

oil at 23, 50 and 90°C. The BDV of the specimen is lower at higher thermal stress than at lower thermal stress.

The Weibull plots for time to breakdown under combined electrical stress (29~34 kV) and thermal stress (23, 50 and 90°C) are plotted in Fig. 4 to Fig. 6. The lifetimes of the specimen applied by the lower voltage stress at 23 and 50°C are longer than those of the specimen applied the higher voltage, as shown in Fig. 4 to Fig. 5. But the characteristic of the lifetimes under electrical stress at 90°C in Fig. 6 has an obscure result unlike that of the lifetimes at 23 and 50°C in Fig. 4 and Fig. 5. But this result is similar to the result of experiment for polypropylene films under ac voltage stresses. Fig. 7 shows the lifetimes under voltage stress on log versus log graph for ac aging at test temperature. The remarkable point in Fig. 7 is an anomalous pattern for the distribution of lifetimes.

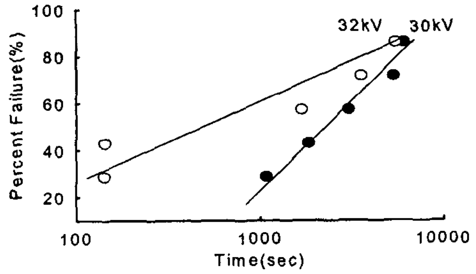

Fig. 5. Weibull plots for time to breakdown under voltage stresses at 50°C.

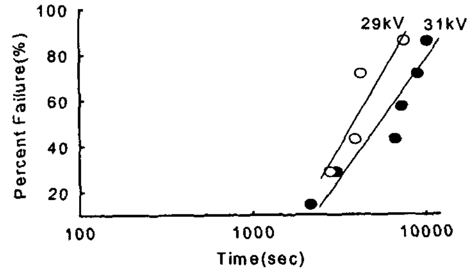

Fig. 6. Weibull plots for time to breakdown under voltage stresses at 90°C.

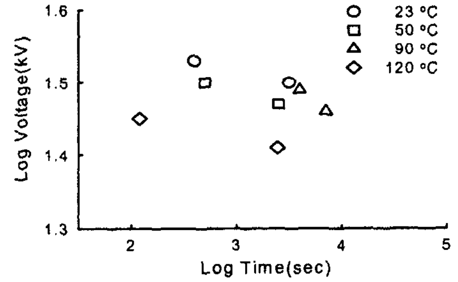

Fig. 7. Lifetimes under voltage stress.

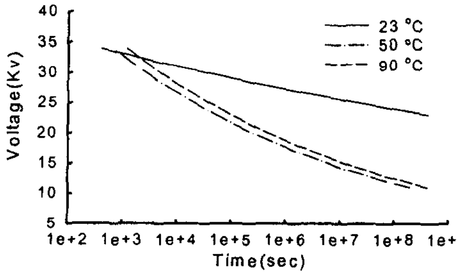

Fig. 8. Lifetime plots for the inverse power equation determin-ed by maximum likelihood method.

Fig. 8 to Fig. 13 represent the lifetimes plots for the inverse power equation and the exponential law equation determined by the three statistical methods, i.e. the maximum likelihood method, the graphical method and the least squares method. The lifetime plots for the inverse power equation determined by the three statistical methods are shown in Fig. 8 to Fig. 10. The lifetime plots for the inverse power equation determined by the maximum likelihood method at 50°C and at 90°C in

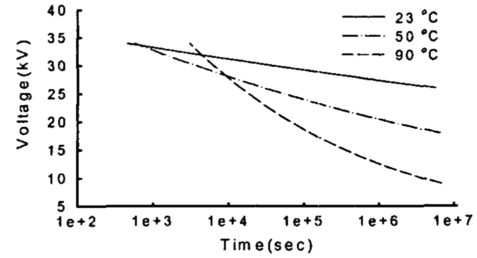

Fig. 9. Lifetime plots for the inverse power equation determin-ed by graphical method.

