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Current Status of Research on Partial Discharge Models in Insulating Materials

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Abstract

This article summarizes four physical models that explain the partial discharge process of the internal air gap of insulating materials: three-capacitance model, induced charge model, discharge randomness model and discharge simulation model with fluid charge equation as the core. The four models all explain the phenomenon of air gap partial discharge to a certain extent. The three-capacitance capacitance model lacks physical meaning, but is conducive to qualitatively studying the actual discharge volume and apparent discharge volume; the induced charge model explains the apparent discharge volume from the perspective of electrostatic field; the discharge randomness model has a good explanation for the partial discharge theory; The charge fluid equation is of great significance to the random simulation of partial discharge and the interpretation of the microscopic process of partial discharge.

Keywords

Partial discharge; Insulating material; Charge fluid equation; Discharge model.

1. INTRODUCTION

Partial discharge refers to the discharge that only occurs in a local area of the insulator, but does not penetrate between the conductors that apply voltage, that is, the discharge between the two electrodes does not completely bridge the electrodes, and the insulation between the two electrodes is not completely broken down. [1-4] Discharge refers to the breakdown of gas, and partial discharge is related to insulating structure and insulating medium. According to the insulation structure, there are corona discharge, surface discharge, air gap discharge and other discharges. Among them, the discharge forms with simple insulation structure include corona discharge and surface discharge. Their residual charge does not accumulate or only accumulates in the lower part of the dielectric. This article only reviews the partial discharge of the internal air gap of the solid insulating material where the charge accumulation is more complicated.

In power equipment, the phenomenon of air gap partial discharge is very common, such as: cables, high voltage bushings, etc. In the process of producing insulating materials for power system applications, micro cracks, impurities, and air gaps inevitably appear due to manufacturing process and cost issues. For example, the preparation of insulating cross-arm core rods and the extrusion of polyethylene cables. When the insulating parts work normally, since the gas has a lower dielectric constant and breakdown field strength than the insulating medium, the insulating performance of the parts will be affected to a certain extent. Therefore, it is of great significance to study the internal air gap discharge model of solid insulating materials.

F H Kreuger improved on the air gap discharge dual-capacitor model[5] proposed by A Gemant, and then proposed a three-capacitor model[5]. Using the three-capacitor model, the

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actual and actual discharge expressions can be derived. The three-capacitance model solves the problem of the relationship between the discharge intensity and the discharge volume in the pulse current method to a certain extent, but the key capacitance concept in this model does not hold. Later, the induced charge model of A Pedersen[6] successfully explained the physical meaning of the pulse current method, but only qualitative analysis was possible. The above two models are mainly used to study the instantaneous change of the charge at both ends of the electrode during partial discharge, and it is difficult to explain the problems related to the discharge characteristics such as the randomness of the discharge. Discharge randomness is an important characteristic of partial discharge. In order to further reveal the discharge mechanism, the researchers ignored the discharge process and performed random simulations based on discharge area and discharge time delay [8-10].

Both the simulation based on the randomness of the discharge time delay and the simulation based on the randomness of the discharge area have certain shortcomings. The former ignores the expansion of the streamer on the interface during the air gap partial discharge process, and the latter ignores the air gap discharge process. In practical problems, the continuous partial discharge process can be analyzed by the equivalent idea of superimposing a single discharge in a time series. The effect of the previous discharge on the next discharge can be realized by changing the electric field distribution and the discharge time delay in the air gap.

The charge fluid equation model well simulates the expansion of the single discharge current injection on the interface and the development in the air gap, but the amount of calculation is large, and the current algorithm is immature, which can not realize the effective simulation of the randomness of the discharge intensity in the continuous discharge process . Wu Kai [11] uses the difference method to solve the equations, which overcomes the shortcomings of traditional algorithms that cannot solve three-dimensional problems, greatly reduces the amount of calculation, and realizes continuous partial discharge simulation under AC voltage. The disadvantage is that this method is still difficult to simulate the propagation process of the streamer in the air gap.

