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The Early Counterpulse Technique Applied to Vacuum Interrupters

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

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R. W. Warren*

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*Industrial Staff Member. Westinghouse Corporation, 1310 Beulah Rd., Pittsburgh, PA 15235.

THE EARLY COUNTERPULSE TECHNIQUE APPLIED TO VACUUM INTERRUPTERS

by

R. W. Warren

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 as well as large reductions in contact erosion. The factors establishing these new limits are presented and ways are discussed to make further improvements.

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. At low source voltages the first alternative is attractive because of its simplicity and low cost. At voltages above 1 kV, however, this choice becomes more difficult and costly to implement, and the problems related to contact heating and erosion become dominant. Within this regime counterpulse systems find their major application.

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 current interruption cycles³ before these erosion phenomena end its life.

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 technique (ECT) requires a long counterpulse, a fast actuator, and a rugged interrupter. Because of its potential for lower contact erosion and a larger interruptible current, the ECT has attracted other investigators. An air-blast interrupter⁴ to be used with the tokamak JET and a special SF₆ switch⁵ 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. If contact life could be extended by a factor of 10 or more by the ECT so that 10⁵ to 10⁶ operating cycles could be achieved, many new applications for such switches would be found, applications now filled by much more expensive solid-state devices.

In this paper results are reported for the ECT. These results include the development of special techniques and components, the measurement of the new limits on interruptible current and voltage, the measurement of erosion, and a determination of the factors which set these new limits on current, voltage, and erosion.

II. EXPERIMENTAL PROCEDURES

A. Special Features of the Early Counterpulse Technique

The circuit, discussed in detail elsewhere,² used in these 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

Fig. 1
Test Circuit.

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. R_1 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. The current rapidly passes through zero. 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 ECT to succeed, VI must open its contacts at time t_3 , somewhere 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 . If VI opens before t_0 , the arc current will be high, interruption unreliable because of electrode hot spots, and erosion severe. If VI opens after t_1 , the arc current will be small, but no opportunity for interruption, that is, current zero, will occur.

Figure 3 shows a measurement of the voltage across VI during this cycle. At t_0 is shown an inductive transient generated when the counterpulse occurs. At t_3 is shown a jump of 20 volts which occurs when the electrodes separate and the arc voltage develops. At t_1 is shown current interruption and the rapid development of the subsequent recovery voltage. No special feature is visible at t_2 .

There are four obvious problems with the ECT which must be overcome and which have been the main focus of these investigations. The first is the difficulty in opening the interrupter in the short interval between t_0 and t_1 in

Fig. 2
Current During Counterpulse .

Fig. 3
Voltage Across Interrupter.
The Trace is 2.56 ms Long.

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. The third is the probability that at some current level the ECT will fail due to a memory effect. By this is meant interference by the very high current being carried shortly before counterpulse with the subsequent interruption attempt at a low current. Contact popping, to be discussed below, is one example of such a phenomenon. There are others. The fourth problem involves electrode erosion. Does the ECT really reduce erosion substantially as promised, or does some unexpected phenomenon interfere?

The remainder of this report is arranged to address these four problem areas. First, the special components and techniques used to achieve reliable operation of the ECT are presented, followed by a discussion of high-voltage problems and restrikes, high-current problems and memory effects, measurements of erosion, estimates of the cost penalty associated with the ECT, and finally recommendations for further development of the components.

B. Special Components and Techniques

Figure 4 shows the special actuator used in these tests with a conventional 4-in. vacuum interrupter mounted on it. The actuator was made for these tests by Ross Engineering Co.⁶ and 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- μ F capacitor bank charged between 2 and 5 kV. The peak coil current is several tens of kiloamperes. The actuator was designed to maximize the acceleration of the moving electrode. Figure 5 shows measurements made of

Fig. 4
High Speed Actuator and 4-in. Interrupter.

its displacement at three different voltages. Accelerations as high as 10^6 cm/s² have been achieved.

Figure 6 shows the unusually large saturable reactor that was used. It is composed of 133 separate 0.004-in. thick tape-wound magnetic cores like those shown below, each threaded by one turn of 4/0 electrical cable. Each of the

Fig. 5
Inter-electrode Gap vs Time for Three Driving Voltages.

cores has a flux rating of 8×10^{-3} Wb, for a total flux of 1 Wb. Because of the gapless tape-wound construction of these cores, their unsaturated inductance is very large. When used in the circuit of Fig. 1, the eddy current losses in the cores obscure the effects due to their finite inductance and produce the constant positive slope in the nearly flat part of the counterpulse shown in Fig. 2.

