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Application of the FDS method for assessment of HV epoxy–mica–glass insulation

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The mechanism of degradation of epoxy–mica–glass insulation has been investigated as well as its kinetics depending on service conditions. The most important factor there is production quality. Basics of dielectric spectroscopy in time and frequency domain and application of this method for estimation of HV insulation condition were described. Research conducted on insulation models showed that good indicators of insulation conditions are the value of charge and time of relaxation in low frequencies range. An example of application of FDS measurements was given for estimation the quality of technology in postproduction tests. The method is very accurate and allows identifying defective production technology and insulation aged in service.

Key words: *epoxy–mica–glass insulation; FDS; quality test*

1. Introduction

The most commonly applied insulation structure in HV machines is thermosetting composite epoxy–mica–glass. Depending on the technological advancement of a producer, this composite is manufactured in the processes of impregnating successive layers of mica and glass mat with epoxy resin or vacuum pressure impregnation (VPI). Most difficulties in achieving the appropriate quality of the final product are in processing technology. To the most frequent defects belong gas caverns in an insulation volume, insufficient adhesion of a resin to fibreglass and mica or improperly cross-linked resin.

Measurements of long-time dielectric strength of composite layer insulation show that even using materials of a very good quality cannot guarantee long period of insulation operation if proper processing methodology has not been applied [1]. The presented examples (Fig. 1) confirm observations that first inclusions appear during the production process. Their number and geometry depend on production technology and

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its quality [2]. In the first case (VPI – Fig. 1a) the most common defect is delamination of interface resin–glass or mica. On the other hand, in impregnation technology the usual defect is formation of inclusions (Fig. 1b). The other kinds of defects, also having a vital role, appear in the structure of resin reinforcement interface and result from physicochemical phenomena during cross-linking process.

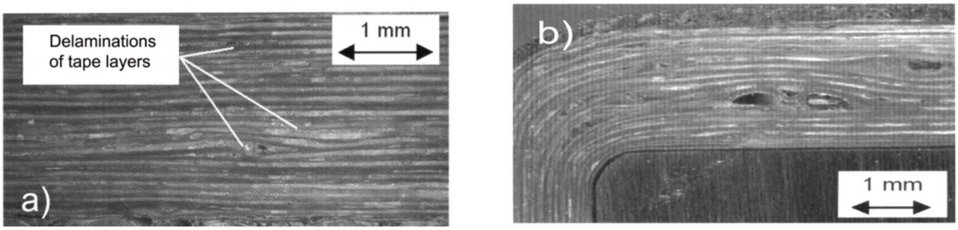

Fig. 1. Examples of improperly manufactured HV composite insulation [1]

Quite complicated process of fabrication of insulation (e.g., the VPI method) may lead to formation of "rubber" regions between the polymer liquid and completely polymerised area. These regions stop the resin from flowing into free spaces of reinforcement. This situation, characteristic of the first stage of polymerisation, is irreversible [3].

A typical property of all kinds of composite insulations are internal mechanical stresses. They can be formed during natural matrix shrinkage, during gelation but also due to differences in thermal expansion of the matrix, reinforcement or filler. For example, in fibreglass–resin structure, cutting tensions for 115 °C reach the value of ca. 20 MPa [4]. It was found [5] that during cooling down a composite from curing to room temperature, for ca. 1 μm distances between fibres, stretching stresses appear with the values up to 50 MPa, which are higher than the composite strength. Internal mechanical stresses are located mainly in the interface, which usually is the first place where cracking starts, even for small distances between fibres. According to many authors, the interface is the weakest point of the insulation structure, where environmental exposure is concentrated [6]. The influence of internal mechanical stresses on degradation of fibreglass based insulation was emphasized. Even small mechanical stresses, up to 10% of the permissible value, can lead to initiation of partial discharges (PD) [7].

2. Methods for production quality assessment

Understanding phenomena described above allows one to search for the best methods of identification of the interface condition and assessment of resin cross-linking level, both in the stage of production optimisation and quality control. Standard measurement techniques, used for many years, allow cavern detection (PD) or completely wrong resin processing (measurements of tanδ, insulation resistance, voltage test). In the case of assessing resin cross-linking level, an unambiguous method is the differential calorimetric analysis (DSC). By this method, the thermal capacity ΔC_p and glass transition temperature of polymer matrix T_g may be determined. Both of these parameters are strictly connected to morphological structure of the resin and contain information on the hardener selection and the level of reaction between the hardener and resin. For instance, in properly manufactured epoxy insulation of the B class, the glass transition temperature T_g is in the range 145–155 °C. For classes F and H these values are 185–190 °C and 210–215 °C, respectively. The obvious disadvantage of DSC measurements is necessity to take material samples from final products. Recently a method of identification of viscoelastic phase and space charge in the interface of composite insulation, based on dielectric relaxation measurements in ultralow frequencies (FDS) or in very long times (PDC) [8]. The basis for these methods is modified equivalent circuit of insulation, which consists of one relaxation structure in the range of high frequencies and of two such structures in medium (C_{MF}) and low (C_{LF}) frequencies (Fig. 2).

