Study on the Calculation of 35 kV Parallel Gap Arcing Time Considering the Influence of Wind Load

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Abstract

Wind load is the important factor influencing arc-extinguishing of arc. Establishing arc chain motion model of 35 kV parallel gap under wind load condition, the electromagnetic force, air resistance and wind force of a single arc element are analyzed by using the chain arc model. The arc motion parameters were solved. The arc anti-resistance and arc resistance are calculated; the criterion of arc extinguishing is defined; the arc burning time is calculated, and the arc burning time is obtained. Through the calculation of arc ignition time, it can be seen that the magnitude of wind load affects the arc free time. When the wind load increases, the arc ignition time will be shortened.

Subject Areas

Mechanical Engineering

Keywords

Wind Load, Arc, The Chain Arc Model, 35 kV Parallel Gap, Wind Force

1. Introduction

Modern lightning protection measures are divided into "blocking" and "de-blocking" [1] [2] [3] [4] [5]. The core idea of the "blocking" type of lightning protection is to improve the lightning resistance of the line as much as possible to reduce the lightning trip rate. This approach is suitable in the case of few power points and a weak grid, but the "blocking" type of lightning flashover means that it requires huge investments and is technically difficult to implement [6]. The core idea of the "de-escalation" type of lightning protection is to allow a small increase in the lightning trip rate of the line and to divert the lightning flow to

protect insulators from damage and avoid lightning strikes [7]-[15].

The most typical "channeling" method is to install parallel gaps next to insulators. Japan, Germany, France and other countries have been studying the use of parallel discharge gaps on overhead transmission lines since the 1960s, and have accumulated a wealth of technical data and operational experience, and now almost all insulator strings are equipped with discharge gaps of different shapes [16] [17] [18].

In this paper, we propose a method to calculate the arc ignition time of 35 kV parallel gaps under the influence of wind load, draw the corresponding conclusions by calculating the arc ignition time and compare the difference of arc ignition time considering the influence of wind load. Therefore, the research in this paper can effectively reduce the accident rate of lightning strikes and ensure the reliable operation of power lines.

2. Working Principle of 35 kV Parallel Gap Device

The structure schematic of 35 kV parallel gap device is shown in Figure 1. The parallel gap device is mainly a pair of metal electrodes connected in parallel at both ends of the insulator string to form a protection gap. Under the action of electrodynamic force and wind load, the arc will move toward the electrode end and burn at the electrode end of the parallel gap, so that the arc length will be elongated and the arc energy will be decayed, then the arc will be extinguished, effectively protecting the insulator from arc burns.

3. Parallel Gap Arc Burning Time Calculation Method

3.1. Arc Element Modeling

An arc chain model is established as shown in Figure 2.

For any current element, the force analysis is shown in the following Figure 3.

