A Study of the Arc of a Radial Magnetic Field (RMF) Contact Geometry at Currents below the Natural Constriction Level

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Abstract- **A study was carried out to investigate vacuum arcs at low currents on Radial Magnetic Field (RMF) contacts used in commercial Vacuum Interrupters (VI). The RMF contacts operate by moving the naturally constricted arc in a predictable and controlled way in order to have interruption of short circuit currents of 20kA or more. Arcs on RMF contacts at large short circuit currents have been widely studied, but there is little published about how these contact geometries work at low currents. This is of interest as the vast majority of switching operations for VI are actually carried out at load currents, which are typically less than 3150A rms, and are all below the natural constriction level for the arc. The study was to investigate how these naturally diffuse arcs behave under the magnetic fields induced by the RMF contact geometries.**

The study consisted of a series of high speed films of commercial RMF contacts in a demountable vacuum chamber switching a range of currents from 400A to 3150A rms. The films showed that although the arc moves predictably at high short currents which are in the kA range, for these low currents the diffuse arc behaves quite differently. In fact there is some indication in the films that although parts of the arc try to rotate as they would do at higher currents, much of the arc does not, and in fact the Radial Magnetic Field may in fact inhibit the diffusion of the arc which would normally occur. This is normally not a problem in service, but it may indicate that optimizing the contact geometry for the highest short circuit currents may in fact not give the best performance at lower currents.

I. INTRODUCTION

The development of arc control systems for Vacuum Interrupters (VI) has been ongoing for over half a century[1,2]. The vacuum arc is naturally diffuse at low currents, but at higher currents the diffuse arc collapses and instead forms a constricted arc which covers a much smaller area of the contact surface with a very high current density. This in turn causes the contact surface to overheat resulting an a failure to withstand the transient recovery voltage seen after current zero. This limitation was overcome from the 1960's onwards by applying a magnetic field in the radial direction relative to the arc[3,4,5].

The Radial Magnetic Field (RMF) does not prevent the arc constriction, but instead forces the arc to move, thereby reducing the local power input to the contact surface and preventing overheating. This technique has been widely applied for many years[6,7,8], and is so effective that RMF contacts are used in commercial VI to interrupt all levels of short circuit current from 13.1kA rms up to very high currents such as 63kA rms and above[8].

However, the focus of the original R&D efforts and subsequent product development has primarily focused on the interruption of the high short circuit currents[9], and little research has been carried out into the interruption of the lower currents which are significantly below the constriction level. This is important however, as in reality the main use of VI is to switch load currents normally from a few hundred amps up to 3150 A, where the arc is still in the naturally diffuse mode. In fact the interruption of short circuit currents is a relatively rare event, and many vacuum interrupters will never see this during their operational life.

Our experiment was set up to investigate the interruption process for these low currents, and specifically the interaction of the radial magnetic field with the naturally diffuse arc.

II. DISCUSSION

A. Radial Magnetic Field (RMF) geometry

Figure 1 shows the contacts tested. These are of the "Swastika" type and create the radial magnetic field by forcing the current to flow along the "petals" formed by the slotting of the contact disc.

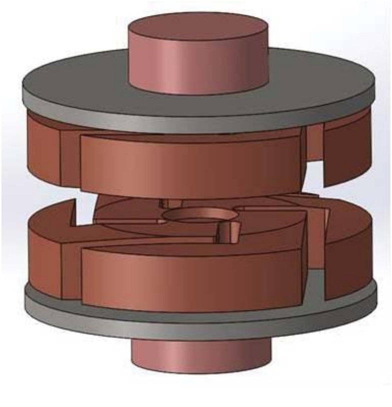

Figure 1: The contact design; RMF "Swastika" style 51mm diameter

The test contacts are commercial VI contacts, 51mm in diameter, and are made from a Copper Chromium

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material which is 75% Copper and 25% Chromium. The current enters and exists the contact system via a stem located at the centre of each contact. The moving and fixed contacts are mirror images of each other and the flow of current through the stems and "petals" [material between slots] of the contacts generate the radial magnetic field. The actual contacts after test are shown in Figure 2,

Figure 2: The contacts after test

Figure 3 shows the movement of the constricted arc under a high short circuit current. The arc moves from position A to B, to C, to D, and so on, eventually performing two or more revolutions of the periphery of the contact. The arrows show the magnitude and direction of the force. These values were calculated by modelling the contact geometry using electro-magnetic Finite Element software (MagNet).

