The Effect of Inflation Pressure on the Dielectric Recovery Strength of SF_6 Circuit Breakers

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Abstract SF_6 gas is widely used in high-voltage power equipment due to its excellent arc extinguishing performance. During the process of breaking fault current in a circuit breaker, the thermal electrical breakdown problem in the post arc phase is significant. This article is based on a 252 kV high-voltage circuit breaker model, combined with the real gas model of SF_6 gas and the valve plate motion model, and uses the thermal critical breakdown field strength (E_{cr}) of SF_6 to study the calculation method of the recovery strength of the post arc medium. The critical breakdown field strength data under different charging pressures are simulated. The results indicate that increasing pressure Increasing pressure will lead to the decrease of E_a/E_{cr}, and the dielectric recovery strength will increase versus. The research results of this article are of great significance for the optimization design of high-voltage circuit breakers.

Keywords CFD analysis · Dielectric recovery strength · SF_6

1 Introduction

High voltage SF_6 circuit breakers are the key equipment in the power system [1]. During the process of breaking fault current in a circuit breaker, the thermal electrical breakdown problem in the post arc phase is significant. Therefore, in-depth analysis of the thermal re-breakdown mechanism of the circuit breaker has important significance for the maintenance of the circuit breaker.

In recent years, extensive research has been conducted on the simulation of the interruption process of high-voltage SF_6 circuit breakers. A two-dimensional magnetohydrodynamic (MHD) arc model was established for the arc burning stage to study

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the complex physical processes inside the arc extinguishing chamber during the disconnection process of high-voltage gas circuit breakers [2, 3]. *Yan* et al. used the MHD model to study the arc behavior of arc extinguishing chambers with different principles, and compared it with the measurement results of arc voltage in air compressor circuit breakers and air pressure in the expansion chamber of self-energy expansion circuit breakers, verifying the effectiveness and feasibility of the MHD model [4, 5]. After the current crosses zero point, the temperature of the gas medium between the contacts rapidly cools from tens of thousands of K during the arc stage to thousands or even hundreds of K, so it can withstand a certain recovery voltage. However, when the recovery voltage is greater than the critical strength of the medium, heavy breakdown may occur. Many scholars have also conducted corresponding research on the electrical breakdown characteristics of SF_6 gas within a certain temperature range [6–8]. Literature [8] provides the calculation results of the equivalent critical breakdown field strength of SF_6 gas under different pressure and temperature ranges. On this basis, Seeger further studied the breakdown characteristics of high-voltage gas circuit breakers by combining arc MHD simulation with electrical breakdown characteristics analysis [6].

This article establishes a magneto-hydro-dynamic model of a 252 kV self-blasted circuit breaker. The dielectric recovery was evaluated, and the recovery of the medium under different inflation pressures was compared. The research results of this article are of great significance for the optimization design of high-voltage circuit breakers.

2 Simulation Models and Calculation Methods

2.1 Arc Model

Computational fluid dynamics (CFD) analysis has been widely used since the last century, especially in the field of design and manufacturing of high-voltage switchgear. During the process of circuit breaker short circuit current breaking, there are complex arc plasma physical phenomena in the surrounding airflow field. This article uses a two-dimensional MHD arc model to simulate the motion of the arc during the breaking process of a circuit breaker. This includes physical processes such as thermal convection, thermal radiation, electromagnetic fields, and nozzle material erosion. Describe the arc behavior based on the basic form of the Navier Stokes equation with added source terms:

$$\frac{\partial \rho \phi}{\partial t} + \nabla(\rho \phi \vec{v}) - \nabla(\Gamma \nabla \phi) = S_{\phi} \tag{1}$$

where, ρ is the mass density, Φ is a dependent variable that varies with the type of equation: mass conservation, momentum conservation, energy conservation, and component transport equation. S_{Φ} is the source item.

