THE USE OF OPTICAL SPECTROSCOPY IN THE ANALYSIS OF ELECTRIC FUSE ARCING

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Abstract

Optical fibres were inserted into electric fuselinks to observe the light emission from fuse arcs. By recording the emission spectra using a rapid-scanning spectrometer and photo-multiplier tube and measuring the relative intensities of the most prominent wavelengths it was possible to estimate fuse arc temperatures. The results indicated that these temperatures were of the order of 7000K . and remained virtually constant throughout the duration of the arc.

1. Introduction

The high temperature of a fuse arc plasma causes it to emit light with characteristic spectral lines [1]. By obtaining the spectrum of the light it is possible to assess the temperature of the arc, providing that the time taken to collect the spectrum is short enough for the temperature to be regarded as constant and long enough for the area observed to be in local thermodynamic equilibrium.

Inserting quartz optical fibres into fuselinks it is possible to observe light emissions from electric fuse arcs. Employing fibres with diameters roughly equal to the mean sand grain diameter it follows that the operation of the fuse, even during arcing, will only be marginally affected.

2.0 Test Fuses

Test fuses were constructed as illlustrated in figure 1, using glass reinforced plastic bodies with zinc end caps and copper tags.

Elements comprised a length of 7.14mm (± 0.7%) wide, 0.1 mm (± 2.5%) thick, 99.97% pure silver strip, with a single notch punched at its centre.

Notch dimensions were controlled to better than 2%. The fuse body was drilled perpendicular to the plane of the element using a 1mm drill. A glass capilliary tube was inserted to within 3 mm of the element and glued into place using epoxy resin. A 200 micron quartz optical fibre was introduced and allowed to rest on or near to the restriction. It was then glued into place using epoxy resin. The fuses were filled

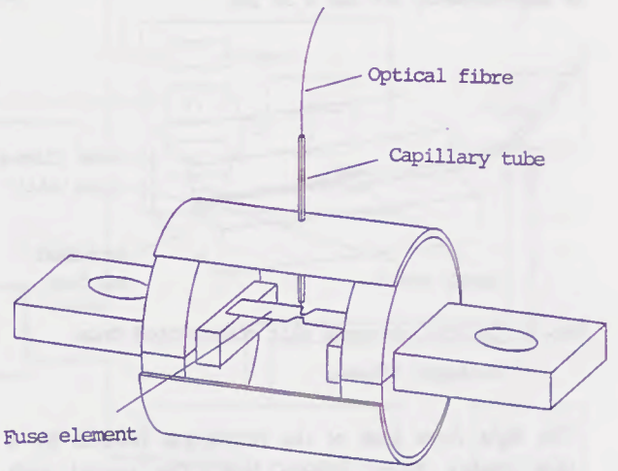

Fig. 1 Test fuse showing placement of optical fibre.

with 97% pure silica grains with a minimum diameter between 250μm and 640μm. The sand was compacted into the fuse body by precisely controlled vibration.

3. Rapid Scanning Spectrometer

A rapid scanning spectrometer (RSS) was constructed, as shown in Fig. 2 to enable the spectra of light emitted from test fuselinks during arcing to be analysed.

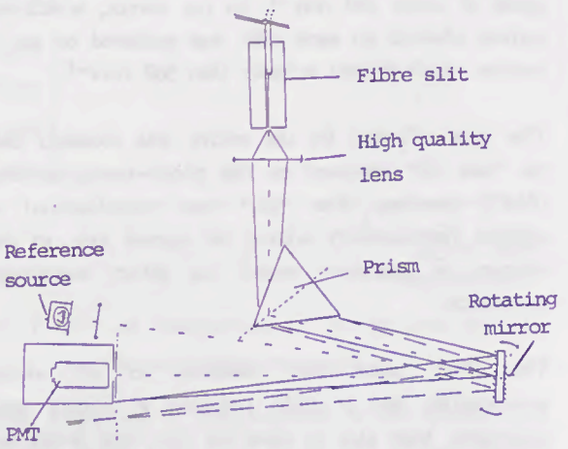

Fig. 2 Rapid Scanning Spectrometer.

The light emanating from each test fuse was transmitted through the optical fibre inserted in its body and a standard connector to a bundle of four 50 μm fibres. The free end of the bundle was exposed

from its protective sheath, and the four fibres glued to a machined-flat surface, using clear epoxy resin. The fibres were laid down touching their neighbours, with the final centimetre aligned horizontally. (Fig. 3). The front surface of the block, including the ends of the fibres, was then machined flat and polished. This formed the "entrance slit" to the RSS with dimensions of approximately 200 μm x 50 μm.

