

THE PRELIMINARY ANALYSIS UPON THE MOVEMENT BEHAVIOR OF ELECTRONS IN PULSED VACUUM ARC

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Abstract: This paper, in the viewpoint of plasma, presents the preliminary analysis upon the movement behavior of electrons in the pulsed vacuum arc, the superposition of rotary motion with drift in electric field as the result of the impacts by the magnetic field and electric field. The analysis and the corresponding experiment phenomena agree well.

Key word: Movement behavior, Pulsed vacuum arc, Rotary motion, Drift in electric field

1. Introduction

The pulsed vacuum arc, occurred in the operations of the vacuum circuit breaker largely used in power systems [1] and the trigger vacuum switch (TVS) wide used in pulsed power [2], will radiate high frequency electromagnetic interference (EMI) and put serious influence on the equipments sensitive to electromagnetic field, as well as the electromagnetic radiation generated by arcing in low density plasma in outer space [3][4]. Hence the analysis upon the movement behavior of electrons in vacuum arc is helpful to the comprehension of the mechanism and characteristics of that EMI, and helpful to improve the methods to keep that EMI away.

2. Experiment setup

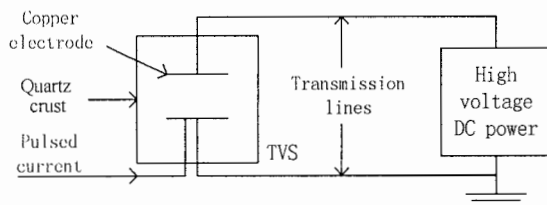


Fig.1 the schematic diagram of the experiment setup

As shown in Fig.1, the high voltage provided by the high voltage DC power is applied to the electrodes of the TVS through the conductor transmission lines, and the pulsed current is generated to ignite the vacuum arc in the TVS. The TVS, being cylinder, has

quartz crust and two plane copper electrodes, and the inner vacuum pressure is more than $1 \times 10^{-4} Pa$.

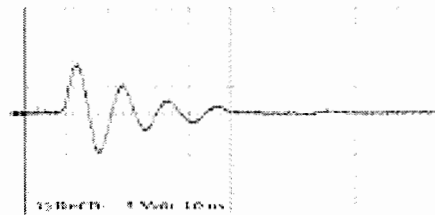


Fig.2 the waveform of the arc current

High voltage being 10KV, the peak of the arc current is about 10KA and the period about $12.5\mu s$, as shown in Fig.2. In this paper the subsequent analysis will be carried out on the basis of this set of parameters (10KV/10KA/ $12.5\mu s$).

3. Distribution of the electric and magnetic fields

As shown in Fig.3, the distance between two electrodes in the TVS is 3cm. Neglecting the brim effect, the electric field there with the direction of negative Z axis is even.

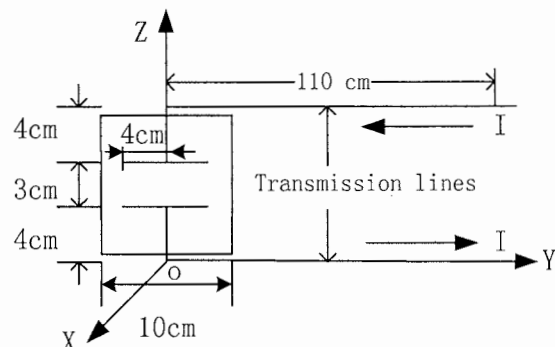


Fig.3 the schematic diagram of the transmission line currents and the TVS

As shown in Fig.3, both upper and down transmission lines are 110cm long and the height of the TVS about 11cm. Accordingly the magnetic field, produced by the transmission line current, can be seen as the composition of the near electric fields of two pieces of half-infinite-long lines. On the other

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hand, the circuit current flows anticlockwise, therefore the magnetic field in plane YOZ is along X axis.

