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DETERMINATION OF CR DENSITY IN THE ACTIVE PHASE OF A HIGH-CURRENT VACUUM ARC

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Abstract. Melting and evaporation of the anode surface strongly influence the interruption capability of vacuum circuit breakers, because they lead to injection of atomic vapour into the inter-electrode gap. Determination of the vapour density and its dynamics with respect to different anode phenomena is therefore of great importance. Results of Cr density measurements in a high-current vacuum arc by using broadband absorption spectroscopy are presented. The vapour density of atomic Cr is determined after the formation of anode spots as well as close to the current zero. Cr I resonance lines at 425.43 nm have been used for the analysis. An AC current pulse with maximum value of 7 kA and a frequency of 100 Hz is applied to a vacuum arc between two cylindrical butt electrodes made of CuCr7525 with a diameter of 10 mm. The high-current anode modes are observed by means of high-speed camera imaging. The temporal evolution of the Cr ground state density is presented and discussed.

Keywords: vacuum arc, anode spot, absorption spectroscopy.

1. Introduction

The application of vacuum circuit breakers in medium voltage is still growing. Among other advantages this type of devices has a high grade of environmental compatibility and, therefore, has distinct perspectives for future applications. The great interest in developing vacuum circuit breakers for high-voltage applications leads to continuous basic research in the field of vacuum arcs. It is well known that the high-current anode phenomena have a distinct impact on contact erosion and interrupting capability [1, 2]. Therefore, studies of related processes during the arcing as well as after the arc extinguishing are of great importance for application-driven research.

In the high-current modes the anode emits metal vapour into the arc column which can exist also after current interruption and is a potential reason for failure of vacuum interrupters [1]. Axial and radial behaviour of the arc spectra which consist of different atomic and ionic lines during various high-current anode modes was recently investigated by means of emission spectroscopy [3].

In the case of low optical emission, like e.g. during and after the current zero crossing, another techniques must be used for quantitative analysis. The broadband absorption technique is applied in high-current vacuum arcs to determine the Cr I density within first several milliseconds after current zero in case of anode spot type 2 in [4]. The chromium density after current zero is compared for two types of anode spot in [3].

In the present work a broadband absorption technique is used for diagnostics of high-current vacuum arcs in order to determine the chromium ground state density in the presence of anode spot during the active phase and close to the current zero. AC 100 Hz as an interrupting current with a peak value of about 7 kA is applied.

2. Experimental Setup

The schematic representation of the experimental setup is shown in Fig. 1. The power source which consists of capacitors, inductances, charging and control units was used to generate a sinusoidal alternating current at 100 Hz. Five LC elements are applied in parallel. The capacitance and inductance of each branch amounts to 512 µF and 4700 µH, respectively.

An ultra high vacuum chamber with a basic pressure below 2×10^{-8} mbar is equipped with mounting adapters for different electrodes. In this work, cylindrical butt electrodes made of CuCr7525 alloy with a diameter of 10 mm are used. The upper electrode is fixed and serves as an anode which is connected to the power supply. Whereas the lower electrode which is the cathode can be moved down simulating the opening of a vacuum circuit breaker. The contact opening speed is adjusted to 2 m/s. The chamber is equipped by two optical quartz windows which make it accessible for optical diagnostics. The diameter of the windows of about 20 cm allows for application of several diagnostic techniques simultaneously.

The observation of the arc dynamics and of the anode activity is realized by means of a high-speed

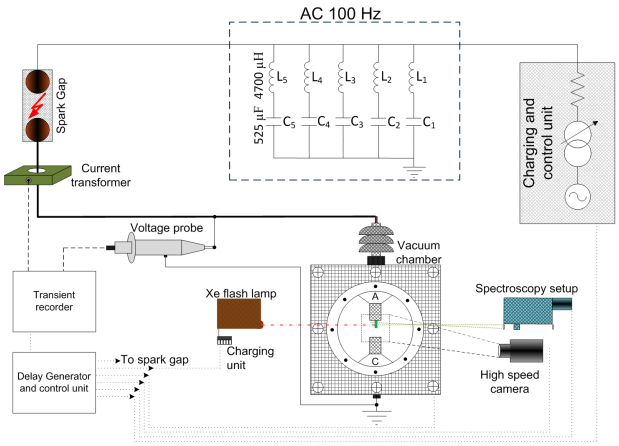

Figure 1. Electrical setup and test object configuration. Five LC elements are coupled in parallel in order to obtain pulses of AC 100 Hz. Spark gap and delay generator are applied for triggering and time control of the experiment.

