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THE EARLY COUNTERPULSE TECHNIQUE APPLIED TO VACUUM INTERRUPTERS*

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ABSTRACT

Interruption of dc currents using counterpulse techniques is investigated with vacuum interrupters and a novel approach in which the counterpulse is applied before contact separation. Important increases have been achieved in this way in the maximum interruptible current and large reductions in contact erosion. The factors establishing these new limits are presented and ways are discussed to make further improvements to the maximum interruptible current.

I. INTRODUCTION

A dc current can be interrupted by a mechanical switch only if its current can be forced to zero while it is arcing. Commonly, this is accomplished either by designing the switch to generate an arc voltage greater than the source voltage or by adding an extra counterpulse circuit that injects into the switch an oppositely-directed current pulse large enough to create a transient current zero.

For several years, experiments with counterpulse circuitry have been conducted at the Los Alamos Scientific Laboratory (LASL) on interrupters to be used in fusion applications. A conventional approach has been used following the lead of early workers such as Greenwood.[1] The electrodes of the switch are separated at full current and an arc occurs between them. The counterpulse is applied several milliseconds later when the electrode separation has reached approximately 1 cm. The two major limitations found with this approach are both related to the long interval of arcing at full current. The arcing heats the electrodes and generates incandescent hot spots that are prolific electron emitters. These hot spots cause reignition of the arc, providing the upper limit to the current that can be successfully interrupted.[2] In addition, the prolonged arc erodes the electrodes and deposits conducting films of electrode material on shields and insulating surfaces. Measurements made at LASL indicate that in spite of these problems, a vacuum interrupter can interrupt large currents and still have a long life. At 25 kA, for example, an interrupter should achieve 10,000 or more interrupting cycles before these erosion phenomena end its life.[3]

We have attempted to remove both of these limitations by employing a less conventional counterpulse technique. In this technique, the counterpulse is applied before the electrodes are parted so that their initial separation and subsequent arcing take place at currents much lower than the initial value. This early counterpulse (EC) technique requires a long counterpulse, a fast actuator, and a rugged interrupter. Because of its potential for lower contact erosion and a larger interruptible

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current, the EC technique has attracted other investigators. An air-blast interrupter[4] to be used with the tokamak JET and a special SF_6 switch[5] used with the Crossed Field Tube are examples of such developments. Vacuum interrupters have advantages relative to these other types primarily because of the lower erosion expected for the contacts and the resulting longer life.

II. THE EARLY COUNTERPULSE TECHNIQUE

The circuit, discussed in detail elsewhere,[2] used in the tests is shown in Fig. 1. Energy storage capacitor C_1 in conjunction with switches S_1 and S_2 and inductor L_1 establish a slowly decaying current, I, in VI, the interrupter under test. The counterpulse is fired by closing switch S_3 which connects capacitor bank C_2 to VI. This generates the desired reverse-current pulse. L_2, a saturable reactor, helps to shape the reverse-current pulse so that the switch current is close to zero for a long time. R1 is used as a final dump resistor for the energy initially stored in C_1 and C_2 and is connected by S_4 after the interruption phenomenon is completed.

Figure 2 shows schematically, the behavior of the current flowing through VI. At time t_0 the counterpulse is initiated. At t_1 the current in the switch passes through zero for the second time and interruption may occur. At t_2 the capacitor C_2 and the saturable reactor L_2 have exhausted their charge and flux so that the counterpulse ends. For the EC technique to succeed, VI must open its contacts between t_0 and t_1. With this timing an arc will start and burn at low current and interrupt as the current passes through zero at t_1.

There are two obvious problems with the EC technique which must be overcome and which have become the main focus of these investigations. The first is the difficulty of opening the interrupter in the short interval between t_0 and t_1 in the face of jitter from various sources. The second is the rapid development of the recovery voltage at a time when the arc has barely extinguished and the electrodes have barely separated. The possibility of reignition of the arc at this time is high but can be reduced by several measures.

1. A high-average velocity of separation of the electrodes.
2. A large saturable reactor and counterpulse bank.
3. A snubber circuit (an RC series combination) placed across VI.

The actuator used in these tests was made by Ross Engineering Co.[6] It is operated by two repulsion coils, one stationary and one connected to the moving electrode of the interrupter. The coils are energized by a 300 μF capacitor bank charged to 2 to 5 kV. The peak coil current is several tens of kiloamperes. The actuator was designed to maximize the acceleration of the moving electrode. Accelerations of 10^6 cm/sec^2 have been achieved. The saturable reactor is composed of 133 separate 4-mil tape-wound cores, each threaded by a 4-0 electrical cable. Each of the cores has a flux rating of 0.008 Wb for a total of about 1 Wb. Because of the gap-less tape-wound construction of these cores, their unsaturated inductance is very large.

The counterpulse bank is unusually large. We used 360 kJ of capacitance connected in different ways to provide either 1.8×10^{-3} F at 20 kV or 0.45×10^{-3} F at 40 kV.

