

# PROPOSED FUNDAMENTAL CHARACTERISTICS DESCRIBING DIELECTRIC PROCESSES IN DIELECTRICS

By

E. NÉMETH

Department of High Voltage Engineering and Electrical Apparatus,  
Technical University Budapest

(Received February 24, 1971)

Presented by Prof. Dr. T. HORVÁTH

## 1. Introduction

An insulation may be investigated for a number of various so-called "non-destructive" dielectric properties (e.g. loss factor, resistivity, dispersion factor, etc.). Until now in practice, these properties were usually considered as mostly independent ones, though in fact, these are in a very close relation. Excluding local flaws likely to cause surface or inside discharges, at voltages lower than the breakdown strength only the phenomena of conduction and polarization occur in the dielectrics in response to the field strength. All dielectric quantities measured on dielectrics are affected by these two processes only, though to various degrees. Still to establish a relation between the measured quantities and the fundamental processes, the introduction of so-called "fundamental characteristics" describing the processes of conduction and polarization in the dielectric is needed. Thereby a possibility is given to an exact treatment of the relation of the measured quantities to the fundamental characteristics, and through these latter of each measured quantity to the others (Fig. 1).

Conduction in a material can unambiguously be described by the specific conductivity  $\alpha$  referred to unit volume (or by its invert. the specific resistivity  $\rho$ ). Dielectric polarization, however, is a by far more complex phenomenon than is conduction, so that it cannot be described by a single quantity. Still there exist general characteristics suitable to describe phenomenologically the process of polarization in dielectrics due to an electric field. The present paper offers a summary of the system of the fundamental characteristics and their interrelations with the characteristics of dielectrics.

## 2. Fundamental dielectric characteristics of dielectrics

Conduction is the phenomenon in the dielectric when in response to an external electric field, the charge carriers in the material transport charges from one electrode in the dielectric to the other. When a constant field strength

$E$  is applied to the dielectric the arising conduction-current density, unchanging in time, may be written as

$$J_c = \alpha \cdot E \tag{1}$$

where  $E$  [V/cm] the field strength, and  
 $\alpha$  [A/V · cm] the specific conductivity.

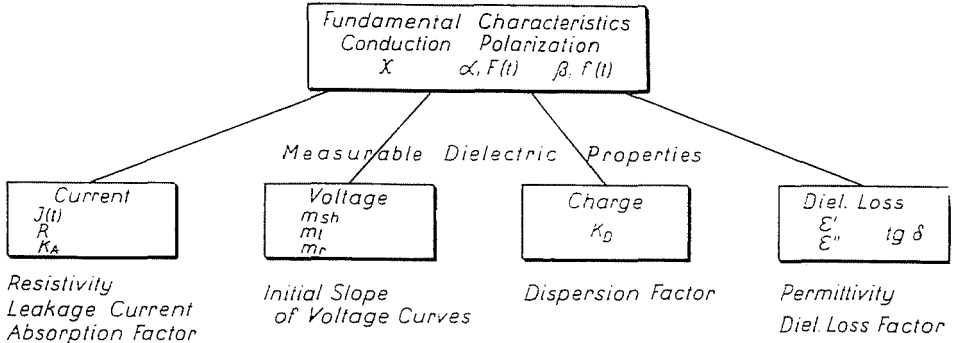


Fig. 1

Polarization, the process where the centres of gravity of the positive and negative charges in the material, originally neutralizing each other, are shifted from one another by the field, and an electric momentum of volume develops in the material, is not so simple to describe. At an abrupt change of the field strength the polarization cannot follow immediately it and will settle with a time lag at the value corresponding to the changed field strength. This time lag depends on the mass of the charge carriers, on its elementary charge, the apparent resistance to the displacement of the charge carriers, etc.

Magnitude and rate of rise of the polarization of a dielectric (the rate of lagging of the polarization behind the field) are in close interrelation with the structure of the material.

In general, each type of polarization is linked up with a definite group of charge carriers of the material. This close relation offers more information on the condition of dielectrics and its change for some reason (e.g. ageing) by studying the rate and process of polarization than that of conduction.

In the following discussion the term "polarization" will be used in general sense, i.e. for any process in the dielectrics involving — in response to the electric field — a reshuffling of the charges and being reversible, i.e. with ceasing of the field the original condition will be restored. Accordingly, the processes concomitant of the formation of field charges will come under the same heading

(in contradiction to certain authors who do not want to have processes included in the notion of polarization) [9].

At a survey of the fundamental characteristics lending themselves for a description of polarization we shall set out from two preliminary conditions [2, 8], viz.

