PERIODICA POLYTECHNICA SER. EL. ENG. VOL. 36, NO. 2, PP. 121–130 (1992)

INVESTIGATION OF THE RELATIONSHIP BETWEEN THE RETURN VOLTAGE AND POLARIZATION SPECTRUM OF INSULATIONS

M.E. GHOURAB and E. NÉMETH

High Voltage Department
Technical University of Budapest

Received: November 12, 1992.

Abstract

The step-by-step method has been used to calculate the value and determine the shape of the return voltage after a longer charging-up the insulation with a DC voltage, followed by a temporary short circuit [1]. In this paper is given a computer simulation method to investigate the long time-constant range of the polarization spectrum. This range can be investigated by successive calculation of the value of polarizability (polarization intensity), or the initial slope of the return voltage curve obtained at different ratios between the charging and the discharging times. Also the simulation method is used for the investigation of the polarization spectrum obtained from the return voltage measurements. Finally a comparison has been done between the calculated and experimental results.

Keywords: dielectric, insulation, simulation, return voltage, polarization spectrum.

Introduction

As a response of applying a voltage to polar dielectrics, polarization processes of different time constants are normally resulted. If the voltage is removed, these processes decay to their original positions. The time constants of these processes depend on the mobility, charges, etc. of the charge carriers. The most of the technical insulations have a continuous distribution of relaxation times (time-constants) [2,3], and from the point of view of practice it has a great importance to investigate this range. Different dielectric parameters give information about the different parts of the spectrum, (e.g., loss factor measured at different frequencies, thermally stimulated discharge method, DC parameters measured with different values of charging and discharging times [4-6]). In a recently contribution [1], an exact step-by-step method for modelling the long time-constant range of the polarization processes has been explained. In this paper this method is used to investigate the polarization spectrum by return voltage calculation. The dependence of the shape of the spectrum on the degradation of the insulation is explained as well.

Description of the Method

After the application of an electric field to the dielectric, the elementary polarization processes response with a delay according to their relaxation times. In the calculation the continuous distribution function can be approximated by a series of delta functions at regular distances. The weights of the delta functions can be obtained from the assumed value of relative permittivity. The development of polarization processes after charging time t_{ch} can be given by

$$P(t_{ch}) = E_0 \sum_{i=1}^{n} \alpha_i (1 - e^{t_{ch}/\tau_i}) \quad \text{A sec/cm}^2 \tag{1}$$

where, E_0 is the applied electric field V/cm. α_i is the polarizability of the i-th elementary processes (a quantity which measures the intensity of polarization in the dielectric) A sec/V cm. τ_i is the time constant of the i-th elementary process within the range $\tau_i - \frac{\Delta\tau}{2} < \tau < \tau_i + \frac{\Delta\tau}{2}$ and n is the number of elementary polarization processes. It is clear that the development of the elementary polarization processes are different during the charging time. The relative value of the development of the i-th elementary process over its steady state value after t_{ch}, is

$$r_i' = \frac{p_{i(t_{ch})}}{p_{i0}} = (1 - e^{-t_{ch}/\tau_i}). \tag{2}$$

where $p_{i0} = \alpha_i E_0$ is the steady state polarization in equilibrium. After switching-off the voltage and discharging the dielectric, the polarization will not instantaneously become zero, because there is a certain time required for the processes to return back to neutral positions. Therefore, the i-th elementary process after a very long charging-up, $t_{ch} \simeq \infty$ diminishes to

$$p_{i(t_{sc})} = p_{io} e^{-t_{sc}/\tau_i} A \quad \text{sec/cm}^2. \tag{3}$$

where t_{sc} is the discharging time. Similarly the relative rate of excitement r_i'' after t_{sc} time over its equilibrium value can be expressed by

$$r_i'' = \frac{p_{i(t_{sc})}}{p_{i0}} = e^{-t_{sc}/\tau_i}. \tag{4}$$

Therefore, we can illustrate that after a given t_{ch} charging and t_{sc} discharging period what will be the relative rate of excitement of the processes. *Figs.* (1) and (2) show the dependence of the resulting value of the relative rate of excitement, $r_i = r_i' r_i''$ on the values of charging and discharging times, respectively. In these figures is assumed a uniform distribution of the elementary polarization processes in 5 decades of time constants between 10^{-1} to 10^4 seconds. From these figures it can be seen that by increasing the charging time the value of r_i increases. While increasing of the discharging time, this value of r_i is decreased. Since the return voltage is brought about by the elementary polarization processes, the return voltage value is proportional to the area under these curves.

