

# Determination of Thermal Ageing Influence on Rotating Machine Insulation System Using Dielectric Spectroscopy

**Abstract.** The electric rotating machines have to meet the requirements in terms of safety, reliability and efficiency. This paper discusses the measurement dielectric spectroscopy of coils in asynchronous 6 kV driver before and after thermal ageing. Measurements for low frequencies were made by Isothermal Relaxation Current analysis, which is a non-destructive DC diagnostic measurement method for electrical machines. Measurements for high frequencies were made directly with LCR meter.

**Streszczenie.** Artykuł przedstawia pomiary metodą spektroskopii dielektrycznej izolacji uzwojeń w maszynie wirującej przed i po starzeniu. Dla małych częstotliwości przeprowadzono analizę prądu izotermicznej relaksacji. Przy dużych częstotliwościach wykorzystano miernik LCR. (Badanie wpływu starzenia termicznego maszyn elektrycznych metodą spektroskopii dielektrycznej)

**Keywords:** IRC analysis, insulation system of rotating machine, coil, thermal degradation.

**Słowa kluczowe:** izolacja maszyn wirujących, starzenie termiczne..

## Introduction

High-voltage rotating machines have to meet the requirements in terms of safety and reliability. These requirements are mainly related to electrical insulating system, which belongs to the most important parts of rotating electric machines (quarter of all failures still are related to insulation system) [1,2].

The insulating system is the most influenced by ageing process and this effect on insulating system can't be removed. Due to the ageing caused of thermal and electric stresses, defects as cavities, electric tree and others appear. They abbreviate lifetime of electric devices because of defect creation [3]. Since ageing can't be precisely defined, that is why tests are repeated at regular intervals (e.g. every two years).

It is important to know the state of electric devices insulation system as dependency of the operation time [4]. One of the methods for detecting the state of insulation ageing is isothermal relaxation current analysis (IRC - analysis). The IRC analysis is non-destructive diagnostic method and it is based on the monitoring of the current response (charging or discharging current) in time domain and transfer data to frequency domain. The other method is measuring of complex admittance in frequency domain directly and calculation of dielectric loss factor.

## Insulation of high-voltage rotating electrical machines

Rotating electric machines are used to convert electricity into mechanical energy and backward, depending on whether they work as a motor or a generator [5].

The asynchronous electrical machines are the most used electrical machines. Their power is from 100 W to hundreds kW. High-voltage insulation of stator winding can be divided into:

- insulation of coil and bars,
- slot section of insulation,
- insulation of end winding.

According to technology and mode of the binder we can divided insulation of high-voltage electrical machine to the two groups [6,7]. Resin-rich technology is based on three component composites (glass fabric, mica paper and suitable binder from 30 to 40 %). This composite is in a form of tape and is reeled continuously or discontinuously.

Primary role in VPI technology has absorbent mica tape, which is saturated by impregnant. The VPI consists of three components (glass fabric, mica tape and binder -7 %). Coils are multiwrapped by the tape.

## Dielectric relaxation spectroscopy (DRS)

For the diagnostic of dielectric materials was developed some of diagnostic methods. One of these methods is DRS.

The principle of method is investigation of electrophysical properties of dielectric materials. The polarization features can be observed in DC or AC electric field and according to this, the DRS can be divided into methods measured in frequency or time domain.

In general, properties of dielectrics can be characterized by the DC conductivity, relative permittivity and the dielectric response function.

Dielectric spectroscopy for the evaluation of the dielectric response in time domain uses polarization and depolarization current and in the frequency domain uses relative permittivity and dielectric loss factor. DRS uses these values for dielectric response evaluating.

Character measured in time domain is not suitable for precise evaluation of the dielectric properties investigated. The data measurement in the time domain must be transformed into the frequency domain. For this transformation Fourier transform is used in [9]

$$(1) \quad \hat{\varepsilon} = \varepsilon_{\infty} + (\varepsilon_s - \varepsilon_{\infty}) \int_0^{\infty} \varphi(x) e^{-j\omega x} dx$$

where:  $\varepsilon_s$  - static permittivity,  $\varepsilon_{\infty}$  - optic permittivity,  $\varphi(x)$  - function of decline.

## IRC analysis

The dielectric spectrum is one of the basis electrophysical characteristics of materials. The dielectric spectrum describes dependence of the selected dielectric variables on the frequency of forced signal. The main part of the dielectric spectrum in time domain is in the area  $10^{-3} \div 10^5$  s [6]. It is possible to monitor this area with DC measurement methods. These methods are based on monitoring of voltage (current) response. It was proven that there is a strong relationship between the mechanical, thermal and electrical ageing and dielectric properties of material. Isothermal relaxation current correlates with the density and duration of the stress [8]. Using voltage limit to service level the IRC analysis is a destruction free diagnostics method.