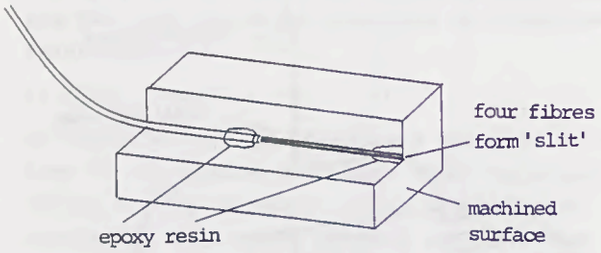

Fig. 3 Optical entrance slit constructed from multiple fibres.

The light from ends of the fibres was focused by a high quality 50mm camera lens. The optical path length was of the order of 1000mm giving a magnification of almost 20, and a final image width of around 1mm.

The light was then dispersed by a 60° prism onto a rotating mirror. To achieve a wavelength resolution of better than 1.5nm a complete spectrum (from ~450nm to ~850nm) had to be collected in 30 μs. Prism dispersion was about 5°, so the mirror had to rotate through 5° in less than 30μs, and complete one revolution in 2.2ms. This corresponds to a rotational speed of about 460 revs^{-1}. So the mirror, which was surface silvered on each side, was mounted on an air turbine which rotated at more than 500 revs^{-1}.

The light reflected by the mirror was focussed onto the "exit slit" mounted on the photo-multiplier tube (PMT) housing. The "slit" was manufactured to operate symmetrically around the optical axis, so that changes in aperature would not affect wavelength calibration.

The PMT used was sensitive to all visible wavelengths, had a rapid response to ensure good resolution, high gain to cater for low light levels and low dark current to improve final signal to noise ratio.

Barrow [2] provides fuller details on the construction of the RSS, along with the method of calibration. Fig. 4 shows the variation in system response with wavelength.

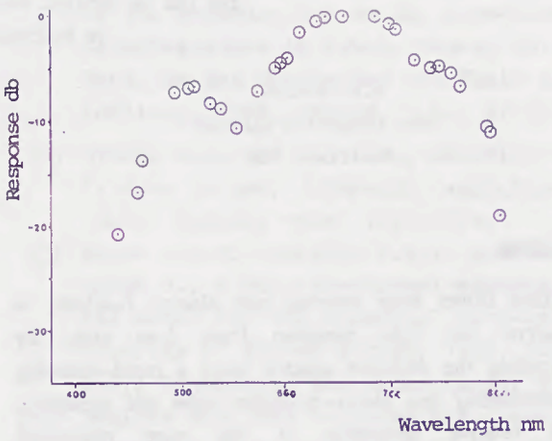

Fig. 4 System response: sensitivity vs. wavelength.

4. Experimentation

The test configuration is shown in Fig. 5. With the applied voltage set at 255V, the prospective fault current was 525A at a power factor of 0.2 lagging. Using point on wave control, accurate to two electrical degrees, the circuit was closed at the applied voltage zero, to ensure substantial arcing. The fuse current and voltage waveforms were recorded and the fuse arc spectrum during a preselected "time window" in the arcing period was captured.

Fig. 6 shows a sample trace of the PMT output.Three multiplets are readily observed. The wavelengths of the component parts are:

i) 635.5nm: 634.7nm and 637.1nm
ii) 505.1nm: 504.1nm and 505.6nm
iii) 597.2nm: 595.8nm and 597.9nm

Because of the variation in system response with wavelength (Fig. 4) the peaks recorded were multiplied by appropriate correction factors to find their relative intensities.

4.1 Possible sources of error

The possible sources of error which could affect these results are that

(i) the optical fibre will act as a heat pipe, causing a localised reduction in temperature particularly during prolonged pre-arcing.

(ii) light energy will escape from the arc, potentially reducing the arcing time and arc energy.

