Direct Current Interruption with RLC Circuit-Convoluted Arc Interaction

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Abstract— **Investigations are reported into the use of an electromagnetically convoluted arc, external to a magnetic field (B-field) producing coil, in combination with a parallel R, L, C resonant circuit for interrupting quasi-steady currents. In order to elucidate the complex interactions between the arc, B-field and R, L, C circuit, the B-field producing coil is energised independently from the current to be interrupted and the R, L, C circuit.**

Experimental results are presented for the time variation of the currents flowing through the arc gap, the B-field coil and the parallel L, C, R circuit, along with the voltage across the arc gap. An insight is gained into the role of various effects, which are produced by the complex interactions and which might be used to advantage for direct current interruption.

***Index Terms*—Arc discharges, ablation, current interruption, magnetic fields, plasma arc devices, plasma control.**

1 Introduction

THE interruption of high levels of direct current (DC) at high and medium voltages is attracting much interest because of the advent of power transmission from renewable sources such as wind, solar, etc. Attempts to find an alternative to sulphur hexafluoride (SF6) [1] as the arc quenching medium and to obtain more efficient DC interruption techniques are ongoing [2, 3]. Current interruption in DC systems is more problematic than in alternating current (AC) systems since there is no natural current-zero available.

One of the techniques for producing a current zero artificially during direct current flow is with a current oscillating R, L, C circuit connected across the interrupter arc gap [1, 4]. The use of such circuits in rotary and non-rotary arc circuit breakers have been previously investigated with arcs in atmospheric pressure SF6 gas [1, 4].

In this paper, the form of electromagnetically convoluted arc unit previously used for interrupting AC arc currents [5] was connected in parallel with an R, L, C circuit for producing an artificial current zero.

The effects of various parameters (e.g. arc extinction voltage peak, time at which current interruption occurs, re-strike voltages etc.) upon the current interruption process are reported. An insight into the role of various processes in such a complex system has been obtained.

2 Basic Principles

Previous investigations of electromagnetically convoluted arcs have involved two main geometries, namely a geometry with the arc convolute within the electromagnetic B-field producing coil and a geometry with the arc outside the B-field coil (Fig. 1a, b) respectively). A further variant of the geometry with the arc outside the B-field coil involves an insulating polytetrafluoroethylene (PTFE) cylinder outside the B-field coil so forming an annular gap within which the convoluted arc exists (Fig. 1c). The present investigations involve the third geometry (Fig. 1c), [5].

a)

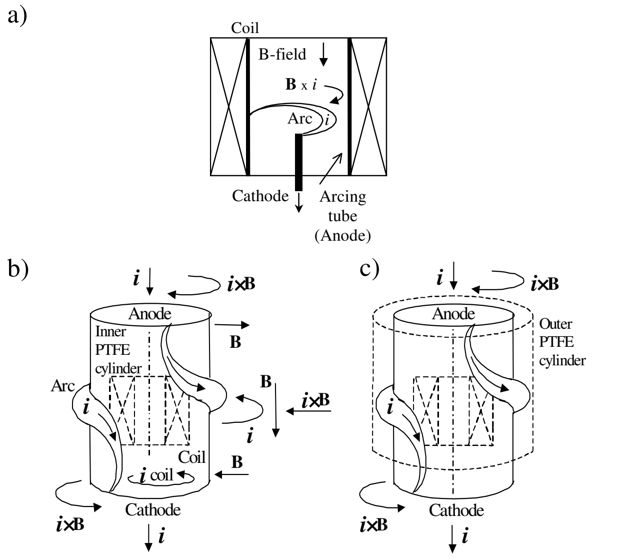

Fig. 1. Schematic diagrams of B-field convoluted arc geometries. a) Arc within the B-field coil; b) Arc outside the B-field coil; c) Arc in annular gap outside the B-field coil.

In addition, the present investigations involve an R, L, C circuit in parallel with the arc gap whilst the B-field coil is excited separately from the arc sustaining current.

