Study on the Mathematical Model of Dielectric Recovery Characteristics in High Voltage SF\textsubscript{6} Circuit Breaker\textsuperscript{*}

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Abstract According to the stream theory, this paper proposes a mathematical model of the dielectric recovery characteristic based on the two-temperature ionization equilibrium equation. Taking the dynamic variation of charged particle’s ionization and attachment into account, this model can be used in collaboration with the Coulomb collision model, which gives the relationship of the heavy particle temperature and electron temperature to calculate the electron density and temperature under different pressure and electric field conditions, so as to deliver the breakdown electric field strength under different pressure conditions. Meanwhile an experiment loop of the circuit breaker has been built to measure the breakdown voltage. It is shown that calculated results are in conformity with experiment results on the whole while results based on the stream criterion are larger than experiment results. This indicates that the mathematical model proposed here is more accurate for calculating the dielectric recovery characteristic, it is derived from the stream model with some improvement and refinement and has great significance for increasing the simulation accuracy of circuit breaker’s interruption characteristic.

Keywords: SF\textsubscript{6}, high voltage circuit breaker, dielectric recovery characteristic, the breakdown voltage, experiment of dynamic breakdown, Saha ionization equilibrium

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(Some figures may appear in colour only in the online journal)

1 Introduction

The breaking process of a circuit breaker contains three phases, namely arcing, arc-extinguishing and dielectric recovery. The process during which the arc gap gradually turns from the arc channel to the insulation dielectric is called dielectric strength recovery, and the dielectric strength in the arc gap is characterized by the voltage that can be withstood by the gap. Whether or not the interruption succeeds depends critically on the “competition” between the post-arc dielectric strength recovery and the transient recovery voltage (TRV) \cite{1}. Previous studies mainly, among other things, have focused on the fault arc plasma with the emphasis on the transport property calculation, numerical analysis of arc dynamic characteristics and arc extinguishing characteristic researches. The objective of the arc study is to quickly achieve the extinction of fault arc, maximizing the variation range of the dielectric conductivity in the arc gap, therefore enabling the rapid recovery of the dielectric insulation performance. In the heart of the dielectric strength recovery are the thermal recovery and electrical recovery of the post-arc dielectric, which concern the energy diffusion process of the remaining post-arc energy under the action of the circuit breaker’s puffer and the ionization process of space charges under the action of the chamber’s electric field, respectively. However, there is a relatively small volume of studies on the recovery theory of the dielectric strength in the post-arc phase, among which the detailed studies are based on the calculation of the gas flow field and the electric field, taking the calculated result of the stream theory as the dielectric strength criterion. These studies, while having referential significances to a certain extent, though, do not fully represent the complex physical process of the circuit breaker’s interruption. So far, no studies have come up with the mathematical model of the dielectric recovery characteristic accordingly and provided the mathematic relation between the dielectric recovery speed and the chamber’s puffer property. Moreover, the lack of direct measurements of dielectric recovery characteristics under different working conditions is another issue. Consequently, both the studies on the dielectric recovery theory and the experimental investigation are incomplete.

Domestic and foreign scholars have studied the

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mathematical model and the simulation method for the arc energy and gas flow changing process from the perspective of fluid mechanics, through which they have obtained influences of the gas blowing of the puffer process on the dielectric recovery characteristic to predict the circuit breaker’s interruption characteristics. In the literature [2], the relevant two-dimensional unsteady model of the arc was established and the theoretical calculation result of the dielectric recovery characteristic was gained by solving the mass-conservation equations, the momentum-conservation equations and the energy-conservation equations in the mathematical model. In the literature [3], the arc mathematical model of SF$_6$ gas was established based on the magneto hydrodynamics to analyze the dynamic changing process of the arc in the SF$_6$ circuit breaker. In the literatures [4-6], the calculation of the chamber’s gas flow field was achieved by using the application software in combination with self-programming, which made the way of simulation calculation more expansive, and a large amount of theoretical calculation work was done for the multi-physical field during the interruption process. In the literatures [7,8], researches were conducted on the prediction of critical dielectric strength of hot CF$_4$ gas and critical breakdown electric field of hot carbon dioxide. In the literatures [9,10], researches were conducted on the mechanism of the development and extinction of the non-equilibrium arc with multiple ignitions, the mathematical model of the low-current arc was established which was applied to the design and development of the dedicated switch for the ultra-high voltage capacitor bank. However, due to the complexity of the chamber structure of the SF$_6$ circuit breaker and the uncertainty of physical property parameters of the gas dielectric during the puffer process, the mathematical simulation is still based on a number of assumptions which results in approximation to a large extent. So to improve the simulation method, the transport process of microscopic particles during the dielectric recovery process should be studied deeply to illuminate the objective law between microscopic parameters of the particle movement and macroscopic parameters of the dielectric movement.

