Collision Effects on Sheath Development after Interrupting a Vacuum Arc

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***Abstract*- Sheath development dominates the initial stage of dielectric recovery process after interrupting a vacuum arc. The objective of this paper is to simulate sheath development after interrupting a vacuum arc considering collision between ions and background neutral metal vapor. We adopted Particle in Cell-Monte Carlo Collisions (PIC-MCC) method and a one-dimensional sheath model was developed. We assumed a Maxwellian velocity distribution for the neutral metal vapor, ions and electrons at temperature 0.2eV, 2eV and 3.5eV at the start of recovery, respectively. The results show that a higher density of background neutral metal vapor tends to increase the completion time of sheath development. Moreover, the completion time of sheath development becomes faster as the rising rate of a TRV increases, and the completion time of sheath development becomes slower as initial ion density increases.**

I. INTRODUCTION

Sheath development has been extensively studied in order to understand dielectric recovery behavior of a vacuum circuit breaker [1-6]. After current zero, there are many particles remained in a switching gap including metal vapor, residual plasma and droplets[7]. Moreover, the decay of these particles, which is under the influence of a transient recovery voltage (TRV), plays a decisive role in the sheath development.

At the beginning of a dielectric recovery process, quasi-neutral plasma which is composed of ions and electrons remains in a contact gap with background neutral metal vapor. Moreover, both electrons and ions move away from a cathode to an anode. With the effect of a TRV, the electrons quickly reverse their moving direction toward the post-arc anode (former cathode) due to their lighter mass, but the ions first remain there. Thus, a sheath forms in front of the post-arc cathode (former anode) and develops toward the post-arc anode. Moreover, the potential drop from the TRV impresses across the sheath and nearly no voltage drop across the rest plasma. Therefore, the contact gap is divided into two regions: the positive ion sheath and the quasi-neutral plasma. The sheath development dominates the initial stage of dielectric recovery processes after current zero. In this stage, the residual plasma does not dissipate from the contact gap at all and a very high electric field in front of the post-arc cathode resulting from the sheath development may lead to a breakdown process.

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In order to describe a dynamic positive ion sheath, many researchers have developed various numeric models. Andrews and Varey[1] provided a continuous transition model which was deduced from Child's law and the ion matrix model to describe sheath development. This model is so successful that many researchers refer to it to predict sheath development after current zero[8]. Childs and Greenwood[2] improved the continuous transition model by adding an ion-neutral fluid to the model. Thus, the improved model can describe the whole physical processes just before current zero and after current zero. Sarrailh et al.[6] proposed a new model based on the Maxwell-Boltzmann law and took account of the effect of collisions between neutral vapor and ions using direct Monte-Carlo collision simulation. This model is an important improvement to the Andrews and Varey's model in light of considering the collision effects in sheath development. However, in the Sarrailh et al.'s model, the collision frequency of electrons is supposed to be constant in order to make sure the electron temperature decays naturally, which does not agree with practical situation of sheath development because the collision frequency will decline as the plasma density decays.

The objective of this paper is to simulate the evolution of sheath development considering the collisions of ions and the background neutral metal vapor at the initial stage of dielectric recovery process after current zero. We adopted Particle in Cell-Monte Carlo Collisions (PIC-MCC) method and a model with one dimension in physical space and three dimensions in velocity space was developed. The velocity of the sheath's edge and the decay rate of the ion density were calculated. We also evaluated the influence of neutral vapor density, the rising rate of the TRV and the initial ion density on the evolution of the sheath development.

II. SIMULATION OF SHEATH DEVELOPMENT

A. Priciples of PIC-MCC

In the PIC-MCC[9], one do not care any single particle, but collective clouds of them called "macro-particle" which represents a group of particles. At a large distance the force between two

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macro-particles can be represented by a Coulomb force. But the force starts to become weaker than the corresponding Coulomb force as the two macro-particles contact. Moreover, we adopt Monte Carlo method to simulate the collision of the two macro-particles at a small distance.

