Polarisation and conduction in ceramic insulators

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Abstract

The paper reports on the dielectric response and conductivity calculation based on the absorption current and the recovery voltage measurements. The time-domain measuring methods have been used for assessment of an electrical grade ceramics made from quartz and alumina porcelain. The measured data were converted into the form of complex permittivity. Experimental results indicated occurrence of a polarization process with relaxation time of about 100 s. The relaxation time and the conductivity appear to be very sensitive to the temperature variation. They could be prospective indicators of the changes generated by temperature and ageing of material.

Introduction

The dielectric dispersion in ceramic insulators relates to their structure and also to the amount of defects created in material during the operation. Therefore, the relaxation frequency is a good indicator of the changes generated by radiation or by the thermal ageing of material. The relaxation frequency connected with dispersion processes is proportional to the insulator temperature. In the case when the relaxation frequency drops to the range bellow 1 Hz, some special types of the time-domain measurements are regularly used.

Theoretical background

A linear dielectric is in electric field entirely characterized by its dielectric response $h(t)$. The dielectric response can be calculated from the current flowing through the dielectric after application of a step electric field E_0. The current density in this case is

$$i(t) = \gamma_0 E_0 + \varepsilon_0 E_0 \delta(t) + \varepsilon_0 E_0 h(t), \tag{1}$$

where γ_0 is the specimen conductivity which does not depend on time or frequency, $\delta(t)$ is the Dirac function and ε_0 is the vacuum permittivity. This type of measurement requires a highly specialised apparatus [1].

As the measurements of polarisation currents in dielectrics are often influenced by noise, the measurement of recovery voltage is sometime used instead of it. During the recovery voltage measurement a constant voltage U_0 (electric field E_0) is applied to the test object for $0 \le t < t_1$. This time period must be long enough for settling of all the polarisation processes. In the time period $t_1 \le t < t_2$ is the object short-circuited and then it is left in open-circuit condition. The voltage on the test object is measured for $t_2 \le t$ with a high input impedance voltmeter. If the dielectric response $h(t)$ is known, the recovery voltage $u_r(t)$ can be calculated by means of the inverse Laplace transform [2]

$$u_r(t) = L^{-1}\left[\frac{U_0 C_G h(p)}{\frac{1}{R_0} + p\varepsilon_\infty C_G + pC_G h(p)}\right]. \tag{2}$$

Here p is the Laplace transform parameter, ε_∞ is the optical permittivity of the dielectric, C_G is the geometric or vacuum capacitance and R_0 is the specimen resistance.

For calculation of the dielectric response from Eqs. (1) or (2) we use an optimisation procedure. The measured data of $i(t)$ or $u_r(t)$ are fitted by the functions from the right sides of Eqs. (1) or (2). An important step in the searching process is a proper choice of the analytical type of the dielectric response. The empirical responses of Cole-Cole or Havriliak-Negami [3, 4] are suitable in many cases. Recently, the universal response of Jonscher is preferred [5]. Unfortunately, this response cannot be expressed in an analytical form. Instead of it, an approximation can be used as [6]

$$h(t) = A\left[e^{-\frac{t}{\tau}} \left(\frac{t}{\tau} \right)^{-m} + \left(1 - e^{-\frac{t}{\tau}} \right) \left(\frac{t}{\tau} \right)^{-n} \right], \tag{3}$$

where A, τ, m and n are the dielectric response parameters. The parameters m and n are bounded to intervals: $0 < m < 1$, $0 < n < 2$. The Laplace transform of the response according to Eq. (3) is

$$h(p) = A\left[\frac{\tau^m \Gamma(1-m)}{\left(\frac{1}{\tau} + p \right)^{1-m}} - \frac{\tau^n \Gamma(1-n)}{\left(\frac{1}{\tau} + p \right)^{1-n}} + \frac{\tau^n \Gamma(1-n)}{p^{1-n}} \right], \tag{4}$$

where Γ is the Gamma function.

Experimental part

The theoretical considerations described in the preceding part were applied to the resorption (discharging) current and the recovery voltage data measured on the commercially available alumina body insulator. The measurements were aimed at finding the parameter, which is sensitive to the temperature and structure changes of the investigated system. Generally the insulators are of grain structure with three major phases: Al_2O_3 (corundum phase), α-quartz (SiO_2) and $3Al_2O_3 .2SiO_2$ (mullite). The corundum phase ensures the good mechanical and electrical properties of the porcelain matrix. A small amount of mullite does not weaken the mechanical strength. Formation of mullite is influenced by sintering and heat treatment [7].

For the measurements, specimen with diameter of 70 mm and thickness of 5 mm was cut from the ceramic core of the insulator. The resorption current was measured after charging the specimen with 500 V for 3600 s. During the recovery voltage test a charging voltage of 100 V was applied to the specimen for period of 3600 s. Next, the sample was short-circuited for 0.1 s by means of a computer-controlled relay and then connected to the high input impedance voltmeter. For the resorption current measurements and the recovery voltage measurements a Keithley 6517A electrometer was used with build in source of charging voltage. The value of $C_0 = \varepsilon_\infty C_G$ needed for calculations was measured by the HIOKI Z HiTESTER 3531 at 1 kHz.

