Contemporary Diagnostic Methods of HV Rotating Machine and Transformer Insulation

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Abstract
Dielectric polarization of insulating materials is analyzed to assess the condition of HV motor insulation. Ramp application of the test voltage, measurement of the dielectric loss factor (*tg***δ**), and capacitance at very low frequency (***F****requency* ***D****omain* ***S****pectroscopy*) are used to evaluate the condition of composite solid insulation. Examples of large HV rotating machines are presented that experienced different operating conditions. It has been concluded that FDS can be used to assess the condition of "epoxy-mica-glass" insulation in service and during production, as well as acceptance tests.
Measurements of ***P****olarization and* ***D****epolarization* ***C****urrent* (PDC), as well as FDS are employed to evaluate the condition of paper-oil insulation of HV transformers. A co-relation between cellulose conductivity and certain parameters of PDC can be used to assess the condition of paper-oil insulation, and specifically its water content. Measurements have confirmed an agreement between the water content determined using FDS and the ***R****ecovery* ***V****oltage* ***M****easurements* (RVM).

INSULATION DIAGNOSTICS OF HV MOTORS AND GENERATORS

Ageing process of insulation in service

Composite "epoxy-mica-glass" insulation is commonly used for to stator windings of rotating machines. Usually ***V****acuum-****P****ressure* ***I****nsulation* (VPI) technology is employed, and different manufacturing processes are employed by different makers. Superposition and impregnation of subsequently laid insulation layers is also used. Ageing of such insulating structures depends on the mechanical stress, vibrations and temperature [1, 2].
These factors may result in de-lamination at the interface between epoxy resin and mica, or reinforcing material and result in electrical treeing. An insulation with improperly cured epoxy, or with a weaken adhesion between the resin and reinforcing fibers is prone to a faster degradation under electric field stress. Mechanical stress and vibrations change the insulation structure without significant chemical reactions. They may result in a change of packing density and breaking adhesion ties at the materials interface. However, chemical hardening and physical relaxation of the insulation are dominant processes at the temperature lower than polymer matrix vitrification (T_g). The thermal ageing starts a few tens degrees above this temperature (T_g), and overheating for extended time results in de-lamination and electrical treeing. It follows that a sufficiently low working-temperature is essential for reliable operation of HV rotating-machine insulation. To attain this objective, the correct hardening technology of the composite insulation is the major pre-requisite.
Changes of the insulation morphology occur at the interface "epoxy resin – reinforcing fibers" during hardening, physical relaxation and ageing [1, 2, 3]. Such changes generate a space charge that changes the dielectric relaxation, as predicted by Maxwell-Wagner theory. Similar effects are also observed at the pre-hardening, and final hardening of the epoxy resin. It follows, that monitoring the dielectric relaxation can reveal changes in the insulation properties, such as de-lamination. Recording of the insulation leakage-current induced by ramp application of the test voltage is recommended by the IEEE standard as one of the diagnostic test of rotating machine insulation, in addition to the resistance and absorption co-efficient measurement, as well as detection of partial discharges. Recently measurements of tg**δ** and capacitance at the very low frequency-range, and of the polarization-depolarization current [3, 4] are gaining popularity, and have been recognized as efficient diagnostic methods.

Test voltage ramp as the method to asses the condition of rotating-machine insulation

The current induced by five subsequent steps of the DC voltage by $\Delta U=0.3U_N$, in the range from 0.3 to $1.5U_N$, is used to assess the condition of rotating-machine winding-insulation. The test voltage is applied for 10 minutes at the first step, and for 5 minutes during the subsequent steps. It has been assumed that the insulation resistance does not depend on the test voltage level, and that the polarization current decays exponentially. With these assumptions, one can calculate i_{30} and i_{30C}, and measure i_{30M} after 5 minutes from the time the test voltage attained $1.5U_N$. A detailed description of the test procedure is given by the IEEE Standard No.4, 1978, "Standard for High Voltage Testing". An absorption co-efficient K_a is used to assess the examined insulation condition: $K_a = \frac{i_{30M}}{i_{30C}}$.

