Study of low-voltage circuit breaker by analysis of complex spectra including the self-reversed profiles of CuI resonance lines

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A low-voltage circuit-breaker operating in air is studied by optical emission spectroscopy. An important quantity of copper vapours coming from electrodes is present in the arc plasma. The existence of one central hot emissive region and one peripheral cold region is brought to the fore. A radiative transfer model with two homogeneous regions of the arc, a central hot emissive one and a peripheral cold one, is developed to describe the spectral profile of two main copper resonance lines and other neighbouring copper lines. This model gives several parameters of the plasma such as the electron density and temperature, the copper vapour densities and the depths of the two regions. The total quantity of copper vapours in the emissive zone is also estimated. The time evolution of the electron density and temperature in the emissive region is obtained also from intensities and profiles of other CuI lines.

1. Introduction

To avoid the damage which can appear during an accidental short-circuit in an electrical supply network, a fast current interruption is necessary [1]. Various types of circuit breakers are used depending on the characteristics of voltage and current to interrupt. The main components of a circuit breaker are the two metal contacts, which ensure the passage of the current during the normal operation of the network. The contacts are made of copper or an alloy containing copper or other materials such as iron or carbon. In low-voltage circuit breaker (LVCB), these contacts are usually in a sealed enclosure filled with air or simply in ambient air.

The electron density and temperature and – obviously – the quantity of metal vapours occurring in the plasma during the contacts opening are important physical parameters for the current interruption. Indeed, these quantities modify the transport coefficients and the emission of radiation, leading to the success or the failure of the interruption [2-3].

It is well-known that, from one shot (separation) to another, the circuit breaker arc presents important fluctuations [2-4], due to the jitter over the separation time. It leads to different values of the current and to modifications of contact surfaces. Moreover, because of the high values of the current, plasma at the first instants following the contacts separation has a very high density of metal vapours.

In this paper we present, for experimental conditions close to real operating conditions, an experimental study with time resolution on a circuit breaker arc with copper electrodes and currents of about 1000 A at the time of the interruption.

2. Experimental set-up and measurements

The set-up used for this study is presented in figure 1. The copper electrodes, with cylindrical form, have a diameter of 3 mm, with their ends in contact slightly conical when not yet used. During the normal operation of the network, a current passes through the electrodes, which are maintained in contact by a flexible blade. The short-circuit current is simulated by an impulse of current generated by the discharge of a capacitors bank with a total capacity of 110 mF, initially charged to a voltage of about 30 V.

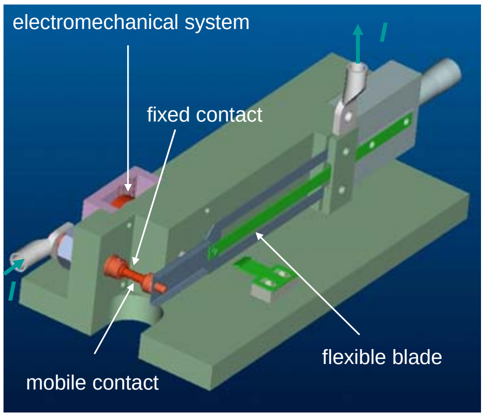

Figure 1. Experimental sketch of the circuit breaker

The current of the discharge was measured using a current transformer. The voltage was measured between the fixed electrode and the end of the flexible blade which supports the mobile electrode. An optical fibre viewing the area between the electrodes carries to a photodiode a part of the light emitted by plasma. The time evolutions of the current, the arc voltage and the electric signal generated by the photodiode were recorded with a digital oscilloscope Lecroy LT 344. We made simultaneously, for each shot, electrical, optical and spectroscopic measurements with temporal resolution.

About 100 μs after the current start, an electromechanical system separates the electrodes. The mechanical jitter leads to different separation instants and consequently to different values of the current. Figure 2 gives the voltage, current and light evolutions for one given shot. Before the contacts separation, the arc voltage increases, due to the wires resistance and inductance. At the separation, a voltage jump (about 13-14 V) appears, equal to the total voltage fall on the electrodes. After the separation, the voltage increases slightly. Shot after shot, the electrodes are strongly eroded.

A special situation appears for the first use of a set of electrodes: the contacts separation appears after the maximum value of the current. This phenomenon is accompanied by a strong emission of light and an important expulsion of fine metal droplets.

