Simulation of Arc Breaking in a 550 kV 80 kA SF_6 Circuit Breaker

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Abstract As the structure of power grid becomes increasingly complex and the capacity keeps increasing, the short-circuit current endurance of existing switching devices can no longer meet the needs of the development of power grid. The rated short-circuit current of 550 kV circuit breakers needs to be increased from 63 to 80 kA, which puts forward more stringent requirements on the breaking capacity of circuit breakers. In this paper, based on the magnetohydrodynamic model of arc burning in the arc extinguishing chamber of the circuit breaker, a 550 kV SF_6 auto-expansion circuit breaker was simulated for 9 ms under the working condition of 80 kA short-circuit current breaking. The distribution of temperature field, pressure field and electromagnetic field in the arc extinguishing chamber during the breaking process was obtained, together with the characteristic of the hot flow field. Through the comprehensive analysis of temperature field, pressure field and boundary conditions, this paper describes the arc burning process of circuit breaker in the arc extinguishing chamber, and accurately analyzes the physical process of circuit breaker when it breaks off, which provides some reference value for the optimization design of circuit breaker structure.

Keywords Auto-expansion circuit breaker · Magnetohydrodynamics · Arc simulation · Temperature · Pressure

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1 Introduction

With the continuous expansion of power grid scale in our country, the level of short circuit current is increasing year by year. Excessive short circuit current can harm the safe and stable operation of power system and electrical equipment [1]. The current short-circuit current endurance capacity of the existing 500 kV main grid frame can no longer meet the needs of power grid development. It is urgent to develop a large-capacity switching device with large capacity, high reliability, and considering the renovation of old station and new project. Modern electric power transmission and distribution networks rely on SF_6 AC high-voltage circuit breaker technology because of the remarkable arc quenching properties and dielectric insulation of this gas [2, 3], which is of great significance to the reliable operation of power system [4]. The large-capacity 550 kV GIS with 8000 A current flow and 80 kA break capacity is the most advanced technical solution with high economic reliability and wide application scenarios. In view of this, it is of great significance to study 550 kV 80 kA SF_6 circuit breaker.

As the rated short circuit current of the 550 kV SF_6 circuit breaker is increased to 80 kA, a series of problems are brought, such as extremely high energy of the arc extinguishing chamber, extreme pressure gradient, higher medium recovery requirements and more serious nozzle ablation. It is necessary to carry out in-depth theoretical research on the electromagnetic-thermal-fluid-mechanical coupling process and the key mechanism affecting the breaking performance. Through arc simulation, the typical distribution characteristics of airflow field, temperature field, pressure field and electromagnetic field in the short-circuit breaking process can be obtained, and the key parameters affecting the breaking of circuit breakers can be defined.

Based on the established two-dimensional axismetrical model of circuit breaker, the breaking process of the 550 kV auto-expansion circuit breaker at 80 kA short circuit was simulated, and the temperature and pressure distribution of the arc extinguishing chamber in the process of arc burning was obtained. The analysis of the physical quantity and boundary conditions lays a theoretical foundation for the optimal design of circuit breaker [5].

2 Circuit Breaker Simulation Model

2.1 Simulation Structure Model and Boundary Conditions

The 550 kV auto-expansion high-voltage SF_6 circuit breaker calculation structure model is composed of dynamic arc contact, static arc contact, nozzle, expansion chamber, pressure chamber, cooling chamber and valve structure. The nozzle material is PTFE. Since the circuit breaker is a two-dimensional axismetrical model, the flow hole is equivalent by using the principle of constant flow to ensure the accuracy of calculation. The specific parameters of the circuit breaker are as follows:

(1) The effective value of rated short-circuit current is 80,000 A, frequency is 50 Hz, and the standard sinusoidal current is 1 ms at the moment of arc-starting;
(2) In the calculation, the initial radial velocity and axial velocity of the flow field are 0 m/s, the initial temperature is 300 K, and the inflation pressure is 0.6 MPa;
(3) The average motion speed of the mechanism in the process of motion is 6.5 m/s.

