ESTIMATION OF RESIDUAL LIFE IN ELECTRICAL INSULATION

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INTRODUCTION

In the recent past, many attempts have been made for designing optimal stresses on electrical insulation for long service lives. The more important, but not fully understood concept is the aspect of remaining life or the residual life, as it is usually called. Prediction of residual life requires considerable knowledge of the processes leading to insulation degradation. The remaining life or the integrity of insulation at any point in time can be determined by destructive test methods and to a lesser degree of accuracy using diagnostic methods (non destructive methods). The diagnostic tools employed in characterizing insulation degradation may be either loss tangent tip-up ($\Delta \tan \delta$) or any partial discharge quantity, like the total charge transfer, quadratic rate, partial discharge magnitude or discharge energy per cycle. It is imperative that the remaining life of apparatus insulation can be estimated using only diagnostic properties. But the accuracy of estimation would be very poor unless a correlation between destructive and diagnostic property is established and later confirmed with experimental evidence.

Unfortunately, it is found to be very difficult to establish such correlations because of the fact that for most insulation the scatter involved in the experimental results of the diagnostic properties with time are very large. A series of ageing experiments conducted on epoxy bonded mica tape (Class F insulation) in this laboratory revealed that if experiments are conducted very carefully on identical specimens it is possible to connect the reduction in dielectric strength as a function of ageing time with $\Delta \tan \delta$ and discharge energy per cycle. In analyzing the insulation failure data, the Inverse Power Law Model (IPM) is considered applicable. Wolff (1) has suggested that the remaining life of Polyethylene Cable could be estimated based on the critical loss tangent increase. It has been observed that increase in loss tangent cannot be used directly as an index of degradation because of very poor reproducibility of results. On the other hand, the loss tangent tip-up considered by Kelen (2) defined as

$$\Delta \tan \delta = \tan \delta_{1.5U} - \tan \delta_U \qquad \ldots \quad (1)$$

where U is the rated voltage or stress, appears to be more meaningful. Accordingly, the present approach envisages correlating this property with reduction in breakdown voltage (dielectric strength) for arriving at the failure criterion.

EXPERIMENTAL

Figure 1 shows the specimen geometry used in the series of experiments. Epoxy bonded mica tape of width 15 mm and thickness 50 μm is wound tightly over aluminium conductors of cross section 25 x 12.5 mm. The edges of the coductors are rounded smooth to reduce the stress concentration. The tape insulation is wound with an overlap of 5mm. The total thickness of the insulation was between 2 and 2.5 mm. The epoxy insulation is cured by subjecting it to the temperature and compression as specified by the manufacturer of the tape. The ends of the conductors are enclosed by tightly fitting aluminium shields having a curvature shown in the figure to suppress partial discharges (corona) from the ends of the conductor. Silver loaded epoxy paint was applied at the middle of the specimen to form the measuring and guard electrodes.

The loss tangent values were measured at rated and 1.5 times the rated voltage (rated stress is assumed to be 1.7 kV/mm) using model 2805 Tettex Transformer Ratio Bridge and a standard compressed SF_6 capacitor of 100 pF capacitance. The discharge energy per cycle was measured using a model-5 discharge detector and pulse height analyser (PHA) duly calibrated to read charge magnitudes over predetermined intervals of time (typically 15 to 30 sec).

A large number of identical specimens had to be used in the experiments so as to be able to acquire accurate data. About 50 specimens were put on ageing under electrical stress at a time. To fix the ageing stress, a few unaged specimens were subjected to power frequency alternating voltage and their breakdown voltages were measured. The stresses used are in terms of the acceleration factor, g, which is the ratio of stress applied during ageing to breakdown stress. The values of g used in the series of experiments were 0.24, 0.25 and 0.26, and were so chosen that all the specimens put on ageing at a particular stress, breakdown in a duration of about 3000 hours to yield complete data. An elapsed time indicator designed and developed in this laboratory was used to record the times to failure of the specimens. The characteristic (nominal) breakdown voltage for each sample packet was arrived at, by plotting the results on a Weibull paper and extracting the 63.2th percentile.

