DIGITAL COMPUTER ANALYSIS OF THERMAL BREAKDOWN VOLTAGE IN SOLID DIELECTRICS

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Introduction

The rapid growth of energy transfer voltage levels in recent years has set increasingly stricter demands against high voltage insulations. The dimensioning and the calculation of breakdown proof insulations are based on the permissible maximum voltage (generally the test voltage) and the permissible maximum temperature rise for the involved insulation materials. The heat resistance classes of the individual materials are relatively easy to establish from the corresponding standard specifications, but as to the breakdown voltage the situation is rather different. In principle three types of breakdown are distinguished: the electric breakdown, the breakdown caused by internal or surface ionization and the thermal breakdown. The clear delimination of these individual types of breakdown is rather difficult in practice, as several of these types may be involved simultaneously in the breakdown mechanism. Our present understanding of the breakdown mechanism is limited, their exact process is unknown as yet. The literature offers two basic theories for the mechanism of pure electric breakdown, those of HIPPEL (slow electrons) and FRÖCHLICH (fast electrons) [4, 5, 19, 21]. Although both theories contain several approximations and assumptions, they reflect well enough the main regularities of the breakdown mechanism. At present, extensive research all over the world is devoted to clearing up the exact process of the breakdown mechanisms (for instance the papers presented at the International Symposium on High Voltage held in March 1972 in Munich reported on several of these research programs). In the case of high voltages ($>$100kV) the probability of the third type, the so-called thermal breakdown is highest. In spite of the fact that this phenomenon has been known since the turn of the century [17, 27], no uniform, general theory could be developed in this field either. The common objective of the suggested theories was to determine the so-called thermal breakdown voltage. The initial theory of WAGNER making a great many simplifying assumptions [24, 25, 26] has been gradually refined (and partly refuted), among others by ROGOWSKY [18], KÁRMÁN [15], BERGER [4], FOK [6], GOODLET [9], COOPLE, HARTREE, PORTER and TYSON [3], GEMANT [7, 8], and the two WHITEHEAD [28, 29, 30]. INGE and WALTER [10—13] and RAYNER [17] should be mentioned for their experimental results as well. This list is far from being complete, ampler references are found in [22].

Notations

E	— electric field strength [V/m]
p_0'	— dielectric losses per unit volume and per unit field strength at temperature ϑ_0 [W/mV²]
b	— thermal coefficient of the temperature dependence of $p'(\vartheta)$ [1/°C]
ϑ_0	— reference temperature [°C]
ϑ_k	— ambient temperature [°C]
α	— heat transfer coefficient [W/m² °C]
F	— heat transfer surface [m²]
λ_1	— dielectric thermal conductivity [W/m °C]
λ_2	— electrode thermal conductivity [W/m °C]
q_b	— dielectric internal heat source [W/m³]
$2h$	— dielectric thickness [m]
$2U$	— dielectric energizing voltage [V]
U_{lab}	— thermal breakdown voltage [V]
m	— electrode thickness [m]
Q_{be}	— additional heat inflow to the dielectric [W]
R	— cable core resistance [Ω/m]
tg δ	— power factor
t	— time [sec]

1. The conceptions of thermal instability and thermal breakdown voltage

Thermal breakdown differs basically from pure electric breakdown by the decisive role of the temperature (or by the nonlinear temperature dependence of the individual electric parameters). Namely, the permanent losses in the dielectric are partly used to raise its temperature and partly are transferred to the ambient. By restricting our consideration to the dielectric losses the temperature dependence of these losses may be written up in the following form [19]:

$$Q_{\text{tg}\,\delta} = \int_V p_0' \cdot E^2 \cdot e^{b(\vartheta-\vartheta_0)}\, dV \qquad [\text{W}] \tag{1}$$

where

$$p_0' = \frac{f \cdot \varepsilon \cdot \tan\delta(\vartheta_0)}{1.8 \cdot 10^{10}} \qquad [\text{W}/\text{m}\cdot\text{V}^2]\,.$$

ε being the permittivity, f — the frequency and $\text{tg}\,\delta(\vartheta_0)$ the power factor at the reference temperature ϑ_0, while the heat quantity possibly transferred to the ambient is [16]:

$$Q_{\text{le}} = \alpha \cdot F(\vartheta - \vartheta_{\text{k}}) \qquad [\text{W}]. \tag{2}$$

The formed ($Q_{tg\delta}$) and the transferable (Q_{le}) heat quantities versus temperature are shown in Fig. 1, revealing the existence of a quasi-equilibrium state, where

$$Q^*_{tg\delta} = Q_{le} \quad \text{and} \quad \frac{\partial Q^*_{tg\delta}}{\partial \vartheta} = \frac{\partial Q_{le}}{\partial \vartheta} . \tag{3}$$

Beyond this critical ($Q^*_{tg\delta}$) value of heat losses, thermal instability ensues, because more heat develops permanently, than can be transferred. As the dielectric losses are highly dependent on the voltage (they are proportional to U^2), there exists a critical voltage causing exactly the loss $Q^*_{tg\delta}$. This value is defined as the thermal breakdown voltage. This is why in the case of thermal