The following will summarize the four physical models of partial discharge, introduce their basic principles, and analyze their characteristics in detail.

2. THREE-CAPACITOR MODEL

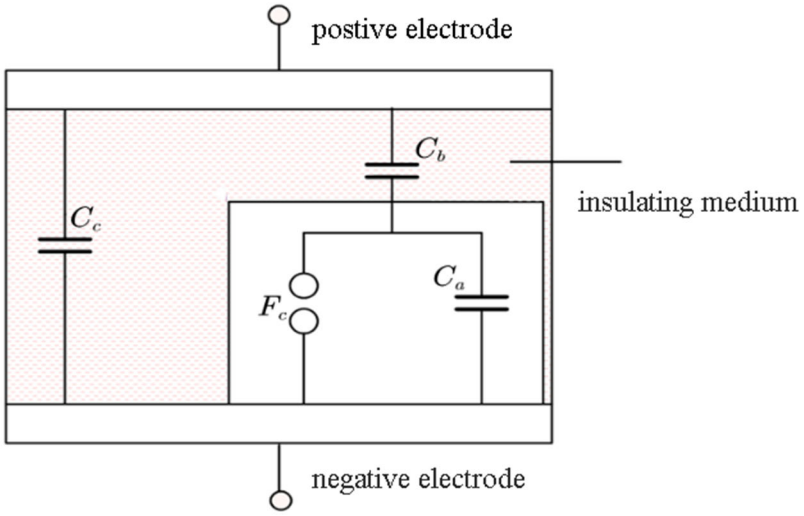

Figure 1. The model of A-B-C capacitance

The three-capacitor model explains the phenomenon of partial discharge from the perspective of the circuit. It uses the idea of equivalent substitution to simplify the air gap and

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impurities inside the material into a capacitor network. The structure is shown in Figure 1. Among them, C_c is the air gap capacitance, C_a is the other part of the dielectric capacitance, F_c is the discharge air gap, and C_b is the capacitor in series with the discharge air gap.

During the discharge process, the voltage across the air gap changes to ΔU, and the actual discharge amount of the air gap can be derived as (1):

$$Q_c = \Delta U_c (C_c + \frac{C_a C_b}{C_a + C_b}) \tag{1}$$

Since the object of discussion is a solid insulating material and the air gap is small, if the conditions are established, the formula (2) can be obtained:

$$Q_c \approx \Delta U_c (C_c + C_b) \tag{2}$$

During the experiment, the actual discharge volume of partial discharge is difficult to obtain directly, and the transient change of the charge at both ends of the electrode during breakdown can be directly measured. During partial discharge, the voltage at both ends of the electrode changes as ΔU_a, and the transient charge at both ends of the electrode can be deduced as (3):

$$Q_a = \Delta U_a (C_a + \frac{C_c C_b}{C_c + C_b}) \tag{3}$$

The duration of a discharge is more than ten nanoseconds [12], which is extremely small compared with the circuit charge and discharge constant, so the influence of the power supply on the charge transient can be ignored. If the voltage change on C_b is ΔU_b, the formula (4) can be obtained:

$$\Delta U_c = \Delta U_a + \Delta U_b = \Delta U_a \frac{C_a + C_b}{C_b} \approx \Delta U_a \frac{C_a}{C_b} \tag{4}$$

Comprehensive (3) formula can be derived to (5) formula:

$$Q_a \approx \Delta U_c C_b \tag{5}$$

Where Q_a is the apparent discharge capacity. Due to the linear relationship between the discharge energy parameter and the apparent discharge volume[2], and combining (2) and (5), it can be seen that Q_a can be used to evaluate the strength of partial discharge.

If C_b is the capacitance value between the upper surface of the air gap and the motor, (5) can be further rewritten as (6):

$$Q_a = \Delta U_c \varepsilon_0 \varepsilon_r \frac{S}{d_i} \tag{6}$$

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Among them, S is the average discharge area. d_i is the thickness of the series dielectric of the discharge air gap, ε_r is the relative dielectric constant, and ε_0 is the vacuum dielectric constant. This expression relates the apparent charge to the position of the air gap.

