R L C Induced Current Oscillations in Convoluted Arcs with Independently Activated Magnetic Fields

Leonid M. Shpanin, Gordon R. Jones, Jim E. Humphries, Joseph W. Spencer,
Noel Y. A. Shammas, Sarath B. Tennakoon,

Abstract— **Experimental results on atmospheric pressure arc plasma convolutes in air around a polytetrafluoroethylene (PTFE) cylindrical shroud containing a magnetic field (B-field) producing coil are presented. In this contribution, the B-field coil was energized by a separate current to that flowing through the arc and a separate R, L, C, circuit was connected across the arc gap. Thus the magnitude and time duration of the B-field was independent of the arc current and high-frequency current oscillations produced by the parallel R, L, C circuit. Experimental results for the time variation of the current through and voltage across the arc plasma for these different conditions are presented along with high-speed photographs of the oscillating current arc. The effects of varying the B-field upon plasma pulsations formed by the independent B-field and R, L, C current oscillations are discussed.**

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

I. INTRODUCTION

Arc plasma convolutes formed electromagnetically are of interest in pulsed plasma, high voltage current interruption in power network and plasma processing applications. One manifestation of such helical arcs has been with the arc inside the magnetic field producing coil [1-2]. This method can significantly limit the fault current flowing through the electric arc and prevents the arc length from developing to an extent, which would require a substantial voltage. Zhang *et. al.* reported that this technique together with the RLC circuit connected across the arc gap could produce high-frequency current oscillations which they used to create an artificial current zero for interrupting direct (as opposed to alternating) fault currents in power networks [3]. Afanasiev *et. al.* [4] and Ennis *et. al.* [5] demonstrated the arc current limitation capability of an expanding helical arc, without applying the RLC circuit connected across the arc, using a fuse wire wound around an insulated cylinder for arc initiation**.**

Shpanin *et. al.* [6] produced an electromagnetically convoluted helical arc plasma, without a fuse wire, which was formed around the outside of a magnetic field producing coil (by connecting the latter in series with the arc gap). Such arc plasma forms have already been investigated for the production of plasma pulses [7-8] and the interruption of currents in high voltage electric power networks with arcs in air at atmospheric pressure [6 and 9]. The potential of such a convoluted arc device for interrupting high voltage direct currents (HVDC), rather than alternating currents, in electric power networks has also been indicated by Shpanin *et. al.* [10]. This paper presents new investigations beyond previous ones [10-11] into atmospheric pressure convoluted arcs in air through the use of a separately energized B-field coil and a separate R, L, C circuit connected across the arc gap. Results are presented for various currents flowing in the different circuits supported by high-speed arc photographs of the arc subjected to high-frequency current oscillations. The use of separately energized B-fields enables the influence of different B-fields on the oscillatory current behaviour of convoluted arcs of a given current to be elucidated.

II. ARC CONVOLUTION TECHNIQUE AND TEST CIRCUIT

Fig. 1a shows a schematic diagram of the arc convolute unit whilst Fig. 1b shows a test circuit for producing electromagnetically convolved arcs with an independently activated magnetic field. The arc was formed in an annual gap between a PTFE cylinder containing a B-field producing coil (L2), and an outer, concentric PTFE cylinder. Tests were also performed without the outer PTFE cylinder in order to gain optical access to the arc discharge. Such geometries have been used previously for producing pulsed plasmas and for current interruption applications [6-9]. In this contribution, a quasi-direct current arc, maintained by a capacitor bank C.B. 1 (Fig. 1b), was initially formed between annular electrodes around the inner PTFE cylinder. The B-field for electromagnetically controlling the arc was produced by a B-field coil activated by a separate capacitor bank C.B. 2 independent of the arc

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L. M. Shpanin, N.Y.A. Shammas, S.B. Tennakoon are with the Centre of Energy Efficient Systems, Faculty of Computing, Engineering and Sciences, Staffordshire University, Stafford ST18 0AD, U.K. (e-mail: leonshpanin@googlemail.com).

G. R. Jones, J. E. Humphries, J. W. Spencer are with the Centre for Intelligent Monitoring Systems, School of Electrical Engineering, Electronics and Computer Science, University of Liverpool, Liverpool L69 3GJ, U.K. (e-mail: G.R.Jones@liverpool.ac.uk).

