Research on Post-arc Recovery Characteristics of Sheath in Long-Gap Vacuum Circuit Breaker

Ying Feng, Dege Li, Jintao Zhang, Ziang Tong, and Jianwen Wu

Abstract Due to the proposal of China's the goals of carbon peaking and carbon neutrality, vacuum circuit breakers have become the best choice for SF6 replacement due to their advantages of zero carbon emissions and strong breaking capacity. However, there are only 126 kV and below single-break vacuum interrupters for high-voltage transmission levels, and 252 kV vacuum interrupters have not yet been put into use for commercial products. The 252 kV level vacuum switch has the characteristics of high withstand voltage level and long contact gap distance, and its breaking capacity is closely related to the recovery process of the back-arc medium. In this paper, the Continuous Transition Model (CTM) model of the back-arc sheath is adopted, and the transient recovery voltage of the 220 kV transmission line model is input as a parameter. Parameters, the curves of the length of the sheath, the surface electric field intensity of the new cathode, and the power density with time are obtained, and the time spent in the recovery phase of the back-arc sheath, the maximum value of the surface electric field intensity, and the maximum power density are obtained, which is high voltage level, long gap vacuum circuit breaker design provides theoretical support.

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1 Introduction

With the proposal of China's the goals of carbon peaking and carbon neutrality, vacuum circuit breakers have become a promising technology choice due to their outstanding advantages of strong breaking capacity and zero carbon emissions [1]. At present, SF_6 gas is still widely used as the arc extinguishing medium of circuit breakers with high voltage level for power transmission, which has a strong greenhouse effect. The rated voltage levels of commercial single-break vacuum interrupters are only 72 kV and 126/145 kV [2], and no mature commercial products have yet been put into use at the 252 kV level. Therefore, it is urgent to carry out research on key technologies of vacuum circuit breakers.

The advantage of using vacuum start technology is that the medium can be recovered quickly during the post-arc process [3]. The research on the post-arc process is of great significance for improving the breaking capacity of vacuum circuit breakers and adapting to the multiple rapid reclosing requirements of transmission and distribution networks. The sheath development stage is the first stage of the dielectric recovery process after the vacuum circuit breaker. The Child-Langmuir law gives a lower bound on the time of this process. Andrews and Varey further proposed the Continuous Transition Model (CTM) of post-arc growth of sheath, which can more accurately solve the relationship between post-arc sheath length and time [4]. Based on this, Orama and Glinkowski further proposed a method for solving the ion density and gave three breakdown criteria based on the calculations [5]. Bing L coupled the mathematical model of the key parameters of the residual plasma and metal vapor after the arc with the CTM equation set for a frequency 126 kV three-break tandem vacuum circuit breaker, so that the initial conditions for the solution of the post-arc sheath are expanded from constants to functions about time [6]. Liu studied the post-arc dielectric recovery process for multi-break DC vacuum circuit breakers, accounting for the effect of metal vapor density, and proposed that there are two types of particles, fast and slow, in the sheath growth process, and improved the CTM model [7]. Ding, Yuan and He conducted a study on the medium frequency circuit arc opening process of mechanical vacuum DC circuit breakers, accounting for the influence of the arc burning process to improve the CTM model [8]. They found that in the frequency range of 50–50,000 Hz, the sheath growth rate shows a nonlinear relationship with the increase in frequency, while the slow particle dominance in the mid-frequency band leads to slow sheath growth, which is not conducive to arc breaking. There is also the Particle-in-cell (PIC) method for the study of post-arc particle motion. This method uses a numerical algorithm to calculate the microscopic motion of post-arc particles, which does not require assumption of parameters, but is too computationally intensive due to the extremely large number of particles. Sarrailh

[9] and Jadidian [10] have made improvements to the PIC model, trying to reduce the computational effort, but the solution is still difficult.

This paper investigates the effect of sheath growth on the post-arc process of long gap contacts at high voltage levels for the post-arc dielectric recovery process of 252 kV vacuum circuit breakers.