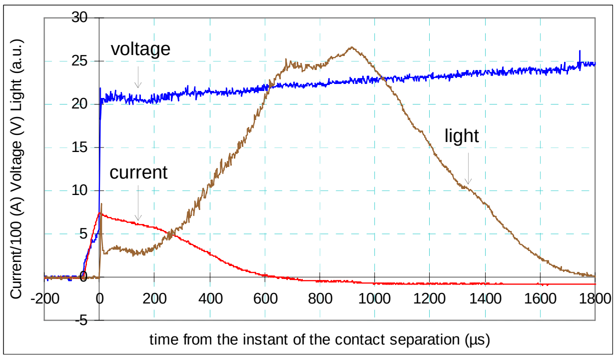

Figure 2. Evolutions of arc voltage, current and light

3. Spectroscopy of the emitting arc

Thanks to a special optical device, the light emitted by the arc is seen in the same manner by two optical fibres. The first one carries the light on the entrance slit of an Acton spectrometer with a 1200 grooves/mm grating, and the second one carries the light on the entrance slit of a Mechelle 5000 spectrometer, with an echelle grating. Two intensified CCD cameras are placed in the exit focal plans of the two spectrometers. With a chosen delay from the contacts separation, the two systems record simultaneously spectra, during 10-20 μs (time much smaller than the arc lifetime, which approaches 2 ms). The first spectrometer is mainly used for the determination of the spectral profile of a certain line. It records a spectral band of 13 nm, with a dispersion of 22 pm/pixel. The second system is used mainly for the determination of the lines intensities. It records a spectre between 200 and 800 nm, with a resolution of about 4000. A deuterium halogen lamp is used for a relative or absolute calibration in energy.

The plasma was supposed to be in local thermodynamic equilibrium (LTE). This assumption was checked a posteriori. The values of the electron temperature and density which we obtained indicate that the Griem criteria [5] for LTE are satisfied.

3.1 Light emitted at the contact separation for new electrodes. Absorption at CuI 510.6 nm line in a cold peripheral region of the arc

The spectre of the light emitted at the separation of new contacts presents a strong continuum radiation with the line CuI 510.6 nm in absorption (figure 3). The continuous radiation is emitted by a hot and dense core of the arc. Absorption is due to the copper atoms which constitute the cold zone which surrounds the central core, and which are in the level $4s^2\ ^2D$ at 11202.6 cm^{-1}. Our model considers two different copper regions in the arc, each of them rectangular and homogeneous [2]. The first region corresponds to the central hot core of the arc. The intense light emitted by this core has the spectral distribution $I_1(\lambda)$. This light passes through the peripheral zone of the arc, called zone 2, mainly composed of copper vapours at lower temperature. The peripheral zone, with an optical depth:

$$\tau_2(\lambda_0;\lambda) = \pi r_0 \lambda^2 f_{lu} P_{w,\lambda_0}(\lambda) n_{l2\_5106} d_2 \qquad (1)$$

produces the absorption of the light emitted by the central core, according to Beer–Lambert law:

$$I_{12}(\lambda) = I_1(\lambda)\cdot e^{-\tau_2(\lambda)} \qquad (2)$$

The spectre $I_{12}(\lambda)$ of the transmitted light is collected by the optical fibre for spectral analysis.

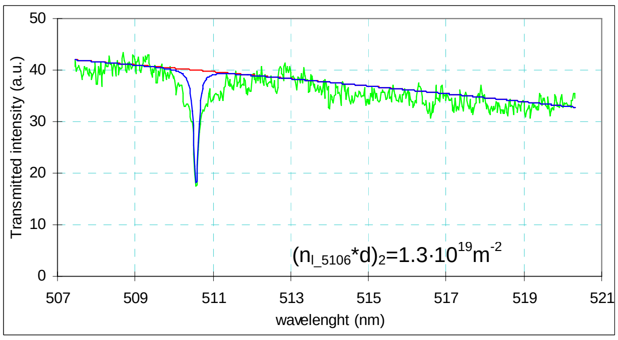

Figure 3. Arc spectre and its best fit (new electrodes)

In the optical thickness formula of the absorption zone are included the classical electron radius r_0, the oscillator strength f_{lu} and the Stark profile $P_{w,\lambda_0}(\lambda)$ of the CuI 510.6 nm line, with w the half width at the half maximum, the density n_{l2_5106} of copper atoms in the absorbing level of the 510.6 nm line and the thickness d_2 of the absorption zone. The contribution of the stimulated emission in the absorbing zone is neglected.