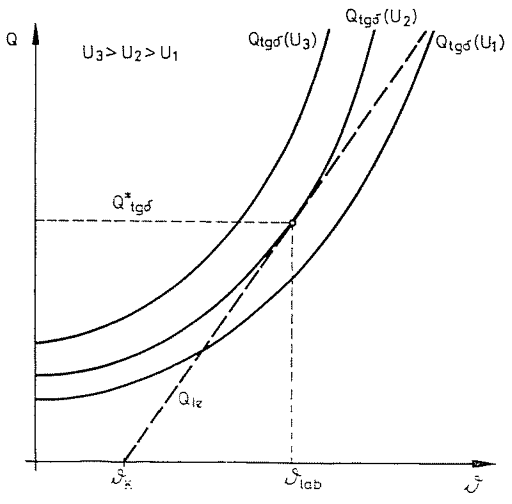

Fig. 1. The developed ($Q_{tg\delta}$) and the transferable (Q_{le}) heat quantities temperature

breakdown this thermal breakdown voltage is considered to be the breakdown voltage, as breakdown does not occur immediately after switching the voltage on. This is reasonable because if a dielectric medium is kept long enough under a voltage surpassing this value by whatever little amount, the breakdown is sure to occur. From the above it follows that the thermal breakdown voltage, — in close relations with the conditions of heat transfer and temperature distribution —, cannot be considered as a material characteristic, such as permittivity. This very fact greatly impairs the exact theoretical calculation of the thermal brakdown voltage. The calculation of the thermal breakdown voltage requiring also the knowledge of the temperature distribution in the dielectric represents an additional difficulty.

2. The differential equation, and the applied model

In order to calculate the temperature distribution, — and hence the thermal breakdown voltage — in a dielectric with an internal heat source (dielectric losses), the so-called KIRCHHOFF—FOURIER differential equation of heat conduction must be solved for the case of specified boundary conditions [2]. The general form of this differential equation is:

$$\operatorname{div}(\lambda \operatorname{grad} \vartheta) + q_b(\vartheta) = \frac{\partial \vartheta}{\partial t} c_f \cdot \gamma_f . \tag{4}$$

There is no known general solution for Eq. (4). For sake of simplicity, model arrangements with linear heat flow will be chosen. Our models are shown in Fig. 2. As steady state is considered, Eq. (4) is substantially reduced for our one-dimension models, namely

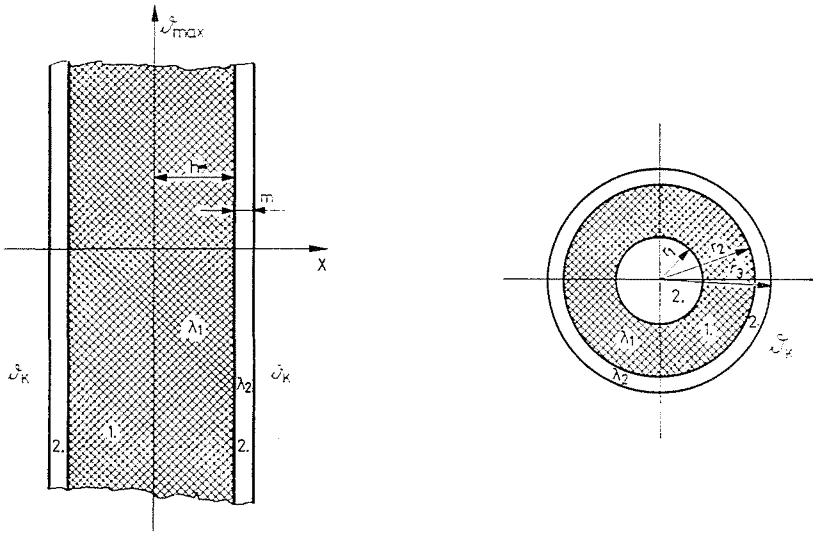

Fig. 2. Plane and cylindrical model. 1 — dielectric, 2 — electrodes

to
$$\frac{d^2 \vartheta}{dx^2} + \frac{q_{b1}(\vartheta)}{\lambda_1} = 0 \quad \text{for the plane} \tag{5}$$

and to
$$\frac{1}{r} \frac{d}{dr}\left(r \frac{d\vartheta}{dr}\right) + \frac{q_{b2}(\vartheta)}{\lambda_2} = 0 \tag{6}$$

for the cylinder.

The internal heat source is expressed from (1), eliminating the field strength, as

$$q_{b1}(\vartheta) = \frac{p_0' \cdot U^2 \cdot e^{b(\vartheta - \vartheta_0)}}{h^2} \, [\mathrm{W/m^3}] \quad \text{for the plane} \tag{7}$$

$$q_{b2}(\vartheta) = \frac{p_0' \cdot U^2 \cdot e^{b(\vartheta - \vartheta_0)}}{r^2 [\ln (r_2/r_1)]^2} \quad \text{for the cylinder.} \tag{8}$$

By introducing the relative units:

$$\Theta = b(\vartheta - \vartheta_k) \quad z = \frac{x}{h} \quad R = \frac{r}{r_1} . \tag{9}$$

Eqs. (5) and (6) reduce to

$$\frac{d^2 \Theta}{dz^2} + B_1 \cdot e^{\Theta} = 0 \text{ for the plane} \tag{10}$$

and

$$\frac{d^2 \Theta}{dR^2} + \frac{1}{R} \cdot \frac{d\Theta}{dR} + \frac{B_2}{R^2} \cdot e^{\Theta} = 0 \quad \text{for the cylinder} \tag{11}$$

where

$$B_1 = \frac{p_0' \cdot U^2 \cdot e^{-\Theta_0} \cdot b}{\lambda_1} \quad \text{and} \quad B_2 = \frac{p_0' \cdot U^2 \cdot e^{-\Theta_0} \cdot b}{\lambda_1 [\ln (R_2)]^2} \tag{12}$$

So for the calculation of the thermal breakdown voltage Eqs (10) and (11) are to be solved for given boundary conditions, with consideration to Eq. (3).

