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EMPIRICAL MODEL FOR QUASI DIRECT CURRENT INTERRUPTION WITH A CONVOLUTED ARC

L. M. SHPANIN[1]*, G. R. JONES[2], J. R. HUMPHRIES[2], J. W. SPENCER[2],
N. Y. A. SHAMMAS[3], S. B. TENNAKOON[3],

[1]University of Warwick, CV4 7AL, Coventry, UK
[2]University of Liverpool, L69 3GJ, Liverpool, UK
[3]Staffordshire University, ST18 0AD, Stafford, UK
*L.Shpanin@warwick.ac.uk

ABSTRACT

This contribution considers various aspects of a quasi direct current, convoluted arc produced by a magnetic field (B-field) connected in parallel with an RLC circuit that have not been considered in combination. These aspects are the arc current limitation due to the arc convolution, changes in arc resistance due to the B-field and material ablation, and the relative significance of the RLC circuit in producing an artificial current zero. As a result, it has been possible to produce an empirical equation for predicting the current interruption capability in terms of the B-field magnitude and RLC components.

1. INTRODUCTION

The use of an electromagnetically convoluted electric arc has been previously described for interrupting alternating current (A.C.) and quasi steady direct current (D.C.) [1-3]. The interpretation of results obtained for interrupting quasi steady currents has hitherto been predominantly concerned with exploring the current oscillations produced by a RLC circuit connected parallel to the arc gap [4]. The interaction of different magnitudes of B-field with an RLC circuit with a quasi steady current arc has also been reported [5].

This contribution seeks to address, from the quasi steady arc aspect, the complex combination of current limitation by the convoluted arc, the effect of the B-field in changing the arc resistance and the role of the RLC induced current oscillations in producing an artificial current zero. Using established test results, an empirical model is produced which quantitatively incorporates these interacting effects and with the potential of predicting the quasi direct current interruption capability of this type of convolute-arc interrupter as a function of B-field magnitude and RLC component values.

2. EXPERIMENTAL CONDITIONS

The principle of operation of the convoluted arc device plus parallel RLC circuit has been described by Shpanin *et. al.* [1-4]. Fig. 1a shows a simplified schematic diagram of the arc convolute producing system plus RLC circuit.

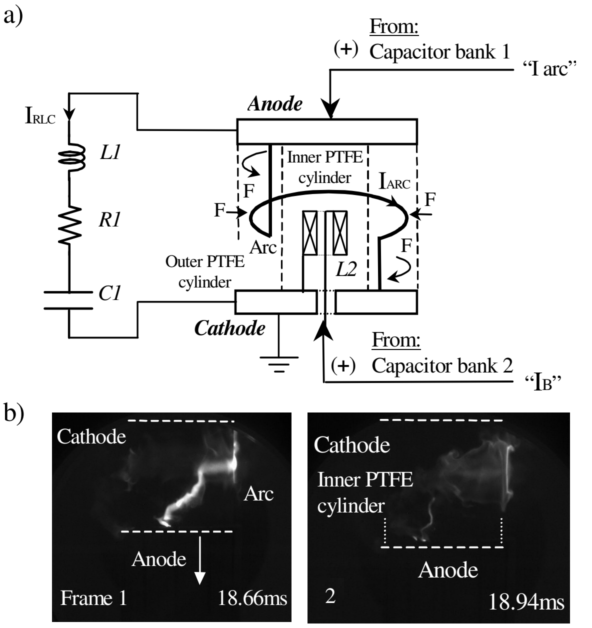

Fig. 1 Convoluted arc. a) Schematic of convoluted arc and system components; b) Convoluted arc images.

Briefly, the arc convolute is produced by separating two annular contacts, around a coil, which is separately excited and produces a spatially varying B-field. As the contacts are separated along the coil length an arc is drawn such that its initial short length is rotated by the Lorenz forces produced by the local B-field. When the contact gap has increased sufficiently, the two ends of the arc column are contra rotated by the opposite radial B-field components at either end of the coil. As a result, the arc column is automatically convoluted around the insulating housing of the B field coil to encourage ultimate current interruption.

