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TITLE: VACUUM INTERRUPTERS USED FOR THE INTERRUPTION OF HIGH DC CURRENTS

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VACUUM INTERRUPTERS USED FOR THE INTERRUPTION OF HIGH DC CURRENTS*

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Summary

Conventional ac vacuum interrupters are being used to interrupt currents in pulsed energy storage systems. They have been tested with dc currents of up to 37 kA. The limit to the current which can be successfully interrupted has been measured as a function of various parameters. Among these are 1) the size of the interrupter, 2) the magnitude of the counterpulse current, 3) the nature and flux rating of the saturable reactor used, and 4) the kind of "snubber" circuit used. Fragmentary data have also been collected on electrode erosion rates and on mechanical failure of the bellows. A description is given of the circuits used in these tests and of the results found for a representative selection of the commercially available domestic interrupters.

More recently efforts have been made to increase the values found for the maximum interruptible current. The techniques used have included connecting interrupters in parallel and operating them in an impressed axial magnetic field. The results of this work are discussed.

Introduction

Many of the approaches to fusion require the storage and transfer of large amounts of energy on a rapid time scale, posing problems not only for the storage systems but for the transfer circuitry. Since the energies involved in reactor size devices are typically 10 MJ and transfer times range from 1 μs to 1 s, the power levels can be extremely high. A major area of concern is the switching required in these systems, particularly interrupting switches. The use of solid state thyristor swiches or "plasma valves" of various kinds is attractive because of their anticipated long life. They are, however, prohibitively expensive when compared to the mechanical switches which are presently employed by the utility industry. These, in contrast, have small prospect of meeting the goal of thousands to millions of operations required for reactor applications. Because of this cost-performance split, unusual switching concepts or extensively modified components which have the potential to be inexpensive and at the same time provide a long operating life should be examined with fusion applications in mind. This paper is a report of such an examination of vacuum interrupters.

During the last several years the Los Alamos Scientific Laboratory has been pursuing research on current interruption with commercial vacuum interrupters. This work arose in connection with the development[1] of an inductive energy storage and transfer system for the Scyllac Fusion Test Reactor (SFTR) and more recently has been directed toward applications in tokamak ohmic-heating (TOH) circuitry.

To meet the requirements of SFTR, i.e., 500-MJ energy storage to be delivered to a load coil in 1 ms, a system of modules was developed. The maximum current and voltage for these modules was set rather arbitrarily at 25 kA and 60 kV. These were felt to be the highest current and voltage that the various components could easily sustain. These limits and the transfer time of 1 ms then determined the module size, 400 kJ. A diagram

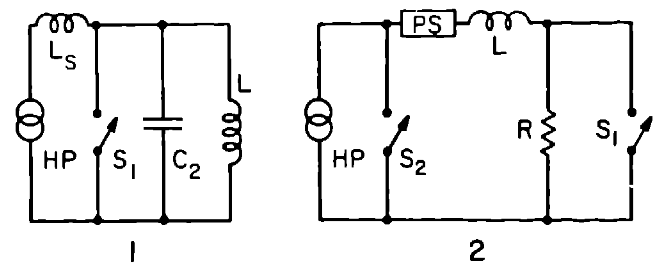


Fig. 1. Simplified circuit of an energy storage and transfer module.

Fig. 2. Simplified circuit of a tokamak ohmic-heating system.

of the circuit of one module is shown in Fig. 1 where L is the load coil, Ls is a superconducting energy storage coil, and HP is a generator which raises the current in Ls and switch S1 to 25 kA in several minutes. At this time switch S1 is opened, transferring the current to the circuit containing L and C2. If L and C2 have the correct values, all of the energy originally stored in Ls is transferred to C2 and then to L in 1 ms. If switch S1 is closed when this transfer has been accomplished, the energy can be held in L as long as desired.

