A study of the Motion of High Current Arcs in Splitter Plates using an Arc Imaging System

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Abstract— **Arc modelling is a valuable tool in the evaluation of the switching performance of low-voltage switching devices (LVSDs) prior to testing real products. All modelling process requires a validation of the results against experimental studies. In this study an arc imaging system is used to investigate the arcing phenomena in splitter plates. The imaging system is applied to a flexible test apparatus which allows the control of important feature of a typical LVSD. The results show the formation of the arc into the plates and the separation of the arc as a restrike occurs in the main arc chamber. The phenomena results in a rapid reduction in the arc voltage before the arc re-enters the plates.**

Keywords-component; Arc Imaging, Splitter Plates.

I. INTRODUCTION

Low-voltage switching devices (LVSDs) are usually utilized to turn on and off the electric current in the distribution power network by industrial, commercial and residential users. They are essential for end users as switching and protective measurements because their primary functions are to carry, make and break the current under normal circuit conditions as well as to clear fault currents and to ensure safety for both humans and other connected equipment against overload or short circuit accidents.

In general, a LVSD consists of three essential parts, namely, a trip unit, an operating mechanism and a quenching chamber as shown in Fig. 1. The trip unit is a current sensing and triggering element that releases the operating mechanism and makes it drive to break the current in the event of short circuit or prolonged overload currents. The operating mechanism linked to the movable contact moves it towards the opening or closing direction either manually or automatically. The quenching chamber is an interruption space where the arc appears, elongates, and finally extinguishes after the contact separation.

The quenching chamber of a LVSDs normally includes a movable contact, a fixed contact, splitter plates, a magnetic yoke and a vent as shown in Fig. 2. When a LVSD interrupts a current, the arc is established between the contacts and then elongates along with the motion of the movable contact. At the same time, the arc moves forward and enters the splitter plates due to the action of the magnetic and gas blow forces. Finally, the arc may extinguish or re-ignite after current zero. During the process described above, the characteristics and behaviour of the arc in the quenching chamber are crucial to guarantee the successful arc extinction and the fault current interruption. As a result, the arc parameter during switching operation has a significant influence on the switching performance of a LVSD.

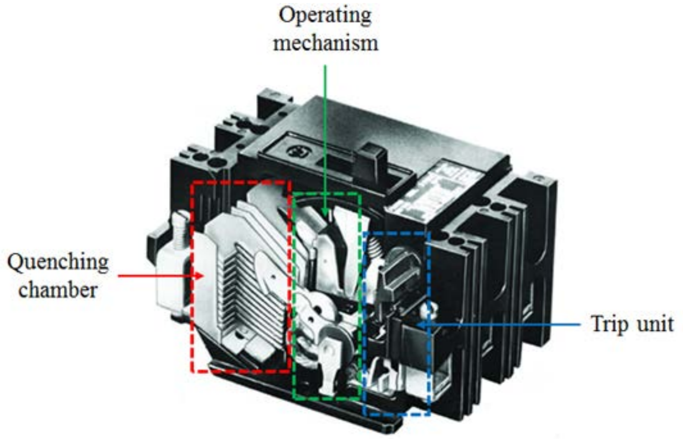


Fig.1 A typical structure of LVSD

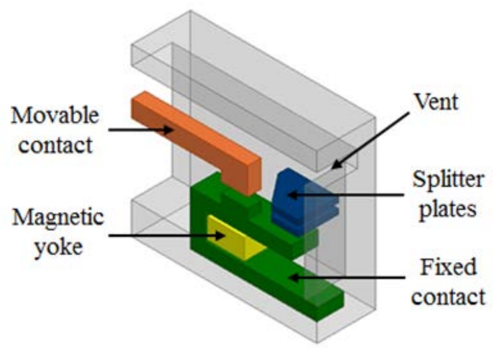


Fig. 2 Structure of quenching chamber, including splitter plates

There are a number of geometries that can be used in LVCD’s and in the case of a current limiting device, the arc chamber will be a region prior to which the arc will enter a number of splitter plates designed to enhance the arc voltage and thus limit the circuit current. In order to optimize the design and development of circuit breaker technology, it is essential to gain an understanding of the events that occur as an arc moves from a contact region, where the arc is initiated by opening contacts; through an arc chamber to the arc stack or splitter plates. Fig.3 shows an example system with the opening contact region at the top of the chamber and the splitter plates (arc stack) at the bottom of the chamber. The arc motion through chamber is the result of electro-magnetic forces driving the plasma column into the plates. The physics of the transfer process through the arc chamber is a complex multi-physics problem, and as yet to be fully solved.