The overall current interrupting arc is therefore exposed to the following conditions:

(i) Quasi steady arc current decrease from the main capacitor source.
(ii) Arc length increasing with time as the contact gap increases.
(iii) B-field distribution varying with distance across the fully open contact gap to induce the formation of an arc convolute.
(iv) B-field magnitude slowly decreasing with time as the coil current decays.
(v) Ablation of the outer insulating wall of the B-field coil container by the convoluted arc.
(vi) Current oscillations produced by the parallel connected RLC circuit.

Empirical modelling of the current interruption process therefore needs to accommodate all these complex aspects.

3. EXPERIMENTAL RESULTS

Fig. 2 shows some typical time variation of a number of parameters during arcing with the system of Fig. 1. These are shows the time variation of arc current and voltage, plus the contact travel and independently produced B-field for initial values of quasi direct current of 1.5kA, B-field of 195mT and a contact gap of 115mm. Oscillatory current variations, produced by the parallel RLC circuit [2-4] are superimposed upon a slowly decaying arc current accompanied by arc voltage fluctuations superimposed upon a gradually increasing voltage. During this period the B-field reduces from 195mT to 51.6mT at current interruption. Also shown as dashed curves on Fig. 2a, b are the calculated mean current and voltage on which the oscillations are superimposed. In addition, the time is indicated at which the arc contacts gap is approximately equal to half the B-field coil length.

Fig. 3 shows results of some arc properties derived from test results of the form given on Figs. 2. Fig. 3a shows the mean quasi steady arc current as a function of time for three arc controlling B-fields – 0, 34, 195mT. The time and current level at which current interruption occurred with each B-field can be distinguished. Fig. 3b shows the mean quasi steady arc voltage as a function of the mean arc current for the same three B-fields. The arc voltage varies inversely as the arc current, the particular variation being dependent upon the B-field value.

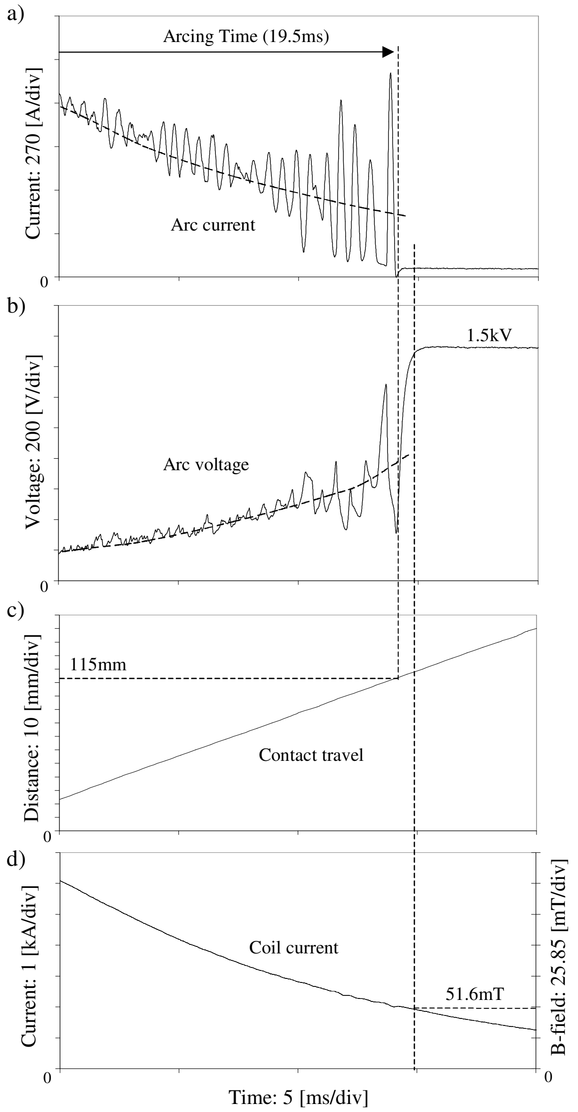

Fig. 2 Typical time variation of various convoluted arc parameters. (1.5kA initial peak, 195mT, with RLC circuit; “__” overall; “---" quasi steady): a) arc current; b) arc voltage; c) Contact gap length; d) B-field of the coil.

