

Convoluted Arc With Flux Concentrator for Current Interruption

Shpanin, L, Jones, G & Spencer, J

Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:

Shpanin, L, Jones, G & Spencer, J 2017, 'Convolute Arc With Flux Concentrator for Current Interruption' *IEEE Transactions on Plasma Science*, vol 46, no. 1, pp. 175 - 179

<https://dx.doi.org/10.1109/TPS.2017.2778801>

DOI 10.1109/TPS.2017.2778801

ISSN 0093-3813

ESSN 1939-9375

Publisher: IEEE

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Copyright © and Moral Rights are retained by the author(s) and/ or other copyright owners. A copy can be downloaded for personal non-commercial research or study, without prior permission or charge. This item cannot be reproduced or quoted extensively from without first obtaining permission in writing from the copyright holder(s). The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the copyright holders.

This document is the author's post-print version, incorporating any revisions agreed during the peer-review process. Some differences between the published version and this version may remain and you are advised to consult the published version if you wish to cite from it.

Convolute Arc with Flux Concentrator for Current Interruption

Leonid M. Shpanin, *Member, IEEE*, Gordon R. Jones, and Joseph W. Spencer

Abstract-- Further considerations are given to the use of an electromagnetic flux concentrator for arc plasma control in a rotary arc current interrupter. Such flux concentrators have been previously proposed for plasma fusion and other plasma applications. The possible extension of the proposed method for enhancing the interruption of direct currents with a rotary arc interrupter is discussed with the aid of theoretical modelling of the concentrator geometry and with its possible enhancement of ablation from the arc containing cylinders.

Index Terms-- Flux concentrators, arc discharges, plasma arc devices, magnetic fields, current interruption, ablation.

I. INTRODUCTION

SEVERAL evolving aspects of high voltage current interruption which are currently commanding attention include the interruption of direct currents (D.C.) rather than alternating currents (A.C.) and the drive towards avoiding the use of sulfur hexafluoride (SF₆) gas as an arc quenching agent because of its potential for causing Global Warming [1]. Meanwhile, technology based upon the evolution of various forms of electromagnetic control of electric arcs has been investigated over several years with potential for current interruption applications [1-3]. Examples of particular forms of such devices include, as well, an electric arc convolute rotating around a polytetrafluoroethylene (PTFE) cylinder housing a magnetic field (B-field) producing coil, a similar arrangement with an outer PTFE cylinder with the arc rotating in the annular gap between the outer and inner PTFE cylinders etc. [4, 5]. More recently the possibility of including a metal solid cylindrical shape slug as a B-field flux concentrator around the outer PTFE cylinder (as used in plasma confinement [6]) for enhancing the arc compressing B-field has been theoretically suggested [7].

This contribution considers an extension of the theoretical description for the effect of the geometry of the metallic flux concentrator for producing Lorentz forces for enhancing arc quenching for D.C. interruption. In particular the effect of different radii for short axial length concentrators are

considered for rectangular cross section concentrators rather than a conical cross section concentrator of extended axial length which has hitherto been considered.

II. ELECTROMAGNETIC ARC QUENCHING

The possibility of interrupting A.C. currents by electromagnetically rotating an electric arc with a B-field produced by a current carrying coil embedded in a PTFE cylinder around which the arc rotated, has been demonstrated with the device arrangement shown on Fig. 1, but without the flux concentrator used [4, and 5].

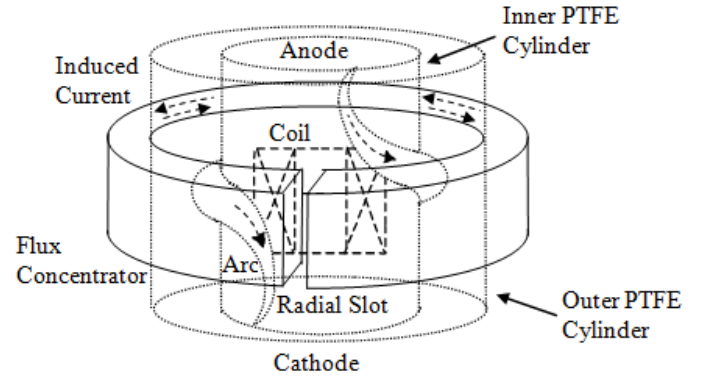


Fig. 1. Rotary arc interrupter with the flux concentrator and outer PTFE cylinder.

