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DC And AC Aging Of HV Encapsulated Flyback Transformers

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Abstract:- This paper presents the result of accelerated aging tests under AC, DC and DC-AC superimposed voltages on high voltage encapsulated transformers of multi-layer insulation system. The paper aims to find a mathematical model to estimate the lifetime of the insulation when exposed to AC and DC voltages. The statistical distribution of times-to-breakdown were presented by Weibull probability distribution, and related to the test aging voltage by the inverse power law model. The arbitrary constants of the combined Weibull-inverse power law model were evaluated using maximum likelihood estimation. It was found in this study that aging of the insulation system at AC voltage is mainly caused by dielectric losses and partial discharges in the voids in the bulk of the insulation, whereas at DC voltage insulation the failure is attributed to thermal breakdown. It was also found that the presence of small AC voltage component superimposed on DC high voltage accelerates the aging process very significantly and causes insulation failure in very short time.

Key-Words:- Accelerated insulation aging, lifetime characteristics, Weibull distribution, HV measurement

1 Introduction

Polymer materials are currently used as electrical insulation in many high voltage electrical and electronics applications for their excellent electrical, thermal and mechanical properties. Examples of such applications include cables, X-ray equipments, TV sets, computer monitors, sensors and encapsulated transformers. In these applications the insulation is not only stressed by DC voltage, but AC ripples are superimposed on the DC voltage. Therefore, it is necessary to understand the aging behavior of the electrical insulation under AC, DC and DC-AC superimposed voltages.

Accelerated aging tests of insulation material are performed in order to assess the quality of the insulation and predict its lifetime under normal operating conditions. Electrical aging is accomplished by testing the insulation (specimen or device) using high electrical stress levels for either short periods (few seconds or minutes) or long periods (few hours or days). The accelerated test data are then considered as a base for extrapolation to obtain an estimate of the lifetime of the insulation when the device or material is operated at normal (low) operating conditions for relatively long time periods (decades) of years [1-6].

The statistical distribution of the times-to-breakdown is presented by Weibull probability distribution. The time-to-breakdown is related to the test aging voltage by the inverse power law model (IPL). The lifetime function can be extrapolated to give an estimate of lifetimes at working voltages far smaller than those used in aging. The parameters of the combined Weibull-IPL can be estimated using maximum likelihood estimation (MLE) [7-10].

In this paper, the aging behavior of multi-layer high voltage encapsulated transformer under AC, DC and DC-AC superimposed voltages and at room temperature is studied. The coils of the transformer under study are wound with many layers of fine gauge magnet wire (MW), wound on polyester bobbins, impregnated with epoxy and encapsulated with polyester compound as shown in Fig.1 [11,12].

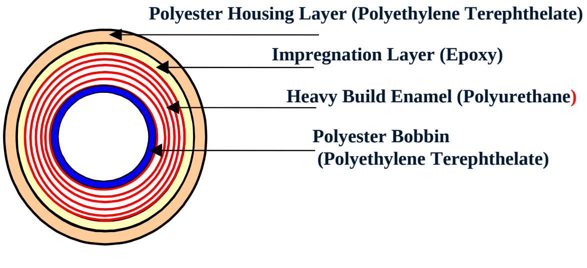

Fig.1: Insulation of encapsulated transformer

2 ELECTRICAL AGING MODELS

Electrical stress is considered as one of the main factors causing deterioration of electrical insulation. The inverse power law model is an empirical model that commonly used to relate the electrical stress to the time-to-breakdown as given in (1) [1,2],

$$L(V) = k\,V^{-n} \tag{1}$$

where L is the time-to-breakdown in hours, usually it is a Weibull scale parameter α at 63.2% probability, or any other percentile, V is the applied voltage in volts, and k, n, are constants to be determined for the specific tested material or device. The inverse power law is considered valid, if the data being plotted on log-log graph fits a straight line.

