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ORIGINAL ARTICLE

Research on Improved Schwarz Arc Model Considering Dynamic Arc Length

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Abstract
Establishing an accurate arc model is significant for simulating arc characteristics and research on arc high impedance fault detection. This paper firstly expounds arc physical properties, and theoretically analyzes the relationship between arc length and arcing voltage. Then, the magnetohydrodynamic model of AC arc is established by COMSOL Multiphysics, and the influence of arc length on electric field intensity, temperature, voltage and current of arc plasma is analyzed. Secondly, based on the influence of arc length on arc, an improved Schwarz arc model considering dynamic arc length is proposed, which not only considers arc time constant and dissipated power as functions of arc conductance, but also introduces arc length. The comparison error of the arcing voltage of the improved Schwarz model with actual measured data is 5%. In addition, the arcing voltage is compared with calculation results of theoretical formula and simulation results of magnetohydrodynamic model, which verifies the validity of improved arc model. Finally, the improved arc model is compared with Mayr model, Schwarz model and cybernetic model from the perspectives of arc voltage and current, and analysis shows that the improved arc model is reasonable in simulating arcing voltage, arc steady-state combustion voltage, and current zero-break characteristics.

Keywords Arc model · Arc length · Schwarz model · Arcing voltage

1 Introduction

The probability of single-phase grounding fault in 10 kV power distribution system is high, and when the single-phase grounding fault occurs in the contact between overhead conductors and branches and other media in the distribution network, it is usually accompanied by unstable grounding arcs [1]. The high temperature around arc and the grounding point may even cause accidents such as fire, which may lead to serious system equipment accidents and personal safety accidents [2]. The arc fault data of the actual distribution network is difficult to measure. Physical development of and electrical characteristics of arc can be studied through simulation analysis, so as to establish an accurate arc model, which can further exactly simulate arc characteristics of the fault point and arc grounding fault characteristics, which is of great significance for the research on single-phase arc grounding fault detection, fault line selection and location in power distribution system.

Many scholars have done a lot of research on the establishment of arc models in order to accurately simulate arc process. In Ref. [3] the authors solved the mathematical

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expressions of Cassie model and Mayr model according to the electrical breakdown theory and the thermal breakdown theory, respectively, and obtained the resistance expressions of the two arc models. The linear combination of the two is used to accurately describe the two breakdown processes of arc zero-break period. In Ref. [4] the authors used the current flowing through the arc as an independent variable to establish a transition function and combined Mayr model with Cassie model. The dynamic distribution of the two models can be reasonably allocated according to the magnitude of arc current. The combined model can more completely and accurately describe the arc states at different arc currents. Ref. [5] considered the corona discharge in early stage of gas discharge, and considered the corona discharge process impedance on the basis of the Mayr model arc impedance, so combined the corona discharge process with the Mayr arc spark discharge process to completely reflect the whole process of arc occurrence. It used a diode and a voltage source in series and parallel to simulate arc discharge, and a resistance that simulates corona discharge impedance was in parallel with them. When current is less than the given threshold, the diode is not turned on, and the parallel resistance is connected to the circuit to simulate corona discharge; when current is greater than the given threshold, the diode conducts to simulate an arcing process. In Ref. [6] by analyzing the curve of arc resistance with time, the authors divided arc resistance into a steady-state area and a transient area and expressed them in sections. The proposed arc mathematical model contains load parameters, which can reflect the influence of different loads on arc development. In Ref. [7] the authors improved the model from the perspective that steady-state arc conductance in cybernetic model is related to the voltage drop per unit arc length. Based on the fact that the voltage drop per unit arc length decreases with the increase of arc current amplitude, the steady-state arc conductance in cybernetic model was more accurately described, and an improved cybernetic arc model with better simulation effect was obtained. In Ref. [8] the authors obtained Schwarz model parameters under different experimental conditions through arc experiments, and established a Schwarz arc model parameter prediction model by neural network training, which can predict model parameters under different electrical and environmental conditions. Ref. [3–8] focused on the accurate expression of arc resistance, which is significant for the improvement of the arc resistance, but they seldom considered the influence of arc time constant and arc length on actual arc development.

This paper is organized as follows. In Sect. 2, the physical characteristics of arc is expounded, and the relationship between arc length and the arcing voltage is theoretically analyzed. The magnetohydrodynamic model of AC arc is established by COMSOL Multiphysics simulation software, and the effect of arc length on the physical and electrical properties of arc plasma is studied in Sect. 3. In Sect. 4, based on the influence of arc length on arc and the existing arc mathematical model, an improved arc mathematical model based on Schwarz model is proposed, which not only considers arc time constant and dissipated power with arc conductance, but also introduces arc length. Besides, four models including Mayr model, Schwarz model, cybernetic model and improved Schwarz arc model are built, and the voltage waveform of the improved Schwarz arc model is compared with the measured waveform, and the relationship between arc length and the arcing voltage is compared with theoretical calculation. In addition, the characteristics of the four arc mathematical models are compared and analyzed from three perspectives of the arcing voltage, the stable combustion voltage and the "zero-break" characteristics of current. The analysis shows that the improved Schwarz arc model proposed in this paper has a good effect in reflecting electrical characteristics of arc.