2 Continuous Transition Model of Post-arc Sheath

2.1 Bohm Sheath Model

The continuous transition model is used to describe the variation of the length of ion sheath with time in the post-arc process. This method is based on the assumption that the distribution of post-arc plasma satisfies the Bohm sheath model, that is, the sheath region can be divided into sheath, pre-sheath and plasma regions sequentially from the new cathode to the new anode.

Some assumptions of the Bohm sheath model are as follows.

1. The electron distribution follows a Boltzmann distribution. Electron temperature is T_{e}, in the plasma region.
2. The thermal motion of the ions is neglected, i.e., the temperature of the ions in the sheath is assumed to be zero in the sheath region. Thus, the ions in it are subjected to electric field forces only and make directional motion.
3. At the boundary between the sheath and the pre-sheath, the electron density is equal to the ion density.
4. The hypothesis of a pre-sheath region is introduced, and this region allows the directional acceleration of ions in the plasma region to Bohm velocity with a region thickness in the order of the Debye length. The Bohm speed is shown in the following equation:

$$v_{Bohm} = \left(\frac{kT_i}{m}\right)^{\frac{1}{2}} \tag{1}$$

2.2 Continuous Transition Model

The CTM model is shown in Eqs. (2–4) as follows:

The sheath length varies with time as follows:

$$l^2 = \frac{4\varepsilon_0 U_0}{9eZN_{\mathrm{i}}}\left(\left(1 + \frac{u(t)}{U_0}\right)^{3/2} + \frac{3u(t)}{U_0} - 1\right) \tag{2}$$

The surface potential of the sheath is as follows:

$$U_0 = \frac{M_i}{2e}\left(v_i - \frac{dl}{dt}\right)^2 \tag{3}$$

The post-arc current is as follows:

$$i(t) = \frac{\pi D^2 Z N_i e}{4}\left(v_i - \frac{dl}{dt}\right) \tag{4}$$

The variables and constants are as follows:

t is time, and time 0 is defined as the instant when the sheath begins to grow. l is the axial length of the sheath as a function of time. ε_0 is the vacuum dielectric constant, which takes the value of 8.85×10^{-12} F/m. U_0 is the surface potential of the sheath. e is the electronic charge, which takes the value of 1.602×10^{-19} C. Z is the average charge of the ion, which takes the value of 1.3–1.85 when the contact material is Cu. N_i is the ionic density in the plasma region. $u(t)$ is the voltage at both ends of the gap, which takes the value of the transient recovery voltage (TRV) when applied to the circuit breaker. M_i is the ion mass, which takes the value of 1.06×10^{-25} kg for copper ion. v_i is the ion movement speed, which take the value of 1×10^3–2×10^4 m/s for the copper ion in the vacuum interrupter. D is the effective diameter of the plasma. This parameter is the radial diameter of the plasma before the arc current crosses zero. In this paper, the cathode contact diameter is taken.

For long vacuum gap high current arc opening, if the arc is in the diffusion state, the initial plasma density is proportional to the rate of change of current at the current zero point.

The initial ion plasma density is as follows:

$$N_{i0} = \frac{4I_1}{v_i \pi D^2 Z e} \tag{5}$$

The ion density is as follows:

$$N_i = N_{i0} e^{-\frac{t-t_1}{\tau}}\left(1 + \delta_{AMP}\frac{l^2}{l_{gap}^2}\right) \tag{6}$$

The variables and constants are as follows:

t_1 is the moment when the sheath starts to grow. I_1 is the post-arc current at the moment the sheath starts to grow, i.e., the post-arc current at the initial moment of TRV. τ is the time constant of plasma diffusion decay, generally taken as 0.5–10 μs. δ_{AMP} is the space charge distribution coefficient of ions in the gap, generally taken as 0–10. l_{gap} is the length of gap.

