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AGEING AND DEGRADATION OF ELECTRICAL MACHINES INSULATION

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Abstract

The ageing and degradation of electrical machines insulation are phenomena that determine the life-time of electrical machines in operation. The intensities of these phenomena depend on the nature and values of electrical, mechanical, thermal and environmental stresses that act (permanently or temporary) on the insulations. The paper presents an experimental study of the effects of thermal, mechanical and electrical stresses on the electrical characteristics of some paper mica, glass fibers and epoxy resin insulations. The samples (bars) were subjected to uni- and multifactor ageing using several laboratory setups and the variations of capacity and loss factor with the ageing time and applied voltage were measured. The results analyze shows that the Isotenax tape insulations have a better behavior than P722 tape insulations and that the multifactor stresses (electrical + mechanical +thermal) cause a more pronounced modification of the loss factor and capacity than the unifactor ones.

Key words: *electrical machines, epoxi-mica insulations, unifactor and multifactor ageing*

1. INTRODUCTION

The unexpected removal from service of the electrical machines is generally due, to the deterioration of some essential components. The statistics performed on 70 damaged hydro-generators show mechanical, thermal, electrical, etc. damages and that 56 % of the failed machines showed insulation damage (Fig. 1) (Bruetsch et al. 2008, CIGRE Study Committee 2003). The causes which determine the failure of the insulation systems can be divided into seven groups with different weights (Fig. 2) (Bruetsch et al. 2008). It is found that besides partial discharges and winding contamination, the insulation ageing is the most important factor that causes damage (failure) of the insulations.

In (IEC 2011) it is shown that the ageing represents „irreversible changes of the properties of an Electrical Insulation System (EIS) due to action by one or more stresses". Also, it is highlighted that "some changes (e.g. hydrolytic changes) can be partly reversible if the ambient conditions change and that ageing leads to degradation of the EIS".

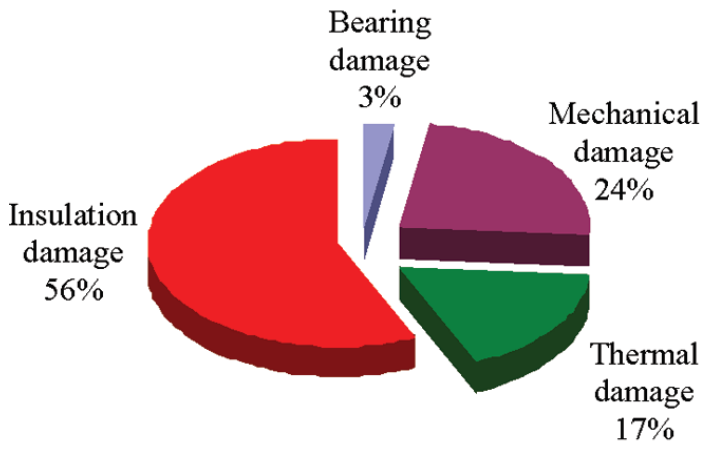


Fig.1. Damages of hydrogenerators (Bruetsch et al. 2008)

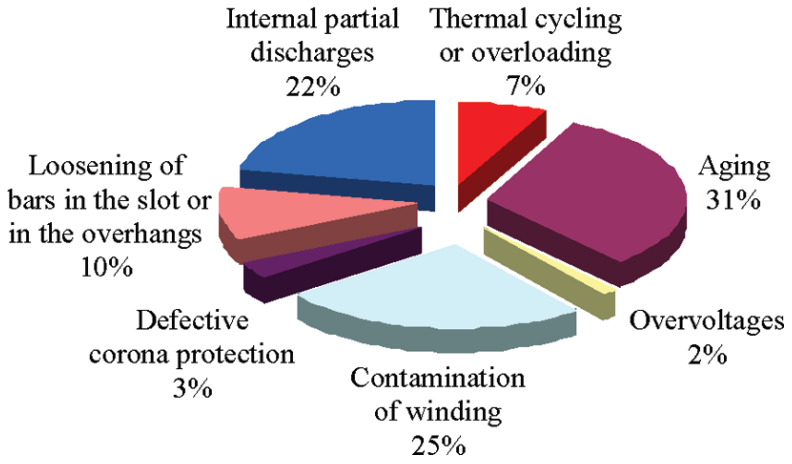


Fig. 2. Causes of insulation systems damages (CIGRE Study Committee 2003)

The stresses of the insulation systems of electrical machines in operation may be accidental (of short term) or permanent (of long term) and are directly related to their operating regimes:

a) continuous operating regimes (used for determination of the structures and the dimensions of the insulation systems);

b) overload regimes (which determine, for a limited period of time, an important increase of the insulations stress (thermal, mechanical) ;

c) abnormal operating conditions, consisting in the appearance of overload voltages or short circuits and generates intense sudden stresses (electric shock, thermal, mechanical) (Notingher 2002).

Electrical stresses (normal, accidentals) lead to the inception and development of partial discharges, electrical and water trees, worsening the electrical characteristics of the insulations and their degradation and failure. Mechanical stresses (between conductors, conductors and magnetic cores, etc.) determine insulation abrasion and detachments, and also the occurrence of cracks inside them, making easier the failure of the insulation. Thermal stresses lead to weight loss, thickness reduction and insulation resistance to humidity, producing a reduction of the electrical and mechanical properties. The environmental stresses (oxygen, humidity, radiation, etc.) increase the chemical reactions and/or initiate new degradation reactions of the insulation.

Analyzing the stress actions in time over the insulation systems it can observed the inception and the development of three phenomena, more or less distinct: ageing, degradation and their failure. The insulation failure (electrical, thermal and electromechanical) is manifested by the inception of some macroscopic channels with high electrical conductivity (Notingher 2005). These channels cross the insulation between conductors separated by them and lead to the removal from service of the insulation and hence of the electric machine. Degradation and ageing of insulation are phenomena that eases the insulation failure, but which are not always clearly separated. An analysis of these phenomena is presented in (Notingher & Plopeanu 2009), depending on the electric field strength and duration (Fig. 3) as well as the dimensions, duration and their effects (Table 1).

The essential difference between the degradation and breakdown phenomena consists in the fact that the degradation is a process that takes place in a long period of time, while the failure is a process that occurs suddenly and it is catastrophic, insulation being unable to support the nominal voltage after its failure. For example, the degradation caused by the development of electrical trees may takes hours, days, months or even years until the insulation damage (its failure) (Notingher 2002, Notingher 2005, Notingher & Plopeanu 2009). In both cases, the dielectric strength of the insulation decreases: less for degradation and much more for failure.

Even though the influence of the ageing process on insulation deterioration is less clear, it is widely accepted that the breakdown time decreases if the strength and application time of the electric field increases, even in the apparent absence of their degradation (for example, electrical trees) (Notingher & Plopeanu 2009). On the other hand, the ageing is considered as a process that develops at molecular scale (Crine & Vijh 1985, Lewis 2001)

and that contributes to change (worsening) of other properties (electrical, mechanical, etc.) of insulation. These changes ease the inception and development of their degradation mechanisms (Notingher 2002, Notingher 2005).

In this paper, the mechanisms of ageing of the insulation are analyzed. Results of an experimental study performed on samples of mica paper and epoxy resins subjected to simple and combined stresses (electrical, thermal and mechanical) regarding the dependence of the capacity and loss factor with stress duration and strength are presented.

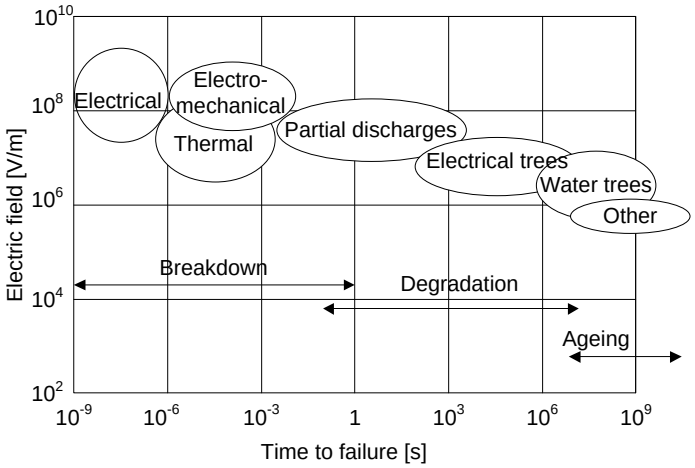


Fig. 3. Values of electric field strength and duration of the mechanisms that lead to the insulation damage (Fothergill 2006).

