Research on Gap Breakdown Process of Circuit Breaker Under Double Lightning Overvoltage

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Abstract. Aiming at the gap breakdown and opening failure of 110 kV circuit breaker under double lightning overvoltage, the dielectric discharge model of 110 kV circuit breaker is established, the influence of overvoltage characteristics on arc reburning is studied, and the arc development transient process and arc temperature distribution characteristics are obtained. The results show that the reburning process of fracture gap is obviously affected by the contact structure and the time interval of lightning overvoltage. The contact ablation seriously affects the distribution of arc temperature field, resulting in a significant increase in arc temperature, which is easy to cause the arc reburning of circuit breaker, With the increase of lightning overvoltage time interval, the longer the arc cooling time generated by the first lightning current is, which is more conducive to the extinction of arc. The research provides a basis for high-voltage insulation coordination and circuit breaker optimization design of power system.

Keywords: Circuit breaker · Lightning overvoltage · Gap breakdown

1 Introduction

Under the background of the development of transmission lines to EHV and UHV, the safe and stable operation of transmission lines becomes very important. Due to the rainy season in southern China, lightning accidents occur frequently. High voltage transmission lines often face the risk of lightning impulse, and lightning accidents have the characteristics of high frequency and great harm [1–3], which seriously affects the safe and stable operation of power lines.

Arc is a combustion process accompanied by dissociation, de-dissociation, diffusion and recombination [4–6]. Arc combustion is a complex physical and chemical process. Therefore, study of arc theory and establishment of arc model are very important to study the arc development process [7, 8]. Cassie model and Mayr model [9, 10] in 1939 and 1943 first appeared. Based on the energy conservation equation, the mathematical form is simple, which provides a theoretical basis for early people to study arc theory.

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At present, power accidents caused by superimposed lightning strike occur from time to time. The main reason is that after the superimposed lightning strike hits the line, if another lightning flashover occurs when the circuit breaker cuts off the short-circuit current, it will cause arc re ignition [11, 12]. At present, there are two theories based on arc reburning: 1) arc insulation strength recovery theory, 2) Arc energy balance theory, J. Slepian put forward the theory of arc insulation strength recovery, and considered that the rise speed of gap voltage is greater than the recovery speed of dielectric strength is the main reason for arc reburning [13], but this theory ignores the certain relationship between voltage recovery and dielectric strength recovery. A. M. Cassie put forward the arc energy balance theory and believed that the arc reburning was caused by the increase of arc temperature and reburning because the input energy of the arc was greater than the output energy [14–16]. The arc energy balance theory comprehensively explains the extinction or re ignition of the arc after zero break from the perspective of energy balance.

The dielectric recovery characteristics of high voltage SF6 circuit breaker are related to whether the circuit breaker can successfully break the arc. Lin Xin team of Shenyang University of technology applied CFD fluid simulation software to calculate the electric field distribution in the arc extinguishing chamber, and obtained the gas dielectric recovery characteristics and compressor cylinder characteristics of SF6 circuit breaker [17–19]. Cao Yundong et al. Used the new method to obtain the distribution of air flow field in the arc extinguishing chamber of SF6 circuit breaker, and calculated the recovery characteristics of SF6 gas medium under different conditions [20]. Wang Erzhi et al. studied and analyzed the recovery characteristics of gas medium in the presence of shock wave [21].

The above research conclusions lay a theoretical foundation for the insulation theory and optimization method of high voltage electrical equipment. Under the condition of double overvoltage, the gap dielectric breakdown and reburning process of circuit breaker are affected by overvoltage characteristics, circuit breaker fracture motion characteristics and gap temperature characteristics, and the physical process is complex. The above research has certain limitations in this process. The gap discharge process and thermal characteristics under the condition of double overvoltage need to be deeply studied.