The circuit arrangements for achieving a separation of the arc current, B-field current and R, L, C circuit is shown on Fig. 2.

As a result, there are several permutations of possible operating conditions, which can be employed. These are summarised on Table 1.

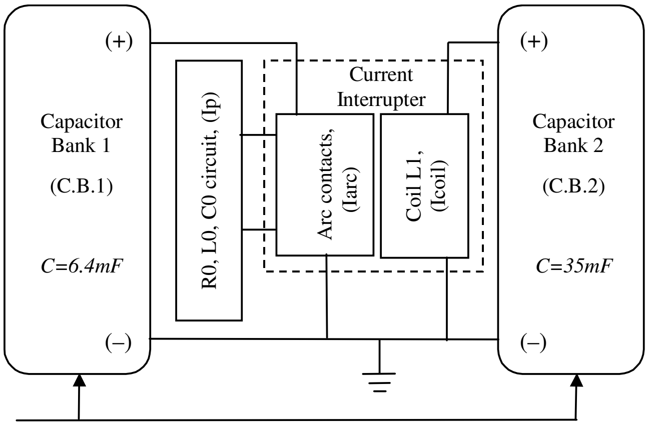

Fig. 2. Schematic diagram of the circuit interconnections for the parallel L0, C0, R0 and high voltage supply circuits. (Where: L1 is B-field producing coil of the current interrupter (CI).

Table 1. Configurations of convoluted arcs tested with outer PTFE cylinder. Where: A = arc, B = B-field, C = R0, L0, C0 circuit.

Configuration:	Tested
A	-
A + B	Yes
A + C	Yes
A + B + C	Yes

This indicates that there are three facets to the arc and Direct Current (DC) interruption with the annular gap configuration.

The first is the control and extinction of an arc electromagnetically with no R0, L0, C0 circuit (A + B, Table 1) [5] when the arc contacts (and hence the arc column) extends in parallel along the length and outside of a B-field producing coil (Fig. 1c).

The second is the use of a parallel R0, L0, C0 circuit across the convoluted arc gap (A + C, Table 1) [4] to generate high-frequency current flow through the arc, with no external B-field.

The third is a combination of both the B-field and the parallel R0, L0, C0 circuit. By separately exciting the B-field coil, the effects of the B-field and R0, L, C0 circuits may be discriminated.

2.1 B-Field Alone

With the first facet (previously described by [5]), with the opposite arc current flow in relation to the arc contacts, the anode arc section is exposed to an outward radial B-field produced by the B-field coil. This causes the arc to rotate in an anticlockwise direction. When the arc gap is fully opened, the arc section is exposed to the inward B-field, at the opposite end of the coil, which causes that arc section to counter rotate in a clockwise direction [6]. The present investigations involved the third geometry (Fig. 1c), [5]) but with the anode and cathode positions reversed (and hence also the arc current).

The central arc column section forms a convolute around the inner PTFE cylinder by the action of the axial B-field component at the middle of the coil length upon the azimuthal arc current flow. At current close to zero, the inward Lorenz force vanishes and the arc plasma ring is no longer compressed against the inner PTFE cylinder [3, 5].

2.2 R, L, C Parallel Circuit Alone

With the second facet, perturbations in arc voltage cause the R0, L0, C0 circuit to produce high-frequency current oscillations to be superimposed upon the main DC arc current. When the amplitude of these current oscillations are sufficiently high, they force the arc current to zero so that current interruption may occur.

