Diagnosis of Post-Arc Residual Plasma in Vacuum Breaker

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Abstract: The residual plasma in the gap between the anode and cathode has an important influence on the recovery characteristics of the medium after the arc current zero in the vacuum arc extinguishing chamber. A diagnostic system for post-arc residual plasma is proposed and designed to diagnose the density of residual plasma during sheath expansion. The experimental platform is built on the basis of the synthetic circuit and detachable vacuum chamber. The diagnostic system uses Langmuir probe array to diagnose the post-arc plasma density change in vacuum interrupter, which reflects the dynamic process of sheath expansion in the gap. The effect of different current sizes and contact spacing on residual plasma is discussed in this paper. The plasma densities diagnosed by different position probes are used to analyze the post-arc characteristics of vacuum circuit breakers from a micro-level. The accuracy and reliability of the diagnostic system are verified by comparing with the previous studies, which provides some reference value for the future research on the post-arc micro-characteristics of vacuum breaker.

1. Introduction
With the trend of global warming becoming more and more serious, environmental protection has become one of the important considerations for the development of various industries at home and abroad. In recent years, in the field of power switches, vacuum switches have been widely used for their excellent insulation and arc extinguishing ability, low carbon and environmental protection, easy maintenance and long service life.

Long time and other advantages, it has become one of the key development directions of switches in the field of low and medium voltage [1]. The post-arc characteristics of vacuum switches have an important influence on the successful opening and closing of current, and the arc is composed of plasma.

At present, domestic and international researchers have carried out a considerable amount of work on the static and dynamic insulation characteristics, open-end gain characteristics, dynamic voltage equalization, operating mechanism and magnetic field regulation of vacuum switches and achieved a lot of results, but there is no in-depth and detailed study on the microscopic characteristics such as electron density, electron temperature and sheath layer development of the plasma in the gap when the vacuum switch arc current exceeds zero [2].

Whether the vacuum switch can successfully open and close the short-circuit current has a direct relationship with the existence of post-arc plasma in the arc extinguishing chamber. When the arc current transitions near the zero region, for most cases, the vacuum arc will extinguish itself when the arc current drops to a threshold of only a few amperes, and after the arc current crosses zero, the Transient Recovery Voltage (TRV) of opposite polarity rises in the contact gap and a sheath layer forms near the cathode and gradually expands. When the current is successfully interrupted, the residual post-arc plasma is
discharged from the gap, however, when the plasma in the gap does not diffuse out of the gap in time, there is a risk of reigniting the arc, resulting in the failure of the vacuum switch to interrupt the short-circuit current [3], and the voltage drop in the contact gap is almost always located in the sheath layer between the cathode contact and the plasma. Obviously, the density and spatial distribution of the post-arc plasma as well as the dynamic process of the expansion of the cathode plasma sheath layer play a key role in the successful opening and closing of the fault current. Some progress has been made in measuring the plasma parameters and modeling the cathodic plasma sheath layer and its dynamics by a single Langmuir probe [3-6].

2. Materials and Methods

The structure of the probe measurement circuit part is shown in Figure 1. R0 is the voltage divider resistor; R1 is the measurement resistor, and the probe current is obtained by measuring the current flowing through the resistor; U0 is the bias voltage, because the value of saturated electron current is usually larger than the value of saturated ion current, and it is more convenient to collect saturated electron current for measurement than saturated ion current, so the bias voltage value is set to 36V, which enables the Langmuir probe to operate in saturated electron current mode; D0 and SCR are diodes and TVS tubes, respectively, to prevent damage to the control circuit and oscilloscope from breakdown by the high arc voltage received on the probe during the opening of the arc extinguishing chamber.

Figure 2 gives a schematic diagram of the probe. The Langmuir probe material used in this paper is a molybdenum wire with a diameter of 1.1 mm, and the probe is covered with an Al2O3 tube with an inner diameter of 2 mm for insulation. This provides, on the one hand, a sufficiently large probe surface area and, on the other hand, a sufficiently small probe size and thus high spatial resolution in the radial and axial directions.