This figure shows such an arc being rotated in an annular gap between two concentric PTFE cylinders (width 1 cm) and with a metallic flux concentrator outside the outer PTFE cylinder. The axial B-field produced by a conical cross section flux concentrator of fixed radius and axial length longer than the B-field inducing coil has been considered theoretically [7].

It has been shown experimentally [8] that at the axial location at which the axial Lorentz force (F) is theoretically a maximum, the radius of the inner PTFE cylinder suffers a maximum reduction due to ablation of the PTFE.

Such an arrangement without the metallic flux concentrator has been demonstrated for interrupting a quasi D.C. current [9]. The B-field producing coil in such a concentric cylinders arrangement (without a flux concentrator) has been independently activated from the quasi-direct arc current between the anode and cathode using a resistor-inductor-capacitor (RLC) circuit connected across the arc gap.

This provided a means for:

L. M. Shpanin, is with the Centre for Mobility and Transport, Faculty of Engineering, Environment and Computing, Coventry University, Coventry CV1 2JH, U.K. (e-mail: leon.shpanin@coventry.ac.uk).

G. R. Jones, is 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).

J. W. Spencer is 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: joe@liverpool.ac.uk).

- (a) Encouraging the formation of high frequency oscillations of the current through the arc to assist current interruption.
- (b) Investigating the influence of different magnitudes of B-fields on the behavior of the arc plasma carrying a fixed current.

An illustration of the current and arc voltage variations from such tests is shown on Fig. 2 for the interruption of a quasi-direct current of 600A peak with a B-field of $\sim 35\text{mT}$ (at current interruption) with 2kHz current oscillations. The results of such tests are shown on Fig. 3a,b.

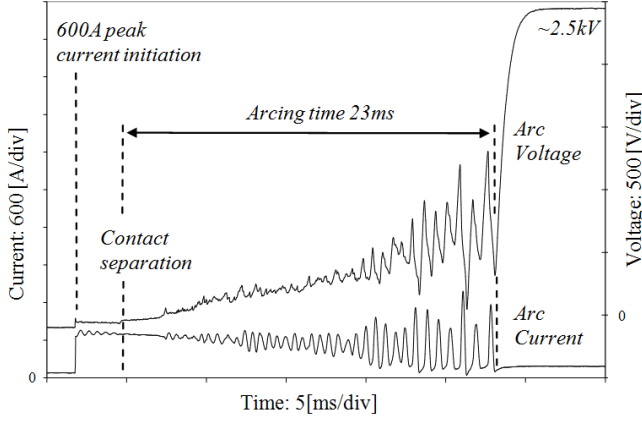


Fig. 2. Interruption of a quasi-direct current (600A initial value) with a convoluted arc device, without a flux concentrator (Fig. 1); Operational conditions: Interrupter gas - atmospheric pressure air, B-field coil (150mT) energized separately with a current of 5.8kA, Outer PTFE cylinder - inserted around the device; R, L, C circuit connected across the arc gap to produce arc current and voltage frequency oscillations of 2kHz [9].

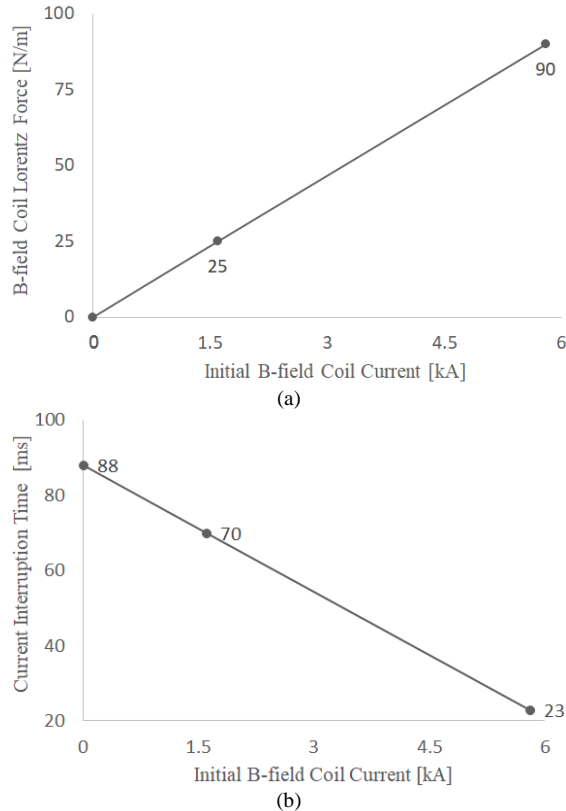


Fig. 3. Variations produced by a separately activated B-field coil, (a) Lorentz Force vs coil current, (b) Time of current interruption vs coil current.

