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Two Factors Failure Model of Oil-Paper Insulation Aging under Electrical and Thermal Multistress

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Abstract – Converter transformers play important roles in high-voltage direct current transmission systems. This paper presents experimental and analysis results of the combined electrical and thermal aging of oil-impregnated paper at pulsating DC voltages. Breakdown voltages and time-to-breakdown of oil-paper specimens were measured by using short-time and constant-stress tests. The breakdown characteristics of combined electrical and thermal aging on insulation system were discussed. According to the relationship between failure time and aging temperature, the two-parameter Weibull model was improved. On the basis of the competing risk algorithm and the improved Weibull model, the two factors failure model was calculated. And the influence of temperature in the insulation system has been analyzed. This model performs better than the two-parameter Weibull model when both time and temperature are considered as variables in estimating the lifetime of oil-paper insulation.

Keywords: Converter transformer, Oil-paper insulation, Combined electrical and thermal aging, Pulsating DC voltages, Two factors failure model

1. Introduction

The oil-paper insulation is widely used in oil-filled converter transformers for both traditional and new energies [1, 2]. The insulation of windings connected with converter valves have to withstand AC, DC and strong harmonic voltages in converter transformers [3]. Harmonic voltages originate from repetitive impulse voltages generated by valves when they are switched on and off. The failure probability of converter transformers is about twice as that of transformers for AC power transmission. Insulation failures of valve-connected windings account for about 50% of the total faults of converter transformers [4].

Electrical aging of oil-paper insulation under AC and DC combined voltages has been studied for about two decades. Previous studies investigated the breakdown properties of oil-impregnated paper at pulsating DC voltages with different magnitude ratios of DC to AC voltages [5]. Reference [6] presented electrical breakdown strength of oil-paper insulation under pulsating voltages, which consisted of AC, DC, and impulse voltages. The failure probability of insulation materials was presented under the electrical breakdown tests [7]. Using the Weibull distribution for oil-immersed transformers, the aging effect on insulation reliability was evaluated [8]. The Weibull distribution of oil-immersed insulation systems in power transformers was discussed [9], [10]. The new model includes the Weibull distribution was established by using a three-parameter lifetime distribution [11]. The lifetime distribution were described by modeling of bathtub shape function [12]. In addition, the independent Weibull competing risk model was discussed under accelerated life test [13]. The incomplete data was analyzed by using Weibull competing risk model [14]. Publication [15, 16] have involved on study of n-fold Weibull competing risk model. Furthermore, failure evaluation model of oil-paper insulation under AC-DC combined voltages was established by using Weibull distribution [17].

This paper presents experimental and analysis results of the combined electrical and thermal aging stress of oil-impregnated paper at pulsating DC voltages. The breakdown strengths of specimens were obtained by using short-time tests. Constant-stress tests at pulsating DC voltages determined the two-parameter Weibull distribution and improved failure model. The breakdown characteristics of pulsating DC voltages on insulation system were discussed and the temperature component behavior in the insulation system was analyzed. Based on the two factors competing risk algorithm and the parameters of Weibull model, the two factors failure model was established and calculated. This model shows the influence of temperature on the failure probability of specimens. And it optimizes traditional two-parameter Weibull distribution when both time and temperature are considered as variables in estimating the lifetime of oil-impregnated paper insulation.

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2. Experiments

For converter transformers, voltages across winding-to-ground insulation containing components of DC and AC voltages were determined, as shown in Fig. 1. Windings of delta-connected single-phase transformers withstand pulsating DC voltages with a magnitude ratio of DC to AC peak values equal to 1:1. The pulsating DC voltages across the windings in wye-connected single-phase transformers consist of AC and DC components with a magnitude ratio of DC to AC peak values equal to 3:1 [3].

