DIELECTRIC SPECTROSCOPY IN TIME AND FREQUENCY DOMAIN

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Abstract: This contribution deals with the complex permittivity (complex capacitance) determination task from the point of view of its frequency dependence, in order to extend the possibilities of the rotary electric machine insulation system condition evaluation in routine operation. It describes the differences of complex permittivity (complex capacitance) imaginary part determination in time and frequency domain caused by the influence of continuous test voltage increase in charging current measurement on complex permittivity (complex capacitance) and its imaginary part estimation. The contribution shows the elimination of this influence where only measured charging current, corrupted by superposition of dielectric responses function *f(t)*, is available.

Key-Words : insulation system, complex permittivity, dielectric response function, dielectric spectroscopy.

1. Introduction

The response of the insulation system of rotary electric machine to electrical and thermo-mechanical stress is captured by discharge activity, loss factor tg δ and polarization spectrum monitoring. Polarization spectrum measurement is performed in time and frequency domain and partially blends together. Basically point is the insulation system dielectric response function *f(t)* monitoring which describes simple relations based on polarization processes in insulant [1] [2]. Account on this, dielectric response function *f(t)* monitoring is good instrument for the insulation system specific condition evaluation. Dielectric data conversion from time to frequency domain is reliable for the high voltage insulation system of rotary electric machines. Dielectric response function *f(t)* determination in time domain is executed mainly from discharging current measurement [2 - 4] or from recovery voltage measurement. Dielectric response function *f(t)* and loss factor tg δ measurement provides information related with changes in material [2]. Time demand on discharging current and recovery voltage measurement represents tens of hours for phase and therefore this measurement is unrealized in diagnostic routine for economic reasons. This contribution deals with imaginary part of complex permittivity (complex capacitance) determination from charging current measurement because of less time demand. However while using this method, dielectric response function *f(t)* is not measured for technical reasons but charging current is measured. It is corrupted by superposition of dielectric responses function *f(t)* like effect of continuous, not step test voltage increase. Because the geometrical capacitance C_g is unknown, in this contribution is considered the complex capacitance.

Measured object was the generator high voltage insulation system of thermal class F and nominal voltage 15.75 kV. The insulation system capacitance at 50 Hz and voltage 0.2Un was 887 nF. The generator operation began in 1992.

2. Fitting an absorption current by linear combination of exponentials

The method of resolving an absorption current (conductivity) into its components has an origin in the theory of distribution of relaxation times. According to this theory there is a continuous distribution of potential barriers in dielectric. As the relaxation times are proportional to the potential barriers magnitude, they also have their own distribution. It should be mentioned that some serious objections to the acceptance of this theory exist [3 - 5]. In spite of this fitting of experimental data by a sun of exponentials is a commonly used method preferably in the field of diagnostics and also in modeling interfacial polarization of a multi-layer dielectric [3 - 4]. Calculation of Fourier transform in this case is easy. Suppose that the absorption current i_a (absorption conductivity γ_a) is give as [3 - 4]

$$i_a(t) = C_g\,\gamma_a(t) = \sum_{i=1}^{n} C_g\,\gamma_i \exp(-t/\tau_i).\ (\ 1/\Omega\mathrm{m}\ ) \quad (1)$$

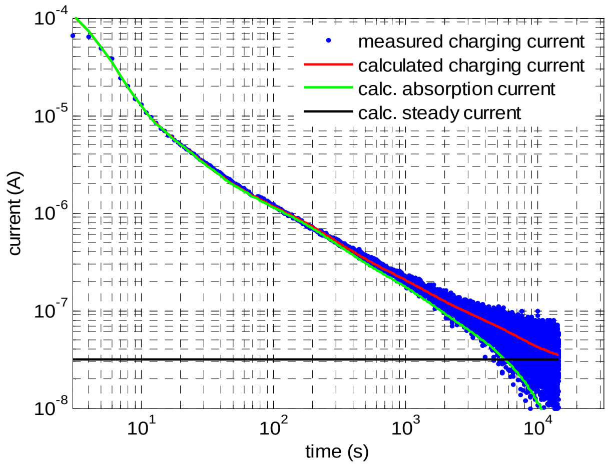
After introducing new parameters $C_g\,\Delta\varepsilon_i = C_g\,\gamma_i\,\tau_i/\varepsilon_0$ and performing the Fourier transform we have for complex capacitance $C_g\ \varepsilon^*$ [3 - 4]

$$C_g\,\varepsilon^*(\omega) = C_g\,\varepsilon_\infty + \sum_{i=1}^{n}\frac{C_g\,\Delta\varepsilon_i}{1+\omega^2\,\tau_i^2} - j\sum_{i=1}^{n}\frac{C_g\,\Delta\varepsilon_i\,\omega\tau_i}{1+\omega^2\,\tau_i^2}\,. \quad (2)$$

To finding parameters γ_i, τ_i some static optimization methods are used. In our case Nelder-Mead optimization method and the least squares method were used. The optimization begins with fitting of the measured data by one exponential. Optimized parameters τ_i and parameters γ_I are determined by means of the least squares method. The number of exponentials is incremented by 1 while all parameters γ_i, τ_i are positive [3 - 4]. In measuring charging current, the equation (1) is edited with steady current. Parameter steady current is also determined by the least squares method.

