JOURNAL OF ENGINEERING
ANNALS OF FACULTY OF ENGINEERING HUNEDOARA

THE TANGENT OF LOSS ANGLE tgδ IN ELECTRIC INSULATION

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ABSTRACT
This work examines analytically the dependence of the tangent of loss angle on the electric field frequency loss and the temperature of the insulator. The result is the connection between the resonant frequency and the corresponding temperature of the insulator, during which tgδ reaches the relaxation maximum and is released the largest amount of energy in the insulator at the account of the field.
Keywords:
tangent of loss angle, electric insulator, electrical field, insulation material, energy

1. THEORETICAL TREATMENT

The electrical insulator in the work process of electrical equipment converts part of the active electrical field energy in heat, which heats up the insulation material. The energy of the field, named dielectric loss, affects substantially the behavior of the insulator in the work process.

The specific dielectric loss P, W/m³, identified as a unit of volume, depends on the parameters of the insulator and on the degree of intensity E of the electrical field.

$$p = \omega.\varepsilon_r.\varepsilon_o.tg\delta.E^2 \tag{1}$$

where ε_r is the relative permittivity;
ε_o- the dielectric constant;
ω- the angular frequency;
tgδ- the tangent of loss angle.

Commonly, tgδ is considered a main characteristic for each type of insulation, which determines its momentary condition along with its degree of ageing.

The dielectric loss in the insulator and tgδ respectively depend on the electrical conductivity and the so called slow polarization. The slow polarization runs with a certain time constant τ, to which corresponds a certain natural angular frequency ω_o.

Analytically, tgδ is represented by two components: $tg\delta_1$, determined by the electrical conductivity; and $tg\delta_2$, by the action of the slow polarization.

When the angular frequency of active electric field ω becomes equal or approximate to the value of the natural frequency of the slow polarization ω_o the second component of tgδ reaches a maximum called relaxation maximum. In this case, the largest amount of energy is released in the insulation material at the account of the field.

The position of the relaxation maximum in the tgδ graph depends on the angular frequency ω and on the temperature of the insulator T. This temperature determines the time constant of polarization τ, i.e. its natural angular frequency, ω_o.

In the event of a simultaneous change of the angular frequency ω and the temperature of the insulator T, the relaxation maximum in tgδ shifts. When the temperature rises the relaxation maximum shifts towards higher frequencies and vice versa.

It would be interesting to understand the tgδ=Φ(ω, T) function shown in Figure 1 and to be able to determine the position of the maximum resulting from the various combinations of the two variables (ω, T). The experimental deduction of this function in a broad range of change of both variables is practically inconvenient.

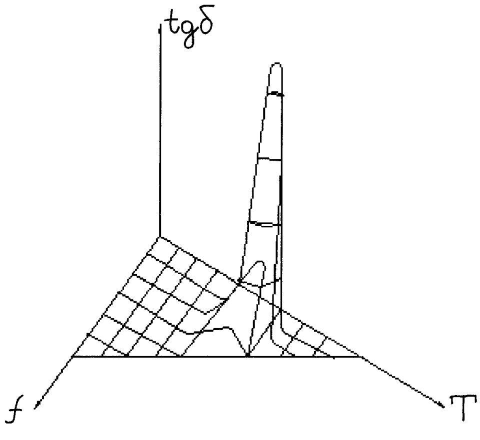

Figure 1. Tgδ=Φ(ω, T) function

This paper attempts to determine analytically the relationship between ω и T, where the value of tgδ would reach its maximum.

We examined a homogeneous insulator with polar structure in which a dipolar polarization takes place. We ignored the effect of electrical conductivity on the dielectric loss and tgδ and focused only on the slow polarization component of $tg\delta_2$.

An alternating sine-shaped voltage u=Um.sinωt with angular frequency ω=2πf influences the insulator.