2.3 B-Field and Parallel R, L, C Circuit

The third facet (parallel R0, L0, C0 circuit plus B-field), has been previously described in conjunction with the arc inside the B-field coil (Fig. 1a), [4]. However the deployment with the arc outside the coil has some different and advantageous aspects. In this case, when the length of the convoluted arc is increased around the coil by the Lorenz forces (Fig. 1c), the arc voltage increases, charging the parallel capacitor C0 to the same voltage as that across the arc. If the arc length is suddenly reduced due to self short-circuiting of the arc convolute, the arc voltage is rapidly reduced. As a result, the capacitor discharges itself through the arc. Therefore, if the parallel circuit R0, L0, C0 is connected across the arc gap of the interrupter ((CI), Fig. 1c), the discharge of C0 will produce high-frequency current oscillations (Ip) through the arc (Iarc), (Fig. 1c) at the natural frequency of the R0, L0, C0 circuit. By separating the arc power source, the B-field coil and the R0, L0, C0 circuit, the individual effects of each of the three facets can be more conveniently assessed.

3 Test Circuit

The experimental test circuit used for the present investigations is shown in Fig. 2. It consisted of two independently but synchronously operated capacitors bank units (C.B.1 and C.B.2). CB1 (6.4mF) generated quasi-direct current electrical arcs of up to 1.5kA at 4kV.

CB2 (35mF) produced B-field coil currents up to about 5.8kA, at 4kV. Each capacitor bank included an ignitron, which was connected in series with current limiting resistors (~2.7Ω for the arc of 1.5kA or ~6.7Ω for the arc of 0.6kA, C.B.1 and ~0.7Ω, C.B.2). These ignitrons were triggered to conduct quasi-steady currents through the interrupter (CI) and B-field coil (L1) at predetermined times. In addition, both units included ignitrons for short circuiting the two DC circuits in order to dump the remaining energy from the capacitor bank units.

A series combination of L0, C0, R0 circuit was connected in parallel with the arc convolute interrupter (Fig. 2) with L0, C0, R0 having values of 96µH, 66µF and 0.1Ω respectively. These component values were based upon values from previous work deploying a similar test circuit, but using a different type of arc convolution unit [4].

Three CWT type Rogowski current transducers R.C.1, R.C.2, R.C.3 were used to measure the DC current waveforms of the arc (Iarc), coil of L1 (Icoil) and L0, C0, R0 (Ip) circuits respectively (Fig. 2).

4 Experimental Results

Experimental results are presented for the time variation of the currents through the interrupter arc, the B-field coil and the R0, L0, C0 circuit along with the voltages across the electric arc convolute.

Fig. 3 shows an example of the time variation of various currents and arc voltage when a quasi direct of 1.5kA peak was interrupted with a B-field of ~35mT (at current interruption). Fig. 3a shows the arc voltage and current waveforms.