It shows how the Lorentz force produced (Fig. 3(a)) and the time at which current interruption occurred (Fig. 3(b)) varied with the B-field produced by the separately activated coil current. The results show that the use of a relatively low B-field (41.4mT) producing a Lorentz force of 25N/m only provided a small reduction in the time at which current interruption occurred (70ms compared to 88ms) However, the use of a higher B-field (150mT) leads to current interruption at a shorter arcing time (23ms). Further details are provided in Appendix I.

As a result there is the possibility of enhancing such current interruption by increasing the arc compressing B-field in a convenient and economical manner using a flux concentrator ring in the interrupter as shown on Fig. 1. An insight into such a possibility may be gained using a theoretical approach suggested in [7].

III. THEORETICAL ASSESSMENT OF A FLUX CONCENTRATOR

In this contribution, a theoretical analysis has been made for a flux concentrator with a rectangular (rather than conical) cross section of axial length (3cm) less (rather than longer) than the length of the B-field producing coil (5cm). As a result the electrodes regions of the convolute arc will be less influenced by the radial field of the flux concentrator once the arc convolute is formed.

Fig. 4 shows a schematic diagram of the geometry of the rectangular cross section flux concentrator in a rotary arc interrupter with an inner PTFE cylinder containing the B-field coil of radius R1, an outer concentric PTFE cylinder of inner radius R2, a flux concentrator of inner radius R3, mean radius R4 and axial length b . The flux concentrator is located centrally and uniformly along the length of the arc gap anode and cathode. A current i_2 is induced in the concentrator due to the B-field from the arc rotating coil.

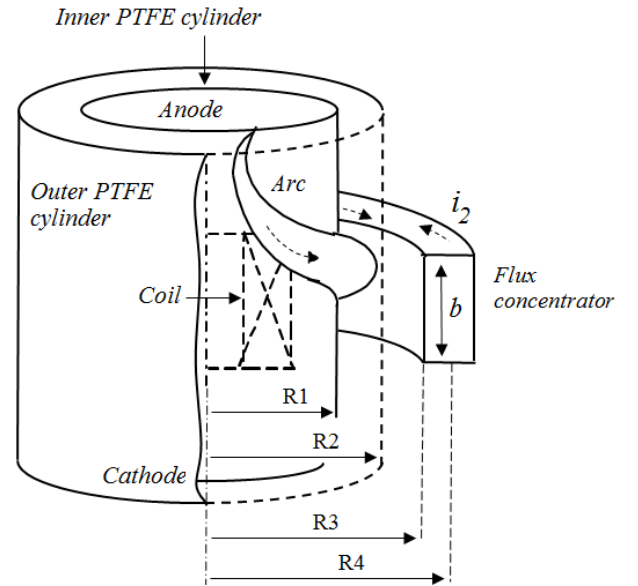


Fig. 4. Schematic diagram of flux concentrator geometry; R1 - Outer radius of inner PTFE cylinder; R2 - Inner radius of outer PTFE cylinder; R3 - Inner radius of flux concentrator; R4 - Mean radius of flux concentrator; b - Axial length of flux concentrator cylinder.

Also in the present investigation the concentrator had a rectangular cross section rather than a conical one of a single radius as considered previously. The behavior of the flux concentrator may be described using the theoretical approach used by Shpanin *et al.* [7] for a preliminary description of the electromagnetic behavior of some rotary arcs.

The Lorentz force produced in such an arrangement by a flux concentrator B-field acting on an arc carrying a current I_{arc} is given by [10] (Equation AII. 4, Appendix II):

$$F = I_{\text{arc}} \times \frac{\mu_o \times \sqrt{\frac{\epsilon' \times L_1'^2}{L_3}}}{2 \times R_3} \quad (1)$$

Where R_3 , μ_o , ϵ' , L_1' , L_3 and i_l are defined in Appendix II.

This implies that the Lorentz force is approximately proportional to the inverse of the inner diameter (R_3) of the flux concentrator.