3. Previous calculation methods

As the analytical solution of Eqs (10) and (11) is extraordinarily difficult, the initially derived relationships for calculating the thermal breakdown voltage hold only if a rather great number of simplifying assumptions were true. This situation changed when V. A. FOK in the twenties of this century established the conditions of thermal breakdown voltage, Eq. (10), for symmetrical arrangements and derived the following relationship for the thermal breakdown voltage:

$$U_{\text{lab}} = 1.414 \sqrt{\frac{\lambda_1 \cdot e^{-\Theta_0}}{b \cdot p_0'}} \cdot \varphi(c) \tag{13}$$

where

$$c = \frac{\lambda_2}{\lambda_1} \cdot \frac{\alpha h}{\alpha \cdot m + \lambda_2} \approx \frac{\alpha \cdot h}{\lambda_1}$$

and $\varphi(c)$ is the so-called Fok-function, named after him. The derivation and the tabulated function are found in [22].

Up to now, expression (13) was generally accepted for calculating the thermal breakdown voltage, in spite of its validity restricted to certain cases. In a most frequent practical case where additional heat flows to one side of the dielectric (e.g. in cables the joule losses occurring in the cores heat the internal side of the insulation) the relationship derived by Fok does not apply any more.

4. The principle of the general calculation method

With the advance of the digital computers the solution of the differential equations has become ever less problematic, so it seemed reasonable to develop an algorithm for the calculation of the thermal breakdown voltage with a more general scope. In 1965, TASCHNER and WIDMANN [20] developed a possible method for this algorithm. The algorithm developed by the author of the present paper deviates in its fundamentals, although our results show similar

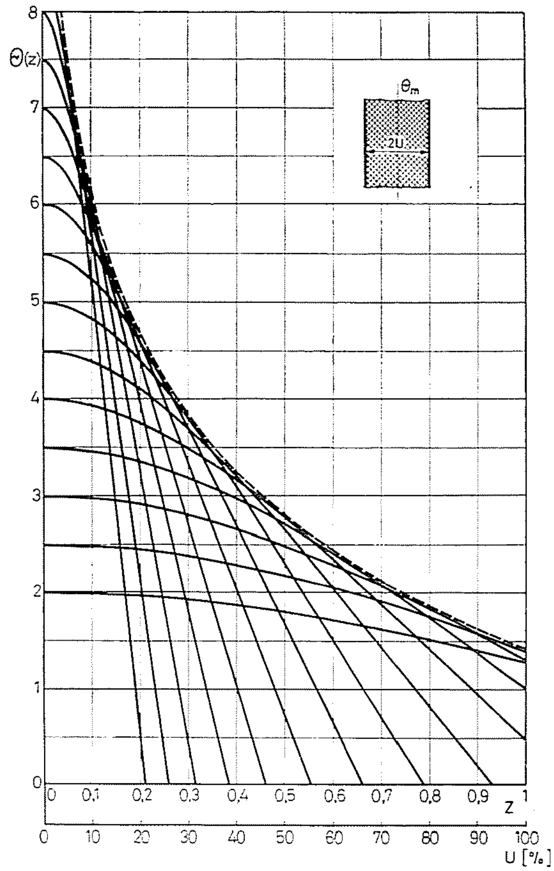

Fig. 3. Temperature distribution of a plane dielectric with the temperature of the hottest point as parameter. Symmetrical arrangement (scheme)

features. The train of thought of the algorithm is as follows: the differential equations (10) and (11) versus the maximum temperature rise of the dielectric (or versus its maximum temperature, if the ambient temperature is given) as parameter, is easy to solve by a computer. We have prepared the solution in the analog-digital simulation language BOCS [14] according to the flow chart given in the appendix. The whole program written in the BOCS language was run on a computer type MINSK-22 of AKI (Research Institute for Automation of the Hungarian Academy of Sciences). The results are shown in Figs 3 and 4. Due to the use of relative units these results are perfectly general. The obtained set of curves has a well definable envelope curve representing exactly the $\Theta = f(z)$ curve belonging to the stable-instable limit position. In the case of homogeneous electric field distribution there exists a linear thickness-voltage

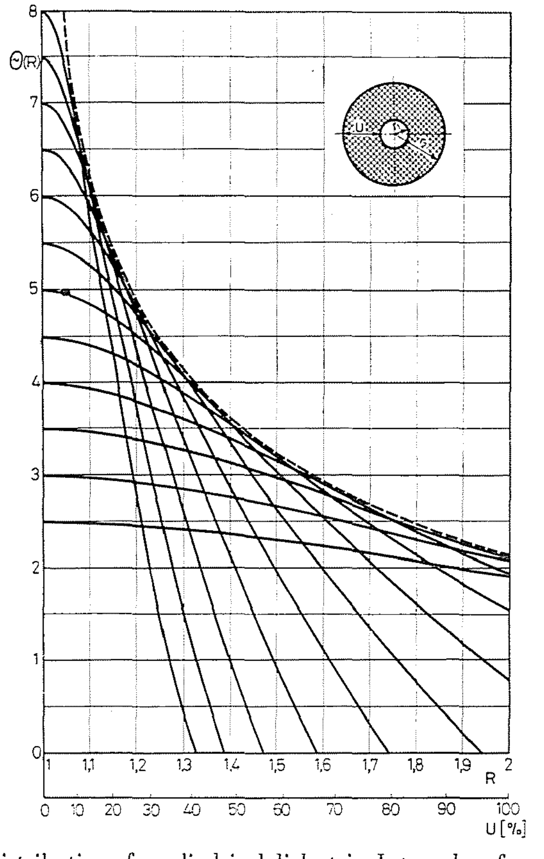

Fig. 4. Temperature distribution of a cylindrical dielectric. Internal surface thermally insulated