3. Determination of loss capacity in time and frequency domain

The determination of time constant in frequency domain was performed on the base of the measurement of dielectric parameters frequency dependences by the use of IDA200 measurement system. The measurement was performed on phase L2 (winding temperature 27.0 °C), as well as on phase L3 (winding temperature 26.6 °C) with density 13 measured points per decade. Frequency measuring range was from 0.00034539 Hz to 1000 Hz on phase L2 and from 0.00041245 Hz to 1000 Hz on phase L3. The results of dielectric spectroscopy in frequency and also in time domain for phase L2 and L3 are shown in graphs (fig. 2 and 3). The loss capacitance determination in time domain was performed from charging current measurement, which is less time demanding. The charging current measurement was performed by measuring instrument MEGGER type: Meg 10-01, 10 kV. Two 4 hours records on phase L2 and L3 were measured under voltage 2500 V. Winding temperature for phase L2 was 24,4 °C at the beginning and 24,1 °C at the end of the measurement, and for phase L3 it was 31.17 °C at the beginning and 29.8 °C at the end of the measurement. The charging current was replaced by linear combination of the exponential functions (absorption part) and steady part. This linear combination of the exponential functions' replacement [3 - 4] and the steady part are in this case dependent on time, since its measured values enter the calculation. It is possible to assume that this fact is caused by the deformation of charging current as a consequence of the continuous test voltage increasing and a big time constant of the measurement system. Such a system is not able to monitor the current change up to approximately 5 seconds form the start of the measurement. An indemonstrable linear combination of the exponential functions' replacement and of the steady part at the measurement beginning is caused by the deformation. Therefore, the replacement was performed for charging currents at intervals <T_{start} ; 14400 sec>, where T_{start} is from 5 sec up to 15 sec starting with voltage connection to object. The results from time domain were transformed by Fourier transformation. Input data for these transformations were taken from the records that were evaluated as least biased on the basis of the correlation factor. For the phase L2, T_{start} = 5 sec was considered to be the least biased estimation (fig. 1a). For the phase L3 it was the one where T_{start} = 7 sec (fig. 1b).



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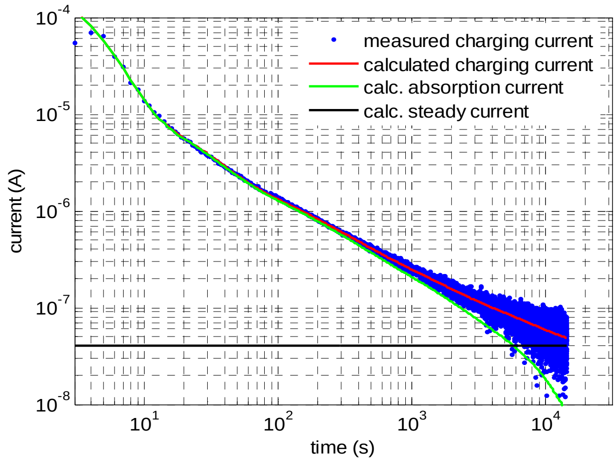

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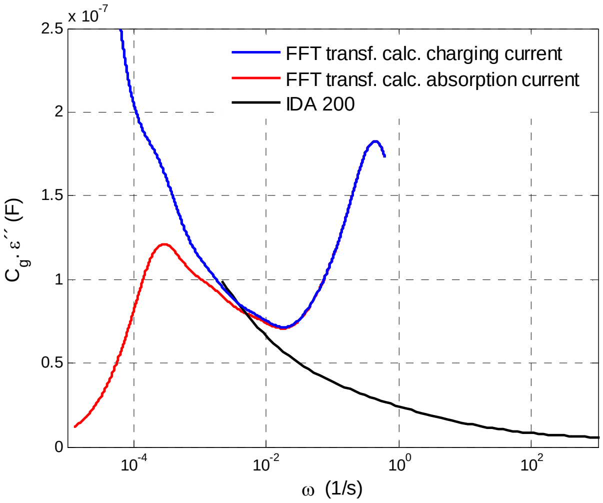
Fig. 1 Time dependency of the insulation system's charging current and its replacement by the linear combination of the exponential functions (absorption current) and the steady part (steady current) for measurement lasting 14 400 sec and Tstart which was considered to be the least biased on the basis of the correlation factor:

a) for the phase L2 and the temperature range 24.4 °C – 24.1 °C, Tstart=5 s;

b) for the phase L3 and the temperature range 31.17 °C – 28.6 °C, Tstart=7 s .