2 Arc Physical Properties

2.1 Physical Properties of Arc

2.1.1 The Composition of the Arc

The generation mechanism of arc mainly includes strong electric field emission and thermal electron emission. The strong electric field causes free electrons on the surface of cathode to be emitted into the gap between two electrodes, which is the strong electric field emission; the surface of cathode is seriously heated, and the electrons in cathode get kinetic energy and escape under the action of the local high temperature, which is the thermal electron emission. The continuous development of arc mainly depends on the effect of collisional dissociation and thermal dissociation. The free electrons emitted by the strong electric field and thermionic collide with the neutral point in the medium, and the positive ions and free electrons are continuously generated. The high temperature of arc makes the microscopic particles move violently and promotes the collision between particles, so the arc can develop and burn.

In arc combustion process, the entire arc can be divided into a near-anode area, an arc column and a near-cathode area [9]. The composition of arc is shown in Fig. 1. The space occupied by the near-anode area and near-cathode area is extremely small, the lengths of the areas near two electrodes are exceedingly short, and the electric field intensity is greatly high. Nevertheless, arc column area is the main part of the whole arc, and the length of arc column area can reach several centimeters, and the electric field intensity of it is much smaller than that of the area near two electrodes.

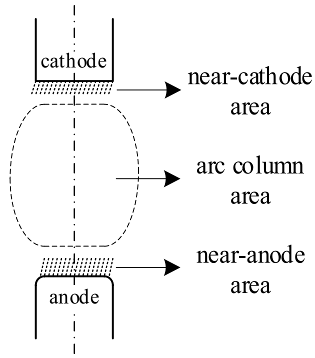

Fig. 1 Diagram of arc components

2.1.2 Arc Diameter

The arc diameter generally refers to the diameter of the arc column area, which is one of the important physical characteristics of arc. In actual arc combustion process, arc diameter is not constant along the length of arc, that is, the arc column is not a certain cylindrical shape. The diameter of arc column is related to various factors such as current, environment pressure, the material of medium and the material of two electrodes. The arc diameter d is proportional to the square root of arc current i. For copper electrodes, when the arc ignites freely in atmosphere, the approximate calculation formula for the diameter of arc column is $d = 0.27i^{1/2}$. However, this formula is no longer applicable when subjected to longitudinal blowing of compressed cold air. The brightness of arc can roughly reflect temperature distribution of arc and indirectly reflect arc current density and arc diameter. Therefore, in actual observation, the brightness of arc image is usually used to roughly estimate arc diameter.

2.1.3 Arc Temperature

In the initial formation stage of arc, the energy is continuously obtained from the power source, and the microscopic particles in the arc gap continue to collide, so that arc temperature rises rapidly, and the rise of arc temperature promotes the collision between particles. When arc burns stably, the temperature at the center of arc column can reach 10^4 °C. It is difficult to accurately measure arc temperature due to factors such as high temperature, short occurrence time and small volume. At present, arc temperature is mainly estimated by the spectral analysis method. According to the existing research, following rules can be summarized: (1) Arc temperature decreases exponentially from the center of arc column along the radial direction; (2) Along the axial direction of arc column, arc temperature decreases with the increase of the distance from two electrode surfaces; (3) Arc temperature rises with the increase of arc current.

2.1.4 Energy Balance of Arc

When arc burns stably, the energy balance state is reached, that is, the input energy of arc is equal to the energy dissipated. If the input energy is greater than the energy dissipated, arc will burn more vigorously, otherwise, arc will tend to be extinguished. The dissipation of energy includes conduction heat dissipation, convection heat dissipation and radiation heat dissipation. When arc is free to burn, the effect of conduction heat dissipation and convection heat dissipation is equivalent, and the effect of radiation heat dissipation is relatively weak and often ignored. The discharge of arc energy is affected by various factors such as air pressure, environment temperature, gas flow rate, etc. At the same time, these external physical conditions will also affect arc development.

2.2 Influence of Arc Length on Arc

It can be obtained from the Thomson discharge theory, assuming that the kinetic energy of the electron is reduced to 0 after the electron collides with the gas micro-particles, and the number of collision ionization completed by an electron moving a unit distance in the direction of electric field can be expressed by the collision ionization coefficient α:

$$\alpha = \frac{Ap}{T}e^{-\frac{Bp}{TE}} \tag{1}$$

where E is the electric field intensity in arc column region; p is atmosphere pressure, T is environment temperature, A and B are empirical coefficients. Taking a uniform electric field as an example to analyze, assuming that the number of electrons emitted by cathode reaching a very short region dx of arc column per unit time is N, then the number of N electrons passing through the dx region increases to dN

$$\mathrm{d}N = \alpha N \mathrm{d}x \tag{2}$$

Separating the variables in Eq. (2) and integrating both sides of the equation at the same time can obtain the following equation:

$$N = n_0 \mathrm{e}^{\alpha x} \tag{3}$$

where n_0 is the initial value.

Suppose the distance between two electrodes is l, the number of electrons emitted from cathode surface is N_-, and the number of electrons reaching anode surface is N_+

$$N_+ = N_- \mathrm{e}^{\alpha l} \tag{4}$$

then the number of positive ions generated in arc column is

$$\Delta N = N_+ - N_- = N_-(\mathrm{e}^{\alpha l} - 1) \tag{5}$$

The number of electrons generated by positive ions hitting cathode surface under the action of an electric field is $\beta\Delta N$, where β is the surface ionization coefficient, that is, the average number of electrons generated by each positive ion hitting cathode surface. If air gap breakdown occurs and self-discharge is maintained, the electrons released due to the impact of positive ions on the surface of cathode must be at least equal to the amount of electrons emitted from the surface of cathode last time, that is

$$\beta\Delta N = N_{-} \tag{6}$$

Equations (5) and (6) can be combined to obtain Eq. (7):