One can notice that the continuum can be fitted by a straight line with a weak slope. The best theoretical approach of the experimental profile using equations (1-2) is presented in figure 3.

The theoretical profile of absorption gives the product $n_{l2\_5106}d_2$ of the density of copper atoms in the absorbing level by the absorption zone thickness. The knowledge of this product $n_{l2\_5106}d_2$ allows the calculation of the dependence in temperature of the product $n_{l2\_5153}d_2$ which describes the possible absorption at 515.3 nm. n_{l2_5153} represents the density of copper atoms in the state 4p ^{2}P at 30535.3 cm^{-1}, the lower level for the CuI 515.3 nm line. Calculations indicated that the electron temperature of the absorption zone should be lower than 4000°K. Indeed, with a temperature higher than 4000 K, the absorption at 515.3 nm must be visible.

3.2 Determination of the electron temperature and density during the arc evolution

The spectra emitted by the arc at various instants of its evolution present atomic and ionic lines of copper coming from the electrodes and oxygen and nitrogen, coming from air. The electron density was obtained from the Stark width of the Lorentz profile of the CuI line at 515.3 nm [6]. The electron temperature was determined by ratios of atomic intensities of two lines (CuI 510.6 / 515.3 nm) or of an atomic line (CuI 515.3 nm) and a group of ionic lines (CuII around 508.9 nm) knowing the electron density. A special attention was given to the effects of the self-absorption of the radiation in plasma on the apparent width of the CuI line 515.3 nm and on the intensities of the mentioned lines. The thickness of the emissive zone was estimated by the self-absorption of the CuI resonance lines (Section 3.3).

The electron density decreases from values close to 10^{17} cm^{-3} at the separation towards values closed to $3\cdot10^{16}$ cm^{-3} at the end of the arc. The electron temperature obtained from atomic lines decreases from values between 10 and 12 kK during the first half of the arc time towards values between 6 and 8 kK at the end of it. The values of the electron temperature given by ratios of an atomic line and a group of ionic lines are between 13 and 15 kK at first half of the arc time. This fact can be explained by an inhomogeneous emissive area of the arc, with hotter zones containing more ionized copper.

3.3 Radiation transfer during the early stages of the arc. Use of self-reversed CuI resonance lines for arc diagnostic

The arc spectre in the area near to 326 nm is very rich in information. The spectre, shown in figure 4, presents the resonance lines of CuI at 324.7 and 327.4 nm, with strong absorption in their centre. This spectre includes three other CuI emission lines. The lines at 324.3 and 326.8 nm come from the upper energy levels around 72000 cm^{-1} and the third one at 328.0 nm comes from the level at 43726 cm^{-1}.

The two resonance lines come from the same multiplet. Consequently one can suppose that they have same Stark broadening effect. But their apparent spectral widths are very different. This fact indicates the existence of an optically thick emissive area. The optical depth is larger as the difference between the apparent widths of the resonance lines is larger. This optical depth is a measure of the density of copper atoms in the emission zone multiplied by the thickness of this zone. The spectral widths of the resonance lines are primarily a measure of Stark broadening produced by the electrons. In fact, the Doppler broadening is negligible.

The absorption profiles in the centre of the resonance lines indicate the presence, between the emissive zone and the optical fibre, of copper vapours in their fundamental state. The relative intensities of the other CuI lines, coming from high excited levels, are a measure of the temperature in the emissive zone. The absolute intensities of the lines are also a measure of the emissive area (perpendicular to the direction of observation) of the plasma.

We will use a model with two regions for the arc mentioned above, the central strongly emissive zone 1 and the peripheral absorbing zone 2. With the temperature of the central zone calculated from other lines (Section 3.2), the emission coefficient of the five lines mentioned of CuI and the continuous radiation is:

$$\varepsilon_{zone1}(\lambda) = \sum \varepsilon_i(\lambda) + continuum(\lambda) \qquad (3)$$

where $\varepsilon_i(\lambda) = \frac{n_{ui}}{4\pi}\frac{hc}{\lambda_i}P_{w_i,\lambda_i}(\lambda)$ is the spectral emission coefficient of line i, n_{ui} is the density of copper atoms in the higher level of line i, $P_{w_i,\lambda_i}(\lambda)$ is the Lorentz profile of the same line and $continuum(\lambda)$ is the dependence (considered as linear) of the continuous emission, the significance of the other physical quantities being usual.