The geometry described in Fig. 3 is based on a flexible test apparatus (FTA) used to enable studies of arc motion under controlled experimental conditions. The optical fibre positions shown correspond to the positions used in previous investigation of arc root motion. The geometry presented has been used in a number of previous investigations where an optical fibre based arc imaging system (AIS) has been used to provide quantitative data on the nature of arc motion during the initial stages of a short circuit event, with a particular focus on the motion of the arc roots, [1-5]. These studies have provided important information to circuit breaker designers on the optimization of commercial devices.

A. Arc Motion Studies and Splitter plates

There have been a limited number of studies of the arcing processing in splitter plates. In [6] computational fluid dynamic (CFD) models were developed and tested against a simplified arc chamber with a single splitter plate. The arc was imaged with a high speed camera providing images every 50 μsec. It will be shown in this paper that a higher sampling rate (1 MHz) is required to image the high frequency events as the arc enter the plates. In [7] the research is mainly focused on modelling the process to include metallic vapour ablation from splitter plates, and an extension to the modelling work present in [6].

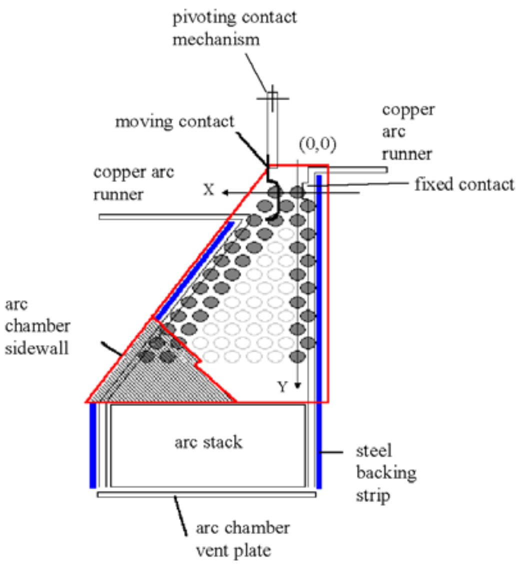


Fig.3 Schematic of the arc chamber of the FTA showing the moving contact and with optical fiber positions using in previous studies. Grey fibre were used to plot arc root postion. [6,7]

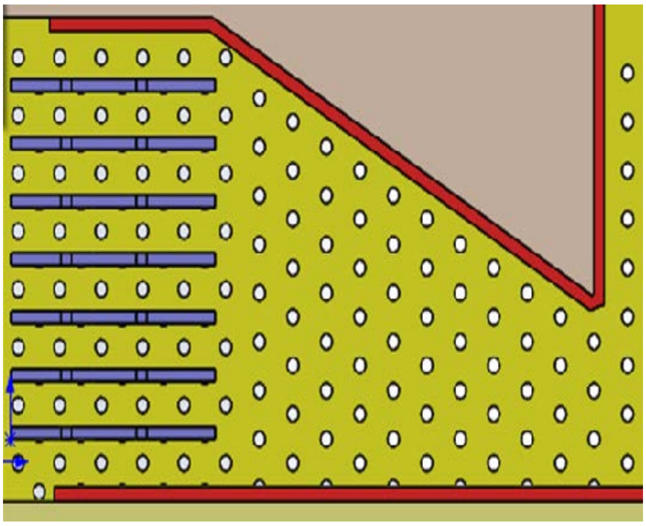


Fig.4 Schematic of the arc chamber of the FTA with new optical fiber positions for investiation of splitter plate arcing

II. THE ARC IMAGING SYSTEM (AIS)

The original AIS from 1990 used in [1-5], was upgraded to a portable 1MHz (AIS) in 2009, as described in [8,9]. Results from the new AIS were presented in a previous investigation of cathode root motion in the flexible test apparatus (FTA), using the same configuration as in Fig.3, [10].

