Preliminary Spectroscopic Investigation of HVCB Contacts Erosion

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Spectral emissions from arcs in air between electrodes used in high-voltage circuit breakers (HVCBs) have been investigated at AC currents up to 32kA peak. Time-resolved average temperature and copper atoms concentration have been derived from the arc spectra. The copper vapor mass deduced from these measurements was used to estimate the electrode erosion rate which was compared with directly measured material loss. High speed photographs of the arc were taken to provide further electrode erosion information. The results indicate the possibility of using the approach for online monitoring of in-service HCVBs.

Keywords: spectroscopic, condition monitoring, electrode erosion, HVCB

1 INTRODUCTION

Electrode erosion which occurs in HVCBs affects a Circuit Breaker's current breaking capability and limits its electrical service life time [1, 2]. There have been several investigations of electrode erosion during arcing using optical techniques such as spectroscopy [3-6]. In this contribution, a combination of high speed photography and spectroscopic measurements has been applied to investigate a free burning arc in a prototype HVCB enclosure. The arc burned between a copper cathode and copper tungsten anode (as used in HVCBs) but without a gas flow nozzle. This provided a convenient arrangement for preliminary investigation of the relationships between arc radiative emission parameters and electrode erosion rate. Experimental results are presented for relating the optical emission from the electric arc and the mass of copper vaporized from the surface of the cathode which has a major influence on the electrical service life of a HVCB [3].

2 EXPERIMENTAL APPARATUS

The experimental arrangement used for the arc investigations along with the optical measurement systems is shown on Fig.1 (a) and (b). The arc burned in air between two electrodes (Fig.1 (a)) – a copper tungsten finger anode (diameter 47mm) and a copper rod cathode (diameter 18mm) similar to the contacts in HVCBs (Fig. 1 (c)). The arc gap was formed by moving the cathode with respect to the fixed anode giving a fully opened gap of 100mm.

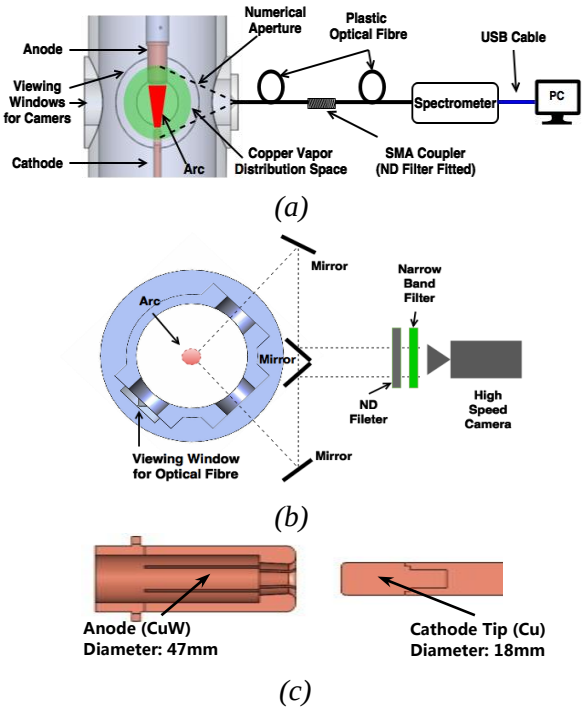

Fig.1: Experimental System (a) Arc gap and optical fibre spectral system (b) Optical system for high speed image capture (c) Anode and cathode (cross section)

Optical access to the arc within the test enclosure was via three windows in the test chamber wall (Fig.1 (a) and (b)) at the same height as the arcing gap.

The electric arcs were sustained by 60Hz half cycle currents produced by a LCR test circuit (L = 184uH, C = 35mF). This also provided a low level direct current prior to ignitron switching it to the half cycle with peak currents up to 32kA. The current was measured with a shunt resistor of 1.19mΩ.