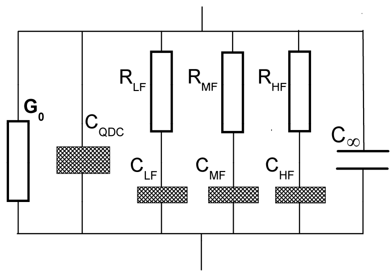

Fig. 2. The equivalent circuit of a composite insulation

In most cases, the dipole relaxation in composites of high molecular mass and apparent phase boundary proceeds at asymmetric or continuous distribution of time constants, in accordance with Jonscher's universal response or the Havriliak–Negami (H–N) laws [9, 10]. On the other hand, the measurements of PDC in those laminar materials have proved that the distribution, following the fractional exponent law $i(t) \propto t(-n, -m)$ [8], always accompanies relaxation processes. Thus, to reflect the nature of the processes, the equivalent insulation composite model (Fig. 2) should have capacitors CLF, CMF and CHF, which should satisfy the dipole relaxation requirements by Jonscher. Nonetheless, the loss capacity CQDC represents the DC response according to Jonscher.

In the frequency domain, the equivalent circuit in Fig. 2 can be described with the Havriliak–Negami function as follows [10]:

$$\varepsilon^*(\omega) = \sum_{k=1}^{3} \frac{\Delta\varepsilon_k}{\left(1+(\omega\tau_k)^{\alpha_k}\right)^{\beta_k}} + \varepsilon_\infty - j\left(\frac{\sigma}{\omega\varepsilon_0}\right)^N \tag{1}$$

where: $\varepsilon^*(\omega)$, ε_∞ are the complex and optical dielectric permittivity, $\Delta\varepsilon$ – polarizability, σ_0 – dc conductivity, τ – relaxation time, α, β, N – constants, ω – pulsation.

The theoretical grounds of the application possibility of the H–N equation to the analysis of relaxation processes in thermosetting composites in LF and MF range are given in [8]. Based on the model investigations, the criteria for the assessment of the epoxy–mica–glass insulation quality with use of FDS measurements have also been presented there. Values of times τ_{LF}, τ_{MF}, dispersion of relaxation times α_{LF}, α_{MF}, polarizability $\Delta\varepsilon_{LF}$, $\Delta\varepsilon_{MF}$ and conductivity σ_0 are basic coefficients characterizing insulation. The hardening level of a resin and the presence of the viscoelastic phase can be identified based on the coefficients τ_{LF}, α_{LF}, $\Delta\varepsilon_{LF}$. In the case of resin hardened improperly, when viscoelastic phase occurs, usually short times of the relaxation are obtained ($\tau_{LF} < 400$ s) with relatively large values of the coefficients α_{LF}, $\Delta\varepsilon_{LF}$ ($\alpha_{LF} \geq 0.6$). However, the aged resin is characterized with high polarizability $\Delta\varepsilon_{LF}$ and a wide dispersion of the relaxation times (α_{LF} between 0.1 and 0.3). Viscoelastic phase, large inhomogeneity and delamination are associated with the space charge which can be characterized by the relaxation times on the level of several tens of seconds and the dispersion coefficient α_{MF} in the range 0.5–0.9.

Application of Eq. (1) for assessment of composite insulation manufacturing quality needs measurements of capacitance C_{coil} and losses coefficient $\tan\delta$ of windings in the frequency range 0.1 mHz–100 Hz. Then, by the analysis of the characteristics of electric permittivity of the insulation ($\varepsilon' = C_{\text{coil}}/C_0$) and analysis of its losses ($\varepsilon'' = \varepsilon'\tan\delta$), dipoles and space charge relaxation time τ, polarizability $\Delta\varepsilon$, and conductance σ are determined.

3. Experiences in assessment of the epoxy–mica–glass insulation

3.1. Assessment of insulation of 6 kV motors stator coils

Application of FDS and PDC measurements for assessment of quality of final products may be presented on an example of epoxy–mica–glass insulation of 6 kV motor stator coils. It was the layer epoxy–mica–glass insulation and the coil had been delivered to recipient within the order on larger quantity. The analysis of the real and imaginary part of complex permittivity, based on Eq. (1), showed that in the range 10^{-1}–10^{3} Hz large relaxation structure can be found, which predominates high and low frequency relaxations. Calculated relaxation parameters ($\tau = 0.023$ s, $\alpha = 0.21$, $\beta = 0.79$, $\sigma = 1.2\times10^{-16}$ S/m) prove, that these are dipole processes of the H–M model with wide and asymmetrical dispersion. The value of time constant τ indicates that this relaxation structure is a large viscoelastic phase, as β relaxation of hardened resin is in the range 10^{-6}–10^{-8} Hz, while time constant of space charge polarization in the phase interface is ca. 10^{1}–10^{3} s.