In this paper, the Saha ionization equilibrium equation for the SF$_6$ gas concerning two-temperature conditions is established to calculate microscopic parameters such as electron density and temperature under different pressure and electric field conditions. The breakdown electric strength of the SF$_6$ gas is calculated by using the stream theory and the Rather breakdown criterion, also the mathematic relation between macroscopic parameters and microscopic parameters of the particle movement during the dielectric recovery process is given. The mathematical model for the coupling between the electric field and the gas flow field in the circuit breaker’s chamber is established to calculate the distribution of the electric field and gas flow field, and the mathematical model for the dielectric recovery characteristic is used to calculate the dielectric recovery characteristic curve for the cold-state interruption process of the circuit breaker, then the influences of the puffer characteristic and the electric field distribution in the chamber on the dielectric recovery speed are analyzed. The experiment loop of a 126 kV SF$_6$ circuit breaker with cold-state dielectric recovery characteristic has been built to measure the breakdown voltage under different electrode separation conditions, to which theoretical results are compared to verify the validity of the theoretical research.

2 Mathematical model of dielectric’s insulation recovery strength

According to the stream theory, the dielectric recovery process relates closely to the charged particle’s ionization and attachment process in the chamber. If the ionization process beats the attachment process, the number of electrons will quickly increase and reach the threshold, then breakdown occurs in the dielectric gap; but if the attachment process beats the ionization process, the number of electrons will quickly decrease, while the number of neutral particles quickly increases enabling the rapid recovery of the dielectric insulation strength. So as we can see, the space charged particle is the critical factor that influences the dielectric recovery process. This process possesses two significant features: one is that dielectric recovery is a continuous dynamic variation process rather than an inverse process of the dielectric breakdown; another is that during the dielectric recovery process, the energy variation under different physical processes cannot be characterized by only one temperature due to the uneven distribution of the particle density and the large temperature gradient as well as the dynamic variation of the ionization process. For this reason, in this paper the Saha ionization equilibrium equation concerning two temperatures is established to solve the variation tendency of the electron density and temperature under different pressure and electric field conditions, and the influences of the macroscopic parameter on the microscopic parameter are analyzed.

The general form of the two-temperature Saha dynamic equation can be derived by modifying the Saha ionization equilibrium equation for the dielectric recovery process as follows [11]:

$$n_e \left( \frac{n_{r+1}}{n_r} \right)^\frac{\tau_k}{\tau_e} = 2 Z_r^{r+1} \left( \frac{2m_e \pi k T_e}{\hbar^2} \right)^{3/2} \exp \left( \frac{-E_{I_{r+1}}}{kT_e} \right).$$

(1)

Here, $n_e$, $n_r$, and $n_{r+1}$ are the electron density and the particle density of particles A$_r$ and A$_{r+1}$, respectively; $Z_r$ and $Z_{r+1}$ are the partition function of particles A$_r$ and A$_{r+1}$, respectively; $k$, $h$, and $m_e$ are the Boltzmann constant, the Planck constant and the electronic mass, respectively; $E_{I_{r+1}}$ is the ionization energy of the $(r+1)$-order ionization reaction above; the electron
temperature $T_e$ and the heavy particle temperature $T_h$ are no longer equal to each other. The general form of the two-temperature gas state equation is as follows:

$$p = n_e k T_e + (n_i + n_i + n_{a_d}) k T_h. \quad (2)$$

Here, $n_e$, $n_i$, $n_a$, and $n_{a_d}$ are the electron density, the ions density, atomic density and molecular density respectively.

