Fluid simulation model and analysis of partial discharge characteristics of tip defects

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Abstract: The tip discharge is modeled and the micro discharge characteristics are studied. The hydrodynamic model of tip discharge in transformer oil is established. The development process of streamer discharge under pulse voltage is analyzed. The distribution of space charge density and space electric field under different pulse voltage amplitude and rising edge is obtained. The numerical results show that: with the increase of applied voltage amplitude, the average velocity of streamer development changes more significantly with the same discharge spacing; the steeper the rising edge pulse is, the faster the average discharge development speed is and the larger the discharge radius is. At the same time, according to the change law of streamer morphology development under AC voltage, the discharge frequency is less, the amplitude is higher, and the phase distribution is narrow when the applied voltage is positive half cycle. When the applied voltage is negative half cycle, the discharge times are more and the phase distribution is wide, and the tip discharge has obvious polarity effect.

1. Introduction

High voltage electrical equipment plays an important role in the power system. It is of great significance to maintain the safe operation of high-voltage electrical equipment and ensure its reliability. Partial discharge is the main cause of insulation failure of high-voltage electrical equipment. Partial discharge is a discharge phenomenon in the form of pulse. There are many types of partial discharge in high-voltage electrical equipment, including[1]: free metal particle discharge, tip discharge, suspension discharge, insulation internal defect discharge, discharge caused by insulator surface dirt, etc. According to the metal tip that is burr, the tip discharge can be roughly divided into high-voltage conductor (high potential) tip discharge and equipment shell (low-voltage point) tip discharge[2]. In the case of fast transient over-voltage, such defects have serious consequences and may cause serious damage to the equipment[3]. Therefore, it is of great significance to study the discharge characteristics of high voltage electrical equipment.

In the early 19th century, the United States and other developed countries began to pay attention to the establishment of numerical calculation model of partial discharge. So far, many scholars have carried out in-depth research in this field. At present, the streamer discharge model is mainly established based on streamer theory. The streamer discharge model is mainly divided into three models: particle model, fluid model and fluid particle mixing model[4]. The adaptability and flexibility of the finite element method to the complex model structure has been widely used in various fields. Scholars at home and abroad have made great breakthroughs in the analysis of partial discharge characteristics with the help of finite element method[5].
Reference[6] studied the characteristics of pulse discharge under dielectric barrier based on the simplified kinetic model of chemical reaction. In reference[7], the two-way streamer propagation characteristics of water vapor with different concentrations were studied by adding photoionization as the source term in the continuum equation of charged particles. The streamer discharge model was established in references[8] and[9], the equation was solved by flux correction transmission method, and the discharge dynamic process was analysed. References[10] and[11] established hydrodynamic models to study voltage amplitude, electrode structure, electric field distribution and charge distribution of streamer discharge. Reference[12] used three-dimensional network to simulate partial discharge sequence, and studied propagation characteristics of partial discharge, distribution of surface charge and characteristics of discharge current. In reference[13], the characteristics of metal tip discharge are analyzed by combining simulation and experiment. In reference[14], considering the influence of space charge and surface charge on electric field, the discharge characteristics with or without dielectric barrier are analyzed, and the validity of simulation results is verified by experimental results. The effects of rising edge, pulse frequency and relative permittivity on the current characteristics of dielectric barrier discharge (DBD) were studied in reference[15]. In reference[16], a one-dimensional self consistent fluid model was studied to analyze the distribution of electric field and carrier density under different voltages.

In this paper, the finite element theory and field-circuit coupling method are used to solve the electronic continuity equation, ion continuity equation and Poisson equation, establish a numerical simulation model of cylindrical tip discharge, and analyze the microscopic discharge characteristics of the tip discharge: establish a numerical simulation model of tip discharge in transformer oil, and solve the tip discharge model through grid selection; analyze the development of the streamer morphology of streamer discharge and the change of gap voltage and current density in the case of AC voltage and pulse voltage; analyze the distribution of space charge and electric field and the discharge current and voltage characteristics of the discharge gap under different pulse voltage amplitudes; analyze the effects of different rising edge pulse voltages on the characteristics of tip discharge.