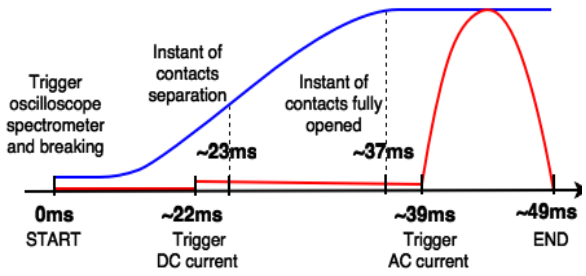

Fig.2: Time sequence of experimental processes (blue curve represents the displacement of cathode; red curve represents current)

The optical arrangement used to obtain high speed images of the arc is shown in Fig. 1 (b). The images were produced by a high speed camera (Phantom V7.1) with 4000 frames per second and exposure of 2us. The images were captured via a ND16 neutral density filter and a 521.8nm narrow band filter (2nm FWHM). The camera viewed the arc from two perpendicular directions on the same frame via two windows and appropriate mirrors (Fig. 1 (b)).
The arrangement used for the spectral emission measurement is shown in Fig. 1 (a). This used optical fibres (ESKA SH-4002 acrylic and fluorinated polymers, numerical aperture 0.5) which suffered no degradation after exposure to arcing. The whole arcing gap area was within the field-of-view of the optical fiber. Spectra were captured with a high speed spectrometer (Exemplar LS, spectral resolution of 0.6nm, minimum integration time 1050us, maximum data transfer speed 950 spectra per second). 9-10 spectra could be captured during an arcing period of ~10ms. Neutral density filters were fitted into an SMA coupler (Fig. 1 (a)) in order to avoid optical saturation of the spectrometer and the spectra were suitably compensated.

3 EXPERIMENTAL PROCEDURES AND RESULTS

Fig. 2 shows a time sequence of the operation of the arc producing system. On electrode separation a DC current flows to produce a low current arc until the electrode gap was fully opened when the main half cycle alternating current was triggered to produce the high current arc to be investigated.
Fig. 3 shows a number of image frames obtained with the high speed camera. Each frame

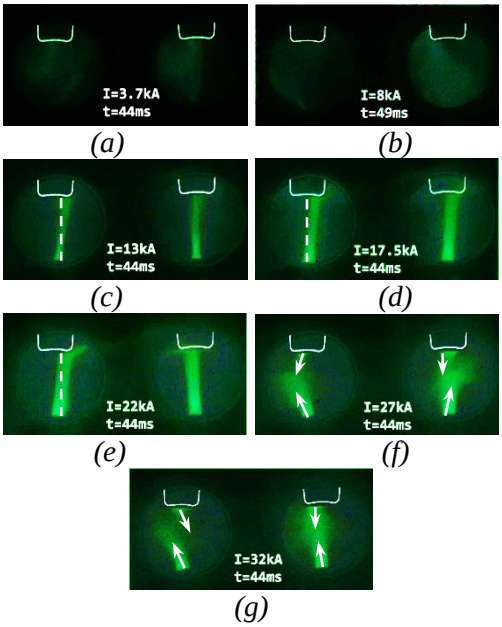

Fig.3: High speed arc images for various current levels at a time of ~ 44ms (a) 3.7kA, b) 8kA, c) 13kA, d) 17.5kA, e) 22kA, f) 27kA, g) 32kA)

contains two images of an arc taken from orthogonal directions. The images show that a copper vapor core from the cathode is produced for currents above 8kA (Fig.3(c), (d), (e), (f) and (g)). The diameter of the core increases at a higher current of 22kA (Fig.3 (e)) whilst at an even higher current (27kA, Fig. 3 (f)) there is evidence of a vapor jet being produced by the copper-tungsten anode as well as the jet from the copper cathode. In addition, there is evidence of the plasma column being unstable and inclined from the gap axis at 8, 27, 32kA (Fig.3 (b), (f), (g)).
Fig. 4 shows a typical result obtained with the high speed spectrometer in the form of spectral line intensity versus wavelength at various times during a test. This shows a pronounced increase in in the amplitude of many spectral lines at 39ms followed by a decrease at 49ms which time interval corresponded to the duration of the AC half cycle.