For fitting the resorption current data, the dielectric response of Eq. (3) was used. The response parameters were found by the step optimisation of m and n in intervals (0, 1) and (0, 2) respectively. The parameter τ was optimised between the minimum and the maximum value of the discharging interval. The parameter A was calculated straight from the value of current at the time τ. The measured resorption currents are in Fig. 1. The data converted into the form of loss factor in the frequency range are in Fig. 3. The calculated parameters of the dielectric response function are in Table 1. During these measurements the conductivity of specimen was also calculated from the difference of the absorption and resorption currents. The conductivity data are in Table 2.

The recovery voltage data were processed under the assumption that Eq. (2) is valid. The dielectric response was approximated by the same formula as in the case of discharging currents. The unknown parameters were optimised with help of a Nelder-Mead type simplex search method. The inverse Laplace transform was performed by algorithm published in [8].

Typical results of the measured recovery voltage data are shown in Fig. 2. The calculated dielectric response parameters are in Table 1.

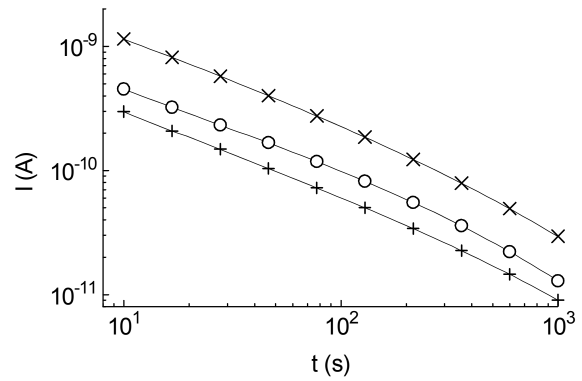

Fig. 1: Resorption currents of insulator
Temperature: + 21 °C, o 45 °C, x 80 °C

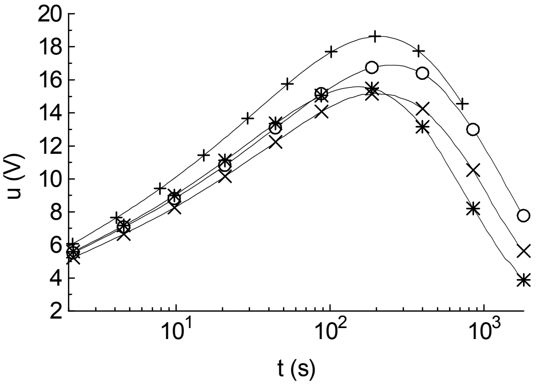

Fig. 2: Recovery voltage of insulator
Temperature: + 21 °C, o 36 °C, x 46 °C, * 58°C

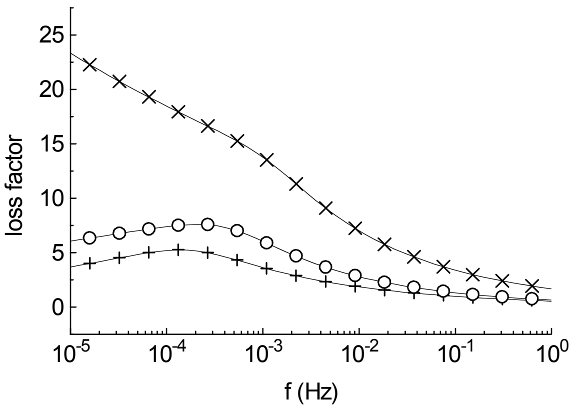

Fig. 3: Loss factors calculated from the currents
Temperature: + 21 °C, o 45 °C, x 80 °C

temperature (°C)	A (10^{-2} s^{-1})	τ (10^2 s)	m	n	type
21	0.3	10.6	0.7	1.2	a
45	1.1	4.5	0.7	1.1	a
80	6.0	1.6	0.7	0.9	a
21	2.1	7.9	0.6	1.7	b
36	1.8	2.7	0.7	1.4	b
46	2.0	2.6	0.7	0.8	b
58	2.8	2.0	0.7	0.8	b

Table 1: Parameters of the dielectric response calculated from the resorption current (a) and from the recovery voltage (b)

temperature (°C)	21	45	80
conductivity (10^{-13} S m^{-1})	1.2	3.8	59.3

Table 2: The values of conductivity calculated from the absorption and resorption currents

Conclusion

The low frequency dispersion process was observed in specimens of electrical grade ceramics. A possible explanation of this process could be the migration polarization on the grain boundaries in the bulk of insulating system. The increase of temperature influences mainly the relaxation time τ and the low-frequency slope of the loss factor (n). The most important finding from our experiments is, that the type of polarisation varies with temperature. Its nature is changed from a dipolar to a hopping one. It is indicated by the value of parameter n, which is less than 1 for the high temperatures. As it can be seen in Fig. 3, loss factor of the hopping charges polarisation has no maximum in the frequency range. On the other hand, the temperature dependence of the dc conductivity has not shown any departure from the expected behaviour. Sensitivity of selected parameters to the structure changes can be utilized in the next work for assessment of the porcelain structure during ageing.

When comparing the absorption current and the recovery voltage method, it must be pointed out, that the trends of temperature changes of the calculated parameters from both methods are similar. Relative good agreement of the absolute values of parameters can be achieved for n and m, but there is an unexpectedly high difference for parameter A. The difference is probably caused by a high sensitivity of the optimisation method using Eq. (2) to small measuring errors and also by a great number of unknowns, which have to be calculated from this equation. The result depends also on the initial estimation of parameters. The differences of parameters could be judged by an independent method, e.g. by the measurements in the frequency domain.

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