3 Combined Weibull-IPL Model

The Weibull distribution has been widely accepted to describe the statistical behavior of solid dielectric insulation with respect to failure under constant voltage test on electrical insulation [7-10]. For accelerated aging analysis, the two-parameter Weibull probability density function (*pdf*) is commonly used

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

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. The parameters of the aging model can be calculated by combining the proposed aging model to the Weibull *pdf*. For the IPL aging model, the combined Weibull-IPL *pdf* can be derived by setting the scale parameter $\alpha = L(V)$ in (1) and substituting in (2). The combined Weibull -IPL *pdf* is given by:

$$f(t,V) = \beta\left(\frac{V^n}{k}\right)\left(\frac{V^n}{k}t\right)^{\beta-1} \exp\left[-\left(\frac{V^n}{k}t\right)^{\beta}\right] \tag{3}$$

For m aging tests with N independent failure times t_1, t_2,…, t_N, the likelihood function associated with these failure times is the joint density function of the N random failure times. The logarithmic likelihood functions for complete data are given by:

$$\Lambda = \ln L = \sum_{i=1}^{N} \ln\, f(t_i;\beta,k,n) \tag{4}$$

The maximum likelihood estimates of β, k, and n are obtained by maximizing Λ. The maximum likelihood estimates of β, k, and n are the simultaneous solutions of three equations such that:

$$\frac{\partial\Lambda}{\partial\beta} = 0,\quad \frac{\partial\Lambda}{\partial k} = 0,\quad \frac{\partial\Lambda}{\partial n} = 0 \tag{5}$$

Since the shape parameter β varies at each stress level (even though it is assumed constant) due to sampling error, etc. the MLE gives a common shape parameter β.

4 Test Procedures And Setup

A schematic diagram of the aging setup is shown in Fig.2. In the aging test 20 transformers were aged simultaneously at constant voltage (AC or DC) until breakdown. The high voltage (HV) source is connected to one electrode, while the other electrode is grounded. The ground electrode is obtained by painting the surface of the plastic cup by copper conducting paint. The tested samples were immersed in transformer oil to avoid surface flashover or partial discharges.

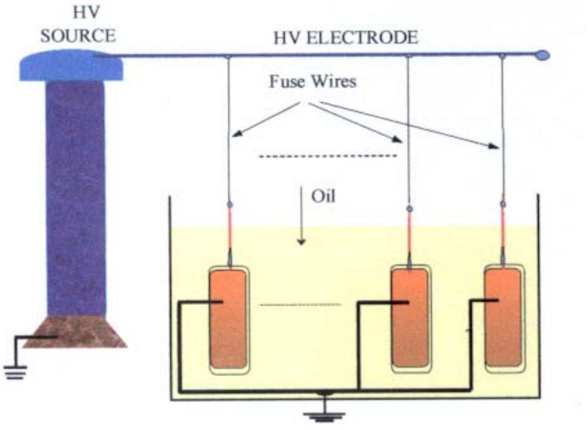

Fig.2: AC/DC aging setup

5 Experimental Results

The experimental results of the aging tests on the encapsulated transformers at AC, DC and DC-AC superimposed voltages are presented in this section.

5.1 Accelerated Aging under AC Voltage

Four aging tests at 30 kV, 25 kV, 20 kV, and 15 kV AC voltages were conducted on the samples. The aging AC voltage was kept constant until all samples are broken-down. Weibull probability distributions of the breakdown times at the above voltages are shown in Fig.3.

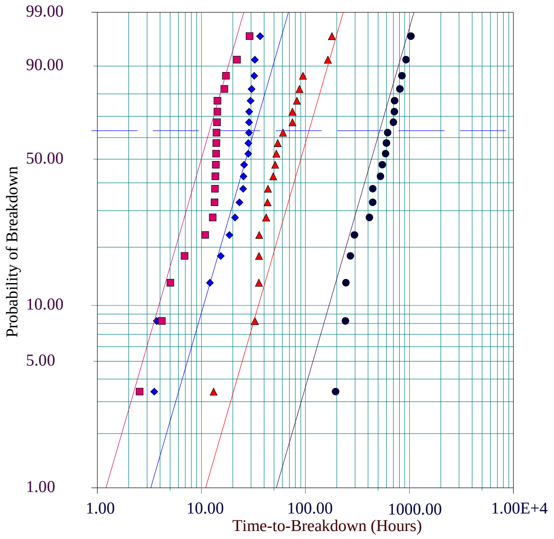

Fig.3: Weibull probability distribution under AC voltage, β=2.01, 30 kV, 25 kV, 20 kV, 15 kV

