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DEGRADATION OF H.V. GENERATOR INSULATION UNDER MECHANICAL, ELECTRICAL AND THERMAL STRESSES

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ABSTRACT

The paper presents the results of ageing experiments under combined electrical, mechanical (vibration) and thermal stresses on epoxy bonded mica insulation. Actual 11 kV machine coils designed for use in 1 MW rotating machines are used as the specimens. Both diagnostic and destructive tests were carried out to assess the amount of ageing. It was observed that the incremental loss tangent and partial discharge energy per cycle increase monotonically with time of ageing and that the dielectric strength fell monotonically. thus indicating a high degree of correlation between these properties.

1. INTRODUCTION

Phenomenological models for insulation degradation under combined electrical and thermal stresses based on Eyring formalism was proposed by the author some time ago [1]. Similar models have also been proposed by Simoni [2]. In the study of degradation of rotating machine coils, particularly the region around the exit of the conductors from the stator frame, it is very necessary to consider a third stress in mechanical vibration of the overhang. The overhang vibration induces a time-varying stress at the coil fixity which can be treated as a fatigue. Therefore the most practical ageing condition would be to conduct ageing experiments when the vibration is combined with thermal and electrical stresses.

Over the past few months such experiments are being run in our laboratory on actual 11 kV machine coils insulated with epoxy-mica systems. To reduce the time factor in the ageing experiments, the degradation processes are accelerated by applying stresses of magnitudes higher than the rated levels. To acquire credible results it becomes necessary to generate truncated data by applying lower stresses and deliberately curtailing the experiments at a predetermined time. Several diagnostic and destructive properties have been monitored throughout the ageing period.

This paper details experimental methods under the combined stress conditions, results of diagnostic measurement and methods of data interpretation on a statistical basis.

2. THEORETICAL ASPECTS

Based on the physical mechanisms of failure under different stress conditions a functional relationship between the generalised stress S_i and time t to failure can be written as:

$$t = f(S_i | p_k) \qquad (1)$$

where p_k are the undefined constants. As applied to electrical insulation, one would be interested in expressing the time that elapses from the instant of application of stresses to the time at which the failure ensues. A generalised time stress model represented by Eq.(1) is quite complex, besides being practically unsuitable. Therefore, degenerate models involving known stresses have to be developed based on the relevant functional forms for each stress-time relations.

In an earlier work [1], the author has developed formal expressions for insulation life L(T,E) involving two stresses, electrical and thermal in the form:

$$L(T,E) = L_o \, \mathrm{Exp}(-B\bar{T}) \, \mathrm{Exp}[-(a-b\bar{T}).\lambda(E) \qquad (2)$$

where $\lambda(E)$ is an unknown function of electric stress, L_o is the life at room temparature and at an electric stress E_o, which is small, a, b and B are constants to be evaluated.

The ageing failure of rotating machine coils is greatly influenced by the existence of a third stress in mechanical vibration. The length of the coil overhang beyond the slot exit vibrates freely. The bottom and top layers of conductor insulation at the slot exit are subjected to alternating sinusoidal compression and tension. It was therefore thought to transform the vibration problem into an equivalent fatigue problem.

The failure of insulation has been assumed to be due to inception and propogation of fatigue cracks which are in turn widened by electrical tree-like channels and hence account for an eventual failure. It can be seen that, temparature, apart from serving as a secondary agent does not enter explicitly into the mechanical-electric stress life equation. Therefore, a heuristic model for ageing under combined electrical and vibrational stresses has been put forward based on Miner's [3] theorem with the following assumptions:

1. The flexing cycle in sinusoidal
2. Work done during every cycle is purely additive and is deemed to be responsible for eventual failure
3. The inception of a crack marks the beginning of a degradation process and the crack propogates to a critical level at which failure is deemed to have occurred.
4. A certain minimum amount of work must be done by the vibrational force against the elastic structure of the material in whatever way the force is applied.