$$\alpha = \frac{\ln\left(1+\frac{1}{\beta}\right)}{l} \tag{7}$$

For a uniform electric field, $E = U/l$, which can be combined with Eq. (1) to obtain Eq. (8):

$$\alpha = \frac{Ap}{T}e^{-\frac{Bpl}{TU}} \tag{8}$$

Equations (7) and (8) can be combined to obtain Eq. (9):

$$U = U_{\mathrm{b}} = \frac{Bpl}{T\ln\left[\frac{Apl}{T\ln\left(1+\frac{1}{\beta}\right)}\right]} \tag{9}$$

where U_{b} is the minimum breakdown voltage of air gap, that is, the arcing voltage. When two electrodes are copper electrodes, the arc ignites freely in the air, take appropriate parameters [10] $A = 0.0668$, $B = 1.88$, $p = 101325$ Pa, $T = 293$ K, $\beta = 0.025$, and draw the relationship curve between minimum breakdown voltage U_{b} and arc length l, which is shown in Fig. 2.

It can be seen from Fig. 2 that the relationship curve between the minimum breakdown voltage and arc length is a tick shape, which is consistent with the Basin experimental curve. When arc length is about 0.2–0.5 cm, the minimum breakdown voltage decreases with the increase of arc length; when arc length is greater than 0.5 cm, the minimum breakdown voltage grows with the increase of the arc length. The physical reason behind it can be roughly explained as follows: When the arc length is small, with the increase of arc length, the number of collisions of microscopic particles increases, the collision ionization effect increases, and the breakdown voltage decreases. However, when arc length continues to increase, the diffusion and recombination deionization are significantly enhanced, the impact ionization is weakened, and the breakdown voltage will increase to enable electrons to obtain greater energy to enhance impact ionization [11].

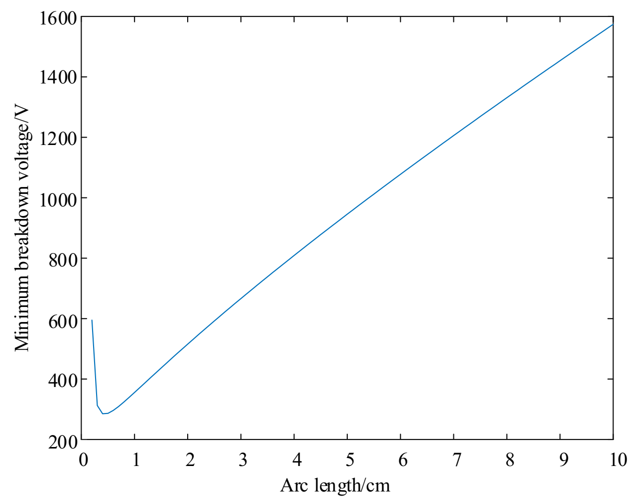

Fig. 2 The relationship between the minimum breakdown voltage and arc length

From the above analysis, it can be seen that arc length has a certain degree of influence on arc development. Ref. [12] pointed out that the application of arc model to high impedance fault model can simulate the nonlinearity and asymmetry of the fault current. While in the actual distribution network when an arc fault occurs in the line, due to factors such as wind disturbance, the arc length is not fixed [13], and its random change makes the fault current random. Therefore, the arc length parameter is introduced into the arc model, which is of great significance for accurately simulating the randomness of faults.

3 Simulation Analysis of Arc Magnetohydrodynamic Model

Arc combustion process involves multiple physical fields, and the arc plasma is coupled with multiple physical fields such as electromagnetic field, thermal field, and flow field. In order to analyze the internal physical characteristics and external electrical characteristics of AC arc, a magnetohydrodynamic model of AC arc was established by using COMSOL Multiphysics simulation software [14], and the effect of arc length on physical characteristics such as electric field intensity, temperature and electrical characteristics such as arc voltage and arc current and so on of arc plasma is explored.

The simulation circuit built in COMSOL is shown in Fig. 3, which mainly includes AC voltage source, transition resistance, arc magnetohydrodynamic model, voltmeter and ammeter. AC voltage source is 10 kV, 50 Hz, transition resistance R is 100 Ω, two electrodes of arc are copper electrodes, the air gap between two electrodes is 5–50 mm, the air gap pressure is one atmosphere pressure, and the initial

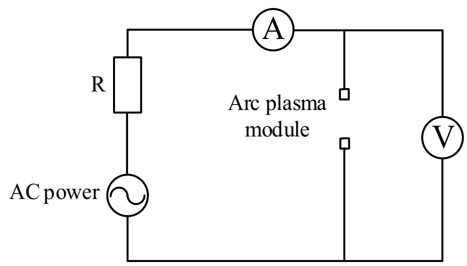

Fig. 3 Arc simulation circuit in COMSOL

temperature is 25 °C. The arc magnetohydrodynamic model is slightly simplified to facilitate the convergence of simulation calculations, so the following assumptions are made: (1) The arc plasma is assumed to be an equilibrium plasma; (2) The arc plasma is an axisymmetric model; (3) The flow of arc plasma is laminar flow; (4) The influence of arc combustion on the area near two electrodes and the ablation effect on the contacts of two electrodes are ignored.

3.1 Influence of Arc Length on Electric Field Intensity

Taking the middle moment of the stable combustion of the arc in the first half cycle, the electric field intensity distribution of arc column with different arc lengths is shown in Fig. 4. It can be seen from Fig. 4 that the electric field intensity near two electrodes can reach about 90000 V/m, and electric field intensity in the center of arc column is about 2000 V/m. With different arc lengths, the electric field intensity of the area near two electrodes is much larger than that of the center of arc column.

