AN EXPLOSIVE OPENING SUPERCONDUCTING SWITCH

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Abstract

A superconducting YBCO tube was tested as an opening switch to demonstrate novel switching concepts for inductive energy storage. The tube was connected in series with a 1.2 mH inductor, and a 4800 μF capacitor bank which was charged to a predetermined level and discharged through the circuit. No measurable dissipation was observed for test discharges of 8 ms duration, with maximum pulse amplitude increasing for each test while the YBCO was superconducting at 77 K. At the highest current pulse maximum of 95 A, the switch was opened by exploding a short length of detonating cord inserted into the center of the tube. The current decreased to zero, and the voltage increased to maximum in approximately 160 μs, resulting in a voltage gain of over 25 for current commutation purposes. The data indicate that high Tc ceramic materials have potential in this application.

Introduction

Two methods are often used to generate high energy pulses. A large capacitor bank may be slowly charged and rapidly discharged using a closing switch to produce a very high current pulse. Alternatively, a current can be slowly increased in a circuit having a large inductor and then interrupted suddenly using an opening switch to generate a very large voltage pulse. There is one advantage to the second approach: a greater energy density may be stored in a magnetic field than in an electric field. In order to take advantage of the latter, a reliable, clean, and fast opening switch is essential.

Many different schemes have been used in efforts to develop switches capable of repetitive high power operation.1 Switches used in inductive energy storage schemes must meet certain criteria.2 Ideally, one would like to see the following properties in an opening switch: The switch should be able to carry large currents for times long enough to establish a magnetic field in an inductor. It must open rapidly to a high impedance state. It must be able to withstand large voltages which will develop after opening. It must recover rapidly to allow repetitive operation.

Superconductors have the ability to carry large currents in the superconducting state, with little or no dissipation, for indefinite periods of time. A laser operated switch using thin film conventional superconductors such as NbN and NbCN has been successfully demonstrated,3 and some of the characteristics of such a switch have been studied.4 Most recently, laser switching has been demonstrated using thin film oxide superconductors.5 These studies however, concentrated more on the demonstration of rapid switching and recovery, which occurred at sub microsecond time scales, rather than on interrupting or transferring large amounts of power. A large open circuit impedance is required for an opening switch to transfer large amounts of power. A superconductor in the normal state typically has resistivities on the order of hundreds of micro-ohm-centimeters making this requirement difficult to meet. The requirements of high impedance in the open state and repetitive operation seem to be incompatible at the present time. If one is willing to relax the criterion that a superconducting switch be repetitive, then the other criteria can be satisfied and an extremely useful device can be made with the advantages of high power densities and easy coupling to superconducting magnetic energy storage devices.

A large open state resistance device may be obtained at the expense of repeatability if one allows the switch to be destroyed in the process of opening. Although explosive opening switches have been successfully utilized for many years, there is room for improvement. When a normal state metal conductor carrying a large current is opened, either by a shaped charge or by a simultaneous series of such charges, undesirable effects are possible. Intense heat buildup can occur during current commutation resulting in conductor melting, or the conductor can arc-over at the points of conductor separation. Either event can cause a decrease in both rise time and amplitude of the voltage pulse, which is a function of the speed with which the switch achieves a high impedance state.

A superconducting ceramic switch has the potential to overcome these difficulties. A ceramic superconductor capable of carrying a large current with little or no dissipation can be shattered with an explosive, or an exploding wire or foil. The brittle nature of the material would result in the sudden fragmentation of the conductor with each small piece in series with other pieces, minimizing the conditions for arc-over, and giving rise to a sudden, high-resistance open condition. All this can be confined to a small volume since superconductors are capable of carrying large current densities.