In this paper both the AIS and the FTA are used for an exploratory investigation of high current arc motion inside splitter plates. To achieve this, a new optical head has been designed to expose regions of the splitter plates, as shown in Fig.4. Fig's 3 and 4 shows the test chamber, used to investigate the relationship between contact opening velocity and the cathode and anode arc root dynamics as the arc transverses the arc chamber, [1-5]. The arc chamber is mounted in the horizontal plane, and is designed to simplify the geometry of a typical arc chamber. The anode and cathode conductors are shown with a steel backing plate in Fig.3 to enhance the electro-magnetic influence. The circles show potential positions of the optical fibres in the array; referred to as the optical head. The optical head is mounted behind a quartz glass section which seals the arc chamber and is then connected to the data logging system using bespoke optical connectors, [8]. The technical specification of the AIS system is detailed in [9,10]. The key specifications are shown in table 1. The system is further detailed in [8]. The AIS has potentially 1026 channels, using a maximum of 64 data cards with 16 channels per card. In the experimental set up used in this work, 7 cards have been used providing 112 optical fibres connected with 2m of fibre from the AIS to the experimental apparatus, FTA, as detailed in table 1.

Each fibre position is withdrawn 25 mm into the optical head to reduce the field of view of the individual fibre, [8]. Fig 5 shows an image of the arc chamber used in this work with the corresponding optical fibre positions; it shows the contact region on the right and the splitter plates on the left.

A. Arc Imaging

There are two modes of arc imaging; **mode 1** uses dynamic thresholds; while **mode 2** uses fixed thresholds corresponding to the maximum light intensity for the whole data set I(max). With dynamic thresholds the maximum value is the maximum light intensity across all the fibres at a given frame number or time, $I_{max}(t)$. The images are created with a different maximum intensity $I_{max}(t)$ for each frame, this is best suited for viewing the arc when the light intensities are low; for example at the start of the arc. Mode 2 is best suited for an overview of the arc process when the arc is in the chamber, as the image intensity scale will be fixed, allowing a systematic comparison of arcing events. In addition to the mode of imaging there are a number of methods for creating images.

1) *Method 1. Group Contours.* Contours are grouped for the whole array which then creates an image of the arc. The method is ideally suited to the low intensity resolution data, [1-5], however with increased bit resolution from 6 to 8 a number of new methods of imaging have been developed.

2) *Method 2. Point Contours.* Each fiber position is illuminated with color coded concentric circles, where the color of each embedded circle is related to a percentage of the maximum light intensity level, using either mode 1 or 2 to define the maximum level. The key advantage over method 1 is that, with the increased bit resolution of the light intensity, multiple conducting paths are detectable.

3) *Method 3. Simulated images.* This allows the creation of realistic images of the arc discharge process at sample rates not possible with conventional video or photographic methods. The fiber spots are interpreted as the nodes of a planar triangulation, which is automatically produced by means of the classical Delaunay algorithm [9].

TaiCaan Technology System (AIS)	AIS specification	AIS experimental
Maximum Framing or sample rate	6 MHz	1 MHz
Number of Optical Fibres	1024	112
Light Intensity Resolution	8bit (0-255)	0-255
Memory Allocation	512K	512K
Data storage time at Maximum Framing rate	83 ms	500 ms
Fibre Length	100 m	2 m
Signal Gain	1 - 32	1

Table 1. System specification and experimental specification

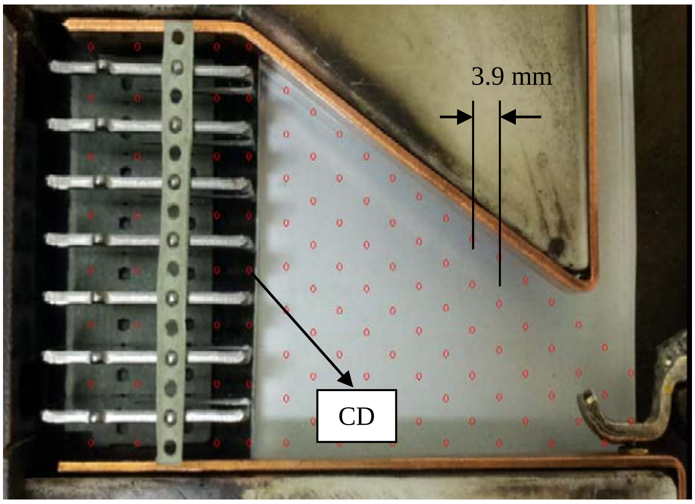


Fig.5 The addressing of fiber positions in the optical array, with expanded fibre sequence along the cathode runner.