The three-capacitor model unifies the randomness theory of partial discharge, and establishes the relationship between the discharge energy and the air gap, and the apparent and actual discharge volume. However, the capacity in the strict sense is composed of a conductor and an insulating medium between them. In fact, C_b and C_c do not exist. This model lacks physical meaning and can only be used to qualitatively understand the phenomenon of air gap partial discharge in solid insulating materials.

3. INDUCED CHARGE MODEL

From the perspective of the electrostatic field, the induced charge model explains the transient phenomenon at both ends of the electrode during discharge. Discharge involves the generation, disappearance and movement of electric charges. Ignoring the charge exchange process between the electrode and the dielectric, the apparent charge can be equivalent to the induced charge on the electrode, as shown in Figure 2:

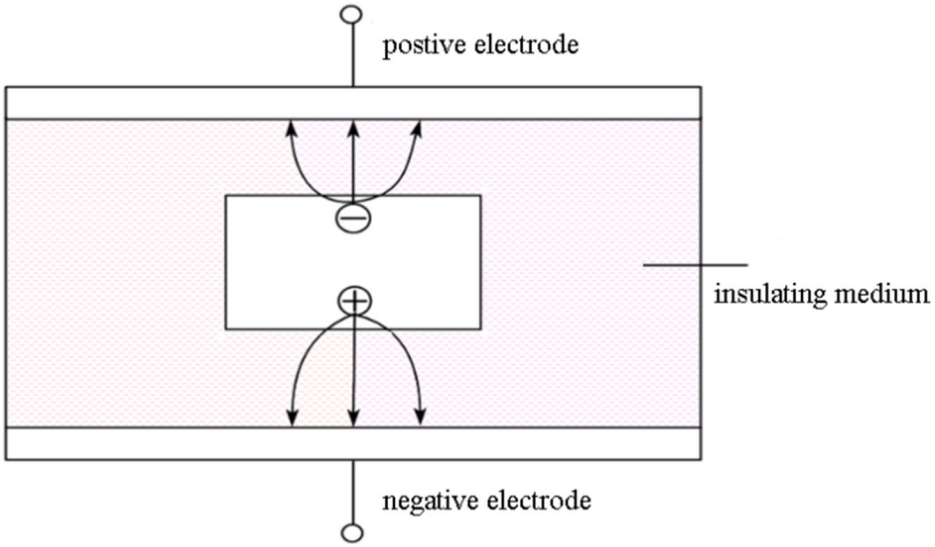

Figure 2. The model of induced charge

In order to quantitatively analyze the magnitude of the induced charge, the following methods can be used to solve it, one is based on the electric polarization intensity, and the other is based on the electric displacement vector. The following two methods are discussed in detail with the negative electrode as the research object.

3.1. Solve Induced Charge based on Electric Polarization

The charge induced on the electrode is mainly related to the space charge generated by the discharge and the polarization of the dielectric. Combining the two parts, the induced charge expression (7) can be obtained:

$$Q = -\iiint(\phi\rho + \Delta\vec{P}\cdot\nabla\phi)\mathrm{d}V - \iint\sigma\phi\mathrm{d}S \tag{7}$$

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ϕ satisfies the Laplace equation, is continuous at the air gap and the interface, and is a dimensionless unit related to the position of the charge. The positive electrode is 0 and the negative electrode is 1. ΔP represents the amount of change in polarization caused by partial discharge in the air gap.

3.2. Solve Induced Charge based on Electric Displacement Vector

According to the electromagnetic field theory, in a linear uniform dielectric, there is a point charge dq between the two electrodes, and the space charge induces the charge at the negative electrode as dQ, which can be deduced from equation (8):

$$dQ = -\lambda dq \tag{8}$$

λ is a dimensionless function related to the position of the charge. The expression (9) of the total amount of negative electrode induced charge is further derived:

$$Q = -\iiint \lambda \rho dV - \iint \lambda \sigma dS \tag{9}$$

ρ is the charge density of the air gap body, σ is the surface charge density at the interface between the solid insulating material and the air gap, and dS and dV are the area microelement and volume microelement, respectively.