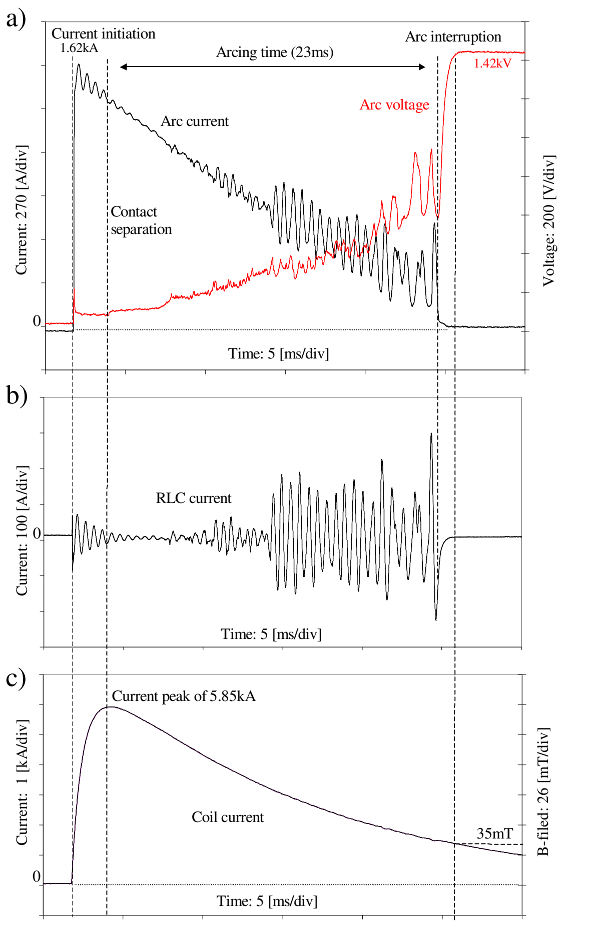

Fig. 3. Time variation of system currents and arc voltage when interrupting a quasi direct current (1.5kA peak, atmospheric pressure air). a) Arc current (I arc) and Voltage; b) R0, L0, C0 current (Ip); c) Coil current (~5.8kA peak producing 150mT B-field). (Initial C.B.1, C.B.2 (Fig. 2) voltages 4kV peak).

Fig. 3b shows the current flowing through the R0, L0, C0 circuit (Fig. 2).

Fig. 3c shows the B-field coil current during and post arcing. These results show that high frequency currents of frequency ~2kHz occur during arcing (Fig. 3b) through both the arc and the R0, L0, C0 circuit.

Fig. 4 compares the time variation of quasi direct currents all of peak value 1.5kA, but under different operating conditions (Fig. 4a), and the corresponding arc voltages (Fig. 4b).

Curve (1) (Fig. 4a) is for capacitor bank C.B.1 discharging through the closed interrupter (CI) (Fig. 2) showing an uninterrupted current of duration ~80ms.

Curves (4) (Figs. 4a, b), are results with the R0, L0, C0 circuit connected, but without the B-field coil energised, indicating an arc duration of ~55ms.

Curves (3) (Figs. 4a, b) are results with the B-field coil energised (5.8kA peak current), but without the R0, L0, C0 circuit connected, indicating an arc duration of ~26ms.

Curves (2) (Fig. 4a, b) are results with the B-field energised

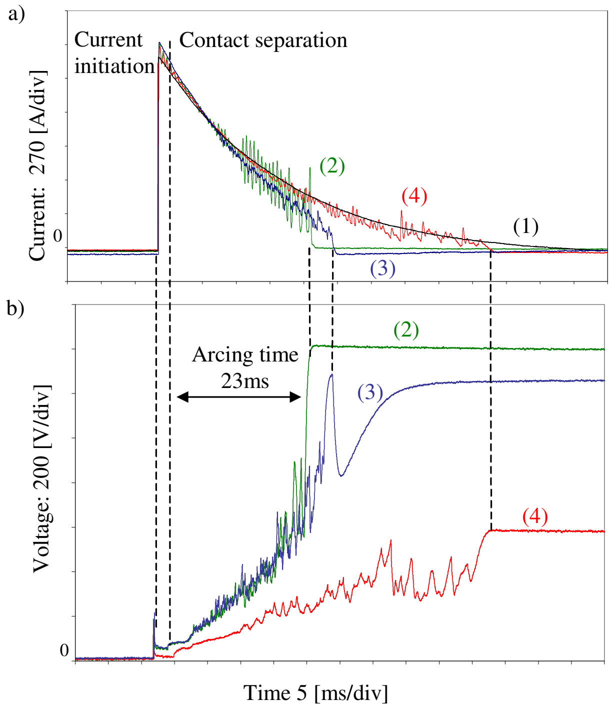

Fig. 4. Interruption of 1.5kA peak quasi DC under different conditions (air, atmospheric pressure). a) Interrupter current waveforms b) Voltage waveforms; (1) Contacts closed; (2) Contacts open plus B-coil and R0, L0, C0 connected circuits; (3) Contacts open plus B-coil, without R0, L0, C0 connected circuit (coil peak current ~5.8kA); (4) Contacts open, without B-field circuit, but with R0, L0, C0 circuit connected. (Initial voltages on C.B.1 and C.B.2 = 4kV).

and the R0, L0, C0 circuit connected, indicating an arc duration of ~23ms.

