Abstract – Langmuir probes operating in the electron saturation current mode were used to fix a time of sheath approaching a probe position. Probe current was traced just before and after current zero followed by escalation of the transient recovery voltage in a gap with copper electrodes. Probe measurements were accompanied with tracing of post-arc currents. Basic plasma parameters such as the electron temperature and the electron concentration were measured in the vicinity of the arcing gap. Frame imaging with the use of a 4-channel high-speed frame camera allows identifying a position of a hot spot. The data set mentioned above and collected statistically allowed us to reconstruct experimentally the sheath dynamics after the arc current zero.

1. Introduction

Close to the current zero, the vacuum arc gets self-quenched when the discharge current becomes equal to a threshold value lying within few amperes for the majority of metals. After the current zero, an insulating vacuum gap is restored due to expansion of the cathode sheath under the action of transient recovery voltage (TRV) across the gap. Success of recovery of electrical insulation depends on ability of the expanding cathode sheath to prevent growth of the electric field strength and arc reignition. Therefore, the information on the cathode sheath dynamics after current zero is of primary importance. The problem was treated with computational modelling [1] which requires experimental verification.

In the present work, an attempt of reconstruction of cathode sheath dynamics by experimental methods has been undertaken. The probe method was chosen for diagnostics of vacuum arc plasma. Probe measurements were realised in the mode of the electron saturation current.

2. Experimental set-up and methods

Figure 1 shows the experimental set-up. At the ground of experiment lays the Weil-Dobke synthetic circuit simulating operation of VCB in real electric networks without distortion of phases. The synthetic circuit produced 10-ms arcs of the peak current varied within 8 to 15 kA, followed by the standard TRV pulse of amplitude up to 41 kV and rise time varied within 20 to 100 μs.

The contact gap was formed by two identical copper electrodes of 2 cm in diameter. The gap was surrounded by the copper shield simulating a shield inside a commercial VCB. An additional screen was installed to surround the electrode being an anode under the arc current pulse and a cathode under the TRV pulse. This measure allows us to record separately the post-arc current (PAC) collected by the electrode holder and by the electrode itself. The Rogowski coils G₁, G₂, and G₃ were used for PAC measurements. All the coils were properly screened against the electromagnetic noise.

Experiments were carried out at the residual pressure below $10^{-7}$ mbar.

Either single or double probes were used for plasma diagnostics at arc burning. A probe was made from a molybdenum wire and a ceramic tube. Coincidence of tube and wire axes was set accurate to 0.1 mm with the purpose of electrical insulation between a wire and a tube. The outside butt-end of a wire was rounded (Fig. 2, a). This gives the opportunity to provide broad enough probe surface up to 20 mm² with keeping the condition of the cylindrical geometry of the probe and high enough spatial resolution in the radial and longitudinal directions as well.

A set of single probes was used for investigation of sheath dynamics in the open gap after current zero (CZ) followed by the TRV pulse. To resolve the plasma boundary dynamics, longitudinal disposition of probes in a set has been chosen (Fig. 2, a). This gives the dynamics in the longitudinal direction in a single shot. To resolve the dynamics in the radial direction, statistical measurements were performed at different distances from the gap edge.

3. Investigations of plasma parameters and sheath dynamics

A double probe was formed by two probes located near the mean plane of the gap. Plasma electron temperature was measured by fitting probe volt-amperic characteristic (VAC) with the formula

$$i_i(V) = i_i \cdot \text{th}\left(\frac{e(V - \Delta V)}{2kT_e}\right),$$

where $T_e$ is the plasma electron temperature, $i_i$ is the ion saturation current, $V$ is the probe voltage, and $\Delta V$ is difference in probe arm potentials [2]. Temperature values measured with using a double probe depend on
neither probe voltage frequency, arc current, nor the moment of data acquisition in the course of arc burning. All the values of plasma electron temperature were close to 3 eV. We believed further, that the plasma electron temperature after CZ is change slightly and equal to the mean measured at arc burning.

Double probe VAC contains information about plasma density also. To resolve plasma density, knowledge about ion velocity distribution function is required. It is not an easy task since ion distribution function meets dramatic change at CZ. Cathode spots emit plasma flows expanding with velocity $v_d \approx 10^6$ cm/s which exceeds the both thermal velocity and Bohm velocity. In this case the ion current could be described approximately by the equation

$$i_{is} = i_{dir} S_{cs} e < Z > n_e v_d \approx S_{cs} n_e v_d,$$

(2)

where the area collecting the ion current is the probe part faced the flow:

$$S_{cs} = 2Ra = 1.2 \cdot 5.1 \text{ mm}^2 = 6.1 \text{ mm}^2.$$

This gives the plasma density as follows

$$n_e = i_{is} / (0.4 S_{probe} (2kT_e/Mi)^{1/2}),$$

(4)

where the area collecting the ion current is the whole probe surface $S_{probe} = 19 \text{ mm}^2$.

As a result, we have two extreme estimations for plasma density and they differ in factor 2.7. Actual ion velocity distribution is situated between extreme ones. It tends to the low-energy margin with increase in vapour density and cathode spots extinction. It means that equation (4) is more suitable after CZ while long before CZ plasma density is described by equation (3).