From Green's reciprocity theorem, we can get formula (10):

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla \lambda) = 0 \tag{10}$$

λ is 0 for the positive electrode and 1 for the negative electrode; the boundary condition of the contact surface between the air gap space and the insulating medium is equation (11)

$$[\varepsilon_0 \varepsilon_r]_+ [\frac{\partial \lambda}{\partial n}]_+ = [\varepsilon_0 \varepsilon_r]_- [\frac{\partial \lambda}{\partial n}]_- \tag{11}$$

$\frac{\partial \lambda}{\partial n}$ represents the part where λ is perpendicular to the interface, and -, + represent the inner and outer sides of the interface. Using (9) and (10), the distribution of λ, space charge, surface charge and the amount of induced charge on the electrode can be derived.

4. PARTIAL DISCHARGE RANDOMNESS MODEL

The randomness of partial discharge is manifested in the irregularity of discharge time and intensity, and the random change of current waveform during continuous discharge. At present, the commonly used models for the research of discharge randomness are: the random model based on the discharge time delay and the random model based on the discharge area.

By simplifying the circuit network of the three-capacitor model, the relationship between the actual amount of charge generated in the air gap (12) can be obtained:

$$Q_c \propto \Delta U_c C_c \tag{12}$$

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202104_7(4).0051

Substituting the voltage expression into the formula (13):

$$Q_c \propto C_c(E_c - E_r)d_c \tag{13}$$

E_c and E_r is the electric field in the air gap before and after the partial discharge occurs, and d_c is the air gap height.

Other parameters remain unchanged, and E_c changes randomly, and the discharge intensity changes randomly. Under certain limited conditions, the transition of the discharge pattern during the partial discharge aging process of the air gap of the solid insulating material can be obtained [13]. On the basis of E_c randomness in the acquisition and development of discharge seed electrons, a randomness model of discharge intensity was established. The uncertainty of seed electron acquisition, the uncertainty of the applied voltage and the randomness of the residual charge distribution generated by the discharge affect the air gap electric field distribution and determine the uncertainty of E_c.

C_c is the capacitance formed by the air gap between the charges accumulated on the upper and lower surfaces in the insulating material. The random change of C_c is determined by the randomness of the discharge point area during continuous discharge [14]. When other parameters remain unchanged, the change rule of discharge intensity can be obtained.

Partial discharge randomness model can be used to qualitatively understand the theory of partial discharge, and explain most of the phenomena of partial discharge to a certain extent. However, because the model ignores the physical process of discharge, it cannot be used in the simulation of the randomness of discharge current.

5. CHARGE FLUID EQUATION

The charge fluid equation follows the principle of conservation of charge and consists of three sets of equations. The charge fluid equation describes the physical processes related to the generation and movement of anions, cations and electrons. This equation can be used to explain the physical processes of electron adsorption, electron impact ionization, charge diffusion and migration, and the specific expressions (14), (15), (16):

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (W_e n_e) - D_e \nabla^2 n_e = (\alpha - \eta) n_e |W_e| - \beta_e n_e n_p + s \tag{14}$$

$$\frac{\partial n_p}{\partial t} + \nabla \cdot (W_p n_p) - D_p \nabla^2 n_p = \alpha n_e |W_e| - (\beta_e n_e n_p + \beta_n n_n n_p) + s \tag{15}$$

$$\frac{\partial n_n}{\partial t} + \nabla \cdot (W_n n_n) - D_n \nabla^2 n_n = \eta n_e |W_e| - \beta_n n_n n_p \tag{16}$$

In the formula, n_n, n_p, n_e represents the concentration of anion, cation and electron, W_n, W_p, W_e represents the migration speed of anion, cation and electron, D_n, D_p, D_e represents the diffusion speed of anion, cation and electron, α is the ionization coefficient, η is the adsorption coefficient, and β_n, β_p is the anion, cation and electron The recombination coefficient, s represents the generation of secondary electrons.