2. Simulation model of tip discharge
The electrode structure adopted in this paper is pointed plate type, which is a tip anode. The angle between the center dotted line and the inclined edge is 27 degrees and the gap distance is 1.5 mm. The lower plate is the cathode of the electrode. The electrode structure is a closed container filled with transformer oil. The electrode structure is shown in Fig.1(a). The axisymmetric simulation model of corona discharge is established by using finite element software, as shown in Fig.1(b).

![Electrode structure and model of simulated calculation](image)
3. Simulation analysis of partial discharge characteristics of tip defects

3.1. Influence of pulse voltage on streamer development characteristics

The slow streamer discharge is closely related to the applied voltage. For different insulating media, the starting voltage and stopping voltage of streamer discharge are different, which is related to the properties of the medium itself. The insulating medium used in this chapter is transformer oil, and its relative dielectric constant is 2.2. The expression of applied pulse voltage is shown in formula (1).

\[ U = K \cdot U_0 \left( e^{\frac{t}{15 \times 10^3}} - e^{\frac{t}{15 \times 10^8}} \right) \]  

In the above formula (1), \( K \) is the voltage compensation coefficient, \( t \) is the time, unit is ns, \( U_0 \) is the peak value of pulse voltage, unit is kV.

The amplitude of applied voltage is 40kV, and its rising edge is a pulse voltage of 50ns. The distribution nephogram of electric field intensity of transformer oil at 30ns, 80ns, 120ns, 250ns, 350ns, 500ns and 900ns is simulated and analyzed, as shown in Figure 2 (a) below. We can clearly see the streamer discharge from the tip of the high electrode and development to the ground electrode process and morphology distribution. When the time is 30 ns, the electric field strength in the transformer oil reaches above the critical field strength of the molecular ionization of the transformer oil, and the streamer morphology begins to develop along the electrode axis away from the high-voltage extreme. With the ionization of transformer oil molecules under the action of strong electric field, the electrons continuously migrate to the high electrode side, and the positive charge tends to develop towards the cathode. The streamer head position develops continuously to the ground electrode, and the maximum electric field reaches \( 3.5 \times 10^8 \text{ V}\cdot\text{m}^{-1} \), which is similar to the "Ionization Wave" pushing mode. It can be seen from Fig. 2(a) that the development volume of streamer head is smaller than that of 80ns at 30ns, and when the head volume of 120ns is greater than 80ns, this is due to the continuous ionization of oil molecules in the initial stage of streamer development. In the initial stage of streamer, with the increase of electric particle density, the conductive space charge density increases, and the electric field intensity generated by space charge is enhanced, and then interacts with the applied electric field, resulting in the electric field strength of the head being larger, and the electric field intensity of the streamer position is smaller after the streamer development.

![Fig.2 (a) Streamer discharge development during different times; (b) The electric field intensity of the streamer develops during different times](image)

As shown in Fig. 2(b), the relationship between the electric field intensity and axial distance at different times can be seen when the discharge gap is 1.5mm and the 40kV pulse voltage is applied. The
streamer morphology shows a peak movement along the axial direction of the electrode, and the peak value of the electric field is far away from the high electric extreme and gradually moves towards the earth electrode. It can be seen from Fig. 2(b) that the electric field distribution can be divided into three stages. Firstly, the electric field near the high electrode is relatively flat, which is due to the cancellation between the electric field generated by the applied voltage and a part of the electric field generated by the charged particles. After the electric field flattening stage, the electric field enters the peak stage. The electric field distribution in this area is characterized by large gradient on both sides of the peak value, and the electric field distribution presents normal distribution. This is due to the effect of positive charge. After the peak, the size of the electric field begins to decrease, because the positive charge has not developed to this position. It can be seen from Fig. 2(b) that the discharge distance between the tip and the plate is 1.5mm. When the streamer head is at 900ns, the streamer development distance is 1.2mm, the average streamer development speed is 1.47km/s, and the streamer development channel radius is about 0.06mm.