In the calculation process, the initial pressure is consistent with the inflation pressure, the end of the dynamic arc contact is set as the flux, namely the second type of boundary, the current density is applied, the end of the static arc contact is set as the potential value, namely the first type of boundary condition, the potential is 0. The static contact is set as a static component, and the dynamic arc contact and nozzle are set as moving components. Transparent contact is introduced to compensate arc axis deviation caused by hollow structure [6]. The fluid–solid coupling method is used to calculate the electric field. The region of dynamic and static arc contacts and the region of flow field are solved jointly.

2.2 Arc MHD Model

The arc is regarded as a conducting compressible fluid and follows the three principles of mass conservation, momentum conservation and energy conservation [7]. It is considered that the arc is in a neutral state and in local thermodynamic equilibrium and local chemical equilibrium [8]. The Navier–Stokes equations with source terms are used to describe the arc, and the governing equations of MHD arc simulation can be formed by coupling the electric field equation and the magnetic field equation.

(1) The standard form of the Navier–Stokes equation

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla \cdot (\rho\phi\overrightarrow{V}) - \nabla \cdot (\Gamma\nabla\phi) = S_\phi$$

(2) Conservation of mass

$$\frac{\partial\rho}{\partial t} + \nabla(\rho \cdot \overrightarrow{V}) = 0$$

(3) Conservation of momentum

Axial momentum is conserved

$$\frac{\partial(\rho w)}{\partial t} + \nabla(\rho\vec{V}w) = -\frac{\partial p}{\partial z} + \nabla \cdot ((\mu_l + \mu_t)\nabla w) + J_r B_\theta + \nabla \cdot \overline{\overline{\tau}}$$

Conservation of radial momentum

$$\frac{\partial(\rho v)}{\partial t} + \nabla(\rho\vec{V}v) = -\frac{\partial p}{\partial r} + \nabla \cdot ((\mu_l + \mu_t)\nabla v) + J_z B_\theta + \nabla \cdot \overline{\overline{\tau}}$$

(4) Conservation of energy

$$\frac{\partial(\rho H)}{\partial t} + \nabla(\rho\vec{V}H) = \nabla\cdot\left(\left(\frac{\lambda_l+\lambda_t}{c_p}\right)\nabla H\right) + \sigma E^2 - q + \nabla\cdot\left(\overline{\overline{\tau}}\cdot\overrightarrow{V}\right)$$

(5) Electromagnetic field equation

$$B_\theta = \frac{\mu_0}{r}\int_0^R J_z r dr$$

$$\nabla\cdot(\sigma\nabla\varphi) = 0$$

where, ρ—density, kg/m^3; ϕ—a physical quantity to be solved; $\overrightarrow{V}$—velocity vector; t—time/s; Γ—diffusion coefficient; S_ϕ—source; w—axial velocity component/m·s^{-1}; p—air pressure/Pa; μ_l—laminar viscosity coefficient/kg·m-1·s^{-1}; μ_t—turbulent viscosity coefficient/kg·m^{-1}·s^{-1}; J_r—radial current density/A·m^{-2}; B_θ—circumferential component of magnetic field/A·m^{-1}; $\nabla\cdot\overline{\overline{\tau}}$—viscous term; v—radial velocity component/m·s^{-1}; J_z—axial current density/A·m^{-2}; H—enthalpy/J·kg-1; λ_l—laminar thermal conductivity W·m^{-1}·K^{-1}; λ_t—turbulent thermal conductivity/W·m^{-1}·K^{-1}; c_p—specific heat at constant pressure/J·kg^{-1}·K^{-1}; σ—electrical conductivity/S·m^{-1}; E—electric field intensity/V·m^{-1}; q—radiation source term/J·m^{-3}; $\nabla\cdot\left(\overline{\overline{\tau}}\cdot\overrightarrow{V}\right)$—viscous dissipation term; μ_0—vacuum permeability/H·m^{-1}; R—arc radius/m; φ—potential/V.

In this paper, the k-ε turbulence model in ANSYS FLUENT is used to describe the momentum and energy exchange between mass points under turbulent flow. The viscosity μ_t and thermal conductivity λ_t in the above equation can be calculated according to the k-ε turbulence model. The NEC method of net emission coefficient can provide relatively accurate results in arc plasmas dominated by axial flow [9], which is based on net emission coefficient. It is applied to consider the thermal radiation of arc [10], as shown in Fig. 1.