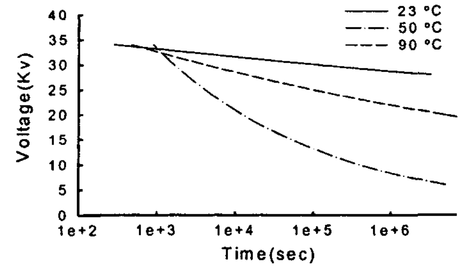

Fig. 10. Lifetime plots for the inverse power equation determined by least squares method.

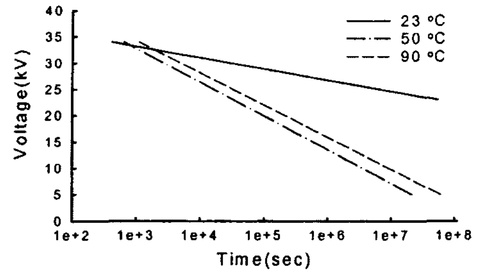

Fig. 11. Lifetime plots for the exponential law equation determined by maximum likelihood method.

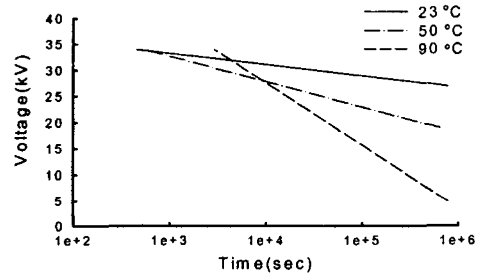

Fig. 12. Lifetime plots for the exponential law equation determined by graphical method.

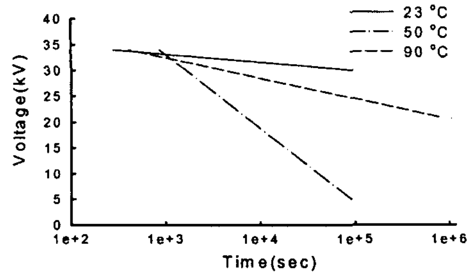

Fig. 13. Lifetime plots for the exponential law equation determined by least squares method.

Fig. 8 are similar each other. The pattern of lifetime in Fig. 8 and Fig. 10 is almost same. The lifetime in Fig. 8 and Fig. 10 is much longer at 90°C than at 50°C. But in Fig. 9 lifetimes for the inverse power equation determined by graphical method are longer at 50°C than at 9°C. Fig. 11 to Fig. 13 are lifetime plots for exponential law equation determined by the three statistical methods. The lifetime pattern for the exponential equation in Fig. 11 to Fig. 13 is like the lifetime pattern for the inverse power equation.

Table 1 represents the estimates of the Weibull parameters (α: scale parameter, β: shape parameter) obtained from the graphical, the maximum likelihood method and the least squares method for lifetimes under combined voltage and thermal stresses. Simple computer programs, i.e. SAS and FORTRAN programming based on the maximum likelihood method and the least squares method to calculate the parameters estimates using iterative procedure were developed and Kao's WPP was used in the estimation of the parameters for the graphical method. The failure times in each set of data points were sorted to the ascending order and the cumulative probabilities (or failure percent) obtained using the relation: F(I)=[I/(N+1)]100%. In the relation, I is the occurrence frequency and N is the number of data point.

In Table 2 the calculated constants of life equation for simultaneous electrical and thermal stresses are given. To calculate the constants of life equation, the numerical approach of Gauss Jordan method etc. is used. The scale parameter estimates for lifetime are also fitted to the life models proposed by Ramu and Simoni (Equa-

Table 1. Graphical, maximum likelihood and least squares estimates for lifetimes under combined voltage and thermal stresses

Stresses		Weibull Parameters					
		Graphical		Maximum Likelihood		Least squares	
Temp. °C	Voltage [kV]	α	β	α	β	α	β
23	32	3850	1.26	3480	1.88	5199	1.26
	34	460	1.50	407	1.17	280	0.89
50	30	3600	0.95	2680	0.81	1659	0.34
	32	1400	0.50	1307	0.61	1203	0.41
90	29	7650	1.45	7201	2.38	7480	1.35
	31	5200	0.65	3395	0.77	2340	2.25

*α: Scale parameter, β: Shape parameter.