(a) the investigations have been confined to a range of field strength where there is a linear relation between the value of polarization and field strength, i.e. the principle of superposition will hold for the dielectric; and

(b) that the polarization is the resultant of elementary polarization processes in the dielectric in response to the electric field exponentially with different time constants.

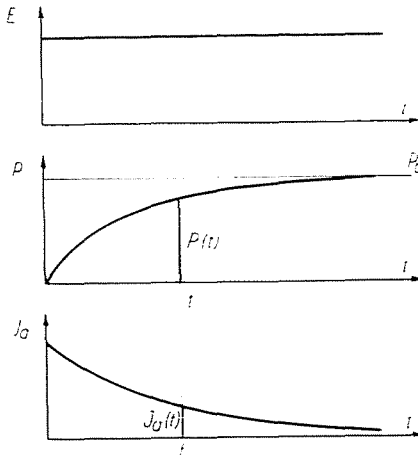


Fig. 2

Applying at time  $t = 0$  a constant field strength  $E$  to the dielectric, polarization will settle at a steady state value corresponding to the field strength with a time lag (Fig. 2).

By time  $t$  after applying the field, the polarization is expressed by

$$P(t) = P_0 \cdot F(t) = \alpha \cdot E \cdot F(t) \tag{2}$$

where

$$P_0 = \alpha \cdot E \tag{3}$$

is the steady state value of polarization.

In these relations:

- $P \left[ \frac{A \cdot s}{cm^2} \right]$  the polarization (bound charge density on the electrodes),
- $E \left[ \frac{kV}{cm} \right]$  the field strength,

$\alpha \left[ \frac{A \cdot s}{V \cdot \text{cm}} \right]$  proportionality factor between polarization and field strength.  
 i.e. the *polarizability* (polarization induced by unit field strength).  
 and  
 $F(t)$  the *relaxation function of polarization* describing the development of polarization in time [2, 7].  
 The limiting values of relaxation function are

$$\begin{aligned} \text{for } t \rightarrow 0, & \quad F(t) \rightarrow 0; \\ t \rightarrow \infty, & \quad F(t) \rightarrow 1. \end{aligned} \quad (4)$$

With development of polarization the charge bounded on the electrodes tends to grow. In the external circuit maintaining the field this growth will cause an accessory current, the so-called absorption current or anomalous charging current density

$$J_a(t) = \frac{dP(t)}{dt} \quad (5)$$

as referred to unit cross section of the dielectric.

With polarization approaching its steady state value this current decaying in time monotonously tends to zero. Similarly to polarization the absorption current is proportional to field strength, so that its initial value can be written as:

$$J_a(0) = \beta \cdot E \quad (6)$$

where  $\beta$  is the proportionality factor between absorption current density and field strength. Though in conformity with Ohm's law, the proportionality factor between field strength and current density is — by definition — the conductivity characteristic to conduction of dielectric (see Eq. (1)), so that (following a forgotten proposal of SMEKAL [9]) the proportionality factor  $\beta$  characteristic to the polarization in the material may be called "polarization conductivity".

In time the absorption current decays monotonously and tends to zero. Similarly to (2) the time-dependence of the absorption current density may be expressed by

$$J_a(t) = \beta \cdot E \cdot f(t) \quad (7)$$

where  $\beta \left[ \frac{A}{V \cdot \text{m}} \right]$  the polarization conductivity, and

$f(t)$  the current relaxation function (or: current decay function) expressing the time-dependence of the absorption current [2].

The limiting values of the relaxation function are

$$\begin{aligned} \text{for } t \rightarrow 0, \quad f(t) &\rightarrow 1; \\ t \rightarrow \infty, \quad f(t) &\rightarrow 0. \end{aligned} \quad (8)$$

### 2.1. Fundamental characteristics in case of a polarization with a single time constant

When there arises polarization with a single time constant  $T_p$  in the dielectric, the value of the fundamental characteristics may be written as follows:

the polarization-function

$$P(t) = \alpha_p E (1 - e^{-\frac{t}{T_p}}) \quad (9)$$

where  $\alpha_p$  the polarizability referred to the arising polarization, and

$F(t) = (1 - e^{-\frac{t}{T_p}})$  the relaxation function of the polarization.

Consequently if there is a polarization of a single time constant in the dielectric, the macroscopically measurable resultant polarization will show an exponential change.

