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Loss of Dielectric in Alternating Electric Field

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Abstract

Based on the latest research development of dielectric loss and dielectric relaxation, we have carried out experiments and research analysis on the dielectric properties under alternating electric field. This paper mainly expounds the characteristics of dielectric loss under alternating electric field, and carries out related calculations and derivations. Conduct experimental studies and variation analysis on loss sources. For the dielectric relaxation, we propose Cole-Cole(CC) model and Havriliak-Negami(HN) model, and obtain the relevant selection scheme under the test.

Keywords

Dielectric Relaxation; Dielectric Loss; CC Model; HN Model.

1. Introduction

The study of dielectric loss is often an important part of research in various fields, and dielectric loss cannot be ignored for power systems. Based on the characteristics of the dielectric, the dielectric loss in the alternating electric field has different characteristics than the electrostatic field. For the research of dielectric loss in alternating electric field, many of them are analyzed by studying the measurement of loss tangent and structural characteristics. Few studies analyze the essential source of loss to reduce loss. Few rationalized model solutions have been proposed for dielectric relaxation problems.

We first analyzed the essential characteristics of the dielectric loss, and the sources of the dielectric loss were divided into three categories for calculation and research. According to the changes of different influencing factors in the alternating electric field, we drew the change graph through experiments. At the same time, based on the dielectric relaxation problem, we propose Cole-Cole(CC) model and Havriliak-Negami(HN) model. for analysis. For the properties of materials with different parameters, we give different options through experiments.

2. Dielectric Loss

2.1 Basic Problems of Dielectric Loss

Dielectric loss refers to the energy consumed by the dielectric to convert electrical energy into heat energy per unit time and unit volume.

The energy consumed by the dielectric per unit time and unit volume in the DC electric field is:

$$\omega=\gamma_V E$$

The electrostatic energy density of a dielectric with static permittivity ε_s in an electrostatic field is:

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$$\omega_s = \frac{\varepsilon_s E_0^{\ 2}}{2}$$

Therefore, both the stored energy density and the dissipated energy density are related to the dielectric properties. That is: the stored energy density is related to the static permittivity ε_s; the consumed energy density is related to the conductivity γ_V of the medium. Neither involves the relationship of the frequency of changes in the electric field.

In the alternating electric field, each correlation vector (I, j, V, E) may have a phase difference, so it is necessary to introduce a medium characteristic parameter related to the medium frequency: complex permittivity (ε^*).

If the phase difference between D and E is δ:

$$\dot{D} = \varepsilon^* \dot{E}$$

$$\varepsilon^* = \varepsilon' - i\varepsilon''$$

The real and imaginary parts of the complex permittivity are respectively:

$$\begin{cases} \varepsilon' = \dfrac{D_0}{E_0}\cos\delta \\ \varepsilon'' = \dfrac{D_0}{E_0}\sin\delta \end{cases}$$

$$j = \varepsilon^* \frac{\partial \dot{E}}{\partial t} = (i\omega\varepsilon' + \omega\varepsilon'')\dot{E}$$

Therefore, we know that the first component of current density has a phase difference of 90° from the electric field intensity, which is the reactive component. The second component of the current density, which is in phase with the electric field, is the loss component and the active component.

Energy dissipated per second per unit volume of a medium in an ALTERNATING current field:

$$w = \frac{\omega}{2}\varepsilon'' E_0^2$$

2.2 Source of Dielectric Loss

The phase difference δ between D and E causes dielectric loss, mainly from the following three sources:

2.2.1 Dielectric is a Non-ideal Insulator, Which has Leakage Conductance and Produces Leakage Loss

The $tg\delta$ value determined by this loss is:

$$tg\delta = \frac{G}{\omega C}$$

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It can be seen that $tg\delta$ value is related to the frequency of electric field change, dielectric conductivity and dielectric constant.

2.2.2 Slow Polarization and Anomalous Dispersion Occur in Dielectric

For example, the thermal ion polarization and thermal steering polarization related to thermal motion have a long establishment time. When the frequency of electric field changes exceeds a certain limit, these slow polarizations cannot be established in time, resulting in polarization hysteresis. The polarization intensity of the medium lags behind the electric field strength E. At this time, part of the energy will be consumed, resulting in dielectric loss.

General dielectric leakage conductance is not large, slow polarization loss is the main part of dielectric loss, there are special rules.

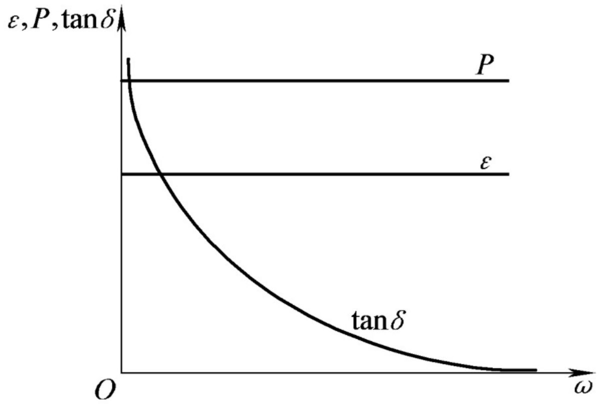

Fig. 1 The relationship between P and $tg\delta$ and ω due to conductance in a medium