ANALYTICAL PROCEDURE

The time taken for the breakdown voltage to fall to 50% of its original value would be very long. It would be both expensive and time consuming an exercise to wait until such a condition is reached. To minimise this expenditure, therefore, it is necessary to work out an empirical expression involving curve fitting to the experimental data points. The expression so derived can later be used as a functional relationship between the property and time, to analytically arrive at the time to 50% U_d, the breakdown voltage.

The procedure involves conducting ageing experiments on several identical specimens under electric stress and studying the dyna-

mics of degradation in terms of reduction in breakdown voltage, increase in loss tangent tip-up and discharge energy per cycle. Repeated experimentation on mica epoxy resin components have shown that the characteristics mentioned above have considerable scatter. However, a polynomial of degree two can be fitted to the data by statistically minimising the vertical deviations, in the form

$$y = A+Bt+Ct^2 \qquad \ldots \quad (2)$$

where t is the ageing time and y is the value of any property at time t. The fitted curve should be compared to the corresponding points of the actual data and the goodness of fit should be established. The coefficients of correlation, r, between the destructive and non destructive properties mentioned should be very high. In the present work, r > 0.9. This is an important pre requisite for this analysis. It should be realised that, unless such a fitting is backed up by considerable experimentation and analysis, one would be reaching dangerous conclusions.

Figure 2 shows, to an arbitrary scale, the changes in properties mentioned above with respect to time. It was observed that the rate of fall of breakdown voltage was much higher than the rate at which the loss tangent tip up and discharge energy increase. Furthermore, since the breakdown voltage is a destructive property, which gives a very definite idea of the integrity of insulation at any point of time, this has been used as a reference index to denote the amount of ageing. The actual time to 50% reduction in breakdown voltage would be of little interest, because, this part of the characteristic would be very steep and it would be both hazardous and inaccurate to assign the degree of degradation in the property, in this region. A more meaningful way of characterizing the time to 50% fall in breakdown voltage would be to consider the point of intersection of .the tangents to the curve drawn at $U_d=U_{d0}$ and $U_d=U_{d0}/2$ as the actual time to failure. This means that the insulation system is deemed to have failed soon after the slope changes by a cognizable amount. This time τ (see Fig.2) has therefore been used as time to 50% U_d in the present work. In doing so, one would be arriving at a pessimistic estimate of life. This, however, should not be a cause for concern as the designs would be on the safer side.

For mica epoxy composite insulation it is possible to empirically represent the ;decrease in breakdown voltage as a function of increase in loss tangent tip-up thus:

$$U_d(t) = U_{d0} - \left| \frac{(\tan \delta(t) - \tan \delta(\tau))}{f} \right| \quad \ldots \quad (3)$$

where $U_d(t)$ is the value of the breakdown voltage at any time t. $\tan \delta(t)$ is the loss tangent tip up at time t. U_{d0} is the initial breakdown voltage. $\tan \delta(\tau)$ and f can be arrived at, by referring to Fig.2. f is the ratio of the slope of the tangent DE drawn to $\Delta \tan \delta$ vs. t curve to the slope of the tangent BC drawn to U_d vs. t curve and $\tan \delta(\tau)$ is the value of $\Delta \tan \delta$ at time t = τ.

The slopes of tangents are arrived at analytically using Eqn.(2) to retain higher degrees of accuracy. The Eq.(3) can therefore be regarded as a representation of the degree of ageing in terms of any non destruc-

tive property and with the assumption that 50% or less-loss in breakdown voltage is the end of life criterion.

Calculation of Remaining Life

The procedure described above should be repeated for each value of the stress applied during ageing. The 50% probable life could be estimated analytically.

Now the Inverse Power Law connecting the life and applied stress written as

$$L = Kg^{-n} \qquad \ldots \quad (4)$$

is applied to calculate the endurance coefficient n for the material. The constants K and n are independent of temperature and stress within reasonable limits. If L is the expected life, and L_e is the elapsed life, which is known, then the remaining life R is

$$R = L - L_e \qquad \ldots \quad (5)$$

In a practical situation (for epoxy bonded mica insulation structure) where initial value of loss tangent tip-up and p.d. energy per cycle are known, Eqn.(5) can be applied to evalute R, the remaining life by following changes in these properties and using the appropriate value of n.