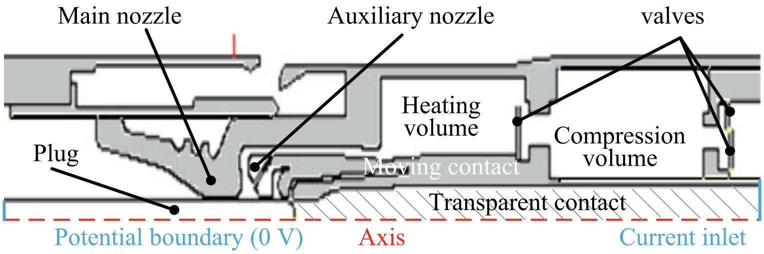


Fig. 1 High voltage circuit breaker calculation model and boundary condition settings

2.2 Calculation Model for High Voltage Circuit Breakers

The simulation in this article is based on a 252 kV level self-blasted circuit breaker model. Due to the symmetrical structural characteristics of the arc extinguishing chamber, the model used in the calculation is half of the circuit breaker profile. Figure 1 shows the physical model of the circuit breaker. Considering that the self-energy SF6 circuit breaker has a hollow arc contact structure, a "transparent contact" is introduced in the model to prevent arc deviation. The maximum stroke of the moving parts is 166 mm. When opening, the distance between the dynamic and static arc contacts is 78 mm, and the average speed during the movement of the mechanism is 5.5 m/s.

Import ANSYS FLUENT for magnetic fluid simulation, with boundary and initial conditions set as:

(1) The interior of the switch is filled with SF_6 gas;
(2) The effective value of the set short-circuit current is 35 kA, the frequency is 50 Hz, and the arc is ignited for half a cycle;
(3) The initial inflation pressure is 0.6 MPa and 0.7 MPa, and the pressure outlet boundary is shown in the figure;

2.3 Valve Plate Motion Model

The action of the valve is mainly determined by the force difference on the two sides of the valve. When the air pressure in the chamber increases, the force on the side of the valve will increase. If the force driving the valve to open is F_k and the force driving the valve to close is F_g, the percentage P_F of the difference in force on the two sides of the valve can be expressed as:

$$P_F = \frac{F_k - F_g}{F_k} \times 100\% \tag{2}$$

Considering the influence of factors such as friction and pressure fluctuations on the valve, a threshold of $\pm$ 2% has been introduced to prevent the valve from oscillating back and forth. The action criteria of the valve are:

When $P_F > 2\%$, the force driving the valve to open is greater. If the valve is in a closed state at this time, the valve will open, otherwise it will not act. If the pressure relief valve is already in an open state, it will tend to move in the direction of larger opening scale;

When $P_F < -2\%$, the force driving the valve to close is greater. If the valve is in an open state at this time, the valve will close, otherwise it will not act. If the opening scale of the relief valve is large, the relief valve will tend to move in the direction of the smaller opening scale;

When $-2\% \leq P_F \leq 2\%$, the valve does not operate, i.e. it remains in its current state.

2.4 SF_6 Thermal Critical Breakdown Field Strength

Due to the large amount of heat generated during the arc stage, the temperature increases, leading to gas decomposition. The critical breakdown field strength of gases is related to the types of particles, collision ionization, adsorption, and recombination processes. The electron energy distribution of weakly ionized gases will deviate from the Maxwellian and Druyvesteyn distributions. By solving the Boltzmann equation with two approximations, the electron energy distribution function (EEDF), reduced ionization reaction coefficient, and reduced adsorption reaction coefficient of the hot gas can be obtained. The reduced critical breakdown field strength $(E/N)_{cr}$ of the gas at different temperatures can be determined. Finally, the product of $(E/N)_{cr}$ and particle number N can be used to obtain the critical breakdown field strength E_{cr} of the hot gas. Figure 2 shows E_{cr} under different pressures between 300 and 3000 K. E_{cr} is a function of temperature and pressure.

2.5 Calculation Method for Recovery Strength of Post Arc Dielectric

Taking the pressure and temperature distribution in the arc extinguishing chamber at the end of the thermal recovery phase as the initial state of the electrical recovery phase, the E_{cr} of each point in the arc extinguishing chamber is obtained by linear interpolation of the critical breakdown field strength data table, and the electric field strength E_a of each point in the arc extinguishing chamber is calculated according to the applied voltage U_a. By comparing the value of E_a/E_{cr} and 1, it is determined that breakdown occurs in the arc extinguishing chamber, i.e. in the area where $E_a/E_{cr} > 1$ occurs. In addition, taking the weakest point between fractures, i.e. the maximum $E_a/$

