Electromagnetically Convoluted Arcs for the Interruption of Quasi Direct Current

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Abstract- **This paper describes a novel technique for interrupting direct currents (D.C.) with an electromagnetically convoluted arc in air at atmospheric pressure. Investigations are reported on the effects of using a separate current for producing the arc convolving electromagnetic field (B-field) to that being interrupted and using a separate R, L, C circuit in parallel with the arc contacts. Experimental results are presented for the time variation of currents flowing through the arc gap, the B-field coil and the parallel R, L, C circuit, along with the voltage across the arc gap.**

Index Terms- **Current interruption, arc discharges, magnetic fields, plasma control, arc plasma devices, ablation.**

I. INTRODUCTION

The interruption of high levels of D.C. current 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 find more efficient D.C. interruption techniques are ongoing [2, 3, 4 and 5]. Current interruption in D.C. systems is more problematic than in alternating current (A.C.) 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 RLC circuit connected across the interrupter arc gap [2, 6]. The use of such circuits in rotary and non-rotary arc circuit breakers have been previously investigated with arcs in atmospheric pressure SF6 gas [2, 6]. The quasi direct current interruption in D.C. systems is more difficult than in A.C. systems since there is no natural current-zero available there. As a result, it is still a challenge to implement the current interruption system efficiently without the use of the external electrical circuit across the contacts gap producing a current zero artificially. One of the techniques for producing a current zero artificially during D.C. current flow is with using an oscillating current produced by an RLC circuit connected in parallel with the interrupter arc gap [2, 6].

In this paper, not only was the form of electromagnetically convoluted arc unit previously used for interrupting A.C. arc currents [7, 8, 9 and 10] connected in parallel with an RLC circuit for producing an artificial current zero, but the electromagnetic field convolving the arc column was produced by a different current to the one being interrupted.

II. TEST CIRCUIT AND CURRENT INTERRUPTION CONCEPT

The principle of the quasi direct current interruption is based upon two facets (Fig. 1a, b). The first is the control and extinction of an arc electromagnetically [7, 8 and 9] when the arc contacts (and hence the arc column) extends in parallel along the length and outside of a B-field producing coil (Fig. 1a). The second is the use of a parallel RLC circuit across the convoluted arc gap [6] to generate high-frequency current flow through the arc.

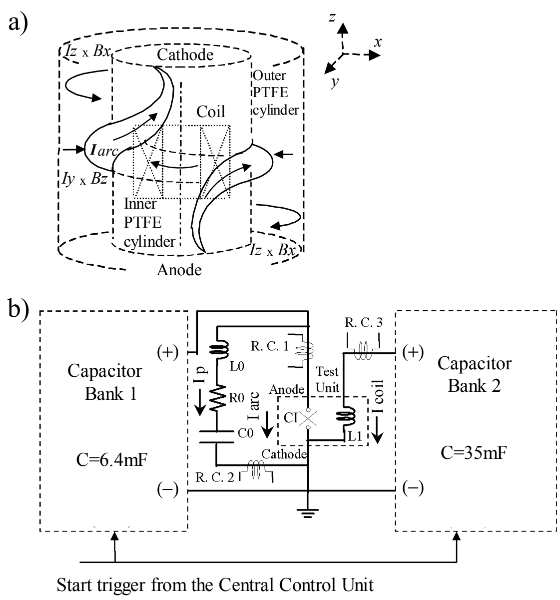

Fig.1. Schematic diagrams of the two facets involved in the D.C. current interruption method. a) The convoluted arc unit. b) The parallel R0-L0-C0 and high voltage supply circuits. L1 is the magnetic field producing coil of the interrupter.

The first facet involves the arc lengthening principle described previously [7, and 8] but with the anode rather than the cathode being movable. This movable anode arc section is exposed to an outward radial B-field produced by the B-field coil at the top section of the coil location. This causes the arc to rotate in an anticlockwise direction. When the arc gap is fully opened, the movable anode arc section is exposed to the inward B-field at the bottom level of the coil, which causes that arc section to counter rotate in a clockwise direction (Fig. 1a). 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 [7, and 8].