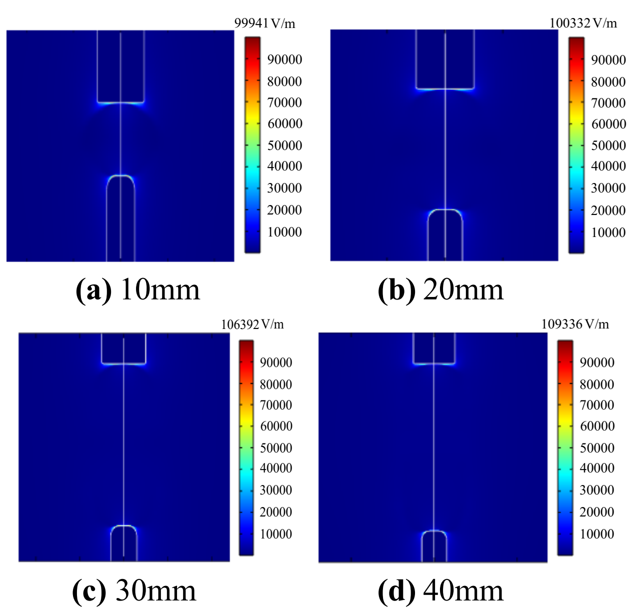

Fig. 4 Arc electric field intensity distribution of different arc lengths

The relationship between the maximum electric field intensity and the average electric field intensity of arc column axis section and arc length is shown in Fig. 5. When arc length is less than 10 mm, the maximum value of electric field intensity of arc column axis section decreases with the increase of arc length. When the arc length is 10–50 mm, with the increase of arc length, the maximum electric field intensity in the arc column axis section increases gradually, but its increasing rate gradually becomes slower with the increase of arc length; When arc length is 5–50 mm, the average electric field intensity of arc column axis section rises with the increase of arc length, but the rate of rise with the increase of arc length is basically unchanged, roughly showing a linear change.

3.2 Influence of Arc Length on Temperature

Taking the middle moment of the stable combustion of arc in the first half cycle, the temperature distribution of arc column with different arc lengths is shown in Fig. 6.

The relationship between the maximum temperature and the average temperature of arc column axis section and arc length is shown in Fig. 7. It can be seen from Fig. 7 that when arc length is 5–50 mm, the maximum temperature of arc column axis section changes with arc length without a certain rule. The average temperature of arc column axis section grows with the increase of arc length, and roughly shows a linear increase relationship. This is because with the increase of arc length, the space ratio of arc column area rises. In addition, temperature in arc column region is extremely high, resulting in an increase in the average spatial temperature.

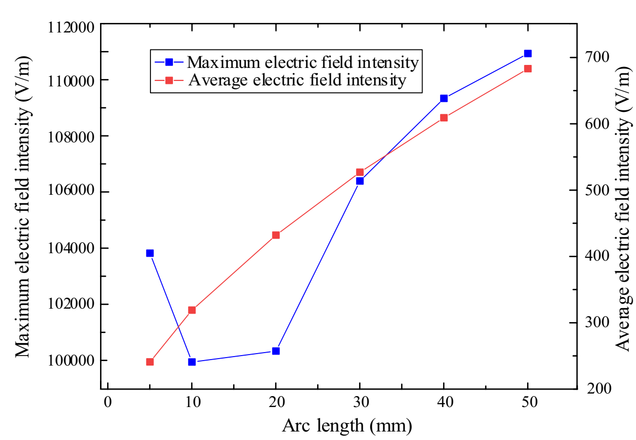

Fig. 5 The relationship of arc column axis section maximum electric field intensity and average electric field intensity with arc length

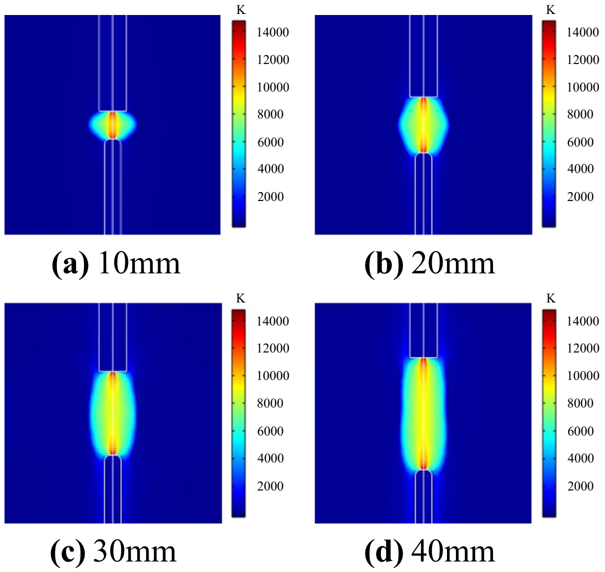

Fig. 6 Arc temperature distribution of different arc lengths

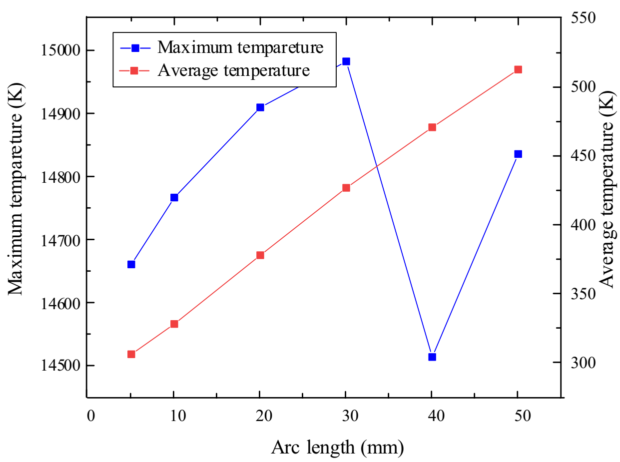

Fig. 7 The relationship of maximum temperature and average temperature of arc column axis section with arc length

