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Multistress Life Models of Epoxy Encapsulated Magnet Wire under High Frequency Pulsating Voltage

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Abstract - This paper presents an attempt to develop probabilistic multistress life models to evaluate the lifetime characteristics of epoxy-encapsulated magnet wire with heavy build polyurethane enamel. A set of accelerated life tests were conducted over a wide range of pulsating voltages, temperatures, and frequencies. Samples of fine gauge twisted pairs of the encapsulated magnet wire were tested using a pulse endurance dielectric test system. An electrical-thermal lifetime function was combined with the Weibull distribution of lifetimes. The parameters of the combined Weibull-electrical-thermal model were estimated using maximum likelihood estimation. Likewise, a generalized electrical-thermal-frequency life model was also developed. The parameters of this new model were estimated using multiple linear regression technique. It was found in this paper that lifetime estimates of the two proposed probabilistic multistress life models are good enough. This suggests the suitability of using the general electrical-thermal-frequency model to estimate the lifetime of the encapsulated magnet wire over a wide range of voltages, temperatures and pulsating frequencies.

Keywords: Lifetime models, magnet wire, epoxy encapsulation, high frequency, pulsating voltage

1. Introduction

Statistical lifetime analysis of insulation breakdown of polymer materials is a widely known approach. It relies on the statistical analysis of failures that are attributed to the breakdown of the electrical insulation due to presence of degrading stresses, such as electrical, thermal and other aging factors [1-3]. In this approach, insulation life is determined by measuring the time-to-breakdown of identical specimens of the solid insulation subjected to life tests. Life tests, however, show that the times-to-breakdown are widely variable. This variation is best modeled by the Weibull probability distribution [4]. Conducting life tests at realistic working stresses are not possible due to the time constraint. Instead, breakdown data are obtained without paying much attention to the details of the breakdown mechanism. Thus, accelerated life tests are performed in laboratory so that the insulation life is severely reduced. The main goal of the life tests is to establish mathematical models for the aging process and the stresses causing it. The constants of these models need to be estimated from life tests where the lifetimes at a variety of stress levels are measured [5-8]. Traditionally, the parameters of the lifetime model were calculated either graphically using graphical method or analytically using regression analysis or maximum likelihood estimation [4]. Once the constants are estimated, the lifetime at any particular stress including normal operating conditions can, in principle, be estimated. In addition, the statistical life models can be used to give information about the electrical insulation including lifetime characteristics, probability of failures, lifetime percentiles or any time percentile under any operating conditions

In this paper, two probabilistic multistress life models were developed to estimate the lifetime of encapsulated magnet wire. An electrical-thermal life model was developed by combining the Weibull probability distribution to a new proposed electrical-thermal relationship. Then, maximum likelihood estimation was used to estimate the parameters of the proposed combined Weibull-electrical-thermal model. Furthermore, a generalized electrical-thermal-frequency model was also developed. The parameters of the new proposed general model were estimated using linear regression technique.

2. Experimental Test Setup

Accelerated life tests were conducted on dielectric sam-

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ples of encapsulated twisted pairs of fine gauge magnet wire (AWG 41). The life tests were conducted under high frequency pulsating voltages and high temperatures. The magnet wire insulation comprises heavy build polyurethane film with nylon overcoat. Moreover, the twisted pairs are encapsulated under vacuum with epoxy resin. Five test specimens were placed in an air-circulating oven and tested by high frequency pulse generators at a time. The voltage pulse amplitude, frequency, rise time, duty cycle, and the oven temperature are all controlled by a computer as shown in Fig. 1. The accelerated life tests were conducted over a wide range of voltages at pulsating frequencies of 15, 25, and 40 kHz, and at elevated temperature of 155, 165, and 180° C. Furthermore, the accelerated life tests were conducted at a rise time of 200 ns and duty cycle of 16%. A typical pulse voltage waveform generated by each pulser is shown in Fig. 2.