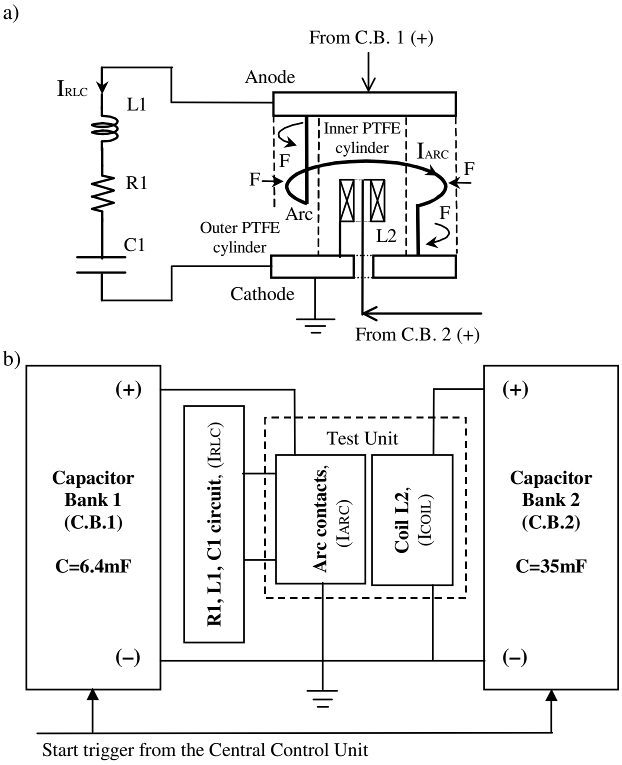

Fig. 1. Schematic diagram of the convoluted arc test unit and the interconnection of the separate capacitor banks (C.B.1, C.B.2). a) Experimental Test Unit; b) Test circuit - C.B.1 supplying the main arc current (I arc), C.B.2 supplying the B-field producing coil current (I coil), R1, L1, C1 circuit across the arc gap. (C.B.1=6.4mF, 4kV; C.B.2=35mF, 4kV; R1=0.1Ω, L1=96µH, C1=66µF; L2=16µH).

sustaining bank C.B. 1. An outward radial B-field component of the coil, close to the fixed cathode, interacts with the axial arc current to produce an azimuthal Lorenz force to rotate this section of the axial arc clockwise. When the arc gap is fully opened, the movable anode arc section is exposed to the inward B-field at the top level of the coil forcing the arc to rotate in an anticlockwise direction. Such a magnetic field arrangement forces the central arc column section to become convoluted and the current carried by this section to be predominantly azimuthal. The azimuthal arc plasma current and axial B-field of the coil produce an inward radial Lorenz force compressing the arc column tightly onto the coil containing PTFE shroud [6]. When the arc current ceases to flow the inward Lorenz force vanishes and the arc plasma ring is free to expand radially or axially. An R1, L1, C1 circuit is connected across the arc contacts of the test unit (Fig. 1a, b) which can produce high-frequency resonant current oscillations if electrically perturbed [10-11].

In practice, the length of the arc between the anode and cathode is increased by its convolution around the B-field producing coil (L2, Fig. 1b) so that the arc voltage increases, charging the parallel capacitor C1 to this higher arc voltage. If the arc length is suddenly reduced due to self short-circuiting of the arc convolute, the arc voltage is also suddenly reduced, so that the capacitor C1 discharges through the arc. With the parallel circuit R1, L1, C1 connected across the arc gap the discharge of C1 produces high-frequency current oscillations (IRLC) through the electric arc (IARC) (Fig. 1a, b). For the present experiments, the test circuit shown in Fig. 1b was used to produce a quasi-direct current of initial value 600A at 4kV from C.B.1 (C=6.4mF, limiting resistor of 6.7Ω) and currents through the B-field coil of 0kA, 1.6kA, 5.8kA at 4kV from C.B.2 (C=35mF, limiting resistor of 0.7Ω,). Both capacitor bank units were operated synchronously from a Central Control Unit. A R1, L1, C1 series connected circuit was connected across the convoluted arc contacts (Fig. 1a, b), the values of R1, L1, C1 being 0.1Ω, 96µH and 66µF respectively. These component values were taken from the previous work using a different arc convoluting unit and with the B-field coil activated by the arc current [3]. Three CWT type Rogowski current transducers [10-11] were used to measure the current waveforms of the arc (IARC), B-field coil and R1, L1, C1 (IRLC) circuits respectively (Fig. 1b). High-speed photographs of the arc plasma column were taken during the main arcing phase without the outer PTFE cylinder using a Phantom camera, Model 7, at a framing rate of 7200 frames per second (fps) and exposure of 8µs.