For the single-probe Langmuir probe, the value of the electron density \( n_e \) can be found in the saturated electron current density expression derived from a previous study

\[
j_{es} = \frac{1}{4} e n_e v_e
\]

where \( v_e = (8kT_e/\pi m_e)^{1/2} \) is the electron thermal velocity, and on the other hand

\[
j_{es} = I_{probe}/S_E
\]

Strictly speaking, \( S_E = 2\pi r_E(1 + r_E) \) is not the surface area of the probe, but the region of the plasma emission boundary around the probe, separated from the probe by the sheath layer, as shown in Figure 2. The thickness of the sheath layer around the probe depends on the plasma density around the probe and the potential difference between the probe and the plasma. However, it has been shown [4,5] that, for the conditions of this paper, the sheath thickness on the probe surface is less than 0.25 mm when the plasma density is higher than 1011cm\(^{-3}\). Therefore, to facilitate evaluation and discussion, the original surface area \( S_P \) of the probe is used instead of the plasma emission boundary \( S_E \) in Eq. (2). By this approximation, the final electron density The formula is

\[
n_e(\text{cm}^{-3}) = A_i \times I_{probe}(A)
\]

Which

\[
A_i = \frac{4}{e v_e S_P}
\]
The electron temperature in the vacuum switch is stabilized at 3eV, and the electron thermal velocity corresponding to this electron temperature is set at 108cm/s. The current collected on the probe when the arc current crosses zero can be converted to electron density by the above formula, and the measurement and diagnosis can be made at different locations in the vacuum chamber by setting the scanning probe array. The post-arc plasma density distribution within the vacuum switch and the dynamic process of sheath layer development.

For the study of the vacuum switch on and off process of arc current over zero in the vacuum chamber plasma density distribution and sheath layer development dynamic process, a corresponding experimental circuit was built as shown in Figure 3. The vacuum pump can pump the air pressure of the vacuum chamber to 10^{-4}pa. The current source composed of capacitance and inductance can generate a current of 50Hz at the frequency. The value of C1 is 16000μF, L1 is 600μH. Because the upper and lower pole plates of the vacuum switch are fixed, so a spark switch is needed to turn on the upper and lower pole plates to produce an arc, the control signal is given by the console, which is passed to the trigger device through the optical fiber to produce an electric spark to turn on the upper and lower pole plates in the vacuum switch.

3. Results & Discussion

3.1. Single Probe Diagnostic Test

The present experiments were performed in a vacuum switch with removable interchangeable contacts, in which both the upper and lower electrodes had a diameter of 80 mm and were made of CuCr35 alloy. The probes were positioned outside the gap and were placed on an adjustable bracket, by adjusting the bracket position to diagnose the plasma density near the anode and cathode, respectively. A schematic diagram of the structure is shown in Figure 4. In this paper, a single-probe diagnostic test was performed based on this structure.

In order to investigate the variation of electron density in the gap between different arc current sizes, the arc current size was varied by changing the voltage value for charging the capacitor. The tests were carried out at arc current sizes of 2-5 kA, respectively, and the waveforms of electron density sizes for different cases are shown in Figure 5.
As can be seen from the waveform diagram, as the arc current increases, the value of the electron density in the gap between the upper and lower plates also increases. When the value of arc current is small, the plasma in the gap is quickly discharged. But when the arc current increases, the amount of plasma in the gap increases, and the rate of discharge from the gap is slower than the former. It has been shown that the arc current has a large effect on the plasma density in the gap after the vacuum switch is turned on and off.

