Transient modelling and simulation of the forced arc extinguish period of the circuit breakers

Daopin Chen¹,³, Zhiyang Xie¹, Zhenxing Wang², Zhiyuan Cao² and Jing Yan²

¹Foshan Power Bureau, Guangdong Power Grid, Foshan, China
²State Key Laboratory of Electrical Insulation and Power Equipment, Xi’an Jiaotong University, Xi’an, China
495012433@qq.com

Abstract. Plasma transport during continuous extinction processes from high-current arcs to fully extinction is an important issue in the study of vacuum arcs. In this research a 3D hybrid plasma model has been developed to study the extinguish period of the DC vacuum arc. The model treats the electrons as a massless fluid and ions as macro particles. The ion-neutral collision processes including both charge exchange collisions and momentum exchange collisions are considered with Monte-Carlo method. By this approach, the vacuum arc model consists of plasma jets ejected from multiple cathode spots is established and the behaviours of ions under the collisions with neutral atoms are simulated. It is shown that a large number of low-speed ions are generated in the interelectrode region due to the chare exchange collisions between ions and neutrals. And as the arc current drops to zero, the proportion of low-speed ions to the total ions at each moment becomes higher and higher.

1. Introduction

In recent years, vacuum interrupters (VIs) with their unique advantages have developed rapidly in the power grid, spacecraft, renewable energy systems, and rail transit [1]. During an interruption process, vacuum arcs are formed in the interelectrode region. Unlike gaseous arcs, the discharging media of the vacuum arcs is entirely dependent on the production from contacts. The production including ions, electrons and neutral atoms is generated during the arcing time and gradually dissipated after current zero [2]. What’s more, the dielectric recovery process, which determines the performance of the VIs, depends on the transportation processes of these particles.

Numerical simulations are effective tools for investigating the physical processes of vacuum arcs. Among the studies, the influence of the ion-neutral collisions has attracted a lot of interests of researchers. Sarraïlh et al. [3] proposed a Maxwell-Boltzmann model and took account of the collisions between neutral atoms and ions using the Monte-Carlo method to study the effect of neutrals on the plasma dynamics during the sheath expansion. Moreover, Sarraïlh et al. [4] developed a post-arc model that takes into account the neutral atoms. It was found that the fast neutrals created in the cathode sheath by charge exchange collisions with ions can lead to a Townsend breakdown. Wang et al. [5] established a full kinetic model to study the effect of the metal vapor on the sheath expansion during the post-arc period. They found that the existence of the neutral atoms slowed the sheath
expansion in the gap and caused formation of a high electric field in front of the cathode surface. However, these researches are mostly focused on the post-arc phase which is after the current zero. As for the period before the current zero, the existence of neutral atoms is often ignored in the simulation works [6-8], not to mention the collisions between the ions and neutral atoms.

The objective of this paper is to investigate the role of ion-neutral collisions during the extinguish period of the vacuum arc. A 3D hybrid vacuum arc model based on our previous work has been developed [9], in which the ions are considered as macro particles and electrons as a massless fluid. The ion-neutral collision processes are implemented by the Monte-Carlo method. As a result, the spatiotemporal distribution of the ion density and the ions velocity distribution during the extinguish period are presented.

2. Model

2.1. Physical model

The physical model of the vacuum arc is demonstrated in Figure 1(a), which has three dimensions in both the physical space and the velocity space. Based on our previous work, the cathode spots are set to discrete plasma sources, and the vacuum arc consists of plasma jets ejected from the multiple cathode spots. In addition, each cathode spots can be independently turned on or off. The neutral atoms are considered as a uniformly distributed background metal vapor in the entire simulation area. As shown in Figure 1(b), the cathode spots are set in a circular distribution and each cathode spot is marked with a serial number for the sake of simplicity.

![Figure 1](image-url)

Figure 1. (a): The schematic of the multiple cathode spots vacuum arc model; (b): The settlement of the cathode spots on the cathode spots.