In this case the absorption current may be written as

$$J_a(t) = \frac{d}{dt} [\alpha_p \cdot E (1 - e^{-\frac{t}{T_p}})] = \frac{\alpha_p}{T_p} \cdot E \cdot e^{-\frac{t}{T_p}} \quad (10)$$

From Eqs (10) and (7) it follows that

$$\beta_p = \frac{\alpha_p}{T_p} \quad (10a)$$

and

$$f(t) = e^{-\frac{t}{T_p}}$$

i.e. in this case the current will decay exponentially.

Obviously, both functions  $F(t)$  and  $f(t)$  satisfy the boundary conditions given in (4) and (8).

### 2.2. Fundamental characteristics for superposed processes of several time constants

If in response to an electric field several superposed exponential processes of different time constants take place in the dielectric, then the resultant polar-

ization does not develop exponentially. As is known, the elementary polarization processes of different time constants are not to arise necessarily with the same intensity in the material, so that polarizability  $\alpha$  will change dependent on the time constant  $T$ . i.e. [2, 7, 8].

$$\alpha = \alpha(T)$$

Several attempts have been made to define the relationship between the dielectric parameters measured on dielectrics and the distribution of polarization by approximating the density function of polarizability of the material with a function of arithmetical form. Though these hypothetical distributions are not of general validity, and produce a result conforming to experience only for testing particular dielectrics and within a specified range of time constants, i.e. each of these distributions is valid for certain types of polarization only [1, 5, 10, 11, 12, 13].

In the following we shall demonstrate that by making use of the system of fundamental characteristics as outlined here, no concrete knowledge of the distribution of polarization is necessary to establish a direct relationship between the fundamental dielectric processes and the measured dielectric characteristics. To describe the distribution of polarization according to time constant, let us introduce the density function  $q_z(T)$ , viz.

$$q_z(T) = \frac{1}{\alpha_0} \frac{d\alpha}{dT} \quad (11)$$

where  $\alpha_0$  is the resultant polarizability of elementary polarizations in the time constant range under test  $T_1$  to  $T_2$

$$\alpha_0 = \sum_{T_1}^{T_2} \alpha_k \quad (12)$$

The range limits  $T_1$  and  $T_2$  are defined by the dielectric property measured on the dielectric. (Polarization ranges of other time-constants are tested when e.g. the loss factor is measured, or for absorption current measurements with d.c. voltage.)

It follows from the interpretation of the density function that the polarizability  $\alpha_k$  resulting from elementary polarizations with time constants within the range of a width  $\Delta T$  around the time constant  $T_k$  (Fig. 3) may be written as

$$\alpha_k = \Delta \alpha(T_k) = \alpha_0 \cdot q_z(T_k) \cdot \Delta T \quad (13)$$

whereas the steady state value of the elementary polarization so generated:

$$\Delta P_{0k} = \Delta P(T_k) = E \cdot \Delta \alpha(T_k) = E \cdot \alpha_0 \cdot q_z(T_k) \cdot \Delta T \quad (14)$$

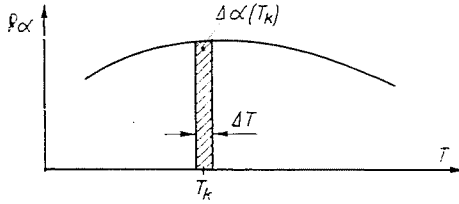


Fig. 3

If the range  $\Delta T$  is sufficiently narrow, after applying a field strength  $E$  at  $t = 0$  the elementary polarization develops exponentially with the time constant  $T_k$ , i.e.

$$\Delta P_k(t) = E \cdot \alpha_0 \cdot \varrho_z(T_k) \cdot \Delta T \cdot (1 - e^{-\frac{t}{T_k}}) \tag{15}$$

The resultant polarization can be obtained as the sum total of the elementary processes, i.e. as the integral of the elementary polarization between time constants  $T_1$  and  $T_2$  with respect to  $dt$ :

$$P(t) = E \cdot \alpha_0 \int_{T_1}^{T_2} \varrho_z(T) \cdot (1 - e^{-\frac{t}{T_k}}) dT = E \cdot \alpha_0 \cdot F(t) \tag{16}$$

From Eqs (2) and (16), the value of the function  $F(t)$  is:

$$F(t) = \int_{T_1}^{T_2} \varrho_z(T) \cdot (1 - e^{-\frac{t}{T_k}}) dT \tag{17}$$