So, for samples estimation of plasma density with (3) gives $3 \cdot 10^{14} \text{ cm}^{-3}$ (at arc current 6 kA) and $6 \cdot 10^{13} \text{ cm}^{-3}$ (at arc current 1.2 kA).

But the probe current signal goes down to the noise level just before CZ. This makes difficult measuring plasma density with a double probe. Abrupt fall in the probe signal can be explained tentatively in terms of decrease in plasma density below the limit when a double probe works properly, i.e. probe...
sheathes becomes thicker than distance between probe arms. This could take place when cathode spots extinct at CZ or just before CZ. Another effect of cathode spot extinction is the break of the directed plasma flow. The ion current becomes the Bohm one and this gives also reduction in ion current. To estimate the plasma density at CZ, extrapolation is the only opportunity. However, extrapolation gives rather rough estimation as far as a probe signal is not regular enough in peak values of the arc current. Extrapolation gives the ion saturation current at CZ to be in the range of 0.01 to 0.015 A, which gives the plasma density value to be below $3 \times 10^{12}$ cm$^{-3}$ in shots with the peak current up to 10 kA. The maximum current of the double probe is defined by the ion saturation current and in comparison with an electron current it is insignificant. Therefore for research rare ($10^{12}$ cm$^{-3}$ and lower) plasma (near to CZ) is expedient use of the single probe.

In the case of a single probe electron plasma density values were restored with using the equation (5)

$$v_e = \left( \frac{8kT_e}{\pi m_e} \right)^{1/2} = 1.16 \cdot 10^8 \text{ cm/s at } kT_e = 3 \text{ eV}$$

and the electron saturation current density is considered to be equal to current density onto the probe surface, i.e. $j_e \equiv j_{probe} = i_{probe}/S_{probe}$.

$$n_e(t) = \frac{4j_e(t)}{ev_e}, \quad (5)$$

This approximation is the approximation of the thin probe sheath. Disregarding the space of ions in the sheath, the sheath can be considered as a vacuum diode where the emitter of electrons is a plasma surface and the collector is the probe surface. For the cylindrical diode the current density on the collector is known [6]

$$J_c = \frac{4e_0}{9} \sqrt{\frac{2e m}{D^3 n_e^3}} \left( \frac{1}{\ln(R_e^2 / R_o^2)} \right)^{3/2}. \quad (6)$$

Solving equation (6) numerically finds that the sheath thickness $D$ is 0.3 mm for the probe current of 50 mA that is close to the probe radius. Thus it works well under conditions of these experiments if the probe current is $\geq$ 50 mA, i.e. up to $n_e = 10^{10}$ cm$^{-3}$. In our case

$$n_e \approx 1.13 \cdot 10^{12} i_{probe} (A). \quad (7)$$

Investigation of the cathode sheath dynamics was carried out by registration and the analysis of an electronic saturation current to the circuit of a positive probe. Figure 3 presents a sample of typical electron currents to the probes at the arc current of 10 kA in peak. As a rule after CZ the electron saturation current goes down gradually followed by the drop in the probe current. We associate the probe current drop with the opening of probes by the sheath moving away from the ex-arc gap. The drop in the probe current gives us a possibility to fix the sheath dynamics. We consider middle points in probe current drops as moments when the sheath opens probes by half (moments $t_1$, $t_2$, $t_3$ in Fig. 3). Those moments could be fixed accurate to 0.1 μs. After opening of probes the probe current is close to zero and practically does not change at change of the TRV. Thus, a potential probe gives the unique opportunity to record unambiguously the sheath behaviour. Figure 4 presents a sample pattern of sheath dynamics.
vertical position, mm

Horizontal position, mm

Fig. 4. Spline-supplemented 2D plot of probe half-opening delay time vs. probe position at $I_{\text{max}} = 8$ kA and TRV rate of $-0.8$ kV/µs. Probe positions are shown with circles.

As the distance from TRV cathode to the probes is known, average velocity of the quasi neutral plasma edge expansion at the time $t_i - t_V$ can be estimated as

$$v_b = (x^2 + z^2)^{1/2}(t_i - t_V)^{-1},$$

where $x$ and $z$ are positions of probe relative to an upper electrode (TRV cathode). The sheath expansion velocity was measured to be close to the plasma ion thermal velocity (about $10^5$ cm/s). Average electric field strength at the cathode was estimated as

$$E = v_b^{-1}dV/dt.$$ (9)

The electric field strength was estimated such to be about $10$ kV/cm that corresponds to the minimum of the Pashen curve for commercial VCBs [3].

4. Conclusion

In the work the results of measurements of plasma electron temperature and plasma density of high current vacuum arc are presented. Plasma electron temperature and plasma density at arc burning were measured by single and double probes. Plasma electron temperature doesn’t depend on arc current and reaches values up to $3$ eV when it is measured by a double probe. After CZ plasma density goes down to values at which the electron saturation current continues to be the only measurable parameter of probe characteristics allowing one to evaluate plasma density. The sheath electric field strength was found to be about $10$ kV/cm. Such a field is not strong enough to initiate the vacuum breakdown. However, such a field being enhanced by relief irregularities is strong enough to initiate formation of liquid-metal cones followed by the explosion emission and breakdown [7].

References