During the dielectric recovery process, the dynamic variation of the electron density mainly involves the collision process of electrons and various particles (such as the collision process between electron and electron, electron and ion, electron and atom). Averagely, the excess energy that one electron loses every time it collides with a heavy particle is $\Delta \varepsilon_{eh}$, therefore to keep $T_e$ higher than $T_h$, the electron must get power from the external electric field as compensation. The mathematic relation between the electron temperature and the heavy particle temperature can be deduced by the Cullen collision model, which characterizes the binary elastic collision of the electron and the heavy particle [12]:

$$T_e = \left( T_h + \frac{\pi (e E l_{ce})^2}{16 k_B T_e} = \frac{m_e}{m_h} \frac{3}{2} k_B (T_e - T_h) \right) / 2. \quad (3)$$

$$l_{ce} = \frac{1}{\frac{1}{2} n_e Q_e + \sum_{j=1}^{N} n_j Q_j}$$

Here, $m_e$ and $m_h$ are the electron mass and the heavy particle mass, respectively; $E$ is the space electric field strength and $l_{ce}$ is the mean free path; $Q_j$ and $n_j$ are the collision cross section and the particle density of the relevant particle, respectively. It can be primarily confirmed that there are mainly 20 types of particles in the SF$_6$ gas plasma model by studying the decomposition of the SF$_6$ gas and the relevant ionization chemical equations; as for partition functions of various particles, ionizations of SF$_6$ and its decomposition medium, calculating parameters of decomposition energy, they can be found in the literature [13]. The electron density and temperature under different pressure and electric field conditions are acquired by solving the nonlinear equations above using the Newton iteration method, as shown in Fig. 1. The initial temperature was 300 K, and the initial pressures were 0.1 MPa, 0.2 MPa, 0.4 MPa, 0.8 MPa, and 1.6 MPa.

According to the stream theory and the Rather breakdown criterion, the electron avalanche will gradually turn into a stream when the space charge field roughly equals to the external electric field. At this point, it can be assumed that electrons of the avalanche all gather in the globoild at the avalanche head, and the electric field $E_r$ in the avalanche is a spherical field with a radius of $r$ [14], then $E_r$ can be calculated by:

$$E_r = \frac{e \cdot N_e}{r^2}, \quad (4)$$

$$r = \frac{4 k T_e}{e \cdot E}, \quad (5)$$

$$N_e = n_e \cdot \frac{4}{3} \pi r^3. \quad (6)$$

The following formula can be obtained by putting Eqs. (5) and (6) into (4):

$$E_r = e \cdot n_e \frac{4}{3} \pi \sqrt{\frac{4 k T_e}{e \cdot E}}, \quad (7)$$

$$U_b/(1V) = E_{crit}/E_{1V}. \quad (8)$$

Here, $n_e$ is the electron density in per unit volume of the space, $e$ is the electric quantity of the charge, $T_e$ is the electric field temperature, $E$ is the electric field intensity of the space, $k$ is the Boltzmann constant, $U_b$ is the critical breakdown voltage, and $E_{1V}$ is the electric field distribution at 1 V voltage between contacts. When $E_r = E$, the stream will form and the space dielectric will breakdown. At this point, the electric field intensity of the space $E$ is considered to be equal to the maximum electric field intensity $E_{crit}$ that can be withstood by the dielectric. $n_e$, and $T_e$ under different pressure and electric field conditions are gained by solving the two-temperature Saha ionization equation; the calculated $E_{crit}$ is shown in Fig. 2.
3 Calculation and analysis of cold-state dielectric recovery characteristics for circuit breaker

The dielectric recovery process involves the thermal recovery process and the electrical recovery process. The dielectric thermal recovery refers to the dynamic variation process of the temperature, density and pressure of the dielectric in relation to the change of the opening distance between contacts. The dielectric electrical recovery refers to the dynamic variation process of the electric field distribution in the chamber in relation to the change of the recovery voltage and the opening distance between two contacts. In this paper, the combined simulation calculation is conducted for the gas flow field and the electric field under the circuit breaker’s no-load condition to get the distribution of the density, pressure and electric field in the chamber under different separation conditions. The mathematical model of the dielectric recovery characteristic is used to calculate the critical breakdown field strength and breakdown voltage of the dielectric under different separation conditions, then the dynamic variation process of the dielectric recovery is analyzed.

On the basis of solving the Navier-Stokes equations for the gas flow field of the circuit breaker and the $k-\varepsilon$ model of the dielectric recovery characteristic is used to calculate the gas flow field and the UDF (User-Defined Function) module is adopted in combination with the C self-programming to calculate the dielectric recovery characteristic $^{[9]}$. Calculation conditions are: the 126 kV SF$_6$ gas circuit breaker interrupts under the no-load condition, the gas-charged pressure is 0.7 MPa, the initial temperature is 300 K, the opening distance $S_k = 150$ mm, the overtravel $S_c = 50$ mm, and the average opening speed between the arc contacts is 9.6 m/s. The calculation model is shown in Fig. 3 and calculated distributions of the pressure and intensity in the chamber are shown in Fig. 4.