This co-efficient amounts to $K_a \leq 2$ for new, good quality insulation based on epoxy resin, but may attain $K_a > 5$ and even $K_a > 7$ in the case of a severely degraded insulation.

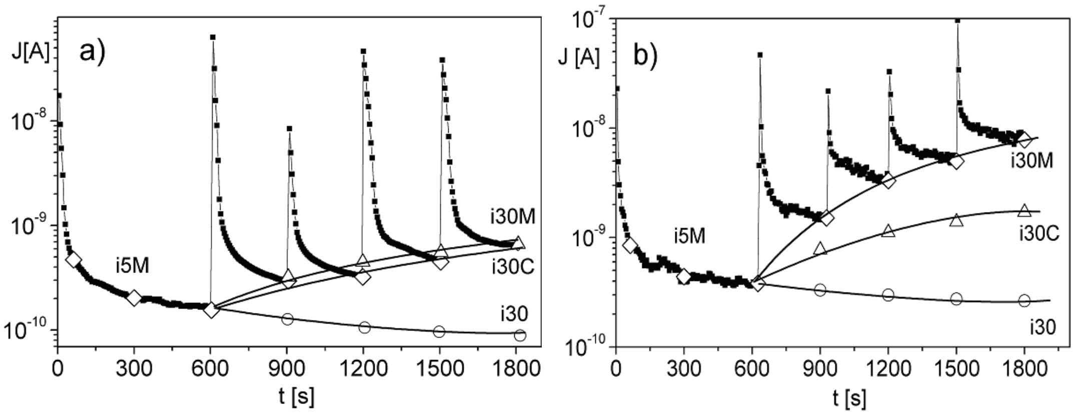

Fig. 1. Record of the leakage current of a new (a) and aged (b) winding insulation of 6kV motor.

To illustrate the test voltage ramp method an aged, overheated stator-winding insulation was examined and compared to a new one. The calculated value i_{30C} is close to the measured value i_{30M} for the new insulation, whereas i_{30C} is much lower than i_{30M} in the case of aged insulation. The calculated respective absorption co-efficient Ka=0.88÷1.09 and Ka=4.7 confirm initial assumptions and expectations of the insulation diagnosis.

Condition assessment of rotating machine insulation using low frequency spectroscopy

Principles of the **F**requency **D**omain **S**pectroscopy (FDS) are described in [3], and its practical implementation to the condition assessment of HV insulation consists in measurement of capacitance C and dielectric loss-factor tgδ as a function of frequency in the range from 0.1 mHz to 100 Hz.
Havriliiak-Negami equation describes dielectric relaxation in polymers and their composites:

$$\varepsilon^*(\omega) = \varepsilon' + j\varepsilon'' = \frac{\Delta\varepsilon}{\left(1 + (\omega\tau)^{\alpha}\right)^{\beta}} + \varepsilon_{\infty} - j\left(\frac{\sigma}{\omega\varepsilon_0}\right)^N \qquad (1)$$

where: $\Delta\varepsilon$ – polarization, $\omega = 2\pi f$ – pulsation, τ – relaxation time constant, σ – conductivity, α, β, N – coefficients, $\varepsilon^*(\omega)$, ε_∞, ε_o – complex, optical and static dielectric permittivity (*dielectric constant* is used in engineering texts, but in reality ε is variable).

In general, this equation links frequency dependent dielectric permittivity of insulation $\varepsilon' = U_{uz}/C_o$ and its real component describing the dielectric loss $\varepsilon'' = tg\boldsymbol{\delta}\cdot\varepsilon'$ with physical properties of the material, such as relaxation time constant τ of dipoles and space charge, polarization Δε, and conductivity σ. With the coefficients α, β, N, these parameters form the base to determine the insulation properties in quantitative terms.
A mica-glass HV-insulation condition-assessment by frequency domain spectroscopy (FDS) in presented on an example of 4 motors and 2 generators of a different rated power and operational history. This last item is of a particular practical importance, since the final conclusion of diagnostic tests depends on the detailed knowledge of the insulation history of repairs, overheating, mechanical and dielectric stress endured over the years of service. For instance, the motor #1 presented in our example had the winding changed, and the insulation should be considered as new despite a long service time of the motor. Motor #2 has been operated for 10 years under moderate load conditions, and its insulation temperature varied within 40°C to 70°C range, much below T_g. Motors #3 and #4 have been operated for 4 years and 10 years, respectively, under heavy overload conditions caused by switching-on under the full load (#3), and temporary overloads (#4) that resulted in the temperature rise to 130°C, and even to 150°C.
Measurements were taken on the winding rod removed from the 230 MVA, 15.75 kV generator stator after 4 years of service, and on a new rod.
A comparison of the insulation condition indicated the lowest operational exposure of the generator windings, then #2 motor, and the most degraded insulation of #4 motor.