5.2 Accelerated Aging under DC Voltage

Likewise, four aging tests were conducted at 90, 80, 70, and 60 kV DC voltage using the setup shown in Fig.2. Twenty units of encapsulated transformers were used in each aging test. The results of the aging test are presented by the Weibull probability distribution as shown in Fig. 4.

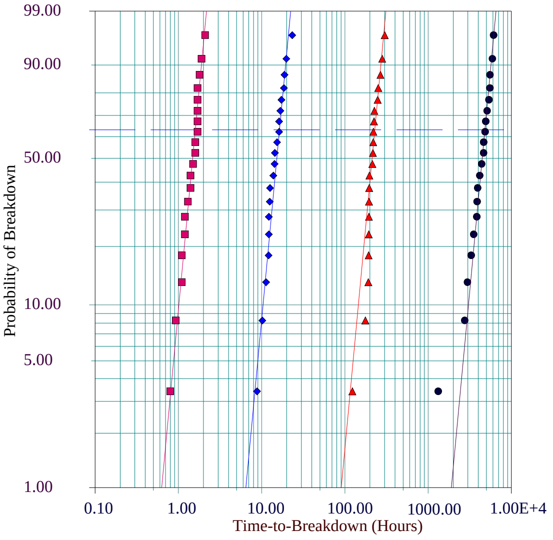

Fig.4: Weibull probability distribution under DC voltage, β=4.95, 90 kV, 80 kV, 70 kV, 60 kV

The electrical inverse power law model was used in combination with the Weibull probability distribution to fit the failure data. The parameters of the combined Weibull-IPL model were estimated using MLE. The estimates of the parameters of the AC and DC aging models are given in Table 1.

Table 1: Parameters of Weibull-IPL aging model

Aging Voltage	Weibull-Inverse Power Law Parameters		
	β	k	n
AC Voltage	2.01	1.28×10^{9}	4.9
DC Voltage	0.810	6.31×10^{38}	19.7

The lifetime characteristics of the multi-layer insulation of the encapsulated transformer at AC and DC voltage are shown in Fig.5. It can be seen in Fig.5 that the insulation system exhibits two different lifetime characteristics at AC and DC voltages. This is attributed to the prevailing mechanism of breakdown. Under AC voltage, the breakdown of the insulation is referred to thermal breakdown caused by excessive dielectric heat losses that increase with the applied voltage. In addition, the partial discharges in the voids cause erosions of in the insulation bulk and thus reduce the dielectric strength of the insulation.

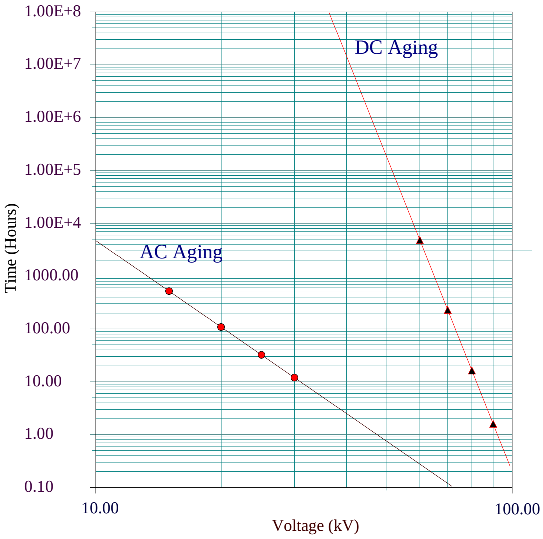

Fig.5: Lifetime characteristics under AC and DC voltages

Similarly, under DC voltage the breakdown is also thermal. The heat losses generated by the Ohmic losses of the insulation resistance increase the conductivity of the insulation, and consequently reduce the dielectric strength. However, this is a slow process, therefore aging at DC voltage is much slower than that at AC voltage even at higher voltages.