Fig. 5 shows the time variation of arc currents, all with a lower initial current value of 600A, with the R0, L0, C0 circuit connected and with three different B-field coil currents (initial values 0, 1.6, 5.8kA giving B-fields of 0, 41.4, 150mT).

5 Discussion

Previous experimental work [5] suggests that the minimum level of Lorenz force (I x B) required to induce a convoluted arc structure is about 6 - 10N/m. The coil used in the present tests could produce such a force at an arc current of 300 - 400A with a B-field of 20-25mT.

High speed photographs (7200 frames per second (fps), 8μs exposure) of an arc used in the present investigation, but with the outer PTFE cylinder removed are shown on Fig. 6. These images confirm that a convoluted arc was indeed formed as indicated by previous work, despite some of the operating conditions being different (i.e., absence of the outer PTFE cylinder, opposite direction of the arc current flow and anode/cathode optical observation condition), [6].

An insight into the interaction of the B-field induced arc convolutions and the R0, L0, C0 circuit may be gained from the time variation of currents shown on Figs. 3, 4 and 5 for different initial quasi steady currents, with and without a R0, L0, C0 circuit and with different levels of B-fields.

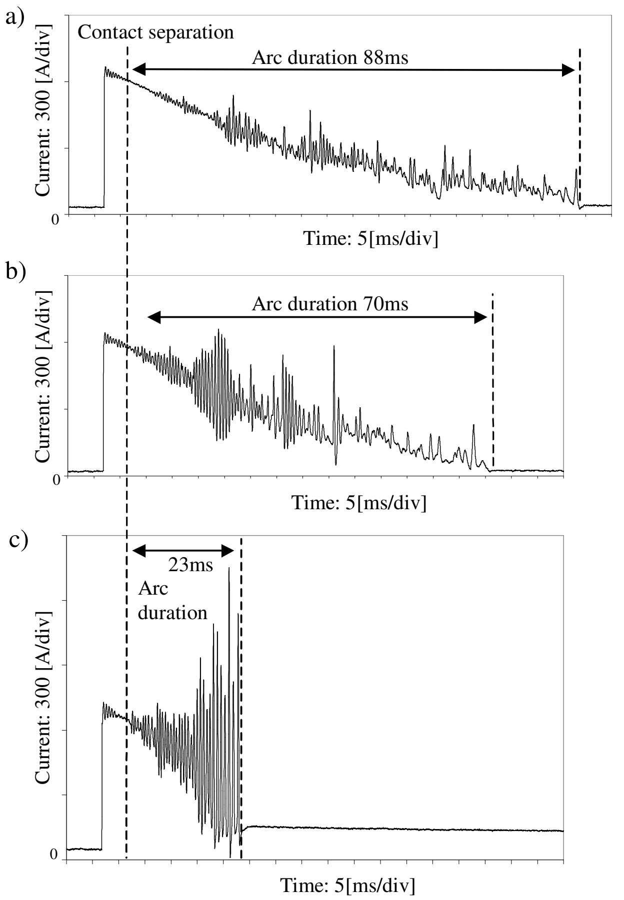

Fig. 5. Time variation of quasi steady arc currents, initial value of 600A, with outer PTFE cylinder and R0, L0, C0 circuit connected across the arc gap with moveable anode. a) No B-field; b) B-field coil current of 1.6kA (41.4mT); c) B-field coil current of 5.8kA (150mT), [6].