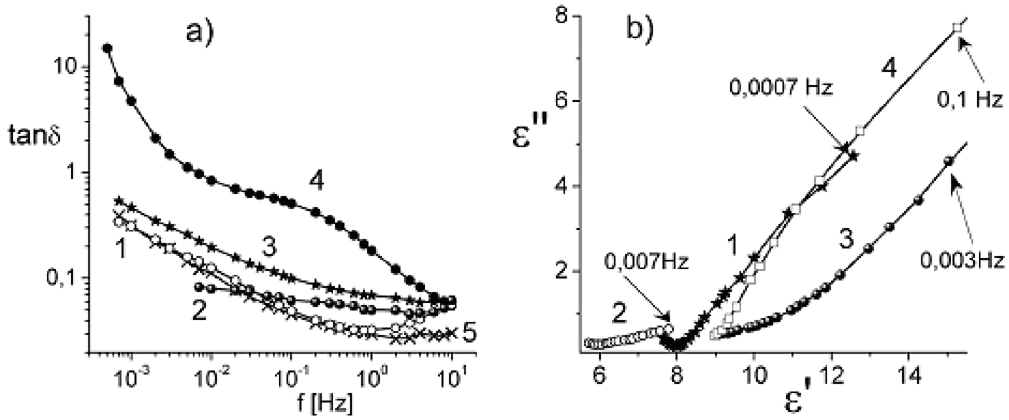

Fig. 2. Recorded characteristics of the examined insulation a) tg**δ**=ψ(f) and b) Cole-Cole diagram. Respective graphs obtained on 6kV motors #1, #2, #3 and #4, and on the new stator coil of #5 generator.

The tg**δ**=ψ(f) graphs reveal a higher dielectric-loss of #1 motor (with new insulation) than #2 motor, in the frequency range below 0.1 Hz, but somewhat lower than #3 motor. The Cole-Cole diagram has indicated a significant change of the insulation capacitance, i.e. its dielectric permittivity ε'.
A shorter relaxation time constant τ, a smaller polarization Δε, and an increased conductivity σ of mainly ionic character result from an extended service time of #2 motor working under moderate load conditions. These changes lead to a lower dielectric loss ε" of the insulation, and can be observed on the Cole-Cole graph as a shift of ε"=φ(ε') characteristic to the left.

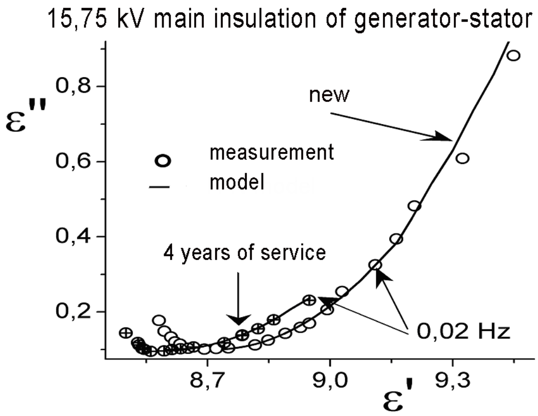

Fig. 3. Recorded (**o**) and simulated (**—**) Cole-Cole diagram of MICADUR insulation of 15.75 kV generator stator. Main insulation of the stator: new and after 4 years of service.

A similar effect is observed in Fig. 3, where #5 generator insulation ε"=φ(ε') characteristic was also slightly shifted to the left after 4 years of service. However, a shorter service time, and a lower insulation temperature resulted in relatively smaller change of polarization Δε and capacitance.