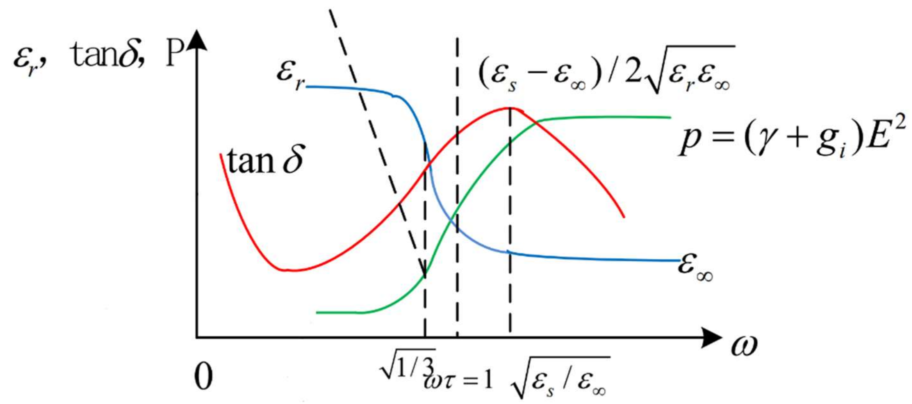

Fig. 2 The relationship between dielectric loss $P(w)$ and $tg\delta$ and ω due to slow polarization

2.2.3 Resonance Effects from Atomic, Ionic or Electronic Vibrations

Light is an electromagnetic wave, the relative speed of its propagation in the medium and the refractive index n of the medium depend on the frequency, that is, the phenomenon of dispersion. Dispersion is accompanied by energy dissipation, and dispersion and absorption coexist.

3. Dielectric Relaxation Theory

Dielectric relaxation refers to the process in which a dielectric reaches a new polarization equilibrium state from an instantaneously established polarization state after the application (or removal) of an external electric field. The time when the dielectric polarization tends to a steady state is called the relaxation time. The relaxation time is closely related to the polarization mechanism and is one of the reasons for the dielectric loss of the dielectric material.

The models we use to analyze the relaxation loss process of dielectrics include Cole-Cole(CC) model and Havriliak-Negami(HN) model. Their mathematical expressions have the same form, the difference lies in the values of α and β.

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{\left[1+(j\omega\tau)^\alpha\right]^\beta}$$

The complex plane diagrams of the complex permittivity of the CC model and the HN model are shown in the figure:

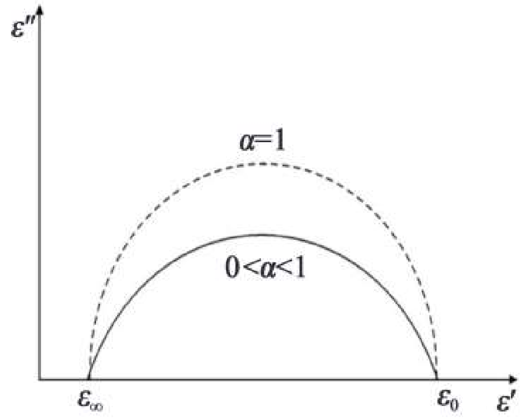

Fig. 3 CC model

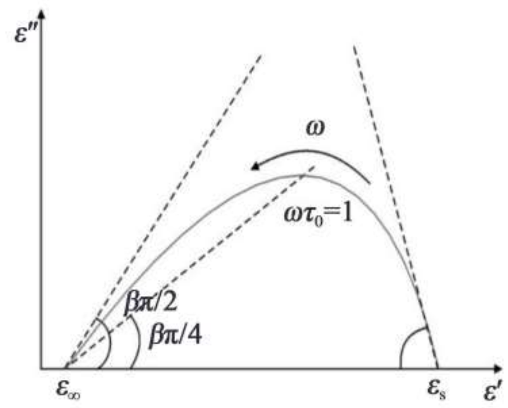

Fig. 4 HN model

According to the theory of complex analysis, the expressions of the real and imaginary parts of the complex permittivity can be obtained as:

$$\varepsilon^{'}(\omega) = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty)\cos(\beta\theta)}{(1+2(\omega\tau)^\alpha\cos(\alpha\pi/2)+(\omega\tau)^{2\alpha})^{\beta/2}}$$

$$\varepsilon^{''}(\omega) = \frac{(\varepsilon_s - \varepsilon_\infty)\sin(-\beta\theta)}{(1+2(\omega\tau)^\alpha\cos(\alpha\pi/2)+(\omega\tau)^{2\alpha})^{\beta/2}}$$

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$$\tan\delta = \frac{\varepsilon''(\omega)}{\varepsilon'(\omega)}$$

$$\theta = \arctan\left(\frac{(\omega\tau)^{\alpha}\sin(\alpha\pi/2)}{1+(\omega\tau)^{\alpha}\cos(\alpha\pi/2)}\right)$$

At the low frequency and high frequency limits, the slopes of the imaginary part of the spectral curves of different relaxation loss models are different in the double logarithmic coordinate, as shown in the table.

Table 1. The slope of $\lg\varepsilon'' - \lg\omega$ at the high and low frequency limits

	CC	HN
α	$0<\alpha<1$	$0<\alpha<1$
β	1	$0<\beta<1$
low frequency slope	0~1	0~1
high frequency slope	-1~0	-1~0

Therefore, according to the slope of the insulating medium spectral curve at the high and low frequency limits, it can provide a basis for the selection of different insulating medium relaxation models.

4. Conclusion

We first analyzed the characteristics of dielectric loss, and compared the loss in electrostatic field and alternating electric field. Modified calculation of losses in electrostatic fields. At the same time, the phase and frequency of each vector are represented by complex conductivity and complex permittivity.

For the sources of alternating electric field losses, we divide them into three categories for analysis. Experiments on the influencing factors are carried out to obtain the relevant change trends, and the analysis and interpretation are combined with the graphics.

In the dielectric relaxation loss, we conducted loss analysis by establishing CC model and HN model, and provided theoretical support for selecting different media at different frequencies through experiments and model analysis. Limited by existing knowledge, it can only be carried out to the current extent.

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