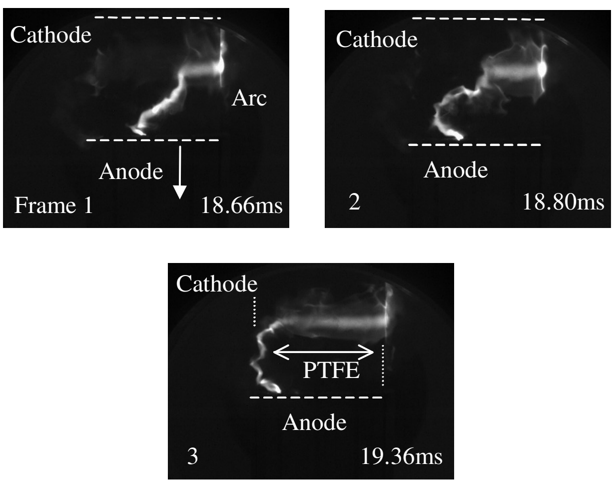

Fig. 6. High speed photographic images proving the formation of an arc convolute for the conditions of the present experiments, but with the outer cylinder removed. (Initial arc current 0.6kA, B-field = 150mT).

5.1 1.5kA Initial Current Tests

The results shown on Fig. 3 indicate that the oscillatory currents through the arc and the R0, L0, C0 circuit commence at the same time (~12ms after contact separation), have the same frequency (~ 2kHz) and similar amplitudes (~ 50 – 100A). This time instant corresponds to the arc contacts gap being similar to the length of the B-field coil (~70mm) [5] when an arc convolution will have been formed and short circuited. Thus this process is responsible for initiating the oscillatory current produced by the R0, L0, C0 circuit. At times longer than 12ms after contact separation, the length of the arc gap becomes greater than the length of the coil, so that the quasi DC arc becomes susceptible to repeated self short-circuiting and convolute re-formation. These repeated arc short circuits are manifest upon the current oscillations as a lower frequency oscillatory envelope of the high frequency current (Fig. 3a, b). A maximum amplitude (~300A) of the high frequency current oscillations (Ip) was generated just prior to the arc current (Iarc) interruption (Fig. 3a) consistent with the high frequency current oscillations producing the required current zero for current interruption.

Fig. 4 allows a number of B-field and R0, L0, C0 related effects to be identified:

a) Comparison of curve (1) (contacts closed) and curve (4) (R0, L0, C0 connected but no B-field) shows that R, L, C oscillations are produced and that current interruption only occurs at a low level of the quasi direct current (70 A) at a time of 55ms.

b) Curve (3) shows that a B-field without the R0, L0, C0 circuit produces enhanced current interruption without the high frequency oscillations at a shorter time of ~26ms and a higher current (~150A). The B-field also has a current limiting effect, reducing the quasi direct current at a given time compared with the current without the B-field.

c) Curve (2) shows that with both a B-field and the R0, L0, C0 circuit connected, the current is interrupted in a shorter time of ~23ms and higher current (~300A) plus with the current limiting effect of the B-field. This shorter time interruption, at higher quasi DC, is associated with the higher amplitude oscillations (compared with the no B-field and no R0, L0, C0 circuit) resulting from the higher amplitude current oscillations produced with the convoluted arc.

d) Comparison of the post arc voltage curves (2), (3), (4), Fig. 4b shows that the residual source voltage following arc extinction is highest when both the B-field and R0, L0, C0 circuit are activated (~1.4kV curve (2)) due to the short arcing duration (and hence reduced power dissipation). The residual source voltage is lowest in the absence of the B-field coil, but with the R0, L0, C0 circuit connected (~0.6kV curve (4)), mainly due to the lower arc voltage (hence lower power dissipation) and despite the prolonged arc duration. With the B-field and without the R0, L0, C0 circuit, the remnant source voltage is intermediate between those of curves (2) and (4) and there is evidence of arc re-ignition in the form of a late voltage collapse (curve (3)).

The results discussed above are summarised on Table 2.

Table 2. Effect of B-field and R, L, C circuit on current interrupted (Io), time of interruption (To), residual capacitor voltage (Vres).

Condition:	Io, [A]	To, [ms]	Vres, [kA]
Closed contacts	-	>80	-
No B-field, with RLC	70	55	0.6
With B-field, no RLC	150	26	1.2
With B-field, with RLC	300	23	1.4

5.2 600A Initial Current Tests

The results shown on Fig. 5 provide an insight into the effect of varying the magnitude of the B-field for a fixed initial arc current and the R0, L0, C0 circuit connected, They also provide an insight into the interruption of a lower fault current (600A) which reduces the Lorentz force promoting arc convolution.