A simplified circuit of a typical tokamak ohmic-heating system is shown in Fig. 2. L is the ohmic-heating coil, PS is a bipolar power supply capable of generating 25 kA or more in L, HP is an energy storage device such as a homopolar generator, R is the "blip" resistor, and S1 and S2 are switches. A complete cycle of operation proceeds as follows. S1 and S2 are initially closed. In a few seconds the power supply ramps the current through L up to 25 kA. S1 is now opened, forcing the coil current to flow through R, generating a high voltage "blip" across R and L. This voltage is coupled to the plasma in the tokamak and serves to initiate the plasma heating. If S1 is now closed and S2 opened, the resonant combination of L and HP will oscillate through a half cycle until the current through L has reversed itself and the plasma current has built to a large value. At this point, S2 is closed and PS is reconnected with the opposite polarity to maintain the current through L and the plasma.

Now one of the most demanding requirements of both of these circuits is that switch S1 must successfully interrupt a current of 25 kA and withstand a recovery voltage of 20 to 60 kV. Vacuum interrupters were selected as the most likely candidate for S1, but since vacuum interrupters were developed for ac uses, little was known about the performance that might be expected of them in these essentially dc applications. Accordingly a special facility was built to test the interrupters and the auxiliary components which might be used with them in a circuit like that shown in Figs. 1 or 2. Complete details of the construction and use of this facility will be discussed by E. M. Honig in a companion paper[2]. The purpose of this paper is to present the progress which has been made on the interrupter test program.

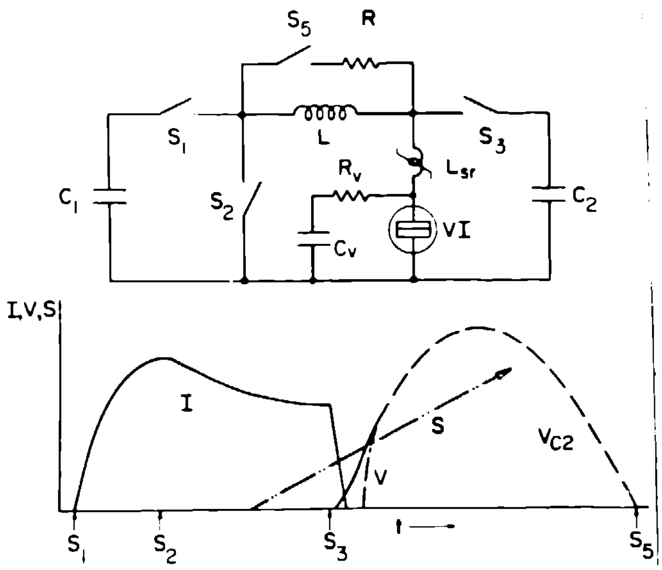


Fig. 3. Simplified test circuit and waveforms of current and voltage.

Experimental Procedures

Figure 3 shows a simplified diagram of the test circuit as well as waveforms as a functions of time of I, the current through the vacuum interrupter; V, the voltage across it; VC2, the voltage across the capacitor bank, C2; and S, the size of the electrode gap. The circuit has been arranged to deliver the current I to the switch under test; to supply a counterpulse, Icp, to the switch to make interruption feasible; and to create a recovery voltage, V, across the switch after interruption. I is generated by discharging C1 through switch S1 into inductors L and Lsr and the interrupter, VI, under test. Switch S2 closes automatically when C1 is fully discharged to maintain I near its maximum value. Icp is generated by discharging C2 through switch S3 into VI. If Icp is greater than I and of opposite sign, the current conducted by VI passes through zero and may interrupt if conditions are favorable. If interruption occurs, the recovery voltage appears across C2 and VI. The energy flowing in the circuit can finally be dissipated in R by closing S5 at the correct time. At the bottom of the waveforms we have labelled the times when the different switches are closed.

Interrupter performance is judged largely from oscilliscope traces. The kinds of signals commonly observed are shown below. Figure 4 shows the current through the interrupter on a long time scale, i.e., 20 ms or so. The quantities referred to in the inset on the photo, i.e., Ip, Io, and dT are respectively the peak current, the current at interruption, and the overall time interval displayed in Fig. 4. Figure 4 shows at to the sinusoidal current rise after S1 closes; at t1, the exponential decay after S2 closes; at t3, the initiation of the counterpulse when S3 closes; and after this, sometimes, the occurence of restrikes.