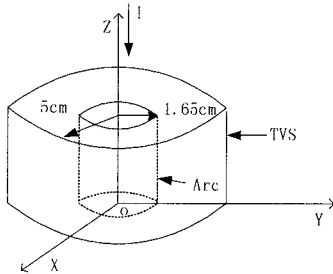


Fig.4 the schematic diagram of the arc in the TVS

As shown in Fig.4, the radius of the TVS is 5cm and that of arc 1.65cm [5]. On even distribution of the current, the value of the magnetic field by the arc current self can be figured out easily. Alternatively the current flows along negative Z axis, then the magnetic field in plane XOY, looked along negative Z axis, is a set of clockwise concentric circles.

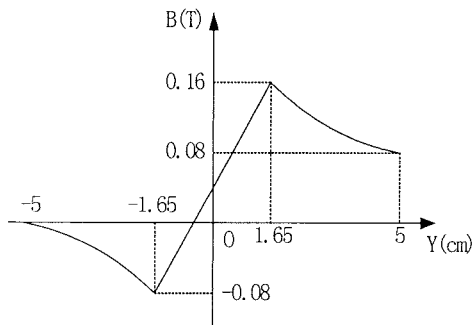


Fig.5 the whole magnetic field in the XOY plane

The whole magnetic field, between the electrodes in the TVS, contains two components: one by the transmission line current and the other by the vacuum arc current self. For instance, under the parameters of 10KV/10KA/12.5 μ s, the distribution of the whole magnetic field in plane YOZ with the direction of X axis is shown in Fig.5.

4. The rotary motion of the electron in stable magnetic field

Based on the orbital theory, the charged particles in the even and stable magnetic field make rotary motion under the lorentz's force, whose radius and period are as followed:

$$r = \frac{mv_1}{qB} \quad (1)$$

$$T = \frac{2\pi m}{Bq} \quad (2)$$

Supposing the magnetic field is 0.16T (in fig.5), the equation above can present the period of electron rotary motion, 0.22ns, far shorter than that of the oscillating current in the circuit. Thus the approximation of the stable electric and magnetic fields is reasonable.

In addition, whether the electrons in the vacuum arc make rotary motion or not lies on two issues: one is the radius of electron rotary motion, and the other the electron mean free path. If the later is far shorter than the former, the electron will make collision with other particles frequently, then the electron rotary motion is impossible.

4.1 The electron mean free path

The collision between the electrons and copper ions in the vacuum arc plasma decides the electron mean free path, that is [6]

$$\bar{\lambda}_e = \frac{1}{\pi n(r_{cu} + r_e)^2} \quad (3)$$

The RMS of the vacuum arc current being 6KA, the density of the particles is about 10^{16} cm^{-3} [7]. The radius of divalent copper ion is about $1.35 \times 10^{-10} \text{ m}$ [8], far bigger than that of electron, so the upper equation can present the electron mean free path, $2 \times 10^{-3} \text{ m}$.

4.2 The radius of electron rotary motion

Accelerated in the interval between consistent collisions, the average velocity of electrons is

$$v_e = \frac{1}{2} \sqrt{\frac{2e}{m_e} (U \frac{\bar{\lambda}_e}{l})} \quad (4)$$

In which the U is the arc-voltage about 20~50V [9] and the l is the distance between two electrodes in the TVS. Hence the radius of electron rotary motion is

$$r_e = \frac{1}{2} \frac{m_e}{Be} \sqrt{\frac{2e}{m_e} \left(U \frac{\bar{\lambda}_e}{l} \right)}$$

$$= \frac{1}{B} \sqrt{\frac{m_e}{2e} \left(U \frac{\bar{\lambda}_e}{l} \right)} \quad (5)$$

Supposing the arc voltage 50V and the magnetic field 0.16T (in Fig.5), the equation above can present the radius of the electrons rotary motion, $4 \times 10^{-5} m$.