The course of the current response after connection and disconnection DC voltage (charging and discharging) is shown in (Fig.1).

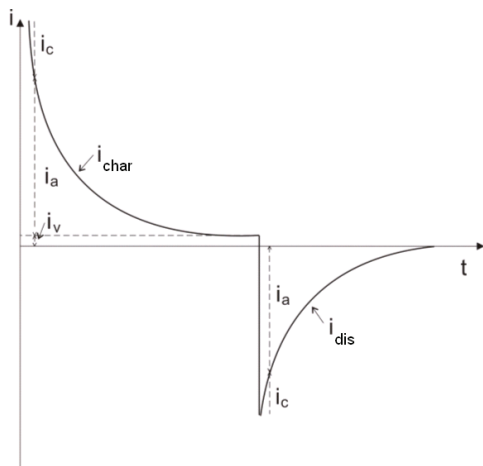


Fig.1. Dependence of the current response on applied DC voltage step [10]

For charging current  $i_{char}(t)$

$$(2) \quad i_{char}(t) = i_c(t) + i_v + i_a(t)$$

where:  $i_c(t)$  - current from geometric capacity,  $i_v$  - steady conductivity current,  $i_a(t)$  - absorptive current.

In case of discharging current  $i_{dis}(t)$  conductivity current is not present, because external electric field, which acts on the dielectric, is equal zero.

Total current flowing through the dielectric is expressed on the basis of presumption of existence of Debye polarization process and Maxwell-Wagner independent model as the amount of the currents with an exponentially decreasing amplitude and time independent component:

$$(3) \quad i_{char}(t) = \frac{U}{R_0} + \sum_{i=1}^n I_{mi} \exp\left(\frac{-t}{\tau_i}\right)$$

where:  $U$  - applied DC voltage,  $R_0$  - DC insulation resistance after infinitely long time,  $I_{mi}$  - amplitude of  $i$ -th elementary Debye's model component,  $\tau_i$  - relaxation time constant of  $i$ -th Debye model component.

### Thermal ageing

Thermal ageing was carried out in dry air oven under 186 °C during 7000 hours. This temperature was the highest as was possible. According to manufacturer references higher temperature can cause different chemical ageing processes in material than there are presented in normal service operation. We supposed that ageing process causes changes in electro-physical structure of material and by these changes of observing quantities in time and frequency domain too. On the contrary, determination of quantity changes allows to define ageing state.

Placement of sample can be seen on left side of Fig.3. Samples were aged and measured inside of oven. Measuring temperature was 20 °C.

### Experiment

The aim of experiment was comparison of insulation system materials on 6 kV stator coils for electric driver before and after thermal ageing. Insulation system of coils was based on epoxy resin and mica materials. IRC analysis used electrometer Keithley K617 instrument in time domain. According of dielectric theory it is possible to transfer data from time to low frequency domain. Direct dielectric

spectroscopy in frequency domain used LCR meter Agilent E4980A. Measuring frequencies were from 20 Hz to 2 MHz. Tests were carried out in laboratory conditions.

### Results of IRC analysis

The scheme of measurement (Fig.2) was same for type of coils.

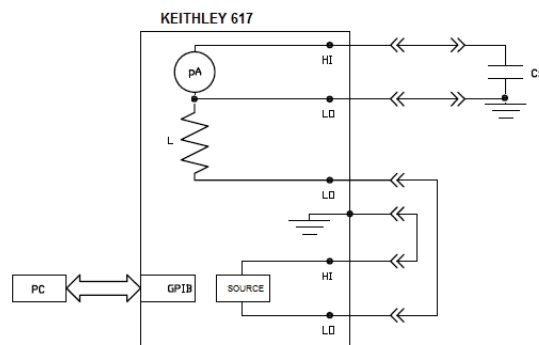


Fig.2. Scheme of measurement

where:  $C_x$  - measured coil, KEITHLEY 617 - electrometer with voltage supply, GPIB - bus, PC - computer.

The testplace is on (Fig. 3). There is dry air oven with coil sample on the left side. Electrometer Keithley 617 and PC with GPIB bus interface are on the right side of figure.