3.3 Influence of Arc Length on Arc Voltage and Current

Take arc voltage and current with different lengths at the middle moment of the stable combustion of arc in the first half cycle, and draw the relationship between the arc voltage and current and arc length as shown in Fig. 8. When arc burns stably, arc presents a low resistance state, arc voltage is high, and arc current is low. It can be seen from Fig. 8 that with the increase of the arc length, arc voltage gradually rises, but arc current gradually decreases. This is because the increase of arc length leads to a rise of arc resistance value presented to the outside.

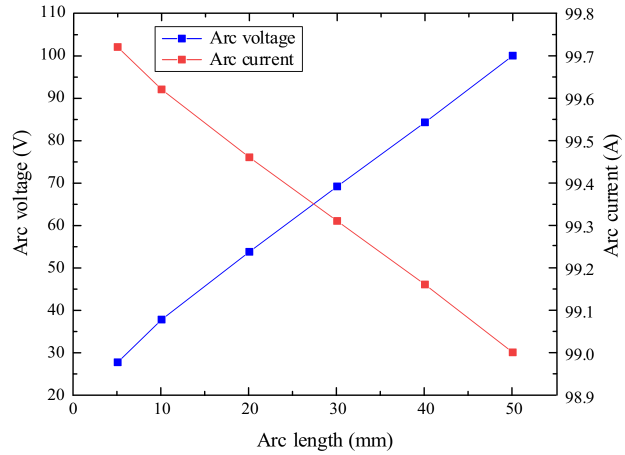

Fig. 8 The relationship of arc voltage and current with arc length

After the above simulation analysis of arc plasma, it can be seen that arc length has a profound impact on the physical properties of arc such as electric field intensity and temperature, and the electrical properties such as arc voltage and current. In terms of physical properties, the average electric field intensity and temperature of the arc column axis section both rise with the increase of arc length; In terms of electrical characteristics, the longer arc length, the lower arc current and the greater arc voltage when arc burns stably. Therefore, considering the influence of arc length on arc physical and electrical characteristics, it is essential to improve the existing arc mathematical model to accurately reflect the influence of arc length that is an important parameter on arc characteristics.

4 Arc Mathematical Model and Simulation Analysis

4.1 Arc Mathematical Model

According to the energy balance relationship of arc: energy q accumulated by the arc per unit length is equal to the integral of the difference between the input power P_r and the dissipation power P_s of the arc per unit length:

$$\frac{dq}{dt} = P_r - P_s \tag{10}$$

The input power P_r of the arc per unit length can be expressed by the following formula:

$$P_r = ei \tag{11}$$

where e is arc voltage per unit length; i is arc current.

Substituting Eq. (11) into Eq. (10), and performing equation transformation:

$$\frac{1}{g}\frac{dg}{dt} = \frac{P_s}{g\frac{dq}{dg}}\left(\frac{ei}{P_s} - 1\right) \tag{12}$$

where g is arc conductance per unit length.

Let the arc time constant

$$\tau = \frac{g\frac{dq}{dg}}{P_s} \tag{13}$$

Then there is the general mathematical expression of the arc model:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau}\left(\frac{ei}{P_s} - 1\right) \tag{14}$$

On the basis of the general form of the above-mentioned arc mathematical model, the arc mathematical model suitable for different scenarios can be obtained by assuming electrical characteristics and thermal characteristics of arc.

4.1.1 Mayr Arc Model

Mayr arc model [15] assumes that the diameter of arc gas channel is constant; arc temperature decreases with the increase of the distance from the axis along radial direction of the section, and is also affected by the arc development time; Radiation diffusion and heat conduction in the radial direction play a leading role in the dissipation of arc energy. The Saha formula can describe the thermal dissociation phenomenon of microscopic particles in arc column at high temperature:

$$g = g_0 e^{\left(\frac{Q}{Q_s}\right)} \tag{15}$$

where g_0 is the conductance at initial moment, and Q_s is the energy required for arc conductance g per unit length to increase from g_0 to e times. Taking the derivative transformation of Eq. (15):

$$\frac{dq}{dg} = \left(\frac{dg}{dq}\right)^{-1} = \frac{Q_s}{g} \tag{16}$$

Equation (16) and Eq. (13) can be combined to obtain arc time constant in the Mayr model:

$$\tau_m = \frac{Q_s}{P_s} \tag{17}$$

Substitute Eq. (17) into Eq. (14) to obtain the mathematical expression of the Mayr arc model:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_m}\left(\frac{ei}{P_s} - 1\right) \tag{18}$$

4.1.2 Schwarz Arc Model

In the early 1970s, a large number of experiments carried out by Dutch scholars Schwarz and others showed that arc time constant τ and dissipation power P_s are not constant [16]. Later, by analyzing a large number of arc experimental data, Soviet scholars found that arc time constant and dissipated power can be expressed as a power function with arc conductance g as the independent variable, and Schwarz model was obtained by improving Mayr model, and its mathematical expression is:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_s g^\alpha}\left(\frac{ei}{Pg^\beta} - 1\right) \tag{19}$$

where P and τ_s are the dissipated power constant and time constant of Schwarz model, respectively. α and β are constants, and their values are affected by the system voltage, loop current and environment. Generally, the value range of α is [0.1, 0.5], and the value range of β is [0.1, 0.9] [17].