4 RESULTS ANALYSIS

The spectral results have been analysed to yield values of an average copper vapor temperature by choosing two copper spectral lines having high emission coefficients (to be easily identified), not resonance lines (to avoid strong self-absorption) and having sufficient difference in their upper energy levels (to pro-

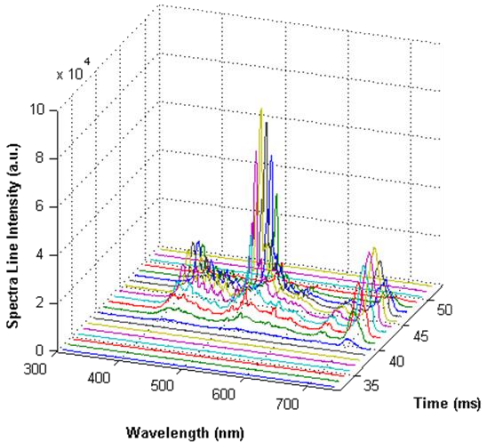

Fig.4: Example of measured spectra (Intensity versus wavelength) at various times during a test

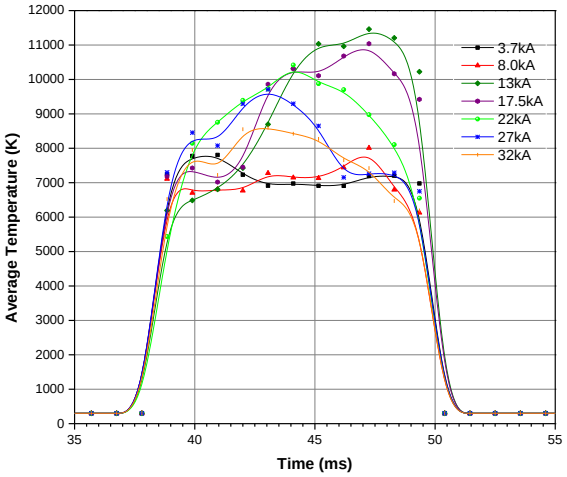

Fig.5: Average arc temperature versus time for various peak arc currents

vide good temperature discrimination) [6]. The selected lines had wavelengths (λ) 521.8, 578.2 nm, with respectively upper energy levels (E) 6.192, 3.786 eV and statistical weights (g) 4.5e8, 3.3e6 s^{-1}.

On the assumption of LTE, the average temperature (T) of the plasma vapor was determined from the ratio of the intensities of these two spectral lines (I_1, I_2) using the Einstein-Boltzmann equation to give the following relationship [6]

$$T = \frac{E_1 - E_2}{k \times \left(ln \frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1} - ln \frac{I_1}{I_2} \right)} \qquad (1)$$

where 1, 2 denote the upper and lower energy levels; A_{nm} is the probability of transition from the upper to the lower level; k is the Boltzmann constant.

The copper vapor concentration (N_0) was determined from the Einstein-Boltzmann equation in terms of the spectral line intensity (I_{nm}) and the average arc temperature (T):

$$N_0 = \frac{I_{nm} \lambda U(T)}{hc g_n A_{nm} \exp\left(-\frac{E_n}{kT}\right)} \qquad (2)$$

where h is the Plank's constant; c is the velocity of light in vacuum; $U(T)$ is the partition function. The spectral line intensity and copper vapor concentration used in the equation (2) are not the absolute values.

If it is assumed that evaporation may be the dominant material removal mechanism from cathode, then the space and time integration of the copper vapor would be the mass loss from the cathode ($m_{erosion}$) given by:

$$m_{erosion} = \int V * m_{Cu} * N_0(t) dt \qquad (3)$$

where m_{Cu} is the atomic mass of copper, t is time and V is the volume covering the whole observation region (the green sphere in Fig.1 (a)).

5 DISCUSSION

The time variation of temperature for various half cycle peak currents (3.7 – 32kA) calculated from the measured spectra using equation (1) are shown in Fig. 5.

