The application of ultra-high speed (1MHz) imaging in the verification of a computational model of arc motion

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This paper focuses on the verification of computational modelling of arc motion under short circuit conditions in low voltage circuit breakers using controlled experimental conditions, where an arc imaging system (AIS) is used to provide quantitative information on arc motion. It is shown that the motion of an arc root on a metallic surface, is linked to the arc voltage and that the computational model provides a representation of the overall arc movement, but is unable to predict high frequency events (1 MHz) associated with the arc entry into splitter plates and re-strikes within the arc chamber. To enable a prediction of arc voltage prior to extinction, referred to as the arc exit voltage, a modification to the arc model is shown and discussed with reference to the observed information from the AIS.

Key Words: High speed imaging, plasma motion, gas discharge, arc modelling.

Introduction

Low-voltage switching devices (LVSDs) are widely utilized in power distribution networks to turn on and off circuits and to extinguish the arc during overload or short circuit conditions. The quenching chamber consists of a movable and fixed contact, splitter plates and vents. During an opening event, an arc is established between the contacts and then forced by electro-magnetic forces into the quenching chamber, where it elongates, increasing the arc voltage before entering the splitter plates. In the splitter plates the arc is divided into smaller arc segments, resulting in multiple arc interactions with the metallic surfaces, and increasing the overall arc voltage as a function of the number of voltage drops associated with each anode and cathode roots. The increase in the arc voltage leads to a reduction in the arc current, and when compared to the prospective current, this is referred to as current limitation. A detailed review of the arcing phenomena associated with LVSD's is described in [1,2]. Enhanced switching performance is achieved by improved current limitation; when the arc quickly enters and stays within the splitter plate region with the arc remaining attached to the surface of the plates. In this paper a flexible test apparatus (FTA) is combined with an ultra-high speed (1MHz) arc imaging system (AIS), to all the verification of the computational models under a controlled experimental condition. A key output parameter from the modelling process is the arc exit voltage (the arc voltage prior to extinction) as this has been shown to be linked to the arc re-ignition after current zero in AC systems, [3].

Arc Imaging System (AIS)

The first solid state optical fibre based arc imaging system was presented in [4]; and described in detail including an overview of the current limiting application and other related technological areas, in [5]. The system was used in a detailed study of parameters influencing arc motion in a flexible arc testing chamber (FTA). In [6] a commercial circuit breaker was used and the AIS used to determine the influence of the magnetic circuits on the arc motion. In [7], the first definition of parameters derived from arc motion analysis was used in the FTA; where the period from arc ignition to passing a particular point on a metallic arc runner (arc root times) were used to determine the influence of the opening contact velocity. In [8], it is shown that the delay in the anode root time from the moving contact, significantly contributed to a delay in arc motion. Prior to this it was assumed that the cathode root motion was the dominate mechanism. In [9], important solutions were introduced to aid the arc commutation from a moving contact. The experimental results presented show the influence of arc chamber venting, current level, current polarity and contact velocity on arc motion, and a solution was proposed to reduce the influence of gas flow on the arc commutation from the moving contact. In [10], a pressure probe and spectral data measurement were incorporated into the FTA. These measurements were used to investigate gas flow characteristics in the arc chamber. The combination of optical and spectral data provided new insights into the nature of arc motion. The influences of arc chamber material, contact material, and contact opening speed, were investigated to improve arc control for a low contact opening velocity. In [11], a new approach to our understanding of the short circuit arcing process is presented by concentrating on the bulk thermal behaviour and energetics of the arcing and gas flow during contact opening. Data is presented on mass and volume flow rates as well as estimates of the gas velocity in the contact region. In [12], new actuation methods were investigated, designed to remove the dependency on a solenoid actuated short circuit opening.

The arc imaging system (AIS) system used in the work described in [4-12], was re-designed in 2010, with a specification shown in Table 1, [13,14]. The optical fibre based (AIS) is described as a ultra-high speed imaging system as it samples at 1MHz and higher, [15] and has the unique feature of a high number of image frames (500,000). Table 1 shows the specification and the experimental settings used in this paper. The system has been designed to improve the light transmission performance with proprietary designed connector blocks, such that users can station the AIS remotely from the arcing event, (up to 100m). The normalisation of the fibre array to provide consistent transmission levels for a known light level is a further innovation in the new design. In the experimental setup used in this paper, as shown in Table 1, an optical filter (ND8) is used to reduce the light intensity recorded, as a consequence of the short optical fibre length (2 m).