RESULTS

On physical examination of the specimens put on ageing, it was observed that some of the failed units had developed irregular semi-conducting surface tracks, deep enough to be seen by naked eye. Such surface failures are also considered as complete breakdown. In specimens which failed due to complete dielectric breakdown, formation of minute tree-like channels were observed. Unfortunately, it was very difficult to produce good photograph of the trees. The changes with time of the breakdown voltage U_d, the discharge energy per cycle and the tan δ tip-up are shown for different stress factors in Fig.3. The points joined by a smooth curve of the type given by Eqn.(2) are fitted analytically. Also around this curve are shown the actual experimental points. Eliminating a few outliers, the experimental and analytical results are reasonably close to each other and hence pass the goodness-of-fit test. The Inverse Power Law plot (Fig.4) is markedly linear with a slope (n) of 5.3.

DISCUSSION

The premise for the method of estimation of remaining life presented here is that the epoxy bonded mica composite does not show a threshold stress and that the degradation characteristics are as shown in Fig.(2). This is in fact proved to be true based on the experiments conducted in this laboratory. However, for any other type of insulation, a similar approach could be used if, as pointed out earlier, it is possible to establish the necessary correlations between the destructive and non destructive properties.

The parameter f in Eqn.(3) is determined based on the slopes of the tangents drawn to the degradation characteristic corresponding to 50% loss in breakdown voltage. However, it is also possible to arrive at f on the basis of a specific increase in the loss tangent tip-up or discharge energy as the case may be, locating the corresponding point on the

breakdown voltage characteristic and then taking the ratio of the slopes of the tangents at these points to determine f. It is to be noted that the value of f determined using different failure criteria would necessarily be different and hence the estimated remaining life would also be different.

Using 50% loss of U_d as the end of life criterion, as an example, at a stress factor (g) equal to 0.25 (Ref.Fig.3(b)), when U_d reduces by 7% of its initial value, tan δ tip-up and discharge energy work out respectively to be 1.64 and 4.19 times their initial values. The calculated, life and remaining life for these values would be respectively 1989 and 3089 hours. It can be inferred that the calculated remaining life is close enough to the experimentally determined value within the accuracy of measurement. It has been observed that, over the time breakdown voltage reduces by 50%, nearly in all cases tan δ tip-up would have increased by a factor of about five compared to its initial value and the corresponding increase in discharge energy per cycle would be around twenty. Therefore in analysing the ageing data one might consider known increments in the initial values of ʌ tan δ and discharge energy per cycle as representing a definite reduction in breakdown voltage.

CONCLUSION

In conclusion, the work covered in this paper details a method of arriving at the remaining life of mica based epoxy insulation used in rotating machines based on diagnostic testing. The authors believe that it might be possible to extend this procedure to other types of dielectric systems as well, provided conditions explained in the paper are adhered to. Work in this direction is being carried out in the authors' laboratory.

REFERENCES

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2. Kelen, A., 'Ageing of insulating materials and equipment insulation in service and in tests', IEEE Trans. EI-12, No. 1, 55-60, Feb. 1977.
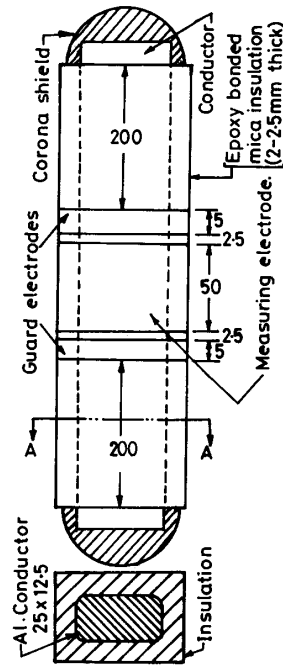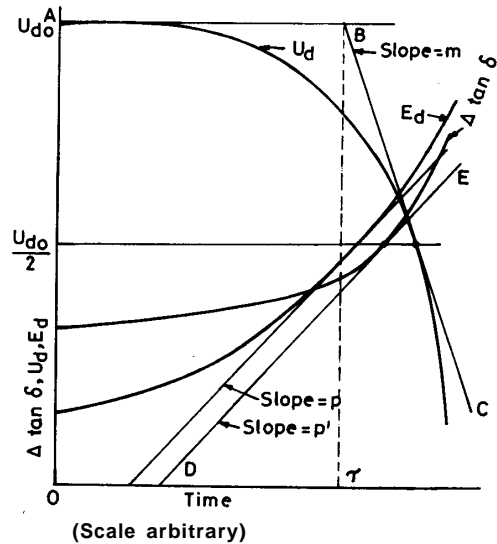
Fig. 1. Specimen geometry