III. EXPERIMENTAL RESULTS

Results are presented for the time variation of currents through the circuit breaker arc (IARC), the parallel R1, L1, C1 circuit (IRLC), the B-field producing coil, as well as the voltage

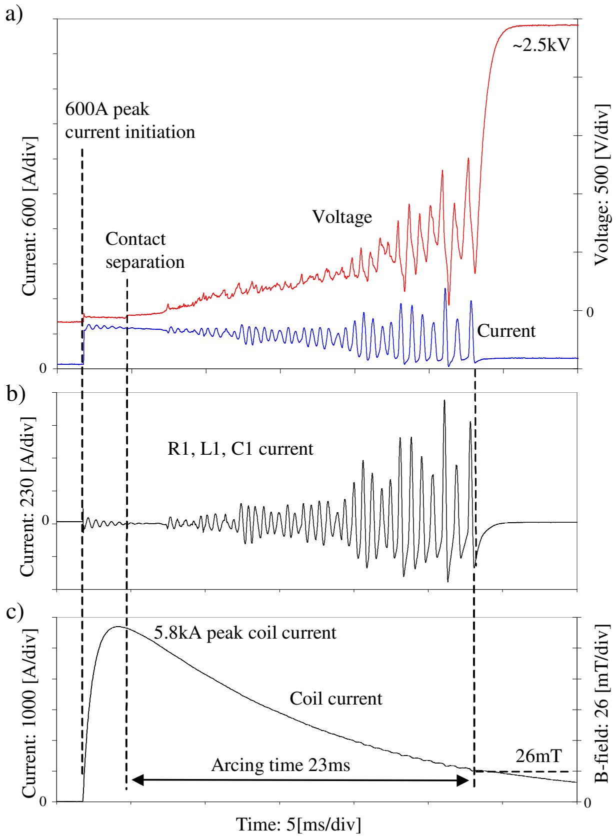

Fig. 2. Time variation of various currents and arc voltages for an arc in atmospheric pressure air, with outer PTFE cylinder, R1, L1, C1 circuit connected, anode moving, B-field coil activated. Initial values of quasi-direct currents: Arc current = 600A (C.B.1=4kV), Coil current = 5.8kA (B = 150mT). a) Arc voltage and current, b) R1, L1, C1 current, c) Coil current.

across the arc discharge. High-speed photographic images of the arc discharge are also presented without the outer PTFE cylinder (Fig. 1a) and with the anode rather than cathode moving. The time variation of the separation of the arc contacts was as already given in [6]. All tests were conducted with arcing in atmospheric pressure air. The experimental results are for a quasi-direct arc current (IARC), of initial value 600A and independently activated B-field coil currents of initial values 0kA, 1.6kA, 5.8kA and a source voltage C.B. 2 = 4kV(Fig. 1b).

Fig. 2 shows experimental results for an initial arc current of 600A, with the R1, L1, C1 circuit connected and with an initial B-field coil current of 5.8kA, which produced a B-field of 150mT. Fig. 2a shows the time variation of arc current (IARC) and voltage. At times after which the arc contact gap exceeded the coil length (10ms - 12ms), regular pulsations of current oscillations occur with similar oscillations on the arc voltage. The maximum amplitude of these current oscillations was of the order of ~350A and the residual voltage after arcing was ~2.5kV. Fig. 2b shows the time variation of the corresponding current (IRLC) flowing through the R1, L1, C1 circuit. The results show regular pulsations of oscillations corresponding to those on the arc current ((IARC), Fig. 2a). The main pulsation occurs during the ~15ms prior to arc extinction and the amplitude of the oscillations increase with time up to arc extinction. In addition, there is a lower frequency envelope superimposed upon the higher-frequency oscillations. Fig. 2c shows the time variation of the B-field coil current (Fig. 1b) which produced the initial B-field of 150mT and which subsequently decayed to 26mT at arc extinction.

