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Factors affecting the results of electrical insulation diagnostic tests

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Abstract:
In this paper the influence of some transient phenomena on the results of dielectric measurements is discussed. The investigation is concerned with the region of very low frequencies or the region of very long times. Based on the solution of Maxwell equations three phenomena were analyzed: the effect of incomplete charging on the values of discharging current, the effect of a deform shape of the step voltage at charging and the effect of multiple periods at evaluation of the alternating current measurements. The results of modeling showed, that the minimum charging time for achieving acceptable results at discharging currents responds approximately to the 50 times of the relaxation time constant. The charging voltage at all experiments has to be checked for its individual time constant. An inadequate long time constant disable us to reveal the parameters of the investigating relaxation process. In the frequency domain, especially in the very low frequency range, it is possible to obtain reliable results after application of minimum three periods of the sinusoidal voltage. Except of this, the paper also provides computational bases for estimation of the differences caused by non-ideal conditions at dielectric measurements.

INTRODUCTION

The diagnostic methods for recognizing of the electric insulation state are mostly based on the measurements in the time domain (e.g. the charging and discharging current) as well as in the frequency domain (the capacitance and dissipation factor). In both cases we try to find the changes of the corresponding parameters during a long-term operation and predict the expected operating life. A common feature of electrical insulations in power equipments is their layer structure. A new type of polarization (migration polarization) is created on the layer interfaces. It depends on the permittivities and conductivities of the individual insulating layers. The polarization is characterized by a long relaxation time. If we want to recognize the phenomena at the interfaces, we must take the dielectric measurements at relative long times (1000 s) or at very low frequencies (0.001 Hz). By conducting a routine measurement we often neglect some transient phenomena, which could lead to erroneous conclusions on the quality of insulation system. In this paper we shall treat some selected phenomena by solving the Maxwell equations with aim at estimation of possible differences between the exact and the real measurable values in the time and the frequency domain.

THEORY

In the theory of dielectrics the electric field *E(t)* is considered as the system input signal and the polarization *P(t)* as the system output signal. The system response to an arbitrary electric field *E* is

$$P(t) = \varepsilon_0 \int_0^t h(t-\lambda) E(\lambda) d\lambda , \qquad (1)$$

where ε_0 is permittivity of free space and *h(t)* is a function called dielectric response, which completely characterize the investigated insulating material or object. In fact, the dielectric response is the impulse function (i.e. the response on the Dirac unit impulse δ) of the input – output system *E(t)* vs. *P(t)*.
In experiments the polarization *P(t)* is not measured directly. A commonly used technique in this field is the measurement of so-called charging current after a step voltage application [1]. The current density can be evaluated from Maxwell equation

$$i(t) = \gamma_0 E(t) + \varepsilon_0 \varepsilon_\infty \frac{dE(t)}{dt} + \varepsilon_0 \frac{d}{dt} \int_0^t h(t-\lambda) E(\lambda) d\lambda , \qquad (2)$$

where γ_0 is the steady state conductivity and ε_∞ is optical permittivity. If the input signal is a *step* electric field E_0, the current density is given by

$$i(t) = \gamma_0 E_0 + \varepsilon_0 \varepsilon_\infty E_0 \delta(t) + \varepsilon_0 E_0 h(t). \qquad (3)$$

As it is seen from (3), the dielectric response can be measured as a variable part of the current after application of a step voltage to the measured object. The complex dielectric susceptibility $\boldsymbol{\chi}$ is simply the Fourier transform of the dielectric response

$$\boldsymbol{\chi}(\omega) = \chi' - \boldsymbol{j}\chi'' = \int_0^\infty h(t) \exp(-\boldsymbol{j}\omega t) dt. \qquad (4)$$

Many times in practice we cannot find the actual dimensions of insulation under the test. That is why we use a formal geometric or vacuum capacitance C_G. The current through the measured object is then

$$I(t)=\frac{U(t)}{R_0}+C_0\frac{dU(t)}{dt}+$$
$$+\frac{d}{dt}\int_0^t C_G h(t-\lambda)U(\lambda)d\lambda, \qquad (5)$$

where $U(t)$ is the voltage on the object. For the sake of transparency we use in text the following variables

$C_0 = \varepsilon_\infty C_G$ for the capacitance belonging to the fast polarizations,

$R_0=\frac{\varepsilon_0}{\gamma_0 C_G}$ for the insulation resistance.

MODEL SOLUTION

To show the possibilities of a mathematical solution of Eq. (5) three phenomena were selected and analyzed:

- the effect of incomplete charging on the values of discharging current,
- the effect of the step voltage deform shape on the values of charging current,
- the effect of multiple periods at evaluation of the alternating current measurements.