The new design has enabled innovations in the quantitative analysis of arc motion. The increased number of optical fibre channels has allowed a detailed investigation of the arc motion in splitter plates, as shown by the fibre positions in the FTA arrangements shown in Fig 1. The venting of the arc chamber is controlled, by the green block on the left. The moving contact (grey) on the right, is triggered by a short circuit event from capacitive discharge system, [4-12]. The 120 optical fibre positions are shown with the white and yellow dots and include 4 positions between each of 7 splitter plates. This allows for the monitoring of the arc in the splitter plates, for comparison with multi-physics computational fluid dynamic (CFD) models. The yellow fibre positions are used to allow the plotting of the arc root motion (X) along the fixed contact runner, with X=0 mm in the contact region to X= 50.7 mm, in the splitter plates (left). A correlation between the light intensity and the plasma temperature, has shown a near linear relationship [16].

Table 1. Arc Imaging System AIS specification

	Max Value	Experiment Values
Sample Rate	6 MHz	1 MHz
Number of Optical Fibres	1024	120
Number of Frames	512,000	512,000
Capture time	0.09 sec	0.5 sec
Light Intensity Resolution	8 bit (0-255)	8 bit (0-255)
Signal Gain	1-32	1-4
Length of Optical Fibre	100 m	2 m
Light Intensity Filter	ND0-16	ND8

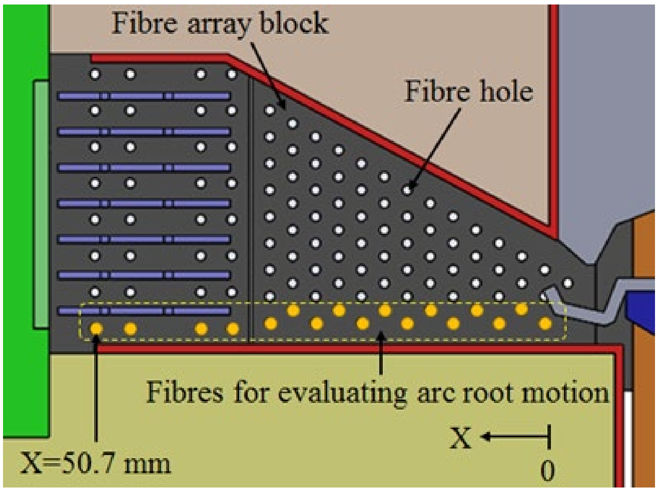

Fig.1 Flexible test apparatus arc chamber (FTA) showing the arc imaging system (AIS) optical fibre positions (white/yellow dots), used for evaluation of arc root motion and the position of optical fibres in the splitter plate region (left). Red lines are Cu conductors, the moving contact grey, vent from the chamber in green.

Arc Root Motion

In this paper the AIS is used to investigate phenomena associated with the arc extinction process, when compared to the previous studies [4-12] where the main focus was on the contact opening and arc motion. A number of prior studies have been conducted, firstly around the venting condition for a simplified arc chamber FTA, [17,18]. In a related study an experimental investigation has been conducted of Re-ignition Evaluators, [3]; where it has been shown that a ratio between the exit voltage, (the arc voltage prior to the current zero) and the supply voltage is a critical factor governing the likelihood of a re-ignition after current zero. The estimation of the exit voltage has been shown to be a critical output from CFD computational models and the AIS and FTA have been used in the evaluation of these parameters.

To determine the arc motion, the yellow fibre positions are used with a centre weighting algorithm, [17,18], to determine the position of the arc root along the lower (red) arc runner in Fig.1. Fig 2, shows a correlation between the arc motion (blue) and the arc voltage (black), over a 1.2 ms window, as the arc enters the splitter plates. It shows high frequency fluctuations of voltage as the arc enters the splitter plates. In region A, (6.7 to 6.9 ms) there are 6 peaks in the voltage over 200 µs, suggesting a fluctuation frequency of 30 kHz, while there is negligible movement in the arc root position. The cathode root trajectory has a limitation to represent the whole arc motion in the chamber [19]. At position B (6.6 ms) there is a rapid apparent backwards movement of the arc root from 48 mm to 30 mm, corresponding to a rapid fall in arc voltage. Although this is presented as continuous movement (Blue), the event is a re-strike of the arc root outside of the splitter plate region, [20], and occurs over a period of 1-3 µs, and is registered in the AIS with the system sample rate of 1 MHz.