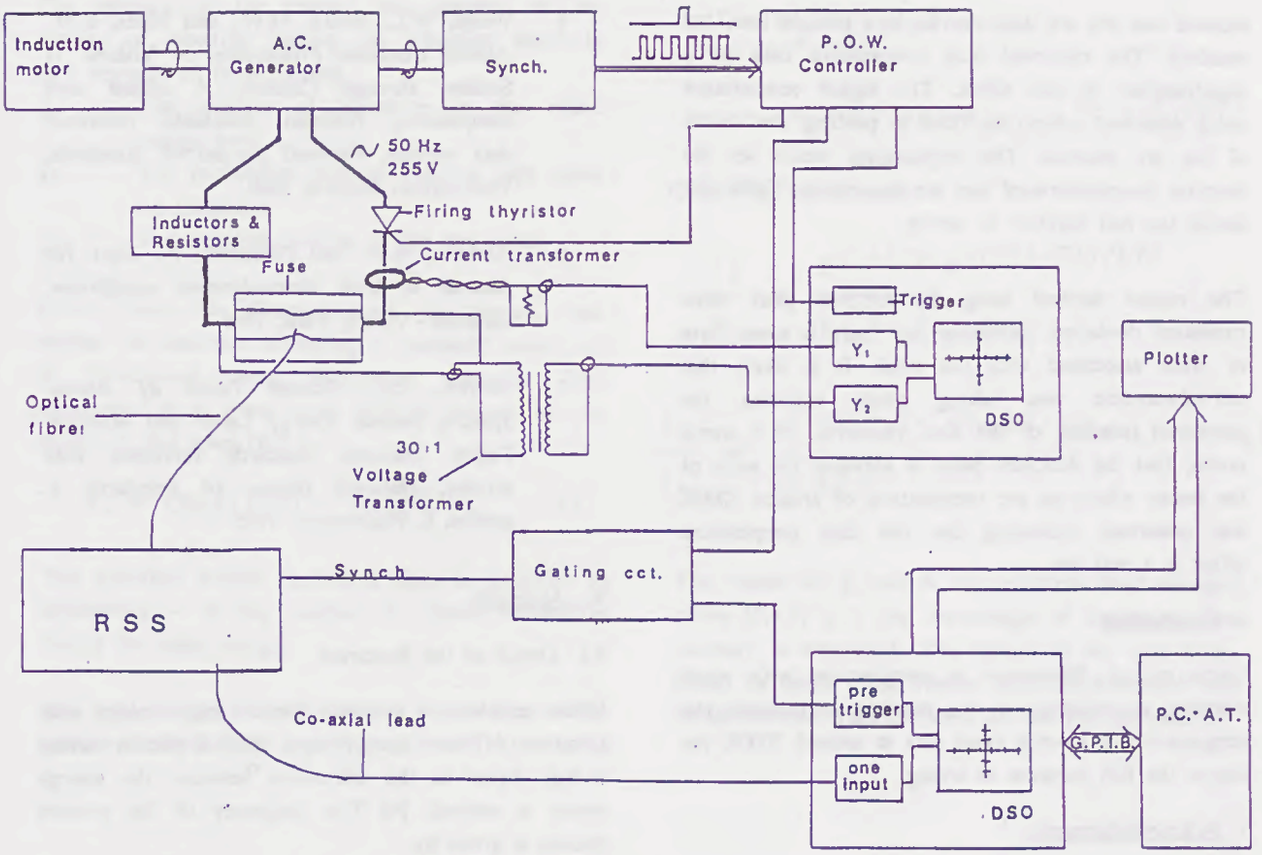

Fig. 5 Test system configuration with Rapid Scanning Spectrometer.

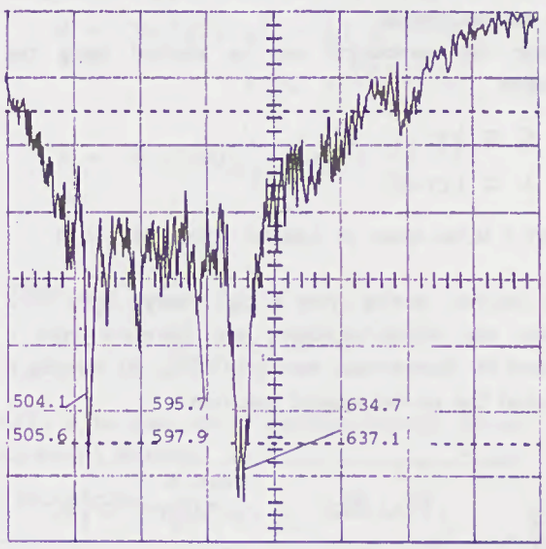

Fig. 6 Emission spectrum of HBC fuse arc.

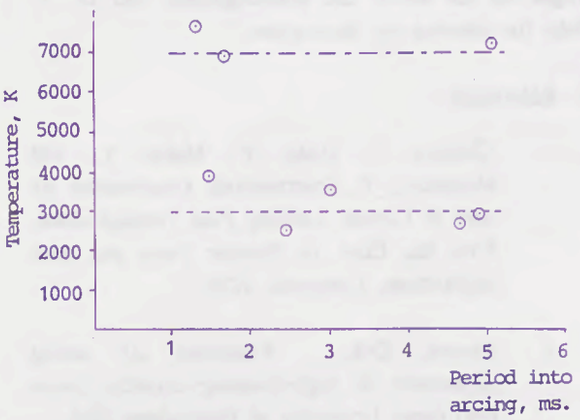

Fig. 7 Plot of temperature vs. period into arcing from emission spectroscopy.

5. Interpretation

To find the arc temperature from the spectral lines it is necessary to compare the intensities of the lines, as explained in the appendix 9. The temperature derived from comparison of the intensities of the 505.1nm and 597.2nm peaks appears to be at one of two discrete levels centred around 7000K and 3000K, see Fig. 7.