The dielectric permittivity is represented by the its two components according to the Debay theory [1.1]:

$$\varepsilon_r = \varepsilon_{r\infty} + \frac{\varepsilon_{ro} - \varepsilon_{r\infty}}{1+(\omega\tau)^2}\,; \qquad \varepsilon_r^{''} = (\varepsilon_{ro} - \varepsilon_{r\infty}).\frac{1+\omega\tau}{1+(\omega\tau)^2} \qquad (2)$$

Where ε_{ro} is the static relative dielectric permittivity;

$\varepsilon_{r\infty}$ - the relative dielectric permittivity at high frequencies.

The time constant τ in the equations (2) depends on the structural specifics and the nature of the insulator. It depends on the temperature T:

$$\tau = A.e^{\frac{a}{T}} \qquad (3)$$

where A and a are constants for the material being considered.

The second component of tgδ, in which is observed the relaxation maximum, is determined in the following manner:

$$tg\delta = \frac{\varepsilon_r^{''}}{\varepsilon_r} = \frac{(\varepsilon_{ro} - \varepsilon_{r\infty}).\omega\tau}{\varepsilon_{ro} + \varepsilon_{r\infty}(\omega\tau)^2} \qquad (4)$$

In order to find the relationship between the resonant frequency ω and the corresponding temperature τ, where tgδ reaches its maximum, we need to calculate the corresponding partial derivatives of tgδ.

$$\frac{\partial tg\delta}{\partial\omega} = \frac{\tau(\varepsilon_{ro} - \varepsilon_{r\infty}).[\varepsilon_{ro} - \varepsilon_{r\infty}(\omega\tau)^2]}{[\varepsilon_{ro} + \varepsilon_{r\infty}(\omega\tau)^2]}\text{, T=const.} \qquad (5)$$

Similarly, we take the derivative $\frac{\partial tg\delta}{\partial\tau}$.

The resonant parameters ω и τ determining the location of the relaxation maximum, satisfy the equation of a hyperbola:

$$\omega\tau = \sqrt{\frac{\varepsilon_{ro}}{\varepsilon_{r\infty}}} \qquad (6)$$

When solving equations (5) and (3) jointly, the result is:

$$\omega = B.e^{-\frac{a}{T}} \qquad (7)$$

Where $B = \frac{1}{A}\sqrt{\frac{\varepsilon_{ro}}{\varepsilon_{ro}}}$ is constant for the insulation in question.

Equation (7) could be represented in the following way:

$$lu\omega = luB - lua\left(\frac{1}{T}\right) \tag{8}$$

The dependency (8) is a straight line in the coordinate system $\left(lu\omega, \frac{1}{T}\right)$. For the purposes of the experiment, it could be built only on two couples of values of the frequency f and the temperature T, which facilitates us to a large extent. The dependence is a straight line defining the correlation between the two resonance parameters.

The absolute value of the relaxation maximum in the tgδ graph depends primarily on the parameters of insulator:

$$tg\delta_{max} = 0{,}5\sqrt{\frac{\varepsilon_{ro}}{\varepsilon_{r\infty}}} \tag{9}$$

This maximum depends indirectly on the temperature due to the change of ε_{ro} from the temperature.

2. EXPERIMENTAL RESULTS

To verify the resulting mathematical model, we used experimental data from reference materials [2]. Using the least squares rule, Figure 2 depicts the equation (8) dependency for different insulation materials.

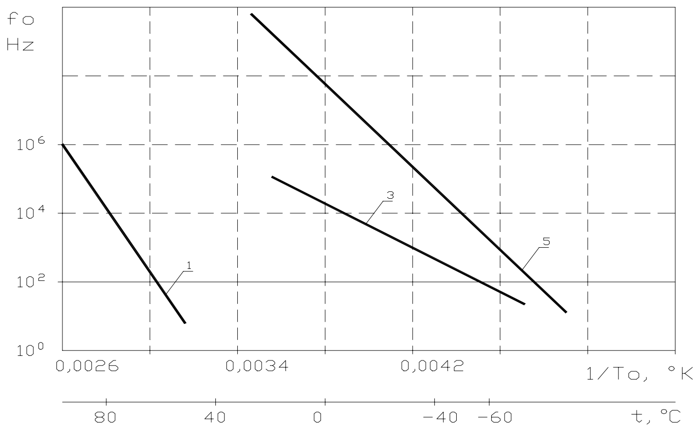

Figure 2. Dependence of frequency of slow polarization whit temperature of different insulation materials

An experiment for the purpose of testing the deduction of a group of curves tgδ = Φ(ω) at a constant temperature and tgδ = f(τ) at a constant frequency was conducted at the *Electrical Materials* laboratory at the Faculty of Electrical Engineering with the Technical University of Sofia.