Fig. 2 indicates the experimental setup for the electrical aging of oil-impregnated paper. A 50 kV DC source and a 50 kV AC source are connected in parallel with the oil tank placed between and around the HV lead of the sources. Digital oscilloscope is LeCroy WaveRunner44Mxi. The oil tank is parallel with the resistor divider that records applied voltage in real time and the divider ratio is 1:1000. During tests, DC and AC voltages were changed in 500 V intervals, and synchronization was increased using the regulating transformer. Both voltages were increased from zero until breakdown. To ensure that the cause of breakdown was always a voltage that was increasing at a constant rate. The signal detection system is consisted of high voltage probe, oscilloscope and computer for real-time monitoring voltage signal.

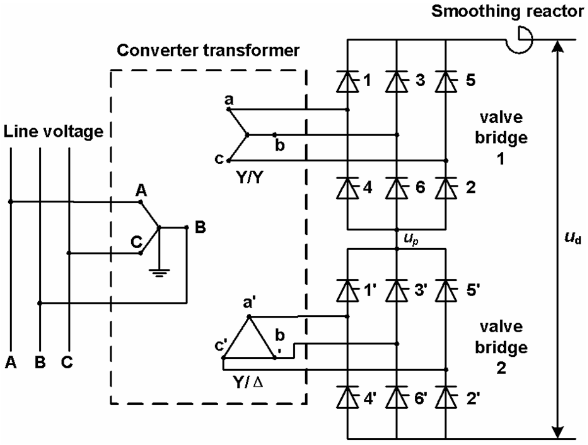


Fig. 1. 12-pulse monopolar converter valve bridge

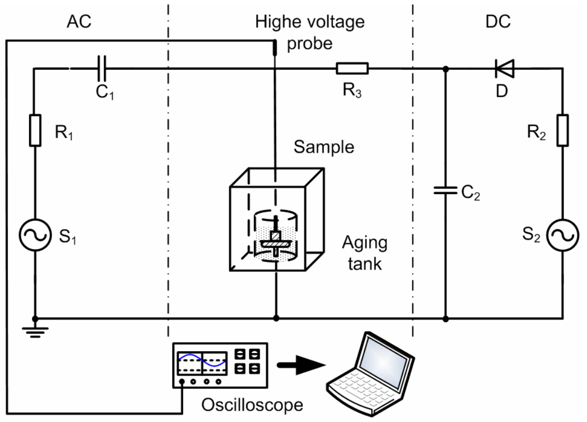


Fig. 2. Experimental system on site

The insulation paper had a diameter and thickness of 80 mm and 0.2 mm, respectively. Insulation paper was dried in vacuum of 50 Pa at 90°C for 48 hours, and then impregnated with transformer oils in vacuum of 50 Pa at 40°C for 48 hours. Karamay 25# transformer oils were used for oil impregnation, but first degassed in vacuum at 40°C. The drying process used in this study reduced water content in the paper to 0.4% weight, and water content in the oil down to 9 mg/kg, which was considered acceptable for the proposed test program. Well oil-impregnated paper insulation specimens were placed in a sealed glass vessel prior to their usage in the experiments.

The experimental system consisted of an oil tank and a rod-plate electrode system. As shown in Fig. 2, the electrode system was designed according to IEC 60243-1 [18]. During the experiments, the electrode system and oil-paper insulation specimens were completely immersed in transformer oils at room temperature. The upper electrode was columnar-shaped, with a diameter of 25 mm. The lower electrode was planar, with a diameter of 80 mm. Both electrodes are made of brass.

Fig. 3 shows the experimental setup for short-time and constant-stress tests. Testing voltages consist of AC voltage and DC voltage sources. Both voltages were supplied at the same time, and then pulsating voltages were applied. Figs. 4 and (1) define the ripple factor *RF* of the pulsating voltages. U_{ac} is the half of peak-to-peak amplitude of AC voltage and U_{dc} is the root mean square amplitude of DC voltage. The rising rates of peak values