The first solution is concerned with influence of so called dielectric memory effect. In this case we intend to calculate the dielectric susceptibility from the discharging current by the Fourier transform. This is often used for separation of the conduction and polarization dielectric losses while the discharging current is free of conduction. Let us define the unit-step function $v(t)$ as: $v(t) = 1$ for $t \geq 0$, $v(t) = 0$ for $t < 0$. If the object is charged with voltage U_0 for the time interval from 0 to t_1 then we have for $U(t)$ in Eq. (5):

$$U(t)=U_0\left[v(t)-v(t-t_1)\right] \quad \text{for } t_1>t,$$
$$U(t)=0 \quad \text{for } t\geq t_1 \qquad (6)$$

As the discharging current starts at $t = t_1$ we can introduce a new scale for time (assigned as t_N) with origin in t_1. From the generally known properties of the convolution integral we can write Eq. (5) for the discharging current I_D as follows

$$I_D(t_N)=U_0\left[C_G h(t_N+t_1)-C_G h(t_N)\right] \qquad (7)$$

Here the term with R_0 was omitted, as the voltage equals to zero. Also the derivation of the unit-step function, which creates the Dirac unit impulse, was omitted because of its non-measurable value. In this way the model of the memory effect is very simple. The only obstacle may be a computation of the dielectric response values $C_G h(t)$, which could be generated from the frequency function of the complex susceptibility. This is specified bellow in the part with results and discussion.

The second solution is concerned with the effect of a deform shape of the step voltage at charging. In fact, the step voltage used for the absorption current measurements has never an ideal rectangular shape. It mostly obeys an exponential law because of a non-zero impedance of power supply. In the same way is the step voltage deformed by a protective resistor in the measuring circuit. Hence we can write the measuring voltage in the form

$$U=U_0\left[1-\exp(-\frac{t}{\tau})\right], \qquad (8)$$

where τ is the time constant of the voltage transient and U_0 is the steady state value of voltage. Under these assumptions we cannot use the expression (3) for calculation of the dielectric response or the dielectric susceptibility, but we must solve the convolution integral of Eq. (5). It is useful to solve this integral also in the case, when the dielectric response is determined from the frequency domain measurement, especially in the range of very low frequency. That is why we use the same computational procedure also for searching the effect of multiple periods at evaluation of alternating current measurements.

The transient phenomena in electrical circuits are generally solved with help of the Laplace transform. In this transform, the convolution integral is changing to the product of the individual functions transforms. In the following text we shall denote the Laplace transform of a time function f as $f(p)$. The expression (5) is changed by the Laplace transform as follows:

$$I(p)=\frac{U(p)}{R_0}+C_0 pU(p)+pC_G h(p)U(p), \qquad (9)$$

A suitable expression for the dielectric response in insulation systems is the Cole-Cole model. In the Laplace transform, it has the form

$$h(p)=\frac{\Delta\varepsilon}{1+(p\tau_0)^{1-\alpha}}, \qquad (10)$$

where $\Delta\varepsilon$ is the permittivity increment, τ_0 and α are the parameters of relaxation times distribution. To solve the convolution integral, we need also the transform of the voltage applied to the system. We shall consider two types of voltages: the first will obey Eq. (8) and the second will be sinusoidal - $U_0 sin(\omega t)$. The voltage transforms $U(p)$ for the mentioned voltages are given by

$$U_1(p)=U_0\left[\frac{1}{p}-\frac{\tau}{1+p\tau}\right], \qquad (11)$$

$$U_2(p)=U_0\frac{\omega}{\omega^2+p^2}. \qquad (12)$$

The time function of current can be derived simply by the inverse Laplace transform of (9).

By analyzing the transient phenomena we used a model object with the dielectric response of the form (10). Some parameters of the model, which have not a significant effect on the calculated results, were kept constant during the analysis. The values of parameters were estimated from our previous measurements on the cable insulations [2]. The investigation was concentrated at finding the next relations:

- the influence of the charging time on the values of loss factor calculated from the discharging current data,
- the influence of the time constant τ in the deform step charging voltage on the loss factor calculated after conversion of data from the time into the frequency domain,
- detection of the harmonic shape distortion for the current flowing through a dielectric during the first four periods of the alternating voltage application.

In the last two cases the inverse Laplace transform of Eq. (9) was performed by algorithm published in [3]. Commonly, in practice we mostly use the parameter known as a complex capacitance ($\boldsymbol{C}=C'+\boldsymbol{j}C''$) rather than the complex permittivity or susceptibility. Therefore majority of our results will be expressed in the form of the complex capacitance imaginary part (C'') instead of the loss factor (ε''). As the analysis is concerned primary with the polarization phenomena, in the modeling presented below we will suppose, that the steady state conductivity γ_0 approaches to zero.