The PIC-MCC program consists of five sequencing steps to complete one time calculation as shown in Fig. 1. The motion of particles is solved by Newton's equation:

$$\frac{d\vec{v}}{dt}=\frac{\vec{F}}{m}=-\frac{q\nabla\varphi}{m}=\frac{q\vec{E}}{m} \quad (1)$$

where *v* is the velocity of the particles, t is the time step of the simulation, *F* is the electric force driving the particles to move, *q* is the electric charge, m is the mass of the particles, φ is the electric potential of the electric field and *E* is the electric field strength. Then the program uses Monte Carlo method to evaluate the possibility of the collisions between particles and background vapor and recalculate the velocity of the particles. The possibility of the collisions can be described as:

$$P=1-\exp[-v\Delta t\sigma(\varepsilon)n(x)] \quad (2)$$

where *P* is the possibility of the collisions, *v* is the velocity of the particles, Δt is the time step of the simulation, σ is the total cross sections of all kind of collisions, ε is the energy of the particles and n is the background vapor density. The program can generate a random number for every macro-particle and a collision event occurs if the random number is less than the possibility of the collisions. Then the program distributes the particle to the cell grid points of simulation according to the weight of the particles. After that the electric field at grids can be solved by Poisson's equation:

$$\nabla^2\varphi=-\frac{\rho}{\varepsilon_0}=-\frac{e}{\varepsilon_0}(n_i-n_e) \quad (3)$$

where φ is the electric potential of the field, ε_0 is the vacuum permittivity, ρ is electric charge volume density, *e* is electron charge, n_i is ion density, and n_e is electron density. Finally, the calculated electric field force is fed back to make the particle continue to move. A review of the PIC-MCC method can be found in[9].

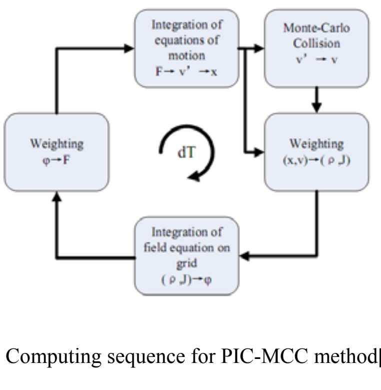


Fig. 1. Computing sequence for PIC-MCC method[10]

B. The Numerical Model

With the aid of PIC-MCC method, we can estimate sheath development and the decay rate of ion density in the dielectric recovery process after current zero considering the collisions between the ions and background neutral metal vapor. A model with one dimension in physical space and three dimensions in velocity space was developed with a gap length of 5mm between the contacts. We assumed a Maxwellian velocity distribution for the background neutral vapor, ions and electrons at temperature 0.2eV, 2eV and 3.5eV[11, 12] respectively at the start of recovery. The grid spacing was equal to half of Debye length and the time step was equal to a tenth of plasma oscillation period. There was no secondary emission from the contact surfaces considered during the simulation processes, and charged particles were absorbed by the boundaries when they reached the boundaries (contact surfaces) of the model. We considered the influence of ion-neutral collisions which include two kinds of collisions: charge exchange collision and momentum exchange collision. The ion-neutral cross section curves have the form[13]:
the cross section of charge exchange collision σ_{ex}

$$\sigma_{ex}=(7.0-0.38\ln\varepsilon)^2\times10^{-20} \quad (4)$$

the cross section of momentum exchange collision σ_{mx}

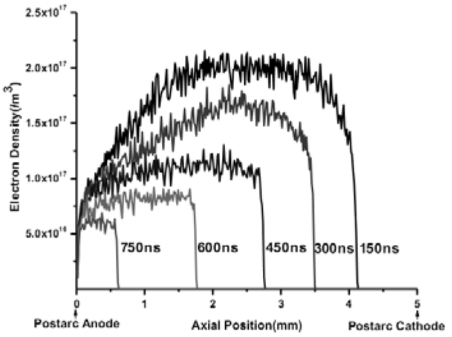
$$\sigma_{mx}=(6.45-0.365\ln\varepsilon)^2\times10^{-20} \quad (5)$$

where ε is the ion energy and σ_{ex}, σ_{mx} are in units of meters squared.

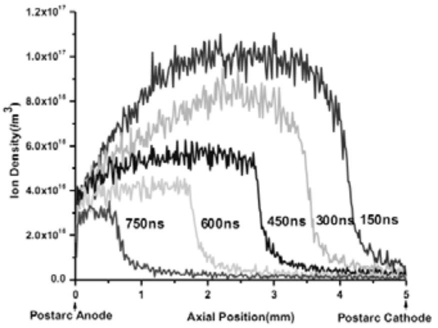
The neutral metal vapor density which remained constant during a simulation was varied from $10^{18}/m^3$ to $10^{21}/m^3$. The plasma was composed of electrons and Cu^{2+}. The initial ion density n_i was varied from $10^{16}/m^3$ to $10^{18}/m^3$. The initial electron density was twice as large as that of the ion to keep plasma neutral. We impressed a negative TRV across a contact gap in vacuum with a linearly rising rate η which was varied from 0.1 kV/μs to 2 kV/μs.

