Characterization of dielectric materials by the extension of voltage response method

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Abstract. The voltage response method measures the decay and return voltages on a charged and shorted dielectric and from the slopes of these voltages the specific conductivity and the polarization conductivity of the material can be determined. These two numbers can characterize the main dielectric processes, namely the conductivity and the polarization, however the phenomenon of polarization is the sum of numerous elementary polarization processes with different intensities and time constants. By changing the shorting time of a charged insulation the elementary polarization processes can be examined separately and the whole polarization spectrum can be investigated more precisely. This paper introduces how the voltage response measurement technique is extended by the variation of discharging times and the mathematical model of the measurement is described. Measurements on a model dielectric and on a dielectric material were carried out and the results have been compared by the results of the calculations.

1. Introduction
The voltage response method measures the decay and return voltages on a charged dielectric. The timing diagram and arrangement of the measurement can be seen in figure 1 and 2, respectively. The decay voltage \( V_d(t) \) can be measured after the relatively long \( t_{ch} = 100−1000 \) s charging period of an insulation, while the return voltage \( V_r(t) \) appears after a few seconds shorting \( t_{dch} \) of the charged arrangement. The initial slope of the decay voltage \( (S_d) \) is directly proportional to the specific conductivity \( (\gamma) \) of the material and the slope of the return voltage \( (S_r) \) is directly proportional to the polarization conductivity \( (\beta) \) of slow polarization processes having time constant higher than the discharging time \( (t_{dch}) \) [1]. These two figures \( (S_d, S_r) \) are successfully used for condition monitoring of the insulation of electric power equipment and cables [2, 3, 4, 5], however the weakness of this method is that the whole polarization spectrum of the material is characterized by only one number \( (S_r) \), whereas the distribution of elementary polarization processes by time constant is not uniform. The different ranges of polarization spectrum can be investigated by the changing of charging \( (t_{ch}) \) and discharging \( (t_{dch}) \) times and in this way the original voltage response method can be extended [6]. In this investigation, the charging time is chosen to constant \( (1000 \) s) and the discharging times were increased step by step. The relationship between the variation of charging-discharging times of return voltage measurement and the peaks of return voltages has been published elsewhere [7], however the usage for characterization of dielectric materials by the slopes of return voltages has not been introduced, yet.
2. Model of the measurement

Professor Endre Németh introduced [1] the relationship between the material properties and the result provided by voltage response measurement. The slope of decay voltage is directly proportional to the conductivity of the insulation

\[ S_d = \frac{V_{ch}}{\epsilon_0} \gamma, \tag{1} \]

where the \( V_{ch} \) is the charging voltage, \( \gamma \) is the specific conductivity of the material and \( \epsilon_0 \) is the permittivity of free space. Similarly, the slope of the return voltage is directly proportional the polarization conductivity of the material (\( \beta \)):

\[ S_r = \frac{V_{ch}}{\epsilon_0} \beta = \frac{V_{ch}}{\epsilon_0} \sum_{i=1}^{n} \beta_{pi}. \tag{2} \]

As equation 2. shows in real dielectrics the polarization conductivity is the sum of the polarization conductivities of the elementary processes (\( \beta_{pi} \)), which remain in activated state after charging and discharging of the insulation. The relation between the polarization conductivity and the polarizability (\( \alpha_{pi} \)) of a given elementary process is \( \beta_{pi} = \alpha_{pi}/\tau_{pi} \), where \( \tau_{pi} \) is the time constant of the process. For the calculation of return voltages the extended Debye model of the insulation is used (figure 3.). In this model \( C_0 \) represents the capacitance of the electrode arrangement without the insulating material (vacuum capacitance). \( R_0 \) is the d.c. resistivity of the insulation and the \( R_{pi} - C_{pi} \) branches (Debye elements) represent the elementary polarization processes of the insulation. The elementary processes can be characterized by their time constants \( \tau_{pi} = R_{pi}C_{pi} \) and intensities, namely the polarizability (\( \alpha_{pi} = C_{pi}/C_0 \)). The relation between the equivalent circuit of an insulation (figure 3) and the parameters provided by the voltage response measurement can be expressed:

\[ S_d = \frac{V_{ch}}{\tau_0}, \tag{3} \]
where \( \tau_0 = R_0 C_0 \). The initial slope of return voltage \( (S_r) \) can be expressed as the sum of the gradients of return voltages generated by Debye (elementary polarization) processes:

\[
S_r = \sum_{i=1}^{n} \frac{V_{C_p i}}{\tau_{r i}}
\]

(4)

where \( V_{C_p i} \) is the remaining voltage of a \( C_{p i} \) capacitor in a Debye element after charging and discharging of the insulation and \( \tau_{r i} = R_{r i} C_0 \). The relation between the extended Debye circuit and the material properties can be expressed by the susceptibility \( (\kappa = \sum_{i=1}^{n} C_{p i}/C_0) \), which represents the intensity of polarization process in the material \( (\kappa = (\epsilon_r - 1)) \) at zero frequency.