Table 1. Characteristics of Breakdown, Degradation and Ageing Processes (Fothergill 2006)

Process/ Characteristic	Breakdown	Degradation	Ageing
Evidence	Direct observation (normally by eye - hole through insulation)	Observable directly (may require microscopic or chemical) techniques	Difficult to observe (may even be difficult to prove existence)
Place	Continuos filament	Occurs in weak parts	Assumed to occur throughout insulation)
Size	> mm (dependent on energy of event)	> μm (may form larger structures)	>nm (molecular scale)
Speed	Fast (occurs in << 1 s)	Less than required service life (hours – years)	Continuous process (whole service life)
Effect	Catastrophic (insulation cannot be used afterwards)	Leads to breakdown (reduces breakdown voltage)	May lead to degradation (may not reduce breakdown voltage)
Examples	Thermal, Electromechanical, Mixed mode, Avalanche, Intrinsec	Partial discharges, Electrical trees, Electrochemical trees	Bond scissions, Nano-voids, Trap formation, Non electrical changes (Oxidation etc.)

2. INSULATION AGEING

Since 1995 the study of the insulation ageing has become an important concern to manufacturers and users of electrical equipments, in order to estimate the life reserve of equipments in operation for 2-3 decades. Three types of ageing models (A, B and C) were proposed. All of them consider that the ageing leads to the appearance of some area of reduced density or free volume and that the ageing rate increases in space charge high concentration area (A), in those with high electro-mechanical stresses (B) or in those of free volumes that allow local high currents (C). All models consider that after ageing, nano-cavities and a greater prevalence of traps charges occur (Fothergill 2007). Models A (Dissado, Mazzanti & Montanari 1995, Dissado, Mazzanti & Montanari 1997, Dissado, Mazzanti & Montanari 2001) admit that the space charge is the ageing cause, charge accumulated in different areas locally enhances the electric field, leading to high electro-mechanical stresses, respectively to inception of centers of ageing (for example, fracture of chemical bonds). Models C (Crine &Vijh 1985, Mazzanti & Montanari 2005) suppose that the space charge formation is an ageing effect and is due to high electric fields that break the chemical bonds and to the electron injection in nano-cavities. Models B (Lewis, Llewellyn & Van der Sluijs 1994, Lewis et al. 1995, Jones, Llewellyn & Lewis 2005, Sayers et al. 2000, Rowe 2007, Lewis 2002) take into account the changing of the material morphology as a result of electro-mechanical stresses that unravel crystallites or interfaces damage in the case of composite materials.

For a better understanding of the stress effects, electrical, thermal and mechanical, on the electrical properties of the insulation, the molecular model proposed by Lewis (Lewis 2009) will be considered.

2.1. *Reactions*

Let us to consider a sample made from epoxy resin insulation. Inside this an atom A is bonded to atoms from its surrounding by strong primary bonds (covalent) and secondary weak (Van der Waals). An entity (area) R_a surrounding the atom A and that is connected to the solide area surrounding it R_b by primary and secondary bonds (Fig. 4), (Lewis 2001) can be defined. It may be said that an ageing of the sample occurs if the local structure of the bonds is changing over time and produce some interactions between R_a and R_b. This change may take place if (i) the weaker secondary bond angles and / or lengths has altered and (ii) one hour more primary bonds is broken (the ends being active and seeking fresh bonding) (Lewis 2001). The evolution in time of the R_a— R_b interractions represents the ageing process, highlighted by three mechanisms:

a) There are only secondary bonds between R_a and R_b, and the system bonds changes its conformation from state (1) to a new isomeric state (2) according to the reaction

$$(1)\ R_a — R_b \leftrightarrow\ (2)\ R_a \sim R_b \qquad (1)$$

where the symbols — and ~ represents all bonds in the two isomeric forms. Since R_a is not strongly connected to R_b, a transition from (2) to another state (3) is more likely than a transition from (2) to (1), respectively R_a moves from its initial environment (1) in a diffusive motion. This constitutes a component of the ageing process (Lewis 2001).

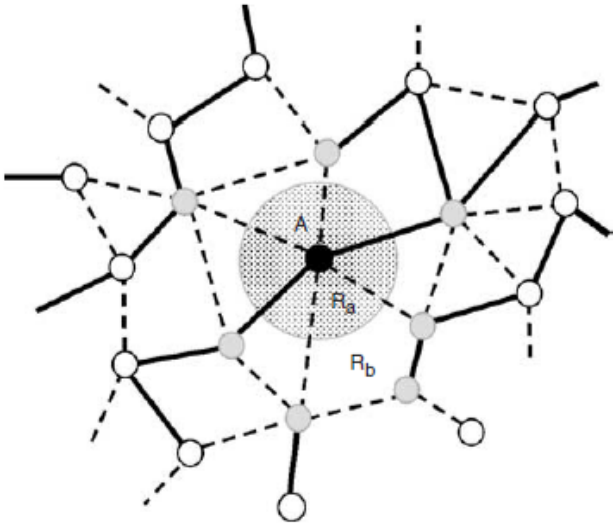


Fig. 4. Representation of the entity R_a bound of surrounding solid region R_b
by primary (—) and secondary (---) bonds (Notingher & Plopeanu 2009)

b) Between R_a and R_b are both primary and secondary bonds (Fig. 4). In these case, strong primary bonds do not allow a diffusive motion and transitions only occur between states (1) and (2).

c) A scission of a primary bond between R_a and R_b may occur. In this case R_a is replaced by a new local entity R_c, with altered physical and chemical characteristics in a changed environment:

$$(1)\ R_a - R_b \leftrightarrow (2)\ R_c \sim R_d\,. \qquad (2)$$

This situation becomes particularly reactive if the bond scission produces free radicals which can initiate chain reactions (in which they are cyclically renewed):

$$(1)\ R_a - R_b \leftrightarrow (2)\ R_a^* \sim R_b^*\,. \qquad (2')$$

Ions may also be formed, according to the reaction:

$$(1)\ R_a - R_b \leftrightarrow (2)\ R_c^+ \sim R_d^-\,, \qquad (2'')$$

and also primary bonds in state (2), which did not exist in the initial state (1).

2.2. *Kinetics*

Free energy G related to the bonds system R_a— R_b has the minimum value G_1 in the abscissa point X_1, X representing the so-called configuration variable (which defines a point in a space with a number of dimensions required to define the total of bond configurations) (Fig. 5), (Lewis 2001). The change of structure and properties brought about by bond reorganizations of various sorts (which represents an indicative of ageing) may be marked by a shift of the configuration variable X along its axis.Thermally induced fluctuations in energy cause excursions of the configuration variable away from the equilibrium value X_1 with energies above G_1. The system

can pass over an energy maximum G_m to reach a new equilibrium at X_2 with energy G_2 (Fig. 5). The transition from state (1) to (2) and the corresponding reconfiguration of the bonds correspond to one of the reactions given by equations (1) or (2). Subsequent thermal activation may cause a transition from X_2 back to X_1, or to a new configuration X_3 (Lewis 2001).

In a representation of the double-well potential (Fig. 5), if $G_1 < G_2$, state (1) is more stable than (2) and conversely if $G_2 < G_1$. For a system in state (1), a low thermal energy input might cause only small excursions of the configuration about X_1. A state (1) requires activation to a transition state of energy G_m before transfer to the state (2). The activation will be at a rate

$$k_{12} = \frac{k_B T}{h} \exp\left(- \frac{\Delta G_1}{k_B T} \right) \tag{3}$$

where k_B is Boltzmann's constant, h is Planck's constant, and $\Delta G_1 = G_m - G_1$ is an activation energy.

The transition from the state (2) back to state (1) will occur at a rate

$$k_{21} = \frac{k_B T}{h} \exp\left(- \frac{\Delta G_2}{k_B T} \right) \tag{4}$$

where $\Delta G_2 = G_m - G_2$.