This function meets the conditions in Eq. (4), since for  $t = 0$ ,  $F(t) = 0$  (the exponential term within the brackets being zero at any optional  $T$ ); for  $t = \infty$ ,  $F(t) = 1$  (the value of the bracketed term being unity) and by definition of the density function:

$$F(t) = \int_{T_1}^{T_2} \varrho_z(T) dT = 1 \tag{18}$$

Let us now investigate the relationship between the characteristics  $\beta$  and  $f(t)$  introduced for the description of the absorption current to the fundamental characteristics describing polarization. From Eqs (5) and (16) the absorption current is:

$$J_a(t) = \frac{d}{dt} [E \cdot \alpha_0 \int_{T_1}^{T_2} \varrho_z(T) \cdot (1 - e^{-\frac{t}{T}}) dT] = E \cdot \alpha_0 \int_{T_1}^{T_2} \frac{\varrho_z(T)}{T} \cdot e^{-\frac{t}{T}} dT \tag{19}$$

At  $t = 0$  the current

$$J_a(0) = \left[ \frac{dP}{dt} \right]_{t=0} = E \cdot \alpha_0 \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} dT = E \cdot \alpha_0 \cdot k \quad (20)$$

when introducing the following notation:

$$k = \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} dT \quad (21)$$

From Eqs (6) and (20) it will be seen that the resultant polarization-conductivity is

$$\beta_0 = \alpha_0 k = \alpha_0 \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} \cdot dT \quad (22)$$

Substituting  $\beta_0$  in Eq. (19), the relaxation function describing the current change:

$$f(t) = \frac{1}{k} \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} \cdot e^{-\frac{t}{T}} \cdot dT \quad (23)$$

The function meets the limiting conditions in Eq. (8), because

$$\text{for } t = 0, \quad f(t) = \frac{1}{k} \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} \cdot 1 \cdot dT = \frac{k}{k} = 1$$

and

$$\text{for } t = \infty, \quad f(t) = \frac{1}{k} \int_{T_1}^{T_2} \frac{\rho_x(T)}{T} \cdot 0 \cdot dT = 0$$

### 3. Relationship between the fundamental characteristics and dielectric parameters measured on dielectrics

#### 3.1. Charging and discharging currents

When in the circuit shown in Fig. 4 at time  $t = 0$  a unidirectional field  $E$  is applied to a dielectric, then the instrument inserted in the external circuit



will first indicate a current decaying in time, and then a steady state value. Be  $J(t)$  the current density referred to unit surface of the dielectric, then:

$$J(t) = J_0(t) + J_a(t) + J_c \tag{24}$$

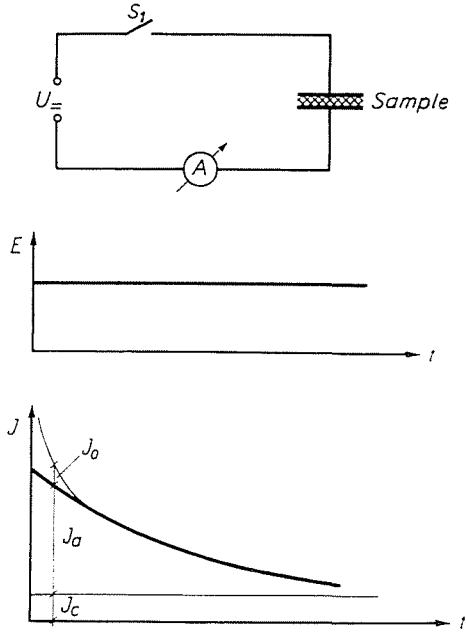


Fig. 4

where  $J_0$  the capacitive component needed for charging up the capacity of the sample,

$J_a$  the absorption component by development of polarization. and  $J_c$  the conductive component [10].

The capacitive component decays exponentially in time, its time constant is determined only by the geometric capacity of the sample to be charged and the internal resistance of the voltage generator. When the two are properly aligned, the capacitive component may be caused to vanish much sooner than the absorptive component.

On the assumption that, owing to its small time constant, the capacitive component will not influence the measured charging current at all. there will remain only two components in this, viz.

$$J(t) = J_a(t) + J_c \tag{25}$$

Form Eqs (1) and (7)

$$J(t) = E \cdot (\beta \cdot f(t) + z) \tag{26}$$

From Eq. (8) the initial current density extrapolated for  $t = 0$  may be written as:

$$J_0 = E \cdot (\beta + z) \quad (27)$$

i.e., its initial value is proportional to the sum total of the "conductive" and "polarization" conductivity (Fig. 5).

After a long time (assumed to be  $\infty$  for the development of the polarization) equally from Eq. (8) the current density is:

$$J(\infty) = E \cdot z \quad (28)$$



Fig. 5

i.e. the steady state value of the charging current is proportional to conductivity only. Hence, from the initial and stabilized values of the measured charging current the values of the conductivity and of the polarization conductivity may be directly established.