In a separate study by the authors, described in another paper to this conference [3] five optical fibres were inserted into fuse links so that the ends of the fibres formed a straight line above the fuse element starting at the restriction. The results of this work

showed that the arc does not lie in a straight line, but wanders. The observed dual temperature may be a manifestation of this effect. The higher temperature being observed when the fibre is probing the centre of the arc channel. This explanation would set the electron temperature of the arc at around 7000K for almost the full duration of arcing.

The results derived using the 635.5nm peak show consistent deviation, indicating that there is some form of error associated with this peak. It is likely that self-absorption was taking place reducing the perceived intensity of the line. However, it is worth noting that the 635.5nm peak is elevated on each of the traces where an arc temperature of around 7000K was observed, indicating that the dual temperature effect is a real one.

6. Conclusions

Using optical fibroscopy in conjunction with rapid scanning spectroscopy it was possible to measure the temperature of electric fuses arcs at around 7000K for almost the full duration of arcing.

7. Acknowledgements

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8. References

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9. Appendix

9.1 Origin of the Spectrum

When an electron traverses from a high energy state (Em) to a lower energy state (En) a photon having energy equal to the difference between the energy levels is emitted. [4] The frequency of the emitted photon is given by

$$Em - En = \triangle E = h\nu$$

where h is Planck's constant and ν is the frequency of the emitted photon.
Hence the wavelength can be derived using the relation

$$c = \lambda\nu:$$

$$\lambda = hc/\triangle E$$

where c is the speed of light.

An electron moving from a high energy level to a lower one within an atom will therefore emit a photon of characteristic wavelength (Fig. 8) forming a spectral line on the emitted spectrum.

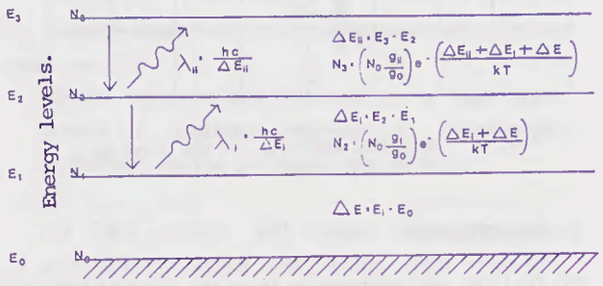

Fig. 8 Illustration of Boltzmann distribution.

The intensity of the emitted line depends on the number of electrons making the transition which in turn depends on three factors.

i) The number of electrons in the raised energy level.

ii) The probability that an electron will make the transition.

iii) The statistical weights of the two states.

Where there is thermodynamic equilibrium, the number of electrons occupying a particular level can be determined using Boltzmann statistics. The population of a given level (Nj) is related to the energy of that level (Ej) by

$$Nj = (N_0 gi/g0) e^{(-Ej/kT)} \qquad (1)$$

The statistical weight (gn) of a state is equal to its degeneracy - ie the number of distinct sub-states having the same energy.

The total number of particles (N) is the sum of the number of particles in a particular level (N_i) over all levels.
ie

$$N = N_0 + N_1 + N_2 + ...$$

combining with equation 1 obtains

$$N = (N_0/g0)(g0 + g1\ e^{-E1/kT} + g2\ e^{-E2/kT} + ...)$$

$$N = (N_0/g0)\sum_{j=0}^{i} gj\ e^{-Ej/kT}$$

$$N = (N_0/g0)\ U(T)$$

where

$$U(T) = \sum_{j=0}^{i} gj\ e^{-Ej/kT}$$

U(T) is the state sum or partition function. Hence equation 1 becomes:

$$N_j = (N/U(T))\ gj\ e^{-Ej/kT}$$

For a volume of gas containing N_j particles in a raised energy state, and with a probability of $A_{j,j-1}$ for the transition under review, the number of transitions in a second is $N_j.A_{j,j-1}$. The transition emits a photon with energy hc/λ and hence the energy emitted per second (intensity) is

$$I = N_j.A_{j.j-1}\ hc/\lambda$$

$$I = (N_j/U(T))gj\ A_{j,j-1}\ \frac{hc}{\lambda}\ e^{-Ej/kT})$$

Comparing the intensity of two lines obtains:

$$\frac{I_1}{I_2} = \frac{g1.A1.2}{g2.A2.1}\ e^{-((E1-E2)/kT)}$$

$$\frac{I_1}{I_2} = \frac{g1.A1.2}{g2.A2.1}\ e^{-(hc/kT)((1/\lambda_1)-(1/\lambda_2))}$$

The values of g and A are available from standard tables [5,6,7]. λ is the wavelength of the line whose intensity is measured. The values of h,c and k are found in many texts. Hence, the temperature T can be determined from the ratio of two line intensities.