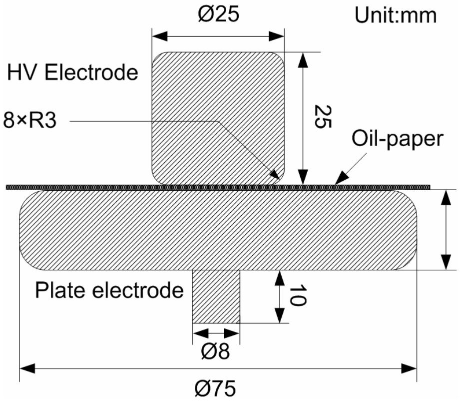


Fig. 3. Electrode system on site

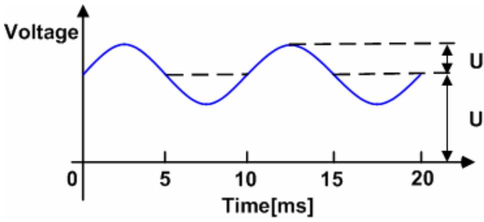


Fig. 4. Definition of ripple factor *RF*

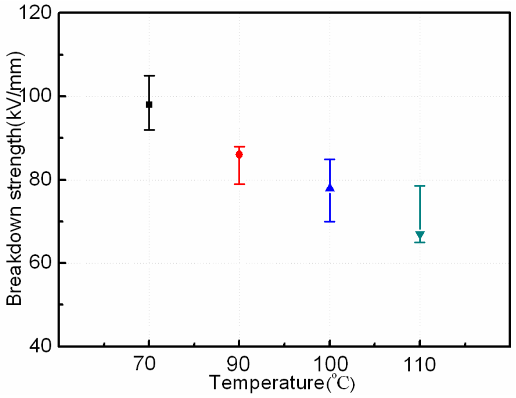


Fig. 5. Median, minimum, and maximum of breakdown strength of oil-paper insulation specimens at four temperatures

of testing voltages were controlled at 1000 V/s. During tests, DC and AC voltages of pulsating DC voltage was changed in 500 V/s intervals, the ripple factor is 1 and synchronization was increased using the regulating transformer. And the aging temperature is 70°C, 90°C, 100°C and 110°C.

$$RF = \frac{U_{ac}}{U_{dc}} \tag{1}$$

DC voltages with positive polarities were used for both short-time and constant-stress tests. Ten oil-paper insulation specimens were prepared for five short-time tests. Median of breakdown voltages of the five oil-paper insulation specimens was considered as their breakdown voltages. More details of short-time tests are in IEC 60243-1 [18]. In the constant-stress tests, voltages used on oil-paper insulation specimens did not exceed the median. And a number of identical specimens were subjected to identical test regimes to cause breakdown. More detailed descriptions of constant-stress tests can be found in references [19, 20]. Over 36 oil-paper insulation specimens were used for experiments with four aging temperatures and the same ripple factor. Therefore, 36 data were obtained.

3. Breakdown Voltage of Oil-paper Insulation

Fig. 5 presents the breakdown strength of oil-paper insulation at four temperatures. The breakdown strength of specimen decreases as the temperature increases. The maximum, minimum, and median breakdown strengths of oil-paper insulation specimens are 15.7kV, 13.8 kV and 13.4kV at 110°C. Test results deviated by less than 15% from the median. Then, the voltage of constant-stress tests is 11 kV.

4. Weibull Distribution of Constant-stress Test Data

Weibull distribution is a popular method used to describe the distribution of time-to-breakdown in constant-stress tests. Failure probability of lifetime of an oil-paper specimen is calculated using two-parameter Weibull distribution for time-to-breakdown, which is shown as follows：

$$F(t) = 1 - e^{-(t/\alpha)^{\beta}}, \quad t > 0 \tag{2}$$

In (2), t is the time to breakdown of an oil-paper specimen. $F(t)$ is the probability of failure at time t. For tests with large numbers of specimens, $F(t)$ is approximately the proportion of specimens broken down by time, where α is the scale parameter and β is the shape parameter. Both α and β are positive. Scale parameter α represents the time when failure probability is 0.632. Shape parameter β is a measure of the spread of failure times of oil-paper specimens. The bathtub curve for different values of shape parameters β indicates the failure condition of specimens in constant-stress tests. Failure rate decreases when $\beta < 1$, and failure rate increases when $\beta > 1$. When $\beta = 1$, an exponential distribution with a constant failure rate is obtained. Table 3 shows the shape parameter β results in tests when β is above 1. As shown in Fig. 6, test results present a wear-out failure.