The field shape in the circuit breaker’s chamber is complex and various dielectrics coexist in the chamber such as the SF$_6$ gas, PTEE and metal. The three-dimensional electric field of the chamber can be simplified as a two-dimensional axisymmetric electric field to calculate in the cylindrical coordinate system for nozzles and contacts in the chamber all have an axisymmetric structure $^{[10]}$. The voltage applied to the moving main contact and the moving arc contact is $\phi_1 = 0$ V; the voltage applied to the static main contact and the static arc contact is $\phi_2 = 1$ V. The influence of the voltage polarity on the electric field distribution of the chamber is ignored. The calculated results of the electric field distribution are shown in Fig. 5.
The recovery characteristic curves of the cold-state dielectric for the circuit breaker are calculated using the mathematical model of the dielectric recovery strength in combination with calculation parameters of the gas flow field and the electric field, as shown in Fig. 6. There is no arc in the recovery process of the circuit breaker’s cold-state dielectric, therefore gas flow parameters only relate to the chamber’s structure and the opening speed. There is an obvious gas flow variation after the small nozzle opens due to the cylinder’s movement. The variation range of the gas pressure in gap A changes from \( P_{\text{min}} = 0.7 \, \text{MPa}, \, P_{\text{max}} = 0.85 \, \text{MPa} \) to \( P_{\text{min}} = 0.74 \, \text{MPa}, \, P_{\text{max}} = 0.94 \, \text{MPa} \), the variation range of the dielectric intensity changes from \( N_{\text{min}} = 44 \, \text{kg/m}^3, \, N_{\text{max}} = 48 \, \text{kg/m}^3 \) to \( N_{\text{min}} = 45.8 \, \text{kg/m}^3, \, N_{\text{max}} = 58 \, \text{kg/m}^3 \), and the maximum value of the electric field in the chamber changes from 10.99 V/mm to 0.13 V/mm. Fig. 6 shows varying curves of the maximum density, pressure and electric field in the gap between the arc contacts in relation to the opening distance. It can be seen that when contacts just separate, there is a fluctuation of intensity in gap A, the pressure increases but the maximum electric field decreases shapely, and the curve of the dielectric’s critical breakdown voltage ascends. It is known from formula (9) that the critical breakdown voltage is inversely proportional to the electric field, so the electric field recovery is the leading factor for the rapid dielectric recovery in the time range between the separation of contacts and the opening of the small nozzle. After the small nozzle opens, the intensity and the pressure quickly recover while the electric field has no obvious variation as the cold gas flow with high pressure and high intensity enters into gap A, as a result the critical breakdown voltage increases rapidly. After the large nozzle opens, the dielectric intensity and pressure decrease rapidly due to the strong gas blowing effect, as a result the critical breakdown voltage decreases. For this reason, the intensity and pressure recovery of the dielectric after the small nozzle’s opening are leading factors of the dielectric recovery characteristic.

From the perspective of the macroscopic process of the cold-state dielectric recovery, the dielectric insulation strength is the recovery process of the electric field and the dielectric intensity. The maximum electric field between contacts will decrease as the opening distance increases. After the small nozzle opens, the dielectric in the cylinder with high pressure and high intensity enters into the gap between contacts and the dielectric insulation strength quickly recovers. From the perspective of the microscopic physical process of the dielectric recovery, the dielectric insulation strength is the dynamic variation of the dielectric’s ionization and attachment process. The electric field between contacts will decrease as the opening distance increases; as a result the collision between electrons and neutral particles in the dielectric gradually recedes, the electron temperature decreases and the ionization process recedes. After the
small nozzle opens, the high-intensity dielectric enters into gap A between contacts; as a result the attachment process between electrons and ions increases, the electron density decreases but the neutral particle density increases, so the dielectric insulation strength quickly recovers.

4 Experimental investigation of dielectric recovery characteristic

The experiment loop of a 126 kV SF\(_6\) circuit breaker with a cold-state dielectric recovery characteristic has been built to measure the breakdown voltage under different electrode separation conditions during a single closing-opening process. Gas-charged pressures of the chamber are 0.5 MPa and 0.7 MPa, respectively; the opening speed \(v_k = 9.6\) m/s, and the experiment circuit is shown in Fig. 7. First ensure that the circuit-breaker to be measured is in the OFF position, then apply a 380 kV DC voltage to high-voltage capacitors C5 and C6 by the DC supply circuit which includes high-voltage testing transformer T and the DC voltage doubling circuit (capacitors C1, C2, C3, and C4 and the high-voltage silicon stacks D1, D2, D3, and D4). High-voltage capacitors C5=0.5 \(\mu\)F, and C6=200 pF, the rated operational voltage is 400 kV DC. Close the circuit breaker and open it soon afterward, measure the charging voltage of capacitor C5 by using resistor dividers R1 and R2, measure the varying curve of the breakdown voltage between the contacts gap with time by using capacitor dividers C6 and C7, and measure the varying curve of the travel between contacts by using the circuit breaker’s travel sensor.