III. RESULTS AND DISCUSSION

Fig. 2 (a) and (b) show the evolution of electrons and ions density distribution along contact gap after current zero. The initial ion density n_i was $10^{17}/m^3$. The background neutral metal vapor density n_0 was $10^{20}/m^3$. The rising rate of the TRV η was 1kV/μs. The electrons and ions decayed with time by the action of the TRV and were absorbed by the post-arc cathode gradually. The decay rate of the electrons was faster than that of the ions so there was a positive space charge expanding between the post-arc cathode and the edge of the plasma. Fig. 2 (c) shows the evolution of voltage drop potential distribution along contact gap after current zero. The whole voltage was applied across the sheath in front of the post-arc cathode and expanded with the sheath development.



（a）



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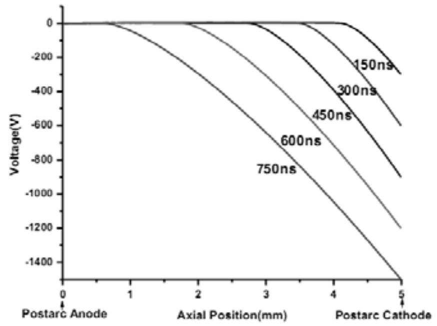
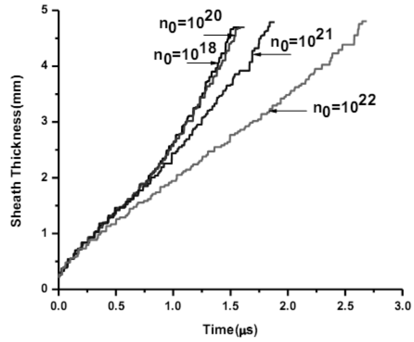


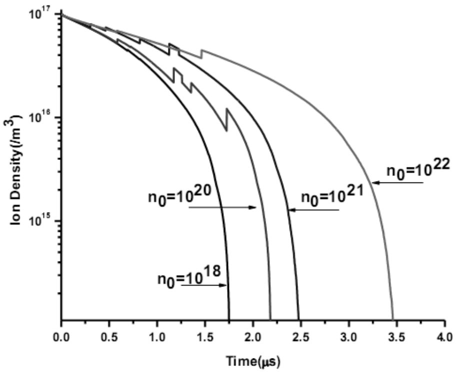
(c)

Fig. 2. The evolution of density and voltage potential distribution along axis after current zero. (a)electron density; (b)ion density; (c)voltage drop potential. $n_i=10^{17}/m^3$, $n_0=10^{20}/m^3$, η= 1kV/μs.

Fig. 3 (a) and (b) show the influence of background neutral metal vapor on the sheath development and decay of the ions. The initial ion density n_i was $10^{17}/m^3$. The rising rate of the TRV η was 1kV/μs. As shown in Fig. 3 (a), the sheath development was correlated with the background neutral metal vapor density and the completion time of the sheath development increased from 1.5μs to 2.7μs as n_0 increased from $10^{18}/m^3$ to $10^{22}/m^3$. In addition, the sheath velocity was much slower with a higher neutral metal density. The results indicate that the collision has a significant influence on the sheath development in a high background neutral metal vapor density but has a low influence on the sheath development in a low background neutral metal vapor density. As shown in Fig. 3 (b), the decay time increased from 1.7μs to 3.5μs as the neutral metal vapor density increased from $10^{18}/m^3$ to $10^{22}/m^3$. The ions tended to remain in the gap longer as the density of neutral metal vapor increased.



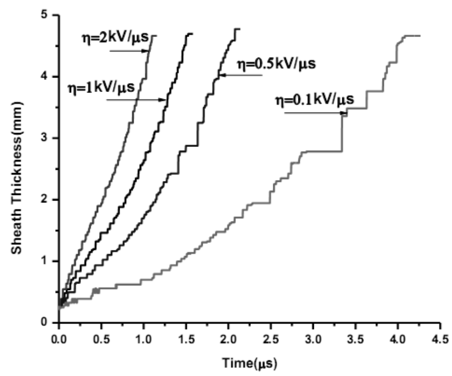
(a)



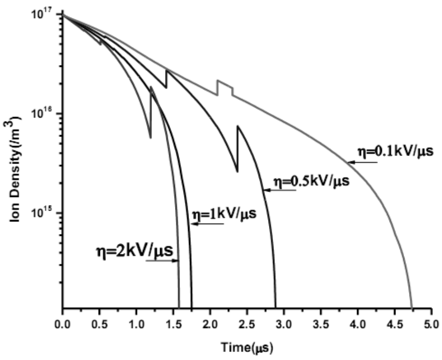
(b)

Fig. 3. The influence of background neutral vapor n0. (a)sheath development; (b)the decay of ion density. ni=1017/m3, η= 1kV/μs.