III. RESULTS

The first experiments were performed with a standard 7-in. interrupter,[7] with an actuator acceleration of 0.3×10^6 cm/sec^2, and a counterpulse bank of 1.8×10^{-3} F. This arrangement gives the longest possible counterpulse and potentially the largest interruptible current. The modest acceleration was chosen to avoid possible stress-induced problems with the actuator or interrupter. With conventional counterpulse techniques, such an arrangement would have given a maximum interruptible current of 21 kA, relatively independent of recovery voltage.

The experiment proceeded by gradually raising I, the current to be interrupted, and at each current level by varying t_3, the interrupter opening time, over its full range, from t_0 to t_1. The experiments were continued with currents up to 35 kA at 25 kV, the limit of the test facilities, with no failures of any kind. A striking observation concerned the visual appearance of the switch during interruption. With conventional counterpulse techniques, the ceramic envelope lights up brightly due to the enclosed arc. With EC techniques, no light could be seen. This is consistent with the reduction of the arcing current by a factor of 300 and arcing time by a factor of 10 produced by EC.

To increase the electrical stresses on the interrupter the value of C_2 was reduced to 0.45×10^{-3} F. This change increased the recovery voltage by a factor of two and decreased the interval t_1-t_0 for opening the interrupter by a factor of two. Under these conditions reignitions were occasionally observed when t_1-t_3 was small, that is, much less than 100 μs. The major new effects observed were a marked increase in the jitter observed in the opening time and a consistent shift of the average opening time as the current increased. These effects combined to make it difficult to time the switch's opening to occur between t_0 and t_1. This effect set a maximum interruptible current of about 20 kA.

To investigate this limit, we substituted three different 4-in. interrupters for the original one keeping $C_2 = 0.45 \times 10^{-3}$ F. With conventional techniques these switches could interrupt 6, 6, and 8 kA, respectively. With the EC technique their limits were increased by a factor of 2 to 2.5, as determined, again, by the onset of marked jitter in the opening time and its shift to later times.

Careful measurements identified two sources of the jitter and shift. One was the tendency of the electrodes to pop apart at high currents. This shows up as a voltage jump before t_0.

The second problem was of a related kind. The "opening" of the switch occurs when the molten bridge which forms between the electrodes ruptures. The lifetime of the bridge depends upon the details of current magnitude, contact pressure, etc., in a complex way.

The effect of these phenomena is to reduce the range of counterpulse settings within which an EC interruption can be achieved. The range is reduced to zero for currents slightly above 19 kA, consistent with the findings that 20 kA is the largest current we can successfully interrupt.

IV. LIFE TESTS

To test the erosion reduction expected of the EC technique, a 4-in. interrupter was subjected to over 1000 interruption cycles at 10 kA. The interrupter was disassembled and the contacts examined after these wholly successful interruptions. The contacts were found to be in near-new condition, the surface markings being caused largely by contact rubbing. We estimate a reduction in erosion brought about by the EC technique of more than one hundred.

V. CONCLUSION

The anticipated features of the EC technique were reduced electrode erosion and increased current ratings. Substantially increased ratings have been realized in these experiments, and the reduction in erosion is very large. The components and techniques used to achieve these improvements are available, convenient to use, and relatively reliable.

The new current limit does not appear to be a basic property of the switches but is instead associated with the actuator, in particular with the force with which the electrodes are held closed. Future work will attempt to raise the current limit further by employing higher closing forces.

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7. Model WL-23231, Westinghouse Electric Corp.

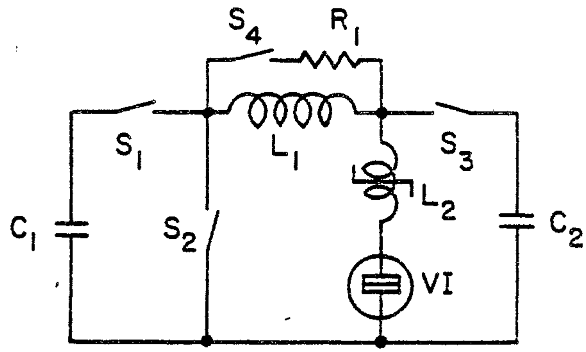

Fig. 1. Test circuit.

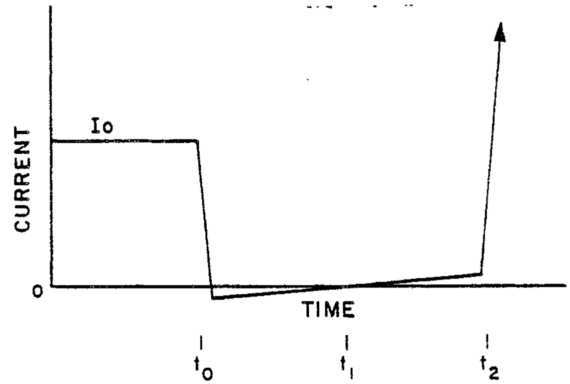

Fig. 2. Current during counterpulse.