Fig. 3c presents the arc resistance (V / I) as a function of the mean quasi steady arc current for the same three B-fields. For all three B-fields, the arc resistance is less than ~0.5Ω for currents above 700A. However, for lower currents the arc resistance increases by typically an order of magnitude, the increase depending upon the B-field magnitude.

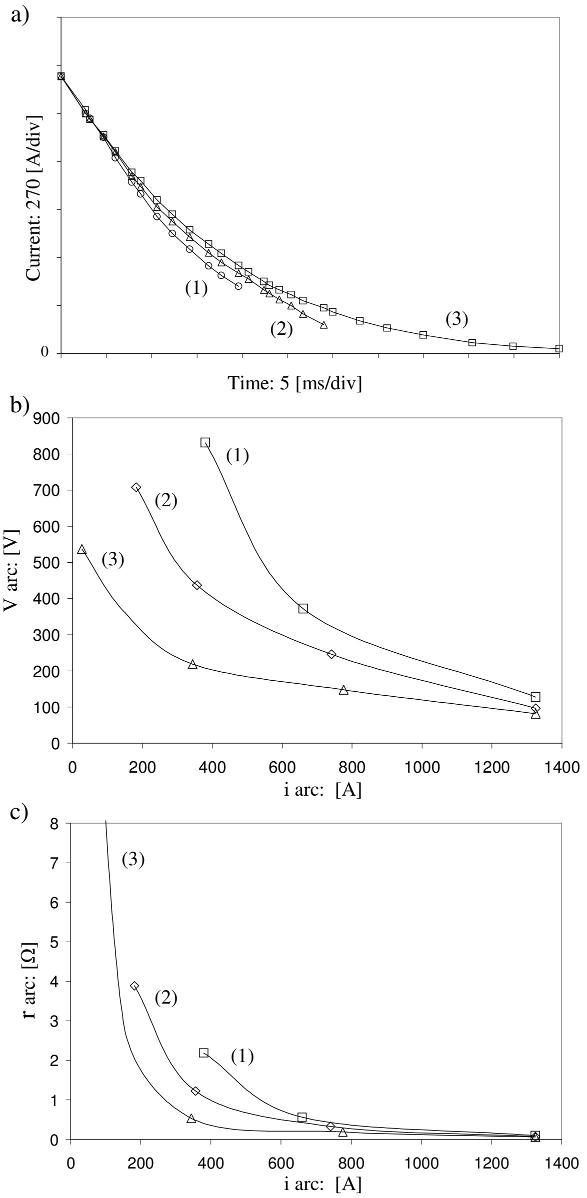

Fig. 3 Derived arc characteristics for various B-fields. a) Arc current versus time; b) Arc voltage versus current; c) Arc electrical resistance versus current. Where: Curves (1), (2,) (3) are respectively for B fields of 195, 34, 0 mT with arc durations of 19.5, 29 and 55ms respectivly.

Fig. 4 shows the quasi steady current level at which interruption occurred for an initial quasi steady current of 1.5kA, as a function of the applied B-field. Also shown are a result for a lower initial quasi steady current of 600A and results for an initial current of 1.5kA with B-fields but no RLC circuit connected in parallel with the arc gap. These results show the extent to which the current interrupted increases with the B-field value and also the effect of the RLC parallel circuit.

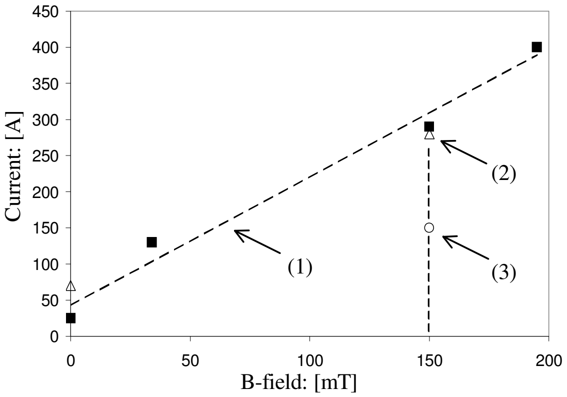

Fig. 4 Quasi-direct current interrupted with different B-fields, with and without an RLC circuit. (1) "■" – (Dashed line), Initial current 1.5kA, with RLC circuit; (2) "Δ" - Initial current 0.6kA, with RLC circuit; (3) "○" - Initial current 1.5kA, without RLC circuit.