If N is the number of double well sites per unit volume at instant t, then $N_1(t)$ is in the state (1) and $N_2(t)$ in (2), resulting the relations (Lewis 2001):

$$N_2(t) = \frac{k_{12} N}{k_{12} + k_{21}} \left(1 - e^{-(k_{12}+k_{21})t} \right) + N_2(0) e^{-(k_{12}+k_{21})t} . \tag{5}$$

$$N_1(t) = N - N_2(t) . \tag{6}$$

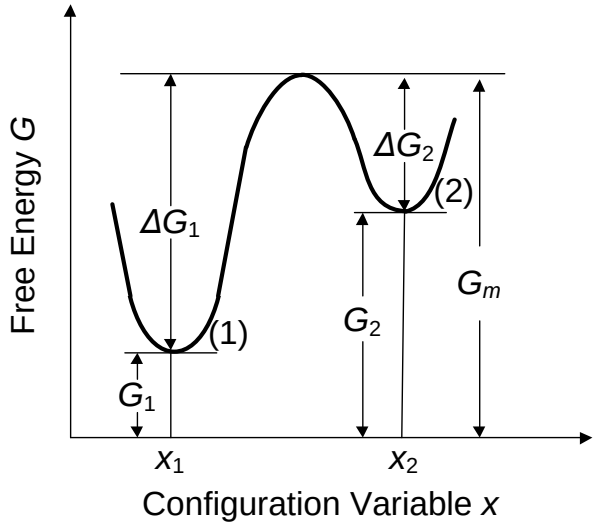


Fig. 5. Free energy of interaction (G), between R_a and R_b entities as a function of the configuration variable (X) for states (1) and (2) (Lewis 2001).

The changes from the initial to the final aged state concentrations vary exponentially in time and, the relaxation time τ of the ageing process is $(k_{12}+k_{21})^{-1}$, respectively (Lewis 2001):

$$\tau = \frac{h}{k_B T}\left(e^{-\frac{\Delta G_1}{k_B T}} + e^{-\frac{\Delta G_2}{k_B T}} \right)^{-1}. \qquad (7)$$

The relaxation time τ has the value $\frac{\alpha h}{k_B T} e^{\Delta G_{\min}/k_B T}$, where α is a factor between 0.5 and 1 and $\Delta G_{\min}$ is the smaller of the two activation energies ΔG_1 and ΔG_2 (Lewis 2001).

As the Gibbs free energy of a system can be expressed in terms of enthalpy (H) and entropy (S):

$$\Delta G_1 = \Delta H_1 - T\Delta S_1, \qquad (8)$$

it results:

$$k_{12} = \frac{k_B T}{h} \mathrm{e}^{\frac{\Delta S_1}{k_B T}} \mathrm{e}^{\frac{\Delta H_1}{k_B T}}, \qquad (9)$$

where ΔH_1 is the enthalpy and $T\Delta S_1$ is the entropic energy of the activation.

In a dielectric loss or mechanical relaxation measurement, it is usually assumed that the rate has the empirical Arrhenius form:

$$k_{12} = Ae^{-\frac{E_A}{k_B T}}, \tag{10}$$

where the parameters A (preexponential or frequency factor) and E_A (activation energy) are equivalent to $\frac{k_B T}{h} \mathrm{e}^{\frac{\Delta S_1}{k_B T}}$ and ΔH_1.

An insulation may have several activation energies, one for each reaction that results in degradation of the material. The total activation energy represents all degradation processes occurring in the material that, taken together, lead to failure (Trnka et al. 2014).

The ageing is closely related to the migration of a foreign element into the solid. The diffusion is an example of equation (1) in which only secondary bonds exist to bind an entity R_a to its surroundings R_b so that it may diffuse away from its initial position. The diffusion coefficient D has the expression (Lewis 2001):

$$D = \frac{k_B T}{h} \mathrm{e}^{-\frac{\Delta G_v}{k_B T}} \mathrm{e}^{-\frac{\Delta G}{k_B T}}, \tag{11}$$

where ΔG_v is the free energy required to create a vacancy and ΔG is the mean of the free energies of activation for transitions between pairs of states (sites).

2.3. *Mechanical and electromechanical stresses*

The mechanical stresses applied to the insulation cause changes in the configuration and conformation of the atomic groups. For a particular reaction entity such as R_a, the stress will cause a deformation of its structure and the double energy will have to take account it (Fig. 6). The stresses σ_1 and σ_2 (applied in the neighborhoods of the sites (1) and (2)) cause the changes $\delta\Delta G_1 = \lambda_1\sigma_1$ and $\delta\Delta G_2 = \lambda_2\sigma_2$ in the activation free energies ΔG_1 and ΔG_2, respectively (λ_1 and λ_2 beeing proportionality factors).

The transition rates become

$$k_{12}^{\sigma} = k_{12}\mathrm{e}^{-\lambda_1\sigma_1 / k_B T}$$
$$k_{21}^{\sigma} = k_{21}\mathrm{e}^{-\lambda_2\sigma_2 / k_B T} \tag{12}$$

where k_{12} and k_{21} are the stress-free rates given by equations (3) and (4) (Lewis 2001).

If the transition (1) to (2) involves a primary bond scission, the reverse transition (2) to (1) is very unlikely and k_{21} is zero. In this case, from (5) and (6), it results:

$$N_2(t) = N - \left(N - N_2(0)\right)\mathrm{e}^{-k_{12}^{\sigma}t}$$
$$N_1(t) = N_1(0)\mathrm{e}^{-k_{12}^{\sigma}t} \qquad (13)$$

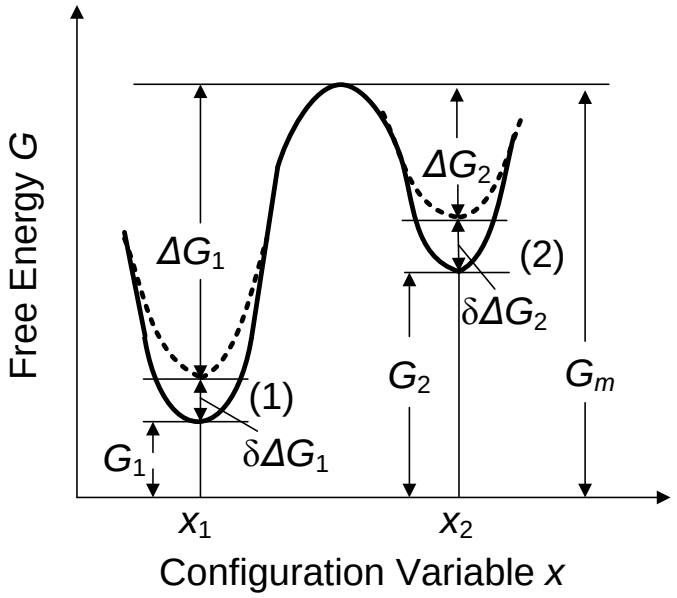


Fig. 6. Free energy of states as modified by applied mechanical stresses.

where k_{12}^{σ} is given by equation (12). If $N_2(t)$ is taken as a measure of ageing, this increases most rapidly when $\lambda_1\sigma_1$ is negative.

High electric fields determine, on one hand, the intensification of electrical conduction process and, on the other hand, mechanical stresses in insulation. Assuming that the polarization $\overline{P}$ and the field $\overline{E}$ are collinear, the induced stress σ_e has the expression (Lewis 2001):

$$\sigma_e = \rho\overline{E} + \overline{P}\mathrm{grad}\overline{E}, \qquad (14)$$

where ρ is the charge density. This stress couples to the medium via chemical and physical bonds and for equilibrium to be established has to be balanced by a mechanical stress σ_m:

$$\sigma_m = -\varepsilon E^2, \qquad (15)$$

where and ε is the electrical permitivitty.

The electrically induced mechanical stress depends on the square of the field E and is thus most important in an insulator where the field is high (at electrode interfaces, inclusions, voids etc.). Corresponding to equation (13) the reaction rates are (Lewis 2001):

$$k_{12}^{\sigma_e} = k_{12}^0 \mathrm{e}^{\lambda_1 \varepsilon E^2 / k_B T}$$
$$k_{21}^{\sigma_e} = k_{21}^0 \mathrm{e}^{\lambda_2 \varepsilon E^2 / k_B T} \quad (16)$$

If the field $E(t)$ have both ac and dc components, respectively $E(t) = E_s + E_{\max} \sin\omega t$, where E_s is the steady dc component, the mechanical stress is (Lewis 2001):

$$\sigma_m = -\varepsilon\left(E_s^2 + \frac{1}{2}E_{\max}^2 + 2E_s E_{\max}\sin\omega t - \frac{1}{2}E_{\max}^2 \cos 2\omega t\right) \quad (17)$$

and the ageing response is a complicated function of time.

The role of electrons in ageing and deterioration of the insulation can be highlighted based on the models described above (Lewis 2001). An electron existing in the solid can be represented as a entity R_a interacting with its surroundings R_b. The electron entity R_a transfers from state (1) to state (2) with a shift of configuration variable from X_1 to X_2 (Fig. 5). The free energies involved will be largely determined by coulombic and polarizing interactions between the electron and its surroundings. The energy G_2 may be greater or less than G_1 and the electron in moving from state (1) to state (2) becomes either more or less strongly trapped. Mechanical and electromechanical stresses will influence the electron entity R_a in a manner similar to that described for atomic and molecular entities.