III. EXPERIMENTAL METHODS

The flexible test apparatus FTA shown in Fig.3&4 is connected to a capacitive discharge system, such that current starts to increase at a defined time prior to the opening of the contacts; a peak short circuit current of approximately 2 kA occurs with a half cycle period of 10ms, with the peak current controlled by the charging voltage of the capacitor bank. In the experimental set up three charging voltages were used 200, 260 and 300 V. In all cases the cathode is connected to the fixed contact. The Cu arc runners were used without the Fe backing plate to reduce magnetic forces on the moving arc, thus allowing a study of the arc motion into the splitter plates without the influence of the external magnetic field enhanced by the Fe plates. The vent behind the splitter plates is 15% open, and the moving contact was connected to a high speed solenoid opening device, (>6 m/s). The contact material used is Silver Cadmium Tin Indium Oxide with 18% metal oxides.

The splitter plates have been modified from a commercial MCB device, with 7 coated Fe plates using a standard entrance geometry shown in Fig 6. These are shown in Fig 5, with 4 optical fibre positions between each plate. To allow the assessment of the arc while inside the splitter plates. Fig 5, shows the actual fibre positions with a superimposed photographic image. The back side of the splitter plates is blocked (not shown) using the insulating fibre material used in the commercial splitter plate. Thus when the arc enters the splitter plates it is prevented from moving directly through. The venting plate with 15% opening allows the gases to vent out from the back of the arc chamber. To allow imaging of the arc whilst inside the plates the side is covered with quartz glass as used in the arc chamber; thus preventing the arc discharge from exiting through the side of the splitter plate array. The optical fibre positions are shown in Fig 5, with the array grid spacing of 3.9 mm in the arc chamber and 4mm in the splitter plates.

Imaging the arc inside the splitter plates causes a number of issues with the maximum light intensity, and the bit resolution of the data. This was not an issue in previous studies where the investigations were centred on the initial opening phase where the light levels are low compared to the maximum light levels. This effect is shown in Fig 7 for the fibre positon identified as CD in Fig. 5, where the maximum normalised light intensity is 1162, compared to value of approximately 10 when the initial arc light is detected on this fibre. Thus imaging the high intensity arc requires a reduction in image resolution for the opening stages of the event.

Fig.6 The splitter plate geometry

A. Normalisation of light intensity across the fibre array

A critical feature of the arc imaging is the ability to normalise the light transmission across all fibres. This facility is provided in the system software, [8], and ensures that all fibres transmission paths are normalised. In the example of fibre position CD in Fig. 5, the normalisation or scaling factor applied is 4.65, thus the maximum light intensity value for that fibre is 1185.75, (255 x 4.65), (see Fig 7).

IV. RESULTS AND DISCUSSION

A. Arc Motion for 300V charging voltage.

The arc voltage, current and light intensity for fibre CD, at the front of the splitter plates is shown in Fig. 7. The contacts open 1 ms after the start of the short circuit event, (not shown). The data in Fig.7 starts 3 ms into the event and thus 2 ms after the opening of the contact, with an instantaneous arc voltage of 34.5 V and arc current of 1443.1 A. At this instant the arc is shown in Fig 8, to be in the contact region with the cathode roots on the fixed contact side exhibiting the highest light intensity. Fig.7 shows the arc voltage increasing to 300 V when the arc enters the splitter plates. The arc is shown in the data for fibre CD to enter the plate around 4.5ms with a small rise in the arc voltage to 125 V and then reverses back to the arc chamber before entering again at 4.733 ms with a voltage of 130 V.

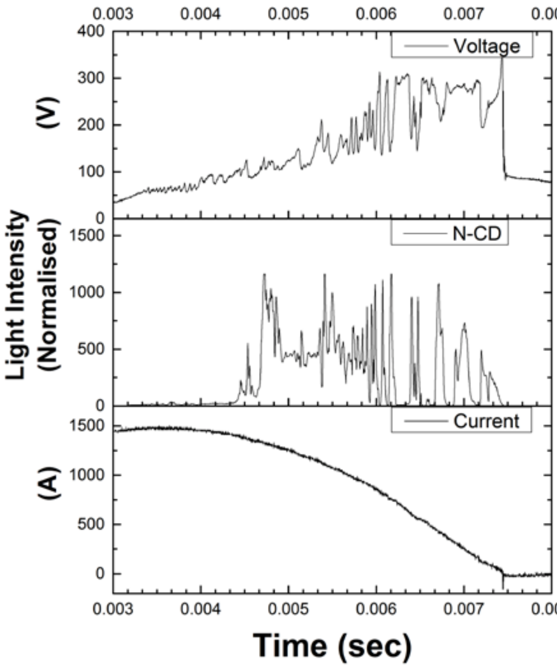


Fig.7 The Arc Voltage and Current and Light intensity on fibre CD for 300V supply voltage.