4.1.3 Cybernetic Arc Model

Cybernetic model is also improved based on Mayr arc model, which assumes that the arc burns stably and the input energy of arc column is equal to the dissipated energy, the dissipated power can be expressed as:

$$P_s = \frac{i^2}{G_k} \tag{20}$$

Substituting Eq. (20) into Eq. (18), the mathematical expression of the cybernetic arc model is obtained:

$$\frac{dg}{dt} = \frac{1}{\tau_k}\left(G_k - g\right) \tag{21}$$

where τ_k is arc time constant of cybernetic model; G_k is the steady-state conductance, and its empirical formula is:

$$G_k = \frac{|i|}{V \cdot L_k} \tag{22}$$

where L_k is arc length, V is the steady-state electric field intensity in arc column, and its empirical value is 15 V/cm.

The empirical formula for arc time constant is:

$$\tau_k = \gamma\frac{I}{L_k} \tag{23}$$

where I is the maximum amplitude of arc current, which approximates the steady-state short-circuit current when the direct ground fault occurs; the coefficient γ takes the empirical value of 2.85×10^{-5}.

Arc time constant and dissipated power in Mayr model are fixed, which is inconsistent with the actual arc development, and there is no arc length parameter in the model, which cannot characterize the effect of arc length on arc development. Schwarz model uses the power function of arc conductance to represent the constant changes of dissipated power and arc time constant during the actual arcing process [18], which improves the accuracy of simulating actual arc development, but there is also no effect of arc length on arc in the model. The cybernetic model can directly set the arc length, which can better reflect the arcing situation of the fault arc and the influence of arc length on electrical characteristics of arc [19]. But when arc length is given, the arc time constant is only affected by the steady-state short-circuit current I, and the change of arc time constant with the change of arc conductance is not considered.

4.1.4 Improved Schwarz Arc Model Considering Dynamic Arc Length

Based on the above analysis of three arc mathematical models including Mayr model, Schwarz model and cybernetic model, this paper substitutes the calculation formula of arc time constant into the mathematical expression of the Schwarz model, that is, substitute Eq. (24) into Eq. (19). In Eq. (24), L_g is the arc length of the improved arc model improving Schwarz model. Accordingly, arc length which is objective and practical factor is introduced to characterize its effect on arc development.

$$\tau_s = \gamma \frac{I}{L_g} \tag{24}$$

The mathematical expression of the improved arc model based on the Schwarz model is as follows:

$$\frac{1}{g}\frac{dg}{dt} = \frac{L_g}{\gamma I g^{\alpha}}\left(\frac{ei}{P_g g^{\beta}} - 1\right) \tag{25}$$

where P_g is dissipation power constant of the improved arc model. The improved arc model not only considers that arc time constant and dissipated power are not fixed during arc development, and they have a power function relationship with arc conductance. At the same time, arc length is introduced, which can reflect the effect of arc length on electrical characteristics of arc, which makes up for the deficiencies of the aforementioned three arc mathematical models. In addition, dynamic random change of arc length can be set, and the model will further reflect the randomness of fault voltage and current signal caused by random change of arc length.

4.2 Improved Arc Model Validation

In order to analyze the voltage and current characteristics of the improved Schwarz arc model proposed in this paper, the model considering the dynamic arc length is built by MATLAB/Simulink. The voltage and current waveforms and arcing voltages with different arc lengths are obtained by simulation to verify the correctness of the model.

4.2.1 Verification of the Arc Voltage Waveform and Arcing Voltage of the Improved Arc Model

In the simulation circuit built by Simulink, power supply is 10 kV, 50 Hz AC source, transition resistance is 300 Ω, the length of the improved arc model is set to change randomly every 0.002 s, and its variation range is 8–12 mm, so as to simulate random variation in arc length of actual arc faults, initial conductance is 10000 S, initial arc time constant is 2.85×10^{-5} s, exponential component of arc time constant is -0.3, initial dissipated power is 2000 W, and exponential component of the dissipated power is 0.01.The voltage and current waveforms of the improved arc model obtained by simulation are shown in Fig. 9.

It can be seen from Fig. 9 that current of the improved arc model with random changes in arc length is distorted near the zero-crossing point, and the voltage waveform is "saddle-shaped" in half a cycle. The arc voltage rises rapidly near the zero-crossing point of arc current to reach the arcing voltage, and it drops rapidly after the arc ignites. In the process of arc stable combustion, arc voltage is low and arc current is high; When arc current crosses zero again, the voltage rises slightly, and then drops to 0 after reaching the arc-extinguishing voltage, and then enters the second half cycle. The arc voltage and current waveforms and their characteristics of the improved arc model are the same as the measured arc voltage and current waveform characteristics