2.4. *Multifactor ageing*

If in the laboratory tests the samples may be subjected to a single stress factor (electrical, thermal, mechanical), in service the insulations are subject to simultaneous stress factors. Considering that in the ageing process the main role is played by the thermal energy kT, the equation for the transition rates between different states has the form (Lewis 2001):

$$k_{12} = \frac{k_B T}{h}\mathrm{e}^{(-\Delta G_1 + \Delta G_C - \lambda_1\sigma + \lambda_1 \varepsilon E^2)/k_B T} \quad (18)$$

where ΔG_1 is an activation energy arising from the intrinsic structure of the insulator, ΔG_C is a modification to this caused by impurity action (a result of impurity diffusion), $\lambda_1\sigma$ and $\lambda_1\varepsilon E^2$ are due to mechanical and electrical stresses and the whole is driven by the thermal energy $k_B T$.

It must be highlight that the equation (18) represents only one ageing process in the solid and there may be several such processes in action simultaneously. It also results that in the case of multiple stresses (electrical, mechanical, thermal) the insulation ageing rate increases. This aspect is highlighted also by the experimental results published in a series of papers concerning the thermal (Notingher 1983, Paloniemi 1981, Montanari & Lebok 1990, Rusu-Zagar e.a. 2013), mechanical (Notingher 1983, Maughan, Gibbs & Giaquinto 1970, Futakawa et al. 1978, Mitsiu et al. 1985, Wichmann 1983) , electrical (Futakawa 1981, Kimura 1983, Wichmann 1977), thermal and mechanical (Rusu-Zagar e.a. 2013), thermal and electrical (Ramu 1985, Simoni 1980, Cygan & Laghari 1990), electrical, mechanical and thermal and/or the environmental (Kimura 1993, Cygan & Laghari 1990, Kimura 1995, Bruning & Campbell 1993), etc. It should be remarked that these studies do not take into account also the effect of synergism that occurs in the case of simultaneous action of stresses (Notingher 2005).

3. EXPERIMENTS

In most of the above papers, variations of the breakdown voltage due to uni- or multifactor stresses are analyzed. In this paper the values of the capacitance and loss factor of some samples from epoxy resin insulations subjected to simple and combined thermal, electric field and mechanical stresses (flexural, torsion) are analyzed. The stress strength values are higher to those from service.

3.1. *Samples*

Tests were performed on three type of bar samples, noted by A, B and C. The samples A were obtained from 20 copper conductors, with a rectangular cross-section 2.3 x 6.3 mm^2 and length l = 80 cm (insulated with glass fibers and epoxy varnish). The conductors were arranged 10 on each row and pasted with epoxy varnish. Over them several layers of thermo-reactive micatape P722 was disposed. The bars thus obtained were pressed at p = 0.6 MN/m^2, for 30 min at T_1 = 145 ºC (for polymerization) and then for 12 hours at T_2 = 60 ºC (for hardening). Depending on the number of layers insulations with thicknesses between 1.5 and 3 mm were obtained. These correspond to nominal voltage between 3 and 10.5 kV. The samples B, with thickness of 1.5, 2, and 3 mm (corresponding to voltages of 3.6 to 10.5 kV) were obtained from Micafil 722 band and test specimens C from Isotenax band (Notingher 1983). All samples (10 for each type) were subjected to a thermal conditioning in an oven without air convection, at a temperature T = 150 ° C for 48 h.

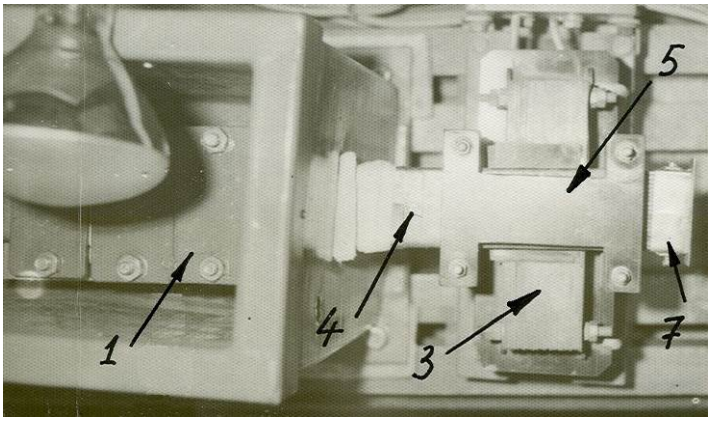
After conditioning for each sample the capacity C and the loss factor tgδ and were measured and the curves $C = g(U)$ and tgδ = $g(U)$ for effective voltage values U between 1 and 12 kV and frequency f = 50 Hz were drawn. For each bar, a measuring condenser was realized. It has the inner armature consisting of beam pipes and the outside one (main electrode of length l_a = 8 cm) made from copper band with 0.2 mm thickness and dielectric - insulation to be studied. At 2.5 mm, on both sides of the outer armature two guard electrodes (2 cm wide) were disposed. These electrodes together with the outer armature were grounded.

3.2. *Set-ups*

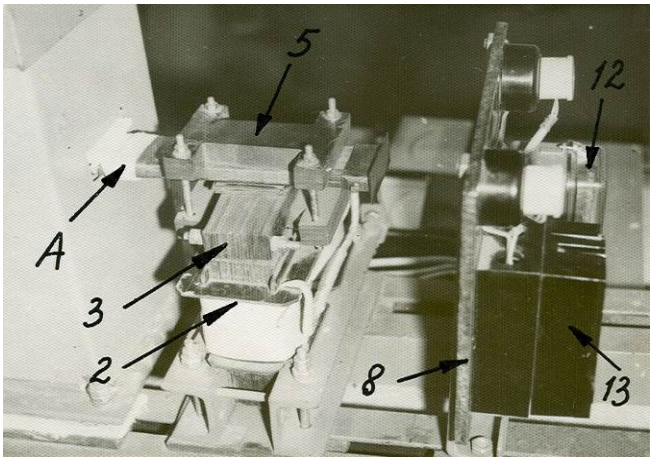
To perform variable mechanical stresses at simple bending the equipment shown in Figure 7 was used. This consists from an embedding device (1) and an ac electromagnet (2), whose mobile armature (3) is fixed to the bar (4) using insulating plates (5). The amplitudes of the deformation of the y bars (measured at their free ends) were varied - by the change of the supply voltage (between 0 and 220 V) - between 0 and 3 mm. At the free end of the tested bar a metallic mirror was fixed. On the plate (8) a graduated ruler (of glass) and a light source were fixed. The electromagnet is powered with the command relay (12) and contactor (13) and develop a minimum force F_{min} = 3 kN - for y = 3 mm - and a maximum force F_{max} = 10 kN - for y = 0.

In order to produce circular bending mechanical stresses the equipment presented in Figure 8 was used. This consists from the embedding device (1), the tested bar (2), the nut (3), the bearings for mounting the axis (4) and the asynchronous motor (5) (P = 7.5 kW and n = 2850 rot / min). The strength of the stresses - in the embedding area A - is determined by the length of the free part (1) and the size of the arrow (y) (measured at the free end, fixed with the nut (3)).

To measure the capacity and the loss factor a Hewlett Packard LCR Meter (Model 42638) and a bridge TETTEX 2840 high voltage (5V… 2 MV, 15 ... 1000 Hz) were used.



a)



b)

Fig. 7. Set-up for alternative mechanical stress at simple bending at 100 Hz:
a) Top view, b) Side view. 1 – Embedding device, 2 – ac electromagnet,
3 – Mobile armature, 4 – Sample; 5 – Plate for armature fixing,
8 - Vertical plate; 12 – Command relay 13 - Contactor.

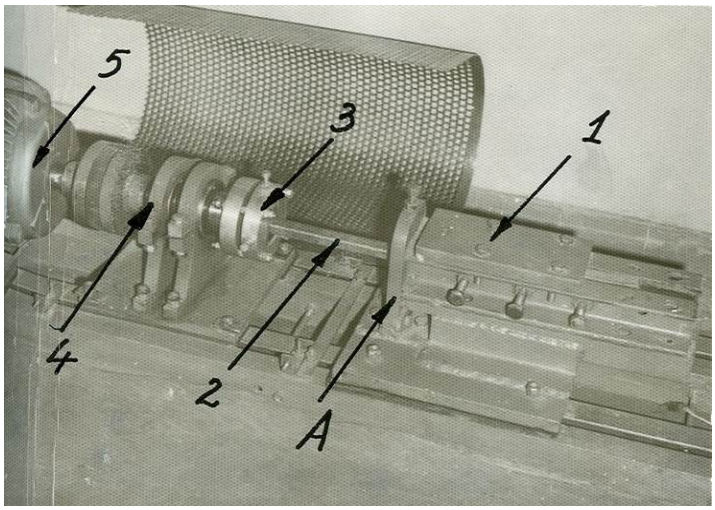


Fig. 8. Set-up for circular mechanical stresses: 1 – Embedding device,
2 – Sample, 3 - Nut, 4 - Bearing, 5 - Asynchronous motor.