The travel curve of the simulation input is shown in Fig. 2.

3 Simulation Results and Analysis

In this paper, according to the breaking current and the burning time, the dynamic changing process of the hot flow field in the process of arc burning is simulated and calculated, and the changing characteristics of the pressure field and temperature field in different positions of the circuit breaker in the process of arc burning are obtained. According to the variation characteristics of the airflow field and the state of the arc

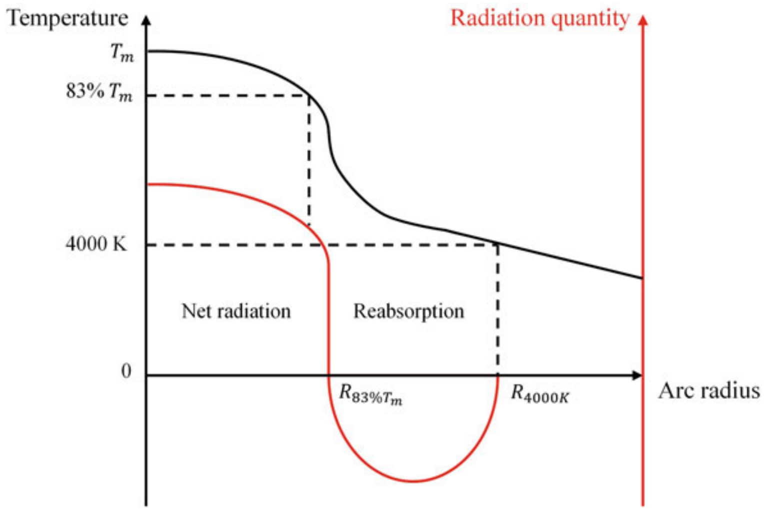

Fig. 1 Arc radiation model based on net radiation coefficient

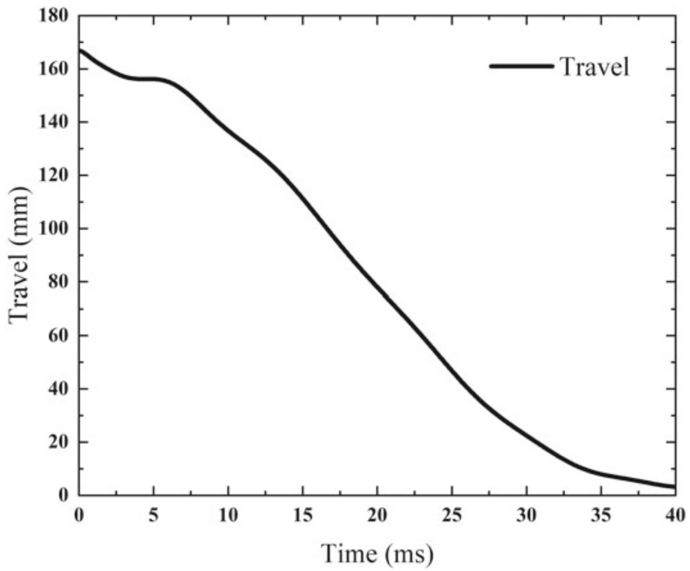

Fig. 2 Simulation input travel curve

extinguishing chamber before the current crossing, the performance of the 550 kV circuit breaker breaking 80 kA short circuit current is evaluated, which provides some reference for the improvement and optimization of the arc extinguishing chamber.

The simulation arc burning time is 9 ms, t is the contact movement time, *i* is the current value. During the whole arc burning period, the maximum temperature of the arc is over 30,000 K and the maximum pressure is 1.87 MPa. Arc burning experienced four processes of enhancement, intensity, attenuation and extinction respectively. The ablation of nozzle and electrode and the influence of non-thermochemical equilibrium state are not considered in the simulation.

3.1 Variation Characteristics of Temperature Field

Figure 3 shows the arc burning process.