Fig.3. Testplace of measurement

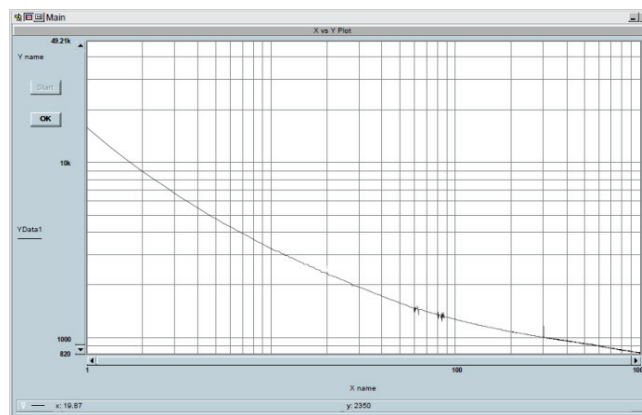


Fig.4. Screenshot of current time dependence of one coil

According to theory of dielectric, polarization process is depended on external electric field and time of applying too. It was decided to measure current for 1000 s. It is sufficient time for excitation of long time processes and it is suitable

for measuring in industry also. Voltage level was restricted by electrometer supply level to 100 V. Increasing voltage level can cause surface discharge troubles [9].  $I(t)$  dependence of the current  $I$  (pA) on the time  $t$  (s) can be seen on the following Fig.4.

Relaxation currents and time constants were obtained to evaluate the charge characteristics in program Matlab. Applied voltage was restricted because of used electrometer Keithley 617 voltage source level and request of absence of space charge generation assurance. Elements  $R_i$ ,  $C_i$  of the Maxwell-Wagner equivalent dielectric model can be calculated from elementary currents and time constants [6]:

$$(3) \quad I_{mi} = \frac{U_0}{R_i} \Rightarrow R_i = \frac{U_0}{I_{mi}}$$

$$(4) \quad \tau_i = R_i C_i \Rightarrow C_i = \frac{\tau_i}{R_i}$$

where  $R_i$ ,  $C_i$  - calculated components of equivalent model,  $I_{mi}$ ,  $\tau_i$  - values obtained from Matlab evaluation.

Table 1. The elementary current and time elements form IRC analysis

7 elements approximation of coils			
new coil		aged coil	
$\tau_i$ (s)	$I_{mi}$ (pA)	$\tau_i$ (s)	$I_{mi}$ (pA)
0.14	306027	0.16	272650
0.56	34022	0.64	27822
2.20	8140	2.67	7728
7.95	2182	14.13	2382
27.96	1353	61.01	818
135.38	499	527.08	411
5145.07	870	45302.45	779

The results of numerical calculation of equation (3) for new and aged coils are shown in Tab.1. Seven elements approximation of measurements was used for calculation of elementary amplitudes  $I_{mi}$  and elementary time constants  $\tau_i$ .

The replacement model of dielectric enables the conversion of dielectric loss factor into the frequency domain in low frequencies. The relationship below is valid for dielectric loss factor  $tg\delta$ :

According to equation (5) and equivalent model in figure 4 it is possible to calculate [7,10] admittance  $\bar{Y}$  as

$$(5) \quad \bar{I}(\omega) = \bar{Y} \bar{U}(\omega)$$

$$(6) \quad \bar{Y} = \frac{1}{R_0} + j\omega \varepsilon_{r0} C_0 + \sum_{i=1}^n \frac{j\omega C_i}{1 + j\omega R_i C_i}$$

$$(7) \quad \bar{Y} = \frac{1}{R_0} + \sum_{i=1}^n \frac{R_i (\omega C_i)^2}{R_i (1 + (\omega R_i C_i)^2)} + j\omega \left[ \varepsilon_{r0} C_0 + \sum_{i=1}^n \frac{C_i}{1 + (\omega R_i C_i)^2} \right]$$

$$(8) \quad tg\delta = \frac{\text{Re}\{\bar{Y}\}}{\text{Im}\{\bar{Y}\}} = \frac{\frac{1}{R_0} + \sum_{i=1}^n \frac{R_i (\omega C_i)^2}{R_i (1 + (\omega R_i C_i)^2)}}{\omega C_0 + \sum_{i=1}^n \frac{\omega C_i}{1 + (\omega R_i C_i)^2}}$$

where:  $\omega = 2\pi f$  - circular frequency,  $C_0$  - capacity of the air electrode system using the geometric capacity of the sample.