It is evident from fig. (2) that correlation between direct and alternate methods is problematic for the angle frequency up to 10^{-2} rads^{-1}. In this case, diametrical differences between measured and loss capacitance $C_g\varepsilon''$ and loss capacitance of the Fourier transformation charging current are present. To what extend is this situation caused by responses function superposition *f(t)*, as a consequence of continuous and not step test voltage increasing, is analyzed below. It is also necessary to notice that voltage dependencies of the dielectric parameters are being considered here. The dielectric spectroscopy in frequency domain was measured under voltage 20 V (5 V) and dielectric spectroscopy in time domain was measured under voltage 2500 V.



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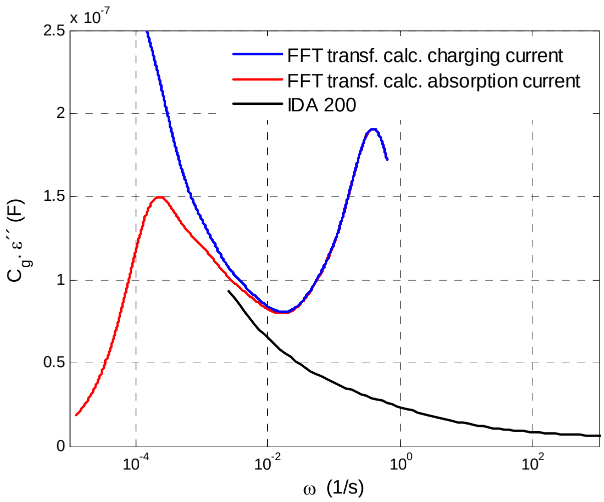

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Fig. 2 Frequency dependency of the loss capacitance as a result of dielectric spectroscopy in frequency domain (IDA200) and in time domain Fourier transformation (FFT) of the absorption current:
a) for the phase L2 , b) for the phase L3.

The resolving of the response function superposition *f(t)* is a consequence of continuous and not step test voltage lays in analytical function of test voltage and in resolving superposition in frequency domain (Equ. 4). For charging current we can write [2]

$$i(t) = C_g \left[\frac{\gamma_0}{\varepsilon_0} u(t) + \varepsilon_\infty \frac{du(t)}{dt} + \frac{d}{dt} \int_0^t f(\lambda) u(t-\lambda)\, d\lambda \right], \quad (3)$$

where $C_g \frac{\gamma_0}{\varepsilon_0} u(t)$ is the contribution of insulating system conductivity,

$C_g\, \varepsilon_\infty \frac{du(t)}{dt}$ - the contribution of rapid polarization,

$C_g \frac{d}{dt} \int_0^t f(\lambda) u(t-\lambda)\, d\lambda$ - the contribution of slow polarization.

For the Laplace transform in frequency domain the following equation is valid [2]

$$I(s) = C_g \frac{\gamma_0}{\varepsilon_0} U(s) + s\, C_\infty U(s) + s\, C_g\, F(s) U(s), \qquad (4)$$

where U(s) is Laplace transform of analytical function of test voltage,
F(s) - Laplace transform of the dielectric response function *f(t)*,
s - operator.
Analytical description of voltage is performed by function

$$U(t) = U_{max} + A_1 e^{\left(-t/\tau_1\right)} + A_2 e^{\left(-t/\tau_2\right)} A_3 e^{\left(-t/\tau_3\right)} \quad (5)$$

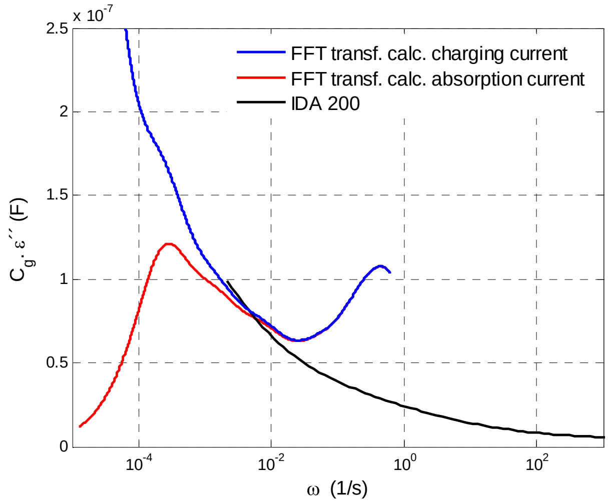
It is inevitable to know the response *f(t)* itself in resolving the superposition. Since measured dielectric response function *f(t)* is devaluated by the superposition of dielectric response functions *f(t)* it is important to apply such an approach which would ensure the acceptance of the above mentioned fact.