2.3 Breakdown Criteria in Vacuum Switches

The CTM model describes the dynamics of the post-arc plasma. However, it is still needed to indicate whether the interrupter will extinguish the current successfully or not. Therefore, three breakdown criteria have been proposed as follows.

$$E_c = 2\sqrt{\frac{eZN_i}{\varepsilon_0}\left(\sqrt{u(t)U_0 + U_0^2} - U_0\right)} \tag{7}$$

$$P_d = N_i v_i\left[\frac{M_i v_i^2}{2} + u(t)eZ\right] \tag{8}$$

$$\left.\frac{\mathrm{d}l}{\mathrm{d}t}\right|_{l=0} < 0 \tag{9}$$

The three equations describe electrical breakdown, thermal breakdown, and breakdown caused by the reversal of the sheath, respectively. The occurrence of electrical breakdown is related to the sheath. The reason is that the post-arc sheath layer is not sufficient to withstand the recovery voltage and thus breakdown occurs. The occurrence of thermal breakdown is related to the electric field strength of the new cathode surface and the current power after the arc. When the surface electric field strength is too high or the current power is too high, the electrode evaporates a large amount of metal vapor. It cannot withstand the gap voltage and thus breakdown occurs. The third cause of breakdown is the return of the sheath length to zero. In this case, the plasma fills the gap again to the point that the conductive path is reconstructed and thus a breakdown occurs. If the direction of the sheath length increase is temporarily flipped while the length is not reduced to zero, the third breakdown theoretically does not occur.

3 Numerical Simulation of the Post-arc Sheath of 252 kV Vacuum Interrupter

3.1 Selection of Key Parameters of 252 kV Vacuum Interrupter

In this paper, the CTM model is used to study the development process of the post-arc sheath layer of the 252 kV vacuum interrupter. To simplify the model, a cylindrical flat contact of pure copper is selected as the material. The key parameters are selected as shown in Table 1.

Table 1 The parameters of 252 kV vacuum arc interrupter

Parameter	Symbol/unit	Value
The average charge of the ion	Z	1.85
Ion mass	M_i/kg	1.06×10^{-25}
Ion movement speed	v_i/(m/s)	5000
Diffusion decay time constant of plasma	τ/s	5
Space charge distribution factor of ion	δ_{AMP}	5
The length of gap	l_{gap}/mm	100

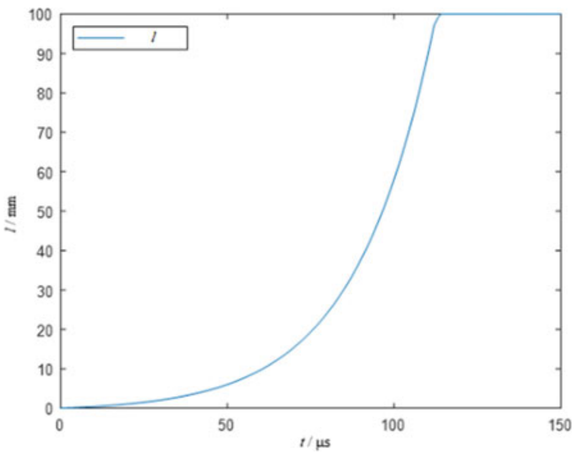
3.2 Sheath Growth Process Based on the CTM Model

In this paper, the CTM model is used to solve the development process of the post-arc sheath of the 252 kV vacuum interrupter.

The CTM model is a first-order higher-order implicit differential equation for the length l of the sheath of the variable to be solved. Therefore, it can be solved by using the ode45 function in MATLAB. The post-arc process and the growth of sheath of the obtained 252 kV vacuum interrupter are shown in Figs. 1, 2, and 3, which are the curves of sheath length, electric field strength of surface and power density with time, respectively.

Analysis of the above Fig. 1 shows that the post-arc sheath of the 252 kV vacuum interrupter initially grows very slowly. With the increase of recovery voltage and the decay of plasma density, the growth rate is gradually accelerated. Finally, the sheath grows to the new anode around 117 μs. The growth time of the sheath is significantly longer than that of the low voltage, small spacing vacuum circuit breaker. The post-arc sheath recovery time is closely related to the plasma density and the ion velocity in the sheath. The spatial distribution of the plasma in the long gap will hinder