Parameters of weibull plots of aging specimens at four temperatures were calculated using the maximum likelihood estimation. Table 1 indicates the calculation results. Fig. 7 shows weibull plots of failure probability to failure time obtained from constant-stress tests.

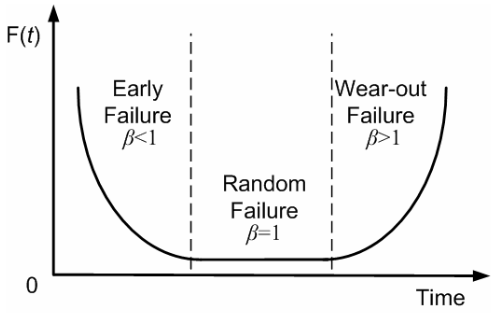


Fig. 6. Bathtub curve for different values of shape parameters β

Table 1. Scale and shape parameters of weibull plots of failure probability to failure time

Temperature(℃)	Weibull Parameter	
	α	β
110	242.48	2.64
100	506.56	2.65
90	781.80	4.34
70	1676	5.13

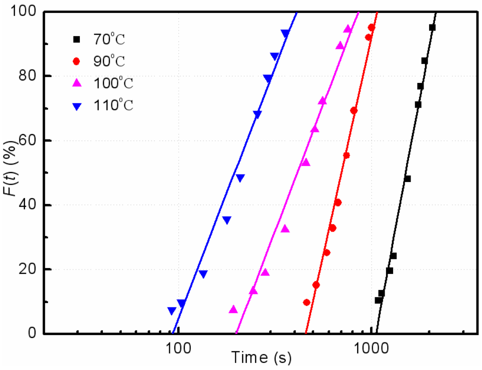


Fig. 7. Weibull probability of failure time at four temperatures

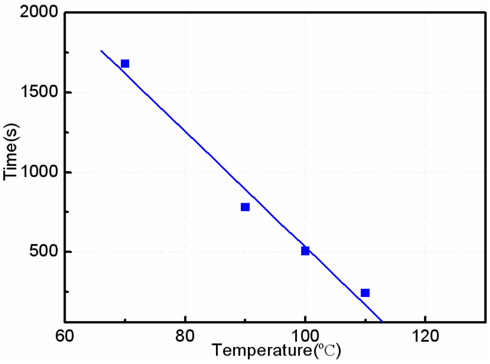


Fig. 8. 63.2% failure time of oil paper insulation at four temperatures

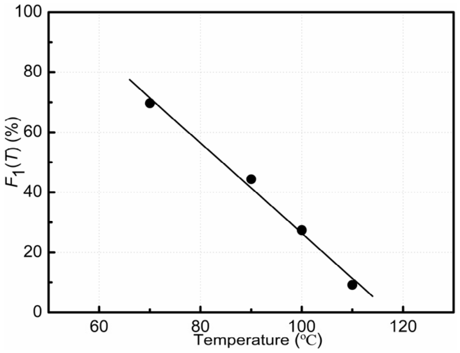


Fig. 9. Weibull failure probability of temperature

As shown in Fig. 7, the plots of failure probability of failure time which is lifetime of oil-paper insulation specimens at pulsating DC voltages are almost parallel. Therefore, the plots have same variation trends in the same failure model. And the probability of failure time of samples is similar at same failure stage when temperature increases. But the results of $F(t)$ could not show relationship between the failure probability of temperature and aging temperatures.