RESULTS AND DISCUSSION

DIELECTRIC MEMORY EFFECT

The basic parameters of the system were chosen as follows:
U_0=100 V, C_G=1.10^{-9} F, ε_∞=3.0, α=0.3, $\Delta\varepsilon$=20, τ_0=20 s.

We suppose that the model system was charged for time t_1 with the step voltage of value U_0 and than the discharging current was measured. The complex capacitance was calculated as the Fourier transform of discharging current in Eq. (7). The dielectric response needed for this calculation was obtained as the inverse Laplace transform of Eq. (10).

When investigating the polarization phenomena, we are interested mostly in the value of relaxation time, which can be calculated from the maximum value of the imaginary part of complex capacitance (C''). This is depicted in Fig. 1.

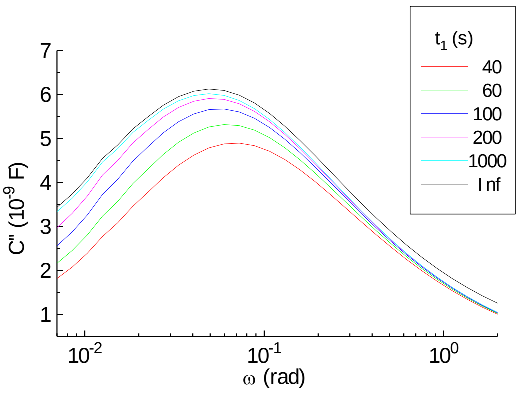

Fig. 1: Frequency dependence of C'' calculated by the Fourier transform for different charging times

The charging time varies in multiples of relaxation time. An incomplete charging influences both the position and the magnitude of relaxation maximum. The process can be analyzed in more detail with help of the Tab. 1. Here we find in separate columns the charging time t_1, the rate of charging time and the relaxation time τ_0, ΔP - the relative error of the peak position against the exact value calculated for infinite charging time and ΔM – the relative error of the peak magnitude against the exact value.

Tab. 1: Dependence of relative errors on the charging time for parameter α=0.3

t_1 (s)	t_1/τ_0	ΔP (%)	ΔM (%)
40	2	-37.5	20.05
60	3	-25.0	13.17
100	5	-12.5	7.33
200	10	0.00	3.48
1000	50	0.00	1.75

It was found that the relative errors are influenced mostly by the parameter α. We checked the values of α in the interval from 0 to 0.5. There was no error of the peak position ΔP in the mentioned interval for the ratio $t_1/\tau_0 \geq 50$. Under the same conditions we achieved the magnitude error ΔM less than 3 %.

According to our experiences the parameter α reaches the value of 0.5 only rarely. A common value is about 0.1. If there are indications that the value is higher than 0.5, the user must perform a separate calculation for this case.

EXPONENTIAL RISE OF VOLTAGE

In the case when the charging voltage is deformed comparing with the ideal rectangular form, the shape of absorption current is significantly influenced by the time constant of the applied voltage. Important changes appear also in the frequency domain (Fig. 2 - 3).

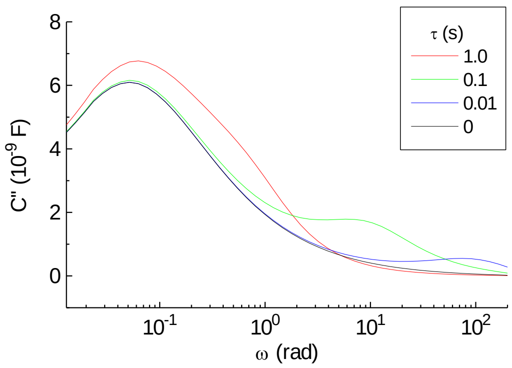

Fig. 2: Frequency dependence of C'' calculated after application of the voltage with the form (8) for various τ. The parameter $\Delta\varepsilon$ equals to 20

A new extreme is superimposed on the existing course of the imaginary part of capacitance. The extreme can be mistakenly evaluated as coming from the second (unknown) relaxation process. The position of this extreme is fixed and can be calculated as $\omega=1/\tau$. The resulting line depends mostly on the value of $\Delta\varepsilon$. If $\Delta\varepsilon$ is relative high (as in Fig. 2), the existing relaxation process overlaps the parasitic process generated from a non-rectangular shape of the charging voltage. On the other hand, a small value of $\Delta\varepsilon$ has a consequence in a small relaxation peak, which fades out under the high parasitic process (Fig. 3).