Lorentz forces have been calculated with this model for an arc and coil current i_l of 15.8kA peak, an inner PTFE cylinder of outer radius R_1 of 5cm and an outer PTFE cylinder of inner radius R_2 of 6cm. Results for the variation of the Lorentz force (F) produced by a flux concentrator as a function of the concentrator inner radius (R_3) are presented on Fig. 5.

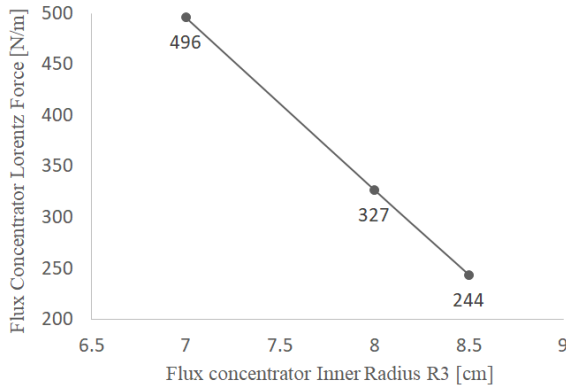


Fig. 5. Variation of Lorentz force produced by a rectangular cross section flux concentrator (axial length of 3cm) as a function of flux concentrator inner radius (where the arc and coil current is 15.8kA).

This shows how the Lorentz force increase from 244N/m to 496N/m as the concentrator radius decreases from 8.5 to 7.0 cm. These values compare with a Lorentz force of 4.9kN/m within the annular arcing space (R_2 and R_1 , Fig. 4) for the same peak current of 15.8kA reported by Shpanin *et al.* [11] without a flux concentrator. Thus it is theoretically predicted that a flux concentrator of inner radius 7.0cm would produce a 10% increase in the Lorentz force.

Further details of the theoretical approach are given in Appendix II, and further details of the calculated parameters are given in Table I (Appendix II).

IV. DISCUSSION OF RESULTS

The implications of the experimental results presented on Fig. 3 are that increasing the Lorentz force on a convoluted arc carrying a fixed quasi-steady current can reduce the time for the current to be interrupted provided the Lorentz force is sufficiently high. A reduction in interruption time from 88 to 23ms was shown to be possible by increasing the Lorentz force from 0 to 90N/m.

Theoretical calculations (Section III) indicate that such enhancement of Lorentz forces of this order of magnitude may be achieved through the introduction of a metal cylindrical flux concentrator of rectangular cross section. Fig. 5 and Table I, Appendix II show that a flux concentrator of internal radius 7cm is capable of producing an additional Lorentz force of 496N/m for a 50Hz primary A.C. peak current of 15.8kA.

There are current interruption implications which arise from the flux concentrator theoretical results in addition to affecting induced flows of the arc surrounding gas in preparing for arc quenching:

- The influence of the flux concentrator on the production of current oscillations which lead to quasi-steady current interruption (Fig. 2) warrants further investigation since it could produce higher amplitude oscillations and hence earlier current interruption.
- The production of ablated material from the outer surface of the coil containing PTFE cylinder may be affected by the concentrator induced Lorentz force. An indication of the amount of such ablated material can be obtained by measuring the shape of the inner PTFE cylinder surface before and after arcing. Such tests [8] show that the PTFE material erosion was mainly concentrated half way axially along the coil axis where the Lorentz forces were also a maximum. A Lorentz force of 5kN/m, with an half cycle of 50Hz A.C. peak current of 14kA, produced 53mm³ ablated material [8], so that an extra Lorentz force of 496N/m (Table I, Appendix II) could potentially produce an extra 5.3mm³ of ablated material. This in turn could reduce the reliance upon the arc quenching capability of the surrounding gas.

V. CONCLUSIONS

Theoretical analysis of the Lorentz force produced by a rectangular (rather than conical) cross section flux concentrator of axial length less (rather than greater) than the length of the B-field producing coil has been performed. The results show that the Lorentz force on the arc plasma can be increased by about 10%. Comparison with experimental

results from tests with different B-field coil exciting currents indicate that such an increase in the Lorentz force should lead to an improved capability of direct current interruption.

Further investigations are needed to validate such a conclusion and to investigate further the effect of increasing the axial extent of the flux concentrator relative to the length of the B-field producing coil.