Model studies revealed such changes of composite insulation polarization-properties in an early stage of ageing [3]. It consists of hardening, physical relaxation, stabilization of physical and chemical properties, as well as improvement of mechanical parameters. A good condition of #2 motor insulation was assessed due to these factors. However, insulation of #3 motor was qualified as aged, and #4 motor insulation as severely degraded. Very high ionic conductivity (σ_o=1.1 pS/cm) and polarization Δε with a short relaxation time constant (τ =28 s) imply presence of large and mobile space charge in the interface area. This may reveal delamination and caverns between the polymer matrix and reinforcement (mica, glass) [1].
The relaxation time constant τ and polarization Δε of the #1 motor and #5 generator winding-insulation indicated a significant difference. The respective values, shown in Table 1, amounted to Δε = 45.62 and $\tau = 1.3\cdot10^4$ s, as compared to Δε = 2.02 and τ = 880 s. This difference was caused by non-stechiometric hardening of the motor insulation. Such insulation is characterized by a large number of non-filled areas and viscous-elastic phase, which accelerate ageing under thermo-mechanical stress [3]. This insulation will be more susceptible to degradation, despite the popular belief that an extended operation at a high temperature may improve the insulation, which was incorrectly hardened at the manufacturing stage.

Table 1. Parameters of dielectric relaxation in the motor and generator insulation for f<10 Hz

Parameter	6kV Motors				15,75 kV Generator	
	# 1 200 kW	# 2 200 kW	# 3 200 kW	# 4 1250 kW	New winding	4 years winding
σ_0 [S/cm]	1e-20	5e-17	4e-15	1e-13	5e-16	5e-16
N	0,14	0,64	0,82	1,00	0,89	1,00
$\Delta\varepsilon$	45,62	8,03	51,63	53,36	2,02	1,62
τ [s]	1,3e+4	1,7e+3	2.3e+04	2,8e+01	820	820
α	0,66	0,22	0,38	0,56	0,47	0,43

These examples show that FDS has been an effective tool to assess the condition of polymeric insulation, to determine how far its ageing is advanced, and specifically to distinguish an incorrect hardening at the manufacturing plant and physical relaxation from the natural ageing. The obtained reveal flaws of the manufacturing process, and FSD can be used for routine, as well as acceptance tests. It is important to note concurrence of condition assessment of the examined polymeric insulation by measurements of its dielectric properties, and by simulation on the model, as well as by chemical analyses. However, knowledge of the machine operational history, and/or reference curves of the examined insulation provide important information.

INSULATION DIAGNOSTICS OF HV TRANSFORMERS

Measurements of resistance, the dielectric loss factor tg**δ** at power frequency, and calculation of the absorption co-efficient R60/R15 have been used for many years to assess the condition of paper-oil insulation. Capacitance between two windings has also been measured at 2Hz and at 50Hz, to derive C2/C50 ratio that reveals the moisture content in transformer main insulation. Recently, usefulness of these parameters to transformer diagnostics was contested [5]. New methods, based on dielectric-polarization relaxation in a broad frequency-range have been proposed [6]. Moisture content cellulose and its thermal degradation can be assessed using these methods. In consequence, the remaining technical life of the transformer can be assessed. Polarization **R**ecovery **V**oltage **M**easurements (RVM), and **P**olarization-Depolarization **C**urrent (PDC) records are taken in the time domain, whereas frequency characteristics of the insulation capacitance and dielectric loss factor tg**δ** are recorded in the range from 0.1 mHz to 100 Hz.

Polarization-Depolarization Current Method

This method may be perceived as a modification of traditional insulation resistance measurement and calculation of R60/15 quotient. A direct voltage is applied to the transformer insulation, and the resulting current charges capacitance of the examined insulation. This current is composed of polarization current i_{pol} that decays, and the constant current determined the insulation conductivity. Subsequently, the charged insulation is short-circuited and an opposite-polarity depolarization-current i_{dep} decays to zero. The rate of current decay depends on polarization relaxation of the paper-oil insulation, and contains several exponential components [5, 6].