In order to study the difference in electron density at different locations of the interarc chamber gap, the electron density near the anode, between the upper and lower plates, and near the cathode were diagnosed by changing the position of the probe on the adjustable holder at an arc current of 5.06 kA and an upper and lower plate spacing of 10 mm, respectively. The electron densities at the different positions are shown in Figure 6. Locations 1, 2, and 3 are near the anode, the center of the gap, and near the cathode, respectively. As shown in the figure, the electron density in the center of the gap at the moment of probe conduction is highest (0s moment), and as the arc current crosses zero (35 μs moment), the plasma is discharged from the plate gap, and the electron density rapidly decreases; because the electric field strength of the cathode is higher than that of the anode when the arc extinguishing chamber turns on the current, the electron density near the cathode is greater than that near the anode, and as the sheath layer develops and expands, the electron density near the electrode is greater than that near the anode. The electron density is also gradually decreasing.

The different contact spacing affects the magnetic induction strength of the gap when the open current is broken [8]. In order to study the plasma density in the gap after breaking the short-circuit current with different spacing of contacts, tests were performed at spacing of 6mm, 8mm, 10m, 12mm and 14mm, with the probe located in the center of the gap. The results of the tests are shown in Figure 7.

At the moment when the arc current passes zero, the electron density in the gap is inversely correlated with the pitch of the contacts, when the pitch is 6 mm, the electron density in the gap decreases slowly, and the plasma gathers in the gap in large quantities, and the chance of reignition is high. When the pitch is 14mm, the electron density in the gap decreases faster, and the plasma is discharged from the gap.
3.2. Scanning Probe Array Test

In order to obtain the overall distribution of electron density inside the arc extinguishing chamber before and after arc extinguishment and the dynamics of sheath layer development, a diagnostic test of post-arc plasma density was performed by scanning probe arrays. As shown in Figure 8-9, the two-bit images of the electron density distribution inside the chamber at the moment when the arc current crosses zero and at the 10μs post-zero moment, respectively, are shown.

From the images, it can be seen that at the moment when the arc current passes zero, the plasma is mainly concentrated in the center of the gap, while with the extinction of the arc, the plasma in the gap is discharged and the plasma is mainly concentrated in the sheath layer formed near the cathode. In the distribution diagram shown in Figure 8-9, the electron density decreases by a factor of 6-7 when the radial distance from the electrode is increased from 2 mm to 20 mm, thus it can be concluded that the plasma density decreases linearly with increasing distance. At the 10 μs instant after the current is zero, the distribution of electron density corresponds to the cathode plasma sheath layer, and the plasma density gradually decreases with increasing distance from the cathode.

4. Conclusions

In this paper, a plasma electron density diagnostic device based on the Langmuir probe diagnostic system is proposed, and the following conclusions are drawn from the post-arc residual plasma diagnostic tests.

(1) When the arc current value is 2kA to 5kA, with the increase in arc current amplitude, the electron density between the upper and lower pole plates of the arc extinguishing chamber increases, which to some extent increases the probability of arc reignition.

(2) The residual plasma after the arc is not evenly distributed in the gap between the interrupting chamber, after the vacuum switch turns off the current, the electrons are mainly distributed near the cathode, in order to increase the reliability of the interrupting chamber, to strengthen the insulation capacity near the cathode.

(3) When the contact spacing is 6mm-14mm, the electron density in the gap at the moment the arc current passes zero is inversely related to the contact spacing, and as the spacing increases, the electron density decreases. The speed of plasma diffusion into the gap is also related to the contact spacing, with the larger the spacing, the faster the plasma diffusion.

(4) The slope of the electron density curve is greatest during the first 5 μs after the arc current crosses zero, during which time the plasma diffuses mainly from the gap into the cavity, followed by a flattening of the electron density decrease. At the moment of arc current crossing zero, the electron density decreases linearly with increasing radial distance from the contact from 2 mm to 20 mm.

Acknowledgments

This paper is one of the phase results of the National Natural Science Foundation of China (51777025) project "Study on the Synergistic Characteristics and Control Mechanism of Multi-Gap Vacuum Arcs of Multi-Break Vacuum Switches".
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