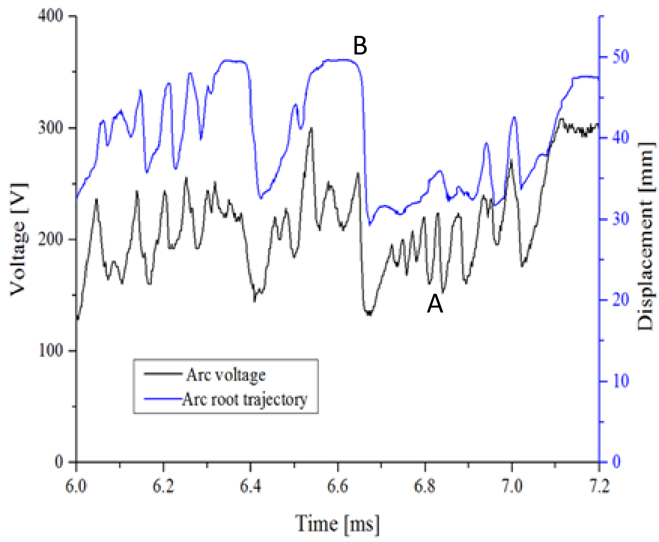

Fig.2 The arc root trajectory as the arc enters the splitter plates, (X) displacement and arc voltage, for a 200 V, short circuit event

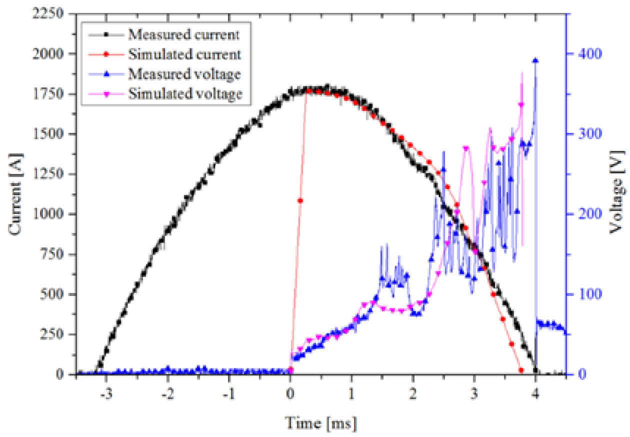

Fig.3 Measured and Simulated V,I for a 200V supply,1750 A peak

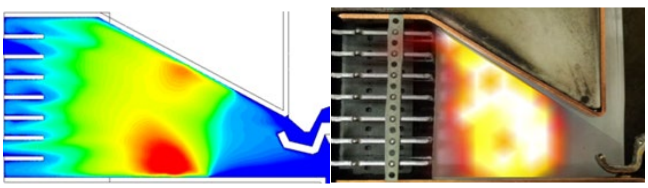

Fig.4 200V supply, ND8 filter, Left, plasma temperature at 2ms, (blue below 5,000 K, and red above 19,000 K). Right, the corresponding arc image at frame 5210.

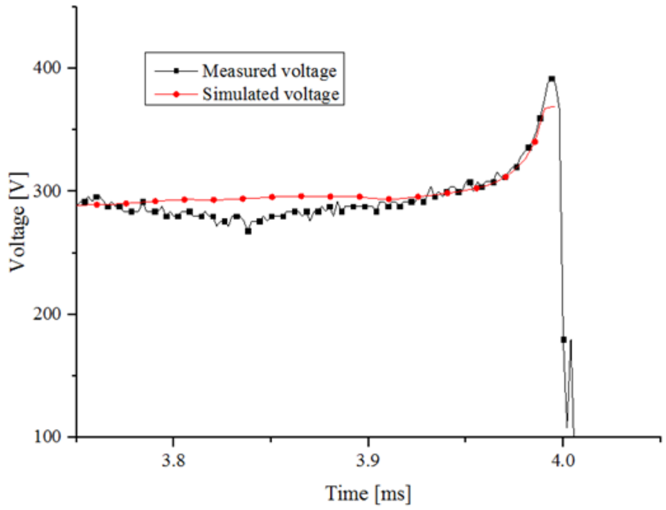

Fig. 5. Measured and simulated arc voltage with modified V-J curve near the current zero point.