In the process of partial discharge, due to the existence of the interface, cations will strike the insulating material, the charge accumulated on the surface will have a "memory effect" on the

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subsequent process, the process of secondary electron generation and the blocking effect of the interface on the stream.

After partial discharge occurs, seed electrons collide with gas molecules, ionize anions and cations, and form electron avalanches. The electrons and cations are located at the collapse head and tail, respectively. Collapsing electrons promote the occurrence of ionization by enhancing the strength of the electric field. Regardless of the photoionization effect, the Thomson discharge is finally formed, and when considered, the streamer discharge is formed. No matter what kind of discharge, electron avalanche will go through the process of charge diffusion, migration and electron adsorption. In actual experiments, the streamer discharge is much stronger than the Thomson discharge [15]. In the simulation experiment, it is customary to assume that there are high-concentration charge pairs at the beginning of the electron avalanche, so as to ignore the initial stage of streamer discharge [11]. When the stream reaches the interface, the surface charge accumulates, the external electric field weakens, and the discharge is extinguished. After the applied voltage increases, the discharge phenomenon may occur again.

The charge fluid equation, combined with FCT, can be applied to single discharge simulation [16-17]. Among them, FCT solves the problem of positive charge concentration and steep concentration gradient in the simulation process. However, the current research on the blocking effect of the interface on the stream is still incomplete. In the observation of partial discharge, the surface charge showed uneven accumulation of charge spots [14]. This phenomenon determines the modeling of the three-dimensional model. After simplifying the discharge process, the difference equation can be used to reduce the calculation amount and simulate the expansion of the streamer at the interface [11]. However, with this method, the charge spots still cannot be obtained, and the final result is only uneven surface charge distribution.

Serdyuk established a two-dimensional model to simulate the ion interaction of solid insulating materials and the propagation process of streamers in the air gap [18]. In addition to completing the generation and termination of the discharge process, they also fully considered the process of charge injection from the electrode.

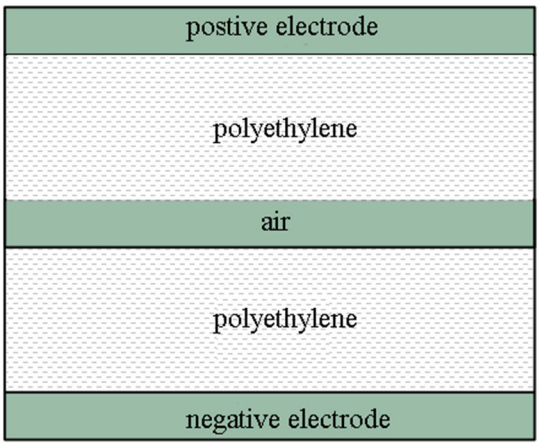

Figure 3. The calculation model of PD based on the charge fluid equations

Using the charge fluid equation in the simulation, we can get the gas discharge and streamer accumulation at the interface, and the actual discharge and induced charge can be calculated. After introducing the randomness of seed electrons and the expansion process of the streamer at the interface, continuous partial discharge can be simulated and the theory of discharge randomness can be explained. It is a relatively mature theory.

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6. CONCLUSION

This article reviews four models to explain the physical phenomena of partial discharge in the air gap of solid insulating materials. Although the three-capacitor model has no physical meaning, it can qualitatively understand the concept of discharge capacity. The induced charge model has a good explanation for the pulse current method. Partial discharge randomness model is the basis for qualitative understanding of partial discharge. The charge fluid equation is of great significance for simulating the discharge process such as the expansion of the streamer at the interface, and at the same time explains the principle of discharge randomness. Finally, we should pay attention to the discussion of this important characteristic of discharge randomness, and use the charge fluid equation to give a clearer explanation of the partial discharge phenomenon.

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