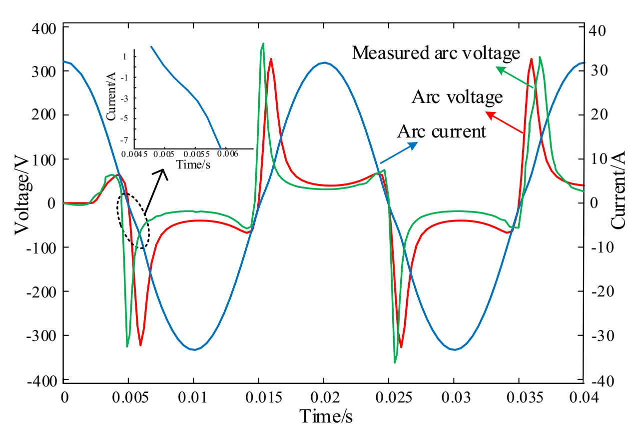

Fig. 9 Voltage and current waveforms of improved arc model and measured arc voltage waveform

given in the literature. And for arcing voltage, simulated arcing voltage of the improved Schwarz arc model is 336 V. The measured arc voltage waveform given in the Ref. [20] is shown in Fig. 9, and the power supply in the experimental circuit of Ref. [20] is an AC source of 10 kV and 50 Hz, and the transition resistance is 300 Ω, which is consistent with the AC source and transition resistance in the simulation circuit of this paper. The measured arcing voltage in Fig. 9 is about 350 V, and arcing voltage simulated in this paper deviates within 5% from the measured arcing voltage in Ref. [20].

4.2.2 Verification of Comparison of Influence Law of Arc Length on Arcing Voltage and Theoretical Calculation

Different arc lengths are set for the improved arc model, and voltage waveforms obtained by simulation with different arc lengths are shown in Fig. 10. The arcing voltages of the improved arc model with different arc lengths are shown in Table 1.

As can be seen from Fig. 10 and Table 1, when arc length is about 0.5 cm, arcing voltage reaches the minimum; when arc length is less than 0.5 cm, the arcing voltage decreases with the increase of arc length; when arc length is greater than 0.5 cm, the arcing voltage rises gradually with the increase of arc length. The simulation results in Fig. 10 and Table 1 show that the arcing voltage law of the improved arc model with different lengths is consistent with Fig. 2 and the analysis in Sect. 2.2, and the simulation data of the arcing voltage with different lengths is similar to theoretical calculation data, which further verifies the correctness of the improved arc model proposed in this paper.

4.3 Comparative Analysis of Arc Models Simulation

In order to analyze the effect of the improved Schwarz arc model proposed in this paper considering the dynamic arc length, the improved arc model is compared with Mayr model, Schwarz model and cybernetic model from arc voltage and arc current by Simulink simulation. The transition resistance in series with arc model is 100 Ω, which is consistent with the transition resistance in COMSOL simulation; dissipated power constant of four models is 4500 W, arc length of the cybernetic model is 40 mm, and the length of the improved arc model varies randomly every 0.002 s between 35 and 45 mm.

4.3.1 Comparative Analysis of Arc Voltage Characteristics

The voltage waveforms of four arc models obtained by simulation are shown in Fig. 11, and the arc voltage waveforms of four models are all "saddle-shaped". The arcing voltage and arc extinction voltage of four arc models are shown in Table 2.

According to theoretical calculation of Eq. (9), when arc length is 40 mm, the arcing voltage is about 809 V; through multi-physics simulation analysis, the voltage

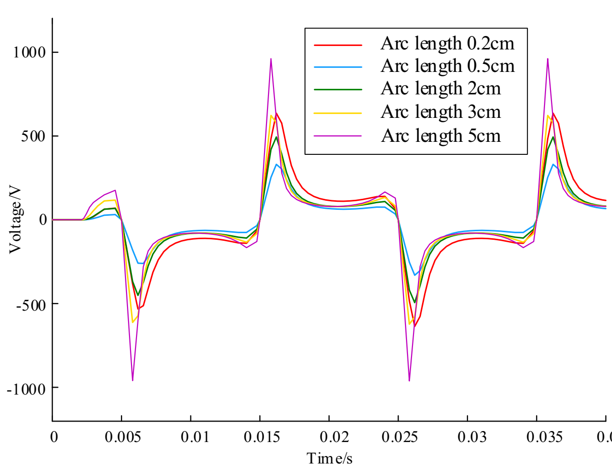

Fig. 10 Voltage waveforms of the improved arc model with different lengths

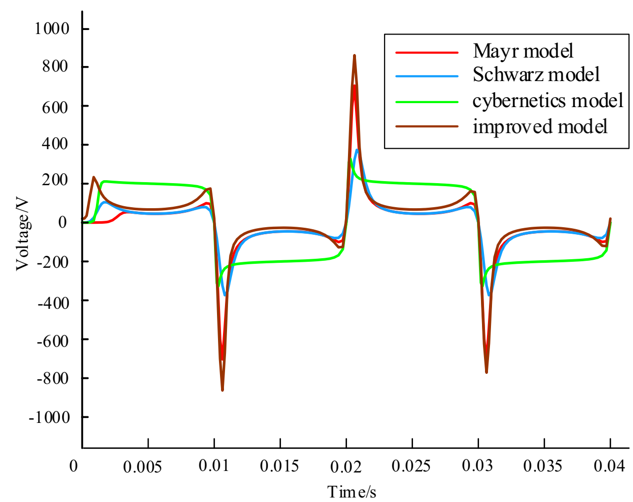

Fig. 11 Voltage waveforms of the arc models

Table 1 Arcing voltages of improved arc model with different lengths

Arc length/cm	0.2	0.4	0.5	1	2	3	5
Arcing voltage/V	632	408	258	322	491	618	946

Table 2 The arcing voltages and the arc extinction voltages of the arc models

Arc model	Mayr model	Schwarz model	Cybernetic model	Improved model
Arcing voltage/V	698	366	324	813
arc extinction voltage/V	93.5	58.2	138	134
stably burning voltage/V	45.3	45.6	199	45.9