video camera (IDT MotionPro Y4) with a recording speed of 20 000 fps. A pulsed high-intensity xenon lamp with a pulse width of 1 ms acts as background radiation source [4]. The xenon lamp is aligned on the left side window of the vacuum chamber. Its radiation is directed through the vacuum arc on the optical axis and coupled to the spectrometer entrance slit that is located near the right side window [4]. Making use of a deflecting and a focusing mirror the arc is observed along a line perpendicular to the electrode surfaces, i.e. along the arc axis. The radiation is spectrally dispersed using a spectrograph (Andor Technology Ltd. Shamrock 750) with 0.75 m focal length. To achieve a high spectral resolution, a grating with 1800 lines/mm and an entrance slit of 50 µm width are used. Registration of acquired spectra spatially resolved in one direction is performed by an intensified charge coupled device (iCCD) camera (Andor Technology Ltd. iStar-DH334T-18H) with a 1024×1024 pixels chip. The arc current and voltage are measured by a Pearson current monitor and a voltage probe Tektronix 6015A, respectively. The voltage probe is connected to the external electrical contacts of the vacuum chamber.

3. Theory

Absorption spectroscopy is performed by positioning the xenon lamp as background radiation source behind the test object. One and the same spectrograph is used to capture the radiation of the plasma and the radiation of the background light. For this purpose two optical paths were aligned to the spectrograph slit making use of different mirrors. One optical path is aligned in such a way that the plasma radiation is captured only, while the other optical path allows for the registration of the radiation of both the plasma and the lamp (cf. Fig. 2). Both optical paths are positioned in the same horizontal plane in parallel to the anode surface.

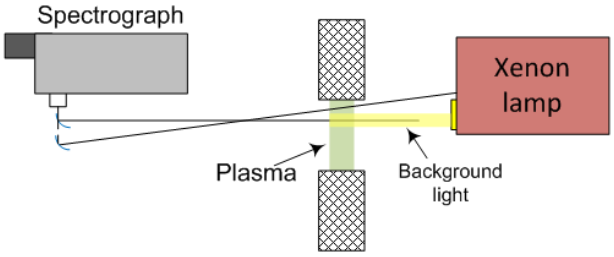

Figure 2. Schematic representation of absorption experiment. Both optical paths are in the same horizontal plane in parallel to the anode surface.

Fig. 3 represents the image of iCCD camera which contains the space-dependent absorption spectra of the background light source and the plasma (Fig. 3a) as well as of the plasma only (Fig. 3b). Both spectra are measured in a wavelength range covered by the spectrometer. The grey colour background corresponds to the light emitted by xenon lamp. As it can be seen from the figure the background light source radiation is less intense than the plasma radiation. Chromium atoms actively participates in the plasma processes becoming excited in collisions with the electrons and emitting the light due to the decay of corresponding excited states. This radiation is added to that of the lamp. After the current zero crossing the density of excited state rapidly decreases and there is no considerable light emission from the plasma. In this case the intensity of the lamp is much higher than that of the plasma leading to dark stripes in absorption spectra [4]. The intensity of the background source is nearly constant in the analysed spectral interval. The three thin vertical lines at 425.43 nm, 427.78 nm, and 428.97 nm correspond to three resonance lines of Cr I. For further evaluation the transmission T has to be calculated by [4]:

$$T = \frac{PL - P}{L} \tag{1}$$

where PL is the radiation of the plasma and the background light source, P means the plasma radiation only and L the background light source only. The background light source spectrum is measured separately and verified to be stable in terms of shot to shot variation. For particle density estimation the results obtained for Cr I 425.43 nm resonance line will be shown. The analysis made in Ref. [4] has clarified that the density obtained with the data for other two lines is very similar. According to the Lambert-Beer law the absorption coefficient k can be obtained from transmittance T by [4]:

$$T(\lambda) = \exp(-k(\lambda)D) \tag{2}$$

where $k(\lambda)$ is the absorption coefficient and D is the effective absorption length which is estimated to be equal to the electrode diameter of 10 mm in the present experiment. The absorption coefficient is related to

