Study on the Influence of Pre-Arc Factors in SF6 Circuit Breakers on Arc Formation Process (Postprint)

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Abstract

This study employs the actual SF6 circuit breaker arc extinguishing chamber structure as the computational model, utilizing gas dynamic equations and adopting a microscopic perspective that considers inter-particle collision reactions to investigate the generation, development, and evolution patterns of arc plasma particle populations following liquid metal bridge rupture and prior to steady-state arc formation, specifically at a contact separation of 3 mm. The research analyzes and examines the influence of varying interrupting currents on plasma microscopic parameters during the pre-arc process through changes in metal vapor content, while simultaneously investigating the impact of different electrode materials on the SF6 arc pre-formation process via differences in secondary electron emission coefficients. The simulation provides fundamental theoretical data for steady-state arc research and holds significance for the development and design of high-voltage switching equipment.

Full Text

Study on the Influence of Pre-Arc Factors on Arc Formation Process in SF6 Circuit Breakers

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Abstract: This paper employs an actual SF6 circuit breaker arc chamber structure as the computational model and utilizes gas dynamic equations to investigate, from a microscopic perspective and considering inter-particle collision reactions, the generation, development, and evolution of arc plasma particle groups before stable arc formation and after liquid metal bridge rupture, specifically at a contact gap of 3 mm. The study analyzes how variations in metal vapor content caused by different breaking currents affect the microscopic parameters of plasma during the pre-arc process, while also examining how differences in secondary electron emission coefficients resulting from different electrode materials influence the SF6 arc pre-arc process. The simulation provides fundamental theoretical data for steady-state arc research and holds significance for the development of high-voltage switching equipment.

Keywords: SF6 circuit breaker, arc, microscopic, pre-arc process

2 Simulation Model for Pre-Arc Factors

With the continuous and steady increase in power demand, higher requirements are being placed on the breaking capacity of high-voltage circuit breakers in upgraded power systems [1]. Circuit breakers inevitably generate arcs during the interruption process. The stage before stable arc formation is referred to as the pre-arc process. Theoretical studies have shown that the pre-arc process provides the initial path for arc plasma development and influences the energy of the steady-state arc. High-temperature arcs can be divided into the cathode region, arc column region, and anode region. The cathode surface, space charge (sheath), and ionization layer (pre-sheath) in the cathode region constitute the foundation for arc generation and existence, and are also prerequisites for studying arc reignition after current zero [2]. These features develop during the early stage of arc formation, i.e., the pre-arc process.

The pre-arc process comprises two stages: the metallic phase arc and the gaseous phase arc, with the particle composition participating in the arc process changing between these two phases [3]. Currently, understanding of the physical mechanisms underlying the pre-arc process remains incomplete, with arc model research primarily focusing on steady-state arc models and post-arc processes.

In the late 1970s, K. P. Brand and J. Kopainsky conducted research on particle composition in SF6 arc plasma at standard atmospheric pressure, ignoring multi-level ionization of atoms and considering only primary ionization reactions [4]. Reference [5] extended the pressure range to 10 atmospheres and incorporated secondary ionization reactions of sulfur atoms into the model, thereby improving calculation accuracy. Reference [6] considered the influence of copper vapor when studying SF6 arc plasma and developed a particle composition model for SF6-Cu mixed gas. Reference [7] obtained through simulation the dynamic variation patterns of various microscopic physical quantities such as charged particle density and average electron energy in the contact gap during the non-equilibrium arcing process of DC low-voltage air arcs, and analyzed the influence of the non-equilibrium arcing process and inter-electrode voltage on air arc formation. However, research on the microscopic dynamic process of SF6 arcs during the pre-arc stage remains relatively scarce. Investigating the microscopic dynamic formation process of SF6 circuit breaker arcs and the influence of pre-arc factors is crucial for deepening understanding of arc formation mechanisms, enriching and improving electrical arc theory, and proposing new arc extinguishing methods.

2.1 Simplified Arc Chamber Model Due to the good axial symmetry of the entire discharge process, this paper employs a two-dimensional simplified model of the SF6 circuit breaker arc chamber, whose geometric structure is shown in [Figure 1: see original paper]. The model consists primarily of contacts, contact fingers, and a nozzle. The contact radius is 11.5 mm, the contact finger inner diameter is 11.5 mm, and the outer diameter is 38.5 mm, with a contact gap of 3 mm. Because of the model's good symmetry, a two-dimensional axisymmetric model is used for the simulation analysis.

2.2 Arc Model Assumptions The arc model in this paper is based on the following assumptions:
1) After switch opening, the contact gap remains fixed at 3 mm;
2) SF6 gas and metal vapor are uniformly distributed between the contacts in the SF6 circuit breaker;
3) Multiplication electrons generated during photoionization are neglected;
4) Convective diffusion of electrons and ions is neglected, with only their migration motion under electric field considered;
5) The arc is assumed to be symmetric, and a two-dimensional axisymmetric model is used for calculation.

2.3.1 Gas Dynamics Model For the pre-arc particle motion process, the Boltzmann equation with collision terms is used for description. By simplifying equation (1) through integration in velocity space and substituting the electron mobility calculation formula, solving for the logarithms of electron number density and electron energy density yields the simplified equation system:

$$\frac{\partial n_\varepsilon}{\partial t} + \nabla \cdot \ {}_\varepsilon = R_\varepsilon$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \ {}_e = R_e$$

where ${}_\varepsilon$ and ${}_e$ are incomplete gamma functions; R_e is the electron source; R_ε is electron energy loss; n_e is electron density; n_ε is average electron energy; D_e is electron diffusion coefficient; μ_ε is electron energy mobility; and D_ε is electron energy diffusion coefficient.

