Combination of voltage response method with non-contact electrostatic voltage measurement to determine the dielectric response of insulating materials

Z Á Tamus
Budapest University of Technology and Economics,
Egry J. utca 18, Budapest, H-1111, Hungary
E-mail: tamus.adam@vet.bme.hu

Abstract. The paper introduces the development of a new voltage response measurement method to determine the dielectric response function of insulating materials. This new method is based on a non-contact electrostatic voltage follower. In this technique, the voltage of the measuring probe follows the surface potential. The probe voltage is connected to the guarding electrode and helps to increase the impedance of the equipment. The paper introduces the built-up of the equipment and the relationship between the slopes of decay and return voltages and the dielectric response function.

1. Introduction
The dielectric response can be investigated in frequency and time domain, as well. In frequency domain, it can be measured by the application of sinusoid voltage on the dielectric and the complex dielectric constant is determined from the amplitude and the phase of the current flowing through the sample. In time domain, a step voltage is applied on the sample and the current responses, namely the polarisation and depolarisation currents, are measured [1]. In case of linear dielectric, the results of frequency and time domain measurements are theoretically equivalent [2]. The measurement of the voltage response of a charged insulation can be also used to characterise insulating materials [3], however this method was developed for insulation diagnostics of high voltage apparatus [4, 5]. The initial technique can characterise the dielectric processes by only two figures (the slope of decay and return voltages) but by the systematic changing of the discharging times, the parts of the polarisation spectrum can be investigated more precisely [6], moreover the equivalent circuit of the insulation can be determined [7]. Application of this method for characterise small material samples is limited, because the capacitance and the resistance of the sample and the measuring equipment are in the same order of magnitude, therefore the effect of the measuring equipment on the result is not negligible. By using of non-contact electrostatic voltage follower can eliminate this problem and the dielectric response can be determined from the results of voltage response measurement. This paper introduces the theory of the new measurement method and the steps of the development.
2. Voltage response method for material characterisation

The voltage response method based on the measurement of decay and return voltages. The initial technique uses a long charging time (usually more than 1000 seconds) and only one short (few seconds) discharging and the slopes of the decay \( S_d \) and return \( S_r \) voltages are used for evaluation (Figure 1). Later this technique have been developed by using more than one discharging with different shorting times and measuring more slopes of return voltages [6] (Figure 2). This development enables detailed investigation of the distribution of polarisation processes.

3. Interpretation of the results of extended voltage measurement method

If a dielectric is connected to a d.c. voltage source, the polarisation current can be expressed as [8]:

\[
i_{pol}(t) = C_0 V_{ch} \left[ \frac{\sigma_0}{\varepsilon_0} + \varepsilon_\infty \delta(t) + f(t) \right],
\]

where \( C_0 \) is the capacitance of the electrode arrangement in free space ("geometric capacitance"), \( V_{ch} \) is the charging voltage, \( \sigma_0 \) is the conductivity of the dielectric, \( \varepsilon_\infty \) is the relative permittivity due to the "instantaneous polarisation", \( \delta(t) \) is the Dirac delta function (represents the capacitive charging current) and \( f(t) \) is the dielectric response function. Since, the dielectric measurements based on d.c. voltage are usually not capable to investigate the "fast" polarisation processes, the capacitance increment due to the "instantaneous polarisation" are considered in the value of geometric capacitance. Therefore in real measurements the \( C_0 \) is had to be replaced to \( C = \varepsilon_\infty C_0 \), where \( C \) is the capacitance of the test arrangement measured at power frequencies.

In case of voltage response measurement, the slope of decay voltage is measured after disconnecting a charged dielectric from the voltage source. After disconnection, the free charge on the electrodes tries to maintain the electric filed, but the conducting current and the absorption current decays it. The initial slope of the decay voltage \( (S_d) \) can be expressed from Eq. 1 by substitution of \( t_{ch} \) and \( C \):

\[
S_d = \frac{V_{ch}}{dt} \bigg|_{t=t_{ch}} = -\frac{i_{pol}(t_{ch})}{C} = -\frac{V_{ch}}{\varepsilon_\infty} \left[ \frac{\sigma_0}{\varepsilon_0} + f(t_{ch}) \right].
\]

Since, by shorting a dielectric charged for \( t_{ch} \) time, the depolarisation current is (after [8]):

\[
i_{depol}(t) = -C_0 V_{ch} \left[ f(t) - f(t + t_{ch}) \right].
\]

From Eq. 3 the slope of return voltage \( (S_r) \) can be expressed after \( t_{dch} \) discharging time:
\[ S_r = \frac{V_{ch}}{\varepsilon_\infty} \left[ f(t_{dch}) - f(t_{dch} + t_{ch}) \right]. \]  

(4)

It can be seen form eq.2, if the charging time is high enough the value the dielectric response function can be neglected and as Németh stated [3] the \( S_d \) is directly propositional to the conductivity. If the \( t_{dch} \) is close to zero, the \( S_r \) is directly proportional to the intensity of "slow" polarisation processes (eq. 4). Németh characterised the dielectric response at 0 time with a conduction like figure, namely the polarisation conductivity [3].

Since the extended voltage response method measures a set of slopes of return voltages as a function of discharging times, the \( S_r(t_{dch}) \) curve is equivalent to the depolarisation current curve (see eq. 3 and 4).