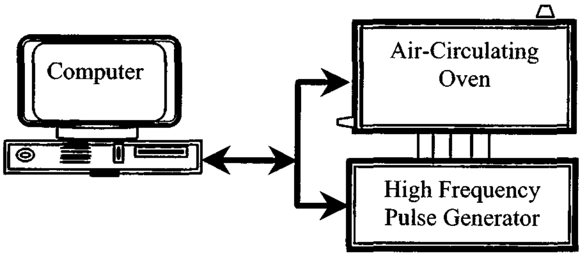

Fig. 1 Accelerated Life Pulsating Test System

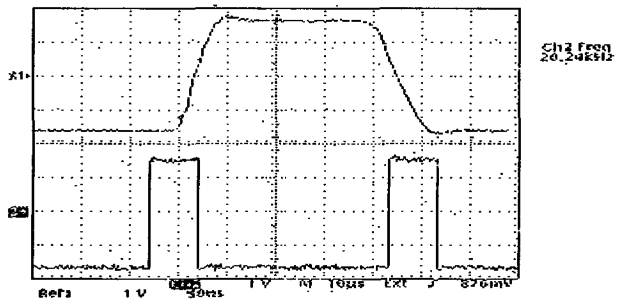

Fig. 2 Typical High Frequency Voltage Pulse

3. Electrical-Thermal Life Model For Encapsulated Magnet Wires

In this paper, a new empirical electrical-thermal relationship is presented for predicting the lifetime of magnet wire insulation over a wide range of operating conditions when the pulse voltage and temperature are the accelerated stresses in a test. This new electrical-thermal model is given by:

$$L(V,T) = C\exp\left(\frac{A}{V}+\frac{B}{T}\right) \tag{1}$$

where:

L: is the lifetime in hours at 63.2% probability.

V: is the voltage in Volts.

T: is the temperature in Kelvin.

C, A, B: are constants to be determined experimentally.

Assuming the time-to-breakdown of the electrical insulation, under combined electrical and thermal stresses, is statistically distributed according to the Weibull probability distribution [4]

$$f(t;\alpha,\beta) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}\exp\left\{-\left(\frac{t}{\alpha}\right)^{\beta}\right\} \tag{2}$$

where t is the time-to-breakdown, α is the scale parameter (lifetime at 63.2%), and β is the shape parameter or the slope of the Weibull cumulative distribution function. Hence, the above electrical-thermal model can be converted to a probabilistic model by setting the scale parameter α equals to $L(V,T)$. Therefore, the combined Weibull probability distribution function can be written as

$$f(t,V,T) = \frac{\beta}{C}\exp-\left(\frac{A}{V}+\frac{B}{T}\right)\left(\frac{t}{C}\exp-\left(\frac{A}{V}+\frac{B}{T}\right)\right)^{\beta-1}\cdot \exp-\left(\frac{t}{C}\exp-\left(\frac{A}{V}+\frac{B}{T}\right)\right)^{\beta} \tag{3}$$

This combined Weibull-electrical-thermal model has four parameters to be estimated by maximizing the likelihood function or the log-likelihood function of the combined Weibull-electrical-thermal model [4]. Since the shape parameter β varies at each stress level due to sampling error, etc., therefore, the maximum likelihood estimation gives a common shape parameter β. In this paper, the parameters were found at three pulsating frequencies of 15, 25, and 40 kHz.

4. Electrical-Thermal-Frequency Life Model For Encapsulated Magnet Wire

Likewise, a new multistress life model that includes the effects of voltage, temperature, and pulsating frequency is also developed in this paper. The developed model represents an interaction of the exponential electrical-thermal model, Eq. (1), and a frequency power law as given by Eq. (4).

$$L(V,T,f) = Kf^{m_1+m_2/V}\exp\left(\frac{A}{V}+\frac{B}{T}\right) \tag{4}$$

where:

L: is the lifetime in hours at 63.2% probability

V: is the voltage in Volts

T: is the temperature in Kelvin

f: is the pulse frequency in Hz.