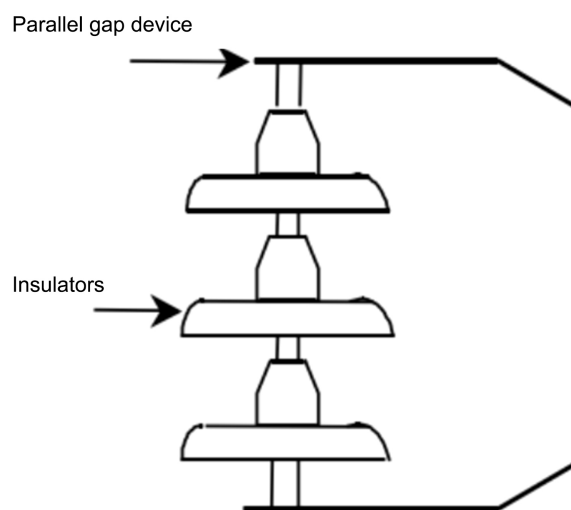$$F_{fi} + F_{di} + F_{zi} = 0 \tag{1}$$

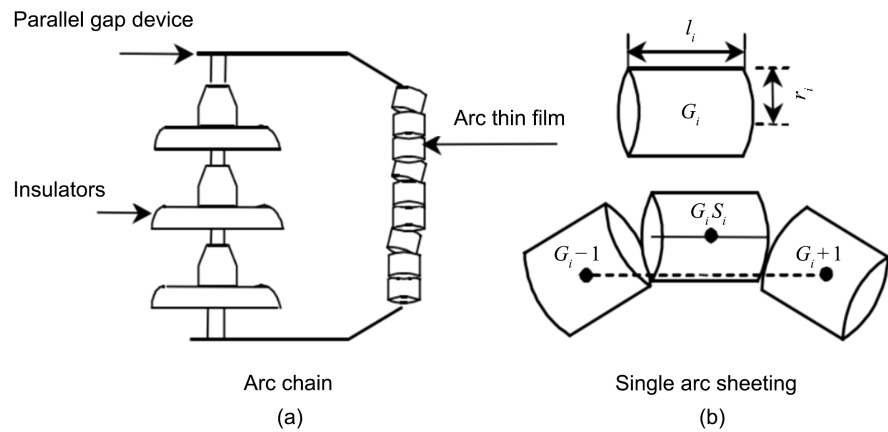**Figure 1.** A schematic diagram of 35 kV parallel gap device.
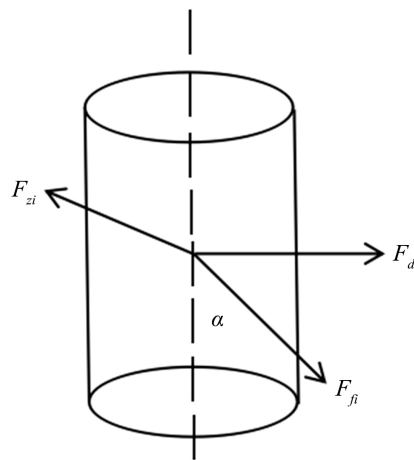
Figure 2. Chain arc model.

Figure 3. Force analysis of arbitrary arc element.

where, F_{fi}, F_{di}, F_{zi} are the wind force, magnetic field force and air resistance respectively for the ith arc element.

The magnetic field force equation:

$$F_{di} = B_i I_i l_i \tag{2}$$

Wind force equation:

$$F_{fi} = \frac{\rho v_f^2 C_s S_i}{2} \tag{3}$$

$$F_{zi} = C_R \rho v_i^2 r_i l_i \tag{4}$$

where, B_i is the magnetic induction intensity of the ith arc element; l_i is the arc length of the ith arc element; v_f is the wind speed; v_i is the velocity of the ith arc element; S_i is the area of the side cross section of the ith arc element; C_s is the shape factor; C_R is a constant; r_i is the radius of the ith arc element.

The joint system of Equations (1)-(4) yields:

$$v_i = \sqrt{\frac{F_{di} + F_{fi}}{C_R \rho r_i l_i}} \tag{5}$$

3.2. Arc Resistivity

The arc resistivity expression is:

$$\rho = \frac{m_e \nu_{ei}}{n_e e^2} = \frac{\sqrt{m_e} e^2 \ln \Lambda}{32\sqrt{\pi} \varepsilon_0^2 T_e^{3/2}} \tag{6}$$

m_e : electron mass, taken as 9.1×10^{-31} kg.

e : electron charged amount is 1.76×10^{-19} C.

ε_0 : vacuum medium constant 8.85×10^{-12} F/m.

T_e : electron temperature.

$$T_e = n_e V = \frac{I}{S} V \tag{7}$$

where, n_e is the electron density, V is the volume of the arc column, and S is the cross-sectional area of the arc column.

$$\ln \Lambda \approx \ln\left(\frac{T^{3/2}}{e^2 n^{1/2}}\right) \tag{8}$$

InΛ: Coulomb logarithm, where n is the number density of particles in the arc and T is the arc temperature. In general, InΛ take the value range of 10 - 20.

3.3. The Solution of Arc Resistance

The moving state of the current element at a certain instant under the wind load is shown in **Figure 4** below.

Then the arc resistance is:

$$R = R_1 + R_2 + R_3 + R_4 + R_5 \tag{9}$$

As shown above, let the arc resistance R_1, R_2, R_3, R_4, R_5 corresponding to the arc length of l_1, l_2, l_3, l_4, l_5, respectively.

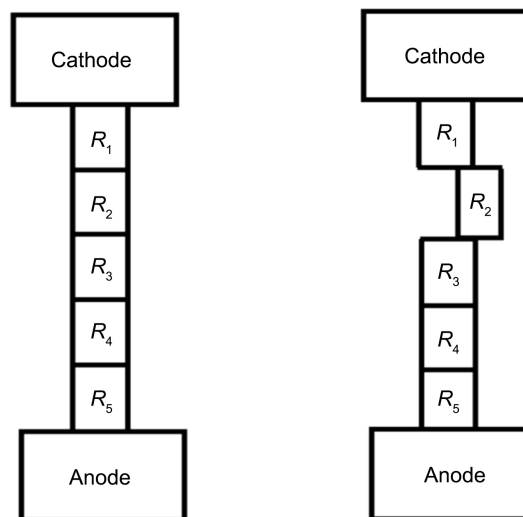**Figure 5** shows the overlapping cross section of the first arc element and the second arc element.

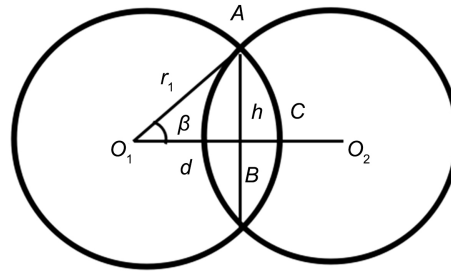**Figure 4.** Arc element motion diagram at some time.