relationship and so, if the field strength is known (e.g. when the thermal breakdown voltage of a given arrangement is to be calculated) the abscissa axis can be calibrated in voltage values as well. In Figs 3 and 4 the relative voltage distributions are given. In this case a set of $\Theta = f(U)$ curves is obtained, whose envelope curve (coinciding with that of the function $\Theta = f(z)$ only if the electric field is homogeneous, as will be shown later) defines a relationship between the voltage and the temperature rise of the dielectric. As the envelope curve represents the limit condition, consequently the voltage calculated from the envelope curve corresponds to the thermal breakdown voltage. For high ambient temperatures the hottest point of the dielectric (point $z = 0$) may have a higher temperature than the maximum permissible for the involved dielectric (according to its heat class). If this permitted maximum temperature is e.g. 140[°C] (thermal stability class F), then $\Theta(0) = 7$ if $b = 0.05$. Be the temperature drop belonging to U_{lab} now 50 [°C], then at ambient temperatures over 90[°C] the voltage applied to the dielectric must be reduced relative to the theoretically permissible value of U_{lab}, or else the insulation suffers thermal breakdown. This means that over 90[°C] ($\Theta = 4.5$) the voltage permitted for the dielectric is obtained from the $\Theta = \mathrm{f}(U)$ curve reaching the temperature of 140[°C] at the centre of the plane ($z = 0$), or in the case of a dielectric cooled on one side, reaching the same temperature on the thermally insulated side, rather than from the envelope curve of the set of $\Theta = \mathrm{f}(U)$ curves.

5. Allowance for parametric variations

As mentioned before, not all parameters influencing the thermal breakdown voltage can be accounted for by the conventional calculation method (based on (13)). An advantage of the general computer algorithm is among others that it permits allowance in a very simple way for the parametric variations and their effects on the thermal breakdown voltage, impossible before in spite of the real influence of these variations. Such a parametric variation is e.g. the additional heat inflow on the uncooled side of the dielectric. This case applies, — as mentioned already — to the real conditions of a cable under load, or of a coil insulation. Quite obviously, the additional heat inflow will still decrease the value of the thermal breakdown voltage by increasing additionally the temperature drop due to the dielectric losses. Let us consider now how this contribution can be allowed for in the solution of Eqs (10) and (11). The condition of the heat continuity [2], [16] on the heated side of the dielectric is:

$$Q_{\mathrm{be}} = - \lambda_1 \cdot F \cdot \left(\frac{d\vartheta}{dx} \right)_{x=0} = - \frac{\lambda_1 \cdot F}{b \cdot h} \left(\frac{d\Theta}{dz} \right)_{z=0} \quad [\mathrm{W}] \tag{14}$$

for the plane and

$$Q_{\mathrm{be}} = - \lambda_1 F \left(\frac{d\vartheta}{dr} \right)_{r=r_1} = - \frac{2\pi \cdot \lambda_1}{b} \left(\frac{d\Theta}{dR} \right)_{R=1} \quad [\mathrm{W}] \tag{15}$$

for the cylinder.

The condition of heat continuity reveals that the boundary condition applied so far to the derivatives of temperature distribution

$$\left(\frac{d\Theta}{dz}\right)_{z=0} = 0 \quad \text{and} \quad \left(\frac{d\Theta}{dR}\right)_{R=1} = 0, \quad \text{respectively}$$

is modified by the additional heat inflow. This means that in the flow chart given in the Appendix the initial condition of the corresponding integrator (in our case integrator No. 1) will be not zero, but a negative number from rela-

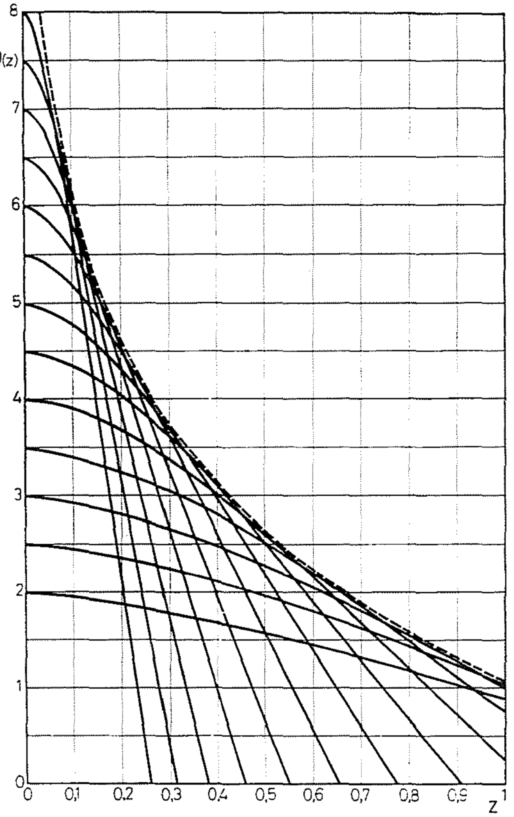

Fig. 5. Temperature distribution of a plane dielectric with the temperature of the hottest point as parameter, heated at $z = 0$, $\Theta(0) = -0.5$

tionships (14) and (15). A clearer notion of the values — in relative units — of the boundary conditions can be gained e.g. by considering the data of a 120 kV cable (made in the GDR, used in our country, too). The model of the cable is shown in Fig. 2 for a cylinder. Its data are: $r_1 = 0.0147$[m], $r_2 = 0.0277$ [m], $b = 0.05$ [1/°C], $\lambda_1 = 0.16$ [W/m°C], $R = 7.3 \cdot 10^{-5}$ [Ω/m], $I_N = 400$ [A] (nominal current). The derivate, as expressed from (15), substituting the above data, is:

$$\left(\frac{d\Theta}{dR}\right)_{R=1} = -\frac{Q_{\mathrm{be}} \cdot b}{2 \cdot \pi \cdot \lambda_1} = -0.581 .$$

Accordingly, Eqs (10) and (11) were solved here with boundary conditions $\dot{\Theta}(0) = -0.5$ and $\dot{\Theta}(0) = -1$, respectively. The results referring to the plane