The average arc column temperature varied from ~ 7,000K for a peak current of 3.7kA to ~ 11,000K at 17.5kA, but was lower at even higher currents (22, 32kA). This trend may be attributed to the variable cooling effect of different levels of copper vapor and its high heat capacity [2] at the low and high peak currents.

Fig. 6 shows the time variation of copper vapor concentration for various peak arc currents calculated with equation (2). The results show some distinctive high peaks of copper concentration for currents of peak values 8, 27, 32kA. These peaks appear to be associated with asymmetric changes in the axial inclination of the plasma column observable on the high speed images (Fig.3 (b), (f) and (g)).

Fig. 7 compares the measured mass loss from

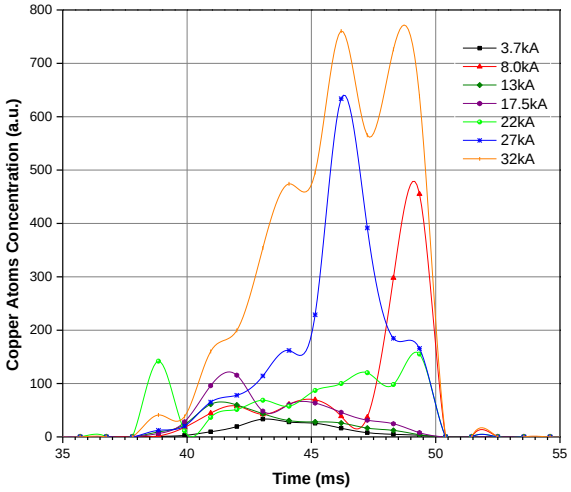

Fig.6: Copper vapor concentration versus time for various peak arc currents

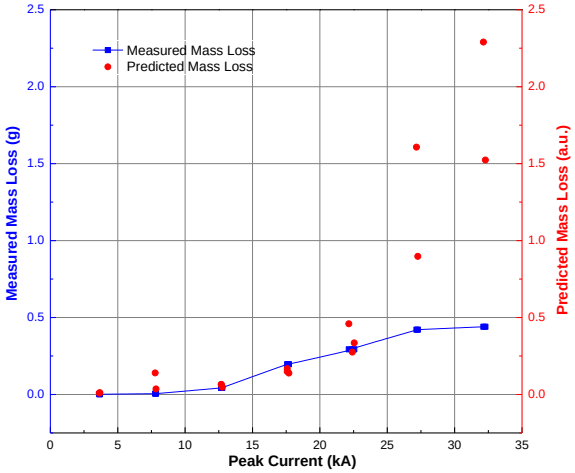

Fig.7: Cathode mass loss predicted by equation (3) compared with measured values for various peak arc currents

the cathode with that predicted from the optical spectra and equation (3). The results show good agreement between the direct and spectroscopic measurements at lower peak currents (< 25kA) with a gradual increase in in the cathode erosion with increasing peak current.

For peak currents ~ 25kA, the spectroscopic values show high level fluctuations compared with the directly measured values (which saturate at a value of 0.45g, in agreement with the results of Engel [7]). These fluctuations appear to be associated with additional copper vapor produced by vapour jets from the anode (Fig.3 (f), (g)) as well as plasma column instabilities.

6 CONCLUSIONS

A novel optical fibre based approach for monitoring electrode erosion rate has been demonstrated. Spectral emissions have been monitored with the system from arcs in air formed between two contacts (copper, copper tungsten) similar to those used in commercial HVCBs. The amount of material evaporated from the arc cathode has been estimated from the captured spectra. The results have been shown to be in broad agreement with directly measured cathode material losses at peak arc currents up to 25kA. Above 25kA, arc instabilities produce fluctuations in the spectroscopic results. Such instabilities may not be as pronounced for arcs burning in a nozzle gas flow (as used in gas flow HCVB). Investigations will therefore be extended to such arcs in a nozzle gas flow with the optical fibre sensor mounted on the nozzle at various positions.

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