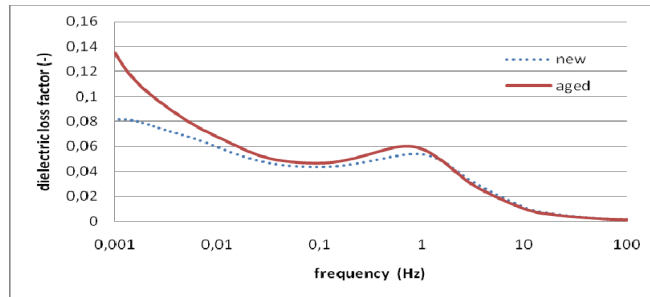


Fig.5. Calculated dielectric loss factor for new and aged samples

Dielectric loss factor  $tg\delta$  was calculated from elements of dielectric equivalent model and measured values in frequency domain are shown in Fig.5 for new and aged coils.

### Results of dielectric measurement

Dependences of capacitance and dissipation factor on frequency in range from 20 Hz to 2 MHz were measured. For all five new and all five aged coils were carried out 100 measurements in each frequency. The differences of measured values between same type of coil in the same frequency were neglectable. Special software was made for this purpose in Agilent VEE (Virtual Engineering Environment). Display screen is in Fig.6.

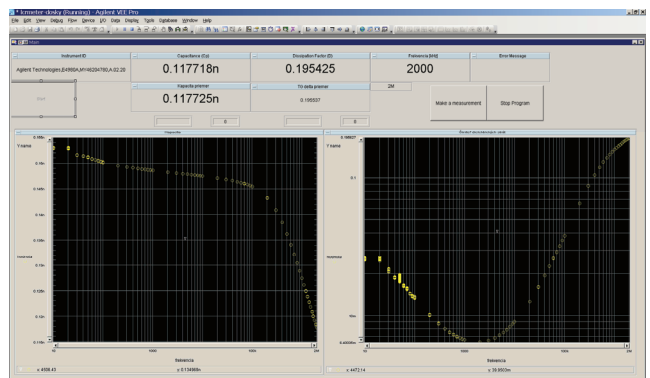


Fig.6. Screenshot of measuring software for capacity (left) and dissipation factor measurement (right)

Comparison of capacity for new and aged coils is in Fig.7

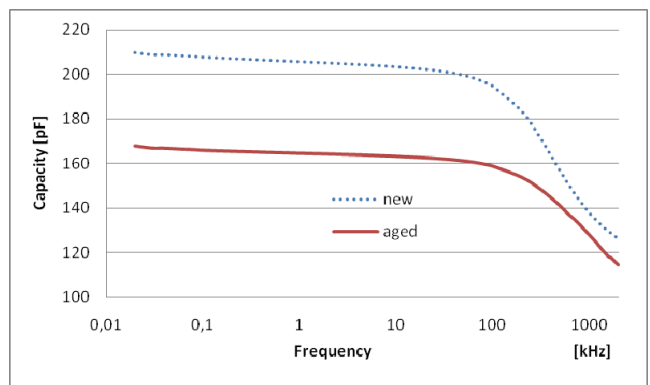


Fig.7. Capacity dependences on frequency for new and aged coils

Comparison of dissipation factor for new and aged coils is on Fig.8.

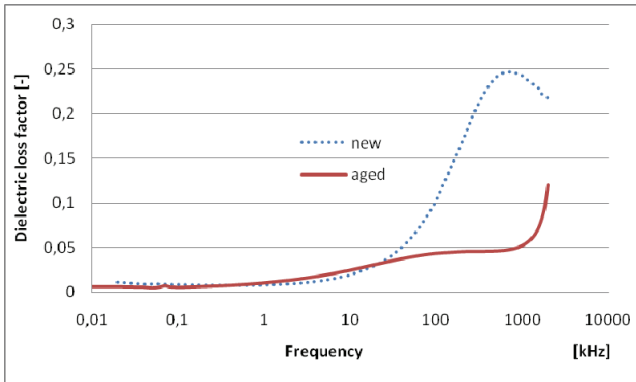


Fig.8. Dielectric loss factor dependences on frequency for new and aged coils

### Conclusion

The aim of this work was the comparison of two states of insulation systems of 6 kV coils for rotating machines. Results obtained for five new samples and five aged samples after 7000 hours of 186 °C thermal degradation. As can be seen from Tab. 1, spectrum in low frequencies moves to long time due to ageing process in electro-physical structure of material. It means that processes in the range of dipole polarization appear later and levels of elementary currents decrease. In the range of high frequencies the difference between new and aged coil is more evident. Dissipation loss factor goes down and it shifts to high frequencies. Decreasing of factor is caused most likely of delamination process among elementary sheets in insulation system and by that formation of air capacitances in serial connection.

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