In inappropriately cured thermosetting composites chemical reactions may occur. They are very slow and can last even for a few years. Taking above under consideration, the coil was tested again after 18 months of the seasoning at ca. 20 °C and relative humidity $RH \approx 70\%$. The analysis of losses ($\varepsilon'' = f(f)$) showed that in the insulation a space charge appeared, with the relaxation time $\tau \approx 27.5$ s (Fig. 3). Its value was so high, that it had prevailed over other relaxation processes.

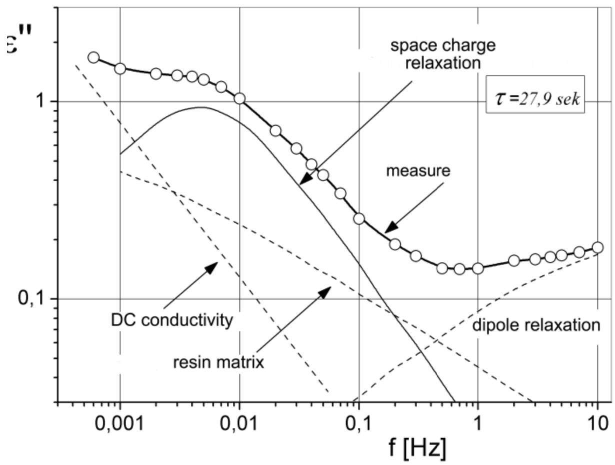

Fig. 3. Analysis of losses characteristic of
6 kV motor coil after 18 months of seasoning

Based on technological processes, discussed above, it can be assumed that this relaxation comes from heterocharge in the interface, generated due to delamination or chemical corrosion. The conclusion can be drawn that mounting this coil in a motor would lead to significant decreasing its lifetime. Service experiences show that a few hard starts of a motor connected with increase temperature of insulation up to 150 °C is enough for insulation failure.

3.2. Assessment of insulation of 15.75 kV generator stator bar

Epoxy–mica–glass insulation manufactured by the MICADUR method has been assessed, taken from stators bars of 230 MVA, 15.75 kV generator. The following samples were examined:

- sample A – a new winding bar ready to be installed in a generator,
- sample B – a bar with regenerated insulation. It had been operated for several years and had its antiarcing layer mechanically removed, insulation losses filled up with chemosetting epoxy composite and new antiarcing layer put on it,
- sample C – a bar from stator winding, operated for several years.

In a new insulation of a generator bar (Fig. 4, sample A) in VLF range the relaxation with time constant $\tau_{LF} = 3.4\times10^4$ s has been observed. The model research [8] and parameters α_{LF} 0.35, β_{LF} =1 derived from Eq. (1) show that this is VLF dielectric response resulting from current flow and ion mass transport. High value of time constant τ_{LF} and low conductivity σ = 1.1×10^{-16} S/m indicate that in VLF range there is no space charge relaxation or free terminal groups of resin and hardener, which have not gone through reactions. The high value of polarizability ($\Delta\varepsilon_{LF}$ = 5.35) usually occurs in disordered structures which is typical of a new epoxy–mica–glass insulation system in which no relaxation of physical structure takes place. This kind of relaxation consists in decreasing free spaces between molecules and improving polymer structure without chemical changes. All these parameters lead to conclusion that insulation from sample A has attributes of a new, properly manufactured composite insulation with correct structure of resin–reinforcement interface, without delamination and presence of unreacted terminal groups of the resin and hardener.