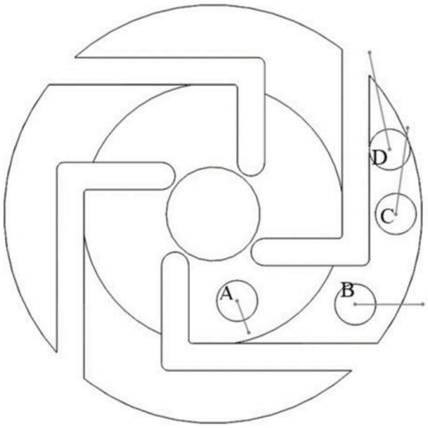

Figure 3: Movement of the constricted arc under short circuit conditions, sequence is A – B – C – D. The arrows show both the direction and the magnitude of force on the arc

However, as the current is very low for load breaking tests, the actual magnetic fields will also be low, and so the effect of the field on the cathode spots will be limited, and at these low currents where there is a naturally diffuse arc it becomes very difficult to model what will happen to the cathode spots, which is why we decided to us high speed photography for the investigation, which is a technique widely used for many years in this field[10].

B. The Experiment

We used a pair of contacts from a commercial Vacuum Interrupter. These were adapted to fit inside a demountable chamber of our own design. The chamber shown in Figure 3 consists of a top and bottom plate, these contain all of the feedthroughs and fittings such as vacuum measurement, pumping, as well as the power feedthroughs. The lower plate power feedthrough also includes a bellows to allow for the contact movement. The wall of the chamber is 12" (30cm) in diameter and is completely transparent, allowing us to film from any direction. Pressure in the chamber is c. 2.0 x 10^{-4} mbar.

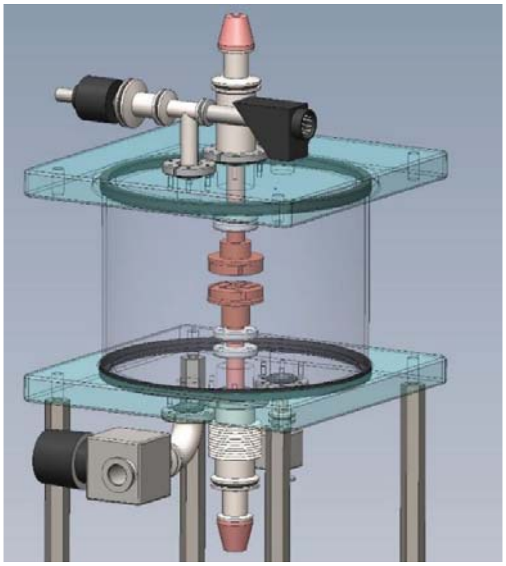

Figure 4: The Demountable Vacuum Chamber

The demountable chamber was inserted into our Synthetic Short Circuit Test plant (Figure 5). This test plant is designed to give one half cycle of single phase current at 50Hz (symmetric or asymmetric) from 250A rms up to 40kA rms. The plant also includes a variable speed magnetic drive which provides the necessary movement of the contact. During the test the current started with the contacts closed and then the moving contact was opened at around 1m/s to a contact gap of 8mm. This pulled an arc between the contacts which continued until the next current zero giving an arcing time of approximately 1ms. This system of operation closely simulates the actual operation of a VI in a circuit breaker and is essential for the study of these low current arcs where initiation of the arc can be crucial for the subsequent movement.

We use a modern digital high-speed camera, the Chronos 1.4, which can take films over a range of speeds up to 38,565 fps. As the frame rate increases, so the resolution decreases, and for these experiments we actually filmed at 8,819 fps with a resolution of 640 x 240 pixels. Arc duration was 10ms, and so we were achieving 88 frames of arcing for each test, which was sufficient for resolving the cathode spot movement.