The counterpulse bank, C_1 , is also unusually large. Three hundred sixty kJ of capacitance was used, connected in different ways to provide either 1800 μ F at 20 kV, 450 μ F at 40 kV, or 200 μ F at 60 kV.

The snubber circuit sometimes used is composed of a series RC combination connected across VI. The capacitance C was varied from 1 to 20 μ F and R was varied from zero to 100 Ω . The purpose of the snubber is to reduce dV/dt across the interrupter after the arc has extinguished.

III. EXPERIMENTAL RESULTS

The first experiments were performed with a standard 7-in. interrupter,⁷ using an actuator acceleration of 0.3×10^6 cm sec⁻², and a counterpulse bank of 1800 μ F. This choice of capacitance gives the longest possible counterpulse, the smallest recovery voltage, and should produce 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 20 kA, 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 performed with

Fig. 6
Saturable Reactor.

currents up to 35 kA at 12 kV, the limit of the test facilities, with no failures of any kind. In addition to the unusually high interruptible current, 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 ECT, 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 ECT.

Interruptions were continued under the maximum conditions until it was clear that not only could unusually large currents be interrupted but that the electrical components, the actuating mechanism, and the bellows of the interrupter operated reliably, showing no deterioration from this duty over extended periods of time. Attempts were then made to increase the electrical and mechanical stresses on the components to find their limits. These limits are reported below.

A. High-Voltage Limits

For a successful ECT interruption, the switch must separate its contacts at a time t_3 which occurs somewhere between the counterpulse time t_0 and the current zero time t_1 of Fig. 2. Clearly the best strategy is to open the switch very shortly after t_0 . The low-current arc which develops upon opening acts to hold the recovery voltage near zero as the electrodes separate. In this way the electrode separation is given a head start in the race of recovery voltage against electrode spacing which determines whether the resulting interelectrode field E exceeds the appropriate breakdown value, E_{BD} , causing a restrike.

These considerations can be put into mathematical form as follows. Assume that the electrodes separate at the optimum time, t_0 , with an acceleration, a . Then their separation, S , is given by $S = a(t-t_0)^2/2$. At the time of interruption, t_1 , the voltage on C_2 is approximately zero. At this time the interrupted current, I , is diverted from V_1 and flows into C_2 causing its voltage, V , to increase linearly as $V = I(t-t_1)/C_2$. In the absence of a snubber circuit, the voltage across the interrupter closely approximates the voltage on C_2 . Figure 7 shows how S and V develop in time according to this model and how the field $E = V/S$ reaches a peak value given by $E_p = I/[2aC_2(t_1-t_0)]$. This peak occurs at time t_p , given by $t_p = 2t_1-t_0$, when the electrodes have separated by S_p and sustain a voltage V_p . By setting $E_p = E_{BD}$, the upper limit to the interruptible current at which restrikes occur is given by

$$I_m = 2aC_2E_{BD}(t_1-t_0) \quad (1)$$

Now t_1-t_0 is determined by the construction of the saturable reactor and the precharge voltage, V_C , present on C_2 before the counterpulse is initiated. Its value can be derived as follows. C_2 supplies a counterpulse current equal to I for a time t_1-t_0 . At the end of this time, C_2 is completely discharged. Thus, $C_2V_C = I(t_1-t_0)$. If the saturable reactor and counterpulse bank are used optimally, the reactor is almost driven out of saturation at t_1 when C_2 is entirely discharged. This condition requires that V_C be adjusted to fit the flux rating of the reactor, that is, $\Phi_0 = V_C(t_1-t_0)/4$. Combining these last two expressions to eliminate V_C gives $t_1-t_0 = 2(\Phi_0C_2/I)^{1/2}$. Substitution of this relationship into Eq. 1 yields

Fig. 7
Gap, Voltage, and Field vs Time for Simple Model.

$$I_m = (4aE_{BD}/\phi_0)^{2/3} \phi_0 C_2. \quad (2)$$

In addition,

$$t_{BD} = 4[\phi_0/(4aE_{BD})]^{1/3}, \quad (3)$$

$$S_{BD} = 8a[\phi_0/(4aE_{BD})]^{2/3}, \quad (4)$$

and

$$V_{BD} = 8aE_{BD}[\phi_0/(4aE_{BD})]^{2/3}. \quad (5)$$

Substituting values appropriate for the preliminary experiments reported above, that is $a = 3 \times 10^5 \text{ cm/s}^2$, $C_2 = 1800 \text{ } \mu\text{F}$, $\phi_0 = 1 \text{ Wb}$, and $E_{BD} = 3 \times 10^5 \text{ V/cm}$ gives $I_m = 90 \text{ kA}$, $t_{BD} = 0.5 \text{ ms}$, $S_{BD} = 0.05 \text{ cm}$, and $V_{BD} = 15 \text{ kV}$. For currents well above 90 kA or when t_3 is significantly later than t_0 , t_{BD} , S_{BD} , and V_{BD} will be less than these maximum values.