During the opening process of the circuit breaker described above, after contacts separate, C6 becomes open, C5 will charge C6 through resistor R and the voltage on C6 will quickly increase. When the voltage on C6 is higher than the critical breakdown voltage of the dielectric between contacts, the gap breakdown will occur between contacts. The breakdown will produce an arc which results in the instantaneous release of C6’s charge, and the voltage on C6 will quickly decrease until the arc extinguishes. The arc current is only of hundreds of a milliamperre because the capacitance of C6 is very small, as a result the arcing time is less than 0.1 ms. The alternated recurring process of charging, breakdown, releasing, arc-extinguishing and recharging will form the repetitive breakdown during the opening process. The breakdown voltage will increase as the opening distance between contacts gradually increases, and there is no breakdown when the opening distance is large enough. During the closing process, breakdown occurs successively as the opening distance gradually decreases, the breakdown voltage will decrease until contacts close. The dynamic breakdown characteristic in the gap of the circuit breaker can be obtained by measuring the breakdown voltage in the gap with time during the opening process and closing process. The voltage on the moving arc contact is of ground potential, and the static arc contact is applied both with the forward voltage and the negative voltage. The maximum voltage between arc contacts of the circuit breaker is 380 kV. The closing-opening experiment operation is conducted under each experiment condition for both positive polarity and negative polarity, and dynamic breakdown voltages under different opening distances of the circuit breaker are measured. The dielectric breakdown voltages are calculated by the stream breakdown criterion and the proposed mathematical model of the dielectric recovery characteristic, respectively, to which the experiment data are compared and analyzed, as shown in Fig. 8. The results show that calculated results are in conformity with experiment results on the whole, while the results based on the stream criterion are larger than the experiment results. This indicates that the mathematical model proposed here is more accurate for calculating the dielectric recovery characteristic; it is derived from the stream model with some improvement and refinement.
5 Conclusion

In this paper, the dual-temperature Saha ionization equilibrium equation for the SF$_6$ gas is established to calculate microscopic parameters such as the electron density and temperature under different pressure and electric field conditions. Critical breakdown field strengths under different pressures are given and macroscopic and microscopic processes of dielectric recovery during the cold gas flow interruption of the circuit breaker are analyzed. The experiment loop of a 126 kV SF$_6$ circuit breaker with cold-state dielectric recovery characteristic has been built to measure the breakdown voltage under different electrode separation conditions, to which theoretical results are compared. Specific conclusions are as follows:

a. During the electrical recovery process of the dielectric, the space electric field decreases and so does the frequency of the collision between electrons and particles. As a matter of course, the energy exchange weakens and the electron temperature decreases while the extent of the electron attachment deepens. As a result the electron number decreases. The critical breakdown field strength of the dielectric increases as the pressure increases.

b. During the cold-state interruption process of the circuit breaker, before the small nozzle opens, the maximum electric field value decreases sharply (changing from 10.99 V/mm to 0.13 V/mm) and the critical breakdown voltage curve of the dielectric quickly ascends (changing from 0 kV to 208 kV); during this period the electric field recovery is the leading factor of the rapid dielectric recovery. After the small nozzle opens, the cold gas flow with high pressure and high intensity enters into gap A; consequently, the intensity and the pressure quickly recover (the pressure changing from 0.94 MPa to 1.32 MPa, the intensity changing from 42.6 kg/m$^3$ to 49.2 kg/m$^3$) and the critical breakdown voltage quickly increases (changing from 208 kV to 1331 kV), during this period intensity and pressure recoveries are the leading factors of the dielectric recovery characteristic.

c. Calculated results are compared with experiment data of the dielectric recovery characteristic, it shows that the mathematical model of the dielectric recovery characteristic gives full consideration to the dynamic ionization equilibrium equation under the two-temperature condition and conforms to the recovery mechanism of the SF$_6$ gas dielectric, which has great significance on increasing the simulation accuracy of the circuit breaker’s interruption characteristics.

References


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