At non-destructive test of insulations the absorption factor  $K_A$  is used for denoting the condition of the insulation, defined by

$$K_A = \frac{J(t_1)}{J(t_2)} \quad (29)$$

From Eq. (26) the absorption factor is:

$$K_A = \frac{\beta \cdot f(t_1) + z}{\beta \cdot f(t_2) + z} \quad (30)$$

When in the dielectric the conduction is predominant, i.e.

$$z \gg \beta \cdot f(t) \quad (31)$$

then the value of the absorption factor is near unity, for

$$K_A \cong \frac{z}{z} = 1 \quad (32)$$

On the other hand, when at the tested time the effect of polarization predominates, i.e.

$$\alpha \ll \beta \cdot f(t) \tag{33}$$

then the value of absorption factor is much higher than unity, and its value is characteristic exactly of the changing of the relaxation function, because

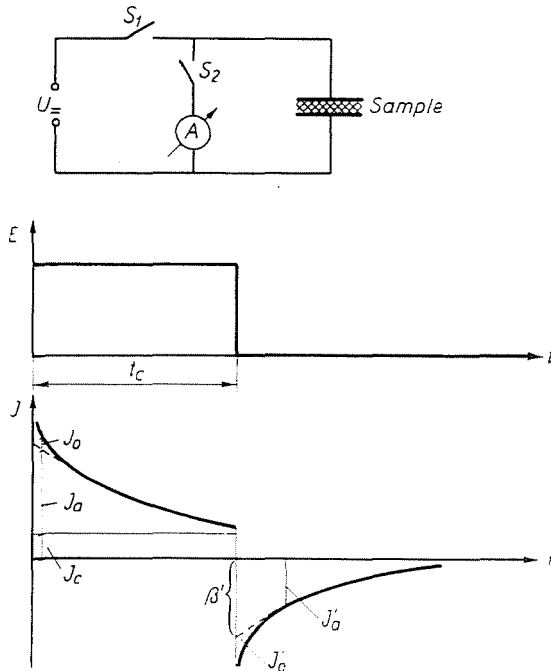


Fig. 6

$$K_A \cong \frac{\beta \cdot f(t_1)}{\beta \cdot f(t_2)} = \frac{f(t_1)}{f(t_2)} \tag{34}$$

From the measured current vs. time graph the relaxation function  $f(t)$  of the dielectric may be directly established.

When the sample had been charged by connecting it to a D.C. generator for the time  $t_c$ , and then the discharge current is measured in a short-circuit (Fig. 6), a current of a sign opposite to that of the charging current can be obtained, this discharge current tends in time to zero. There are only capacitive and absorption components in the discharge current  $J_d$  (there being no conduction, as  $E = 0$ ). so that

$$J_d(t) = J'_0(t) + J''_0(t) \tag{35}$$

The time constant of the capacitive component  $J'_0$  is determined by the capacity of the specimen and by the resistivity of the short-circuit, so it can be made not to affect the discharge current at the examined range of time. Then the discharge current includes the absorption component  $J'_a$  alone. This component arises in consequence of the decay of the polarization developed during charging the specimen, hence, considered Eq. (7)

$$J_a(t) = J'(t) = -E \cdot \beta' \cdot f'(t) \quad (36)$$

The dependence of the value of  $\beta'$  on the time of the charging may be determined as follows:

The polarization developed during the charging time  $t_c$  may be written as

$$P(t_c) = E \cdot \alpha_0 \cdot F(t_c) \quad (37)$$

After a time  $t$  reckoned from the beginning of short-circuiting, the value of the polarization  $P'(t)$  will be

$$P'(t) = P(t_c) [1 - F'(t)] = E \cdot \alpha_0 \cdot F(t_c) \cdot [1 - F'(t)] \quad (38)$$

whence the absorption component

$$J'_a(t) = \frac{dP'(t)}{dt} = -E \cdot \beta_0 \cdot F(t_c) \cdot f'(t) = -E \cdot \beta' \cdot f'(t) \quad (39)$$

will be obtained, where

$$\beta' = \beta_0 F(t_c) \quad (40)$$

Eq. (8) is valid also for  $f'(t)$ .

Since, according to Eq. (4)  $F(t) = 1$  only for  $t_c = \infty$ , else it will always be lower, it follows that the value of  $\beta'$  calculated from the initial discharge-current will also always be lower than the polarization conductivity  $\beta_0$  calculated from the charging current, i.e.  $\beta' = \beta_0$  is met only after an extremely long charging period in view of the development of polarization examined.