3.1. The method of defining pure dielectric response function *f(t)* from charging current

It is possible to use the following method of dielectric response function *f(t)* superposition in measuring of charging current. The method of fitting of the absorption current by linear combination of exponentials can be found in chapter 2. Since this method presupposes continuous distribution of potential barriers in dielectric and it stems from the extended Deby's method, the individual exponentials represent a group of dipoles where individual time constants τ of dipoles' groups are in certain given boundaries [6]. For the Laplace transform of dielectric response function *F(s)* the following equation can be written

$$F(s)=\sum_{i=1}^{n}\frac{\gamma_i'}{s-\tau_i'} \qquad (6)$$

Parameters γ_i', τ_i' are unknown and they do not correspondent with parameters γ_i, τ_i in equation (1) which parameterizes the measured current. In the determination of γ_i', τ_i' parameters, it is inevitable to remove the contribution of rapid polarizations determined by reverse Laplace's transformation of $s\,C_\infty\,U(s)$ from assessed data. By mere subtraction of the contribution of rapid polarizations from the measured current we get the contribution of slow polarizations. Supposing that the equation (5) is valid, it is possible to use similar method in the specification of parameters γ_i', τ_i' as it was mentioned in the chapter 2. The optimization of τ_i' parameter will be reached so that in each optimization step the calculation of an in-between calculation in frequency domain will be performed according to the equation (4) for suggested parameters of the optimization τ_i' (for each exponential function separately). Afterwards, their back transformation into time domain will be performed and there the parameters γ_i' will be calculated by the least squares method. Because of the numeric problems it is necessary to divide the whole process into two steps. In the first step, the fitting should take its place as it is mentioned in the chapter 2 of this document. We get the number of exponentials by which the fitting was realized, but the outcome of such a fitting would bring an incorrect interpretation after transformation into the frequency domain. In the second step, the calculation method mentioned above will be performed, but only with the same number of exponentials as was used in the calculation in the previous step. In the second step, the amount of exponentials is no more expanding and it is final. The secondary advantage of this kind of method is not only the minimization of numeric problems that occur when the number of fitting exponentials grows, but also the lower requirements on the calculation performance. The outcomes of the above described method are shown in the fig. 3. Comparing to fig. 2, it is obvious that the input of continuous growth of voltage is important for angle frequencies 10^{-1} 1/s. The differences between measured loss capacity $C_g\varepsilon''$ in frequency domain, and the loss capacity from Fourer's transformation of the absorption component in the fig. 3 can be caused by the voltage dependence of dielectric parameters as was already mentioned above. This issue is going to be discussed in the next contributions.



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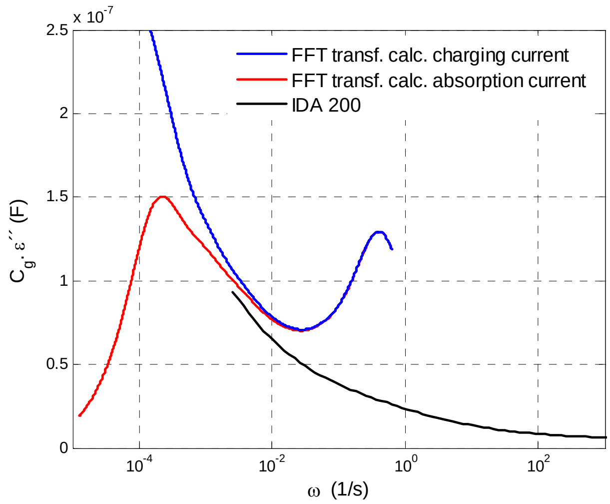

b)

Fig. 3 Frequency dependence of loss capacitance as a result of the dielectric spectroscopy in frequency doamain (IDA200) and in time domain Fourier transformation (FFT) of pure dielectric response function f(t): a) for phase L2 , b) for phase L3.

4. Conclusion

The monitoring of polarization spectrum in operation running is possible not only in frequency domain, but also in time domain. The complex dielectric constant's (complex capacitance's) determination in operation running environment is possible by measuring the charging current, which essentially decreases the length of experiment. In this case, it is necessary to eliminate the test source's voltage-rise effect as described above in chapter 3.2. Otherwise, the significant devaluation of measured parameters occurs. Consecutive differences at determination of complex dielectric constant's (complex capacitance's)

imaginary part in time and frequency domain are apparently caused by their voltage-relation.
The polarization action's time constant estimation, which are seconds up to tens of seconds, can be an important contribution from the point of view of evaluation of insulation system on the base of distribution of relaxing times as another parameter of response function *f(t)*. In fact, described fast polarization actions are mostly results of insulation systems' ageing process.

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