Figure 5 shows the voltage across the interrupter on a similar time scale. V in the inset is the overall voltage interval displayed, i.e., 250 volts full scale. Figure 5 shows, at to, the cosinusoidal voltage variation corresponding to the sinusoidal current rise; at t1, a transient when S2 automatically closes; at t2, a step in voltage when the interrupter VI opens, followed by an increasing voltage, full of noise, which is the arc voltage; and at t3, the off-scale energy-transfer voltage transient. Not shown are much faster traces which are normally taken to show the details of the counterpulse current and voltage to reveal details of the interruption phenomenon.

The primary purpose of these experiments is to investigate the performance of standard vacuum interrupters, i.e., their reliability of interruption vs cuurent, their operating life, and the dependence of these properties on the variables under our control. These variables include the following important ones:

1. The magnitude of the counterpulse current,
2. The type of interrupter, i.e., manufacturer and size,
3. How it is operated, i.e., speed of opening and electrode spacing,
4. Its temperature,
5. The presence of magnetic fields,
6. The properties of the saturable reactor component, and
7. The properties of the snubber component.

Interrupters made by GE, Westinghouse, and ITT-Jennings have been tested. They are normally mounted on an actuator mechanism which is powered by an electronic driver circuit,[3] which, in turn, can be triggered by one electric pulse to open and a different electrical pulse to close. All of the interrupters are tested for a wide range of values of Io and Icp. Their speed of opening can be varied up to a maximum of about 2.5 m/s by making changes in the driver circuit. The

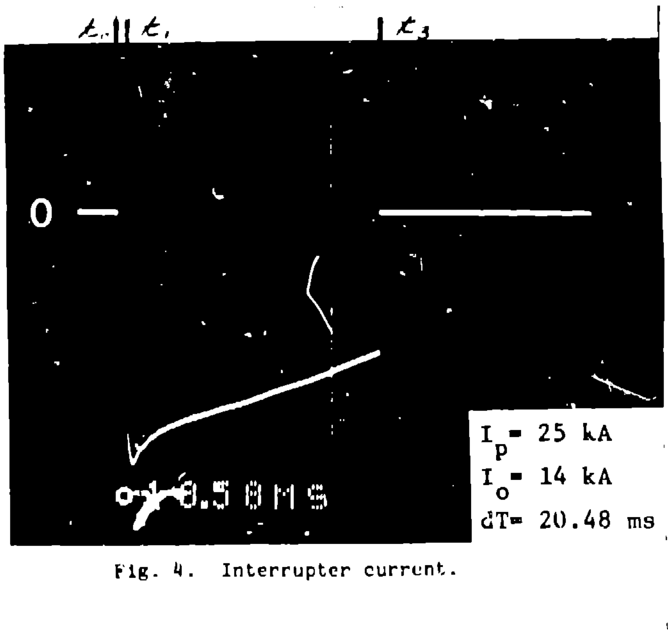


Fig. 4. Interrupter current.

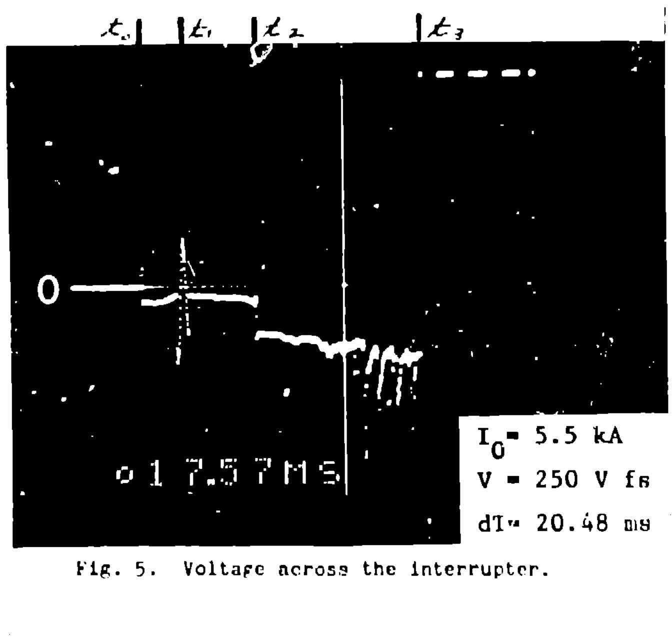


Fig. 5. Voltage across the interrupter.

electrode gap opens to a maximum of about 1.5 cm. We have varied the speed and gap widely, but have chosen 2.5 m/s and 0.7 cm as our standard opening speed and the gap at the time of the counterpulse.