2 Mathematical Model of Switching Arc

2.1 Calculation Model of Airflow Field

The mathematical model of the air flow field of the circuit breaker can be described by navistok equation [21], as follows:

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

where, ρ is density, ϕ is the dependent variable, v is speed, Γ is diffusion coefficient, S_{ϕ} is the source term.

2.2 Calculation Model of Electric Field

Laplace equation [18] is satisfied in the solving region D of the arc extinguishing chamber, and its mathematical is defined as:

$$\begin{cases} D : \nabla^2 \varphi = 0 \\ S_1 : \varphi = \varphi_0 \\ S_2 : \partial \varphi / \partial n = 0 \end{cases} \tag{2}$$

where, D is the solution region, S_1 is the boundary condition of class A, S_2 is the boundary condition of class B, φ is potential, the relationship between electric field strength and potential as follows:

$$E = \sqrt{\left(\frac{\partial \varphi}{\partial r}\right)^2 + \left(\frac{\partial \varphi}{\partial z}\right)^2} \tag{3}$$

3 Arc Characteristics Under Lightning Impulse

By simulating the switching arc of circuit breaker under lightning strike, the arc temperature distribution and thermal process of circuit breaker under lightning strike are studied. In this paper, the lightning current function is shown in Eq. (4). The lightning current value i_0 is 16 kA, and the power frequency current function is shown in Eq. (6). The interval between two lightning currents is 2 ms.

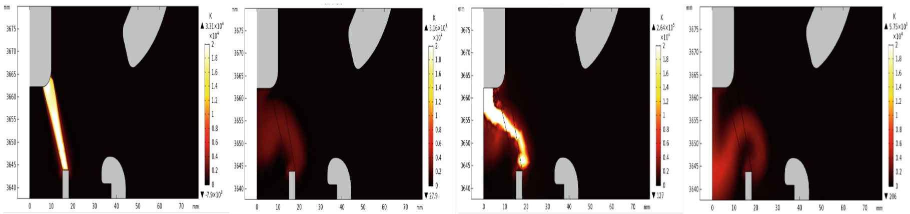
$$i(t) = AI_{\mathrm{m}}\left(1 - e^{-\frac{t}{\tau_1}}\right)e^{-\frac{t}{\tau_2}} \tag{4}$$

$$i_1(t) = 1.02 i_0 \left(\mathrm{e}^{-1.473 \times 10^4 t} - \mathrm{e}^{-5.08 \times 10^6 t}\right) \tag{5}$$

$$i_2(t) = 1 \times \sin(100\pi t + 0.8\pi) \tag{6}$$

3.1 Temperature Distribution Characteristics Under Double Lightning Impulse Current

Figure 1 shows the arc distribution and temperature during the whole arc burning and arc extinguishing process. The arc distribution and temperature changes at 4 time points of 0.01 ms, 2 ms, 2.001 ms and 3 ms are intercepted respectively. It is observed that at the beginning, the arc burns between the two arc contacts and the temperature increases rapidly. Within the first 2 ms, the temperature of the arc increases first and then decreases. At the zero crossing of power frequency current, it will be found that the arc temperature decreases to about 3000 K and the arc tends to extinguish gradually. And the arc shape also gradually bends from the original linear shape to extinction. At 2.001 ms, the arc reignites again. This is because after 2 ms, due to the occurrence of double lightning, resulting in the newly extinguished arc to resume combustion. With the gradual decrease of pulse lightning current, the arc temperature drops again and tends to extinguish at 3 ms.