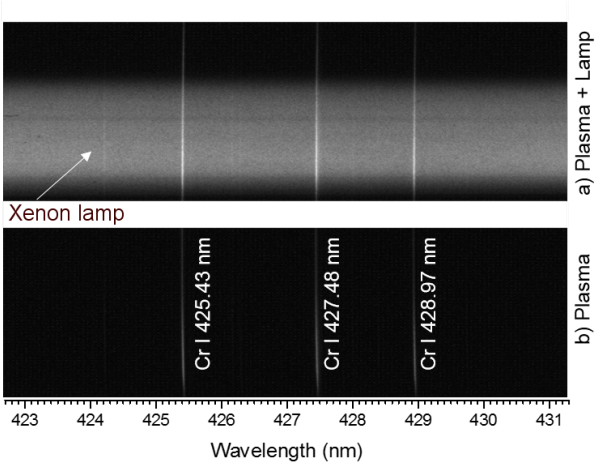

Figure 3. Sample 2D spectrum with three Cr I lines. The vertical dimension of each sub-image is about 3 mm. Anode and cathode are in top and bottom direction outside of the image, respectively.

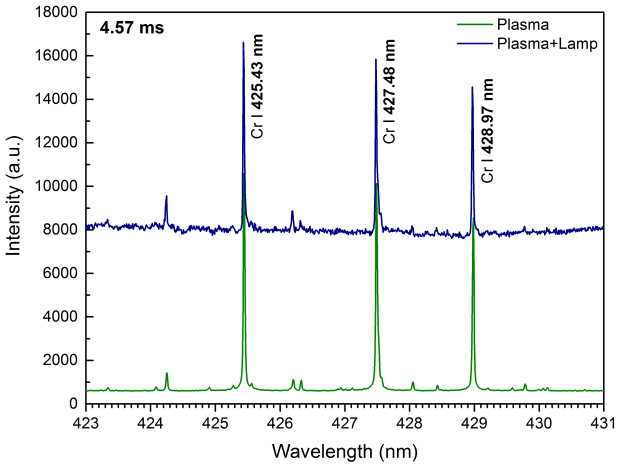

Figure 4. The relative intensities of the plasma emitted light and the background light source integrated along the wavelength.

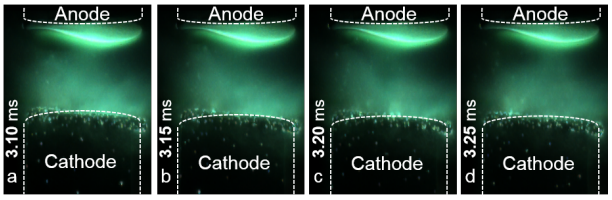

Figure 5. The high-speed camera images during the formation of anode spot type 1. The times are corresponding to the acquisition time of spectrograph.

the lower state population density n_l of the transition by following formula [4]:

$$\int_0^\infty k\,D\,d\lambda = \int_0^\infty \ln\left(\frac{L_\lambda}{PL_\lambda - P_\lambda}\right) d\lambda = \frac{\pi e^2 \lambda_0^2 D n_l f_{\mathrm{lu}}}{4\pi\varepsilon_0 m_\mathrm{e} c^2} \qquad (3)$$

where ε_0 is the electric permittivity, m_e denotes the electron mass, c is speed of light in vacuum, e is the elementary charge, f_{lu} denotes the oscillator strength, and λ_0 is the centre wavelength of the considered transition.

A spectral interval 424−431 nm is chosen to study the ground state chromium density during active phase of the arc discharge. Spectroscopic constants for the selected lines including wavelength, transition probability (A_{ki}), and oscillator strength (f_{lu}) are presented in [4]. The focus of the present study is set on the chromium lines which have better optical accessibility (visible spectral range) than the copper lines (UV range) and to the comparison with the results presented in [4] for the density development after the current zero.

The relative intensities of the plasma emitted light and the background light source integrated along the wavelength corresponding to Fig. 3 are presented in Fig. 4. The signal is averaged over a horizontal stripe of certain height in axial direction in front of anode in order to improve the signal to noise relation. Such procedure imposes the situation when the axial variation of the density is small within considered region. Taking into account that the neutral species are not subjected to the action of electric field the assumption of an homogeneous density distribution can be applied here. The total absorption within one line is obtained by integration over the spectral line assuming a Lorentz profile [4]. As an example, the calculated ground state chromium densities according to (3) for the instant of 300 µs after current maximum using the data for 425.43 nm line is about $2.1 \times 10^{19}\,\mathrm{m}^{-3}$.

4. Experimental Results

In the present work the Cr I density during the active phase is determined applying the method described in section 3. The appearance and extinguishing of the anode spot type I can be detected optically by high-speed camera observation of the anode surface.