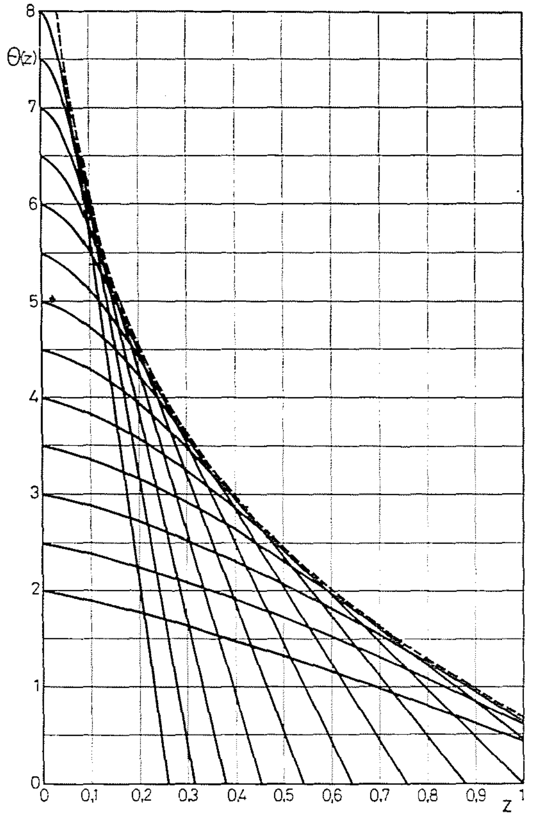

Fig. 6. Temperature distribution of a plane dielectric with the temperature of the hottest point as parameter, heated at $z = 0$, $\dot{\Theta}(0) = -1$

are shown in Figs 5 and 6 and those for the cylinder in Figs 7 and 8. For our cable, $\dot{\Theta}(1) = -0.5$ corresponds to a current load of $0.92\, I_N$ and $\dot{\Theta}(1) = -1$ to a current overload of 30%. Our results hold not only for this case, but due to the applied relative units, they have general validity.

Our results prove unambigously the correctness of our initial assumption that the value of the thermal breakdown voltage is lowered by the additional heat inflow. This is a very noticeable result with respect to the dime s oning of the insulation, as now any possible additional heat inflow can be taken into consideration in the design (or the control) stage. This result is of a still higher interest if we consider that previously this effect was allowed for in the expression (13).

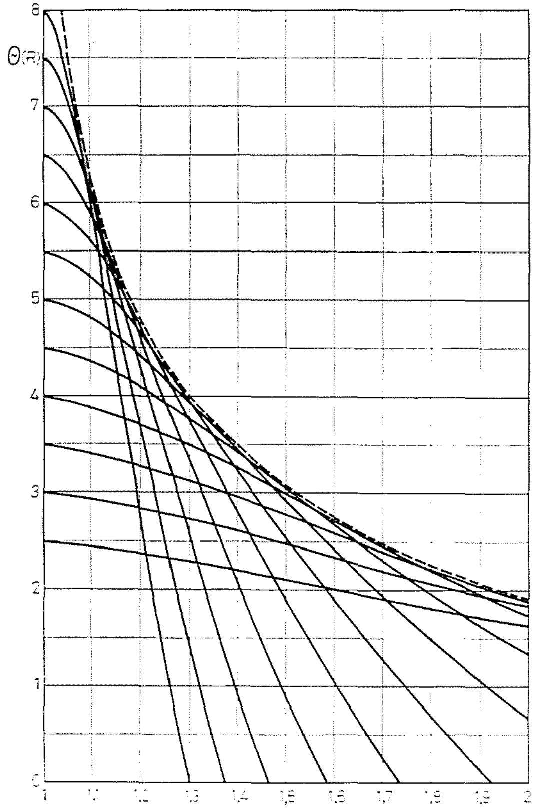

Fig. 7. Temperature distribution of a cylindrical dielectric with the temperature of the hottest point as parameter. Internal surface is heated. $\dot{\Theta}(1) = -0.5$

The effects of other parametric variations are represented by the coefficient B_1 and B_2. The effects allowed for by these coefficients are due — as revealed by Eqs (10) and (11) to the following parameters: ambient temperature (ϑ_k), reference temperature (ϑ_0), exponential loss constant (b), thermal conductivity (λ_1), frequency (f), permittivity (ε), power factor (tgδ), voltage (U).

Coople et al. [7] demonstrated that in the case of plane dielectrics the value of the coefficient B_1 cannot be higher than 0.88 or else Eq. (10) has no real solution. The author extended this conclusion to the case of the cylinder [22] and again the calculation gave 0.88 for the critical B_2 value. Figs 9 and 10

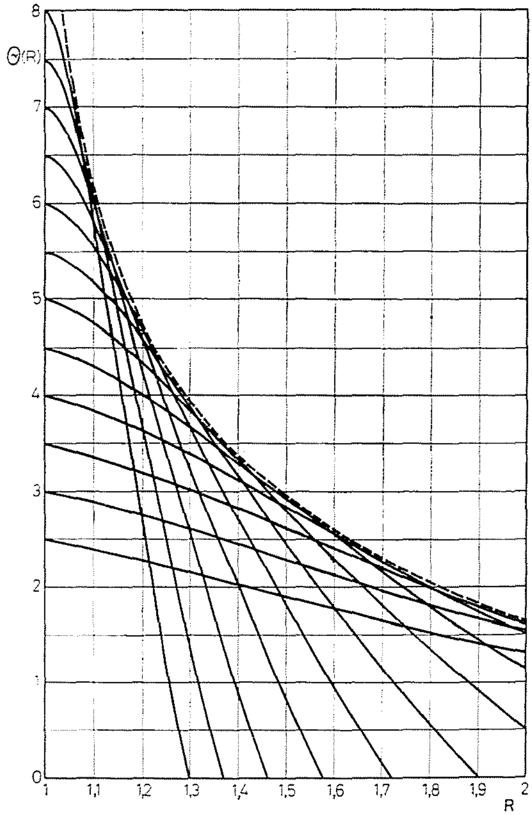

Fig. 8. Temperature distribution of a cylindrical dielectric with the temperature of the hottest point as parameter. Internal surface is heated, $\dot{\Theta}(1) = -1$

show the corresponding solutions calculated for four different B_1 and B_2 values. In this case too, the thermal breakdown voltage is to be calculated from a set of curves and their envelope curve. The figures show that lower B values result in lower dielectric temperature drop and higher thermal breakdown voltages. This is reasonable considering the relationship between the occurring loss and B.

