A Method to Estimate Electron Density in a High-Voltage Fuse’ Arc

Muhammad A. Saqib, Anthony D. Stokes, Brian W. James, and Ian S. Falconer

Abstract—Stark broadening of the Si II doublet at 504.1 nm and 505.6 nm has been used to estimate the electron density in two model silica-sand-filled high-voltage, high breaking capacity fuses. For a 240 mm long fuse which successfully interrupted a test circuit set up to deliver a 4.5 kA prospective current, the electron density fell from \( \sim 2 \times 10^{18} \) cm\(^{-3}\) shortly after arc initiation to \( \sim 1 \times 10^{18} \) cm\(^{-3}\) just before current zero; for a 112 mm long fuse and a prospective current of 1.25 kA the electron density was \( \leq 1 \times 10^{17} \) cm\(^{-3}\) for the duration of the arc.

Index Terms—High breaking capacity fuse, spectral lines, Stark broadening, the fuse’ arc.

I. INTRODUCTION

A high-voltage, high breaking capacity (HBC) fuse is an important component of modern electrical energy distribution system. It is considered superior to the equivalent circuit-breaker for interrupting short-circuit currents because of its short operating time, cost-effectiveness, and self-fault-sensing characteristics [1], [2]. The pre-arcing behavior of these fuses is now well-understood, but a lack of information as to the characteristics of the fuse arc has prevented researchers developing a model which will quantify the behavior of this phase of the operation of the fuses. Although empirical models of the arc have been developed [3] and have been used for some calculations, it is necessary to know the arc temperature and electrical conductivity, which depend on the electron density and temperature of the arc, to model the arc [4]. The lack of knowledge of the arc parameters such as electron density and temperature is particularly acute in the case of HBC fuses which are packed with sand - usually silica sand - to absorb the arc energy.

Although there have been a number of studies to determine plasma temperatures during fuse arcing, there have been few measurements of electron density in the arc. Chikata et al. [5] replaced an opaque fuse holder with a Pyrex glass tube in order to observe the visible radiation from the sand-filled fuse arc, and from Stark broadening of silicon lines obtained electron densities of the order of \( 10^{18} \) cm\(^{-3}\). Cao [6] used an arc in ice to provide access to the radiation emitted, and measured densities of the order of \( 10^{18} \) cm\(^{-3}\) from the Stark broadening of the hydrogen Balmer lines. The drawback of this already reported work is that it does not reflect the actual situation in sand-filled high-voltage fuses in which the burning arcs are constricted by the surrounding silica sand and enclosed by opaque fuse cartridges. The reported measurements [5], [6] are also integrated over the duration of the arc, and do not provide any indication about their variation in the arcing period.

This study reports the investigation of the arc, which is produced inside the model fuses and is surrounded by SiO\(_2\) in opaque fuse cartridges just like in actual fuses. The light from the arc is carried to a monochromator by an optical fibre which is then analysed to make an estimate of the electron density using the Stark-broadening parameters of Si II spectral lines. The model fuses are tested at 6 kV (50 Hz) for 1.25 and 4.5 kA prospective fault currents, conditions likely to be encountered in power distribution networks. The study reports the time-resolved measurements of electron density during the evolution of the arc.

II. STARK BROADENING OF SPECTRAL LINES

As a consequence of the long range of the Coulomb force the collisional broadening of spectral lines from moderately ionized plasmas such as the fuse arc is dominated by the collisions of charged particles with the emitting atoms. This Stark broadening is given for singly ionized atoms by [7, 8]

\[
\Delta \lambda = 0.2 \left[ 1 + 1.75 \times 10^{-4} \frac{\lambda}{e} \left( 1 - 0.1 \frac{\lambda}{e} \right)^{1.0} \right] \times 10^{16} \text{cm}^{-1}
\]

where \( \Delta \lambda \) is the half width of the Stark broadened line in nm, \( \lambda \) is wavelength in nm, \( n_e \) is electron density in cm\(^{-3}\), \( T \) is plasma temperature in Kelvin.

The constants \( \alpha \) and \( w \) are characteristic of the transition of interest, and depend weakly on the plasma temperature. They are tabulated by Griem [9].

III. THE EXPERIMENT

The experimental set-up for these measurements was identical to that used for the fuse arc electron temperature measurements discussed in [10]. Indeed, the data from which the electron density was deduced were obtained from the spectra which had been taken primarily for these electron temperature measurements. It must be clarified here that reference [10] discusses about the time-resolved measurements of arc temperature for a model fuse when it was tested at 1.25 kA fault current whereas the temporal estimation of electron density for two model fuses – of different dimensions – at two fault currents – 1.25 kA and 4.5 kA – is the subject of this paper.
Two experimental versions of a silica-sand-filled fuse, cylindrical in shape with a 0.55 mm diameter uniform silver wire stretched inside the middle of the fuse barrel along its axis, were constructed for these measurements. One was 240 mm long with an inside diameter of 43.7 mm (the long fuse, Fig. 1), the other 112 mm long with an inside diameter of 59.5 mm (the short fuse, Fig. 2). (Commercial fuses use a somewhat different design to ensure the current goes to zero well before reaching its maximum value and that reignition does not occur.) A 6 kV, 50 Hz waveform was applied to the fuse by closing the pneumatically-driven mechanical make switch MS1 in the synthetic test circuit shown in Fig. 3; the values of L and C in this circuit were set to give a prospective current of 1.25 kA for the short fuse, and 4.5 kA for the long fuse. The make switch MS2 in this circuit is switched to crowbar the fuse in the test circuit at current zero in case the fuse malfunctions. The voltage across the fuse was measured with a Tektronix P6015, 20 kV, 1,000\times attenuation high-voltage probe; the current with a 190.8 A/V shunt. A Nicolet Pro 42C digital oscilloscope \[11\] was used to record these signals, as well as a reference pulse to indicate the time at which the arc spectra were recorded.