Figure 5. A cross section of arc element and second arc elements.

$$h = r_1 \sin \beta \tag{10}$$

$$d = r_1 \cos \beta \tag{11}$$

where r_1 is the radius of the first current element; β is the angle between O_{1A} and $O_1 O_2$.

$$S_{\Delta O_1 AB} = \frac{1}{2} dh = \frac{1}{2} r_1^2 \sin \beta \cos \beta \tag{12}$$

$$S_{O_1 AC} = r_1^2 \beta \tag{13}$$

Therefore, the overlapping area S is:

$$S = 4 \times \left(S_{O_1 AC} - S_{\Delta O_1 AB} \right) = 4 \times \left(r_1^2 \beta - \frac{1}{2} r_1^2 \sin \beta \cos \beta \right) \tag{14}$$

$$d(t) = \frac{1}{2} v_2 t \tag{15}$$

where, v_2 is the velocity of motion of the second arc element and t is the time.

$$\sin \beta = \frac{h}{r_1} = \frac{\sqrt{r_1^2 - d(t)^2}}{r_1} \tag{16}$$

$$\cos \beta = \frac{d}{r_1} = \frac{v_2 t}{2 r_1} \tag{17}$$

Then the expression for the overlapping area S can be converted to:

$$S = r_1^2 \left(4 \times \arccos \frac{v_2 t}{2 r_1} - \frac{v_2 t \sqrt{r_1^2 - d(t)^2}}{r_1^2} \right) \tag{18}$$

$$D = 0.26 \sqrt{I} \tag{19}$$

$$r_1 = 0.13 \sqrt{I} \tag{20}$$

where D is the diameter of the arc element.

According to the resistance formula, the simplification gives:

$$R_1 = \frac{\rho l_1}{s_1} = \frac{l_1 \sqrt{m_e} e^2 In\Lambda}{0.5408 \pi I \sqrt{\pi} \varepsilon_0^2 T e^{3/2}} \tag{21}$$

$$R_2 = \frac{\rho l_2}{s_2} = \frac{\sqrt{m_e} e^2 In\Lambda}{32 \sqrt{\pi} \varepsilon_0^2 T e^{3/2}} B \tag{22}$$

Table 1. Arc ignition times at different airflow parameters.

Fault arc current value/kA	Wind load speed/(m·s⁻¹)	Wind load and vertical angle/(˚)	Arc burning time/ms
0.5	200	30	3.93
		45	3.86
		60	3.92
	300	30	2.67
		45	2.68
		60	2.69

$$R_3 = \frac{\rho l_3}{s_3} = \frac{l_3 \sqrt{m_e}\, e^2 In\Lambda}{0.5408\pi I \sqrt{\pi}\varepsilon_0^2 Te^{3/2}} \tag{23}$$

$$R_4 = \frac{\rho l_4}{s_4} = \frac{l_4 \sqrt{m_e}\, e^2 In\Lambda}{0.5408\pi I \sqrt{\pi}\varepsilon_0^2 Te^{3/2}} \tag{24}$$

$$R_5 = \frac{\rho l_5}{s_5} = \frac{l_5 \sqrt{m_e}\, e^2 In\Lambda}{0.5408\pi I \sqrt{\pi}\varepsilon_0^2 Te^{3/2}} \tag{25}$$

$$R = R_1 + R_2 + R_3 + R_4 + R_5 = \frac{\sqrt{m_e}\, e^2 In\Lambda}{32\sqrt{\pi}\varepsilon_0^2 Te^{3/2}} \left(\frac{l_1 + l_3 + l_4 + l_5}{0.0169\pi I} + B \right) \tag{26}$$

Formula analysis:

Arc resistance and electron temperature is inversely proportional to the 3/2 times. As the arc temperature decreases, the arc resistance increases; finally, the arc tends to be extinguished.

3.4. Arc Extinguishing Criterion

Arc resistance gradually grows to infinity, the arc gradually extinguished. In the arc current after the zero number of ms, all meet the condition $\mathrm{d}R/\mathrm{d}t > 0$, the arc is judged to be extinguished.

3.5. Calculation Results

Through the above calculation method can be obtained under different parameters of the arc burning time, as shown in Table 1.

4. Conclusions

1) Through the establishment of the arc model and theoretical calculations, it can be derived that the wind load affects the arc burning time change, when the wind speed increases, the same current value case, the shorter the arc burning time.

2) In the following situations of the wind load speed of 300 m/s, the arc current of 0.5 kA, the wind load and the vertical direction of the angle of 60˚, the

arc burning time of 2.69 ms.

3) According to the calculation results, it can be concluded that the arc in the wind load, the arc temperature decreases; and then the arc resistance increases, the arc extinguishing speed accelerates, the arc ignition time decreases.

Acknowledgements

Conflicts of Interest

The authors declare no conflicts of interest.

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