The observation that no failures occurred up to 35 kA is consistent with these calculations but does not provide a good test of them. Therefore, the large 7-in. interrupter was replaced with a number of different 4-in. interrupters which might be expected to fail at lower currents, and other experimental parameters which might be expected to induce restrikes were also changed. Of the variables-- a , ϕ_0 , and C_2 -- C_2 has the strongest effect upon I_m . C_2 was, therefore, varied from its initial value to values lower by a factor of 4 and 9. Under these conditions, I_m is reduced to 22 and 10 kA respectively; but t_{BD} , S_{BD} , and V_{BD} , being independent of C_2 , retain their previous values.

Failures were now commonly observed. They were of several kinds, restrikes consistent with the above theory when C_2 was small and the recovery voltage high, and of entirely different kinds described below for cases when C_2 was large and the recovery voltage low.

When failures were dominated by restrikes, the corresponding values of I_m were within 25% of the predicted values of 22 and 10 kA derived above. Figure 8, a trace of the voltage across the interrupter versus time, shows an example of such a restrike, whereas, Fig. 9 shows a corresponding example for which no restrike occurred and the voltage proceeded through its normal sinusoidal path. Restrikes rapidly decrease in frequency as I is decreased from I_m . Figure 10 shows the probability of successful interruption versus I as limited by restrikes for a typical interrupter.

Investigations were performed of the effect of snubber networks on restrikes. Snubbers can be effective in reducing the rate of voltage rise following interruption shown in Figs. 8 and 9. If a purely resistive snubber is

Fig. 8
Recovery Voltage vs Time Showing Restrike.
The Trace is 1.28 ms Long.

Fig. 9
Recovery Voltage vs Time With No Restrike.
The Trace is 1.28 ms Long.

Fig. 10
Probability of Interruption vs Current for 4-in. Interrupter.

connected directly across the interrupter, the recovery voltage can be calculated from the value of this resistance and the value of the residual current passing through the saturable reactor during the counterpulse. This current is given, for example, in traces like that shown in Fig. 2. With a resistance of 10Ω and the usual saturable reactor the residual current is so low that the linearly-increasing voltage found after interruption is a factor of 100 or so less than that present without the snubber. The addition of a capacitor of $10 \mu\text{F}$ or more in series with the $10\text{-}\Omega$ resistor retains this beneficial performance and

disconnects the resistor from the circuit as far as dc considerations are concerned.

In spite of the apparently ideal properties of the snubber, its use does not reduce the incidence of restrikes. Figure 11 shows the interrupter voltage observed when the snubber is used. It illustrates the low value of dV/dt after t_1 and shows the reason for the snubber's failure to prevent restrikes, namely, the sudden rise in voltage at t_2 when the reactor runs out of flux. This flux exhaustion, causes the reactor to change from a high to a low impedance and forces the interrupter voltage to rise rapidly towards the sinusoidal voltage present on C_2 . Figure 11 shows that the interrupter voltage actually overshoots that on C_2 before the restrike occurs. This flux exhaustion would be of little consequence if it occurred well after the peak field was reached. For the simple model of restrike used above and for the usual case where t_1 is midway between t_0 and t_2 , flux exhaustion occurs precisely when the peak field occurs. Thus, the snubber can hold the interrupter voltage down to insignificant values at early times, but when the peak field becomes imminent, the reactor switches to a low impedance causing the interrupter field to rise rapidly to values at least as high as those present without the snubber.

Different reactor designs which shift t_1 closer to t_0 can be devised. These allow more time for the snubber to act but do not reduce E_m and, therefore, will not produce fewer restrikes than the present configuration. Circuit modifications which increase C_2 , a , or ϕ_0 will accomplish this improvement.

Fig. 11
Recovery Voltage vs Time Using A Snubber.
The Trace is 1.28 ms Long.