Computation Modelling of Arc Motion in LVSD's

Measured data. The FTA geometry shown in Fig.1 is used as the control volume for the verification of computational modelling. Details of the simulation approach are provided in [21,23]. Fig.3 shows the arc event starting at 0ms, with the blue measured voltage increasing, (to synchronise with the arc model) while the short circuit current is close to the peak value (1750 A). The arc images show that the arc moves rapidly to 1.5ms where it starts to enter the plates, corresponding to the initial raise in the arc voltage (blue) to 150 V. It then re-strikes at 2ms, when the arc voltage drops to 80 V, before re-entering the plates at 2.3ms. After 2.3ms there are a number of high frequency fluctuations in the arc voltage, similar to those discussed in Fig.2. The arc stabilises in the plates at 3.7ms. The exit voltage is shown to be 390V. The images correspond to the data in Fig 3, are shown in [20].

Simulated data. The simulated voltage (pink) is shown to follow the trend of the measured voltage (blue). A drop in the voltage at 1.7ms is observed in the simulation, a re-strike, as in the real event, but in the simulation corresponding to a stationary arc with reducing current flow. The simulated arc fully enters the plates at before 3ms, showing a backwards motion corresponding to a drop in the simulated voltage, before stabilising in the plates at 3.3ms. The simulated exit voltage is lower than the measured exit voltage and occurs earlier. The reduced duration of the simulated event is a consequence of the current limiting effect of the arc remaining for a longer period in the plates.

The CFD model, is shown in Fig.4, for 2ms into the event, as the plasma temperature (range blue below 5,000 K, and red above 19,000 K) in a half section of the arc chamber. In the half section the splitter plates appear to be smaller, because of the cross-section geometry of the plates. The AIS, arc intensity image on the right, is superimposed on a photo of the arc chamber, where the contact is shown in the default closed position. In the simulation the temperature is higher close to the arc root. The corresponding arc image shows the arc roots at a similar location but with the higher temperature (intensity) away from the arc roots. It is noted that some fibres close to the runner are likely to be obscured by the arc runner, leading to a lower intensity. In subjective analysis the arc model provides a good simulation of the real event in both position and voltage, but there are inconsistencies around the temperature distribution, then exit voltage and the arc position during high frequency events.

To improve the prediction of the exit voltage, the simulations shown in Fig. 3, have implemented a modification to the V-J curve, [22,23], shown in Fig. 5 (relationship between the arc root voltage and current density). Where details of the arc voltage prior to extinction for both measured and simulated data are shown. In this case the arc model shows an exit arc voltage of 327V at 3.98ms, while the measured value is 332V, where the exit arc voltage is defined as the arc voltage 20µs prior to the current zero point [23].

Conclusions

The paper presents a methodology for the verification of multi-physics computational fluid dynamic (CFD) models of arc motion, where a simplified arc chamber geometry of a low-voltage switching device (LVSD) is modelled and compared with experiment using a 1 MHz Arc Imaging system (AIS).

It is shown that the analysis of the arc root motion along one runner can be used to parameterise general arc motion but is unable to show detailed fluctuations in the middle of the arc column as it enters the splitter plates. To study the latter would require a selection of fibre positions closer to the region centre of the arc chamber. It is observed that a minimum sample rate of 1 MHz is required to define the arc motion, with re-strike event occurring at this frequency.

The general verification of the arc model is undertaken by subjective observation of the images and shows a good correlation in both position and voltage, but there are inconsistencies around the temperature distribution, possibly linked to the location of individual fibre positions. The critical CFD exit voltage shows an error of -1.5% in voltage and -20 µs in the event time, after a modification to the V-J curve. Both values confirm the robustness of the modelling process.