Several auxiliary circuits have been tested which are commonly used to assist in interruption. Examples of these shown in Fig. 3 are the "snubber" circuit composed of Cv and Rv and the saturable reactor, Lsr.

Results

Interruption Limits

A major experimental result of these investigations can be presented in the form of graphs of the reliability of interruption versus Io and Icp. Figure 6 shows such results for a typical 7-in. interrupter without auxiliary circuits of any kind. Figure 7 shows the results for the same interrupter used with a saturable reactor. In these graphs, I and II designate regions of successful interruption and III failures. Lines are drawn which enclose the successful region for a reliability of both 50% and 90%. Figures 6 and 7 both display an upper limit to Io of 22 to 24 kA, but the range of Icp for which the reliability is high is greatly increased when saturable reactors are used. This is found to be the major contribution of saturable reactors. In contrast, no advantage is found from the use of snubber circuits of various configurations.

When the electrode opening speed and the gap at which interruption was attempted were varied, the reliability was found to depend upon gap but not upon speed. A 5 to 8-mm gap is optimum for all of the interrupters tested.

Data were accumulated in this way for most of the domestic, commercially available interrupters and for a few special interrupters. In Fig. 8 all of the data is presented, where for each interrupter Im(50%) and Im(90%), the maximum currents which can be interrupted with a reliability respectively of 50% and 90%, are plotted versus the diameter of the electrode. The data are plotted in this way because of the approximately linear dependence found. As can be seen, there is little variation among the interrupters supplied by different manufacturers.

An interesting feature of the values of Im reported here is that they are a factor of 2 to 3 less than the limits of the same interrupters when they are used to interrupt ac. The measurements of arc voltage and other considerations indicate that the Im value for a given interrupter is that arc current at which anode spots begin to form. It seems likely[4] that the hot areas which are developed on the anode by the constricted arc cause reignition and failure to interrupt under the test conditions of very high dI/dt. In ac use, on the other hand, dI/dt is so low that the anode hot spots can cool significantly before interruption occurs at the natural current zero. Thus, successful interruptions can occur with ac peak currents far above Im.

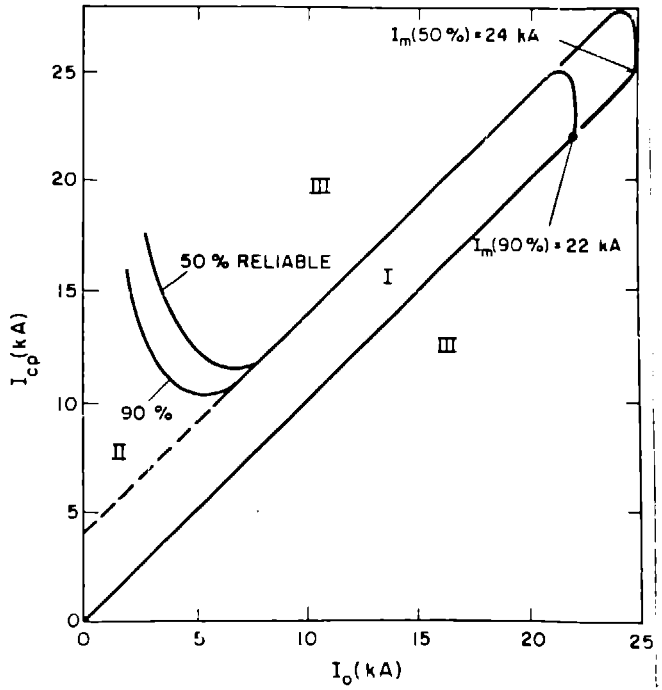


Fig. 7. Reliability versus Io and Icp with saturable reactors.