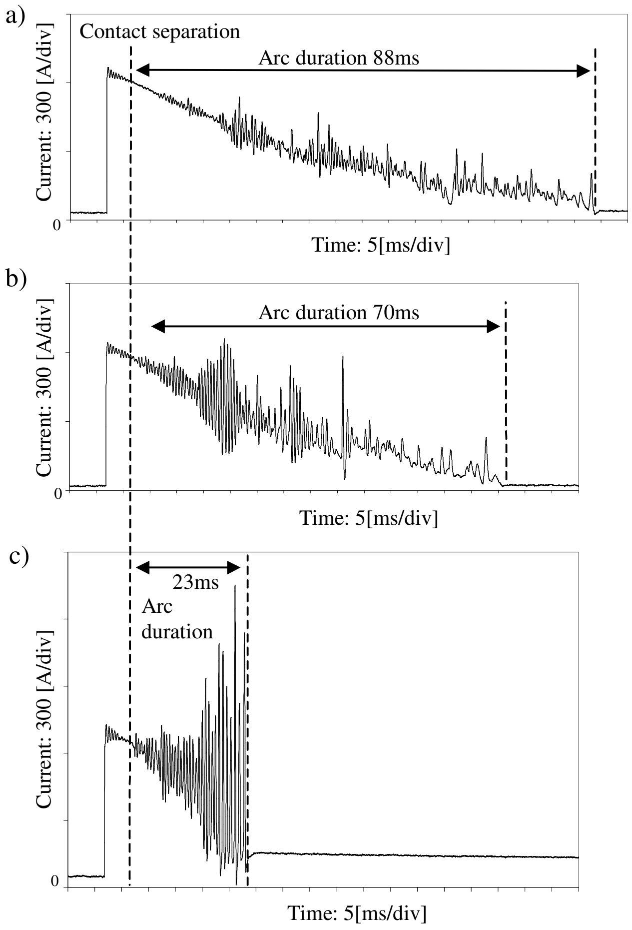

Fig. 3. Time variation of quasi-steady arc current, Initial value 600A, with outer PTFE cylinder and R1, L1, C1 circuit connected, anode moving. a) No B-field, b) B-field coil current = 1.6kA (B-field of 41.4mT), c) B-field coil current = 5.8kA (B-field of 150mT).

Fig. 3 shows the time variation of arc currents (each with an initial value of 600A) for three different B-field coil currents of initial values 0kA, 1.6kA, 5.8kA and which produce B-

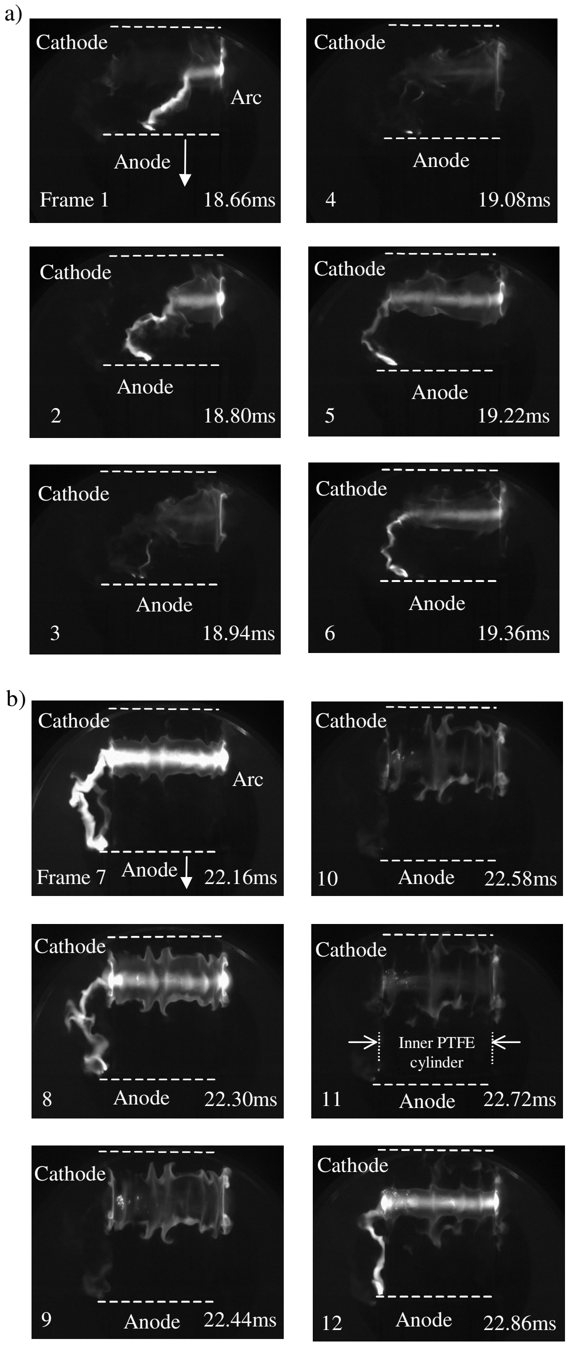

Fig. 4. High-speed photographic images of convoluted arc with current oscillations (atmospheric pressure air, without the outer PTFE cylinder, anode moving). Initial values of quasi-direct currents: Arc current = 600A, Coil current = 5.8kA (B=150mT). a) Arcing time 18.66ms-19.36ms, arc gap = 110mm-120mm; Pulse period ~0.56ms; b) Arcing time 22.16ms-22.86ms, Arc gap = 130mm-140mm, Pulse period ~0.70ms.

fields of 0mT, 41.4mT, 150mT. Fig. 3a, B = 0mT, shows the quasi-steady current wave with noisy excursions superimposed. Fig. 3b, B = 41.4mT, shows the quasi-steady current wave with some moderate amplitude oscillations of well defined frequency superimposed and earlier current truncation. Fig. 3c, B = 150mT, shows the quasi-steady current wave with much higher amplitude oscillations of a well defined frequency superimposed and very early current truncation.