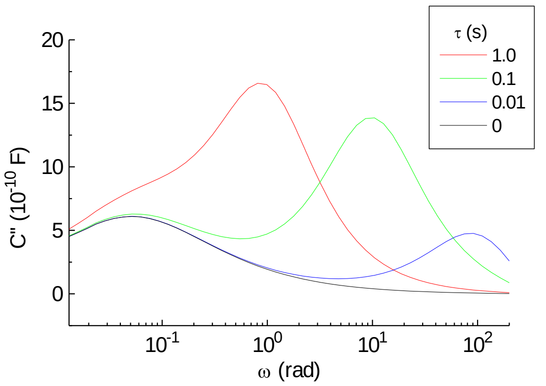

Fig. 3: Frequency dependence of C'' calculated after application of the voltage with the form (8) for various τ. The parameter $\Delta\varepsilon$ equals to 2

SINUSOIDAL VOLTAGE

In this section we suppose, that the applied voltage has the ideal sinusoidal shape. We did not study the influence of the voltage deformation on the current. The subject of our investigation was the transient caused by the harmonic voltage. The result of analysis is important for measurements at very low frequency (typically 1 mHz), where the test should last as short as possible, but with no influence on precision. To make the test in the shortest time assumes the use of data from the first period of the applied voltage. By modeling we can verify if these data are reliable. We have used the same system as in the previous section. The evaluating procedure was as follows: by using equations (9), (10) and (12) we generated the first 4 periods of the current through the model dielectric. The Fourier analysis of the generated current was performed separately for each period. Next, the complex capacitance was calculated from the values of the amplitude and the phase of current. The calculation was repeated for various values of ω near the expected relaxation peak. The resulting values of the imaginary part of the complex capacitance (C'') are depicted in Fig. 4. For the sake of transparency, we plot only the data calculated from the first and the second period. These are compared with the C'' calculated from the model impedance. Generally, the error of the peak position - ΔP is in all cases zero. It means, the phase shift of the impedance does not depend on the period, from which it has been calculated. The magnitude error ΔM has a principle dependence, which is influenced only a little by the model parameters. This principle dependence resides in a great value of error for the first harmonic.

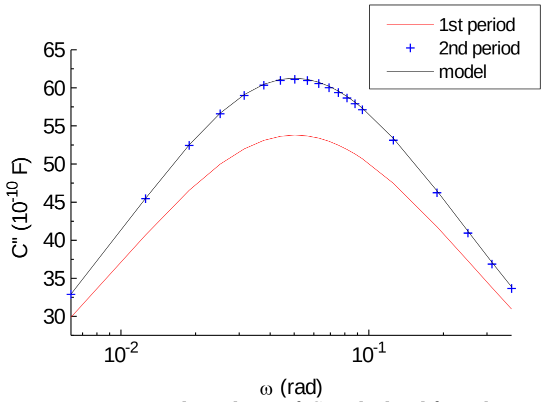

Fig. 4: Frequency dependence of C'' calculated from the current after application of a sinusoidal voltage for various periods

The situation is demonstrated in Tab. 2. Only the parameter $\Delta\varepsilon$ is here varied, but the results are similar if changing the other parameters. The most important conclusion is, that the impedance data calculated from the first period are unreliable. To get more precise results, we must use at least the third period (see ΔM_3 and ΔM_4 in Tab. 2.). The model data have been also proved experimentally at construction of the impedance meter intended for very low frequency measurements [4].

Tab. 2: The peak magnitude error for various periods with $\Delta\varepsilon$ as parameter (the index at ΔM means the sequential number of the individual period)

$\Delta\varepsilon$	ΔM_1 (%)	ΔM_2 (%)	ΔM_3 (%)	ΔM_4 (%)
5	12.22	0.255	0.038	0.035
10	12.21	0.246	0.034	0.004
15	12.21	0.251	0.051	0.022
20	12.20	0.248	0.049	0.021

CONCLUSIONS

Modeling of transient phenomena in a dielectric system indicated a significant influence of all three examined effects on the results of insulation diagnostic tests. It was shown that the dielectric memory effect shifts the magnitude and the position of a relaxation maximum at the complex capacitance measurements. Anyway, this undesirable influence can be predicted and eliminated, if we know the relaxation time of the process. This can be estimated at charging current measurement. The necessary charging time needed for the precise results processing can be calculated online at any instant of the charging process and compare with the values, we have generated by our model analysis. Information on the charging time can thus reduce the total time of the test.

The second investigated effect – deformation of the charging voltage against the rectangular form can be easy identified experimentally (e.g. by the sampling oscilloscope). From an experiment we are able to estimate the time constant τ and find out, whether the peak in the course of *C''* is the measured object property or it is generated by an unsuitable charging voltage. The check of charging voltage is often omitted which can cause some serious errors at test assessment.

By examination of the sinusoidal voltage measurements we find, that they are substantially influenced by the signal duration. The transient lasts approximately 3-4 periods. This phenomenon influences mainly the peak value of *C''*. Although there is a trend of reducing the duration of diagnostic tests, we do not recommend using the results achieved from the first period of voltage. The problem has of course no importance at higher frequencies where duration of the first few periods is negligible.

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