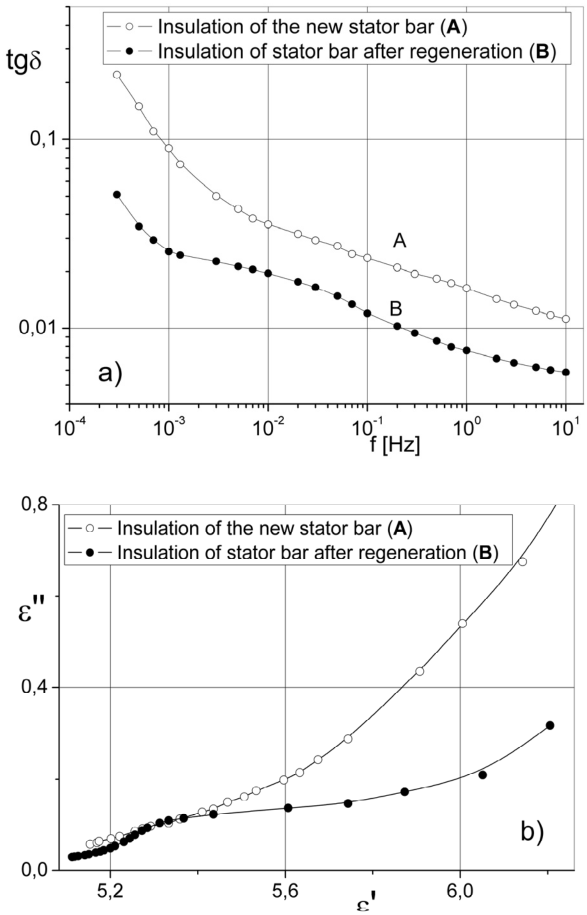

Fig. 4. Loss factor vs. frequency and the Cole–Cole relationships for the new stator bar (A) and the bar after regeneration (B)

In the case of regenerated insulation (Fig. 4, sample B) in the MF range relaxation was observed with the parameters τ_{MF} = 43 s, α_{MF} = 0.64, β_{MF} = 1, $\Delta\varepsilon_{MF} \approx 0.7$, which comes from space charge. It is probably located in the interface between existing epoxy–mica–glass composite and the new layer of insulation, or it may be a result of improper hardening of the chemosetting resin during regeneration. In both cases, such a charge may lead to electrical treeing after long period of operation. Therefore, in this case it is recommended to control quality of insulation after next 1.5–2 years of operation with application of FDS or PD measurements.

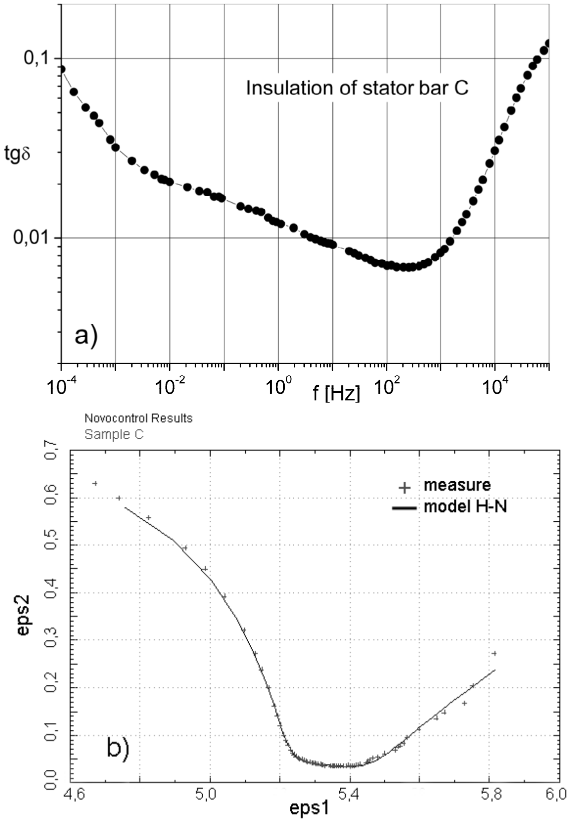

Fig. 5. Loss factor vs. frequency (a) and the Cole–Cole relationships (b) for the stator bar C

In FDS measurements for insulation from exploited generator bar (Fig. 5, sample C) taken in the frequency range 0.1 mHz–1 MHz, two main relaxation processes were found.

The former one occurs in the VLF range, with the parameters $\tau_{LF} = 5.3\times10^3$ s, $\alpha_{LF} = 0.47$, $\beta_{LF} \approx 1$, $\Delta\varepsilon_{LF} \approx 1.46$ similar to relaxation observed in sample A and in previously obtained results for generator bar insulation after four years of operation [11]. The analysis of these results leads to conclusion, that in sample C structure changes took place, typical of the early period of ageing, when resin structure is getting physically stabilized and mechanical parameters are improved without any chemical reactions.

The other process occurring in the HF range, linked with β relaxation of the resin, is influenced mainly with side groups, ion contaminations contained in unreacted resin and hardener. Very short relaxation times and relatively low polarizability (τ_{HF} = 3.9×10^7 s, α_{HF} == 0.7, $\Delta\varepsilon_{HF} \approx 1.9$) suggest that in this case dominating compounds are side groups linked with resin without interaction from unreacted terminal groups of resin and hardener. It can be concluded that in sample C polymer matrix is properly hardened and in the insulation no space is present in resin–reinforcement interface or amorphous phase with high polarizability, typical of deteriorated resin. It should be pointed out that these conclusions have been verified with MDSC and DTMA tests.

Differences in relaxation processes in samples A and C result mainly from physical stabilization of insulation structure in sample C under vibrations and higher temperature of operation (ca. 50 °C).

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