The arc spectra were recorded with a Princeton Applied Research Model 1460 Optical Multichannel Analyzer (OMA), a spectroscopic system in which the spectrum is recorded by a linear photodiode detector array which is coupled to the exit plane of the monochromator by an image intensifier which can be gated "on" by a high-voltage pulse. An optical fiber, inserted in the fuse body to touch the fuse element, was used to transfer light from the arc to the OMA \[12\]. A 62.5 \mu m core diameter multimode silica fiber was used as this material should have negligible effect on the arc characteristics. The other end of the fiber was located at the centre of the 25 \mu m entrance slit of a Jarrell-Ash MonoSpec 27 Monochromator \[13\], which spectrally dispersed the arc radiation.

The OMA was run in the gated mode, synchronized to the triggering of the fuse test circuit. The experiment is initiated by a pulse provided by the OMA, which triggers the closing of the pneumatically operated make switch MS1 (Fig. 3). This pulse is delayed to trigger the high-voltage pulser which gates "on" the image intensifier for a few microseconds at an appropriate time during the arc. This procedure is necessary to synchronize the "read" cycle of the OMA with the operation of the test circuit. The timing circuitry for this experiment is shown in Fig 4. (The switch MS1 closes around 65 ms after activation, and there is a further delay of 1-6 ms before the arc is initiated, depending on the fuse used and the prospective current.)

IV. AN ESTIMATE OF THE ELECTRON DENSITY

The width of the spectral lines recorded in the course of the electron temperature measurements which we are reporting in another paper \[10\] is such that we should be able to estimate an upper limit to the contribution of Stark broadening to the line width. This should, in turn permit the estimation of an upper limit to the electron density in the plasma. Observation of the width of the individual spectral lines acquired at earlier times during the arcing of the long fuse, which were significantly broader than those observed for the short fuse, confirm that the line width is, at least in some cases, broader than the instrumental resolution of the monochromator used. The Doppler broadening corresponding to the electron temperatures we have measured from the relative intensity of Si II spectral lines \[10\] is < 0.01 nm, and will not contribute significantly to the line width. Thus a deconvolution of the instrumental width of the monochromator used from the measured line width should enable the contribution of Stark broadening to be determined and an estimate made of the electron density.
around the Si II doublet at 504.6 and 506.1 nm.

Fig. 6. Expanded view of the region of the spectrum shown in Fig. 5.

The noisy signals, the strong continuum emission and the broad effective instrumental profile for these measurements justify this simple approximation.

Table I

<table>
<thead>
<tr>
<th>Arcing time (ms)</th>
<th>Half width (nm)</th>
<th>Corrected half width (nm)</th>
<th>Electron density $\times 10^{18}$ cm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.83</td>
<td>6.7</td>
<td>2.8</td>
<td>2.0</td>
</tr>
<tr>
<td>0.99</td>
<td>5.7</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>1.20</td>
<td>5.0</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>1.44</td>
<td>5.3</td>
<td>1.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

V. RESULTS AND CONCLUSION

Electron densities estimated using the above procedure on our data for the long fuse at 4.5 kA prospective current are shown in Table I. These results demonstrate that, shortly after arc ignition the density is greater than $10^{18}$ cm$^{-3}$, and decreases during the arc to $\sim 10^{16}$ cm$^{-3}$. The density was so low for the short fuse at 1.25 kA prospective current that it was possible only to show that the electron density was $\lesssim 10^{17}$ cm$^{-3}$.

These results confirm that it should be possible to make reliable measurements of the electron density of the arc in a silica-filled HBC fuse from the Stark broadening of Si II spectral lines provided a grating of higher resolution is installed in the monochromator for the line width measurements.

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REFERENCES

Muhammad Asghar Saqib received his B.Sc. degree in electrical engineering from University of Engineering and Technology, Lahore, Pakistan in 1991, and M.E.S. and Ph.D. degrees in electrical power engineering from the School of Electrical Engineering and Information Engineering, University of Sydney, Australia, in 1996 and 2000 respectively. He joined the Faculty of Electronic Engineering, Gulham Ishaq Khan Institute of Engineering Sciences and Technology, Topi, Pakistan as Assistant Professor in November 1999. Dr. Saqib’s research interests are in the areas of electric arcs’ investigation, power electronics and electrical drives, and renewable energy.