For B = 0, a similar behaviour to the 1.5kA initial current (Fig. 4) is observed i.e. irregular, low amplitude current oscillations leading to prolonged arcing before ultimate current interruption (~88ms).

With a moderate B-field of 41.4mT (1.6kA coil current), a few pronounced groups of higher amplitude (~150A) current oscillations with a well defined frequency (~2kHz) occur. There are three main high frequency clusters (frequency of occurrence ~ 270Hz), each having a shorter duration as time progresses and apparently vanishing before the ultimate current interruption. Each cluster is likely to be produced by an arc convolute collapse. Their gradual decline is associated with the reduction in arc current and the current producing B-field at the later times, which mitigates against the formation of strong arc convolution. For this case, the current limitation (although not pronounced) produced by the arc convolutions, rather than the current zero produced by the R, L, C oscillations would appear to be more influential in producing an earlier current interruption at about 70ms.

With the highest B-field of 150mT (5.8kA coil current), higher amplitude (~300A) current oscillations (frequency ~2kHz) are produced leading to an early current interruption at 23ms. In this case only a single cluster of high frequency oscillations occurred before the quasi direct current was interrupted. There is also evidence of some electromagnetic coupling of low amplitude current oscillations onto the B-field coil where a 50A of 2kHz oscillation is apparent [6].

An implication of these results is that it is advantageous to promote oscillations of sufficient amplitude for current interruption as soon as the arc contact gap is open to the extent of the B-field coil length.

The outcomes of the variable B-field results are summarised on Table 3.

Table 3. Effect of B-field magnitude on current interruption (Io – current interrupted, To – time at which current interruption occurred).

B-field, [mT]	Coil current, [kA]	Io, [A]	To, [ms]
0	0	~20	88
41.4	1.6	~20	70
150	5.8	~300	23

6 Conclusions

The results presented have provided an insight into the combined use of a parallel R0, L0, C0 circuit with a novel form of convoluted arc in atmospheric pressure air for interrupting quasi direct currents.

The investigation has highlighted the complex nature of the various factors, which need to be considered interactively.

These are:

- Use of outer PTFE cylinder.
- Magnitude of arc convolving B-field.
- Use of parallel R, L, C circuit.

Some initial insight into the interaction between these factors has been obtained which may be summarised as follows:

The use of a R, L, C parallel circuit without an imposed B-field provides only limited improvement in current interruption.

The use of a B-field but no R, L, C circuit produces improved current interruption via the formation of arc convolutions which assist both current limitation and arc quenching.

A combination of an applied B-field plus a parallel R, L, C circuit can lead to enhanced current oscillations of higher amplitude which facilitate the production of a current zero and which, with the current limiting capability of the convoluted arcing, produces improved current interruption.

The times to current interruption and current magnitudes interrupted in the present work are similar to those reported by [4]. However the present results were for arcing in atmospheric pressure air rather than atmospheric pressure SF6 used by [4].

The use of an independently energised B-field coil has highlighted two significant aspects:

a) It is advantageous to have a sufficiently high B-field magnitude for producing current oscillations of high enough amplitude as soon as the opening arc gap extends to the full length of the B-field coil.

b) A sufficiently high B-field is required for the efficient interruption of lower level fault currents.

An independently energised B-field is advantageous for satisfying both such requirements, particularly if the B-field coil energisation might be automatically adjustable inversely to the fault current level.

Further investigations are needed for establishing methods for optimising the values of the various parameters governing the system operation such as B-field coil and current, R, L, C components, width of the annular gap between the inner and outer PTFE cylinders, effect of the mutual inductance between the arc plasma convoluted loop and the B-field producing coil.

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