The model is based on the following assumptions: (1) the plasma is quasi-neutral, so that given the ion charge density, the electron density is determined; (2) the temperature of each species remains constant [10]; (3) the metal vapor density is considered to be a constant during the whole simulation; (4) electrons are regarded as a massless fluid.

2.2. Mathematical model

The ions and electrons obey the quasi-neutral condition:

$$n_e \approx Z_i n_i$$

(1)

with $n_e$ being the electron number density, $Z_i$ the mean charge number, $n_i$ the ion number density.

The movement of ions is determined by the Newton’s law:

$$m_i \frac{d\mathbf{v}_i}{dt} = q_i (E + \mathbf{v}_i \times \mathbf{B}) - \frac{q_i j}{\sigma}$$

(2)
\[
\frac{dx_i}{dt} = v_i
\]  

(3)

where \(m_i, x_i, q_i\) and \(v_i\) are the ion mass, ion position, ion electric charge and the ion velocity, respectively. \(E\) and \(B\) are the electric field and magnetic field, respectively. \(\sigma\) is the plasma conductivity. \(j\) is the current density. Besides, the last term in (2) represents the effect of the collisional drag between the ions and electrons.

Momentum conservation equation for the electrons is:

\[
\frac{\partial}{\partial t} n_e m_e v_e = -en_e (E + v_e \times B) - \nabla P_e + \frac{en_e j}{\sigma}
\]  

(4)

where \(m_e, v_e\) and \(e\) are the electron mass, electron velocity and the electron charge, respectively. \(P_e\) is the electron pressure and \(P_e = n_e k T_e\). \(k\) is the Boltzmann constant and \(T_e\) is the electron temperature.

The current density is:

\[j = q_e n_e v_i - en_e v_e\]  

(5)

According to the Maxwell’s equations, the current density is solved by the Ampere’s law and the time evolution of the magnetic field can be calculated from the Faraday’s law:

\[j = \frac{1}{\mu_0} \nabla \times B\]  

(6)

\[\frac{\partial B}{\partial t} = - \nabla \times E\]  

(7)

2.3. Boundary conditions

For the cathode spots on the cathode surface, it serves as a plasma source with an effective radius \(R\) [11]:

\[\pi R^2 v_{i0} n_0 Z_i e = f_i I\]  

(8)

\[n_0 = \frac{v_{i0}}{m_i v_i}\]  

(9)

with \(v_{i0}\) being the initial axial ion velocity, \(n_0\) is the initial plasma density, \(f_i = 0.1\) is the ion current fraction, \(I\) is the current of each cathode spot, \(v\) is the erosion rate.

For the anode side, it is considered as a perfect absorber for the current and particles. Besides, for the magnetic field:

\[\nabla \varphi_{sh} = - \frac{j}{\sigma} + \frac{\nabla P_e}{en_e} + v_e \times B\]  

(10)

with \(\varphi_{sh}\) being the anode sheath potential.

2.4. Ion-neutral collisions

Two kinds of collisions for the \(Cu^+\)-Cu are included in the hybrid vacuum arc model: charge exchange (CE) collisions and momentum exchange (ME) collisions. The ion-neutral cross sections for the copper have the form:

the cross section of CE collisions
\[ \sigma_{ex} = (7.0 - 0.38 \ln \varepsilon)^2 \times 10^{-20} \]  
(11)

the cross section of ME collisions

\[ \sigma_{in} = (6.45 - 0.365 \ln \varepsilon)^2 \times 10^{-20} \]  
(12)

where \( \varepsilon \) is the ion energy.

The probability of a specific collision in a time step is:

\[ P_{tot} = 1 - \exp(-\nu_{rel} n_n \sigma_{tot} \Delta t) \]  
(13)

\[ P_i = \frac{\sigma_i}{\sigma_{tot}} P_{tot} \]  
(14)

where \( P_{tot} \) and \( \sigma_{tot} \) are the total collision probability and total cross section for a certain ion, respectively. \( \nu_{rel} \) is the relative velocity of the incident ion with respect to the atom. \( n_n \) is the neutral atoms density. \( \Delta t \) is the unit time step. \( P_i \) is the probability of a specific collision cross section \( \sigma_i \).