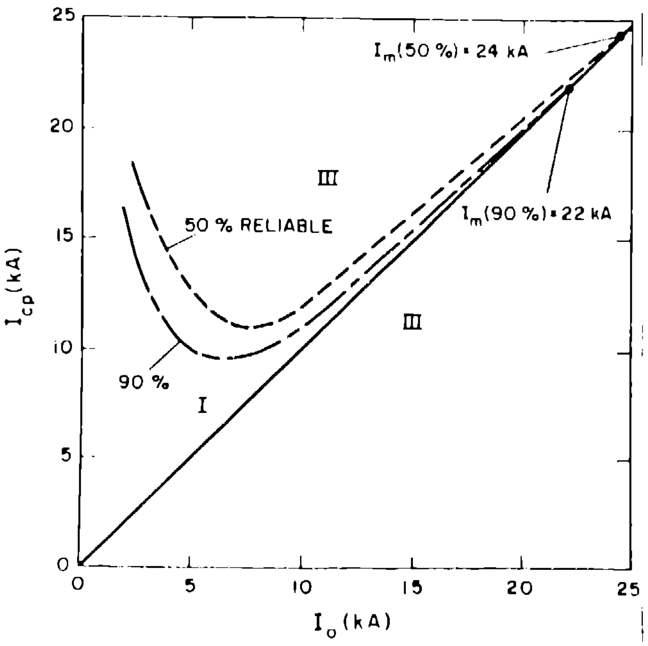


Fig. 6. Reliability versus Io and Icp with no auxiliary circuits.

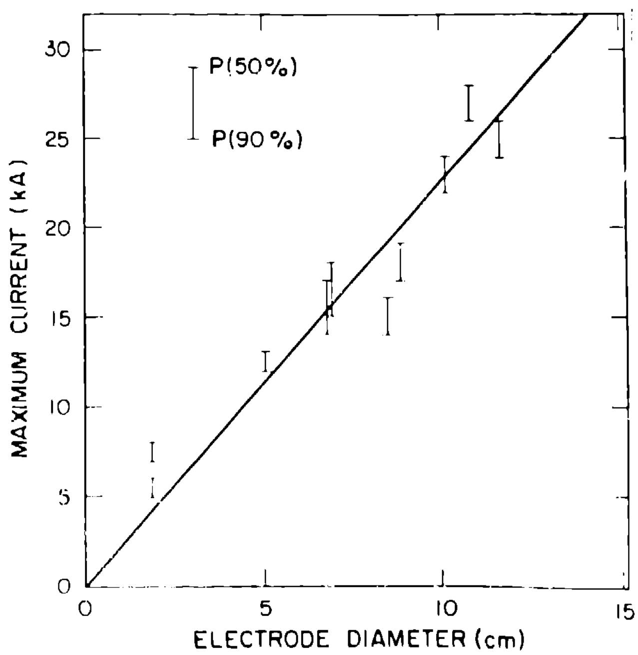


Fig. 8. Im versus electrode diameter.

Life Tests

Since the duty demanded of vacuum interrupters can include thousands or, for some uses, millions of interruption cycles, mechanical and electrical lifetimes are being measured. Three 7-in. interrupters have been opened and closed repeatedly on a standard actuator in a 10-s cycle while carrying no current. The first interrupter was cycled for 74 000 operations, the second 10 400 cycles, and the third 10 900. No mechanical problems of any kind were encountered with the interrupters, but various minor problems occurred with the actuators starting at about 10 000 cycles.

Erosion of the electrodes by the electric arc is expected to be the most serious life-limiting process. Estimates made from experience with ac applications indicate that 10 000 operations might be achieved. Normal testing procedures for reliability give some information about erosion limits, but the mixture of successful interruptions and failures that occurs in these tests gives an overestimate of the erosion that would occur in normal use. Because of this, some special measurements have been made to differentiate between the erosion caused by successful interruptions and by failures. Both erosion rates are found to be quite different in interrupters made by different manufacturers. It seems likely that this is related to the composition of the electrodes. "Bad" electrodes have an erosion rate during successful interruptions of about 0.01 mm per interruption, while "good" electrodes have an order of magnitude less. Thus, the life of bad electrodes is expected to be about 1 000 interruptions and good electrodes 10 000. These results are based upon a relatively small number of interruptions. More extensive measurements are currently being planned.