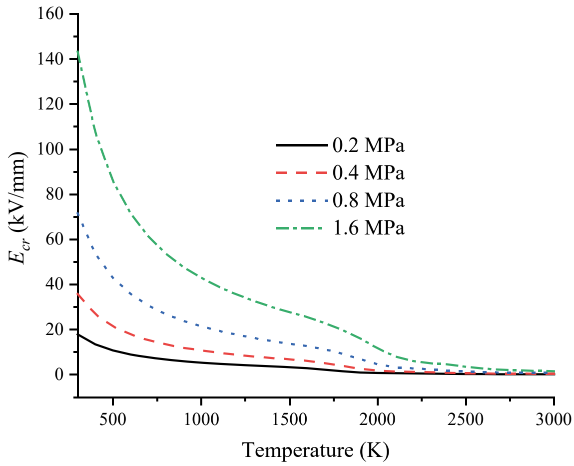


Fig. 2 The Ecr of pure SF6 at 300 K ~ 3000 K for different gas pressure

E_{cr} value, as the reference value, the calculation formula for the critical breakdown voltage Ucr that the circuit breaker can withstand at different times after arc is:

$$U_{\text{cr}} = U_{\text{a}}/(E_{\text{a}}/E_{\text{cr}})_{\text{max}} \quad (3)$$

The above evaluation method is based on the weakest point between ports, and the obtained critical breakdown voltage is much greater than the actual critical breakdown voltage. However, the critical breakdown field strength of each point in the arc extinguishing chamber obtained through temperature and pressure interpolation still has certain reference significance for the recovery of post arc dielectric strength.

3 Calculation Results of Electric Breakdown Characteristics

As shown in Fig. 3, the distribution diagram of temperature and pressure inside the arc extinguishing chamber at the moment of maximum contact rebound under different inflation pressures when the 252 kV circuit breaker breaks the short circuit current. The temperature has dropped to below 500 K after cooling for 12 ms. It can be seen that changing the pressure will affect the temperature distribution inside the arc extinguishing chamber. Increasing the pressure is conducive to the cooling of the arc extinguishing chamber. The lower the internal temperature of the arc extinguishing chamber. By comparing the pressure distribution, it can be seen that the curves of the pressure cloud map distribution are almost consistent.

Figure 4 shows the comparison of E_{cr} and E_a and E_a/E_{cr} distribution at different filled pressure when the contact bounces back to the maximum. It can be observed that the critical breakdown field strength in the nozzle area between the arc contacts

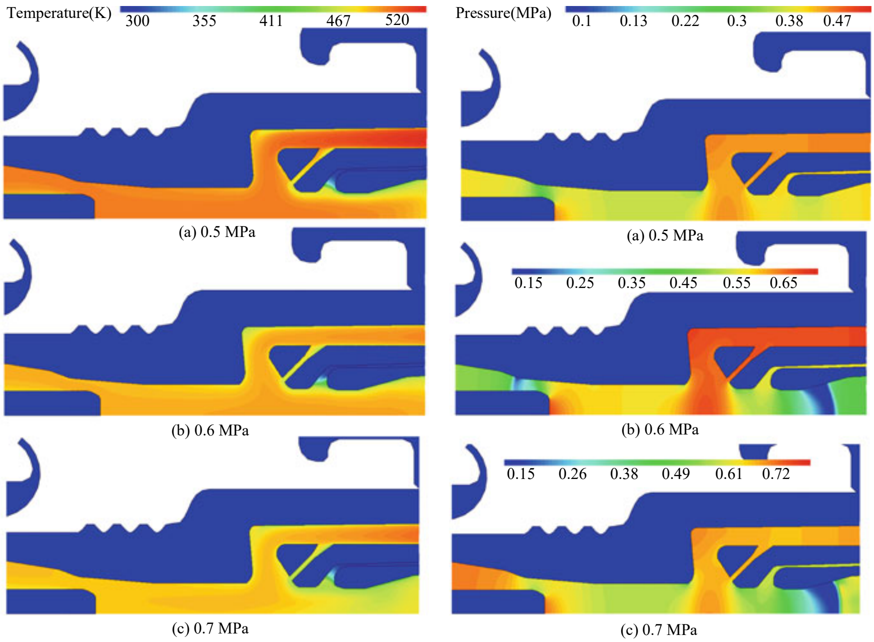


Fig. 3 Comparison of temperature and pressure distribution at different short-circuit currents and maximum contact rebound

gradually increases with the increase of pressure. The distribution of the critical breakdown field strength is consistent with the distribution of temperature and pressure (Fig. 3). The distribution of field strength is similar in several cases, with higher field strength near the end of the arc contact and lower field strength inside the nozzle throat and moving arc contact. Under different pressures, E_a/E_{cr} will decrease with increasing pressure. The distribution of E_a is approximately the same under different pressures, and increasing pressure will lead to an increase in E_{cr}. Therefore, after increasing pressure, E_a/E_{cr} will decrease, and the dielectric recovery strength will also decrease.