5.3 Accelerated Aging under Superimposed DC-AC Voltages

To study the effect of the pulsating voltage (ripples) that appear on the generated DC voltage, an accelerated aging test was conducted at combined AC and DC voltage. In this aging test, the HV DC source was connected to the HV electrode, whereas the HV AC source was connected to the other conducting electrode as shown in Fig.6. The rms value of the AC voltage was set at 10 % of the DC voltage. The results of aging tests a 70 kVDC-7 kV AC and 60 kVDC-6 kVAC are shown in Fig.7.

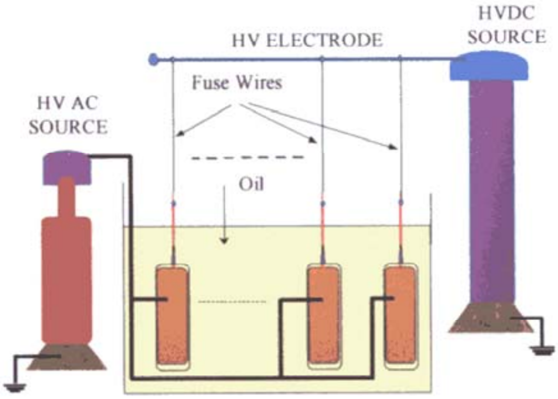

Fig.6: DC-AC superimposed aging setup

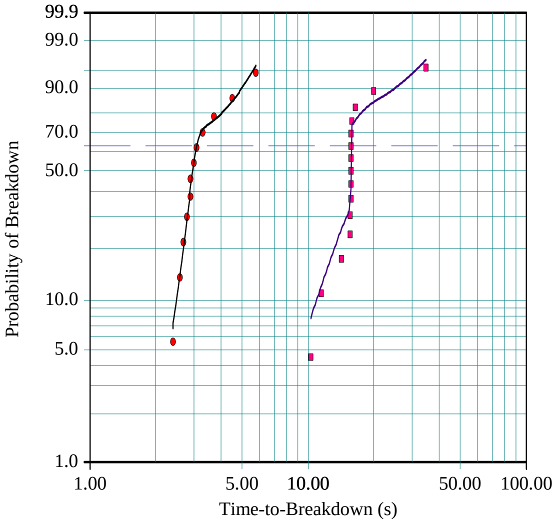

Fig.7: Weibull probability distribution under DC-AC voltage, 70 kV DC-7kV AC

Comparing the results of Fig.4 and Fig.7, one can see that the presence of even small AC voltage superimposed on the DC voltage resulted in failure of the tested samples in very short time. The pulsating voltage accelerates the mechanism of breakdown by activating partial discharges in gas voids in and producing more dielectric losses that deteriorate the insulation life rapidly. One can also observe that such condition yield to multi-failure modes produced by more than one mechanism of breakdown.

6 Conclusion

Accelerated aging tests were conduced on HV encapsulated transformers used for electronic applications. The tests were conducted under AC, DC and DC-AC superimposed voltages. The objective of the study was to study the aging behavior of the insulation system of the encapsulated transformers and develop electrical aging model to predict the lifetime of the insulation at normal operating conditions.

The study shows that insulation aging under AC voltage is much faster than that under DC voltage. This is attributed to the excessive heat produced by dielectric losses and partial discharges in the micro voids. However, under DC voltage the aging process is slow and breakdown results from the reduction of the insulation resistivity due to Ohmic losses. The study also shows that the presence of ripples, pulsating voltages superimposed on the DC voltage would very much accelerates the deterioration of the insulation yielding to very short lifetime.

Lifetime modeling of the insulation system, under AC and DC conditions, by combining the Weibull distribution and the aging model shows the possibility of modeling the lifetime using the inverse power law model. The parameters of the combined Weibull-inverse power law model were estimated using maximum likelihood estimation method.

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