4. RESULTS. DISCUSSION

4.1. *Mechanical stresses*

Three bars of each type were subjected to alternative bending stresses (90 cycles, 8 hours - stress and 16 hours - pause), the free ends length being l '= 20 cm, and the arrow y = 2 mm. After the stresses completion, on each bar 3 electrodes systems for measuring capacitance and loss factor were mounted at 5 cm from the free end of the bar, in the embedding area A (Fig. 7 b) and at 5 cm to the other end of the bar. In the case of circular stresses, bars with lower circular section (20 x 10 mm^2), with insulation thickness g = 2 mm, the arrow y = 1 mm (or y = 2 mm) and length l = 20 - 40 cm (corresponding to an angle to the fixed bar, 0.15 - 0.6 º) were used.

Figure 9 presents the variation curves of the loss factor with the voltage (tgδ = $g(U)$) for samples A (1, 3, 5) and B (2, 4, 6), with insulation thickness of 2 mm, unaged (1, 2) simple bending stresses (3, 4) and circular (5, 6). It is found that, for all samples, the loss factor increases with the voltage. This is due to the increase of the dissipated active power with the applied voltage U, by conduction, polarization and by partial discharges, respectively of the 3 components of tgδ: $tg\delta_c$, $tg\delta_p$ and $tg\delta_{dp}$ ($tg\delta = tg\delta_c + tg\delta_p + tg\delta_{dp}$ (Notingher 2005).

Mechanical stress of the samples led an increase of tgδ values for both kinds of samples. This shows that in the insulation bulk, chemical transformations (molecules fracture, new charge carriers and polar species generation, and/or increase of their concentration, etc.) occurred. These led to the increase of the components $tg\delta_c$ and $tg\delta_p$. Also, some physical transformations (appearance of nano- and micro-cracks, detachments of wire insulation etc.) occurred (Crine & David 2005) leading to development of partial discharges and therefore to the increase of $tg\delta_{dp}$ - respectively an ageing of the tested insulations.

The values of the loss factor tgδ that were determined in the embedded area A are generally higher than those measured at the ends of the bars. Thus, for U = 6 kV, the values of tgδ are higher with about 15% than those measured at the free end and with 8% lower than those measured at the opposite end. This is due to ageing and perhaps to a more pronounced degradation of the insulation in embedding areas of the samples.

It should be remarked that due to the mechanical stresses, the values of the capacity increased very slightly: 0.4 % for simple stresses and by 0.8 % for circular stresses. Because the previous tests were carried out at relative high stresses, tests at lower stresses were also performed. For that, 3 bars type A have been subjected to 90 simple bending cycles with amplitude of only 0.2 mm. In these cases, no

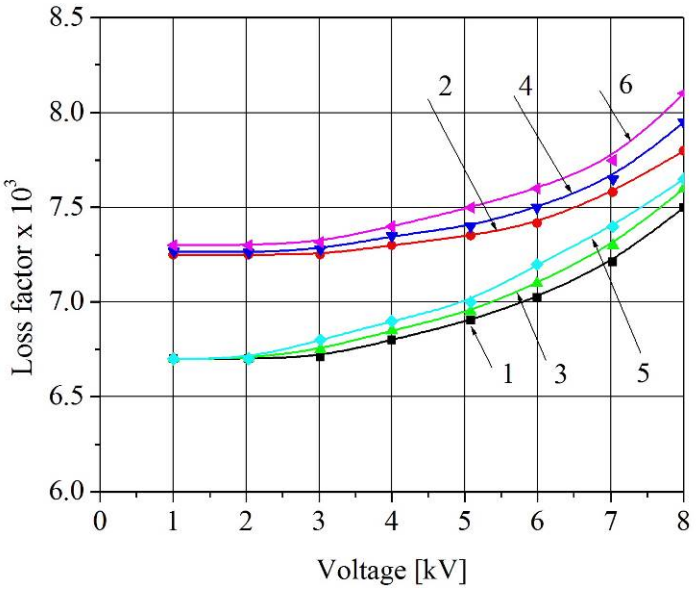


Fig. 9. Variation of the loss factor tgδ with the test voltage U for samples A (1, 3, 5) and B (2, 4, 6), unaged (1, 2), stressed by simple bending (3, 4) and circular (5, 6).

significant changes were observed for *C* and tgδ. In other words, the low mechanical stresses do not appreciably change the epoxy resin insulation properties. The same conclusion was also obtained by Kelen (Kelen 1976), after performing some alternative bending tests (255 h) with f = 900 Hz and y = 0.15-0.2 mm. As it was shown above, the measurement of the capacity and loss factor involves the analysis of a relatively large area of insulation (8 cm), so that any local defects caused by mechanical stresses are not very well observed by the variations of these parameters. For this reason, for all bars stressed at y = 0.2 mm, the breakdown voltage U_{str} (in all three areas provided with electrodes) was determined. Taking as reference the value determined in the fixed area of the bar, it was found that U_{str} reduces by 8.9 % in zones A and by 1.2 % in the free zones. Unfortunately, such tests are destructive and cannot be used to analyze the ageing condition of stator insulation of electrical machines in operation (Srinivas & Ramu 1992).

Significant reduction of U_{str}*'s* in the zone A shows that cracks were produced here and/or detachments of the insulation, phenomena that ease the inception and development of breakdown channels for lower values of voltage. Therefore, it can be said that the mechanical stresses do not produce significant variations of electrical characteristics, but ease the electrical insulation degradation processes (partial discharges, electrical trees) (Sumerder & Weiers 2008).

4.2. *Electrical stresses*

Two groups, each of them consisting from five samples (A and B), with g = 3 mm, were subjected to - 60 cycles of 8 hours - at an effective value U = 25 kVand frequency f = 50 Hz. Then, the capacity *C* and loss factor tgδ values were measured (at U = 10.5 kV and f = 50 Hz). A reduction of both parameters, with 2.8 % for tgδ and 4.2 % for *C* was found in the case of the samples A. These reductions are due to the resin polymerization end, respectively the reduction of the ions and electric dipoles concentration. For the samples B variations of *C* and tgδ have not been remarked.

A new experiment performed on a larger number of cycles (120) has shown an increase of *C* and tgδ, both for samples A and B, due to the ageing of insulation. These increases, however, are very small: less than 0.1 % for both parameters (*C* and tgδ). It results that, in a less time - compared to the operation time of the insulation - electrical stresses do not significantly change the global properties of the insulation, respectively that the electrical ageing is insignificant in relation to the temperature one (according to Notingher 1983).

4.3.*Thermal stresses*

4.3.1.*Short - term stresses*

In an oven with adjustable temperature from 30 to 250 ° C two groups of five bars A and B (with g = 3 mm), provided with electrodes for measuring the capacity and loss factor were placed. The temperature - measured at the surface of the bar from the oven center - was adjusted in steps of 20 º C (up to 100 º C) and 10 º C (up to 160 º C). After 2 hours after the setting of a specific value of the temperature, the bars were removed (one by one) and the values of capacity and loss factor have been measured. The measurement time was less than 2 minutes, while the temperature of the insulation was assumed to be constant. The measurements were performed at U = 10.5 kV, some of the results are shown in Figure 10. It is found that for both types of samples, the loss factor (Fig. 10, curves 1, 2) and the capacity (Fig. 10, curves 3, 4) increase with the temperature *T*. The increase of the capacity is related, firstly, by the weakening of the interaction forces between the electric dipoles and resin molecules (due to the intensification of thermal agitation), so their easier orientation in the electric field. The increase of the loss factor is due to the enhancement of the charge carriers mobility *M* and polar groups (respectively, of the real part of the complex electric permittivity (Notingher 2005)).