It is possible to think that, discounting the possibility of work hardening of the material, (which usually gives rise to crystallinity in metals and thermosetting

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deformations in organic solids like epoxies) every cycle of vibration produces a finite non zero work which is absorbed by the material. If the critical work level is W and work done during every cycle is W_i, then;

$$\sum_i W_i/W = 1 \qquad (3)$$

Suppose the critical work is accumulated over N_w cycles and N_i are the number of cyclic stress applications, it is possible to write;

$$\sum N_i/N_w = 1 \qquad (4)$$

The reduction of vibration problem to a fatigue problem can be accomplished by considering that the number of cycles. N_w to failure be represented as an inverse power law of fatigue stress *S* which can be calculated by knowing the maximum conductor displacement as;

$$N_w = p^1 S^{-r} \qquad (5)$$

where p^1 and r are constant of proportionality and mechanical endurance coefficient respectively. If the mechanical frequency of the conductor vibration is f_m and time for critical damage to accumulate is t_m, then

$$N_w = f_m \cdot t_m$$

and when frequency is constant, p^1/f_m is constant. Therefore,

$$t_m = p\,S^{-r} \qquad (6)$$

Using a suitable failure criterion, it is possible to determine the constants in Eq.(6) A phenomenological model with combined electrical and vibrational stresses at constant temparature is worked out in a similar manner presented in [2] and can be written functionally as;

$$L(E,S) = A\,(E/E_o)^{-n} \cdot (S/S_o)^{-r} \cdot G(E,S) \qquad (7)$$

where A, E_o, S_o, r, n are constants and the quantity $G(E,S)$ is obtained by conducting combined ageing experiments.

3. EXPERIMENTAL

The samples used in the series of experiments were full sized, 11 kV, 1 MW rotating machine coils insulated with mica filled solvent free epoxy resin. The thickness of the insulation over the conductors which are arranged in two adjacent tiers is 2.5 mm for an operating voltage of 11 kV at *50* Hz.

The ageing experiments have been performed at a constant temparature of 155°C (Class F insulation) and at different electrical and mechanical (vibration) stresses. The electric stress was applied using a h.v. transformer rated for 30 kV, 1 Amp. The temparature was maintained more or less constant (±1°C) using a thermostat controlled current transformer, the bar primary of which is the conductor itself in the short circuited condition.

A vibration generator set designed and fabricated indegeneously was used to induce vibrations in the conductor overhang as shown in Fig.1. The vibration test set was capable of developing acceleration of upto **10g** which could be varied from 1g to the maximum limit. The frequencies generated could be varied from **40** to 160 Hz. The maximum amplitude (vertical displacement) realisable was 1000 μm peak to peak and the maximum effective pay load was 5 kg. It must be stated that it requires some experience to choose these factors in an optimal way as to cause failure in a reasonably short time. The mechanical parameters have been measured using appropriate transducers and a sensitive tuned detection circuit.

Reduction in dielectric strength is used as the index of failure. Several diagnostic properties like loss tangent tip-up, p.d. inception voltage and other p.d. quantities have also been monitored during the entire course of experiments. The partial discharge quantities are measured using a conventional Model *5* ERA discharge detector and the loss tangent measurements with the help of a Tettex (Model ***2805)*** Transformer ratio bridge.

It was found necessary sometimes to terminate the experiments before the failure ensued to conserve time, thus generating a truncated data set. The data have been analysed using proven statistical methods.

4. RESULTS AND DISCUSSION

The current research program is a continuing one and some ageing experiments are still running. In order to meaningfully analyse the data so far accrued, the following procedure has been adopted.

The ageing experiments on those specimens which are under ageing test for ***2000*** hours or more have been truncated and the data analysed as a censored set. However, the specimens are continuing to age, and will provide complete data at a later time.

Two sets of experiments were conducted. In the first set, the specimens were subjected to a constant electric stress at **155°C** but varying mechanical stresses. The second set consists in ageing the coils at constant thermal and mechanical stresses, but varying electric stress. It was observed that, to induce reasonably fast ageing the acceleratio should be greater than 4g. For ease of representation, the electrical and mechanical stress applied during ageing are represented as stress factors, G, defined as the ratio of the ageing stress to dielectric strength, and acceleration and frequency respectively.

Diagnostic properties, tan tip up, defined as $\Delta\left|\tan\delta_{0.2U_n} - \tan\delta_{1.2U_n}\right|$ **and** the partial discharge energy / cycle have been plotted in Fig.2 with ageing duration. Fig.3 shows the reduction in dielectric strength, E_d also **as** a function of time. Figs. **4** and ***5*** depict the variations in $\Delta\tan\delta$ and p.d. energy as functions of the mechanical parameter. acceleration, a and electric stress factor, ***G*** respectively after ***2000*** hours of ageing. The ageing test results on specimens which have failed so far are summarised in the Table.