Anthony David (Tony) Stokes graduated B.Sc., in 1960 and B.Eng. with First Class Honors, in 1962, both from the University of Sydney. He joined the Electricity Commission of N.S.W., working on generating plant design, system control and substation equipment. Later he pursued research in the area of high frequency induction plasmas and, after graduating Ph.D. in 1966, undertook studies of the electrical and mining applications of high frequency electrical power.

In 1967 he was appointed Lecturer in Electrical Engineering at the University of Sydney, and is now an Associate Professor. Since 1972 he has been engaged in studies of high power electric apparatus with emphasis on switching equipment and electric arcs. In 1978 he won the Orbit Award of the Australian and New Zealand Association for the Advancement of Science for his film “Circuit Breaker Arce”. In 1979 and again in 1990 he won the John Madsen Medal of the Institution of Engineers, Australia for the best papers in those years. In 1995 he was awarded the University medal of the Gdansk Polytechnic University. In 1997 he was awarded the inaugural CIGRE Distinction medal. In 2004 he attended the Petroleum and Chemical Industry conference of the IEEE to give a key invited paper on Electrical Arcing Burn Hazards. He is the author of over 215 engineering publications and has been the supervisor of 32 higher degree research candidates. He has completed over 78 engineering consultancies for the Australian police, legal firms and engineering organizations.

Professor Stokes has been a Fellow of the Institution of Engineers, Australia, a member of the CIGRE international Study Committee 13, Switching Equipment and a member of the working groups, 13-01, Modeling Methods and 13.04, Electrical Test Techniques. Between 1984 and 1996 he was Convenor of the Australian Panel 13 of the Australian National Committee of CIGRE. He is a member of the Electrical Board of the Standards Association of Australia and of the SAA Committees, EL/7 (Chairman), on Static Electrical Machinery and EL/7 (Chairman), on Switching Equipment and a number of their sub committees. In 1989 he co-founded, and was elected Chairman of the Executive of the Optical Fiber Technology Center at the University of Sydney. He has been a Member of the Organizing Committee of the International Conference on Electric Fuses and Their Applications since 1991. Between 1990 and 1996 he was the Director of the Optical Fiber Sensors Center. In 2000 he moved to an honorary post at the University of Sydney and co-founded the Sydney based engineering company Golden Triangle Enterprises Pty Ltd. He is now its Managing Director.

Brian William James was born in Sydney, and educated at state schools before studying physics at the University of Sydney, where he graduated B.Sc. with First Class Honors in Physics in 1967 and a Ph.D. in Plasma Physics in 1971. He was appointed as a Lecturer in the School of Physics in 1971, where he continued his studies of ionizing shock waves and plasma spectroscopy.

In 1974 he spent a year at Culham Laboratory, where he gained expertise in laser diagnostics. On his return he played a leading role in the design and construction of TORTUS (Toroid of the University of Sydney), a medium-sized tokamak specifically designed for the study of plasma waves and the development of diagnostics which went into operation in 1981. Although he continued to contribute to the TORTUS program, in the 1980s he expanded his interests to the study of processing plasmas.

Professor James’ current research interest is in the experimental study of dusty plasmas, where his leadership has ensured that the University of Sydney team is a key contributor to this aspect of plasma physics.

During his tenure at the University of Sydney Professor James has traveled overseas to continue his researches at the Culham Laboratory (UK), UCLA, Kyushu University (Japan) and the Dublin City University, Dublin, Ireland.

Professor James is an authority on the application of laser and spectroscopic techniques to the measurement of the characteristics of plasmas, and has been involved in the experimental study of a wide range of plasmas ranging from tokamaks to dusty plasmas.

Ian Stuart Falconer was born in Lower Hutt, New Zealand, and educated at state schools before studying physics at Victoria University College [now Victoria University of Wellington], where he graduated B.Sc. in 1957 and M.Sc. in 1959. He continued his studies at the Australian National University, graduating with a PhD in 1963. In that year he took up a Postdoctorate Fellowship with the National Research Council of Canada, where he worked with Stuart Ramsden’s Plasma Physics group, one of the pioneers in the application of lasers to plasma diagnostics.

In 1966 Dr. Falconer accepted a position as Lecturer in the School of Physics at the University of Sydney, where he worked on laser diagnostics of plasmas, using lasers operating at wavelengths from the ultraviolet to the submillimetre regions. He has extended his interests from laser diagnostics to plasma spectroscopy, and from fusion-related plasma to gaseous electronics. He retired in 1997, but continues his association with the University of Sydney’s School of Physics as an Honorary Senior Lecturer.

During his tenure at the University of Sydney, Dr. Falconer has traveled overseas to continue his researches at the University of Hull (UK), the MIT Plasma Fusion Center, the JET Joint Undertaking at Culham (UK), and the Laboratoire de Spectrometrie Physique in Grenoble. He has also worked for a period of several months at the CSIRO’s Division of Applied Physics in Sydney.

Dr. Falconer’s research interests are based around the application of laser and spectroscopic techniques to the measurement of the characteristics of plasmas ranging from fusion plasma to the dielectric barrier discharges that form the pixels of plasma screen TVs.