Figs. 4a and b show examples of high-speed photographic frames of arcing without the outer PTFE cylinder, with the anode moving and with an initial quasi-direct current of 600A, an initial B-field current of 5.8kA and with the R1, L1, C1 circuit connected (i.e. the arc and the B-field coil currents are the same as those for Fig. 2a, b, c, but the outer PTFE cylinder has been removed and with the anode moving).

The frames of Fig. 4a correspond to the time interval of 18.66ms - 19.36ms whilst those of Fig. 4b correspond to 22.16ms - 22.86ms. Frames 1, 2 (Fig. 4a), corresponding to the arc gap being marginally greater than the coil length, show an arc convolute being formed around the PTFE coil containing cylinder by the rotation of the anode arc root. Frames 3, 4 show the disappearance of the arc filament but the persistence of an expanding, weakly emitting plasma shroud. Frames 5, 6 show the reappearance of the arc filament moving along the anode and producing an elongated arc convolute section. The frames of Fig. 4b show a similar behaviour to those of Fig. 4a but with a longer contact gap plus an enhanced arc filament and a more extensive and pronounced plasma shroud.

IV. DISCUSSION

The experimental results presented may be considered in terms of the influence of a number of factors, which are the use, or otherwise of a B-field producing coil directly or indirectly activated, R1, L1, C1 circuit across the arc gap and with or without an outer PTFE cylinder.

A. Directly Activated B-Field Coil, No R1, L1, C1 Parallel Circuit, With Outer Cylinder

Previous investigations [6-9] have been reported with the same arcing unit at fixed as well as at changing arc contact gaps (i.e. where the cathode was moving), but without the R1, L1, C1 circuit, with the B-field coil connected in series with the arc and an initial quasi-steady current of 1.5kA (giving a Lorenz force of 59N/m).

The results of these investigations have shown a sequence of arc convolutes being formed and collapsing with corresponding voltage pulsations at a relatively low frequency of ~250Hz.

B. No B-Field, With Parallel R1, L1, C1 Circuit, With Outer Cylinder, Anode Moving

The experimental results with no B-field but with the parallel R1, L1, C1 circuit (Fig. 3a) show the existence of only irregular current variations superimposed upon the quasi-direct current wave. This indicates the absence of arc convolutions and no substantial R1, L1, C1 circuit effects.

C. Separately Activated B-Field, With Parallel R1, L1, C1 Circuit, With Outer Cylinder, Anode Moving

The experimental results with the indirectly activated B-field and parallel R1, L1, C1 circuit (Fig. 2a and Fig. 3b, c) show that although well defined high-frequency oscillations occur with both B-fields (150mT and 41.4mT), these are more pronounced with the higher B-field. This suggests that a combination of a convoluted arc, produced by the B-field, and the reaction of the parallel R1, L1, C1 circuit is responsible for producing oscillatory currents through the arc discharge. The frequency of the current oscillations with B-fields of 41.4mT and 150mT is about 2kHz (Fig. 3b), being independent of the B-field magnitude in this range. This value is in approximate agreement with the resonant frequency of the parallel R1, L1, C1 circuit according to $f \approx 1/[2\pi\sqrt{(L1C1)}]$. The large current oscillations are initiated after the arc gap length exceeds that of the B-field coil length. This interpretation is consistent with the results of previous experiments [10-11].

D. Separately Activated B-Field, With Parallel R1, L1, C1 Circuit, No Outer Cylinder, Anode Moving

The high-speed images obtained without the outer PTFE cylinder and with the cathode fixed (Fig. 4a and b) provide useful additional evidence in elucidating the current oscillation behaviour of the convoluted arc interaction with the R1, L1, C1 parallel circuit. Frames 1, 2, and 5, 6 of Fig. 4a emphasise the manner in which the arc convolute is formed once the contact gap is long enough, with the cathode region arc filament drawing the arc convolute azimuthally around the inner PTFE cylinder. However, during the time interval 18.94ms-19.08ms (Frames 3 and 4, Fig. 4a) the optical emission from the arc filament is no longer discernible, suggesting a reduction in the arc sustaining current and the decay of the arc filament plasma. Reappearance of the filament (Frame 5), suggests that higher current flow is re-established and the arc convolute continues to be formed.

A similar arc behaviour to that of Fig. 4a is observed on Fig. 4b for the longer arc gap. This emphasises the repeatability of the convoluting process, albeit the arc filament in this case is brighter, implying a higher current flow. The plasma shroud around the arc is also clearer.

Closer inspection of the images of Fig. 4a and b show that the width of the contracted arc filament increased from 11mm (Frame 1, Fig. 4a) to 19mm (Frame 7), Fig. 4b, whilst the width of the plasma shroud increased from 53mm (Frame 3, Fig. 4a to 79mm (Frame 10, Fig. 4 b). Fig. 5a shows the time variation of the plasma shroud diameter determined from frames of the type given on Fig. 4a, b. This emphasises the periodic variation in the plasma shroud diameter and also indicates that the shroud can extend almost to the arc cathode. Furthermore, the period of the filamentary and non-filamentary plasma pulsations changed from ~0.56ms (Frames 1-5) to ~0.7ms (Frames 7-12) (Figs 4 a, b and Fig. 5a).