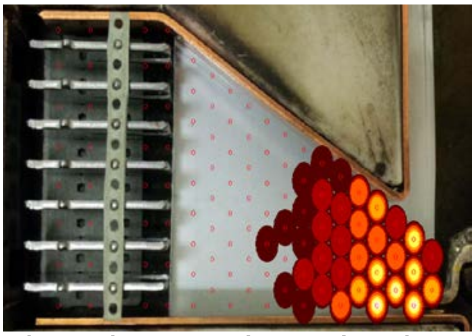


Fig. 8 The arc at the 3 ms. Imaged using mode 1 with contours at 30,40,50,60,70,80,90% of local $I_{max}(t) = 339.3$.

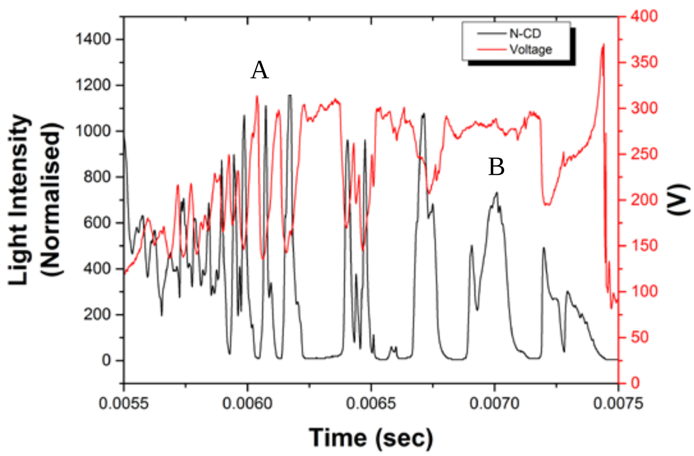


Fig.9 The Arc Voltage and Current and Light intensity on fibre CD for 300V supply voltage zoomed in to show interaction of arc voltage and splitter plates.

Fig 9, is zoomed into to show the interaction between the CD light fibre position and the arc voltage. It is important to note here that most of the light intensity peaks go from zero to the max level around 1180, in periods of less than 100 µsec. This essential observation means that to study the phenomena of the arc entering the splitter plates the high speed camera technology used [6], does not have sufficient temporal resolution. A sample rate 1 MHz or higher is required to show these features. Fig 9 shows a clear correlation between the arc voltage peaks and the low arc intensity at fibre CD, when the arc is fully in the splitter plates. As the arc reverses its position and passes back to the arc chamber the light at CD peaks. A close inspection of the arc images shows that the arc is not reversing, but re-striking in the chamber, creating multiple current paths through the plasma. This is shown in the sequence in Fig.10 corresponding to the first full entry into the splitter plates at point A in Fig.9. Fig. 10(a) shows the arc fully established in the splitter plates at 6.047 ms with an arc voltage of 288 V, 5 µsec later at 6.052 ms in 10(b) the arc re-strikes in the arc chamber without passing the set of fibres at the front of the splitter plates, for example CD. This event appears to then cause the arc at the back of the plates to move back through the splitter plates causing the arc to re-form at the front of the plates in 10(c) at 6.067 ms, a further 15 µsec later, where the voltage then falls to 142 V. This process shows instability in the arc motion in the plates, with the events requiring 1 MHz temporal resolution. The instability is then repeated a number of times in Fig.9 before the arc stabilises at around 6.5ms, where the arc voltage remains relatively stable for the remainder of the event. Once the arc current falls at 7 ms (266 A) the arc is fully established in the splitter plates and no longer restrikes in the arc chamber. Fig. 11 shows the arc established in the splitter plates and bowing out at the centre region where fibre CD is located causing the rise in light intensity shown at B in Fig. 9.