4. DISCUSSION OF RESULTS

The results presented in Section 3 enable the effect of B-field magnitude, the RLC circuit and contact gap on the current interruption capability to be empirically modelled taking account of the time variation of the contact gap length.

4.1 Resistance Per Unit Length of Arc Column

The results presented for the time variation of contact gap length (Fig. 2c), and arc resistance as a function of arc current (Fig. 3b) enable the arc resistance per unit gap length to be calculated for different gap lengths and B-fields. Table 1 shows values of the resistance / gap length for a short gap (less than half of the B-field coil length, 7cm) and for longer gaps (15cm, 12cm) for which arc convolutes may be formed with a B-field. Results for different magnitudes of initial B-field (0mT, 34mT, 195mT) are presented.

Table 1 Mean Arc Resistance / Gap Length for different gap lengths and initial B-fields.

B-field [mT]	Gap (L) [cm]	i arc [A]	r arc [Ω]	r / L [Ω/cm]
0 / 195	~7	~700	~0.2	~0.03
0	15	270	0.7	0.05
34	15	182	4	0.28
195	12	380	2.35	0.2

The results show that the resistance per unit gap length for the longer gaps (12cm, 15cm) with arc convolutions (~0.2 - 0.28Ω/cm) is almost an order of magnitude higher than the value (~0.03Ω/cm) for shorter gaps (~7cm). Also, the resistance per unit length for the longer gaps with a B-field (0.2 - 0.28Ω/cm) is about five times greater than without a B-field (0.05Ω/cm).

4.2 Current Limitation

The current – time results of Fig. 3a indicate that the arc current characteristics with a B field deviate from the B = 0 characteristic, the deviation increasing with time and B-field magnitude. This is indicative of a current limiting action of the arc convolute which increases with the magnitude of the B field. For example with B = 195mT, the interrupted current (~432A) was less than the B = 0 current at the same time (~540A) by 108A; with B = 34mT the interrupted current (~202A) was less than the B = 0 current (~270A) by 68A. Thus current reductions of ~20% are produced with both B-fields just prior to current interruption.

4.3 Current Interruption Prediction

The results of Fig. 4 suggest that the current interrupted varies approximately linearly with B-field, is largely independent of the initial value of the quasi steady current and that the B-field effect depends upon whether there is a RLC circuit connected in parallel with the arc gap. An equation for the current interrupted (I(int.)) may therefore be established of the form:

$$I\,(\text{int.}) = (Io + b(RLC)) + (a + b'(RLC))B \qquad (1)$$

Where: Io is the current interrupted with no B-field and no RLC connected;
(Io + b(RLC)) is the current interrupted with an RLC circuit connected, but no B-field;
"a" is the effect of the B-field in the absence of an RLC circuit;
"b'(RLC)" is the effect of a connected RLC circuit on the B-field influence.
For the present case:
RLC relates to the peak of the oscillating current [3] i.e. (RLC) ~ $\sqrt{Co/Lo}$.
Where: Io =0, B = 90, a = 1, b' = 0.6

The current interruption predicted by equation (1) with the parallel RLC circuit plus various B-fields is in good agreement with experimental results (dashed line, Fig. 4).
If the current limitation considerations of section 4.2 are taken into account, the actual quasi steady current interrupted is ~20% greater than the equation (1) values. Thus the combined effect of current limitation plus B and RLC induced current interruption, may be quantified by a scaled form of equation (1):

$$I(\text{int.}) = 1.2[90\sqrt{Co/Lo} + (1 + 0.6\sqrt{Co/Lo})B] \qquad (2)$$

5. CONCLUSIONS

An empirical equation (equation (2)) has been derived for predicting the direct current interruption of a convoluted arc device which incorporates the effects of the applied B-field, a parallel RLC circuit and, indirectly, PTFE ablation of the B-field coil containing current cylinder. This equation predicts that the current interruption is independent of the initial quasi-steady current, increases with the magnitude of the B-field and that the present RLC circuit doubled the current level interrupted. Although the empirical equation reasonably predicts current interruption for the present operating conditions, further evaluation is of course desirable.

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