E. Comparison of Optical Observations and Arc Current Variations

Although some of the operating conditions are different, a meaningful comparison can be made between the optical images (Fig. 4a, b) and the arc current results (Fig. 3c). In both these cases, the arc current (initial value 600A), the B-field (initial value 150mT) and R1, L1, C1 circuit were all identical. Also in both cases the time variation of the contact separation was the same. The differences were in the absence or otherwise of the outer PTFE cylinder and the anode / cathode optical observation arrangement.

The time variation of the oscillatory arc current and B-field coil currents are shown on an expanded time scale on Fig. 5b covering the same time period as the high-speed image frames of Fig. 4a, b.

The time scales of the high-speed image frames and current waves were synchronised from the contact travel-time characteristics of each test. Such a comparison may be based upon the time variations of the shroud diameter (Fig. 5a) with the time variation of arc current oscillations (Fig. 5b). This shows that the fluctuations in arc plasma optical shroud feature (e.g. [F1- F3 - F5]; [F7 - F10 - F12]) have a similar frequency to the arc current oscillations ([C1 - C3 - C5]; [C7 - C10 - C12]), despite some of the operating conditions for the two tests being different (i.e. presence of the outer PTFE cylinder, anode / cathode optical observation condition). This is highlighted by the positive peaks of each current oscillation corresponding to the trough on the plasma width (indicated by the dashed vertical lines across Fig. 5a and b). Closer inspection of the form of each current oscillation reveals that the minimum current half-loop relative to the quasi-steady current has a lower amplitude than the maximum current half-loop. This is illustrated more clearly on Fig. 6 which shows the oscillatory current maxima and minima relative to the quasi-steady current curve (curve (1)) taken from Fig. 2a and b. Simultaneously, the narrow, highly emitting, high conductivity arc filament has been replaced by a lower emission, lower conductivity but larger diameter plasma shroud (Fig. 4a, b). This implies that the asymmetric current oscillation may be associated with this change in arc plasma structure and accompanying increase in the plasma electrical conductance.

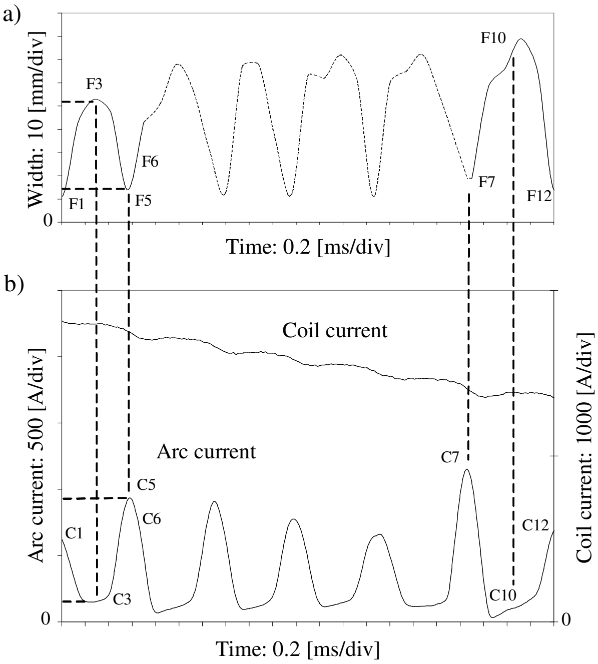

Fig. 5. Expanded time scale (23ms) variations of arc features (atmospheric pressure air, R1, L1, C1 circuit connected). Initial quasi-steady current: Arc current = 600A, B-field coil current = 5.8kA (B = 150mT). a) Plasma shroud diameter, without outer PTFE cylinder, anode moving b) Arc and B-field coil currents with outer PTFE cylinder, anode moving.

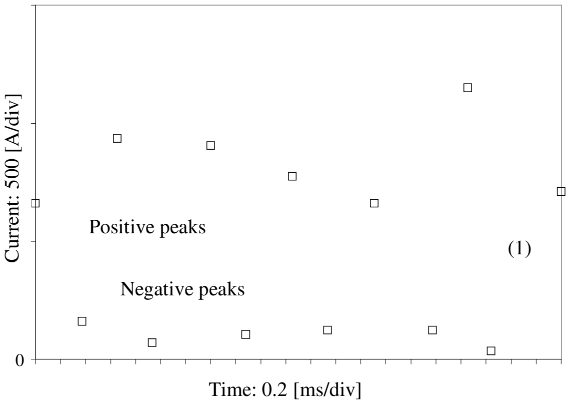

Fig. 6. Maximum positive and negative oscillatory arc currents (With outer PTFE cylinder, R1, L1, C1, circuit connected, atmospheric pressure air, anode moving). Expanded time scale (23ms) variations of arc features. Initial quasi-steady arc current = 600A (B-field = 150mT). Curve (1) is the quasi-steady current determined from Fig. 2a, b initial current of 600A.