3.2. The influence of other factors on streamer development characteristics

(1) Influence of voltage amplitude on streamer development characteristics

The distance between the tip and the plate is 1.5mm. The positive voltage of 40kV, 50kV, 60kV, 70kV, 80kV, 90kV pulse voltage is applied at the tip (the rising edge is 50ns). The influence of different voltage on streamer morphology was analyzed when t = 50ns. The influence of different voltage on streamer morphology was analyzed when t = 50ns. The right side of Fig.3 (a) and (b) shows the distribution of electric field intensity, the legend shows the range of electric field intensity, and the left side of the figure shows the space charge density and equipotential line, and its legend represents the space charge density range. As shown in Fig.3, the larger the applied voltage amplitude is, the faster the streamer development rate is, and the streamer development head is far away from the anode. It can be seen from Fig.3 that both the maximum electric field intensity and the space charge density occur at the head position of streamer development. At the same time, it can be seen that the maximum space charge density and the maximum electric field intensity keep synchronous development.

Fig. 4 shows the relationship between the development position and time of streamer head under different voltages. It can be seen from the figure that the time required for streamer development is the longest when the applied voltage is 40kV, and the shortest time is required for streamer development when the applied voltage is 90kV. It can be concluded that with the increase of applied voltage amplitude, the streamer development time is shorter, and the streamer discharge start time is advanced, that is, the streamer development speed and streamer initial discharge time change with the change of electric field strength.
(2) Influence of rising edge on streamer development characteristics

When the applied voltage amplitude is 40kV, the distance between the tip and the plate is 1.5mm, and the pulse voltage with different rising edge (the time from \( t = 0 \) to the peak value of voltage amplitude is 50ns, 100ns, 200ns respectively). The influence of different rising edge pulse voltage on streamer formation and development is analyzed when the distance between streamer head and tip is 0.28mm, as shown in Fig. 5 below.

The left side of Fig. 5 (a) to Fig. 5 (c) shows the change of electric field intensity, and the right side shows the distribution of space charge and equipotential line. It can be analyzed from the figure that when the discharge reaches the same position (0.28mm away from the tip), the streamer discharge radius with rising edge of 50ns is larger than that of voltage pulse with rising edge of 200ns. As shown in Fig. 5 (a), the discharge radius of streamer is 0.065mm, while that in Fig. 5 (c) is 0.06mm. The reason is that the steeper the rising edge of the voltage is, the shorter the time for the electric field strength to increase, and the faster the ionization rate near the tip. The generation rate of charged particles near the tip is higher than that of charged particles. It can also be seen from Fig. 5 that at the same position, the maximum electric field strength increases with the rising edge, which is due to the decrease of streamer discharge radius, while the small radius enhances the electric field at the head of streamer. On the other hand, the electric field intensity of the head increases with the increase of space charge density.
Fig. 5 Electric field intensity and charge density distribution under different rising edges

Fig. 6 shows the influence of the applied voltage amplitude of 40 kV and the rising time of 50 ns, 100 ns and 200 ns respectively on the average development speed of the streamer head. The results show that the longer the rising time of applied voltage is, the slower the average speed of streamer development is. This shows that the rising time of applied voltage has a certain effect on the formation and development of streamer discharge.

4. Conclusion
In this paper, the tip discharge model in transformer oil is established. The effects of voltage amplitude, discharge distance between needle and plate, and different pulse voltage rising edge on tip discharge characteristics are studied by simulation calculation.

(1) The two-dimensional axisymmetric finite element model of tip discharge is established, and the simulation conditions and parameters are set for the model. The development characteristics of streamer with pulse voltage of 40 kV (rising edge of 50 ns) and the change of electron and positive charge transfer process, as well as the voltage and current characteristics of tip discharge under pulse voltage are studied. The results show that the electric field develops along the axial direction of high electrode and presents a series of moving peaks.

(2) The effect of different amplitude of applied pulse voltage on the characteristics of needle plate discharge was studied. The simulation results show that the larger the pulse voltage amplitude is, the greater the initial electric field value is, the faster the streamer development speed is, and the faster the streamer head is away from the high electrode.
(3) The influence of different rising edge of pulse voltage on the discharge characteristics of tip was studied. The simulation results show that the larger the rising edge value is, the slower the streamer development speed is under the same discharge spacing and pulse voltage amplitude. The rising edge of the pulse voltage is one of the factors that affect the response of the tip discharge.

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