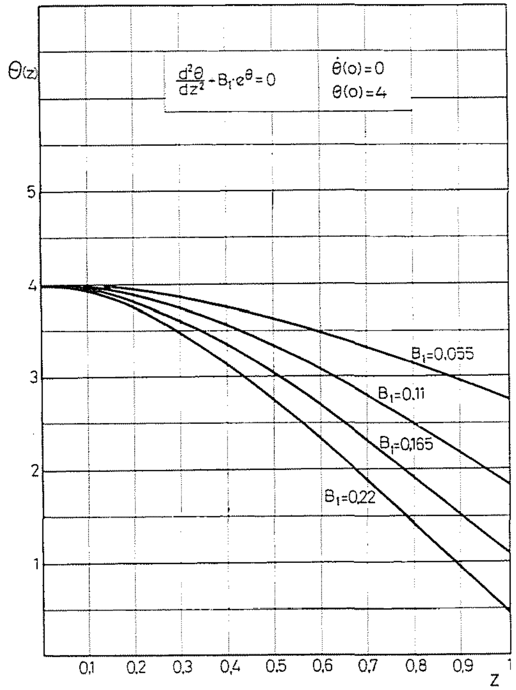

Fig. 9. Effect of the B_1 parameter variation on the temperature distribution in a plane dielectric

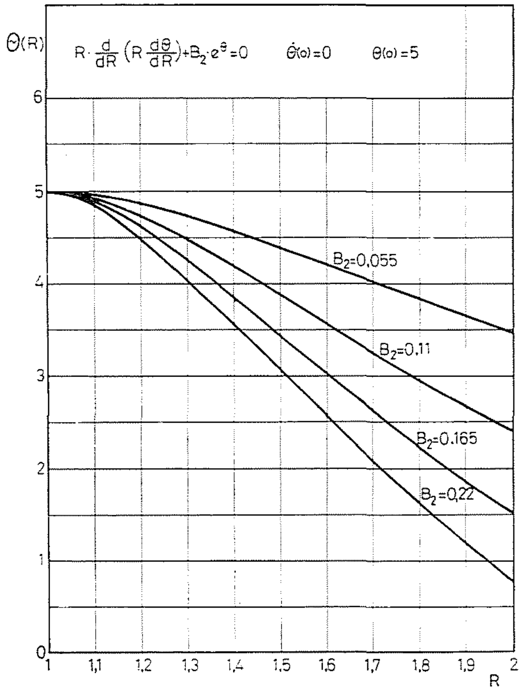

Fig. 10. Effect of the B_2 parameter variation on the temperature distribution in a cylindrical dielectric

6. Allowance for specific cases

So far, in our calculations an exponential dependence of the dielectric losses on the temperature had been assumed. Although this is true in the majority of practical cases in certain cases the specific unit volume loss may include a constant (temperature-independent) term as well [7, 8]:

$$p'(\vartheta) = a + p_0' \cdot e^{b(\vartheta - \vartheta_0)} \quad [\mathrm{W/mV^2}]. \tag{16}$$

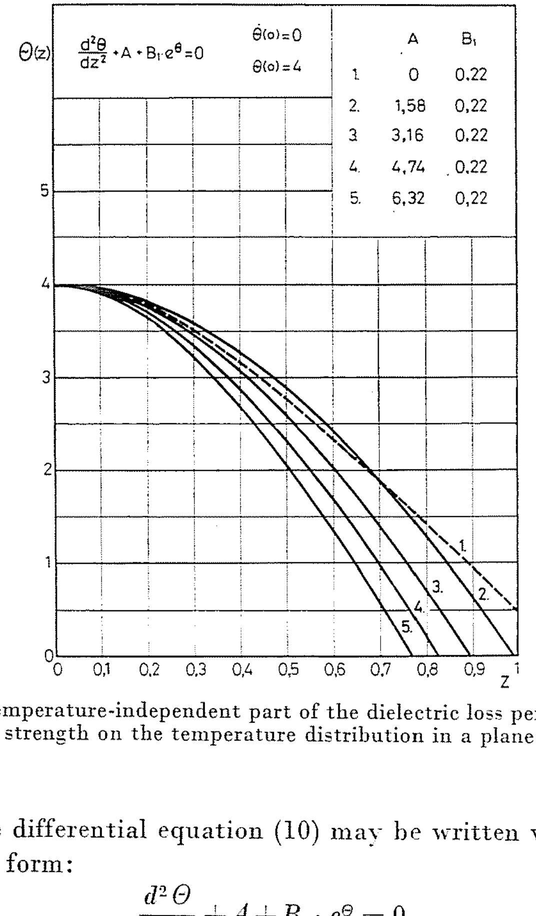

Fig. 11. Effect of temperature-independent part of the dielectric loss per unit volume and per unit field strength on the temperature distribution in a plane dielectric

Accordingly, the differential equation (10) may be written with relative units in the following form:

$$\frac{d^2\Theta}{dz^2} + A + B_1 \cdot e^{\Theta} = 0, \tag{17}$$

where

$$A = \frac{a \cdot b \cdot U^2}{\lambda_1} \quad \text{and} \quad B_1 = \frac{p_0' \cdot U^2 \cdot b \cdot e^{-\Theta_0}}{\lambda_1}.$$