The high-speed camera images during the development of anode spot type 1 are presented in Fig. 5. In the case of the anode spot type 1 a considerable anode activity with usually one large bright spot can be obtained on corresponding electrode. The averaged arc voltage is increased compared to the case without the anode spot.

The corresponding current and voltage traces together with an example of the acquisition time window of the spectrograph are presented in Fig. 6. The maximum current is about 7 kA. The xenon lamp as a background radiation source started earliest at about 2.1 ms. After 500 µs the intensity of lamp is almost constant, the iCCD connected to the spectrograph is triggered to record an image with acquisition time of 100 µs. Notice that different shots at different time instants during formation of anode spot type 1 are performed. A stable operation of the setup is, therefore, necessary to obtain the reliable data. This has been

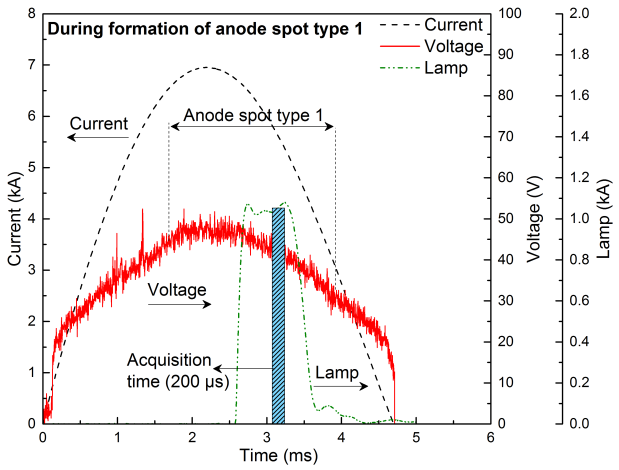

Figure 6. The current and voltage traces together with acquisition time of spectrograph corresponding to Fig. 5. Only anode spot type 1 is observed. The maximum current is about 7 kA.

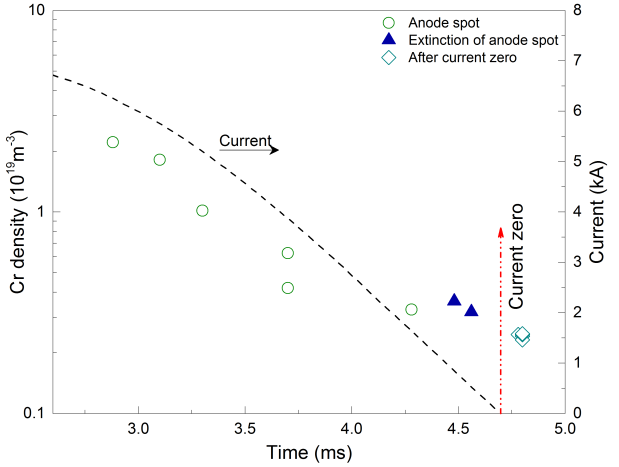

Figure 7. The Cr density during anode spot type 1 based on the method presented in section 3.

obtained by the electrode preconditioning through several shots at the moderate currents (below 5 kA).

The ground state chromium density during the anode spot type 1, after extinction of the anode spot, at the instant of current zero crossing and after the current zero from 2.8 ms to 4.8 ms is presented in Fig. 7. The Cr I density in the time interval between 2.8 and 3.2 ms in which the current decreases from about 5.5 kA to about 4 kA, respectively is about 2.1×10^{19} m^{-3} and 1×10^{19} m^{-3}. When the arc current decreases, the ground state chromium density also decreases. After extinction of the anode spot of type 1, the Cr I density is about 3×10^{18} m^{-3}. The density of the ground state chromium decreases shortly after the instant of current zero crossing (about 100 µs) to the value of about 2.6×10^{18} m^{-3}. These values are in a reasonable agreement with the results presented in [4] $1.5 \pm 0.5 \times 10^{18}$ m^{-3}.The uncertainty in the absolute values of the density is similar to that discussed in ref. [4] and remains less than 15 %.

5. Summary and Outlook

In the present work chromium density during the active phase with pronounced high-current anode modes and after the extinction of the anode spot as well as after the current zero crossing is determined by using a broadband absorption spectroscopy technique. The Cr I resonance line at 425.43 nm is used for estimation of the ground state density. Chromium density determined during the discharge operation with the anode spot type 1 at 2 ms before current zero is about 10 times higher than that after the current zero crossing. The determination of the copper density during and after the high-current anode modes and the anode plume is considered as a future work. The general behaviour of the copper component is expected to be very similar to that of chromium. The differences are expected in the absolute values of particle densities.

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