INVESTIGATIONS ON ELECTRO-THERMAL AGEING OF METAL OXIDE
SURGE ARRESTER ELEMENTS : A REALISTIC LABORATORY SIMULATION

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ABSTRACT: The ageing of metal oxide surge arresters (MOSA) under field operating conditions caused by a combination of electrical and thermal stresses, is simulated in the laboratory in an attempt to characterize the degradation phenomena as well as to identify the significant indices of such a degradation. Other than the widely adopted leakage current index, the prospects of parameters like barrier height (ϕ_B), capacitance, tan delta, nonlinearity coefficient (α) and area ratio as sensitive degradation indices are studied. Also, the effect of electro-thermal ageing on the V-I characteristics as a whole, till the breakdown voltage of the MOSA, is presented. The simulation is carried out on a 'oneday = one year' (of arrester's field life) basis. The accelerated ageing for this purpose followed an empirical transient electrical stress pattern, while the IEC guidelines were followed for selection of continuous operating voltage (c.o.v) of the arrester and the scheme of thermal stresses.

IDENTIFICATION OF DEGRADATION INDICES

The measurement of leakage current through the arrester (or the power loss) at c.o.v, is most convenient and therefore the most widely adopted degradation index. However, as will be seen, it gives only partial information of the ageing phenomena. In order to understand the effect of the degradation to a fuller extent, it is necessary to monitor the variation in other parameters. Those studied in this work are - the barrier height (ϕ_B) (or activation energy), capacitance, tan delta, non-linearity coefficient and area-ratio (area under the V-I curve/total enclosed area) which are also more closely related to the material structure. These 'degradation indices' were measured prior to any ageing and subsequently after each cycle of ageing. Table.1 gives the significant features of the measurements made:

INTRODUCTION

Since the invention of the zinc oxide based nonlinear resistors, more than 20 years ago most of the conventional gapped surge arresters have been replaced by gapless metal oxide surge arresters. Even though there are not many reports of failure of MOSA in the field, it is known that it exhibits obvious signs of ageing. It has been the priority of most researchers in this field to assess the extent of ageing and put forward possible physical explanations for the degradation phenomena. Also prediction of 'life' of MOSA, ie: the period of its reliable operation, on the basis of electrical or thermal degradation studies has been reported in several papers [1,2,3]. However, there have been only limited efforts to study the degradation of MOSA under surges [4], especially under D.C operating voltages. Further, not much work has been done to simulate the real-life situation in the laboratory integrating the thermal and the various electrical stresses. In the present work, attempts have been made to study the degradation of MOSA elements under a combined electro-thermal multiple stress situation. It is thought that such a simulation would be much closer to the real-life situation.

In the context of increasing usage of HVDC for power transmission and the need to know about the suitability of MOSA for HVDC applications, the present simulation has been carried out with the primary objective of studying the mode of degradation of MOSA under continuous D.C excitation. The degree of degradation of the arrester element has been monitored in terms of the variations in the different degradation indices with successive cycles of ageing.

Table.1

Parameter measured	Mode of measurement	Remarks
Leakage current	Measured at the c.o.v (3.0kV d.c) at 60°C	c.o.v = 0.85V _{1mA}
Barrier Height	From the low voltage V-I characteristics (near 40 volts) at two temperatures: $t_1=26^\circ\text{C}$ & $t_2=60^\circ\text{C}$	$\phi_B = \frac{kT_1 T_2 \ln(I_2/I_1)}{(T_2 - T_1)}$ I_1 & I_2 are currents at t_1 & t_2
Capacitance	Measured at 1kHz, room temperature; no external bias voltage	Digital RLC bridge measurement
Tan delta	- do -	- do -
Non-linearity coefficient	Computed from the V-I characteristics till the breakdown voltage	$\alpha = \frac{\ln(I_2/I_1)}{\ln(V_2/V_1)}$
Area-Ratio	From x-Y recorder plots of the V-I characteristics.	$A_{rel} = A_1 / (A_1 + A_2)$ A_1 & A_2 area below & above V-I curve

ELECTRO-THERMAL AGEING PROCEDURE

Selection of applied stresses

The synergic conditions for the simulation of ageing of MOSA under service has been achieved after an assessment of the various probable stresses in the field. Steady stress could be in the form of continuous operating voltage and also due to the uneven voltage distribution along the arrester column. The thermal stresses are usually considered to be due to the solar radiation and pollution effects on the arrester housing and also due to the temperature rise of the metal-oxide elements subsequent to the discharge of high energy surges. The measure of both the above stresses can be judged fairly accurately due to their fixed nature and they have been simulated in the laboratory following the c o d IEC recommendations [5]. On the otherhand, the transient electrical stresses, viz: the lightning overvoltages, switching overvoltages and temporary overvoltages have a varying nature. Hence, in order to simulate the transient stresses, certain empirical stress patterns based on broad probabilistic consideration of stress magnitudes, was adopted.