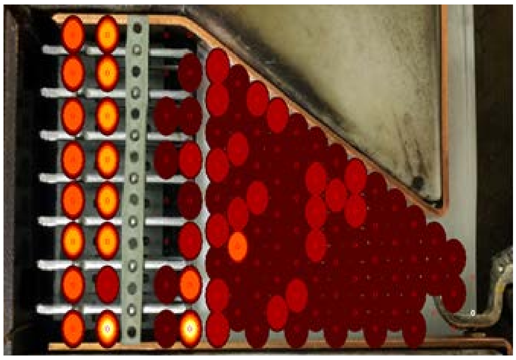
B. Arc Motion for 260V charging voltage

To investigate the influence of the charging voltage, the experiment is repeated with the same configuration but with a reduced voltage of 260 V. The data for the optical fibre position CD is shown in Fig 12. The reduced voltage will reduce the peak current, thus reducing the electro-magnetic forces and slowing the arc motion. This is shown clearly in Fig.12 with the arc reaching fibre position CD at a later time when compared to the 300V test, also shown. The result also confirms the observation form the previous data that the arc is highly unstable as it enters the plates.

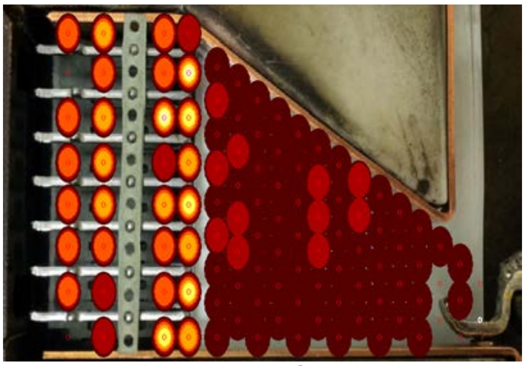
C. The Number of splitter plates

In this study the arc stack has been deuced from 15 to 7 plates to enable the observation. Increasing the number of plates will influence the arc voltage and may also increase the instability.

(a) At 6.047 ms with arc voltage 288.6 V.



(b) At 6.052 ms arc voltage 313.7 V.



(c) 6.067 ms, arc voltage 142 V

Fig. 10, events around point A in Fig 9. (mode 1, 5,15,30,50,70,80,90%)

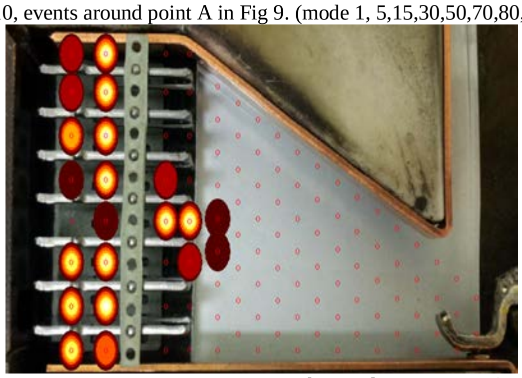


Fig. 11 events at B in Fig 9, 6.960 ms and arc voltage 283.9V. (mode 1, 3,10,20,30,40,50,60%)

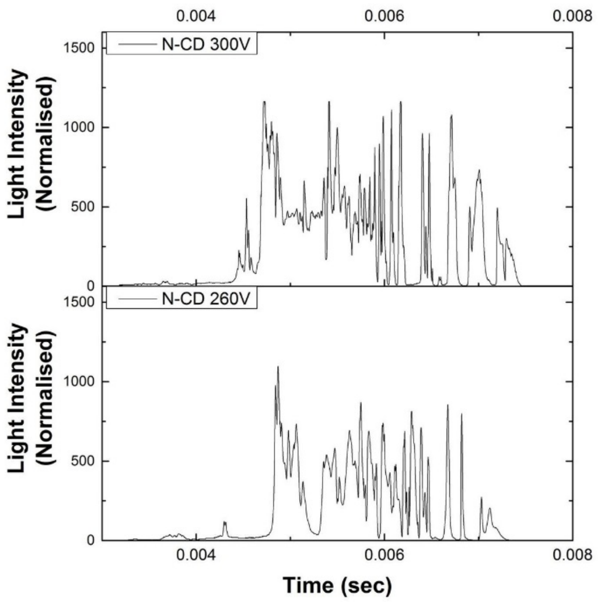


Fig.12 The light intensity on fibre CD for two charging voltages.

CONCLUSIONS

The results show the development of an established commercial arc imaging system to include the investigation of event occurring in splitter plates of a low voltage switching device. The results show that such imaging requires sampling rates of the order of 1 MHz to fully capture the instabilities in the arc motion. It is shows that the arc can enter the plates in a repeated motion. It has been shown that the arc can re-strike in the arc chamber while the arc is still in the splitter plates causing an instability in the arc voltage. These instabilities have been shown in many experimental studies. They are an important observation when consideration is given to the modelling of the events in splitter plates.

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