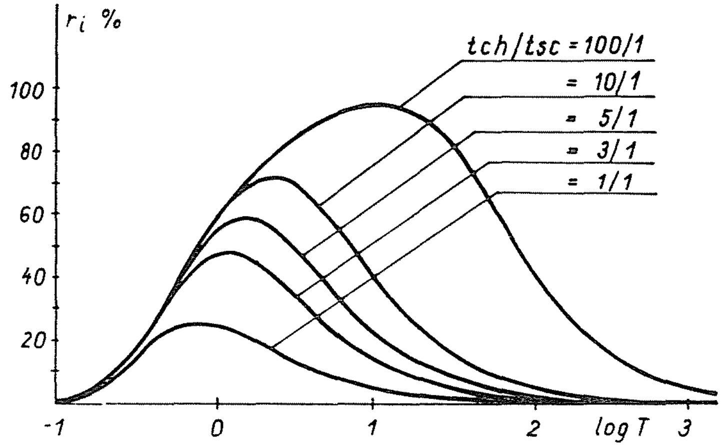

Fig. 1. The dependence of the relative rate of excitement on the processes time constants with charging voltage as a parameter. 5 decades, 5 proc./dec., $\varepsilon_r = 3$, $v_{ch} = 100$ volt.

Dependence of the Return Voltage Slope on the Measuring Parameters

It is proved [7,8] that the initial slope of the return voltage is proportional to the charging voltage v, and to the intensity of the processes causing it, i.e.

$$s_r = \frac{v}{\varepsilon_0} \sum_{i=1}^{n} \beta_i \quad \text{V/sec.} \tag{5}$$

where $\beta_i = \frac{d\alpha}{dt}$ is the polarization conductivity of the i-th elementary process A/V cm, and ε_0 is the permittivity of vacuum A sec/V cm. *Fig. (3)* illustrates the dependence of the slope on the process time constant in the case of single process at different ratios of t_{ch}/t_{sc}. From this figure we can see that there is a maximum nearly at the short circuit time. For a

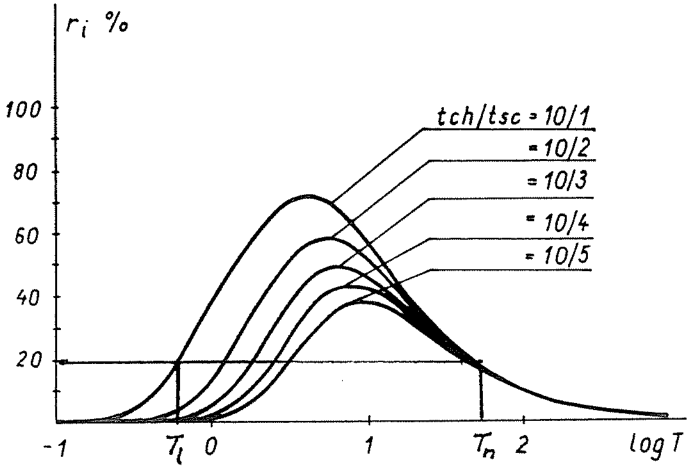

Fig. 2. The dependence of the relative rate of excitement on the processes time constant with discharging voltage as a parameter. 5 decades, 5 proc./dec. $\varepsilon_r = 3, v_{ch} =$ 100 volt.

certain time constant range of the spectrum its increasing rate depends on the value of t_{ch}. If the time constant of the process is greater than the short circuit time, the slope will decrease. Also, we can see that the rate of the increase of the slope on the left side of the diagram is higher than the rate of its decay on the right side. This means that the value of the slope depends strongly on the elementary polarization processes which have the smallest time constant in the investigated range.

From *Figs.*(1) and (2) it is clear that the value and the slope of the return voltage are proportional to the intensity of the polarization processes in the interval:

$$t_l < \tau_i < t_u. \tag{6}$$

where $t_l \simeq 0.5 t_{sc}$ and $t_u \simeq 7 t_{ch}$ are the lower and upper interval limits belonging to r_i equals to 20 % of its maximum value, respectively.