Simulation Scheme

In the laboratory simulation based on the above considerations, one day or 24hrs was considered to be equivalent to one year of arrester's field life. This was taken care of in the simulation by compressing the application of the various transient electrical stresses (assumed to occur within one year) and the steady electrical stress at an elevated temperature, within a span of 24hrs. A typical stress pattern for one day = one year = one ageing cycle, is given in Fig.1.

Fig.1: Typical stress pattern for one day, simulating one year of field service.

Impulse	8/20 μ s		2.4ms	
	5kA	10kA	20kA	1kA
Number of shots/day	18	5	2	1

The metal-oxide elements for the ageing study was taken from a class 3 station class arrester of 30kV, 10kA (nominal) discharge current rating, of an internationally reputed make. The arrester element was about 2.5cm thick and 6.0cm in diameter, with an inorganic protective side mating. On a fresh

specimen of such dimensions at first a preliminary V-I characterisation with D.C voltage was carried out at ambient temperature to obtain the V_{1mA} voltage. The continuous operating voltage is fixed as $0.85V_{1mA}$. Then the following schedule of experiments [Fig.2] were carried out:

Fig.2: Schedule of experiments

EXPERIMENTAL RESULTS AND DISCUSSION

The laboratory simulation of the electro-thermal ageing of the MOSA elements produced significant changes in its characteristics. The extent of variation and its mode in the case of each index and the probable physical explanations for the same are discussed in the next few paragraphs:

Leakage Current & Barrier height

The leakage current at c.o.v exhibits a steady increase with the number of cycles of ageing, see Fig.3. The variation of the barrier height, computed from the low voltage ohmic region of the V-I characteristics, is also shown in the same figure.

Fig.3 Leakage current & barrier height variation with number of ageing cycles.

It is observed that while the leakage current increases by about four times, the barrier height remains more or less constant for the initial few cycles and then suddenly drops by about 50%. This is

rather surprising, since an increase in leakage current and reduction in barrier height, both follow the same phenomena and should therefore be complementary. It has been reported [6] that the leakage current variation due to surge degradation under D.C voltage follows a similar trend as under A.C. But it was observed that leakage current under D.C from an expression similar to that reported for surge degradation under A.C voltages [4], leads to a conservative estimate. Considering a different approach described elsewhere for a relation between leakage between leakage current and the duration of applied D.C voltage, it is found that the contribution of thermal stress along with the c.o.v., on degradation (in terms of increase in leakage current) is directly proportional to t^n , where 't' is the period of stress application, 'n' has been given as 0.5 in most cases [2,3] and 0.84 in one case [7]. From the present data it is evident that the leakage current under D.C c.o.v tends to follow an almost linear relation with the number of ageing cycles. The expression for leakage current [8] is, with usual notations,

$$J_r = J_0 \exp \left\{ \left[\left(\frac{E}{e} \right) \left(\frac{q}{4\pi\epsilon} \right) - \phi_B \right] / kT \right\} \quad 111$$

files only dielectric constant (ϵ) and barrier height (ϕ_B) can change in practice, they could influence the leakage current. The reduction in the dielectric constant (ϵ) is discussed later.

The barrier height variation definitely suggests an asymmetric deformation of the barrier, due to a loss or redistribution of Zn ions [9]. As the voltage applied to the element is increased from a low level to the c.o.v, the barrier height reduces (nearly to zero), increasing the leakage current. When the c.o.v is removed (or reduced to low levels as under ϕ_B measurements), the barrier height recovers, probably due to a reverse redistribution of mobile ions near the grain boundary [9]. Ideally, the recovery should be 100%. However, with ageing such a recovery may not be 100%, as evidenced by the lower values of ϕ_B , seen in Fig.3. This incomplete recovery has become pronounced after about eight cycles of ageing. These changes are not evident at the c.o.v, as the barrier height would have been reduced to near zero by the applied field.