The densities of copper atoms in various energy levels are obtained with Boltzmann distribution. The spectral dependence of the effective absorption coefficient $k(\lambda, T_1)$ is obtained with the Kirchhoff formula with the emission coefficient $\varepsilon_{zone1}(\lambda)$ and the spectral radiation $B_\lambda(T_1)$ of the blackbody.

With rectangular, homogeneous and isothermal core plasma of depth d_1, area S and temperature T_1, the light emitted in a given direction is:

$$\Phi_{1\lambda}(x) = S \cdot B_\lambda(T_1) \cdot \left(1 - e^{-k(\lambda) d_1}\right) \qquad (4)$$

The radiation emitted by the hot core is absorbed by the cold zone 2, characterized by an emission coefficient ε_{zone2}, spectral blackbody brightness $B_\lambda(T_2)$ and an effective absorption coefficient $k(\lambda, T_2)$. For the absorption zone, only the emission coefficient corresponding to the five lines is considered. The electron temperature of the cold zone being lower than 4000 K, the absorption is important only for the resonance lines.

Finally, the flux of light received by the optical fibre, i.e. emitted by the hot arc core and absorbed by the cold peripheral zone, is:

$$\Phi_{12}(\lambda) = S \cdot B_\lambda(T_1)\left(1 - e^{-k_1(\lambda, T_1) d_1}\right) \cdot e^{-k_2(\lambda, T_2) d_2} \qquad (5)$$

The contribution $S \cdot B_\lambda(T_2)\left(1 - e^{-k_2(\lambda) d_2}\right)$ of the emission by the cold zone is neglected.

An iterative procedure allows the variation in the temperature of the emissive zone, the area and optical depths of the two zones, for a better approach of the experimental spectre. Although identical Stark widths of the resonance lines lead to good results, the results are still better if we consider Stark widths proportional to those calculated by Il'in and all [7], which gives for the CuI line to 327.4 nm a value slightly smaller than for the line to 324.7 nm. For the other lines, which come from other upper levels, we did not impose restrictions concerning their spectral broadening. Finally, the temperature, area, electron density and the emission coefficient multiplied by the thickness of the emission zone as well as the absorption coefficient multiplied by the thickness of the absorption zone will be obtained from the self-reversed profile of the resonance lines. Notice that the self-absorption effect in the hot zone has been also taken into account. The total number of copper atoms in the hot zone is thus determined. We present in figure 4 the experimental spectre and its best theoretical approach, after the convolution.

Concerning the values of Stark broadening of the copper resonance lines, according to our knowledge, there is a unique experimental determination for the line at 324.7 nm, by Skuljan and all [8], with a value roughly 3 times larger than the computed value by Il'in and all [7]. By using this experimental value, the electron density obtained from the 324.7 nm line is of $1.9 \cdot 10^{23}$ m^{-3}. Use of the CuI 515.3 nm line from this same spectre recorded by Mechelle 5000 (200-800nm with resolution of about 4000), gives an electron density of $1.1 \cdot 10^{23}$ m^{-3} in rather good agreement with the value yielded from resonance lines.

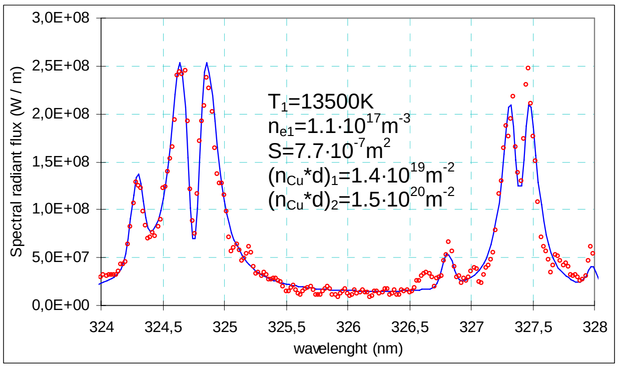

Figure 4. Arc spectre and its best fit (resonance lines)

4. Conclusions

Analysis of complex spectra using a radiative transfer model allowed determining several parameters of an arc created by contacts separation.

The electron temperature of an emissive zone of a circuit breaker was obtained from intensities of various atomic and ionic copper lines, as well as from the resonance lines. The electron density in the emissive zone was obtained from the Stark width of the CuI 515.3 nm line.

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