The second facet (Fig.1b), the use of parallel R0-L0-C0 circuit, is described in [6] and has been adapted for use with the convoluted arc form shown on Fig. 1a. When the length of the convoluted arc is increased around the coil by the Lorenz forces (Fig. 1a), 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 suddenly 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. 1b), the discharge of C0 will produce high-frequency current oscillations (Ip) through the arc (I arc Fig.1b). The magnetic field producing coil L1 (B-field) in the test unit (Fig. 1a) is connected separately from the main circuit in order to examine the performance of the D.C. arc interruption without involving the coil in the arc circuit itself.

The experimental test circuit used is shown in Fig. 1b. It consists of two independently but synchronically operated capacitors bank units (C.B.1 and C.B.2) generating a quasi-direct electrical current of 1.5kA at 4kV (C.B.1, capacitance is 6.4mF) and a coil current of ~5.8kA, at 4kV (C.B.2, capacitance is 35mF) respectively. Each capacitor bank includes an Ignitron, which is connected in series with a current limiting resistor ~2.7Ω (C.B.1) and ~0.7Ω (C.B.2), and is triggered to conduct a quasi-steady current through the interrupter (CI) via C.B.1 or electromagnetic coil L1 via C.B.2. Both units include Ignitrons to short both D.C. circuits in order to dump the remaining energy from the capacitor bank units. A series combination of R0-L0-C0 circuit was connected in parallel with the arc convolute test unit (Fig. 1a) having values of 96μH, 66μF and 0.1Ω respectively. These component values were taken from the previous work deploying similar test circuit, but using a different arc convolute unit [6]. Three CWT type Rogowski current transducers R.C.1, R.C.2, R.C.3 were used to measure the D.C. current waveforms of the arc (I arc), L1 coil (I coil) and R0-L0-C0 (Ip) circuit respectively (Fig. 1b).

III. RESULTS OF EXPERIMENT

Fig. 2 shows an example of the time variation of various currents and arc voltage when a quasi direct current of 1.5kA peak was interrupted with a B-field of ~35mT at current interruption. Fig. 2a shows the arc voltage and current waveforms. Fig. 2b shows the current flowing through the R0-L0-C0 circuit (Fig. 1b). Fig. 2c shows the B-field coil

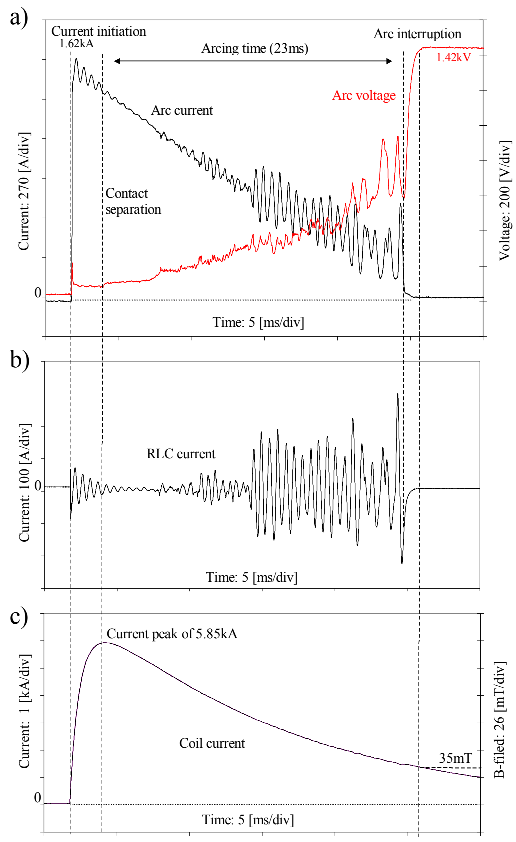

Fig. 2. Time variation of various currents and arc voltage. a) Arc current (I arc) and Voltage; b) R0-L0-C0 current (Ip); c) Coil current (~5.8kA peak producing 150mT B-field).

current during and post arcing. These results show that high frequency (~2kHz) currents are produced during arcing (Fig. 2b).

Fig. 3a compares the time variation of a quasi direct current of 1.5kA peak under different operating conditions. Fig. 3b shows the corresponding arc voltages.