3. Simulation results and discussion

In this paper, the whole simulation framework consists of a steady state calculation stage and a transient process calculation stage. The steady state where all the cathode spots are burning is firstly performed to get the initial condition of the extinguish period, the cathode spots are turned off in a random way to simulate the extinguish period. The extinction time of each spot is 0.25 microseconds and now there are 37 cathode spots settled on the cathode surface, so the total ramp down time of the extinguish period is 9.25 microseconds.

The simulation domain is 30 mm × 30 mm × 10 mm, the cathode is placed at \( z = 0 \) mm and anode at \( z = 10 \) mm. The electrode material is selected as pure copper. The current carried by each cathode spot is 30 A. The parameters of the plasma emitted from each cathode spot in this paper are the same [12]: electron temperature \( T_e = 3 \) eV, ion temperature \( T_i = 0.5 \) eV, mean charge number of ions is 1.85, ion drift velocity \( V_i = 1.0 \times 10^4 \) m/s.

Due to the circular arrangement of the cathode spots as shown in Figure 1, the plasma parameter distribution will be symmetrical at the steady state. Therefore, the simulation results of the vacuum arc parameters in xoz plane are only shown in Figure 2. In Figure 2(a), it can be seen that the plasma jets ejected from the cathode spots interact with each other producing a common plasma column from the cathode to the anode. The maximum of ion number density is near the cathode surface and the density of ions is larger at the arc center than that at the arc edge. In Figure 2(b), it shows that the maximum of the axial current density appears at the arc edge near the cathode and the distribution of the current is not the same with the plasma. This is because the distribution of the current is mainly contributed by the velocity of the electrons, whereas the plasma distribution is related to the positions of the ions and electrons. Besides, one can notice that the current channel does not occupy the entire simulation domain, so the self-generated magnetic field outside the arc plasma becomes smaller and smaller which can be verified by the Biot-Savart Law. The self-generated azimuthal magnetic field is shown in Figure 2(c). It can be seen that the magnetic field is circularly symmetric around the vacuum arc and it is parallel with the electrodes. The value of the magnetic field at the arc center is 0, and it increases from the arc center to the arc edge.
Figure 2. Parameters distribution of the vacuum arc in xoz plane (a: Ion density; b: Current density; c: Magnetic field)

During the extinguish period, the spatial distribution and temporal evolution of the ion number density is shown in Figure 3. t = 0 μs is defined as the instant that the arc current begins to drop and t = 9.25 μs is the instant that the arc current equals to zero. It can be found that the cathode spots gradually extinguish and no longer eject the plasma into the gap with the decrease of the current. And the ion number density on the cathode surface becomes asymmetrical due to the random extinction of the cathode spots. As the current continues to decrease, the number of cathode spots which sustain the plasma reduced, and the interelectrode ion density becomes smaller and smaller. What’s more, from the (c), (d) and (e) of the Figure 3, it can be seen that the distribution of the ions at each moment is mainly dominated by the location of the cathode spots that are still burning. When t = 9.25 μs, the arc current equals to zero and all cathode spots have been extinguished, whereas there is still a large amount of ions in the interelectrode region. The residual ions will directly reduce the speed of the dielectric recovery process during the post-arc period.
Figure 3. Spatiotemporal changes in ion density distribution

(a:0μs; b:2μs; c:4μs; d:6μs; e: 8μs; f: 9.25μs)