Before completing this section on high voltage problems, two comments should be made. The first is an interesting observation made when using snubbers composed only of large capacitors. Under these conditions the low-current arc created after counterpulse is unstable and extinguishes spontaneously well before current zero occurs. This is a well known effect⁹ called chopping. That any benefit can be made of this feature is not obvious.

Second, a comment should be made about the precision of the above model for restrikes and its subsequent experimental verification. Three assumptions of the model are violated in the experiment to some degree. First, the interrupter is not opened at the assumed time t_1 , but is purposely opened somewhat later to avoid jitter problems. Second, the interrupter voltage does not increase linearly with time as assumed but actually increases sinusoidally, as shown by Fig. 9. These two approximations effect I_m in opposite ways and thus cancel to the degree of precision deemed appropriate. Finally, the breakdown field is not a well-defined quantity but depends upon electrode material and surface roughness. The four interrupters tested had electrodes composed of three different materials, Cu-Bi, Cu-W, and CLR, and their surfaces changed during the tests from the initial machined surfaces to become badly pitted and eroded. Variations in I_m of $\pm 20\%$ were seen which appeared to reflect these differences. The corresponding variation in E_{BD} is $\pm 30\%$. The fact that $S_{BD} \approx 0.5$ mm implies that surface roughness must approximate this value to seriously affect E_{BD} . In most cases, the roughness was much less than this amount. Thus, the $\pm 30\%$ variation in E_{BD} is probably caused by material variations. This is consistent with variations found in the literature.⁸

B. High-Current Problems

When any of the 4-in. interrupters were tested at high currents with large values of C_2 , characteristic failures were observed in which the arc voltage changed its sign at current zero but no recovery voltage of any magnitude developed. Examination of arc-voltage traces like that shown in Fig. 3 shows that these high-current failures are of two types which are sometimes easily separable and sometimes very mixed.

In the first of these, termed popping failures, the electrodes spontaneously open soon after the interrupter current is initiated, and several milliseconds before the normal opening time of the contacts. Sometimes a normal opening cannot be seen; sometimes it is seen but is badly mistimed. When the electrodes pop apart an arc develops which adds a 10 to 20-V step to that part of the trace which occurs before normal electrode separation. Figure 12 shows a trace in which popping is apparent while Fig. 13 shows one where it is absent. There are two ways in which popping can lead to failure. One is mistiming of the normal opening to before t_0 or after t_1 . The other is contact heating so that the resulting hot spots cause reignition of the arc. Both types have been seen. They are particularly common in the interrupter with Cu-W contacts.

The causes of popping have been investigated previously.¹⁰ The current at which popping first appears in the present experiments, that is at 15 to 20 kA, is consistent with quoted values in consideration of the contact closing force of 100 lbs. For such contact forces popping is explained by the opening force created by the rapid evaporation of overheated contact points. Alternatively, at higher contact forces popping can also be caused by purely electromagnetic forces.

Fig. 12
Voltage Across Interrupter Showing A Pop.
The Trace is 5.12 ms Long.

Fig. 13
Voltage Across Interrupter Without Pops.
The Trace is 5.12 ms Long.

Under the conditions of these experiments, the dc-voltage drop across the contacts exceeds 0.5 V. Such large voltages guarantee ¹¹ that the contact points are molten and help to provide an explanation for a second kind of high-current failure. This kind of failure will be called bridge failure. Its characteristics can be illustrated by Fig. 14, which shows a plot of the observed opening time of an interrupter versus the time the counterpulse is triggered. Also shown are the observed counterpulse time, t_0 , and the observed interruption time, t_1 . The experimental values of t_0 and t_1 fall on 45° lines as expected, showing very little jitter. The switch opening time, t_3 , was expected to fall on a horizontal line. At a low current, 2 kA, this is confirmed, but as the current is increased the trace of t_3 becomes more and more distorted. This distortion is caused by an interaction between the initiation of the counterpulse and the opening of the contacts. Measurements of the motion of the electrodes do not reveal such an interaction so it must manifest itself on a microscopic scale in descriptions of the details of the individual contact points. Near 20 kA, the interaction is so significant that there is no setting of the counterpulse which generates a point between the diagonal lines of Fig. 14 corresponding to a successful interruption. Thus, a bridge failure is not a failure in the usual sense, but instead is the inability of the operator to set the switch to open at an acceptable time. An important observation deals with the scatter in the measured values of the opening time. This scatter is of the same magnitude as the scatter in t_0 and t_2 except in the region of strong interaction where it is much larger.