4. The new method based on electrostatic voltmeter

As the previous section introduces the slopes of decay and return voltages are characteristic values of the insulating material, but the voltage has to be measured by a lossless voltmeter and the capacitance of the equipment can be neglected. However, these requirements are easily fulfilled during testing real insulations (e.g. high voltage equipment), in case of measurement of small material samples, the capacitance of the sample are in the same order of magnitude of that of the test equipment. Other limitation of the method is that the measurement of characteristic values of the material requires guarded electrode arrangement [9] to reduce the surface current and electric field inhomogeneity at the edges of the electrodes.

However, the issue of lossless voltmeter can be solved by using non-contact voltmeter, the charging and discharging processes cannot be solved by a simple voltage source. A possible solution can be the usage of corona electrode for charging [10, 11, 12], but by this method, charging and discharging times cannot be controlled easily. For the reliable determination of the dielectric response function, definite charging and discharging times is needed, which requires the application of switches however, the impedance of practical switches is similar in range to that of the tested samples.

Previous problems have been solved by the newly developed method. The simplified arrangement of the equipment can be seen in Figure 3. The Figure shows the voltage is measured by a non-contact voltage follower type electrostatic voltmeter (TREK 430 ESVM). In this method, the test probe follows the voltage of the surface [9, 13]. By connecting the probe to the guarding electrode the leakage current on the surface of the sample can be eliminated and the inhomogeneity of the field on the edge of the high voltage electrode can be reduced.

The insulation impedance of the switches can be increased by bootstrapping technique. The initial circuit is complemented by another switch (SW3). One terminal of SW3 is connected to the test electrode. The other terminal is connected to the common terminal of the other switches and a resistor (R) connects it to the probe. The value of the R resistor is not critical, but some considerations are needed to take into account. First, the value has to be lower than the insulation resistance of the SW3 at least by two order of magnitude to neglect the voltage drop on the SW3 switch. Second, the bootstrapping voltage source of the electrostatic voltmeter cannot be overloaded by the R resistor. Third, the charging time of stray capacitances has to be faster than the slopes of the measured voltages.

5. Measurement result

The effectiveness of the arrangement can be demonstrated by a simple comparative measurement. A thin film PVC sample was measured by two methods. In first case, the guarding electrode was disconnected from the test probe in the figure it is denoted by "No Guard". In the second case, the introduced arrangement was used ("Guard"). The test voltage was 1000 V and the charging time was 2000 s in both cases. Figure 4 shows the slopes of return voltages as the function of
As the figure shows in case of short discharging times the difference between the measurement results is negligible, but in "No Guard" case the slopes of return voltages become higher if the discharging times are over 40 s. This can be resulted from that polarisation processes were also developed in the mounting insulation without guarding. The slopes of decay voltages show more significant difference. Without the bootstrapped guard electrode, the $S_d$ value was -59.211 V/s while in "Guard" case it was only 31.803 V/s.

6. Conclusion
The main theory of the newly developed voltage response meter is introduced. The new solution enables to reduce the effect of the equipment on the result, therefore material samples with low capacitance and high resistance can be tested. The relation of the measurement results to the dielectric response is introduced. These results of the test measurement show the effectiveness of technique.

Acknowledgments
Project no. 123672 has been implemented with the support provided from the National Research, Development and Innovation Fund of Hungary, financed under the KNN_16 funding scheme.

References
[1] Helgeson A and Gafvert U 1998 Proceedings of 1998 International Symposium on Electrical Insulating Materials. 1998 Asian International Conference on Dielectrics and Electrical Insulation. 30th Symposium on Electrical Insulating Materials, pp 393–398
[2] Jonscher A K 2008 Dielectric relaxation in solids (Xian: Xi’an Jiaotong University Press) ISBN 9787560527062 756052706X
[3] Németh E 1971 Periodica Polytechnica, Electrical Engineering 15 305–322
[4] Németh E 1999 Science, Measurement and Technology, IEE Proceedings - 146 249–252 ISSN 1350-2344
[5] Oyegoke B, Hyvonen P, Aro M and Gao N 2003 IEEE Transactions on Dielectrics and Electrical Insulation 10 802–873 ISSN 1070-9878
[6] Tamus ZÁ, Csábi D and Csányi G M 2015 Journal of Physics: Conference Series 646 012043 URL http://stacks.iop.org/1742-6596/646/i=1/a=012043
[7] Tamus Z and Csányi G 2015 International Symposium on High Voltage Engineering, ISH 2015
[8] Zawislak S 2003 IEEE Electrical Insulation Magazine 19 5–19 ISSN 0883-7554
[9] Bartnikas R, McMahon E and on Electrical Insulating Materials A C D 1987 Engineering Dielectrics Volume III, Electrical Properties of Solid Insulating Materials: Measurement Techniques ASTM STP 926 (American Society for Testing and Materials) ISBN 9780803104914
[10] Molinie P, Goldman M and Gatellet J 1995 Journal of Physics D: Applied Physics 28 1601–1610
[11] Molinie P 2005 IEEE Transactions on Dielectrics and Electrical Insulation 12 939–950 ISSN 1070-9878
[12] Moliníe P 2018 Proceedings of the 2018 Electrostatics Joint Conference
[13] Noras M A 2002 Trek application note