Based on polyvinyl chloride samples, we obtained the degrees of dependency of tgδ from the temperature at various frequencies of the electrical fields. The results are shown in Figure 3. Based on hardened paper samples, we obtained the degrees of dependency of tgδ from the frequency of the electrical field at various temperature levels. The data is shown in Figure 4.

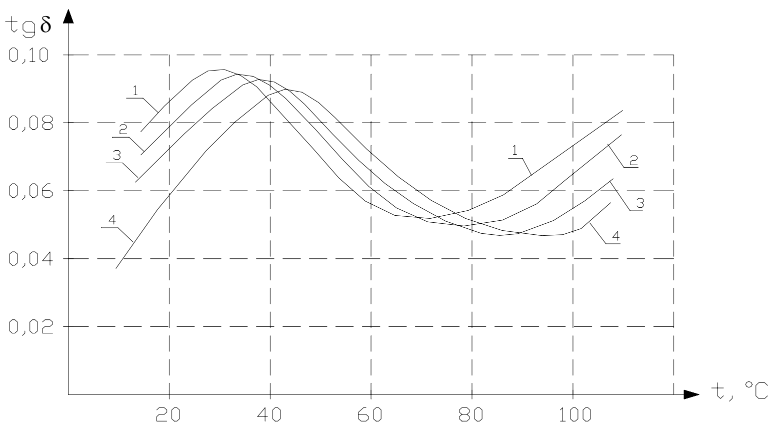

Figure. 3 Dependence of tgδ whit temperature of polyvinyl chloride at various frequencies (1 - at 800 Hz, 2 – at 1500 Hz, 3 – at 5 000 Hz, 4- at 10 000 Hz)

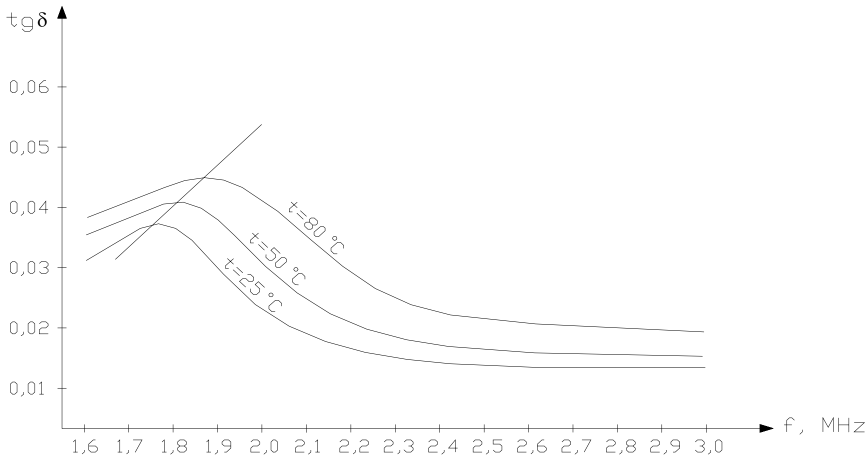

Figure 4. Dependence of tgδ whit frequencies of hardened paper at various temperature levels

3. CONCLUSION

In conclusion, we could say that we found the analytical dependency between the resonant frequency and its corresponding temperature, during which occurs the relaxation maximum. The results expressed in this paper allow us to determine straightforwardly the location of the maximum in the $tg\delta = \Phi(\omega, T)$ dependency for different electrical insulation materials, which is directly associated with increasing the insulation efficiency in electrical equipment.

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