Improving Standard Performance

A standard interrupter is limited in three major ways.

1. Its maximum interruptible current is less than 25 kA due to anode spots.
2. Its life is terminated by erosion after about 10 000 operations.
3. Its continuous current capability is only about 10% of its interruption limit, i.e., about 2 kA, due to heating.

For fusion applications there are potential uses which exceed all three of these limits. Lately, these limitations are being attacked by us by operating standard interrupters in new ways and by testing new kinds of interrupters. We shall discuss several of these approaches below.

Effect of Magnetic Field

There have been several reports[5] of improvements in the interruption of ac currents through the use of axial magnetic fields. Six interrupters have been tested in our system with an axial field; five with an externally-applied field, and one interrupter with an internally-generated field. This latter interrupter and one of the other five with electrodes of a novel configuration were specially built for us by Westinghouse. The kind of performance found for these interrupters is shown in Fig. 9, where the arc voltage is plotted versus magnetic field with Io as a parameter. The open points are experimental tests which were successful interruptions; the solid points failures. The dotted line roughly indicates the boundary between successes and failures. The maximum value of Io for this interrupter with no magnetic field is 13 to 18 kA; with a 0.4-kG field, it is above 30 kA. At higher fields, it appears that the rating will continue to improve.

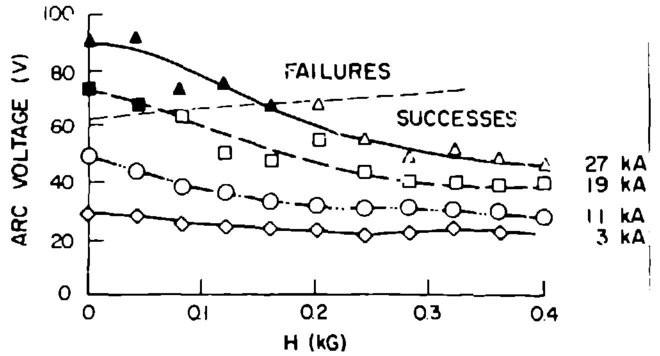


Fig. 9. Effect of axial magnetic fields.

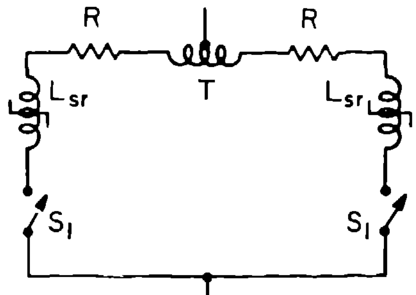
The performance is plotted in this way, i.e., arc voltage versus field, to emphasize the marked changes that occur in the arc voltage because of the field. The field not only reduces the arc voltage but also eliminates the large noise component normally observed, e.g., in Fig. 5. This noise is commonly associated with anode spots. The major effect of the axial field appears to be the suppression of anode hot spots. This phenomenon has been directly observed by others.[6] The reduction in voltage and the absence of anode spots not only increase Im but also are expected to reduce electrode erosion. The magnetic field can be generated by a separate external circuit, by internal coils, or by external coils fed by Io. The versatility and relative ease with which all of these can be done as well as the large improvements seen in Im and assumed to occur in erosion make the use of axial fields very attractive. It presents an obvious means of extending the performance of interrupters in almost any conceivable application. So far, successful interruptions have been achieved with this technique to 37 kA in a single interrupter, which is the limit of the test facility. The test facility limits are being increased to extend the interrupter test levels. The effects of increased axial fields will be explored.