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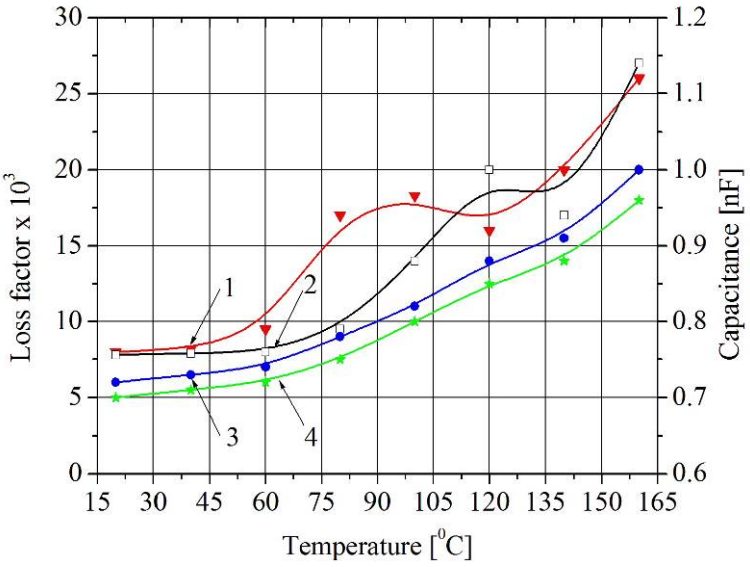


Fig. 10. Variations of the loss factor tgδ (1, 2) and capacity (3, 4)
with temperature *T* for samples (2, 3) and B (1, 4)
(*U* = 10.5 kV, *f* = 50 Hz)).

The shape of the curves tgδ = *g*(*T*) can be explained by the variations of electrical conductivity σ and the level of partial discharges (p.d.) with the temperature *T*. For *T* < 100 ° C, the values of tgδ are more influenced by p.d.: the diffusion coefficient of the gas in the cavities increases with *T*, intensifying p.d. and increases $tg\delta_{dp}$. On the other hand, with the intensification of partial discharges, the mass of the gas in each cavity increases and therefore its pressure. For *T* = 120-130 °C, the pressure has high enough values so that the p.d., level, respectively $tg\delta_{dp}$, and thus tgδ reduce. For *T* > 120-130 °C, the charge carriers mobility *M* becomes high enough so that the term $tg\delta_{\sigma}$ becomes predominant in tgδσ, the increase of *T* leading to a pronounced increase of tgδ.

4.3.2. *Long - term stresses*

Two groups of 5 bars, A and B, were subjected to some longer time thermal stresses, respectively 120 cycles of 10 hours at 135 º C. Each cycle includes a heating period (2 h) (up to 135 ºC), a period during the stresses are done (10 h at 135 °C) and a slow cooling period (12 hours in the oven). Every 10 cycles, the values of capacity and of loss factor were measured at 20 ° C. The variations of *C* and tgδ are shown in Figure 11.

It is found that, in the first 30 cycles, the capacity decreases, and then remains practically constant. The decrease of *C* at the beginning of the stress is due to the decrease of the dipoles concentration (after the polymerization process ends), in accordance with (Chalise, Grzybowski & Taylor 2009). The fact that even after 1200 h the values of *C* does not change show that the insulation has not started to degrade considerably, respectively that polar degradation products did not occurred.

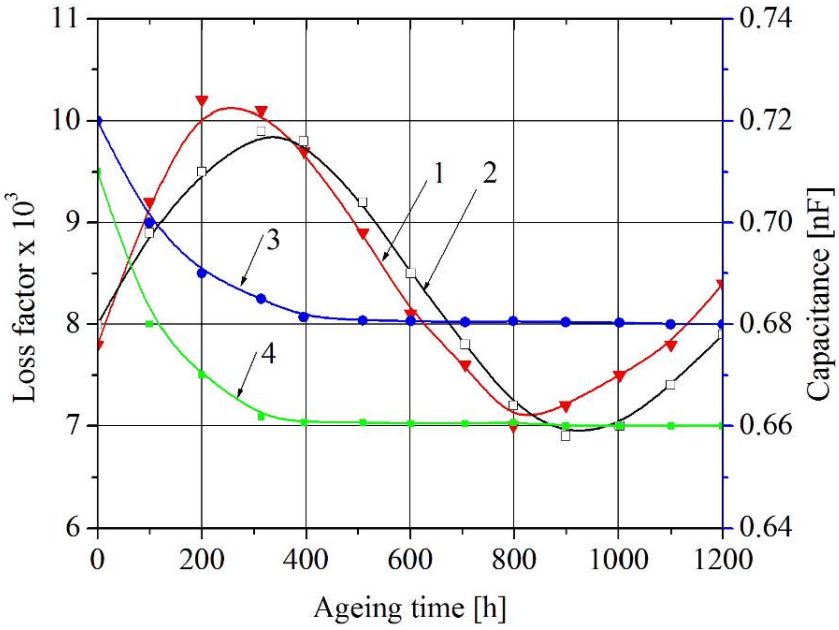


Fig. 11. Variations of the loss factor tgδ (1, 2) and capacity *C* (3, 4) with the ageing time for samples A (1,3) and B (2,4) (*U* = 10.5 kV, *T* = 20 °C).

The loss factor increases in the first part of the ageing test (τ < 200-300 h), by eliminating gas and thus intensifying the partial discharges (which leads to the increase of $tg\delta_{dp}$). As the polymerization process ends (τ > 300 h), the concentration of dipoles and charge carriers *N* decrease, and therefore σ and ε, respectively $tg\delta_c$ and $tg\delta_p$. After a longer thermal stress (τ > 800 h) chemical reactions of decomposition of epoxy resin molecules are producing in insulation. Nano - and microcavities that develop partial discharges may occur. Therefore the concentrations of charge carriers increases and enhance partial discharges, leading to increased $tg\delta_c$ and $tg\delta_p$ and therefore tgδ (Notingher 2005, Carlier et al. 1976, Younsi et al. 2010).

4.4. *Combined stresses*

Three bars, type A, B and C, were subjected to combined thermal, mechanical and electrical stresses (60 cycles: 10 h stresses and 14 hour pause), by using set-up shown in Figures 7, 8 and 12. The bars (*l* = 60 cm and *g* = 3 mm) were covered in a length of 40 cm, with a copper band (being made the outer electrode) - on which 2 layers of glass fabric were disposed (isolating them from the ground) - and then they were fixed in the embedding device (1) (Fig.7). Between conductors beam and the copper band a voltage of effective value U_s = 22 kV and frequency *f* = 50 Hz was applied.

The bars heating was done in a double wall tank (9), using lamps (10) with infrared radiation (*P* = 1.5 kW) (Fig. 12). The temperature was kept constant (135 °C) using a thermometer with contact (11), of the relay (12) and of the contactor (13) (Fig. 7 b). The mechanical stresses were simple bending type, the lengths of free ends of the bars being *l'* = 20 cm and the arrow *y* = 0.6 mm.

Before performing the tests the capacity and loss factor values were measured. Figure 13 shows the variation of the loss factor with the test voltage. It is found that the samples C show lower values of tgδ than samples A and B. This is due to the complete removal of the solvents in the manufacturing process (microcavities concentration being lower) and to a better adhesion of the insulation to conductor (lower detachments area) (Notingher 1983).

After 600 hours of accelerated ageing, the bars were removed and left for 24 hours at room temperature, and then tgδ values have been measured (Fig. 14). It is found that tgδ increases after ageing and that its variations are more important for higher values of the voltage (due to microcracks and detachment occurred, partial discharges develop). On the other hand, it should be remarked that samples C (made from Isotenax band) shows the lowest values of the loss factor.

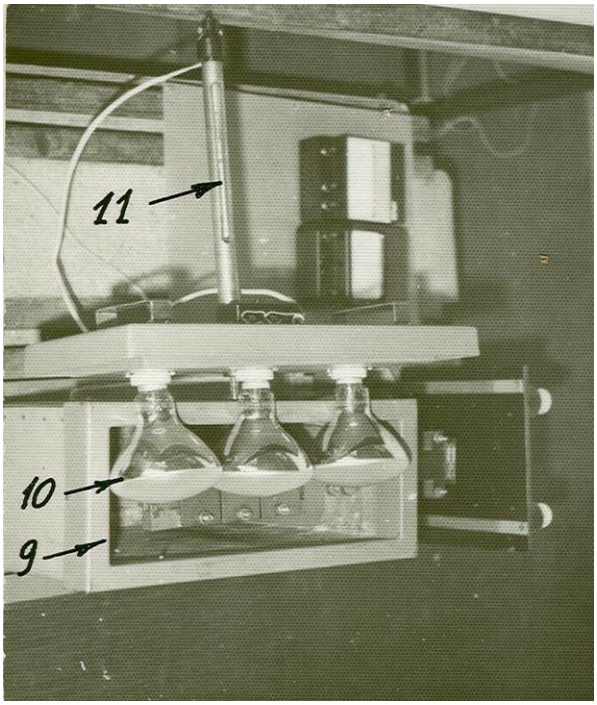


Fig. 12. The thermal stress system of the samples.