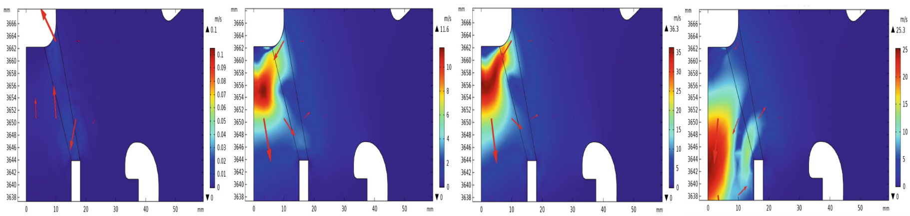


a)0.01ms b)2ms c)2.001ms d)3ms

Fig. 1. Arc temperature distribution diagram between contacts at different times

3.2 Distribution Characteristics of Airflow Field Under Double Lightning Impulse Current

Figure 2 is the variation diagram of air flow velocity in the arc during the whole arc burning and arc extinguishing process under 0.5 MPa. The arc air flow variation diagrams at 4 time points of 0.01 ms, 1 ms, 2.1 ms and 3 ms are intercepted respectively. It is observed that the air flow velocity in the arc is small at the beginning. With the increase of current, the arc current increases at 0.01 ms, The air velocity in the arc also increases. After 2 ms, due to the superposition of new lightning current, the air flow field velocity increases again, and then at 3 ms, the air flow field velocity decreases with the decrease of arc current. The arc shape gradually develops from the original cylindrical arc to the curved arc along the place where the velocity of the gas flow field increases.



a)0.01ms b)1ms c)2.1ms d)3ms

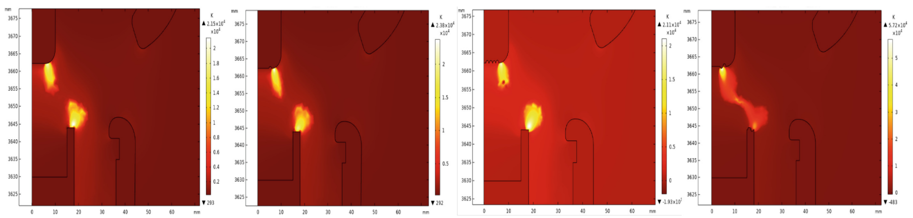
Fig. 2. Air velocity distribution diagram at different times

4 Improvement Scheme of SF6 Circuit Breaker Considering Double Lightning Overvoltage

4.1 Influence of Contact Shape on Arc Discharge Suppression

During the breaking process of circuit breaker contact, due to the generation of arc, the high-temperature ablation of arc will make the contact surface missing or uneven. Because the change of contact shape caused by arc ablation will change the temperature distribution and air flow field of arc between contacts, this section studies the arc temperature change and air flow field under different contact ablation, and compares them with those without ablation. There are three kinds of ablation conditions. One is the loss of a depression with a radius of about 0.5 mm on the static arc contact of the circuit breaker, The second ablation condition is the loss of multiple depressions with a radius of 0.5 mm on the static arc contact of the circuit breaker, the third ablation condition is the loss of multiple depressions with a radius of 0.5 mm on the dynamic and static arc contact of the circuit breaker.

Figure 3 shows the distribution of the influence of contact ablation on arc temperature. It can be seen that the maximum arc temperature of the non ablated contact is 2.15 * 10^4 K, the maximum arc temperature in ablation case 1 is 2.38 * 10^4 K, the maximum arc temperature in ablation case 2 is 2.11 * 10^4 k, the maximum arc temperature in ablation case 3 is 5.72 * 10^4 K. It can be seen that ablation has the greatest influence on the temperature distribution and arc temperature.



a） Non ablated condition b） Ablation condition 1 c） Ablation condition 2 d） Ablation condition 3