Comparing r_e and $\bar{\lambda}_e$, it is reasonable that electrons make rotary motion.

5. The drift of charged particles in electric field

In a stable magnetic field, the perpendicular electric field will arouse a drift of charged particles. Considering a stable electric field, the expression of the drift velocity is [10]

$$\vec{v}' = \frac{\vec{E} \times \vec{B}}{B^2} \quad (6)$$

From the equation above, the drift velocity only relates to the electric and magnetic fields, and the direction is perpendicular to both the electric and magnetic field.

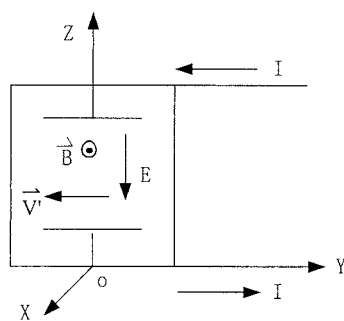


Fig.6 the drift by the transmission line current

In the magnetic field produced by transmission line current, as shown in Fig.6, current flowing anticlockwise in the circuit, the electric field is along negative Z axis. Hence the drift velocity as followed is along negative Y axis.

$$\vec{v}' = \frac{\vec{E} \times \vec{B}}{B^2} = \frac{E}{B} \vec{e}_E \times \vec{e}_B$$

$$= -\frac{E}{B} \vec{e}_z \times \vec{e}_x = -\frac{E}{B} \vec{e}_y \quad (7)$$

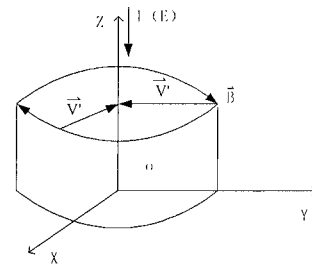


Fig.7 the drift by the arc current self

In the magnetic field produced by arc current self, as shown in Fig.7, the current being along negative Z axis, the electric field is along negative Z axis. For this reason, the drift velocity as followed is along the negative radial direction.

$$\vec{v}' = \frac{\vec{E} \times \vec{B}}{B^2} = \frac{E}{B} \vec{e}_E \times \vec{e}_B$$

$$= \frac{E}{B} \vec{e}_z \times \vec{e}_\phi = -\frac{E}{B} \vec{e}_r \quad (8)$$

6. The analysis upon the experiment phenomena

As shown in Fig.8, arc will leave away from the circuit in the experiment, which has been mentioned in other similar experiments but only explained by the electrodynamic force [11][12]. This interpretation is too simple to fit the experiment, because amounts of charged particles, contained in the arc plasma, will make rotary motion and drift, far different from the movement of the conductor line by the electrodynamic force. Implementing the results above, the phenomena can be interpreted as followed:

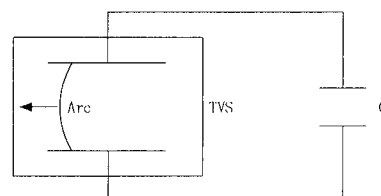


Fig.8 arc leaving away from the circuit

1) The drift in the electric field, under the magnetic field by the transmission line current, is along negative Y axis, and its direction has nothing to do

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with the charge and the mass of the particles. That is to say, the whole arc plasma in the TVS makes a drift along negative Y axis, which coincides with the experiment phenomena;

2) The variation of the current in the circuit has no impacts on the drift since the drift only relates to the electric and magnetic field. If the current inverts, that is both the electric and magnetic field invert at the same time, then the drift remains unchanged.

Conclusions and problems

1) Under the electric and magnetic field, the movement behavior of electrons in vacuum arc is the superposition of rotary motion with drift by electric field.

2) Arc leaving away from the circuit is the macroscopical behavior of the drifts by electric field under the magnetic field generated by the transmission line current.

3) The drifts by gradient, curving and time-varying magnetic field, which are ignored in this paper, are supposed to be considered subsequently in order to get more conclusions.

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