APPENDIX I: EFFECT OF B-FIELD MAGNITUDE ON THE INTERRUPTION OF A QUASI-DIRECT CURRENT OF 600A INITIAL VALUE

Measurements:	Test 1	Test 2	Test 3
Initial coil current, [kA]	0	1.6	5.8
Coil B-field, [mT]	0	41.4	150
Lorentz Force, [N/m]	0	25	90
Current through arc when interrupted, [A]	20	20	300
Time at which current interruption occurred, [ms]	88	70	23

APPENDIX II: LORENTZ FORCE PRODUCED BY FLUX CONCENTRATORS OF DIFFERENT RADII

The preliminary theoretical consideration of a flux concentrator for enhancing rotary arcs control and quenching reported by Shpanin *et al.* [7] may be extended to investigate the effect of different flux concentrator radius and cross sectional shape.

The Lorentz force produced by a B-field flux concentrator (Fig. 4), acting on an arc carrying a current I_{arc} , is given by [10]:

$$F = I_{arc} \times B_{flux_concentrator} \quad (AII.1)$$

Where the flux concentrator B-field applies throughout the entire arc-loop around the B-field coil and is approximated by [7]:

$$B_{flux_concentrator} \approx \frac{\mu_0 \times i_2}{2 \times R3} \quad (AII.2)$$

With the concentrator inner radius $R3$, maximum secondary current i_2 in the flux concentrator (Fig. 4), and permeability of free space μ_0 (1.257×10^{-6} H/m) given by [6 and 7].

$$i_2 = \sqrt{\frac{\mathcal{E}' \times \frac{1}{2} L' i_1^2}{\frac{1}{2} L_3}} \quad (AII.3)$$

Where L' is the effective inductance of the flux concentrator, L_3 is the self-inductance of the central high field region [7], i_1 is a primary current through the arc and B-field coil (which are connected in series) and \mathcal{E}' is the transfer inductive energy loss between the B-field producing coil and the central high field region ($b = 0.03$ m, Fig. 4) of the flux concentrator. Substituting for i_2 and $B_{flux_concentrator}$ in equation (AII.1) from equations (AII.2) and (AII.3) yields:

$$F = I_{arc} \times \frac{\mu_0 \times \sqrt{\frac{\mathcal{E}' \times L' i_1^2}{L_3}}}{2 \times R3} \quad (AII.4)$$

Where \mathcal{E}' is defined by equations (AII.5) and (AII.6), [7]:

$$\mathcal{E}' = \mathcal{E} \left(\frac{b}{b + \frac{R3 \sin \alpha}{1 - \cos \alpha}} \right) \quad (AII.5)$$

b is the axial length of the flux concentrator cylinder, in [m], α is a semi-angle of its conical ends. (For a conical concentrator (previous calculations [7]) $\alpha = 45$ degrees whilst for a cylindrical concentrator (present calculations) $\alpha = 90$ degrees).

$$\mathcal{E} = \frac{\frac{1}{2} L_3 i_2^2}{\frac{1}{2} L' i_1^2} = \frac{(kl - m)^2}{(l + 1 - 2m)} \times \left[l(l + 1 - 2m) - (kl - m)^2 \right] \quad (AII.6)$$

k , m and l reflect the coupling and mutual inductance losses of the flux concentrator in relation to the B-field producing coil [6, 7]; and \mathcal{E} is the transfer loss, which does not depend on the geometry of the flux concentrator, [6, 7]. The values of k , l , m , L' and L_3 are shown on Table I.

Based on an approximate theory [6, 7] (i.e. ignoring a radial slot (Fig. 1) and end effects of the flux concentrator) the transfer loss \mathcal{E} of a rectangular cross section flux concentrator is reduced to \mathcal{E}' (Equation (AII.5)), [6, 7].

Details of results obtained with this theoretical model are shown on Table I for rectangular cross section ($\alpha = 90$ degrees) flux concentrator of three different radii (R3) and an inner PTFE cylinder radius $R1 = 5\text{cm}$, outer PTFE cylinder of inner radius $R2 = 6\text{cm}$.