Fig. 4 (a) and (b) show the influence of rising rate η of the TRV on the sheath development and decay of the ions. The initial ion density n_i was $10^{17}/m^3$. The background neutral metal vapor density n_0 was $10^{18}/m^3$. As shown in Fig. 4 (a), the completion time of the sheath development increased from 0.9μs to 4.2μs as η decreased from 2kV/μs to 0.1kV/μs. As shown in Fig. 4 (b), the decay time of ions increased from 1.6μs to 4.7μs as η decreased from 2kV/μs to 0.1kV/μs. The results indicate that a higher rate of rising voltage tends to expel the ions from the gap more rapidly and the sheath reaches the post-arc anode more quickly.



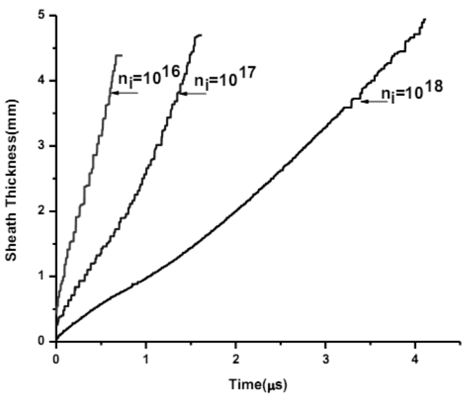
(a)



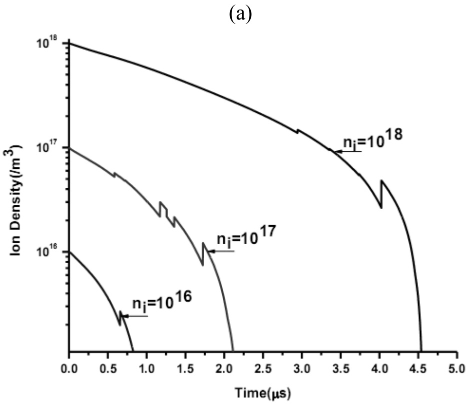
(b)

Fig. 4. The influence of the rising rate η of the TRV. (a)sheath development; (b)the decay of ion density.$n_i=10^{17}/m^3$, $n_0=10^{18}/m^3$.

Fig. 5 (a) and (b) show the influence of initial ion density n_i on the sheath development and decay of the ions. The background neutral metal vapor density n_0 was $10^{20}/m^3$. The rising rate of the TRV η was 1kV/μs. As shown in Fig. 5 (a), the completion time of the sheath development increased from 0.6μs to 4μs as the initial ion density n_i increased from $10^{16}/m^3$ to $10^{18}/m^3$. As shown in Fig. 5 (b), the decay time increased from 0.7μs to 4.5μs as n_i decreased from$10^{16}/m^3$ to $n_i=10^{18}/m^3$. The results indicate that the ions decayed slowly as the initial ion density was higher. Moreover, the possibility of collision between the ions and background neutral vapor was increased if the ion density is higher. Thus the decay time of the ions will increase.



(a)



(b)

Fig. 5 The influence of the ion density n_i. (a)sheath development; (b)the decay of ion density.$n_0=10^{20}/m^3$, η= 1kV/μs.

IV. CONCLUSIONS

We adopted PIC-MCC method to simulate sheath development at the initial stage of dielectric recovery after interrupting a vacuum arc current. Moreover, we considered collision between ions and background neutral vapor in the sheath development. A model with one dimension in physical space and three dimensions in velocity space was developed with a gap length of 5mm between the contacts. We assumed a Maxwellian velocity distribution for the background neutral vapor, ions and electrons at temperature 0.2eV, 2eV and 3.5eV respectively at the beginning of recovery. The results show that a higher density of background neutral metal vapor tends to increase the completion time of sheath development. Moreover, the completion time of sheath development becomes faster as the rising rate of a TRV increases, and the completion time of sheath development becomes slower as initial ion density increases.

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