Therefore, the average polarization conductivity during this investigated range is

$$\bar{\beta} = \sum_{i=1}^{n} \beta_i \quad \text{A/V cm.} \tag{7}$$

where n is the number of the elementary processes, remaining in excitation after short circuit in the interval $t_l - t_u$. By a selective investigation of any

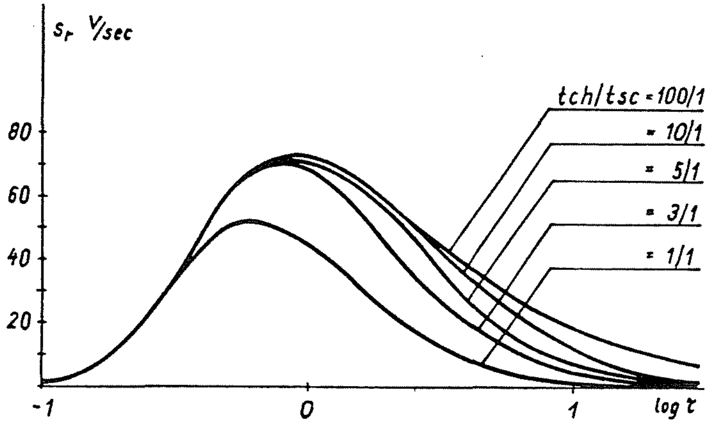

Fig. 3. Time constant dependency of the slope of the return voltage with different values of t_{ch}/t_{sc}. Single process $\varepsilon_r = 3, v_{ch} = 100$ volt.

optional $t_l - t_u$ interval, the long time constant range of the polarization spectrum can be examined by calculating of the value and the slope of the return voltage with charging and discharging times chosen according to equation (6). If the value of the average conductivity is multiplied by the charging time t_{ch} then the quantity

$$\alpha = K t_{ch} \bar{\beta} \quad \text{A sec/V cm} \tag{8}$$

gives the average polarizability of the investigated range. K is an arbitrary constant, its value depends only on the ratio of t_{ch}/t_{sc}. Consequently, the average polarizability of any optional part of the spectrum can be approximately determined from the slope of the return voltage with any arbitrary values of t_{ch}/t_{sc}.

Calculation of K

The arbitrary constant K indicates the ratio between the average polarizability in the investigated range and that value obtained from the calculation of the polarization conductivity. After charging and discharging the dielectric the processes are excited with different ratios depending on their time constants as shown in *Figs.* (1) and (2). Therefore by summation of the intensity of the processes which are still in excited state the value of K is

$$K = \frac{\sum_{i=1}^{n} \alpha_i}{\bar{\beta} t_{ch}}. \tag{9}$$

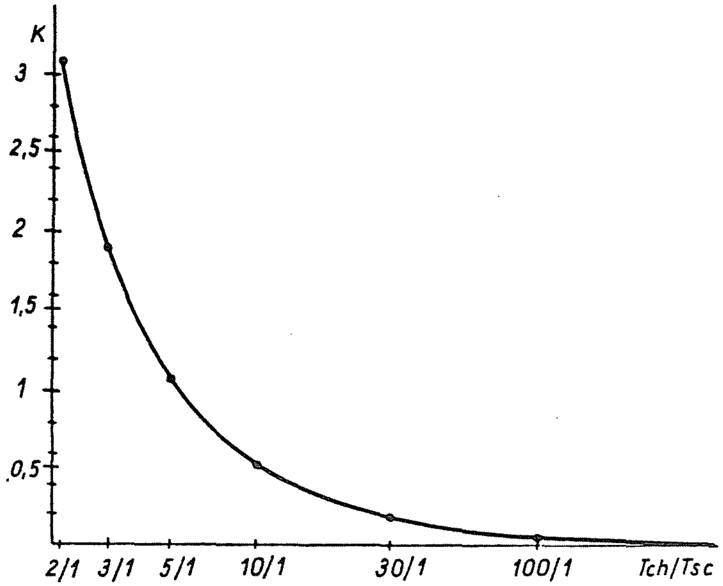

Fig. 4. Dependence of K on the ratio of t_{ch}/t_{sc}.

From *Fig. 4* the value of K decreases with the increase of the ratio of t_{ch}/t_{sc}.

Polarization Spectrum Investigation

The polarization spectrum characteristic of the dielectric can be obtained if the intensity of the elementary polarization processes is known as a function of the time constants. The intensities of these processes are characterized by the polarization referred to unit field strength applied to the dielectric. In our investigation the continuous spectrum has been substituted by a discrete one as shown in *Fig. 5-a.* Where α_i stands for the resultant polarizability of the processes which have a time constant τ_i. *Figs.* (5-a)(5-b) and (5-c) show the original assumed distribution functions which are denoted by letter A. From the assumed distribution functions the slopes belonging to different ratios of t_{ch}/t_{sc} were calculated and from the slopes again the distribution of polarization processes re-calculated. The re-calculated ones obtained from the step-by-step method are denoted by letter B. To control the condition of an insulation it is necessary to make the calculation are three steps per decade of time constant and to co-ordinate in each case the