In the following, the effect of mechanical vibration on insulation degradation is discussed in some detail. The conductor overhang can be considered as a simple cantilever beam rigidly fixed at one end, the other end freely vibrating. Fig.6 shows the mechanics of such a beam with the alternating stress diagram. Knowing the peak displacement of the free end during an oscillation under a sinusoidal force, it is possible to calculate the forces at the fixity. In the present case the free length (unsupported) of the conductor is about 40 cm. and peak to peak displacement is between 400 and 800 μm. The maximum force is written as

$$F = 6d(E_m I)/L^3 \qquad (8)$$

where E_m is the Young's modulus and I is the moment of inertia of the beam. These quantities are tabulated for copper, but for insulation of known geometry and stress-strain ratio, it can be calculated. This force can now be substituted for S in Eq.(7). Now S_o is a small force which produces only a small or negligible ageing, a sort of a threshold force, then Eq.(7) will have the same interpretation of the combined electrica and thermal stress equation given in [2]. The effectiveness of the force on the insulation can be increased by increasing the acceleration or the displacement imparted to the free end of the beam and hence the magnitude of the fatigue force.

It is generally known that the results of diagnostic tests on insulation under electrical and thermal ageing give a poor indication of the degree of ageing (amount of degradation). But as can be seen from Figs.2, 4 and 5, when mechanical stress is also applied, non destructive test results appear to give a clear and systematic indication of the status of insulation, atleast qualitatively. It should be admitted however that the stresses applied are on the higher side and the ageing is accelerated very much more. Even so, the correlation coefficient,r between diagnostic and destructive property-the loss of dielectric strength (Fig.3) is remarkable ($r \sim 0.85$). Regarding the factor G(E,S) and other parameters in Eq.(7), we have not been able to determine them explicitly as the tests are not complete.

The physical nature of failure of insulation under multifactor conditions have long been debated. To the extent we know from our experiments upto now, it is possible that in majority of cases, the failure takes place in a region close to the point of fixity of the coils. It has also been observed that fine tree-like breakdown paths precede a complete breakdown. Planar mechanical cracks were also present in the region induced mainly by the mechanical strain. So a plausible mechanism of failure may be the inception of a microcrack, in which partial discharges or electrical tree mechanisms may become operative during the final stages of failure.

In summary, the work reported in this paper pertains to the acquistion and interpretation of insulation failure data with a view to assessing the amount of insulation degradatio at any point in time. It is possible to qualitatively judge the status of insulation using diagnostic test results when the mechanical stress is also present.

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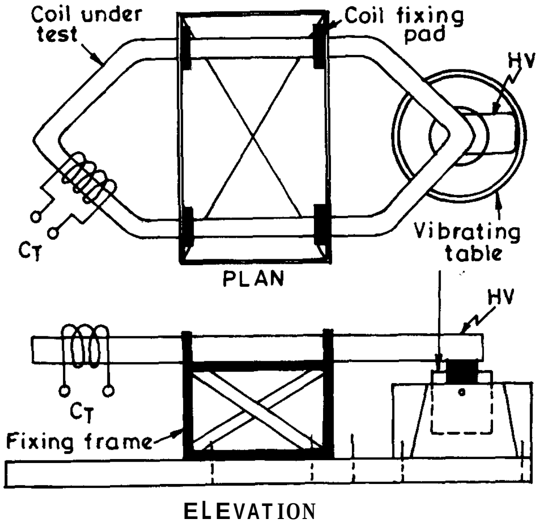

Fig.1: Schematic Diagram of Vibration Test Facility.

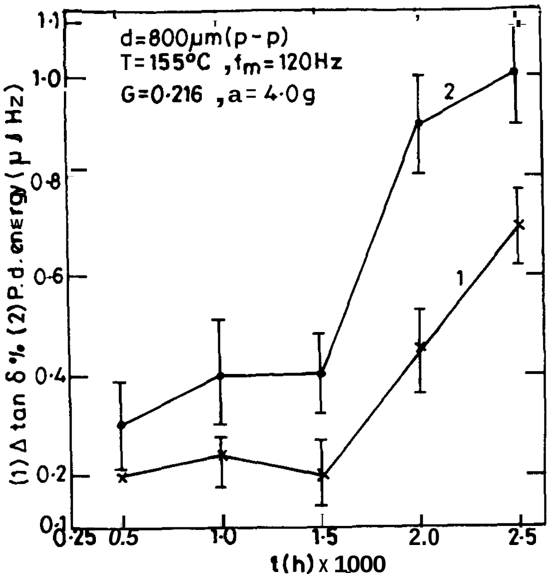

Fig.2: Changes in Δtanδ and p.d. energy with ageing duration.