References

1. McBride, J.W. and Weaver, P.M. (2001) Review of arcing phenomena in low voltage current limiting circuit breakers. IEE Proceedings SMT, 148, (1), 1-7.
2. A. E. Guile, Arc-electrode phenomena, Proc. IEE., vol. 118, no. 9, pp. 1131–1154, 1971.
3. D. Shin, I.O. Golosnoy, J.W. McBride, (2018), "Experimental Study of Re-ignition Evaluators in Low Voltage Switching Devices", IEEE Transactions on CPMT.
4. Weaver P.M, McBride J.W, Arc Motion in Current Limiting Circuit Breakers, The 16th International Conference on Electrical Contacts, Sept 1992, U.K., pp 285-288.
5. Weaver, P.M., McBride, J.W. and Siew, C.C. (2003) Integrated measurement system for high speed unsteady plasma flow and its application to electric arcs. IEE Proceedings - Science, Measurement and Technology, 150, (4), 153-160.
6. Weaver P.M, McBride J.W, "Magnetic and Gas Dynamics Effects on Arc Motion in Miniature Circuit Breakers", IEEE Transactions on CPMT, Vol. 17, No 1, March 1994, pp 39-46.

7. McBride J.W, Weaver P.M, Jeffery P, "Arc Root Mobility during Contact Opening at High current", IEEE Transactions on CPMT, Vol. 21, No 1, March. 1998, pp61-67.
8. McBride J.W, Jeffery P.A, "Anode and Cathode Arc Root Movement during Contact Opening at High Current", IEEE Transactions on CPMT, Vol 22, No 1, March 1999, pp. 38-46.
9. McBride, J.W, Pechrach, K. and Weaver, P.M. (2001) Arc root commutation from moving contacts in low voltage devices. IEEE Transactions on CPT, 24, (3), 331-336.
10. McBride, J.W, Pechrach, K. and Weaver, P.M. (2002) Arc motion and gas flow in current limiting circuit breakers operating with a low contact switching velocity. IEEE Transactions on Components and Packaging Technologies, 25, (3), 427-433.
11. Weaver, P.M, Pechrach, K. and McBride, J.W. (2004) The energetics of gas flow and contact erosion during short circuit arcing. IEEE Transactions on CPT, 27, (1), 51-56.
12. Weaver, P.M, Pechrach, K. and McBride, J.W. (2005) Arc root mobility on piezo-electrically actuated contacts in miniature circuit breakers. IEEE Transactions on CPT, 28, (4), 734-740.
13. McBride J.W, Balestrero A, Ghezzi L, Tribulato G, Cross K.J, (2010), Optical fiber imaging for high speed plasma motion diagnostics: applied to low voltage circuit breakers, Review of Scientific Instruments, 81, (5), 055109.
14. http://www.taicaan.com/arc-imager/
15. P. L. Reu, High/Ultra-high speed imaging as a diagnostic tool, Sandia National Laboratory, Albuquerque, NM 87185 USA, (2011), SAND2011-0978C.
16. D Shin, TG Bull, JW McBride, Experimental Study of Relationship between Arc Light Intensity and Temperature in Low Voltage Switching Devices, IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 10 Issue: 11, pp. 1840-1848, 2020.
17. J.W. McBride, D Shin, T Bull, A study of the motion of high current arcs in splitter plates using an arc imaging system, 28th International Conference on Electric Contact. Edinburgh, June 2016, pp 175-180.
18. D Shin, IO Golosnoy, JW McBride, TG Bull, Experimental study on the influence of vent aperture size and distribution on arc motion and interruption in low-voltage switching devices. 2017. Xian China.
19. Dongkyu. Shin, Thomas G. Bull, and J. W. McBride, "Experimental Study of Arc Motion near Splitter Plates in Low Voltage Switching Devices," IEEE Trans. Components Packag. Manuf. Technol., Vol. 11 Issue: 9, pp. 1452-1460, 2021.
20. Youtube video of arc motion corresponding to the data used;
21. Shin D, Golosnoy I, McBride J.W, (2018), Development of Switching Performance Evaluator and Arc Modelling Tool for Low-Voltage Switching Devices, COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 37,I. 5.
22. A. Mutzke, T. Rüther, M. Lindmayer, and M. Kurrat, Arc behavior in low-voltage arc chambers," in International Conference on Electrical Contacts, France, Jun. 9-12, 2008.
23. Shin D, McBride J.W, Golosnoy, I.O, Arc Modelling to Predict Arc Extinction in Low-Voltage Switching Devices, IEEE Holm conf, USA, October 2018.