Microscopic particles generate motion under the electric field, which is calculated using the Poisson equation:

$$\nabla \cdot (\varepsilon_0 \varepsilon_r \mathbf{E}) = \rho_v \quad \text{or} \quad \mathbf{E} = -\nabla V$$

where ε_0 and ε_r are the gas permittivity in the arc chamber; $\mathbf{E}$ is electric field intensity; and ρ_v is volume charge density.

2.3.3 Inter-Electrode Particle Collision Model Under the action of electric field forces, particles between the contacts move toward the electrodes and collide with neutral particles. Due to the numerous ion species in SF6 gas, this paper primarily considers collision reactions between SF6 gas and electrons, surface reactions of SF6 gas, collision reactions between copper vapor and electrons, and surface reactions of copper vapor. Since ion motion velocities are much slower than electron motion and energy accumulation is low, charge multiplication resulting from ion collisions is not considered in this paper. The collision reactions are listed in the table below. The collision cross-section data for SF6 and copper used in this paper are sourced from the TRINITI database and SIGLO database.

Table: Collision reaction equations between SF6 gas and electrons in space

Reaction
e + SF6 → SF5
e + SF6 → SF6
e + SF6 → SF6
e + SF6 → e + SF6s
e + SF6s → e + SF6
e + SF6 → e + SF6s
e + SF6s → e + SF6
e + SF6 → e + SF6s
e + SF6s → e + SF6
e + SF6 → e + SF6s
e + SF6s → e + SF6
e + SF6 → 2e + SF6

3 Simulation Results Analysis

Using the above model, this paper simulates the pre-arc development process in the SF6 circuit breaker arc chamber under the following conditions: initial temperature 293 K, pressure 15 Torr (1 Torr = 133.3 Pa), contact voltage 500 V, initial electron density 1×10^{13} m ^{3}, Cu ion density 1×10^{13} m ^{3}, electron mobility $4 \times 10^{24}/(\mathrm{V} \cdot \mathrm{m} \cdot \mathrm{s})$, initial average electron energy 4 eV, secondary electron emission coefficient 0.2, and initial average electron energy 5.8 eV. The analysis examines how variations in metal vapor content caused by breaking current changes and differences in secondary emission coefficients caused by contact material variations affect the arc development process.

3.1 Influence of Metal Vapor Content on Arc Formation Process This paper simulates and calculates the pre-arc formation process of SF6 mixed with copper vapor at mole contents of 12%, 8%, 4%, and 0% when the contact gap is 3 mm. [Figure 2: see original paper] through [Figure 4: see original paper] show the ion concentration distributions at different times for various copper vapor contents. It can be observed that at t = 501 ns, the pre-arc sheath has formed with a copper vapor mole fraction of 12%. Since the plasma has developed near the cathode, the cathode electric field is greatly enhanced, enabling electrons to gain substantial energy. The collision probability and effective collision coefficient between particles increase, making various collision reactions in the sheath more intense.

[Figure 5: see original paper] shows the electric field intensity distribution, while [Figure 6: see original paper] shows the mean electron energy distribution. Through comparison, it is evident that for different copper vapor contents, there is a significant increase in ion densities, mean electron energy, and electric field intensity, with arc development proceeding more rapidly.

3.2 Influence of Different Electrode Materials on Arc Formation Process [Figure 7: see original paper] shows the electron density distribution at t = 501 ns for different secondary electron emission coefficients (1, 0.9, and 0.8). The results indicate that the secondary electron emission coefficient significantly affects the SF6 arc formation process. When the coefficient is 1, the arc has already developed near the cathode, with electron numbers outside the sheath region increasing dramatically to 3.9×10^{17} m ^{3}. When the coefficient is 0.9, the plasma arc is about to develop to the cathode, with electron density at the arc column head reaching 5.5×10^{16} m ^{3}. When the coefficient is 0.8, the plasma arc has only developed to the middle position between the two electrodes, with a maximum electron density of only 2×10^{15} m ^{3}.

Comparison reveals that as the secondary electron emission coefficient increases, the arc development channel becomes more concentrated. This occurs because when the coefficient increases, the proportion of newly generated electrons from secondary emission rises. Since secondary electron generation depends on positive ions and positive ions move relatively slowly, secondary emission is strongest at the point with the shortest straight path between cathode and anode, making the arc development channel more concentrated. When the secondary emission coefficient is 0.8, the anode electric field has not yet reversed, and plasma has not formed.

[Figure 8: see original paper] shows the electric field intensity distribution at t = 501 ns for different secondary electron emission coefficients. When the coefficient is 1, the arc has already formed, with electric field intensity near the anode and arc column region being 0, while the electric field near the cathode increases sharply to 1.67×10^{6} V/m. When the coefficient is 0.9, the electric field intensity decreases relatively to 7.3×10^{5} V/m.

From the electron density and electric field intensity distributions at different secondary emission coefficients, it is evident that as the secondary emission coefficient increases, arc development accelerates and the arc development channel becomes more concentrated.

4 Conclusion

To reveal the influence of pre-arc factors on SF6 arc formation in SF6 circuit breakers, this paper established a gas dynamics model considering electron, positive and negative ion drift-diffusion equations, microscopic particle collision equations, and the electric field Poisson equation. Based on actual SF6 circuit breaker structures, the study investigated the effects of different metal vapor contents and electrode materials on SF6 arc formation at a contact gap of 3 mm, yielding the following conclusions:

1. Higher copper vapor content leads to significant increases in electron density in the sheath region, various ion densities, mean electron energy, and electric field intensity. The mixing of copper vapor substantially accelerates arc formation.
2. An increase in the secondary electron emission coefficient of contact materials promotes plasma development toward the cathode, thereby hindering arc extinction, while also affecting arc shape.

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