Curve (1) in Fig. 3a, is for capacitor bank C.B.1 discharging through the closed interrupter (CI) showing an uninterrupted current of duration ~80ms. Curves (2) in Figs. 3a and 3b are the arc current and voltage waveforms with ~23ms arc duration for the circuit with B-field coil and R0-L0-C0 connected. Curves (3) in Figs. 3a, b, with arc duration of ~26ms are for the circuit with a B-field coil but without the R0-L0-C0 circuit connected. Curves (4) in Figs. 3a, b, with arc duration of ~55ms are for the circuit without the B-field coil but with the R0-L0-C0 circuit connected.

The high-frequency discharge current oscillations observed before contact separation (Fig. 2a and b) are due to the effect of the initial heavy current of ~1.5kA peak produced by capacitor bank 1 unit (Fig. 1b) through the connected cables, a series current limiting resistance of the C.B.1 unit and close contacts of the test unit (Fig. 1b) that together introduce the inductance in the circuit. As a result, the initial voltage spike is generated which affect the R0-L0-C0 circuit (Fig. 1b).

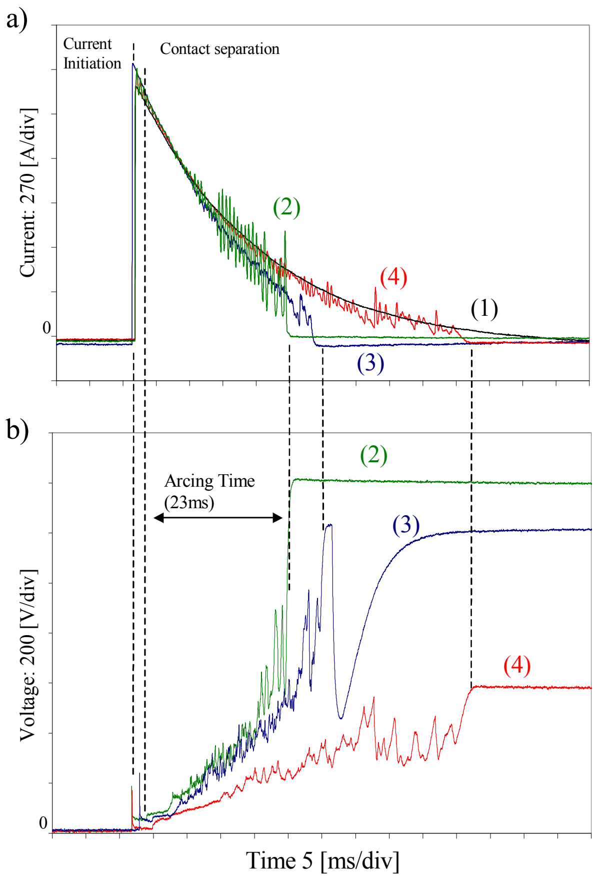

Fig. 3. Interruption of 1.5kA peak quasi D.C. under different conditions. a) Interrupter current waveforms b) Voltage waveforms; (1) Contacts closed; (2) Contacts open plus B-field coil and R0-L0-C0 connected circuits; (3) Contacts open plus B-field coil, without R0-L0-C0 circuit connected (coil peak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

Fig. 4 shows a series of high-speed images of the D.C. arc of 1.5kA peak column formation in the test unit shown on Fig. 1a and b. These images correspond to the D.C. arc of 1.5kA peak obtained at a framing rate of 7500 frames per second (exposure 8µs) using a high-speed camera: "Phantom V7". Three frames shown on Fig. 4 demonstrate the arc

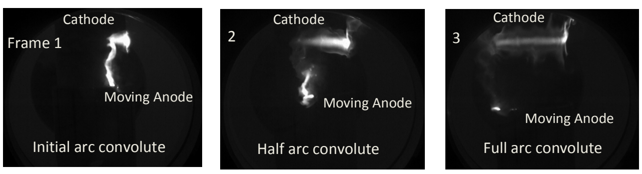

Fig. 4. High-speed camera of the D.C. arc of 1.5kA peak close to the current zero at 21.3ms (frame 1), 21.6ms (frame 2) and 21.9ms (frame 3), with R0-L0-C0 connected circuit. Where: the B-field of the coil is 150mT (corresponds to the coil current of ~5.8kA).

convolute initiation, half and full arc convolute formations in the test unit without the outer PTFE cylinder (Fig. 1a).