Figure 5 shows the variation curve of dielectric recovery strength under different pressures. Near the current zero zone, the arc gradually contracts as the current decreases, and the gas flowing out of the expansion chamber quickly cools the hot gas near the nozzle area. Therefore, the strength of the arc gap medium increases rapidly after the current passes zero. As the rebound process of the circuit breaker begins, around 2.5 ms after zero, the recovery strength of the medium will reach a peak value. The rebound process will increase the background field strength between the contacts and increase the probability of breakdown, The recovery strength of the medium decreases and increases correspondingly with the increase and decrease of rebound. At the same time, the rebound of the contact causes fluctuations in the internal pressure of the arc extinguishing chamber, resulting in fluctuations in the dielectric recovery strength. At 40 ms, the rebound stage ends, and at this time, the dielectric

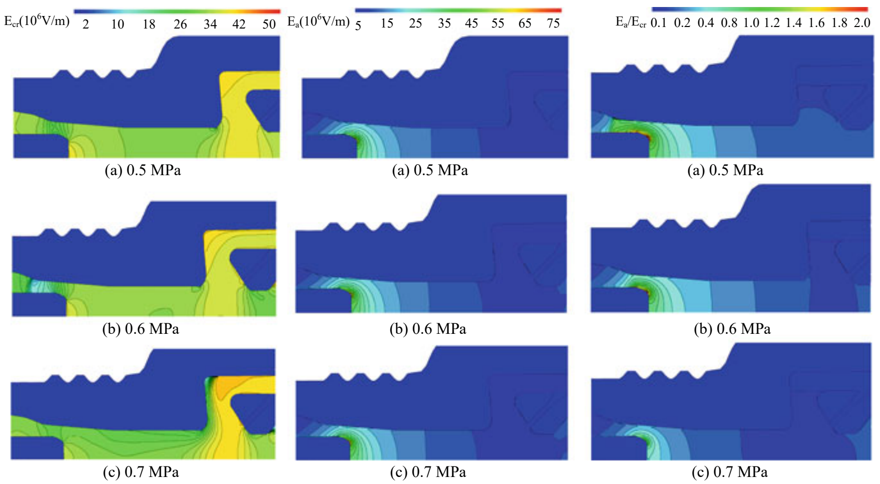
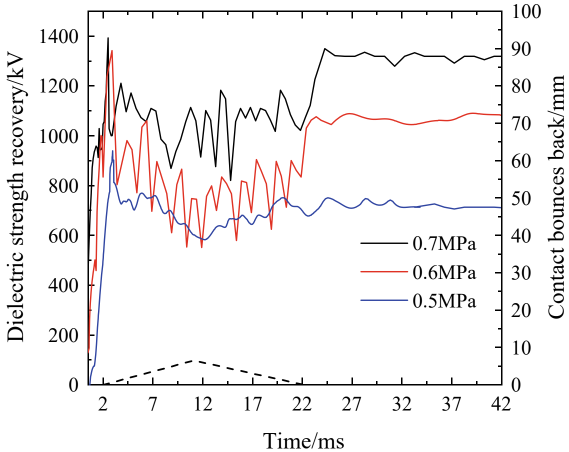


Fig. 4 Comparison of E_{cr} and E_a and E_a/E_{cr} distribution at different filled pressure when the contact bounces back to the maximum

recovery strength inside the arc extinguishing chamber remains almost unchanged. As the pressure increases, the fluctuation of the medium recovery strength during the rebound stage gradually increases. After lowering the atmospheric pressure by one atmosphere, the recovery strength of the quasi cold medium decreases by 31.7%; After increasing by one atmospheric pressure, the recovery strength of the quasi cold medium increases by 27.4%.

Fig. 5 Strength recovery curve of arc gap medium under different pressure



4 Conclusion

This article is based on the 252 kV high-voltage circuit breaker model to study the influence of the filled pressure on the dielectric recovery strength. The following conclusions are obtained:

(1) Regardless of the pressure, the temperature inside the arc extinguishing chamber drops to around 500 K in the post arc stage. Increasing the pressure is beneficial for the cooling of the arc extinguishing chamber and will lead to the decrease of E_a/E_{cr}, and the dielectric recovery strength will increase versus.

(2) Lowering the pressure by one atmosphere will lead to decreases of 34.7% of the recovery strength of the quasi cold condition, and increasing by one atmospheric pressure will lead to increasing by 14.6%.

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