5. Two Factors Failure Models Based on Competing Risks

5.1 Improved failure model of aging specimens

According to ANSI/IEEE 930, x is the probability of failure at a voltage or time in the 2-parameter Weibull distribution function $F(x)$. The temperature could not be the parameter of this model which could show the failure probability of insulation. Figs. 8 shows the relationship between 63.2% failure time of oil paper insulation and aging temperatures from the calculation results in Table 1. Parameters of plot are calculated using linear regression curve fitting method. The fitting equation is t =3891.8-33.49×T and the goodness of fit of failure model is 0.9942. The aging temperature is almost the inverse proportion of failure time.

According to (2) and fitting equation, the improved failure model could show the relationship between the probability of failure and aging temperatures. We define it is $F_1(T)$ to distinguish with two-parameter Weibull distribution function $F(x)$ and it is as fellows.

$$F_1\left(T\right)=1-e^{-(3891.8-33.49*T/1342.2)^{1.25}},\quad T>0 \tag{3}$$

In (3), the improved failure $F_1(T)$ is the probability of failure at temperature and T is aging temperature at constant-stress tests. The parameters of $F_1(T)$ were calculated using the maximum likelihood estimation, α = 1342.2 and β = 1.25. The β equal to 1.25 and it presents a wear-out failure.

As shown in Fig. 9, the failure probability of temperature $F_1(T)$ is almost the inverse proportion of aging temperature. And it is not logical. The increased aging temperature could accelerate the aging progress and increase the failure probability of oil-paper insulation. Therefore, this model could not show the real relationship between the failure probability of temperature and aging temperatures.

5.2 Competing risk model of specimens

A specimen is exposed to the known types of failures or risks such as thermal aging and electrical aging. The specimen lifetime is found to be the time to failure of a series system with n-independent parts, where a part represents risk with failure time for thermal aging. In the competing risk model, the life of a series system is determined by the shortest of the component lives. This model can be used to show the failure distribution of an item where the failure can be caused by one of n-independent causes. The competing risk model is also called compound model, series system model, and multi-risk model in related literature. For a general n-fold competing risk model, distribution function $F(x)$ is indicated as follows:

$$F\left(x\right)=1-\prod_{i=1}^{n}\left[1-F_i\left(x\right)\right] \tag{4}$$

$$F_i\left(x\right)=1-e^{-\left(x/\alpha_i\right)^{\beta_i}},x>0 \tag{5}$$

where $F_i(x)$ is expression of the probability distribution functions for two-parameter Weibull distribution, i = 1, 2,.., n.

Eq. (4) is an n-fold Weibull competing risk model with n subpopulations, where α_i is the shape parameter and β_i is the scale parameter. Units of α is the same as x, such as voltage, electric stress, time, and number of cycles to failure. Shape parameter β is a measure of range of the failure times or voltages. The larger β is, the smaller is the range of breakdown voltages or times.

5.3 Two factors failure models of oil-paper insulation specimens

According to ANSI/IEEE 930, x is the probability of failure at a voltage or time in the 2-parameter Weibull distribution function $F(x)$. And it is less than or equal to t. Lifetime and breakdown strength are important factors for determining the failure probability of oil-paper insulation. Based on the improved failure model $F_1(T)$, we assume that both time and temperature are variable. The principle of two factors failure model is similar with Weibull competing risk model. The details of the two factors failure model are as follows:

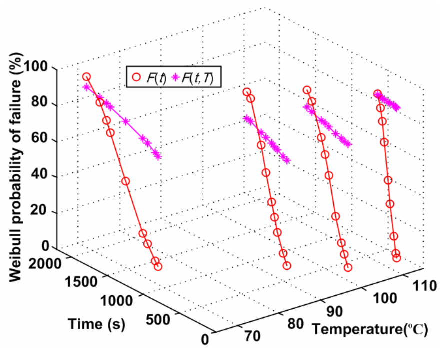
$$F_1(T)=1-e^{-(3891.8-33.49*T/1342.2)^{1.25}} \tag{6}$$