F. B-Field Coil Current

The expanded current: time diagram of Fig. 5b also shows a relatively low amplitude (~50A) current oscillation of about 2kHz frequency superimposed upon the quasi-steady coil current. This suggests that there is electromagnetic coupling of the oscillatory currents produced by the R1, L1, C1 circuit via the arc convolute to the B-field coil. This coupled current is of small amplitude compared with the main quasi-steady coil current so that the B-field component of the Lorenz force controlling the arc convolute is relatively independent of the R1, L1, C1 circuit effect. However, this current coupling implies that there is a mutual inductance between the B-field coil and the arc convolute, which leads to the effective inductance associated with the R1, L1, C1 circuit being greater than L1. Consequently, the period of the resonant current oscillation associated with the R1, L1, C1 circuit is modified, consistent with the experimental observation that the period of the contracted and expanded arc plasma pulsations change from 0.56ms to 0.70ms (Section: *D*) as the current oscillation amplitudes increase with time.

V. CONCLUSIONS

By using an independently energized B-field, an insight into features affecting the oscillatory current behaviour of a convoluted arc device has been obtained from measurements of the various system currents (arc, R1, L1, C1 circuit, B-field coil), the arc voltage and high-speed photographic images. In particular, it has been possible to investigate the separate effects of an oscillatory R1, L1, C1 circuit connected across the arc gap and the convoluted arc forming B-field.

The results suggest that the collapse of the arc convolute leads to a substantial arc voltage reduction which induces the parallel R1, L1, C1 circuit to produce enhanced amplitude oscillatory currents at the natural frequency of the circuit and which flow through the arc discharge. As a result, a sequence of high-frequency current pulses can be formed with potential for producing plasma pulses all at a well defined frequency governed by the R1, L1, C1 circuit.

For the conditions used in the present tests:

- The current oscillations produced by the R1, L1, C1 circuit become pronounced when a sufficiently high B-field (~150mT) is used to form strong arc convolution;
- The frequency of the current oscillations produced by the R1, L1, C1 circuit was ~2kHz;
- This frequency may be modified by the mutual inductance between the arc convolute and B-field producing coil;
- The negative amplitude of the oscillatory current is less than the positive amplitude due to changes in the nature and electrical resistance of the arc plasma.

Further investigations of the behaviour and properties of such convoluted, arc induced oscillations would need to explore the effect of different R1, L1, C1 circuit parameters, higher B-field magnitudes, arc device geometry, synchronization of the oscillation current pulses etc. In addition, the effects of arc convolute collapse and reformation in producing lower frequency (~250Hz-300Hz with a B-field of ~150mT) plasma pulses onto which the ~2kHz oscillations are superimposed are warranted.

REFERENCES

[1] H. M. Ryan, High Voltage Engineering and Testing, 3rd Edition, Institution of Engineering and Technology (IET), ISBN: 978-1-84919-263-7, UK, 2013.

[2] T. Mori, J. W. Spencer, J. E. Humphries, G. R. Jones, “Diagnostic measurements on rotary arcs in hollow polymeric cylinders”, IEEE Transactions on Power Delivery, vol.20, no. 2, Apr. 2005, pp.765-771.

[3] J. R. Zhang, G. R. Jones, Z. Ma, M. T. C. Fang, “Interaction of helical arc devices with interconnected networks”, IEE Proc. of Generation, Transmission and Distribution, vol.143, no.1, pp.89-95, Jan. 1996.

[4] A. A. Afanasiev, M.R. Banault, T.R. Blackbum, G.R. Jones, S.K. Sethuraman, “Characteristic of electromagnetically driven arcs for D.C. switching”, IEE Proc. B, vo1.128, no.5, pp.249-252, Sept. 1981.

[5] M.G. Ennis, J.K. Wood, J.W. Spencer, D.R. Turner, G.R. Jones, P. Coventry, “Current Limiting Properties of an expanding helical arc”, IEE Proc-Sci. Meas. Technol., vol.142, no.3, pp.201-205, May I995.

[6] L.M. Shpanin, G.R. Jones, J.E. Humphries, J.W. Spencer, “Current interruption using electromagnetically convolved electric arcs in gases”, IEEE Transactions on Power Delivery, vol.24, no.4, pp.1924-1930, Oct. 2009.