3. Computation of return voltages on extended Debye model of dielectrics

The aim of the extension of voltage response measurement is the investigation of the elementary polarization processes and to determine the parameters of the extended Debye model of the measured insulation. For this reason the measurement technique is developed: the charged insulation is not only discharged once, but more shorting is executed, therefore different polarization processes remain activated after the different discharging times and more slopes of return voltages are measured. For the calculations and the measurements, thirteen discharging times between \( 2^{-200} \) s were chosen but the charging time was \( 1000 \) s in all cases. At the calculations, the dielectric processes were modeled in the \( 0.1^{-10000} \) s time constant range and the intensities of the processes were varied till the calculated slopes of return voltages became acceptable close to the measured values.

4. Experimental

4.1. Measurement on dielectric model with two Debye elements

The results of the simulation have been validated on a dielectric model, which contains two elementary polarization processes. Using the symbols of figure 3, the parameters of the model can be seen in table 1. The results of the calculations and the measurement show good agreement (table 2).

| i= | 1   | 2   |
|----|-----|-----|
| \( \tau_i \) | 5.16 s | 41.28 s |
| \( R_{p i} \) | 1.72 G\( \Omega \) | 2.10 G\( \Omega \) |
| \( C_{p i} \) | 3.00 n\( F \) | 19.63 n\( F \) |

4.2. Measurement on EPR insulation

The measurements were carried out on the insulation of a four core low-voltage ethylene propylene rubber (EPR) insulated low voltage cable. After the measurement the model of the EPR insulation have been determined by the variations of the parameters of an extended Debye model, which contains four Debye elements. The time constants of the elements were chosen to \( 1, 10, 100 \) and \( 1000 \) s. The calculated parameters of the model are in table 3. The result shows that the slow polarization processes (time constants higher than \( 1 \) s) of such a complex dielectric like an EPR insulated cable can be characterized by only four Debye elements (table 4).
Table 2. Slopes of return voltages of the the model dielectric with two Debye elements \( (R_0 = 57.0 \, G\Omega, \, C_0 = 9.66 \, nF, \, T_{ch} = 1000 \, s, \, V_{ch} = 1000 \, V) \)

| \( t_{dch} \) [s] | 2   | 4   | 6   | 8   | 10  | 15  | 20  | 30  | 50  | 75  | 100 | 150 | 200 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Meas. [V/s]      | 88.0| 74.9| 64.8| 57.3| 51.3| 39.6| 32.6| 23.7| 14.3| 7.6 | 4.2 | 1.3 | 0.4 |
| Calc. [V/s]      | 87.7| 72.4| 61.3| 53.3| 47.3| 37.5| 31.5| 23.9| 14.6| 8.0 | 4.3 | 1.3 | 0.4 |

Table 3. Model of the EPR insulation \( (C_0 = 255 \, pF) \)

| \( i \) | 1   | 2   | 3   | 4   |
|--------|-----|-----|-----|-----|
| \( \tau_i \) | 1 s | 10 s| 100 s| 1000 s|
| \( R_{pi} \) | 48.1 G\Omega | 292 G\Omega | 1.78 T\Omega | 10.8 T\Omega|
| \( C_{pi} \) | 20.78 pF | 34.21 pF | 56.32 pF | 92.69 pF|

Table 4. Slopes of return voltages of the EPR insulation \( (t_{ch} = 1000 \, s, \, V_{ch} = 1000 \, V) \)

| \( t_{dch} \) [s] | 2   | 4   | 6   | 8   | 10  | 15  | 20  | 30  | 50  | 75  | 100 | 150 | 200 |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Meas. [V/s]      | 24.6| 13.4| 9.4 | 7.5 | 6.3 | 4.2 | 3.3 | 2.5 | 1.8 | 1.2 | 1.0 | 0.7 | 0.6 |
| Calc. [V/s]      | 24.4| 12.8| 9.9 | 8.3 | 7.2 | 5.1 | 3.8 | 2.5 | 1.6 | 1.3 | 1.0 | 0.7 | 0.5 |

5. Conclusion

The voltage response measurement is a tool, which developed for measuring the slow polarization processes of an insulation. The initial technique can characterize the polarization processes by only one figure \((S_r)\) but by the systematic changing of the discharging times, the voltage response method have been developed. By this extension of the method, the parts of the polarization spectrum can be investigated more precisely. From the results provided by the extended method the equivalent circuit of the insulation can be determined. The results have been validated on a model dielectric with two Debye processes. Measurement have been carried out also on the insulation of a low voltage EPR cable and the parameters of a Debye circuit have been calculated. The result shows that the slow polarization processes of such a complex dielectric, like an EPR insulated cable, can be characterized by only four Debye elements.

References

[1] Németh E 1971 *Periodica Polytechnica, Electrical Engineering* **15** 305–322
[2] Németh E 1999 *Science, Measurement and Technology, IEE Proceedings - 146* 249–252 ISSN 1350-2344
[3] Tamus Z A and Berta I 2009 *Electrical Insulation Conference, 2009. EIC 2009. IEEE* pp 444–447
[4] Tamus Z A and Németh E 2010 *Int. Conf. on Condition Monitoring and Diagnosis, CMD 2010* pp 721–724
[5] Tamus Z A and Szedenik N 2013 *Journal of Electrostatics* **71** 462 – 466 ISSN 0304-3886
[6] Csányi G M and Tamus Z A 2014 *Electrical Insulation Conference (EIC), 2014* pp 299–302
[7] Ghourab M and Németh E 1992 *Periodica Polytechnica, Electrical Engineering* **36** 121–130