Fig. 1 Relationship between the length of sheath and time



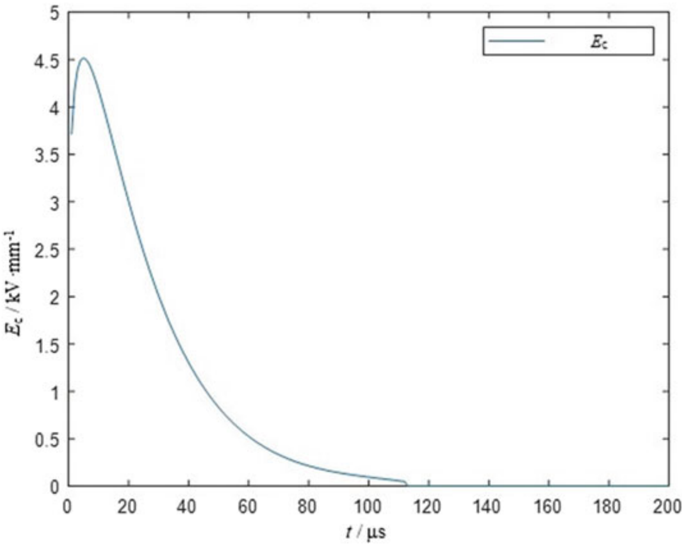


Fig. 2 Relationship between the electric field strength of the new cathode surface with time

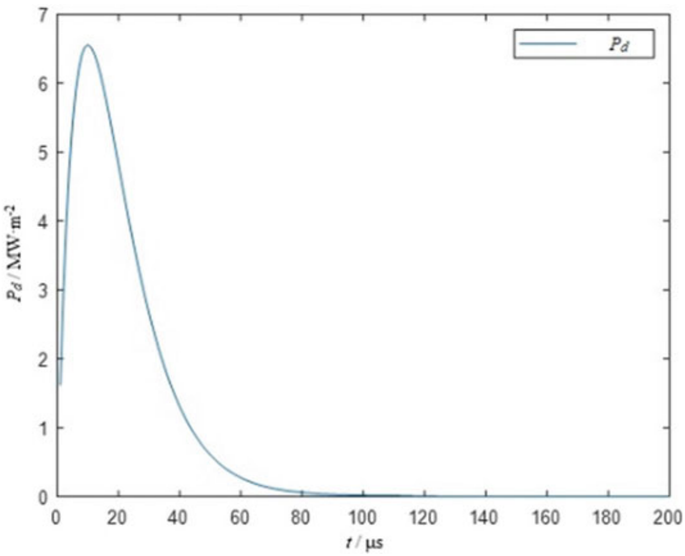


Fig. 3 Relationship between the power density of the new cathode surface with time

the growth of the post-arc sheath, which is harmful for the current breaking of the interrupter. Therefore, the effects of the characteristics of the post-arc plasma and the ions in the sheath should be further studied.

Analysis of Figs. 2 and 3 shows that the surface electric field strength and power density both increase first and then decrease. The maximum surface electric field strength is about 4.5 kV/mm. The maximum power density is about 6.5 MW/m^2. Both peaks appear around the time constant of the plasma diffusion decay time constant (5 μs). This is basically the same trend as the previous research results at lower voltage levels and smaller opening distances. The maximum value of the surface electric field intensity and power density of the vacuum interrupter is affected by many factors such as the contact material and the structure of the interrupter. Moreover, the time constant of plasma diffusion decay also affects the judgment of restrike. Therefore, when designing a vacuum interrupter and selecting contacts, specific analysis should be combined with the actual situation.

4 Conclusion

In this paper, the 252 kV vacuum circuit breaker is taken as the research object, and the post-arc dielectric recovery characteristics of the long-gap vacuum circuit breaker are analyzed by using the post-arc CTM model. The development process of the sheath after the vacuum arc, as well as the evolution law of the electric field intensity and power density on the cathode surface were obtained. The recovery period of the post-arc sheath was found to be about 117 μs. The maximum surface electric field intensity was about 4.5 kV/mm. The maximum power density is about 6.5 MW/m^2. The above research provides theoretical support for the design of high-voltage, long-gap vacuum circuit breakers.

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