[7] B. E. Djakov, L.M. Shpanin, J.W. Spencer, G.R. Jones, “Propulsion of a plasma ring in a rotary arc device at atmospheric pressure”, Journal of Theoretical and Applied Mechanics, Sofia, vol.37, no.1, pp.39-54, March 2007.

[8] L.M. Shpanin, G.R. Jones, J.W. Spencer, “The production of plasma pulses with convoluted arc columns in atmospheric pressure air”, IEEE Transactions on Plasma Science, vol.38, no.3, pp.509-515, March 2010.

[9] L. Shpanin, S. Tennakoon, G. Jones, J. Humphries, J. Spencer, “Electromagnetic arc plasma convolutes in air at atmospheric pressure”, UK & RI IEEE Pulsed Power Symposium, Loughborough, UK, pp.1-4, Sept. 2011.

[10] L. M. Shpanin, N. Y. A. Shammas, S. B. Tennakoon, G. R. Jones, J. E. Humphries, J. W. Spencer, “Electromagnetically Convoluted Arcs for the Interruption of Quasi Direct Current”, Proc of 47th International Universities’ Power Engineering Conference, Brunel University London, pp.1-4, Sept 2012.

[11] L. M. Shpanin, G. R. Jones, J. E. Humphries, J. W. Spencer, N. Y. A. Shammas, S. B. Tennakoon, “Arc plasma convolutes produced with independently activated magnetic fields”, 4th Euro-Asian Pulsed Power Conference / 19th International Conference on High-Power Particle Beams, Karlsruhe, Germany, pp.1-4, Oct. 2012.

Leonid M. Shpanin received the M.Sc. degree in radio engineering from Azerbaijanian Technical University, Azerbaijan and Ph.D. degree in electrical engineering from University of Liverpool, U.K. He conducted the presented research while holding a position as a Senior Researcher in Electrical Engineering, Faculty of Computing, Engineering and Sciences, Staffordshire University, U.K. He is member of the Institute of Electrical and Electronics Engineering (IEEE), U.S.A. and a member of the Nuclear and Plasma Sciences Society (IEEE), U.S.A.

Gordon R. Jones received the B.Sc. degree in physics from University of Wales, U.K., the Ph.D. degree in physics from University of Liverpool, U.K., and the D.Sc. degree from University of Wales, U.K. He is an Emeritus Professor and past Director of the Centre for Intelligent and Monitoring Systems at University of Liverpool. He is author of several books in the area of Chromatic monitoring, high-pressure arcs and SF_6 switchgear. He is a member of the Executive Management Committee of the International Series of Conferences on Gas Discharge and Their applications and is a member of an international study group on switchgear arcs, the Current Zero Club. He was awarded the Institution of Electrical Engineering (IEE) Science, Education and Technology Achievements Medal in 1999 and a Medal of Distinction in 2006 by the Academy of Sciences, Bulgaria. He is a Fellow of the IET, U.K. and member of the Institute of Physics, U.K.

Jim E. Humphries received the M.Phil. degree in electrical engineering from University of Liverpool, U.K. He is a Senior Experimental Officer in the Scholl of Electrical Engineering, Electronics and Computer Science, University of Liverpool. He is responsible for experimental project works at the Centre of Intelligent and Monitoring Systems.

Joseph W. Spencer received the B.Eng. and Ph.D. degrees in electrical engineering from University of Liverpool, U.K. He is Professor of Electrical Engineering, Director of the Centre for Intelligent and Monitoring Systems and Head of School of Electrical Engineering, Electronics and Computer Science at University of Liverpool. He is a member of an international study group on switchgear arcs and Honorary Treasurer of the International Series of Conferences on Gas Discharge and Their Applications. He is a member of the Institution of Electrical Engineering (IET), U.K.

Noel Y. A. Shammas received the B.Sc. degree in physics, the M.Sc. and Ph.D. degrees in electrical and electronics engineering from Salford University, U.K. He is Professor of Microelectronics and Solid-State Electronics at Staffordshire University, U.K. He is a member of scientific committees for many international conferences (including MIEL, EPE, WCE, WSEAS and Michroterm) and steering committee member for EPE, UPEC and ISPS International.

Sarath B. Tennakoon received the B.Sc. degree in electrical engineering from University of Moratuwa, Sri Lanka, the M.Sc. degree from University of Aston, UK and the PhD degree in electrical engineering and electronics from University of Central Lancashire, UK. He is Professor of Power Electronic Systems and Director of Centre for Energy Efficient Systems at Staffordshire University, UK. He is a member of of the Institution of Electrical Engineering (IET), U.K, a member of IEEE, USA and a committee member of IET North West Midlands Network, U.K., and Engineering Professors Council, U.K.