Fig. 3. Arc temperature distribution of different contact conditions

4.2 Influence of Lightning Current Interval on Arc Development

In this section, the arc distribution characteristics of circuit breaker contacts under different lightning current intervals are simulated and studied. The lightning current time intervals are 400 μs, 500 μs and 600 μs respectively. The temperature distribution and size distribution of circuit breaker arc are shown in the three pictures on the left in Fig. 4, and the temperature distribution at the time before the second lightning current in the three different lightning current intervals are intercepted respectively. It can be found that the maximum arc temperature at 399 μs is 8.83 * 103 K. The maximum arc temperature at 499 μs is 7.53 * 103 K. The maximum arc temperature at 599 μs is 6.67 * 103 K. It is found that with the increase of the time interval between the two lightning currents, the final temperature of the arc decreases continuously. The shorter the time interval of lightning current, the gas insulation will be broken down when it has not been restored, which is not conducive to the extinguishment of circuit breaker arc. The three figures on the right show the arc conductivity distribution at the moment before the arrival of the second lightning current under three lightning current intervals, which is corresponding to the three figures on the left. It can be seen that the maximum arc conductivity corresponding to the three times is 2.25 * 10^3 S/m, 1.5 * 10^3 S/m and 1.42 * 10^3 S/m. That is, the arc becomes longer due to the lightning current time interval, the cooling arc extinguishing time becomes longer, the conductivity of the gas also gradually decreases, and the gas gradually returns to the insulation state.

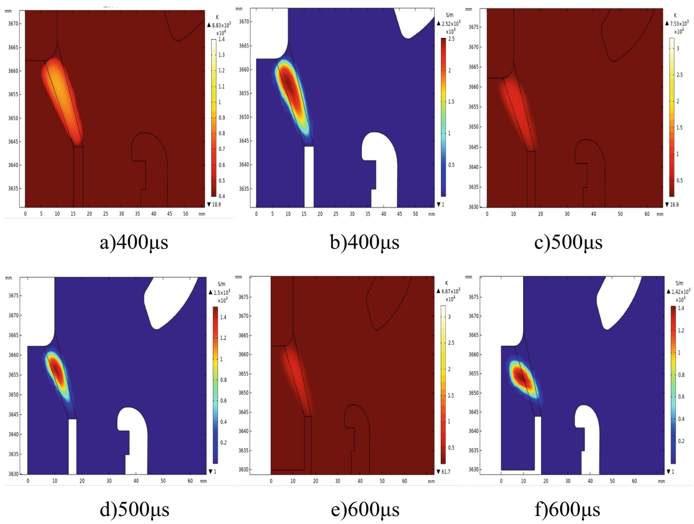


Fig. 4. Distribution diagram of arc temperature and conductivity at different times

5 Conclusions

In this paper, the dielectric discharge model of circuit breaker under double lightning overvoltage is established, the change process of circuit breaker temperature field and air flow field under double lightning overvoltage is calculated, and the effects of contact ablation and different lightning current interval on arc development are studied. The following conclusions are drawn:

1) Double lightning overvoltage will cause the arc to re ignite after zero crossing extinction, affecting the successful breaking of the circuit breaker. The arc temperature increases rapidly under the first lightning impulse. With the decrease of the first heavy lightning current, the arc temperature decreases to about 3000 K at 2 ms, At 2.001 ms, due to the occurrence of the second lightning stroke, the arc reignites again and the temperature rises rapidly. With the decrease of the second lightning current, the arc temperature decreases again and tends to extinguish at 3 ms.
2) Contact ablation seriously affects the distribution of arc temperature field. By observing the distribution of arc temperature field under different ablation conditions, the maximum arc temperature of non ablated contact is $2.15 * 10^4$ K, the most serious contact ablation (i.e. ablation condition 3) and the maximum arc temperature is $5.72 * 10^4$ K, it can be seen that the contact ablation causes a significant increase in arc temperature, which is easy to cause the reignition of circuit breaker arc.
3) By observing the arc temperature distribution before the second lightning stroke under different lightning current intervals, when the lightning current interval is 400 µs, the arc temperature before the second lightning current is $8.83 * 10^3$ K, when the interval is 500 µs, the arc temperature before the arrival of the second lightning current is $7.53 * 10^3$ K, with an interval of 600 µs, the arc temperature before the arrival of the second lightning current is $6.67 * 10^3$ K, it can be seen

that with the increase of the time interval between lightning currents, the longer the cooling time of the arc generated by the first lightning current is, which is more conducive to the extinction of the arc, so as to restore the insulation performance of the gas and avoid the reignition of the arc of the circuit breaker.

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