$$F(t)=1-e^{-(t/800.62)^{1.38}},t>0 \tag{7}$$

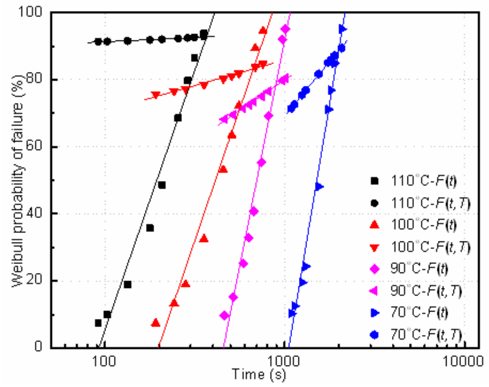
$$F(t,T)=1-F_1(T)*[1-F(t)] \tag{8}$$

The competing risk model could not illustrate the failure probability of temperature directly. However, the two factors failure model indicates the relationship between times, temperature, and failure probability of insulation. Parameters of probability of failure at time t and temperature T were respectively calculated using the maximum likelihood estimation. $F_1(T)$ and $F(t)$ are calculated using two-parameter Weibull distribution. Thirty-six sample points were chosen from the lifetime of specimens at pulsating DC voltages under four temperatures for comparison analysis. Fig. 10 presents the results.

As shown in Fig. 10, $F(t)$ is the probability of failure at time t. $F(t,\ T)$ shows the probability of failure at temperatures and T is aging temperature at constant-stress tests. Parameters are estimated using maximum likelihood estimation. Fig.10 (a) shows curves of $F(t)$ indicate that the plots of failure probability of time which is lifetime of oil-paper insulation specimens under four temperatures have same variation trends. And the failure probability of time is similar at same failure stage. The results of $F(t)$ could not show the influence of increased aging temperature which could accelerate the aging progress and increase the failure probability of oil-paper insulation. Therefore, this model does not show the actual failure probability of insulation. It also shows the curves of failure probability of specimens $F(t,\ T)$ are almost parallel.



(a)



(b)

Fig. 10. Weibull probability of insulation at pulsating DC voltages: (a) Weibull probability of failure model and two factors model; (b) $F(t)$ and $F\ (t,\ T)$ versus time

The two factors failure model $F(t,\ T)$ is the failure probability of time and temperature. Fig. 10 (b) shows curves of the two factors failure model $F(t,\ T)$ indicate that the failure probability of specimens increased with higher temperature. And the calculated result is higher than result of $F(t)$ at same failure time. This model shows the influence of temperature on the failure probability of specimens. The two factors failure model optimizes traditional two-parameter Weibull distribution and remedy it fault. In addition, a greater actual failure probability of insulation and true aging tradition of specimens are obtained. Then, it is beneficial to increase the evaluation accuracy of the insulation condition.

6. Conclusion

This paper presents experimental and analysis results of the combined electrical and thermal aging of oil-impregnated paper at pulsating DC voltages. Short-time and constant-stress tests were used for the oil-paper insulation specimens. To estimate the lifetime of oil-paper insulation, the competing risk algorithm was used to improve the two-parameter Weibull model. The results of research are as follows:

The breakdown strength of oil-paper specimen decreases as the temperature increases at pulsating DC voltages. When the temperature decreases, oil-paper insulation fails more difficult at the same stage. The curves of $F(t)$ indicate that the failure probability of time have same variation trends at four temperatures. And these are similar at same failure stage when the temperature increases. Therefore, the results of $F(t)$ could not show relationship between the failure probability of temperature and aging temperatures.

Based on the relationship between failure time and aging temperature, the two-parameter Weibull model was improved. The results of improved failure model $F_1(T)$ are almost the inverse proportion of aging temperature. So, it also could not show the influence of increased aging temperature on oil-paper insulation.

The two factors failure model $F(t, T)$ shows the relationship between times, temperature, and failure probability of oil-paper insulation. Failure probability of oil-paper insulation increases with the increased lifetime and temperature. The two factors failure model can show the influence of temperature on the failure probability of specimens, and optimizes traditional two-parameter Weibull distribution. This model indicates more actual failure probabilities of combined electrical and thermal aging of oil-paper insulations.

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