The explanation for the unexpected behavior discussed above is based upon a model for separating contact points which emphasizes the formation of a molten bridge between the contacts. The molten bridge can have two causes, the heating at the contacts due to the dc current passing through them or the transient heating generated as the contacts part and their resistance increases. The

Fig. 14
Opening Time of Contacts Showing Delay Caused by Bridge Formation.

former effect should occur wherever the dc-voltage drop across the contacts exceeds 0.5 V, as in these tests. The latter effect has been examined,¹¹ but is not applicable to this work, for the ECT drastically reduces the current when this effect normally shows up, just before the contacts separate. A useful observation made by these workers,¹¹ however, is that molten bridges can form and be dynamically stable for times as long as 300 μ S.

The interpretation of Fig. 14 is that molten bridges do form with lifetimes as long as 300 μ s from molten material present before contact separation. Their lifetimes depend upon the current magnitude, as that effects the amount of molten material available and thus the bridge lengths. Lifetime also depends upon the exact timing of the counterpulse with respect to the initiation of the bridge. If, for example, the current is counterpulsed to zero well after the bridge is drawn, a large amount of material will be contained within the bridge but the large current passing through it will heat and evaporate it very rapidly. This occurs in region A of Fig. 14 and leads to a short bridge lifetime. In contrast, if the current is counterpulsed just before the bridge is drawn, a large amount of material will again be available for the bridge, but now no current will pass through the bridge to shorten its lifetime. This occurs in region B. As a third example, if the counterpulse occurs well before the bridge is drawn, the molten material may partially freeze and limit the melt available for the bridge and, therefore, its lifetime. Such an event occurs at point C. The opening event plotted in Fig. 14 corresponds to the rupture of the bridge and thus is delayed from the constant mechanical opening time by the bridge's lifetime.

At low currents the curve of opening time is flat because little or no molten material is formed and the small bridge, therefore, has a constant short lifetime. At high currents, a point is reached where the curve of Fig. 14 is discontinuous. No setting of the counterpulse will produce an opening between t_0 and t_1 .

According to our models, both kinds of high-current problems should disappear if the voltage drop across the contacts could be reduced until melting was eliminated. This could be achieved by using contacts of lower resistivity material or softer ones, by using higher closing forces, or by using electrodes of larger area containing more contacts. The 4-in. interrupter with Cu-Bi electrodes has contacts which are softer and of a lower resistivity material than the others. It, therefore, should interrupt higher currents before displaying high-current problems. This interrupter did have superior non-popping performance but was not better than the one with CLR contacts in avoiding bridge failures. The metallurgy of all three contact types is complex enough so that their approximately equivalent performance and the failure of simple explanations for this equivalence is not too surprising.

The 7-in. interrupter and one of the 4-in. interrupters used contacts of the same material, CLR. The larger interrupter exhibited no high-current failures up to 35 kA while the smaller one failed at 25 kA, illustrating the beneficial effect of larger electrodes.

The actuator employed in these experiments did not allow significant increases in closing forces to be made. This modification, however, could be accomplished with other actuators, and should increase the high-current limits of both kinds markedly, by more than a factor of 2.

C. Lifetime and Reliability

The charge transferred through the arc during an ECT interruption is about a factor of 3000 less than that carried during normal interruptions. Electrode erosion is commonly found to be proportional to transferred charge.¹² Thus a reduction of erosion and an extension of electrode lifetime by a factor of 3000 appears to be feasible by using ECT. To test this possibility, a new 4-in. interrupter was subjected to a series of 1200 interruptions at 10 kA and 10 kV. This is about one half of I_m , the maximum interruptible current. For comparison, under normal interrupting conditions, I_m is 7 kA, the switch can interrupt this lower current with a reliability of 90%, and in the process of 1000 cycles will loose about 1 mm from its electrode surfaces by arc erosion.

The ECT tests were very successful. All of the 1200 interruptions were uneventful. The erosion of the electrodes was assessed by disassembling the interrupter and examining the electrode surfaces. The erosion was so insignificant that its features had to be examined under a microscope. The pitting observed was superficial, that is, shallower than the grooves formed by the original machining operation. A photo of one electrode is shown in Fig. 15. The erosion was not quantified but appeared to be roughly consistent with the anticipated reduction of 3000, and, therefore, with an electrode life of millions of cycles.