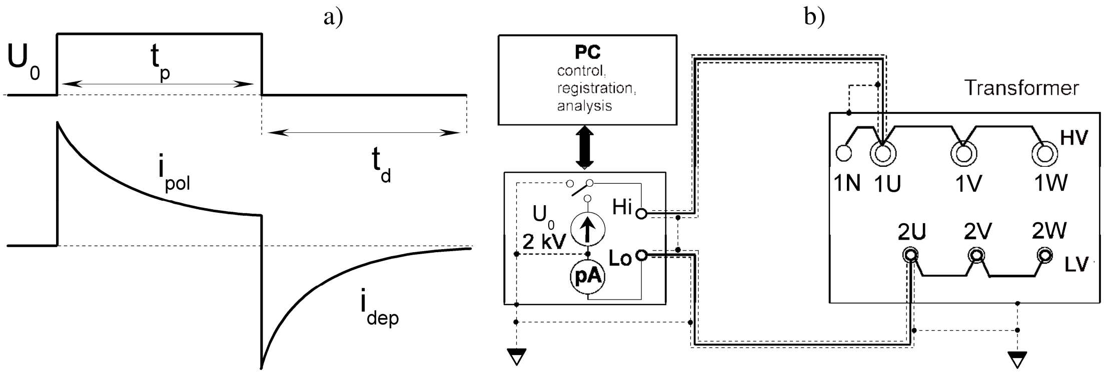

Fig. 4. a) Test voltage U_o applied for time t_p, and the resulting polarization i_{pol} and depolarization i_{dep} current.
b) Typical test circuit of transformer main insulation, with computer-controlled voltage-source and electrometer.

The transformer oil conductivity determines the polarization current magnitude during first 100 s. This conductivity depends on the water content in oil, its acid number, contamination and temperature. The polarization current intensity is proportional to oil conductivity that can be derived from the initial value of i_{pol}. Water content in cellulose (barriers, spacers) can be derived from the i_{pol} and i_{dep} characteristic after 100 s.

Increased water content in cellulose accelerates depolarization and results in a faster decay of i_{dep}, as well as in an increase of i_{pol} after 100 s (Fig.5).

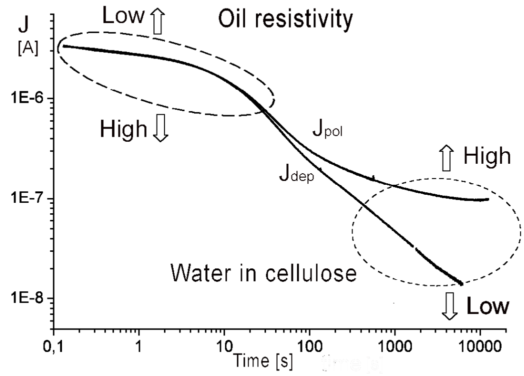

Fig. 5. Polarization i_{pol} and depolarization i_{dep} current plotted against time t_p, with the water content in oil and in cellulose as parameters.

Specialized expert programs compare the i_{pol} and i_{dep} characteristics taken on an examined transformer to the respective curves obtained on pre-conditioned Transformerboard® samples with a known water content and cellulose degradation. Transformer diagnostics in service often relays on a comparison of the characteristics taken on similar transformers, or at subsequent inspections of the same unit. Such procedure allows for identification of transformers that represent a higher operational risk, and scheduling their repairs or decommissioning.

a) b)