### 3.2. The loss factor

When in the dielectric the field strength is changed according to  $E(t)$  then the polarization and absorption component may be calculated with the Duhamel integral [1, 10]:

$$P(t) = \alpha_0 \cdot E(0) \cdot F(t) + \alpha_0 \int_0^t \frac{dE(\tau)}{d\tau} \cdot F(t - \tau) d\tau \quad (41)$$

and

$$J_a(t) = \beta_0 \cdot E_{(0)} \cdot f(t) - \beta_0 \int_0^t \frac{dE(t - \tau)}{d\tau} \cdot f(\tau) d\tau \quad (42)$$

When in a dielectric the field strength fluctuates according to sine function, i.e.  $E(t) = E_m \cdot \sin \omega t$ , then from Eq. (42) the absorption component will be

$$\begin{aligned} J_a &= E_{\max} \omega \left[ \cos \omega t \cdot \beta_0 \int_0^t \cos \omega \tau f(\tau) d\tau + \sin \omega t \cdot \beta_0 \int_0^t \sin \omega \tau \cdot f(\tau) \cdot d\tau \right] = \\ &= E_{\max} \omega [(\epsilon' - \epsilon_{\infty}) \cos \omega t + \epsilon' \sin \omega t] \end{aligned} \quad (43)$$

whence the components of complex permittivity will read

$$\begin{aligned} \epsilon' &= \beta_0 \int_0^t \cos \omega \tau \cdot f(\tau) d\tau + \epsilon_{\infty} \\ \epsilon'' &= \beta_0 \int_0^t \sin \omega \tau f(\tau) d\tau \end{aligned} \quad (44)$$

and the loss factor

$$\operatorname{tg} \delta = \frac{\epsilon'' + \omega \epsilon'}{\omega \epsilon'} = \frac{\epsilon'' + \omega \beta_0 \int_0^t \sin \omega \tau \cdot f(\tau) d\tau}{\omega \epsilon_{\infty} + \omega \beta_0 \int_0^t \cos \omega \tau \cdot f(\tau) d\tau} \quad (45)$$

### 3.3. Initial slope of the discharge and return voltages

When the specimen had been connected to a D.C. generator for a definite period and then disconnected, the charge accumulated on the electrodes is neutralizing through the resistivity of the dielectric, and it can be recorded the discharge voltage decaying in time at a faster or slower rate. When after leaving the specimen connected to the generator for a longer period and then short-circuited it for a short period, after opening the short-circuit the charge bounded by the polarization will turn into free charge owing to the decay of that, i.e., a voltage will arise between the electrodes on the specimen. This phenomenon is called return voltage or dielectric after-effect.

In a previous paper the author has demonstrated that a close relationship exists between the initial slope of the discharge and return voltages and the conduction and polarization of the dielectric. Thus, similarly to dielectric

characteristics hitherto used to characterize the dielectric, the initial slopes of the voltages are apt to qualify the insulation too. For certain materials, (e.g. impregnated paper) the initial slopes are good indications of the quality or condition of the insulation [6].

To describe the condition of insulations, three marginal curves of voltage graphs may be used. These are as follows (see Fig. 7):

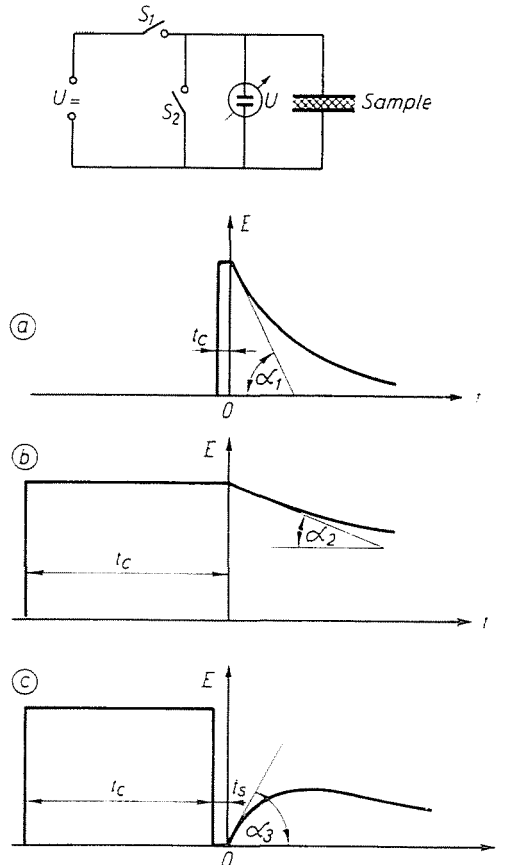


Fig. 7

(a) *Discharge curve recorded after short charging.* The term “short charging” denotes that the voltage is applied to the insulation for a time much shorter than the relaxation time of the polarization range under test, consequently this polarization cannot develop during the period of charging.