Table 2. Calculated constants of life equation for simultaneous electrical and thermal stresses

Temp. °C	Models	Parameters of life equation			
2350	Inverse power	n_1	n_2	K_1	k_2+B
		35.39	85903.65	130.834	301189.8
	Exponential	A_1	A_2	B_1	B_2
		–242.39	7.463	84326.76	–2526.76
5090	Inverse power	n_1	n_2	K_1	k_2+B
		11.02	–412.443	44.879	–3179.21
	Exponential	A_1	A_2	B_1	B_2
		28.77	–0.511	–3261.69	48.897

Table 3. Comparison of the calculated lifetimes for three statistical methods with lower voltage than test voltage

Models	Temp. °C	Statistical methods		
		longer lifetime		
Inverse power	23	Least squares	Maximum likelihood	Graphical
	50	graphical	Maximum likelihood	least squares
	90	least squares	Maximum likelihood	Graphical
Exponential	23	least squares	Maximum likelihood	Graphical
	50	graphical	Maximum likelihood	least squares
	90	least squares	Maximum likelihood	Graphical

tion (6)) and Fallou (Equation (7)). Because the lifetime plots of life equation enable accelerated aging test data to be extrapolated to normal stress levels, it is possible to predict the life of the specimen of rubber insulating gloves under electrical and thermal stresses.

The specimen using inverse power model have a tendency to survive longer than those using exponential model in comparison of two models for the three statistical methods with lower voltage than test voltage (29~34 kV). Thus, from the viewpoint of safety and a conservative idea, the calculated lifetimes of exponential model should be applied to evaluate the lifetime of rubber insulating gloves at normal stresses.

The comparison of the calculated lifetimes by the three statistical methods with lower voltage than test voltage is shown in Table 3. The calculated lifetimes have not a sharp distinction for a particular method. Table 3 shows the method which calculates lifetime to the descending order in each aging model. In case of exponential model for the consideration of safety, graphical method at 23°C, least squares method at 50°C and graphical method at 90°C should be selected. Because the shortest life of rubber insulating gloves is the useful basis for safety.

6. Conclusions

To estimate the life of the specimen of insulating gloves under normal stress using the data collected from accelerated aging test, the statistical methods were used and life models were introduced in this paper.

The important features of this paper are summarized as follows. The BDV of the specimen is higher in transformer oil than in air. The BDV of the specimen is lower at higher thermal stress than at lower thermal stress. Also the strength of linear relationship between voltage stress and percent failure is stronger at higher thermal stress than at lower thermal stress in transformer oil, because the value of correlation coefficient at higher thermal stress is larger than other values. The lifetimes of the specimen applied the lower voltage stress at 23°C and 50°C are longer than those of the specimen applied the higher voltage. But the characteristic of the lifetimes at 90°C has an obscure result unlike that of the lifetimes at 23°C and 50°C. Thus, the distribution of lifetimes under ac stress follows anomalous pattern. In lifetime plots for the life equations, the calculated lifetimes determined by the maximum likelihood method and the least squares method are longer at higher thermal stress (90°C) than at lower thermal stress (50°C). In other hand, the characteristics of the lifetime calculated by the graphical method are different from those of the lifetime determined by the maximum likelihood method and the least squares method.

Since the calculated lifetimes of exponential model are shorter than those of inverse power model, from the viewpoint of safety and a conservative idea, the calculated lifetimes of exponential model should be applied to evaluate the lifetime of rubber insulating gloves at normal stresses. Also as results of comparison of three statistical methods, it is recommended to select lifetime estimation method according to temperatures due to temperature-dependent characteristics. Especially the method which gives the shortest lifetime of gloves should be used in view of safety.

The supplementary point of this experiment is that much more testing is required to get statistically significant results because aging stresses do not result in a clearly defined lifetime. And besides thermal and electrical stresses, the application of other stresses such as mechanical force, radiation, water is necessary for a better understanding of the aging mechanism.

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