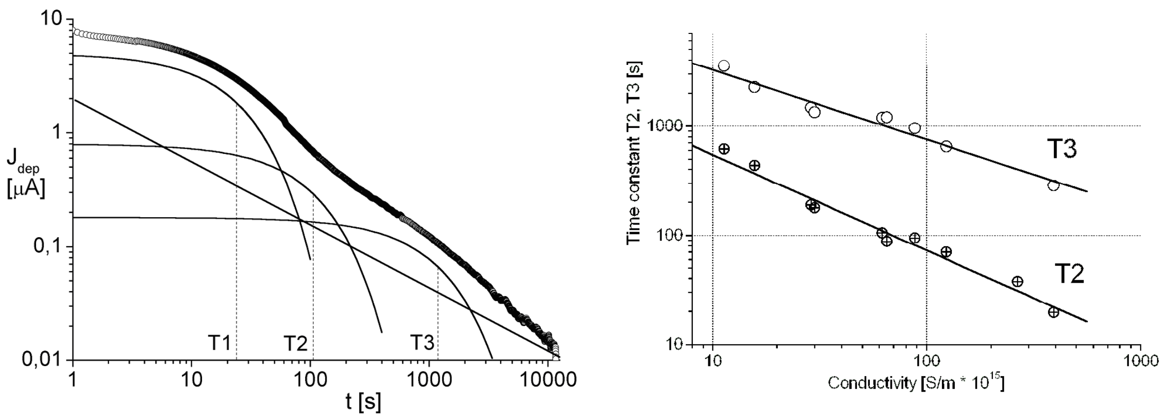

Fig. 6. a) Identification of the i_{dep} exponential components and their time constants. b) The time constants T2 and T3 plotted against cellulose conductivity.

An example of 270 MVA, 220/15kV transformer is shown in Fig.6, where the measured i_{dep} characteristic was analyzed and water content in cellulose determined by comparison to reference data from Transformerboard® samples.

Frequency domain spectroscopy

FDS measuring procedure and the test circuit are the same as used for the time domain measurements, and shown in Fig. 4. An examined insulation capacitance C and tgδ low-frequency characteristics depend on temperature, insulation degradation and water content. This relation has been determined and an effect of increased water-content in cellulose and oil on C and tgδ was associated with certain frequency ranges (Fig.7).

Reference frequency characteristics of capacitance and tgδ have been determined in laboratory conditions for different insulation samples with controlled ageing and water content. They are built-in the software provided by manufacturers of the FDS measuring instrument to facilitate interpretation of recorded curves. Geometry of the examined winding has to be input together with the transformer nameplate data, and the program assesses the insulation condition in terms of ageing and water content. A database of the reference characteristics should preferably be developed for a given type and make of the paper-oil insulation, since the material characteristics do differ, and there are no universal reference curves.

Another approach consists in using the equation (1) and examining the relaxation characteristic of the examined insulation. Such analysis is presented on an example of 75 MVA, 110/10.5 kV transformer manufactured in 1988. Two relaxation time constants τ_1=12.1 s and τ_2=294 s were identified from C and tgδ characteristics (Fig.8) taken on the main insulation at 20°C. The faster relaxation occurs at the oil-cellulose interface, and the slower one reflects properties of Transformerboard® with a high water content.

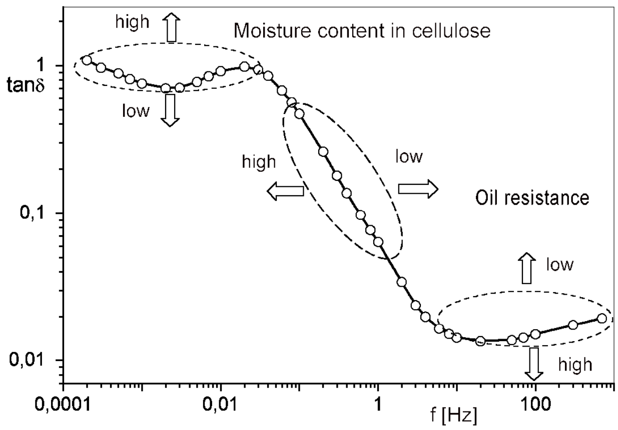

Fig.7. Frequency characteristic of tgδ reveals water content and oil resistance in different frequency ranges.

Water content in cellulose can be assessed using nomograms used by the recovery voltage measurement (RVM) method, since it is based on the time constant of interfacial relaxation. The relaxation time-constant of solid insulating materials, such as Transformerboard®, have to be obtained from the material samples examined in the laboratory.