(b) *Discharge curve recorded after long charging.* The period of “long charging” is chosen in a way permitting the development of the polarization in the dielectric.

(c) *Return voltage curve.* After a long charging period the electrodes on the insulation are short-circuited for a short period, letting the free charge, generating the field strength, to be neutralized, still the polarization developed during the charging cannot follow the abrupt drop of the field, so that the bounded charge subsists. When opened the short-circuit, the bounded charge turns released owing to the slow decay of the polarization and the free charge creates a voltage between the electrodes [3, 4].

Setting out from the difference between the surface charge densities  $D(0)$  and  $D(t)$  for time  $t = 0$  and a later time  $t$ , respectively, the integral equation describing the change of charge on the electrodes in time:

$$D(0) - D(t) = \epsilon_0 E(0) + P(0) - \epsilon_0 E(t) - P(t) = z \int_0^t E(\tau) d\tau \quad (46)$$

whence the function  $E(t)$  describing the change of the field strength futher its derivative for  $t = 0$ , i.e. the initial tangent of voltage curves

$$m = \operatorname{tg} \alpha = \left. \frac{d E(t)}{dt} \right|_{t=0} \quad (47)$$

can be calculated.

An analysis of the three marginal cases will produce the following relationships for the initial slopes:

(a) Discharge curve after a short charging.  $t_c \rightarrow 0$ ,

Initial conditions:

$$\begin{aligned} t = 0, D(0) &= \epsilon_0 E_0, \text{ since } P(0) = 0, \text{ and} \\ t = t, D(t) &= \epsilon_0 E(t) + P(t); \end{aligned}$$

where  $E_0$  is the field strength in the dielectric at charging. Substituting the initial conditions in Eq. (46), the initial slope is:

$$m_{\text{short}} = - (\beta + z) \frac{E_0}{\epsilon_0} \quad (48)$$

(b) Discharge curve after a long charging period.  $t_c \rightarrow \infty$ ,

Initial conditions:

$$\begin{aligned} t = 0, D(0) &= \epsilon_0 E_0 + P(0), \\ t = t, D(t) &= \epsilon_0 E(t) + P(t); \end{aligned}$$

where  $P(0) = \epsilon_0 E_0$  the steady state polarization developed during charging.

From these conditions the slope is obtained as:

$$m_{\text{long}} = - z \frac{E_0}{\epsilon_0} \quad (49)$$

(c) Return voltage curve,  $t_c \rightarrow \infty$ ,  $t_s \rightarrow 0$ .

Initial conditions:

$$\begin{aligned} t = 0, \quad D(0) &= P(0), \\ t = t, \quad D(t) &= \varepsilon_0 E(t) + P(t) \end{aligned}$$

where  $E(0) = 0$  because of the short-circuit.

These conditions yield for the slope:

$$m_{\text{return}} = \beta \frac{E_0}{\varepsilon_0} \quad (50)$$

The initial slope of the voltage curves and the fundamental characteristics of the dielectric are seen to be in a very close relationship.

### 3.4. Dispersion factor

By definition, the dispersion factor is the quotient from free by bounded charges (or charge densities) on electrodes:

$$K_D = \frac{Q_P}{Q_0} = \frac{P}{\varepsilon_0 E} \quad (51)$$

where  $Q_P$  stands for the charge bounded by the polarization developed in the dielectric, and  $Q_0$  for the free charge.

The principle of the measurement of the dispersion factor may be summed up as follows. After an extremely short period of charging the free charge is measured by integrating the current flowing in the short-circuit between the electrodes on the insulation. After a determined period of charging and a short discharging the value of the bounded charge can be measured in a similar way to the above. When during the period of short charging polarization cannot develop, whereas during the sustained period of charging it can fully develop, then from Eqs (3) and (51) the dispersion factor will be:

$$K_D = \frac{z \cdot E}{\varepsilon_0 \cdot E} = \frac{z}{\varepsilon_0} \quad (52)$$

i.e., it is in close relationship to the polarizability of the dielectric.

## 4. Conclusions

In response to an electric field the phenomena of conduction and polarization will arise in dielectrics. Conduction may be characterized by the conductivity  $z$  of the dielectric in an unambiguous manner. Polarization, however, is a time-dependent process, furthermore several coincident elementary pro-



cesses of different relaxation times may be superposed, so this is why the phenomenological description of polarization needs two characteristics, viz. the resultant polarizability  $\alpha$  (characterizing the intensity of the polarization) and the polarization decay function  $F(t)$  (describing its development) are needed. With these two characteristics it is possible to describe the polarization phenomenologically in a clear-cut form. In the present paper the direct relation between the function  $F(t)$  and the density function  $\rho_x(T)$  describing the distribution of the polarization according to time constants (relaxation times) has been demonstrated.