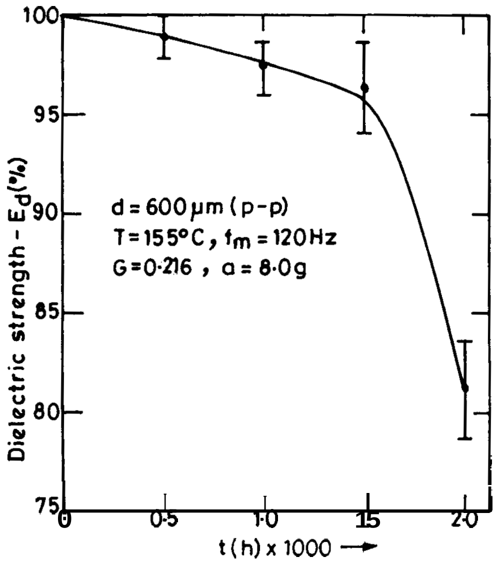

Fig.3: Reduction in initial Dielectric Strength E_d with ageing time t.

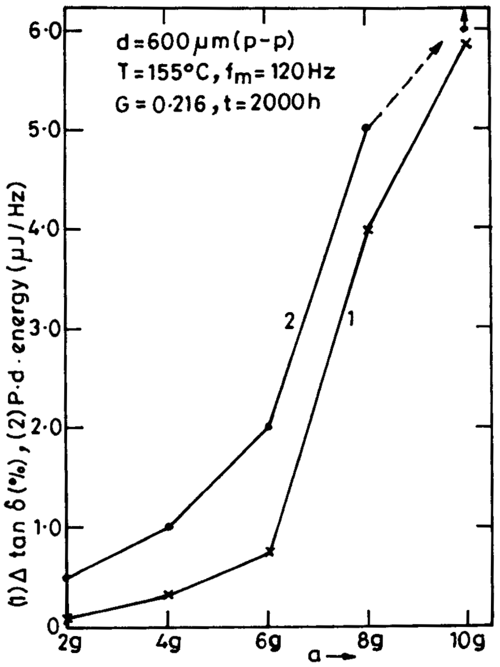

Fig.4: Changes in Δtanδ and p.d. energy of class F insulation with a.

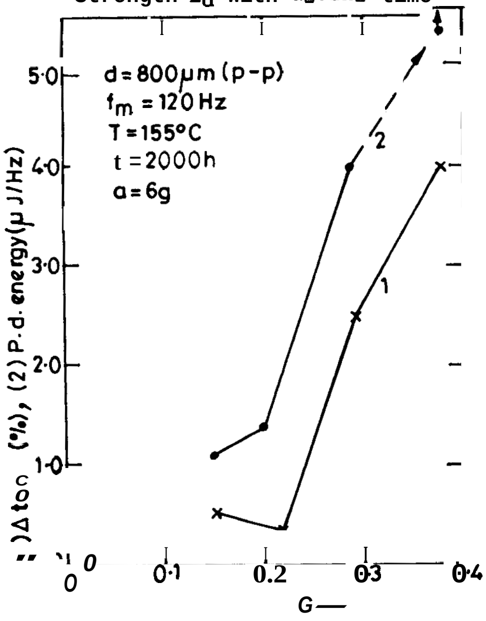

Fig.5: Changes in Δtanδ and p.d. with ageing stress factor G.

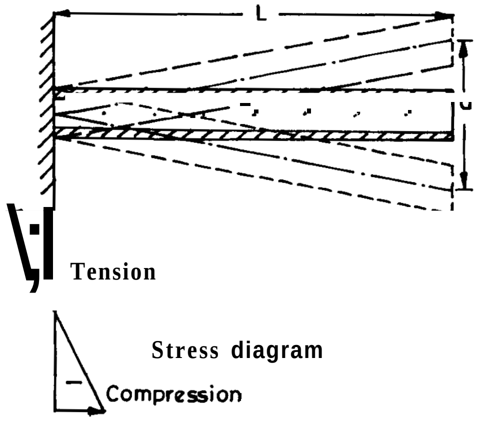

Fig.6: Mechanics of a freely vibrating Cantilever beam.

Effect of simultaneous application of Electrical, Mechanical and Thermal Stress on Insulation Life

Stresses Applied T=155°C		Hours to* failure	Remarks
E	M	raw data	
0	10g	$1964^{1)}$	1) 3 samples
0.316	0	$1690^{2)}$	2) 6 samples
0.24	6g	$312^{3)}$	3) 3 samples

* Criteria: 50% loss of dielectric Strength