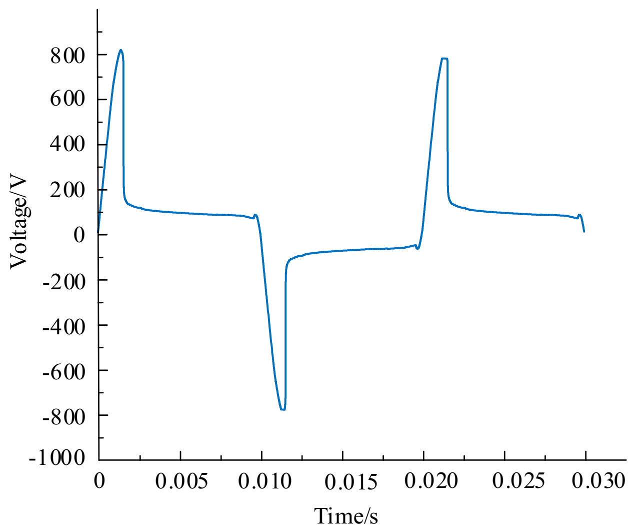

Fig. 12 Voltage waveform of arc magnetohydrodynamic model

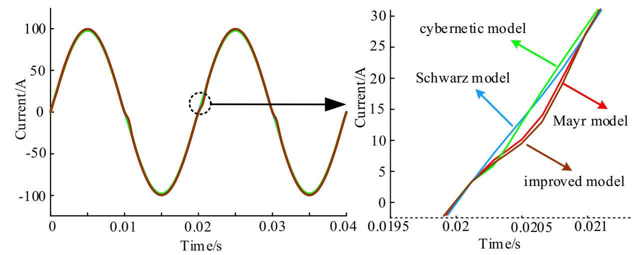

Fig. 13 Current waveforms of the arc model

waveform of the arc magnetohydrodynamic model when the distance between the two electrodes is 40 mm is shown in Fig. 12, and its arcing voltage is about 806 V. In contrast, arcing voltage of the improved Schwarz arc model is in better agreement with the theoretical calculation and multiphysics simulation results. However, Mayr model and Schwarz model do not contain the arc length parameter, so they cannot characterize the effect of arc length on arcing voltage.

In the stable combustion stage of arc, two electrodes are approximately connected, and arc is in a low resistance state, so the arc voltage is relatively low when arc is stably burning. And it can be seen from voltage waveform of the arc magnetohydrodynamic model obtained by COMSOL simulation given in Fig. 12 that the voltage of arc when arc is stably burning is less than 100 V. Compared with cybernetic model arc whose voltage reaches about 200 V in stable combustion which is inconsistent with theoretical and simulation analysis, Mayr model, Schwarz model and the improved arc model are more consistent with theory and practice. Therefore, the improved arc model is better than the other three models in reflecting arcing voltage, and it is also more accurate to reflect the voltage when arc is burning steadily compared with the cybernetic model.

4.3.2 Comparative Analysis of Arc Current Zero-Break Characteristics

The current waveforms of four arc models are shown in Fig. 13. The arc current waveforms have different degrees of distortion near the zero-crossing point, among which the arc current distortion of the improved Schwarz model is the most obvious, followed by Mayr arc model, both of which have a longer zero-break time; The arc current waveform of Schwarz model has the weakest degree of distortion and the shortest zero-break time. Near the zero-crossing point of arc current, the slope of current waveform decreases, which is significantly smaller than that of other sections. Analysis of different literatures [20, 21] under different test conditions, the measured arc current waveforms have obvious distortion. However, the arc current distortion degree of cybernetic model and Schwarz model is very weak. Therefore, the comparison shows that the improved arc model has better effect than Schwarz model and cybernetic model.

Through the above comparative analysis of the voltage and current waveforms of Mayr model, Schwarz model, cybernetic model and the improved arc model, it can be found that the improved arc model has better effects in reflecting the arcing voltage, the voltage when arc is stably burning, and the distortion characteristics near the zero-crossing point of arc current compared with the other three models, and it can better reflect the arc voltage and current and other electrical characteristics.

5 Conclusion

(1) The following conclusions can be drawn from the derivation of the arcing process based on the Thomson discharge theory: the relationship between arcing

voltage and arc length is in the shape of a check mark. When arc length is less than 0.5 cm, arcing voltage decreases with the increase of arc length; when arc length is greater than 0.5 cm, arcing voltage rises with the increase of arc length.

(2) Through the simulation of the arc magnetohydrodynamic model, it can be obtained that the arc length has an important influence on the physical properties such as electric field intensity and temperature in the development of arc, as well as the electrical properties such as the arc voltage and current. In terms of physical properties, the average electric field intensity and temperature of arc column axis section grow with the increase of arc length; in terms of electrical properties, the longer the arc length, the higher arc voltage and the smaller arc current when it burns stably.

(3) This paper proposes an improved Schwarz arc model considering dynamic arc length, which not only considers arc time constant and dissipated power as the arc conductance changes, but also introduces arc length. Setting arc length to vary randomly can further reflect the randomness of the actual arc voltage and current signals. Model verification shows that the improved arc model can better reflect arc electrical characteristics.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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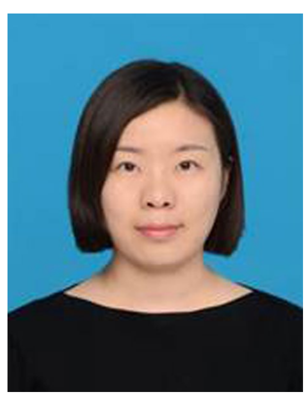

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