The interrupters used in the tests described in previous sections were subjected to interruptions in three distinct regions, well-illustrated by Fig. 14. Those in the region between both diagonal lines resulted in successful ECT interruptions and gave essentially no erosion. Those to the right side of

Fig. 15
Cathode After 1200 Successful Interruptions at 10 kA and 10 kV.

both lines gave normal interruptions which included several milliseconds of arcing and moderate contact erosion. Those to the left of both lines gave no interruptions but lead to severe erosion due to approximately 50 ms of arcing. The experiment described here was performed to evaluate the erosion occurring solely during ECT interruptions.

It is our conclusion that erosion of electrodes subjected solely to ECT is so slight that erosion can be eliminated as a primary cause of switch replacement. Other failure modes exist, of course, the most likely being a vacuum leak in the interrupter's bellows or some mechanical or electrical failure of the actuator. To investigate such limits the energy used to drive the actuator's repulsion coils was gradually increased. At double the normal energy a characteristic failure was observed in the mechanical link between the interrupter and the actuator. A few other mechanical and electrical failures were observed with the actuator at elevated driving energies, but these were not of a fundamental nature, being corrected by minor design modifications. The connecting link problem must be solved to progress to significantly higher accelerations. It may require a redesign by the interrupter manufacturer to strengthen the stem of the moving electrode and to provide a better anchor for the connecting link to the actuator.

The ultimate life of the electrodes, bellows, and other vulnerable parts of the interrupter and actuator can only be assessed by a test program considerably longer than the one employed above. The electrode acceleration used will clearly become a crucial parameter in such tests. Low accelerations will require larger initial investments in capacitor banks and saturable reactors, and high accelerations will require larger operating costs for maintenance and replacements of broken parts.

IV. EXTRA COST OF ECT

The ECT has clear advantages over conventional interruption techniques, but these advantages come at a cost of larger and more expensive components. The purpose of this section is to estimate the added costs and to decide if they are significant or acceptable.

A cost is judged to be acceptable if it falls in the range between the cost of conventional counterpulsed mechanical switches and the high cost of semiconductor switches. The most recent application of a comparable conventional mechanical switch is for the ohmic-heating interrupters on the fusion device TFTR. These interrupters are rated at 24 kA and 25 kV. Their overall cost is in the neighborhood of 40¢/kW. A comparable solid state switch system should cost¹³ around \$5 to \$10/kW. This ratio of 10 to 20 in costs allows the ECT lots of room.

In switch systems like the one used on TFTR the costs of the counterpulse bank, the actuator, and the saturable reactor contribute roughly 10% to the overall system cost. These are the critical components whose size and cost would be greatly increased in ECT. Using for comparison the components employed in the tests reported in this paper, the critical components would increase in cost by a factor of 5 using ECT. With further development work on the actuator the cost of these components might be reduced to an increase of only a factor of 3 over that of a conventional switch.

The pitfalls in comparative costing procedures are recognized. Numbers are likely to be off by as much as a factor of 2. Even so the cost penalty of ECT compared to conventional techniques appears to be less than a factor of 2. This is so much less than the factor of 10 to 20 associated with solid-state devices that for many applications the ECT would be the preferred choice.

V. CONCLUSIONS

The early counterpulse technique has been applied to vacuum interrupters and has been found to fulfill all of its promise. Tests were performed on five different interrupters. The maximum interruptible current was increased in all cases by two to three times that obtained by conventional interrupter techniques. Electrode erosion was evaluated after a series of 1200 wholly successful interruptions and was found to be several thousand times less than has been observed by using conventional techniques. The estimated electrode life is now in excess of one million cycles. The special components which are needed to accomplish this improved performance are available, and their costs are reasonable.

The new limits of current and voltage that have been established are well understood. They are not primarily dependent upon the interrupter itself, but are related instead to the closing force exerted on the contacts by the actuator and to the acceleration provided by the actuator during the opening cycle. The sizes of the counterpulse capacitor bank and the saturable reactor also have important roles in determining the voltage limit.

A further extension of the current and voltage limits is a desirable and, we feel, an easily achieved goal. This goal should be achieved in a manner which will minimize cost and maximize life and reliability. This can best be accomplished, we feel, by greatly increasing the contact pressure with a redesigned actuator, by maintaining or moderately increasing the opening acceleration, and by using a larger capacitance bank and saturable reactor.

The major applications for such ECT switches are those that require repetitive operations accumulating 10^5 to 10^6 cycles during their life. Many fusion applications fall into this category.

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