The flow chart for the solution of this differential equation is also contained in the Appendix. Fig. 11 shows the effect of the variation of A and Fig. 12 that of B_1 with A = const. For sake of comparison, both figures show the cases $A = 0$ as well (in this case the differential equation (17) transforms into (10). Fig. 11 reveals that the growth of the temperature-independent term in the expression of the dielectric loss per unit volume and per unit field strengh implies the lowering of the thermal breakdown voltage. This is easily admitted considering that the presence of A means that a loss occurs even at the rela-

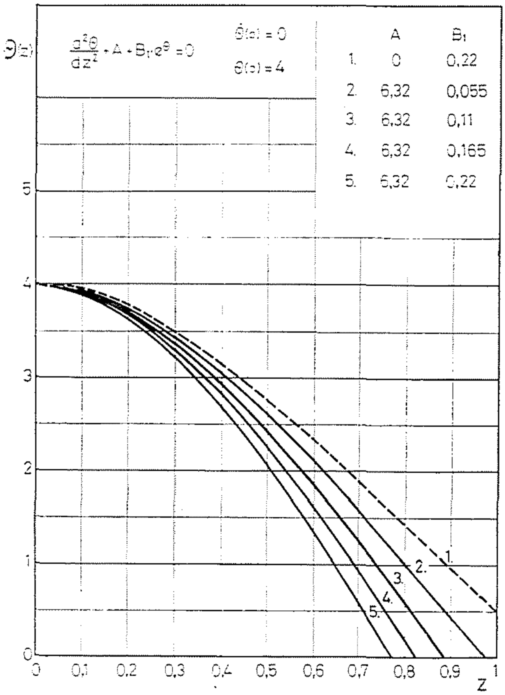

Fig. 12. Effect of the B_1 parameter variation on the temperature distribution in a plane dielectric. The dielectric loss per unit volume and per unit field strength has a constant part too. Symmetrical arrangement

tive temperature $\Theta = 0$ and the loss increases proportionally to the value of A at every temperature against the case $A = 0$. It follows directly that the effect of A keeps diminishing with the rise of temperature. By comparing Figs 12 and 9 it can be established that the effect of the variation of parameter B_1 is lowered by the presence of the constant A factor.*

* the numerical value was chosen on the basis of [7].

7. Allowance for the distortion of the homogeneous electric field in planes

In our previous calculations it was assumed that in a plane dielectric a homogeneous electric field develops after applying the voltage, i.e. a linear potential distribution throughout the dielectric. For thin dielectrics this assumption really holds, but in thicker dielectrics the potential distribution will not be linear due to the specific conductivity of the dielectric and the temperature distribution in it. Naturally, the thicker the dielectric, i.e. the higher the temperature drop, the greater the distortion of the potential distribution. The theo-

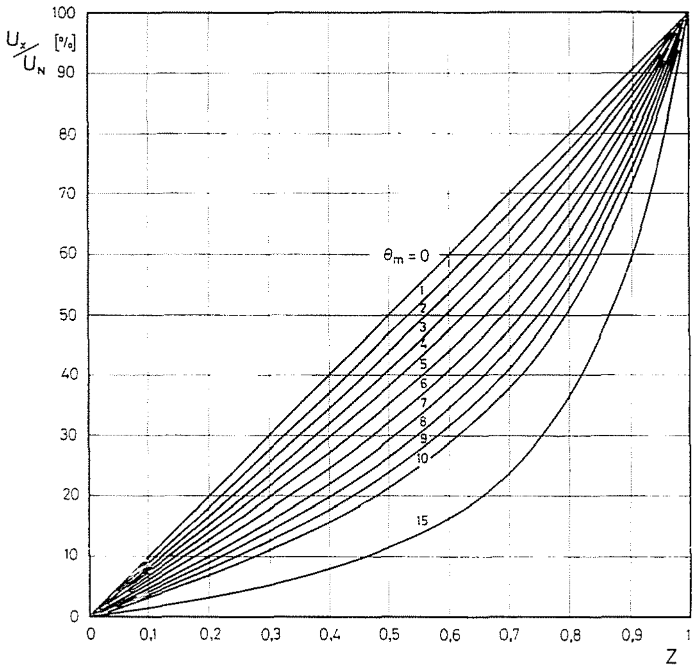

Fig. 13. Potential distribution distortion in a plane dielectric due to the temperature dependence of the conductivity. $c = 0.625$

retical explanation and the calculation method of this distortion are found in [23], whose results are utilized here. In Fig. 13 the dielectric characterized by the value $c=0.625$ (see the meaning of c in expression (13), the percentage distortion of the potential distribution versus the maximum temperature of the dielectric, is shown as parameter. At lower temperatures the distortion is seen to be negligible whereas at higher temperatures it might be considerable.

The distortion of the potencial distribution may be allowed for in the calculation of the thermal breakdown voltage in the following way: the set of the $\Theta = f(U)$ curves for the homogeneous case (see e.g. in Fig. 3) may be replotted with consideration to the set of the $U = f(z)$ curves shown in Fig. 13 into a new set of $\Theta = f(U)$ curves as shown in Fig. 14. This new set of curves has also an envelope curve deviating from that of the set of $\Theta = f(U)$ curves of the homogeneous case. The thermal breakdown voltage can be calculated now from the new envelope curve in the formerly described way. On the basis