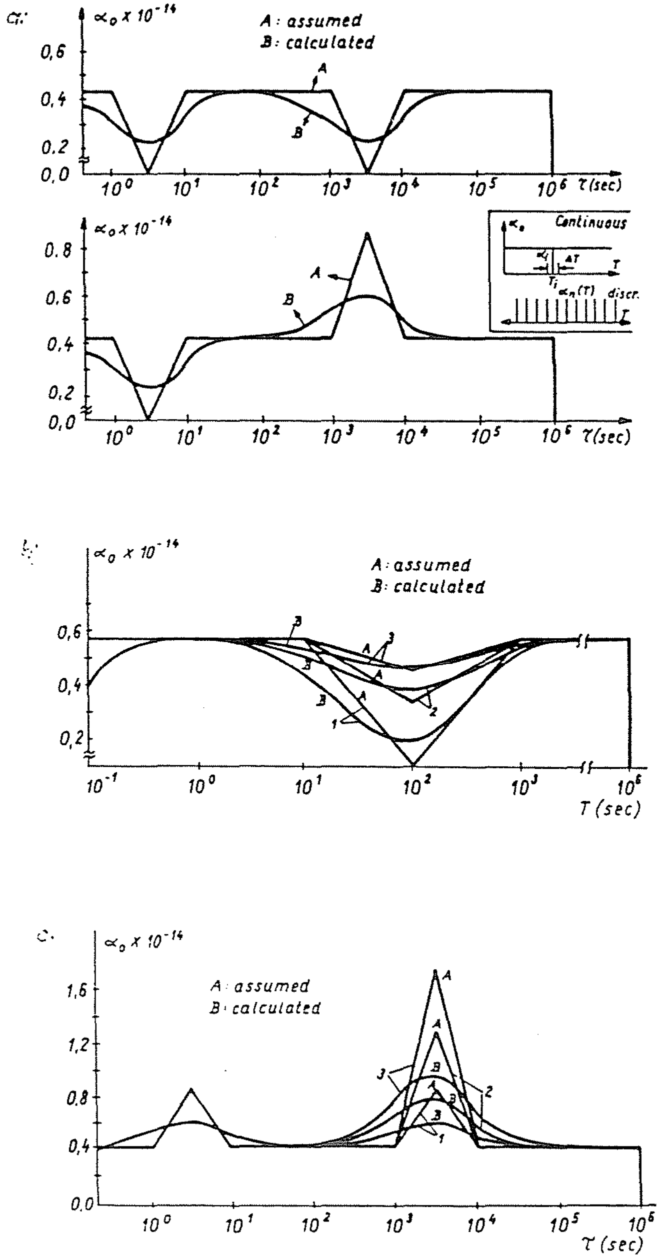

Fig. 5. Comparison between the assumed and calculated polarization spectra with $t_{ch}/t_{sc} = 10$, $\varepsilon_r = 3$, 7 decades 5 proc./dec. $v_{ch} = 100$ volt.

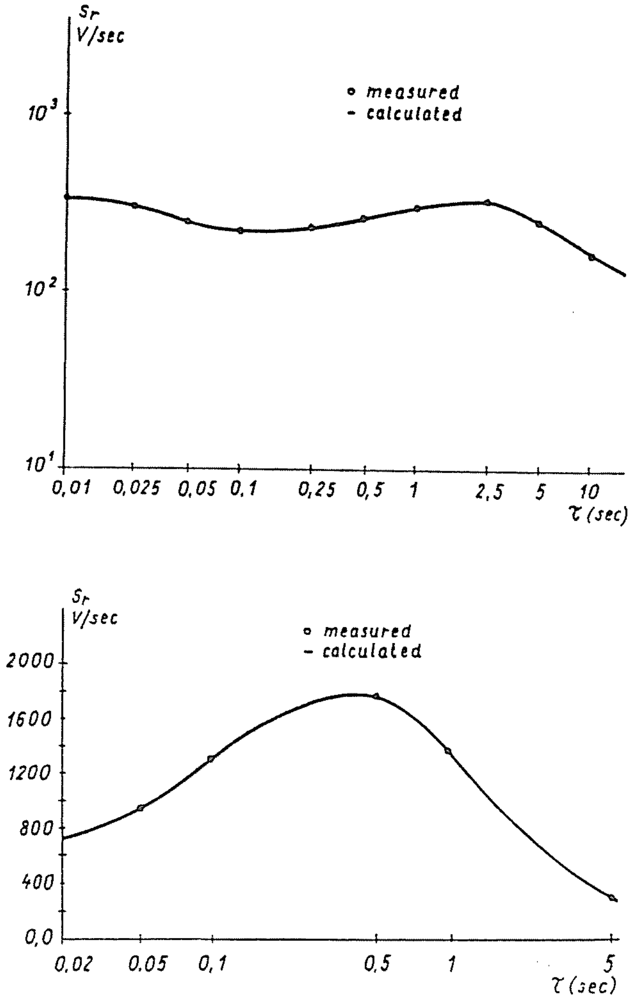

Fig. 6. Comparison between the measured and calculated values of the return voltage slope with a ratio of $t_{ch}/t_{sc} = 2$.