TABLE I
LORENTZ FORCE PRODUCED BY FLUX CONCENTRATORS OF RECTANGULAR CROSS SECTION, AXIAL LENGTH 3CM AND OF DIFFERENT RADII

Calculated parameters:	Conc. 1	Conc. 2	Conc. 3
Inner radius of Flux concentrator ring R3 in [cm], (Fig. 4)	8.5	8.0	7.0
Mean radius of Flux concentrator ring R4 in [cm], (Fig. 4)	10.3	9.8	8.8
Current in Flux concentrator i_2 in [kA], (Equation AII.3)	2.1	2.7	3.5
B-Flux concentrator in [mT], (Equation AII.2)	15.5	21.0	31.4
Flux concentrator Lorentz Force in [N/m], (Equation AII.1)	244	327	496
Transfer loss ϵ' , (Equations AII.5 and AII.6)	0.00036	0.00052	0.00074
l	0.12	0.13	0.15
m	0.24	0.27	0.30
L' , [μH]	12.9	13.3	14.0
L_3 , [μH]	0.27	0.25	0.21

Note: Arc and Coil alternating current $i_1 = 15.8\text{kA}$ peak, Outer radius of inner PTFE cylinder was 5cm; Inner radius of outer PTFE cylinder was 6cm, $k = 1$ corresponds to good coupling, [7] (e.g. inductance of the flux concentrator radial slot far less than the inductance of the B-field coil including the arc convolute loop (Fig. 1))

REFERENCES

- [1] H. M. Ryan, *High Voltage Engineering and Testing*, 3rd Edition, Institution of Engineering and Technology, IET Power and Energy Series 66, UK, 2013, ch.7, pp. 275-302, ch.21.7.1.1, pp.708-709.
- [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, pp.765-771, 2005.
- [3] 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 1995.
- [4] L.M. Shpanin, G.R. Jones, J.E. Humphries, and J.W. Spencer, "Current interruption using electromagnetically convoluted electric arcs in gases", *IEEE Transactions on Power Delivery*, vol. 24, no.4, pp.1924-1930, Oct. 2009.
- [5] L.M. Shpanin, G.R. Jones, J.E. Humphries, J.W. Spencer, "Electromagnetically convoluted arcs confined within an annular gap between two PTFE cylinders", *Proc. of the 19th Int. Conf. on Gas Discharges and their Applications*, China, pp.234-237, Sept. 2012.
- [6] M.N. Wilson, K.D. Srivastava, "Design of efficient flux concentrators for pulsed high magnetic fields", *The Review of Scientific Instruments*, Vol. 36, No. 8, Aug. 1965.
- [7] L.M. Shpanin, G.R. Jones and J.W. Spencer, "Flux concentrator for compressing an arc plasma column in the current interrupter", *Proc. of the 21st Int. Conf. on Gas Discharges and their Applications*, Nagoya, Japan, pp.197-200, Sept. 2016.
- [8] L.M. Shpanin, G.R. Jones, J.W. Spencer, B. E. Djakov, "Control and propulsion of an atmospheric pressure plasma ring", *IEEE Transactions on Plasma Science*, Vol. 36, No.5, pp.2795-2800, Oct.2008.

- [9] L. M. Shpanin, G. R. Jones, J. E. Humphries, J. W. Spencer, N. Y. A. Shammas, S. B. Tennakoon, "R L C - induced current oscillations in convoluted arcs with independently activated magnetic fields", *IEEE Transactions on Plasma Science*, Vol. 41, No.10, pp.2836-2841, Oct. 2013.
- [10] L.M. Shpanin, *Electromagnetic arc control for current interruption*, Ph.D. dissertation, University of Liverpool, Liverpool, U.K., 2006.
- [11] L.M. Shpanin, D.R. Turner, J.E. Humphries, J.W. Spencer, G.R. Jones and B.E. Djakov, "Formation and propulsion of an atmospheric pressure plasma ring", *Proc. of 16th Int. Conf. on Gas Discharges and their Applications*, Xi'an, China, pp.5-8, Sept. 2006.



Leonid M. Shpanin received the M.Sc. degree in radio engineering from Azerbaijan Technical University, Azerbaijan and Ph.D. degree in electrical engineering and electronics from University of Liverpool, U.K. He is a Lecturer in Aerospace, Electrical and Electronic Engineering, Faculty of Engineering, Environment and Computing, School of Mechanical, Aerospace and Automotive Engineering, Coventry University, UK. He is a member of the Higher Education Academy, UK and a member of the Institute of Electrical and Electronics Engineers (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 SF₆ 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.



Electrical Engineering (IET), U.K.

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