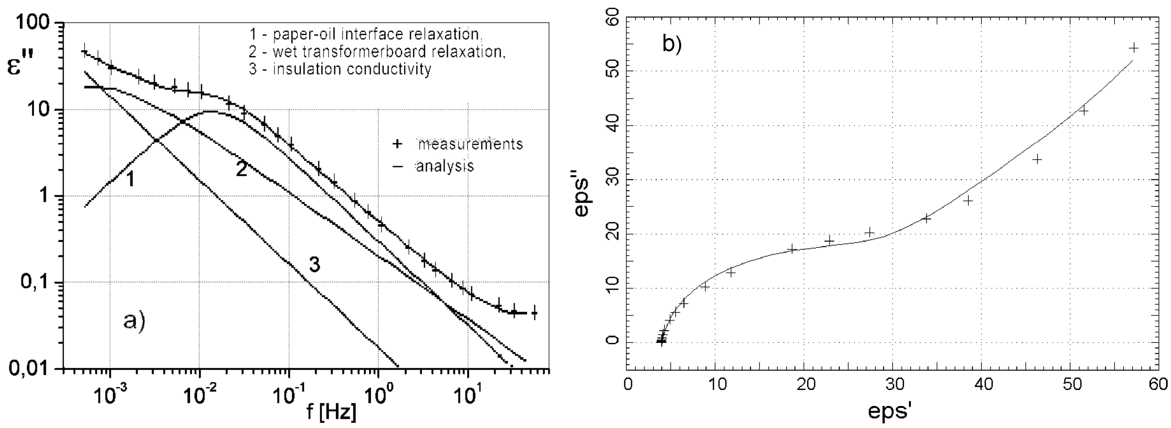

Fig. 8. a) Identification of two relaxation time-constants τ_1 and τ_2 from tgδ frequency characteristic, b) Cole-Cole graph derived from measurements taken on 75 MVA, 110/10.5 kV transformer.

Additional parameters derived from these characteristics are given in Table2.
Water content in the examined insulation was assessed at 3.2% from the time-constant of the interfacial relaxation, and at 3.3% from the relaxation time- constant measured on the Transformerboard® samples, taking into account the temperature corrections.
An important advantage of the FSD methods lies in finding the insulation water-content even if the water-content in cellulose and in oil are not in equilibrium. This method can separate the two polarization structures: at the paper-oil interface and in solid insulation, i.e. Transformerboard®. It should be emphasized that the polarization behavior of wet cellulose is relatively stable, but the properties of paper-oil interface depend on the water-content equilibrium and on products of oil decomposition [5, 7].

Table 2. Dielectric relaxation parameters from measurements taken on 75 MVA, 110/10.5 kV transformer.

Parameter	σ_0 S/cm]	$\Delta\varepsilon_1$	τ_1 [s]	α_1	$\Delta\varepsilon_2$	τ_2 [s]	α_2
Value	8,4· e-15	20,9	12,1	1,00	61,7	294	0,76

The same transformer was also examined using RVM method and the main time-constant Tp = 9.7 s is comparable to τ_1 = 12.1 s that corresponds to 3.3% water-content at 20°C.
In this case the moisture content in paper and oil are in equilibrium, as it is indicated by the well-defined, single peak of Ur and its slope Sr characteristics, as well as by the similar moisture-content obtained using FDS method. Apparently no oil-decomposition products are deposited on the Transformerboard® surface.

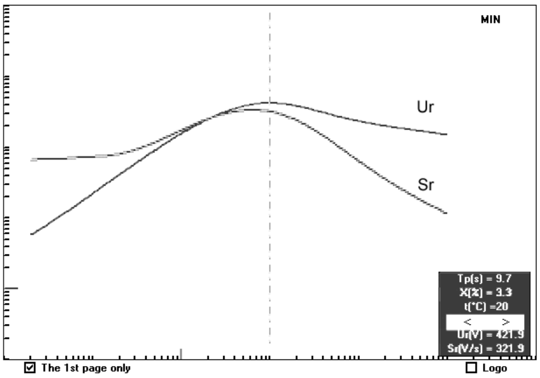

Fig. 9. Time-domain RVM characteristics measured on 75 MVA, 110/10.5 kV transformer insulation: U_r- the polarization recovery voltage and S_r-initial steepness of Ur characteristic.

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