At 0 ms, since the initial phase of the current is 1ms, the current is 34.94 kA. The arc radius is small. Most of the air flows along the arc through the contact gap. The arc cooling effect is weak, resulting in higher arc core temperature, exceeding 25,000 K.

At 2 ms, the current continues to increase, leading more intense arc burning. The arc radius is equal to the throat of the nozzle, which plays a certain hindering role on the airflow, making the airflow basically unable to flow to the downstream of the nozzle.

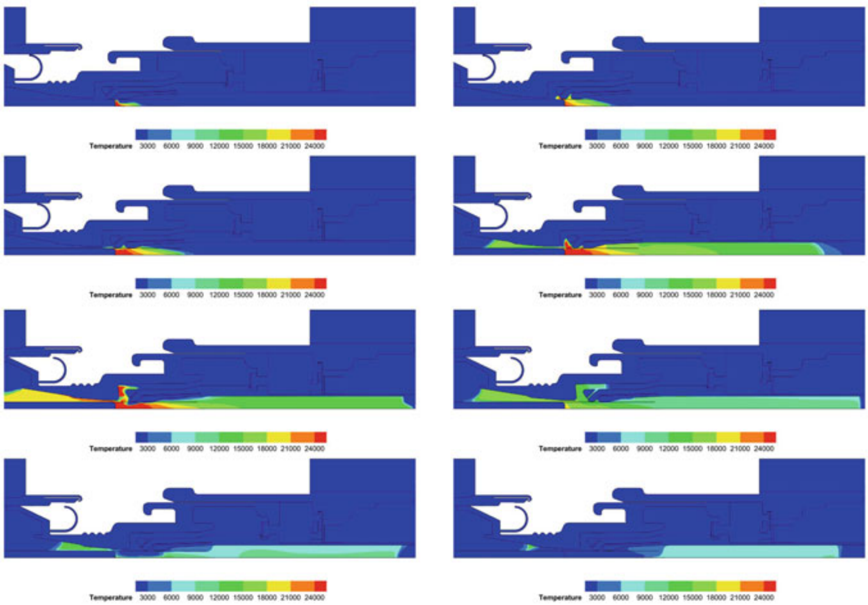

Fig. 3 Dynamic distribution diagram of arc temperature of circuit breaker during arc burning (K)

At 4 ms, the current reaches the peak and the arc core temperature reaches the highest at 30,230 K. The arc burns intensely and its high energy drives the high-temperature gas to spread to the expansion chamber.

At 6 ms, the current decreases to 91.48 kA after passing the peak value. The static contact is in the nozzle expansion position, making a small part of hot gas flow downstream to the nozzle. A part of high temperature gas still rushes to the expansion chamber, but the temperature decreases due to the effect of air blowing.

At 9.0 ms, the current passed through zero for the first time. Weak energy injection and strong cooling effect made the arc unable to maintain the original state and finally extinguished.

3.2 Variation Characteristics of Pressure Field

Figure 4 shows the dynamic distribution of pressure in part of the circuit breaker during arc burning. As can be seen from the figure, the gas pressure in the area where the arc exists is higher.

At 0 ms, the pressure distribution outside the arc is less affected by the arc. The maximum pressure in the arc area is 1.05 MPa, and the upstream pressure of the nozzle is 0.8 MPa.