The parameters K, A, B, m_1, and m_2 are constants to be determined using experimental data. For this model the multiple linear regression method was used to estimate these parameters. The new electrical-thermal-frequency model is linearized into a form such as

$$y = \ln(L) = \ln(K) + m_1 \ln(f) + \frac{m_2}{V}\ln(f) + \frac{A}{V} + \frac{B}{T} \qquad (5)$$

The method of least squares is then used to estimate the regression constants of the multiple linear regression model.

5. Failure Lifetime Percentiles

Once the parameters of the multistress life model are estimated, the failure time percentiles of the magnet wire insulation at different breakdown probabilities can be calculated using Eq. (6)

$$t_p = \tilde{\alpha}[-\ln(1-p)]^{1/\tilde{\beta}} \qquad (6)$$

where, t_p is the time-to-breakdown for which a sample will fail with a probability of failure, p, and $\alpha = L(V,T)$ for the electrical-thermal life models or $\alpha = L(V,T,f)$ for the electrical-thermal-frequency life model

6. Experimental Results

The parameters β, C, A, and B of the combined Weibull-electrical-thermal life models at 15, 25, and 40 kHz pulsating frequencies were estimated using maximum likelihood estimation. Estimates of these parameters are given in Table 1. Next, the developed models were used to calculate the lifetime percentiles at 15, 25, and 40 kHz. Lifetime percentiles at a voltage of 800V and a temperature of 165° C are given in Table 2. The lifetime percentiles show that the lifetimes of the magnet wire insulation increases with increasing the pulsating frequency.

Table 1 Parameter Estimates of the Electrical-Thermal Life Models

Model Parameter	Pulsating Frequency		
	15 kHz	**25 kHz**	**40 kHz**
β	1.529	1.611	1.630
C	1.40E-25	5.81E-13	1.79E-11
A	1444.36	1994.114	2472.601
B	24911.79	11962.83	10207.62

Table 2 Lifetime Percentiles at 800V and 165°C Calculated by the Electrical-Thermal Life Models

%p Percentile	Life Estimates (Hours)		
	15 kHz	**25 kHz**	**40 kHz**
1.0%	0.211	0.294	0.309
10.0%	0.98	1.26	1.31
63.2%	4.28	5.11	5.19
90.0%	7.39	8.58	8.66
99.0%	11.62	13.19	13.25

The parameters of the electrical-thermal-frequency life model were estimated using failure data at pulsating frequencies of 15, 25, and 40 kHz and at temperatures of 155, 165, and 180°C. Estimates of these parameters are given in Table 3. The shape parameter (β) was estimated by averaging the values of the shape parameters corresponding to the test frequencies 15, 25, and 40 kHz.

The lifetime percentiles at 15, 25, and 40 kHz were calculated at 800 V and 165° C. The results are given in Table 4.

It can be seen from Tables 2 and 4 that the results of lifetime percentiles calculated by the electrical-thermal life

Table 3 Parameter Estimates of the Electrical-Thermal-Frequency Life Model

Model Parameter	Parameter Estimates
β	1.590
K	8.0399E-9
A	-8.6354E+3
B	1.5775E+4
m_1	-0.9959
m_2	1.0487E+3

Table 4 Lifetime Percentiles at 800V and 165℃ Calculated by the Electrical-Thermal-Frequency Life Model

%p Percentile	Life Estimates (Hours)		
	15 kHz	**25 kHz**	**40 kHz**
1.0%	0.230	0.270	0.313
10.0%	1.01	1.18	1.37
63.2%	4.15	4.87	5.65
90.0%	7.01	8.23	9.55
99.0%	10.84	12.73	14.77