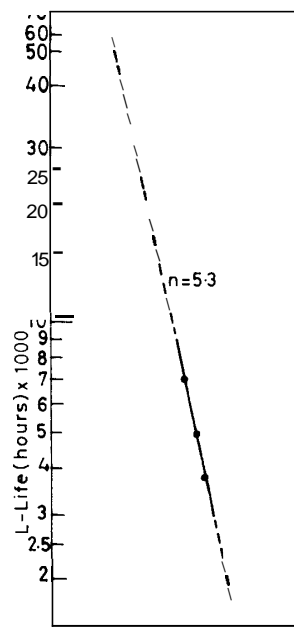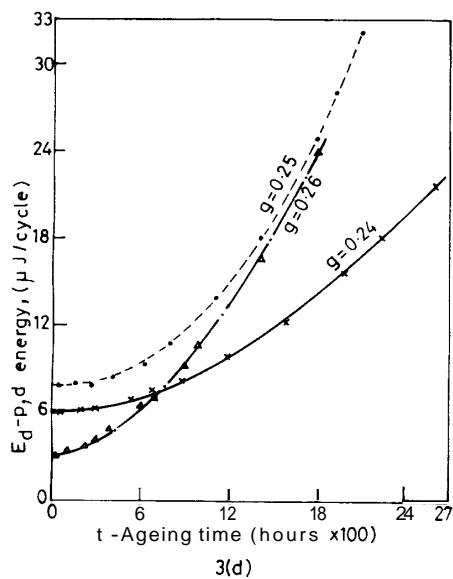Fig.2. Depiction of changes in insulating properties with time

3(a)

3(b)
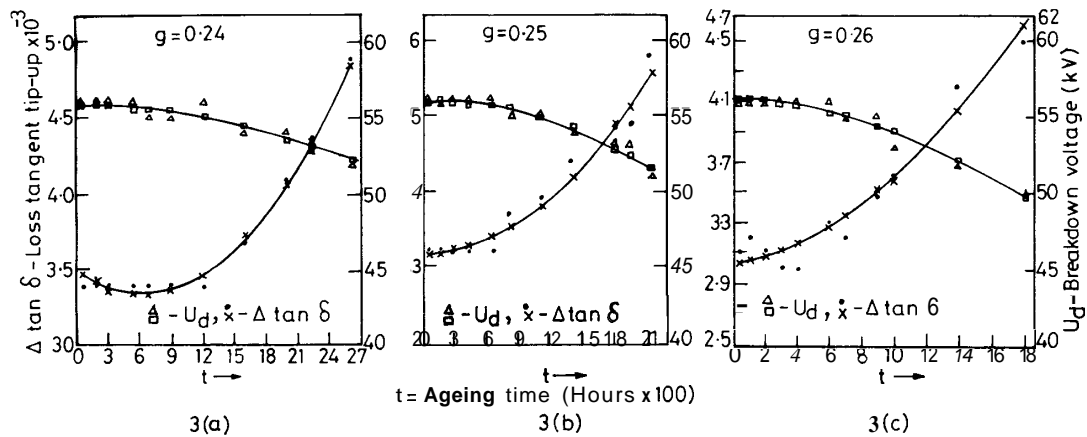
t = **Ageing** time (Hours x 100)

3(c)

3(d)

Fig. 3. Ageing behaviour of Epoxy bonded Mica
Insulation at different stress factors

Fiq.4. Inverse Power Law plot of Epoxy bonded
Mica Insulation