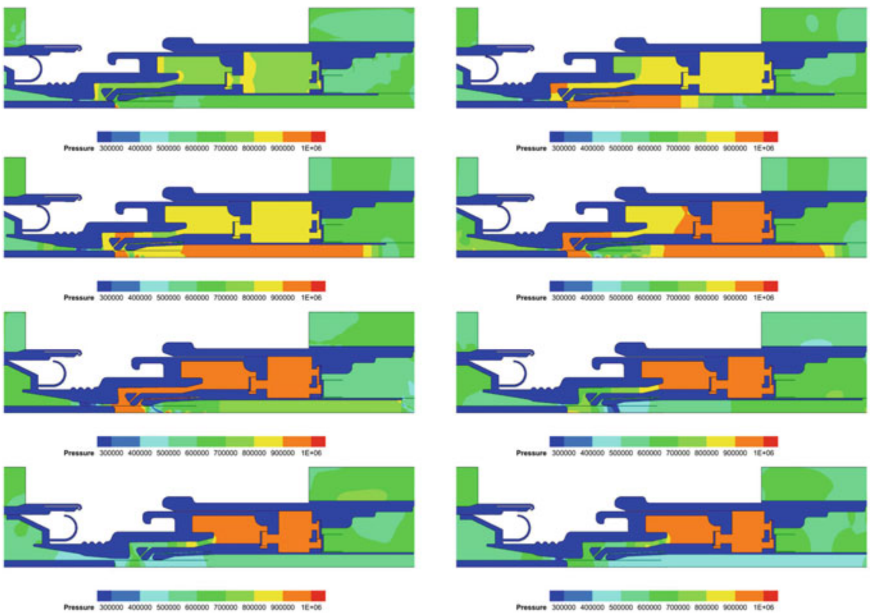

Fig. 4 Dynamic distribution diagram of arc pressure of circuit breaker during arc burning (Pa)

With the gradual compression of the cylinder and the expansion of the arc area, the pressure in the nozzle area gradually increases, among which the pressure at the top of the static arc contact is the largest, increasing from 1.18 MPa to 1.87 MPa.

At 4 ms, the arc burning is the most intense. The dynamic arc contact hollow inner tube is surrounded by a large amount of hot gas, with the minimum pressure at 0.91 MPa.

After 8.8 ms, the arc tends to be extinguished, and the flow field is almost not affected by the arc. The maximum gas pressure appears in the upstream of the cylinder and nozzle. The hot gas of the cylinder makes the pressure much higher than that of the cold state due to the violent arc ignition.

4 Conclusion

Based on the arc burning MHD model, the simulation model of SF_6 circuit breaker arc extinguishing process is established. For the 550 kV auto-expansion circuit breaker whose short circuit current is 80 kA, the arc quenching process of the circuit breaker is simulated. The key flow field parameters such as temperature and pressure are obtained, which can provide certain guidance for the product design. More reference value is offered to the determination of the subsequent optimization scheme.

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References

1. Song Y, Lin S, Zhou T et al (2023) Simulation of airflow field and breaking capacity of 550 kV fast circuit breaker. High Voltage 1–9 (2023). (in Chinese)
2. Hermosillo V, Gregoire C, Vancell D et al (2018) Performance evaluation of CO_2/Fluoronitrile mixture at high short circuit current level in GIS and DEAD-Tank high-voltage circuit breakers. CIGRE Session
3. Jiang X, Jia S, Li X et al (2012) Simulation and analysis of cold flow field characteristics in SF_6 circuit breakers with UDRGM. Chin J Electr Eng 32(7):167–173 (in Chinese)
4. Mu J, Guo J, Li X et al (2012) Review of the numerical ion method for the interruption capability of SF_6 circuit breaker. High Voltage Apparatus 48(3):104–107 (in Chinese)
5. Zhang H et al (2021) Simulation analysis of 550 kV 80 kA SF_6 gas circuit Breaker's interrupting capability in T100a test. In: 2021 3rd Asia energy and electrical engineering symposium, Chengdu, China, pp 235–238
6. Yan J, Fang MTC, Hall W (1999) The development of PC based cad tools for auto-expansion circuit breaker design. IEEE Trans Power Delivery 14(1):176–181
7. Jiang X, Zhao H, Jia S et al (2013) Analysis of the dielectric breakdown characteristics for a 252-kV gas circuit breaker. IEEE Trans Power Deliv 28(3):1592–1599
8. Zhang B, Zhou R, Hao M et al (2022) Research on the application of C_4F_7N gas mixture in a 40.5 kV circuit breaker: part I. Simulation and evaluation of arc extinguishing performance. Chin J Electr Eng 1–12 (2022). (in Chinese)

9. Wang Z, Zhou R, Li Q et al (2022) Study on the dielectric recovery performance of high voltage SF_6 circuit breaker. In: IEEE international conference on high voltage engineering and applications, pp 1–4
10. Zhang J, Fang MTC, Newland DB (1987) Theoretical investigation of a 2 kA DC nitrogen arc in a supersonic nozzle. J Phys D Appl Phys 20(3):368