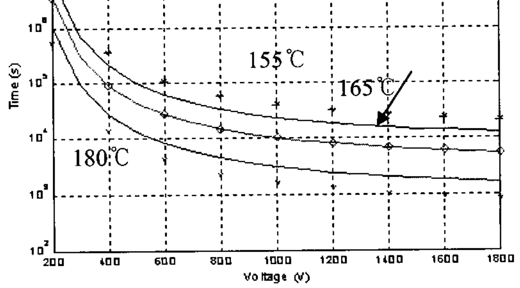

Fig. 3 Encapsulated Magnet Wire V-t Characteristics at 15 kHz.

models at 15, 25, and 40 kHz and that calculated by the electrical-thermal-frequency life model are very close within the experimental and statistical errors. This indicates the capability of the newly developed electrical-thermal-frequency life model in estimating the lifetime of magnet wire insulation over wide ranges of voltages, temperatures, and pulsating frequencies. This can also be shown in Figs. 3-6.

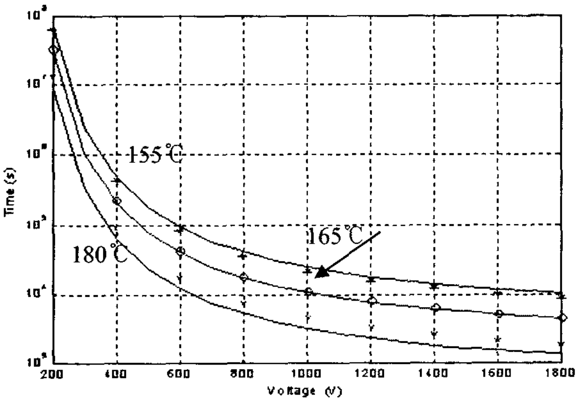

Fig. 4 Encapsulated Magnet Wire V-t Characteristics at 25 kHz.

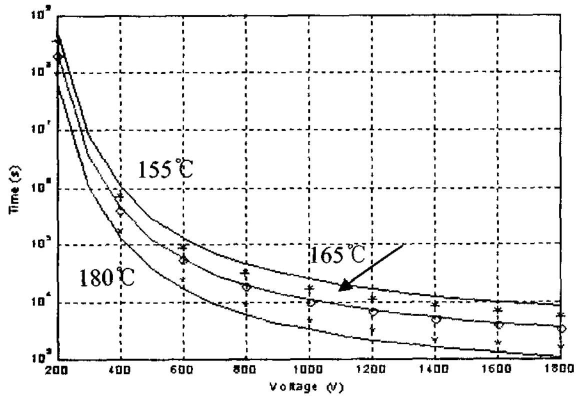

Fig. 5 Encapsulated Magnet Wire V-t Characteristics at 40 kHz.

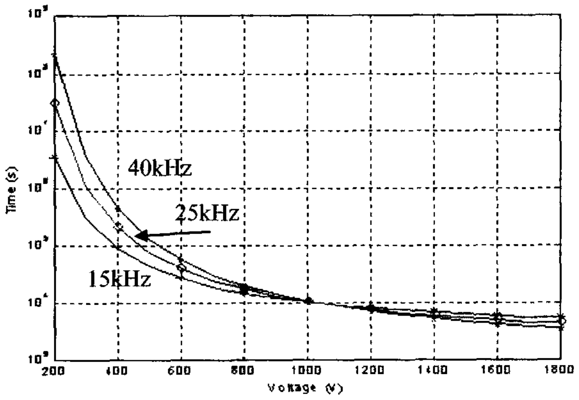

Fig. 6 Encapsulated Magnet Wire V-t Characteristics at 165°C.

7. Conclusion

Two probabilistic multistress life models were developed for epoxy encapsulated fine gauge magnet wire under high frequency pulsating voltages and high temperatures. An electrical-thermal relationship was combined to the Weibull probability distribution function. The parameters of the developed model were estimated using maximum likelihood estimation. Likewise, another generalized electrical thermal-frequency model was developed using multiple linear regression. It was found in this paper that the lifetime estimates of the electrical-thermal-frequency life model are very close to those estimated by the electrical-thermal models over a wide range of voltages, temperatures and pulsating frequencies.

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