The anomalous charging current generated in consequence of the development of polarization may be described by the polarization conductivity  $\beta$  and the current decay function  $f(t)$ . The interrelation of these quantities with the polarizability  $\alpha$  and the polarization decay function  $F(t)$  is discussed. It has been suggested to consider the polarization conductivity  $\beta$  as a characteristic value of the material in like way as the conductivity  $\kappa$ .

The conductivity  $\kappa$ , the resultant polarizability  $\alpha$  and the relaxation function  $F(t)$  on the one part, the polarization conductivity  $\beta$  and the relaxation function  $f(t)$  on the other, may be considered as the fundamental dielectric characteristic values of dielectrics, as these lend themselves more readily for the unambiguous description of the fundamental dielectric processes, in particular for the polarization.

Each of dielectric characteristics of the material (e.g. the charging and discharging currents, loss factor, dispersion factor, initial slopes of discharge and return voltages, etc.) are in strict relation to the fundamental characteristics. This relation opens a way to systematize the characteristics measured on dielectrics via fundamental characteristics (Fig. 1).

### Summary

The measure of the polarization developed in dielectrics may be characterized by the resultant polarizability  $\alpha$ , whereas its development may be described by the polarization relaxation function  $F(t)$ . The absorption current due to the change of the polarization may, — on the analogy of the "conductive" conductivity  $\kappa$  —, be expressed by the "polarization conductivity"  $\beta$ , its changing in time by the current relaxation function (or: current decay function)  $f(t)$ .

The conductivity  $\kappa$ , characteristic of conduction, as well as  $\alpha$  and  $F(t)$  together with  $\beta$  and  $f(t)$ , characteristic of polarization, constitute the "fundamental dielectric characteristics" of dielectrics proposed in this paper, by which the dielectric processes arising in response to electric field can unambiguously be described.

These dielectric processes are in strict relation to measurable dielectric properties of dielectrics (e.g. leakage current, dielectric loss factor, etc.). By using the system of fundamental characteristics proposed here, this relation can be discussed in a clear-cut and demonstrative way and from the measured quantities, the value of the fundamental characteristics may be simply established.

## References

1. COLE, K. S.—COLE, R. H.: Dispersion and absorption in dielectrics. *Journ. Chem. Phys.* **9**, 341—351 (1941); **10**, 98—105 (1942).
2. DANIEL, V. V.: Dielectric Relaxation. Acad. Press, London, 1967.
3. GROSS, B.: Über die Anomalien der festen Dielektrika. *Z. Phys.* **107**, 217—234 (1937).
4. GROSS, B.: On after-effects in solid dielectrics. *Phys. Rev.* **7**, 57—59 (1940).
5. KIRKWOOD, J. C.—FUOSS, R. M.: Anomalous dispersion and dielectric loss in polar polymers. *Journ. Chem. Phys.* **9**, 329—340 (1941).
6. NÉMETH, E.: Zerstörungsfreie Prüfung von Isolationen mit der Methode der Entlade- und Rückspannungen. XI. Internat. Wiss. Koll. TH Ilmenau, 87—91, 1966.
7. O'DWYER, J. J.: Theories on dielectric loss. *Progress in Dielectrics*, Vol. 7, Heywood, London, 1969.
8. SCHWEIDLER, E.: Studien über Anomalien in Verhalten der Dielektrika. *Ann. Phys.* **24**, 711—770 (1907).
9. SMEKAL, A.: Bildung von Gegenspannungen in festen Ionenleitern. *Phys. Zeitschr.* **36**, 742—749 (1935).
10. VAJDA, GY.: Szigetelések romlása és romlásuk vizsgálata (Deterioration of insulations and their testing). Akadémiai Kiadó, Budapest, 1964.
11. WAGNER, K. W.: Theorie der unvollkommenen Dielektrika. *Ann. Phys.* **40**, 817—855 (1913).
12. WAGNER, K. W.: Erklärung der dielektrischen Nachwirkungsvorgänge auf Grund Maxwell'scher Vorstellungen. *Archiv. f. Elt.* **2**, 371—387 (1913).
13. VAN ROGGEN, A.: Distributions of relaxation times and their diagrams. *IEEE Trans.* **EI-5**, 47—52 (1970).

Endre NÉMETH, Budapest XI., Egry József u. 18—20, Hungary