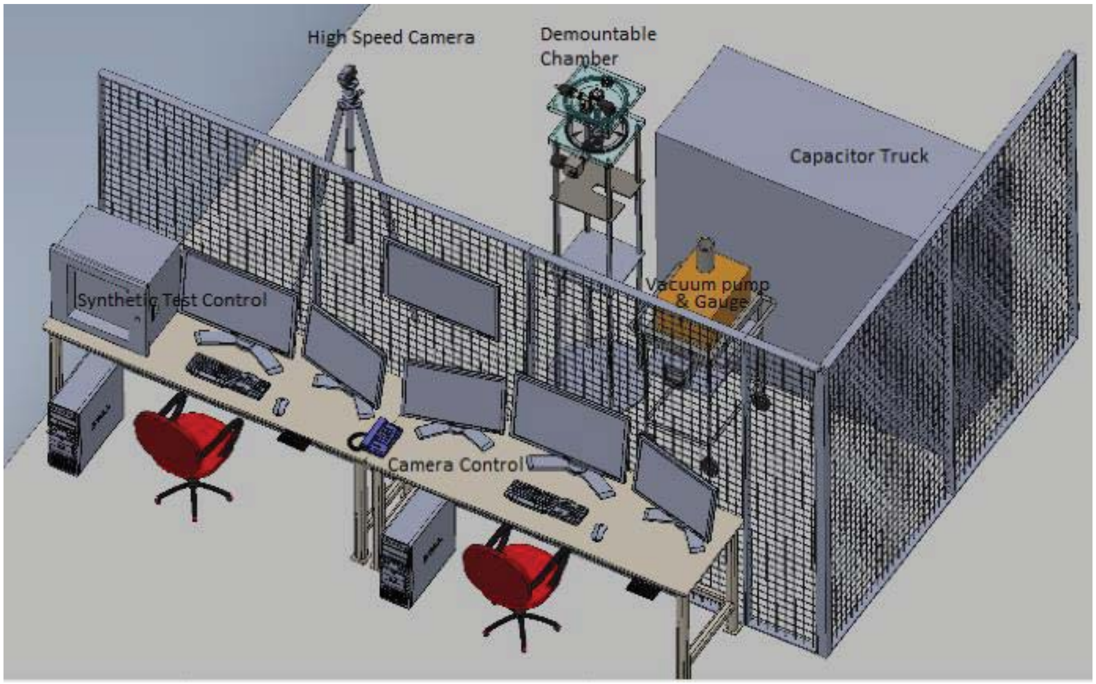

Figure 5: Experimental Layout
(cables & pipes between equipment omitted for clarity)

The camera was positioned so as to show the complete face of the cathode during arcing, in order to record the cathode spot movement. At these low currents there was no visual activity on the Anode

Figure 5 shows the experimental layout in the Vacuum Interrupters Limited (VIL) laboratory. The cables and vacuum pipes are omitted for clarity. We have a number of vacuum demountable chambers, with a typical configuration shown in Figure 6 below.

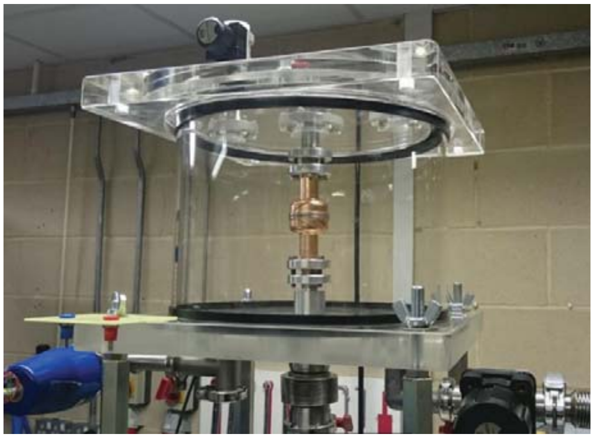

Figure 6: The Demountable Vacuum Chamber
(not Swastika contacts)

C. The Results

The Test Program is shown in Table 1. At each current setting we performed three shots on each polarity. The pictures shown are a typical result for that current rating. On observing the cathode spots, although individual spots showed varied behavior, with some spots appearing to move against the applied field, overall for each current their general movement pattern was consistent. For simplicity of presentation we have grouped the results for each current rating together.

TABLE 1. Experimental Test Program

Film Sequence	Current (Arms)	Film Speed (FPS)	Movement
A	250		Random
B	630		Random
C	1250		Slight rotation at edge
D	2000		Significant rotation
E	2500		Significant rotation
F	3150		Significant rotation

Sequence A @ 250A shows random movement of the Cathode Spots (CS) as is normal with no applied magnetic field. Sequence B @ 630A again shows random behavior of CS with no apparent effect of the magnetic field. Sequence C @ 1250A shows a mixed effect, with many CS moving randomly and moving off the edge of the contact, as is normal, but some show definite rotational movement. Sequence D @ 2000A shows significant rotational movement of CS, but some still continue random motion. Sequence E @ 2500A shows majority of CS in rotational movement, with some random motion. Sequence F @ 3150A shows large majority of CS following the rotational motion. No sign of constriction.

From these results it seems that as the current increases the field eventually is sufficient to make a difference to the CS movement, however, some CS still are not affected by the field even at high currents. For the moment we are not clear why this happens, and what differentiates these CS. We intend to investigate further.

Figures 7 (a-f) show stills from typical films taken at each current setting, normally just after peak current so that the field has had time to affect the motion of the CS.

Figure 7a High Speed Film 650A

Figure 7b High Speed Film 700A

Figure 7c High Speed Film 1250A

Figure 7d High Speed Film 2000A

Figure 7e High Speed Film 2000A

Figure 7f High Speed Film 2500A

III. CONCLUSIONS

The RMF arc control concept is very effective at permitting a VI to interrupt very high currents. What these experiments have shown is that on this design the RMF concept of making the arc move to prevent overheating of the contact surface is not effective at lower currents which are below the natural constriction level of the arc. In fact, there are indications that the presence of the radial magnetic field may in fact inhibit the free movement of the cathode spots, as it was noted that the normal radial movement over the edge of the contact was much less than for a plain disc contact at the same current level. Other researchers have shown that the presence of an Axial Magnetic Field tends to inhibit Cathode Spot movement, and our modelling shows that although the dominant field generated by the contact is Radial, there is still a significant Axial component, which may explain this effect. However, as the power density on the surface is very low at these currents this lack of movement does not prevent interruption at current zero.

Overall it is clear that although these RMF contacts are not optimized for low current switching, they still perform adequately. However it may be useful to investigate further in order to see if it is possible to optimise the performance of RMF contacts both for high short circuit current interruption, and also for the normal current interruption.

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