In order to quantify the effects of the different ion-neutral collision processes in the vacuum arc, four simulations have been conducted with different collision processes. The velocity distributions of the ions in the steady state are shown in Figure 4. The abscissa represents the absolute velocity of the ions, and the ordinate the probability density function. It can be seen that the velocity distribution of the ions without any ion-neutral collision satisfies the Gaussian distribution. When the ME and CE collisions are considered in this model, the ions velocity distribution changed from a unimodal distribution to a bimodal distribution. The ions velocity corresponding to the lower peak is only slight higher than 0. And the ions, whose speed is located in this region, are called low-speed ions, whereas the ions whose speed is located in the higher peak region are the high-speed ions. And the high-speed ions velocity is about 10000m/s. Apart from these two peak regions, there are some medium-speed ions whose velocity is about 3000m/s-6000m/s exist in the simulation domain as shown in Figure 4. However, the proportion of the medium-speed ions to total ions is much smaller than that of the high-speed ions or low-speed ions. Besides, the cases with only the ME collision process or only the CE collision process are also simulated. Comparing the obtained ion velocity distribution in Figure 4, it is clear that the medium-speed ions is mainly produced by the ME collisions between the ions and neural atoms and the low-speed ions is entirely generated by the CE collision between the ions and neutral atoms.
The velocity distributions of the ions with the consideration of ME and CE collisions between the ions and the neutral atoms during the extinguish period are shown in Figure 5. Firstly, it can be found that the overall ions velocity distribution shifts to a higher value as the current decreases. In conjunction with Figure 3, it means that during the extinguish period, as the number of the ions gradually decreases, the mean velocity of the ions gradually increases. Secondly, as the number of ions decreases, the relative proportion of the high-speed ions and the low-speed ions also changed. At $t = 0$ μs, the ratio of the high-speed ions and low-speed ions to the total ions is almost the same, whereas at $t = 9.25$ μs the proportion of low-speed ions is much larger than that of the high-speed ions. In miller’s experiment [13], a large number of low-speed ions were also found at the time of arc extinction, which is consistent with our simulation results. And the production of these low-speed ions is resulted from CE collision process during the extinguish period. What’s more, it indicates that at current zero, most of the residual ions between the electrodes have a lower velocity, which will cause the residual ions to exist for a long time during the post-arc period.
4. Conclusion

Briefly, a 3D hybrid vacuum arc model with ion-neutral collisions has been developed, in which the electrons is treated as a massless fluid and the ions are treated as macro particles. The simulation results show that a large number of low-speed ions are generated in the interelectrode region due to the charge exchange collisions between the ions and neutrals. And as the arc current drops to zero, the proportion of low-speed ions to the total ions at each moment becomes higher and higher during the extinguish period, which is consistent with the experiment results.

5. References

[1] Flourentzou N, Agelidis V G and Demetriades G D 2009 IEEE Trans. Power Electron. 24 592
[2] Schade E 2005 IEEE Trans. Plasma Sci. 33 1564
[3] Sarrailh P, Garrigues L, Hagelaar G J M, Boeuf J P, Sandolache G and Rowe S 2009 J. Appl. Phys. 106 053305
[4] Sarrailh P, Garrigues L, Boeuf J P and Hagelaar G J M 2010 Plasma Sources Sci. Technol. 19 065020
[5] Wang Z X, Wang H R, Zhou Z P, Tian Y B, Geng Y S, Wang J H and Liu Z Y 2016 J. Appl. Phys. 120 083301
[6] Schade E and Shmelev D L 2003 IEEE Trans. Plasma Sci. 31 890
[7] Wang L J, Jia S L, Shi Z Q and Rong M Z 2005 J. Phys. D: Appl. Phys. 38 1034
[8] Shmelev D L and Uimanov I V 2015 IEEE Trans. Plasma Sci. 43 2261
[9] Cao Z Y, Wang Z X, Chen F, Xu Y D, Sun L Q, Geng Y S and Wang J H 2020 J. Phys. D: Appl. Phys. 53 405202
[10] Beilis I I and Zektser M P 1991 High Temp. 29 501
[11] Beilis I I, Keidar M, Boxman R L and Goldsmith S 1998 J. Appl. Phys. 83 709
[12] Kutzner J and Miller H C 1992 J. Phys. D: Appl. Phys. 25 686
[13] Miller H C 1972 J. Appl. Phys. 43 2175

Acknowledgments

This work was supported by the science and technology project of China Southern Power Grid Company (GDKJXM20184109).