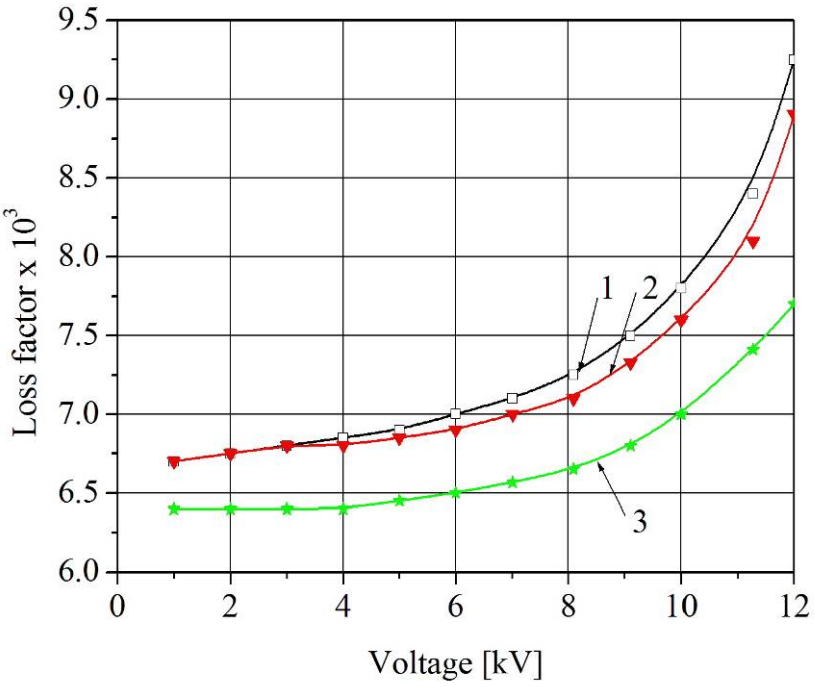


Fig. 13. Variation of the loss factor tgδ with test voltage *U*
for unaged samples A (1), B (2) and C (3).

Combined stresses lead to a more pronounced ageing of insulation, the values of tgδ increasing (more for samples A and less in the case of sample C) with the ageing time (Fig. 14).

The increase of the loss factor does not fully characterize phenomena that occur in the insulation. As shown above, the production of fissures or detachments of insulation ease the trees inception, the probability of their inception and growth rate development increase in the case of combined stresses.

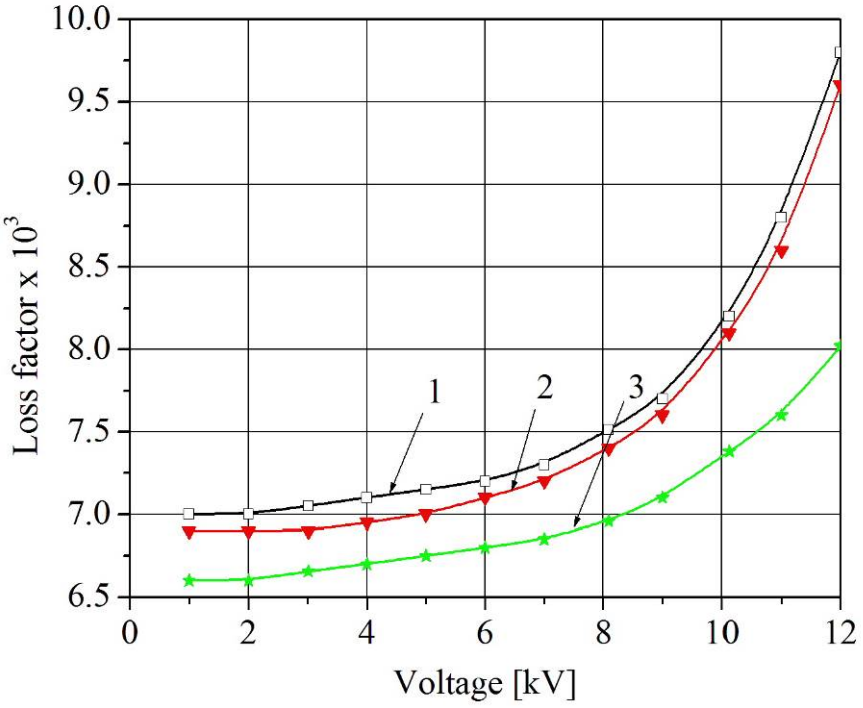


Fig. 14. Variation of the loss factor tgδ with test voltage U
for samples A (1), B (2) and C (3), thermal + electrical + mechanical aged
for 600 h (U_s = 22 kV, T = 135 ° C, y = 0.6 mm).

Thus, the following experiment it was performed: after the circular mechanical stress were performed, a bar type B has been tested to breakdown and the other two have been subjected 400 hours at U = 15 kV. Performing then the breakdown tests a reduction of 9.4 % of E_{str} compared to the sample electrically unaged was found. In the case of samples subjected only to simple electrical stresses (without mechanical stress), the reduction of E_{str} was insignificant. Obviously breakdown occurred - in 78 % of tests (respectively 7 from 9) – in the edge areas (where the electric field is more intense) (Notingher 1983).

In the edge regions, the electric field has been much more intense and in these areas tree channels may occur (Notingher 1983). The channel volume being very small, their existence cannot be evidenced by possible variations of capacity or loss factor. On the other hand, the interfaces play an important role in epoxy/mica insulation, which undergoes change in the multi-stress aging. The changes of components in epoxy/mica insulation lead to the damage of interface. In other words, the deterioration of interfaces is the main reason of insulation ageing (Zhidong 2006).

Tests carried out on samples made in the laboratory cannot model all manufacturing defects and/or during their operation (Sumerder & Weiers 2008). For this, identical bar tests with the one in operation should be performed, fixed in magnetic cores similar to those of electrical machines.

CONCLUSIONS

From the results presented in this paper it results, regardless of the type and strength of the stress, insulation characteristics worsen (C and tgδ increase and E_{str} decreases) with the ageing time, respectively that the samples become aged.

The mechanical tests (unifactor) show that the loss factor increases more in the case of circular stresses. How they are closer to the real stresses of the coil ends, set-up as shown in Figure 8 is recommended for study of the insulation.

The most affected areas by mechanical stresses are located at the exit of the bars from stator slots and the most intense electrical stresses are in the vicinity of the bars edge. Insulation ageing under the action of electric field has not been practically put into evidence by measurements of C and tgδ. This was expected since the tests were performed in an average field (E = 8.3 MV / m), much lower than the dielectric strength of epoxy resins (E_{str} = 30 MV/m).

The action of the electric field $\bar{E}$ is important in the case of combined electrical + mechanical stresses, when - due to defects generated by the mechanical stresses and the action of $\bar{E}$, the breakdown voltage reduced significantly.

Long-term thermal stresses lead to an increase of tgδ stress with the stress time. It is found that insulation B performs better than A (for U = 10.5 kV, tgδ increase by 2.5 % for B and by 4 % for A) respectively that the insulation B ageing more slowly.

Insulation suffer a more pronounced ageing under the action of multifactor stresses, result in accordance with the general model of ageing under the action of single-and multifactor stresses.

The used sample models do not reproduce also possible defects that arise in the manufacturing process of insulation and/or during the operation.

REFERENCES

Bruetsch, R, Tari, M, Froehlich, K, Weiers, T & Vogelsang, R 2008, “Insulation Failure Mechanisms of Power Generators”, *IEEE Electrical Insulation Magazine*, Vol. 24, No.4, pp. 17-25.

Bruning, AM & Campbell, FJ 1993, “Aging in Wire Insulation under Multifactor Stress,” *IEEE Transactions on Electrical Insulation*, Vol. 28, No. **5,** pp**.** 729-754, 1993.

Carlier, J 1976, “Ageing Under Voltage of the Insulation of Rotating Machines: Influence of Frequency and Temperature,” *CIGRE* 15-06, Paris.

Chalise, SR, Grzybowski, S & Taylor, CD 2009, “Accelerated electrical degradation of machine winding insulation”, *Proceedings of Electric Ship Technologies Symposium*, pp. 533–538.