value of the average polarizability to the short circuit time of the calculated range (nearly the central time-constant of this range). By changing the window $t_{ch} - t_{sc}$ the average polarization spectrum can be determined as shown in these figures. From these figures it can be seen that there is a good agreement between the assumed and re-calculated polarization spectra.

Comparison between Experimental and Analytical Results

In order to investigate the polarization spectrum the initial slopes of the return voltage have been plotted versus the time constant. From these plots the polarization maxima can be determined. Also, the conditions of the insulation or the alteration of conditions can be observed from the shape or from the alteration of the shape of the spectrum, i.e. the increasing of maxima or from changing their sites.

Some measurements were carried out by the Hungarian Electricity Board on two transformers. These transformers are of 23 and 31 years of operations. The time constant range of 10^{-2} to 10^{3} second range of the spectrum of the first transformer was investigated in 16 steps. The investigated range of the second transformer was between 10^{-2} to 10^{2} second in 8 steps. In both cases the DC charging voltage was 2000 volt and the ratio between t_{ch}/t_{sc} was 2. As mentioned before the initial slope is affected by the processes which have a time constant range determined by *Eq.* (6). The calculated value of the constant K is 3.1 for t_{ch}/t_{sc} equals 2. Therefore, the value of the average polarizability $\sum \alpha_i$ in the investigated range of the spectrum can be determined by using *Eq.* (8). By using the simulation method and the obtained resultant polarizabilities the initial slopes of the return voltage have been re-calculated. *Figs.* (6-a) and (6-b) show the measured and the re-calculated responses of the slope for the two tested transformers. From these figures we can see that there is a good agreement between the original and the re-calculated results in both cases.

Conclusion

The proposed step-by-step method helps the correct interpretation of results obtained by measuring the return voltage. It has been used for the investigation of the long time constant range of polarization spectrum. The dependence of the initial slope of the return voltage on the measuring parameters has been discussed. The influence of the time window on the measured quantities is investigated as well. Also the relation between the polarization spectrum the measuring parameters and the measured quantities has been explained, too.

Acknowledgements

The authors wish to express their thanks to the Hungarian Electricity Board for the permission of publishing the result of the measurements.

References

1. GHOURAB, E. M. - NÉMETH, E. (1991): Computer Simulation of Dielectric Processes. *Proc. 7-3th 1International Symposium on High Voltage Engineering.* Dresden Germany August 26-30, 1991. Ref. No. 25-01.
2. DANIEL, V.V. (1967): Dielectric Relaxation. London Academic Press.
3. BÖTTCHER, C.J.F. - BORDEWIJK, P. (1978): Theory of Electric Polarization. Vol. 1–2. Amsterdam, Elsevier Scientific Publishing Company.
4. YAMANAKA, S. - FUKUDA, T. - SAWA, G. - IEDA, M. (1984):Residual Voltage on Low-density Polyethylene Film Containing Antioxydant. *Jap. J. Appl. Phys.* Vol. 23 No. 6 pp. 741-747.
5. KYOKANE, S. - YUN, M. - YOSHINO, K. (1986): Effect of Electron Irradiation on Residual Voltage of Polyethylene Films. *Jap. J. Appl. Phys.* Vol. 25, No. 2, pp. 301-302.
6. NÉMETH, E. (1981): Die zerstörungsfreien Prüfmethoden der Isolation. Ermittlung der die Kenngrössen bestimmenden Zeitkonstantenbereiche *9.Wiss.Konf. der Sektion Elektotechn.* TU Dresden B2-04. pp.20-24.
7. NÉMETH, E. (1979): Selective Investigation of Long-time-constant Ranges of Polarization by DC Methods. *3-rd International Conf. on Diel. Mat. Measurements and Applications*, Birmingham, Sept. 10-13 pp. 203-206.
8. NÉMETH, E. (1971): Proposed Fundamental Characteristics Describing Dielectric Processes in Dielectrics. *Periodica Polytechnica Ser. Electrical Engineering*, Vol. 15, No. 4, pp. 305-322.

Address:

Mohamed E. GHOURAB
Endre NÉMETH
High Voltage Department,
Technical University of Budapest,
H-1521 Budapest, Hungary.