Paralleling Interrupters

Connecting several interrupters in parallel is another way to exceed the limits mentioned above. Figure 10 shows a parallel arrangement of two interrupters with which extensive experiments have been performed. A saturable reactor and resistor are connected to each switch and an autotransformer is connected between them. The resistors, R, are sized to maintain approximately equal current division while the interrupters are both closed. The transformer, T, generates voltages to maintain this equal split during the opening of the switches and their subsequent arcing. The saturable reactors, Lsr, help to extinguish the arcs when the counterpulse is applied. The design and testing of this circuit has proceeded uneventfully. Currents up to the limit of the test system at 30 kA have been reliably interrupted. Extensions of this technique to three or more parallel interrupters appear to be straightforward and will be pursued.

Hybrid Switches

The hybrid operation of two different kinds of switches connected in parallel has been investigated as a means to increase the continuous current rating of a vacuum interrupter to match its interruption limit. A very simple commercially-available, high-current manual switch has been modified to operate in oil with pneumatic actuation. It can open in 30 ms, carry 25 kA continuously, and withstand 90 kV across open contacts. It has been interconnected with a 7-in. vacuum interrupter as shown in Fig. 11, where S1 is the vacuum interrupter, S2 is the oil switch, R is an auxiliary



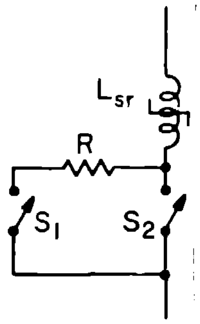


Fig. 10. Parallel connection of interrupters.
Fig. 11. Hybrid connection of interrupters.

resistor of about 1 mΩ, and Lsr is the usual saturable reactor. The purpose of this arrangement is to let S2 carry the current for most of the time, but to open S2, transferring the the current to S1, so that S1 will carry the current while S2 is opening and performing the actual interruption. Two different modes of operation have been investigated where S1 is closed all of the time that S2 is closed but carries only a small fraction of the total current and where S1 is closed only immediately before the interruption.

In the first mode, R was adjusted so that S1 operated within its continuous ratings and carried about 10% of the total current or about 2 kA. When S2 opened, an arc developed in S2 which forced all of the current to transfer to S1 in about 1 ms. This arc caused minor erosion in S2. The final interruption occurred uneventfully in S1 in the usual way.

In the second mode, R was removed and S1 was initially open. It closed only several milliseconds before S2 was opened. The transfer of current to S1 occurred much faster than before because R had been eliminated; but because the electrodes of S1 bounced several times upon closing, some additional arcing and erosion occurred in it.

Either mode of operation of the hybrid switch appears to be entirely feasible. A choice between them will be based upon the relative erosion of S1 and S2 to be determined from further testing.

Early Counterpulsing

Erosion occurs from the time a switch is opened until the time the counterpulse is applied. At counterpulse time the electrode gap must be capable of withstanding the recovery voltage. Erosion could be greatly reduced if the sequence of opening and counterpulsing were reversed, that is, if the counterpulse were used to force the switch current to zero and then the switch was opened. This mode of operation has been used before.[7] It requires accurate timing, a large counterpulse energy supply, a large saturable reactor, and very fast actuator motion. Because of its promise of significant reduction in erosion, work has been started with industry to develop fast actuators for use in testing this mode of operation with vacuum interrupters.

New Switches

A second way to exceed the present limitations of vacuum interrupters is to develop entirely new interrupters especially designed to raise or eliminate these limits. They might, for example, have larger electrodes, have complex electrodes with separate parts intended for the continuous and arcing currents, or have water-cooled electrodes. A cooperative program is underway working with industry to develop improvements such as these.

Conclusions

The properties of conventional interrupters used for the interruption of dc currents have been determined. The important limitations which have been found are being circumvented by parallel connections, by hybrid operation, and by unconventional techniques made possible by very fast actuators. New interrupters are being designed and built by industry which will help to exceed the limits set by present models. It is expected that in the near future the switching requirements of fusion applications will be met inexpensively and reliably by these strategies.

Acknowledgment

The author wishes to express his appreciation to E. M. Honig, who developed the hybrid switch and assisted in its testing, and to Edward Whitaker, who helped with its fabrication.

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