CIGRE Study Committee SC11, 2003, EG11.02, *Hydrogenerator Failures – Results of the Survey.*

Crine, JP & David, E 2005, “Influence of mechanical stresses on some electrical properties of polymers”, *Proceedings of Conference on Electrical Insulation and Dielectric Phenomena, pp. 71–74.*

Crine, J-P & Vijh, AK 1985, “Molecular Approach to the Physico-Chemical Factors in the Electric Breakdown of Polymers", *Applied Physics Communications,* Vol 5, No. 3, pp. 139-63.

Cygan, P & Laghari, JR 1990, “Models for Insulation Aging under Electrical and Thermal Multistress”, *IEEE Transactions on Electrical Insulation*, Vol. 25, pp. 923-934.

Dissado, LA, Mazzanti, G & Montanari, GC 1995, The Incorporation of Space Charge Degradation in the Life Model for Electrical Insulating Materials, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 2, No. 6, pp. 1147-1158.

Dissado, LA, Mazzanti, G & Montanari, GC 1997, “The Role of Trapped Space Charges in the Electrical Aging of Insulating Materials”, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 4, No 5, pp. 496-506.

Dissado, LA, Mazzanti, G & Montanari, GC 2001, "Elemental strain and trapped space charge in thermoelectrical aging of insulating materials", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 8, No. 6, pp. 959-971.

Dissado, LA, Mazzanti, G & Montanari, GC 2001, "Elemental strain and trapped space charge in thermoelectrical aging of insulating materials. Life modelling", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 8, No.6, p 966- 971.

Fothergill, JC 2007, "Ageing, Space Charge and Nanodielectrics: Ten Things We Don't Know About Dielectrics", *Proceedings of International Conference on Solid Dielectrics*, Winchester, UK, July 8-13, pp. 1-10.

Futakawa, A 1981, "Dynamic Deformation and Strength of Stator end Windings During Sudden Short Circuits", *IEEE Transactions on Electrical Insulation* Vol. EI-16, No.1, pp.31-39.

Futakawa, A, Hirabayashi, S, Tani, T & Shibayama, K 1978, Mechanical fatigue characteristics of high voltage generator insulation, *IEEE Transactions on Electrical Insulation*, Vol. EI-13 No. 6, pp. 395-402.

IEC 60505, ed4.0, 2011-07-11, *Evaluation and qualification of electrical insulation systems*.

Jones, JP, Llewellyn, JP & Lewis, TJ 2005, "The contribution of field-induced morphological change to the electrical aging and breakdown of polyethylene", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 12, No. 5, pp. 951- 66.

Kelen, A 1976, "The Functional Testing of HV Generator Stator Insulation", *CIGRE*, Paris, Paper 15-03.

Kimura, K 1993, "Progress of Insulation Ageing and Diagnostics of High Voltage Rotating Machine Windings in Japan", *IEEE Electrical Insulation Magazine*, Vo1. 9, No. 3, pp. 13 – 20.

Kimura, K 1995 "Multistress Ageing of Machine Insulation Systems," *Annual Report of Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Virginia Beach, USA, pp. 205-210.

Lewis, TJ 2001, Ageing - A Perspective, *IEEE Electrical Insulation Magazine*, Vol. 17, No. 4, pp. 6-16.

Lewis, TJ 2002, "Polyethylene under Electrical Stress", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 9, No. 5, pp. 717-29.

Lewis, TJ, Llewellyn, JP & Van der Sluijs, MJ 1994, 'Electrically induced mechanical Strain in Insulating Dielectrics', *IEEE Annual Report CEIDP*, pp 328-333.

Lewis, TJ, Llewellyn, JP, Van der Sluijs, MJ, Freestone, J & Hampton, RN 1995, "Electromechanical Effects in XLPE Cable Models"', *Proceedings of 5th ICSD, IEEE Pub. 95CH3476-9*, pp. 269- 273.

Maughan, CV, Gibbs, EE, Giaquinto, EV 1970 "Mechanical Testing of High Voltage Stator Insulation Systems", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-89 , Iss. 8, pp. 1946 – 1954.

Mazzanti, G & Montanari, GC 2005, "Electrical aging and life models: the role of space charge", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 12, No. 5, pp. 876-90.

Mitsui, H, Yoshida, K, Ishizaka T & Yoshida, H 1985, "Insulation Degradation Characteristics Due to Mechanical Fatigue of Micaceous Insulation," *IEEJ Transactions*, Vol. 105, No, 3, pp. 142-148.

Montanari, GC & Lebok, FJ 1990, "Thermal Degradation of Electrical Insulating Materials and the Thermokinetic Background", *IEEE Transactions on Electrical Insulation*, Vol. 25, No. 6, pp. 1029-1036, 1990.

Notingher, PV & Plopeanu, M 2009, "Accelerated Development of Electrical Trees. Part I: Initiation of Trees", *EEA - Electrical Engineering, Electronics, Automatics*, Vol. 57, No. 4, pp. 11-19.

Notingher, PV 1983, *A Study of Electrical Machines Insulation Stresses*, PhD Thesis, Universitaty POLITEHNICA of Bucharest, Bucharest, Romania.

Notingher, PV 2002, *Insulation Systems*, PRINTECH House Ltd., Bucharest.

Notingher, PV 2005, *Materials for Electrotechnics. Structure. Properties*, Vol. I, POLITEHNICA PRESS , Bucharest.

Paloniemi, P 1981, Theory of Equalization of Thermal Ageing Processes of Electrical Insulating Materials in Thermal Endurance Tests I: Review of Theoretical Basis of Test Methods and Chemical and Physical Aspects of Ageing, *IEEE Transactions on Electrical Insulation*, Vol. EI-16, No. pp. 1-6.

Ramu, TS 1985, "On the Estimation of Life of Power Apparatus Insulation under Combined Electrical and Thermal Stresses", *IEEE Transactions on Electrical Insulation*, Vol. 20, No. 3, pp. 70-78.

Rowe, SW 2007, "Electrical Ageing of Composites: An Industrial Perspective", *Proceedings of International Conference on Solid Dielectrics*, Winchester, UK, July 8-13, pp. 401-406.

Rusu-Zagar, C, Notingher, PV, Navrapescu, V, Mares, G, Rusu-Zagar, G, Setnescu, T & Setnescu, R 2013, "Method for Estimating the Duration of Life Insulation of Electric Motors, *Proceedings of 8th International Symposium on Advanced Topics in Electrical Engineering*, Bucharest, Paper MATEL P3, pp. 1-6.

Sayers, PW, Lewis, TJ, Llewellyn, JP & Griffiths, CL 2000, "Investigation of the Structural Changes in LDPE and XLPE Induced by high Electrical Stress", *IEE DMMA, Conf. Pub. No. 473*, pp. 403-407, 2000.

Simoni, L 1980 "Life Models for Insulating Materials under Combined Thermal-Electric Stress", *Colloquim of Professional Committee of IEE*, Group-52, pp. 1-10.

Srinivas, MB & Ramu, TS 1992, "Multifactor Aging of HV Generator Stator Insulation Including Mechanical Vibrations", *IEEE Transactions on Electrical Insulation*, Vol.27, No. 5, pp. 1009 – 1021.

Sumerder, C & Weiers, T 2008, "Significance of Defects Inside In-Service Aged Winding Insulations", *IEEE Transactions on Energy Conversion*, Vol. 23, No. 1, pp. 9-14.

Trnka, P, Sirucek, M, Svoboda, M & Soucek, J 2014, "Condition-Based Maintenance of High-Voltage Machines—A Practical Application to Electrical Insulation", *IEEE Electrical Insulation Magazine*, Vol. 30, No. 1, pp.32-38.

Tsukui, T, Takamura, M & Kako, Y 1980, "Correlations between Nondestructive and Destructive Tests on High-Voltage Coil Insulations for Rotating Machines", *IEEE Transactions on Electrical Insulation*, Vol. EI-15, No.2, pp. 118-127.

Wichmann, A 1977, "Accelerated Voltage Endurance Testing of Micaceous Insulation Systems for Large Turbogenerators Under Combined Stresses", *IEEE Transactions PAS*, Vol. 96, no. 1, pp. 255-260.

Wichmann, A 1983, "Two Decades of Experience and Progress in Epoxy Mica Insulation Systems for Large Rotating Machines", *IEEE Transactions PAS*, Vol. 102, pp.7 4-82.

Younsi, K, Neti, P, Shah, M, Zhou, JY, Krahn, J, Weeber, K & Whitefield, CD 2010, "On-line Capacitance and Dissipation Factor Monitoring of AC Sator Insulation," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 17, No. 5, pp. 1441–1452.

Zhidong, J 2006, "The Degradation Assessment of Epoxy/Mica Insulation under Multi-Stresses Aging," *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 13, No. 2, pp. 415–422.