Capacitance & Tan delta

The effect of ageing on the dielectric properties of the metal-oxide element is well reflected in the variation of its capacitance and dissipation factor (tan delta) [Fig.4].

While the capacitance shows only a slight variation, tan delta exhibits an increase of about 100%. The loss in the capacitance can be expressed by the often quoted [10] simple RC equivalent circuit of the metal-oxide element - neglecting the ZnO grain resistance. If C_i & R_i respectively correspond to the capacitance and resistance of the intergranular layer, then the intergranular layer resistance R_i can be expressed in terms of the capacitance, C_i and the loss tangent as in eqn(12):

$$R_i = 1/(\omega C_i \tan \delta) \quad 121$$

where: $\omega = 2\pi f$, is the angular frequency of the applied voltage. From this an indirect relationship between the observed increase in tan delta and the increase in leakage current with ageing is evident. An increase in the dielectric loss implies a reduction in the intergranular layer resistance and hence a corresponding increase in the leakage current. Also, this is obvious from eqn(11) considering the ϵ reduction evident from the decrease in capacitance and increase in tan delta,

Fig.4: Capacitance Tan delta (measured at 1kHz) variation with ageing.

Non-linearity Coefficient & Area-Ratio

The value of non-linearity coefficient (a) just below the breakdown voltage shows a remarkable variation - about 70%. This dramatic reduction in a would seem to be the best index to grasp the extent of degradation of the arrester element.

Fig.5 Variation in non-linearity coefficient and Area-Ratio with number of ageing cycles

The non-linearity coefficient has been previously suggested as an index of degradation due to continuous application of D.C voltage alone [7]. In the present case a shows a well defined reduction till about six cycles of ageing, after which it recovers slightly and is more or less constant afterwards. This is in agreement with the peculiar shift shown by the V-I characteristics, which also exhibits a reversal in trend after about six cycles of ageing.

The current drift at constant voltage, is consistent with the changes in the barrier deformation and depends on the biasing polarity. The decrease in a is an indication of change in the slope

of the V-I characteristics as well as the narrowing of the non-ohmic region.

Fig.6 Change in V-I characteristics due to electro-thermal ageing (c1,c7...cycles of ageing)

The area-ratio (A_{rel}) which is computed from the X-Y recorder plots of the V-I characteristics between a current range of 10-40 μ A, also show a fairly consistent decreasing trend. But, unlike in the case of, the extent of variation in A_{rel} is considerably small (only about 30%) and does not show any significant reversal in trend. The changes in the V-I characteristics indicates a recovery from degradation of the metal-oxide element. Further experiments on the effect of thermal stresses alone on arrester elements under D.C excitation has brought about the uniqueness of the electro-thermal ageing procedure in quantifying the degradation behaviour of arrester elements under D.C

CONCLUSIONS

The degradation of metal-oxide surge arrester elements under simulated electro-thermal ageing conditions is carried out and the variation in the different degradation indices monitored. The simulation is framed on the basis of the most probable field conditions, taking into account the various electrical and thermal stresses. The following features are evident from the observations made:

- (i) the leakage current shows a steady increase with successive cycles of ageing. This makes it the most convenient index to monitor in the field. However, it is clear that it gives only partial information of the degradation phenomena.
- (ii) the barrier height shows an initial gradual reduction and subsequent sharp fall, indicative of a reverse redistribution of mobile ions near the grain boundary, and a probable critical state of degradation, when the barrier fails to recover even after the removal of the c.v.
- (iii) the capacitance & tan δ variation reflect the changes in the dielectric properties of the metal-oxide element and confirms the reason for the observed increase in leakage current on the basis of reduction in dielectric constant as well as intergranular layer resistance,
- (iv) the non-linearity coefficient shows promising sensitiveness that elaborates the changes happening

to the electrical properties of the arrester element. Also, the area-ratio and the V-I characteristics show evidence of degradation due to the combined electro-thermal ageing. An indication of the slight recovery from the degradation is seen in the reversal in the low voltage current drift.

Further work to identify the role of the different stresses involved, in causing the observed degradation, is in progress.

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