The images at 21.3ms, 21.6ms and 21.9ms confirm that an azimuthally convoluted arc is formed, concentrated around the mid axial location of the coil and similar to the predicted arc behavior shown in Fig. 1a. At 23ms, the D.C. arc was extinguished at current zero (Fig. 2a) when the arcing gap was about 122mm.

IV. Discussion

Previous experimental work [7, 8, 9 and 10] suggests that the minimum level of Lorenz force (I x B) required to induce a convoluted arc structure is between 6 and 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. An insight into the effect of the B-field producing coil, with and without a parallel R0-L0-C0 circuit, on the quasi D.C. interruption can be obtained from the current and voltage waveforms shown on Figs. 2 and 3.

The influence of the coil's B-field along with the parallel R0-L0-C0 circuit on the convoluted arc produces the high-frequency oscillatory current (Ip) shown on Fig. 2b. These oscillations which occur on both arc (I arc) and R0-L0-C0 (Ip) currents have a recognisable amplitude (~50-100A) about 12ms after contact separation (Figs. 2a, b). The maximum amplitude (~300A) of the high-frequency current oscillations (Ip) was generated just prior to the arc current (I arc) interruption. A similar trend is also apparent on the arc voltage curve (Fig. 2a). At times longer than 12ms after contact separation, the length of the arc gap becomes greater than the length of the coil (~70mm) [7, 9], so that the quasi D.C. arc becomes convoluted and susceptible to repeated self short-circuiting and re-formation (Fig. 2a, b).

Fig. 3a (curves (2), (4)) shows that the effect of the presence of a B-field coil current (I coil) (Fig. 1b) on the arc current (I arc) is to produce:

- lower (~ x ½) quasi D.C. levels at a given time (i.e. current limitation);
- higher amplitude (~ x 2) high frequency arc current oscillations (i.e. enhancing a forced current zero).

The voltage waveforms during arcing (Fig 3b) with and without (curves (2), (4) respectively) the B-field coil show similar trends to the current waveforms - the arc voltages and oscillation amplitudes without the coil being lower (~ x ½) than those with the coil. Such reduction in the amplitudes of the current and voltage oscillations suggests that the arc is not lengthening substantially in the absence of the coil current (I coil). The implication is that with the B-field coil, the capacitor C0, in the R0-L0-C0 circuit (Fig. 1b), is charged more significantly to produce the desirable higher amplitude oscillations when arc self short-circuiting occurs.

As already indicated in section III, the arc duration before current interruption depended upon the parallel circuit conditions. The arc duration time was shortest with both B-field and R0-L0-C0 circuit connected (~ 23ms Fig. 3a curve (2)), intermediate with the B-field but no R0-L0-C0 circuit (~26ms, curve (3)) and longest without the B-field but with the R0-L0-C0 (~ 55ms curve (4)). In each case the current level at which interruption occurred was ~300A (curve (2), Fig. 3a), ~150A (curve (3), Fig. 3a) and ~70A (curve (4), Fig. 3a). In addition, there is evidence on curve (3) (with the B-field but without the R0-L0-C0 circuit) of a low level, negative current flowing post arcing.

Comparison of the post arc voltage curves (2), (3), (4), Fig. 3b shows that the residual source voltage following arc extinction is highest when both the B-field and R0-L0-C0 circuit are activated (~1.42kV 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)). This feature is consistent with the low post arc current already indicated on the corresponding current curve (3), Fig. 3a.

V. 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 results show that high frequency current oscillations, which are advantageous for direct current interruption, can be produced by the combination of a magnetic field producing coil and an R0-L0-C0 circuit connected across the arc gap. It is concluded that the magnetic field and R0-L0-C0 circuit combination reduces the time to current interruption compared with the separate use of the magnetic field and R0-L0-C0 circuit.

The present arc convolute form produces similar current interruption levels and arc durations before interruption compared with the work of Zhang *et al* [6]. However, it has the following advantages. The convolute arc, investigated in this paper, is in atmospheric pressure air and ablated material rather than in SF6 gas and at much higher pressure (~3 atmospheres) investigated previously by Zhang *et al* [6].

The separate B-field coil excitation may allows higher B-field levels to be produced for better current interruption by the use of controlled coil currents.

Future work would need to address the possible effect of the mutual inductance between the arc plasma convoluted loop and the magnetic field producing coil.

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