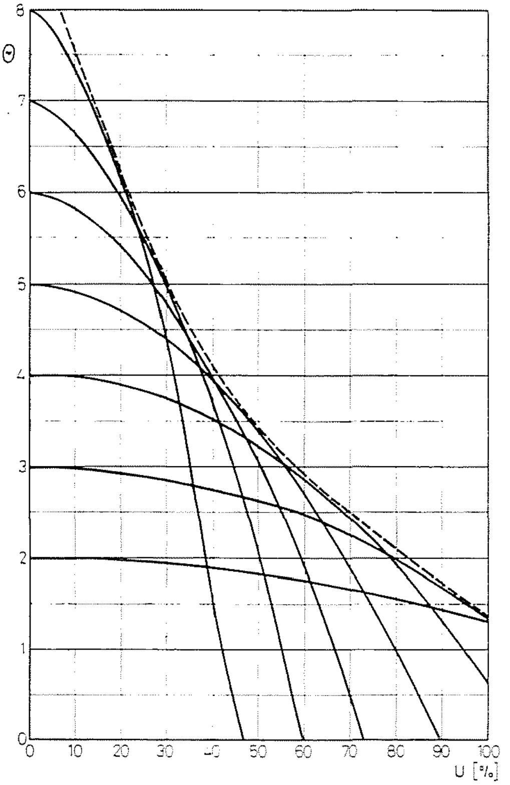

Fig. 14. Set of curves required for evaluating the thermal breakdown voltage with allowance for the potential distortion in a plane dielectric. Symmetrical arrangement

of this train of thought the distortion of the potential distribution relative to the theoretical (non-homogeneous!) $U = f(\ln R)$ curve may be allowed for also in the case of cylindrical arrangements.

Due to the use of relative units, our results are of general validity and the sets of curves corresponding to the individual parametric values may be regarded as if they were precalculated curves.

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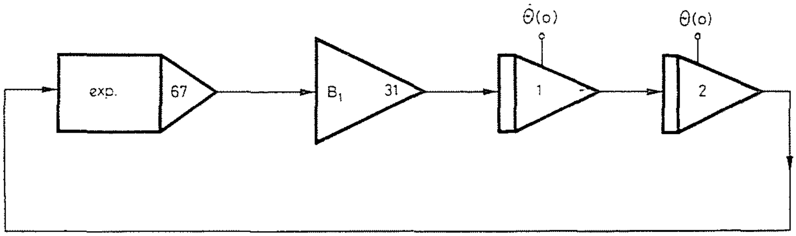
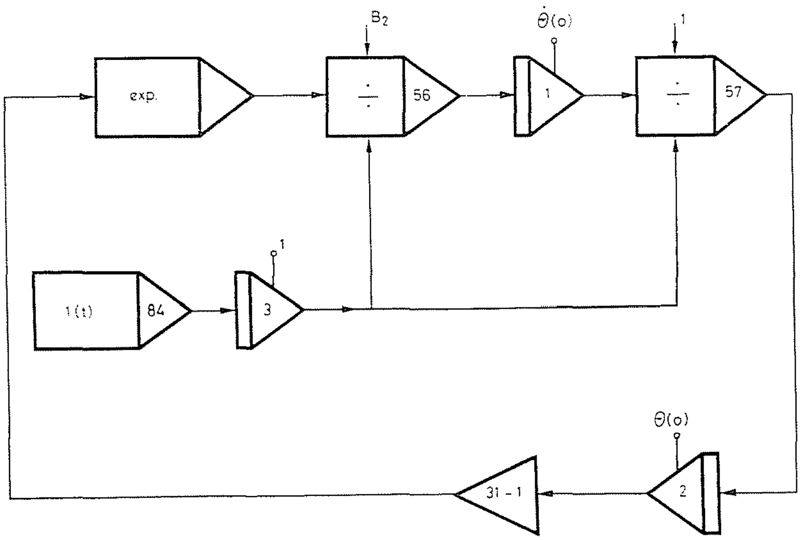
Appendix

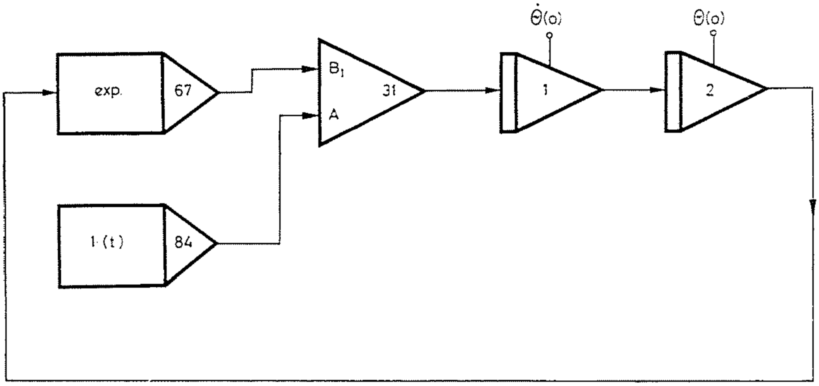
Flow chart for the solution of differential equation of heat conduction (10), (11) and (17) for the following boundary conditions: at the points $z = 0$ and $R = 1$ with specified values of $\Theta(0)$ and $\dot{\Theta}(0)$ and with specified values of the parameters B_1 and B_2, respectively. The programs were prepared in the analog-digital Bocs language. The elements in the flow chart correspond to the notations of the analog computer, but the individual operations were performed in the digital way by the computer.



App. 1. Flow chart of the solution of differential equation (10)



App 2. Flow chart of the solution of differential equation (11)



App. 3. Flow chart of the solution of differential equation (17)

Summary

A new, general algorithm for the calculation of the thermal breakdown voltage is described, based on the use of a digital computer for solving the differential equation of the temperature distribution in the dielectric. The effects of the boundary condition variations on the thermal breakdown voltage, with special regard to the case of additional heat inflow are demonstrated. The results are expressed by precalculated sets of curves. The described calculation method holds equally for plane and cylindrical dielectrics, as well as for the temperature dependence of dielectric losses.

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