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Experiment and Procedure

Attaching electrodes to the ceramic material is a problem that has been addressed, and viable solutions ranging from the simple to the complex have been found. We used the following procedure which is not optimum but was sufficient for our purposes. Electrode attachments were accomplished by first painting the contact areas of the ceramic with a metallo organic gold ink. This was allowed to dry and then fired in flowing oxygen using the following time temperature profile: Ramp from room temperature to 100 °C (approximately 5 deg./min), hold at this temperature for about 30 minutes, continue to 700 °C (at 5 deg./min), hold for 30 minutes at this temperature and a very slow cool down (approximately 1 deg./min) to room temperature. The painted areas were then coated with an indium-gallium eutectic alloy which was liquid at room temperature. Both current and voltage leads were made by wrapping copper braid around the treated areas and twisting the ends to physically secure the braid to the cylinder. This mechanical clamping of the braid to the indium-gallium eutectic coated gold ensured good electrical contacts. The current leads were also used to support the YBCO tube in the liquid nitrogen dewar as shown in Figure 1. The dewar was fabricated from two metal pails nested one inside the other, and the intervening space was filled with an expanding polyurethane foam resin for thermal insulation. The result was a sturdy, inexpensive, and expendable container that held liquid nitrogen well enough for our experiment.

The YBCO tube, which served as our superconducting opening switch, was connected in series with an SCR, an inductor, and a capacitor bank as shown in Figure 2. There was no load connected to the circuit, but the configuration is one typically used for high current switch testing of explosive opening metal switches. Since only a principle was being demonstrated to show feasibility, currents were scaled down to levels consistent with the materials available. The samples that were tested in these experiments both carried more than 100 A in other experiments, but for a feasibility demonstration of a superconducting opening switch, this value was considered adequate.

In order to find the maximum amplitude current pulse the superconducting YBCO switch element could carry under these transient conditions without dissipation, the voltage across the switch element was carefully monitored for each current pulse. For each test the individual current pulses were increased in amplitude, reaching a maximum of 95 A for the last attempt. After observing no voltage at microvolt level sensitivities, we were confident that no significant dissipation was occurring under transient conditions at the target current, and connected a voltage divider across the switch element in anticipation of the large voltages expected when the switch was opened at maximum current. The data was subsequently rescaled and plotted to show the actual voltage developed across the switch element.

Results and Discussion

Two tubes were available for testing. Both were tested in exactly the same way. No measurable voltage was noted for either tube under the transient conditions described above. For the first sample we had to rely on estimates of timing and behavior.
Consequently, interesting voltage and current data, occurring as the cylinder shattered, were lost. However, with the timing information from the first attempt, data were obtained on the second. The results are displayed in Figure 3 which shows the current pulse waveform, and Figure 4 which shows the voltage developed across the exploded switch, both with a common time scale. At t=0, the current flow in the primary circuit was initiated by firing the SCR. The current pulse rose to a maximum value of 95 A in 3.9 ms, at which time the explosive was detonated. The voltage across the switch then increased to a maximum of 960 V in 160 μs, and decayed to zero in less than 20 μs.

The detonating cord explodes in times on the order of microseconds. At this instant, an intense pressure front is located in the volume occupied by the explosive, and a shock wave is generated which, because of the intense pressures present during an explosion, propagates outward at velocities greater than the velocity of sound in liquid nitrogen. The velocity of sound in liquid nitrogen has the value of approximately 880 meters per second. At these velocities, it takes the shock wave only microseconds to travel from the center of the tube where the explosive was located, to the cylinder wall a little over one centimeter away. The shock wave shatters the cylinder as it expands radially outward.

The shattering of the cylinder and the resistance increase as the breakup occurs, is seen in Figure 4 to take place over an interval of 160 μs. This is considerably longer than the time it takes for the shock wave to pass through and cause the breakup of the superconducting cylinder. Previous experience suggests that the 160 μs time interval can be significantly shortened by applying a thin plastic foam layer to the outside of the ceramic cylinder. This results in a large acoustic impedance mismatch causing the shock wave to be reflected back into the cylinder instead of passing through it, which should result in a faster opening of the switch.

It is advantageous to switch large currents, as the energy stored in an inductor is proportional to the square of the current. The material used in this experiment was polycrystalline YBCO which had current densities on the order of hundreds of amperes per square centimeter. In order to achieve total currents of interest for a scale up to approximately ten kiloamperes, YBCO rods or fibers
would have to be bundled to carry the required total current. The sensitivity of these materials to magnetic fields is a problem, since the capacity of each fiber to carry current is reduced when it is in the magnetic field of the other fibers.

The hollow cylinder geometry used in our experiments was chosen to minimize the self field of the superconductor. The magnetic field at the surface of a conductor is directly proportional to the current and inversely proportional to the diameter. Consequently, in order to increase the current carried by the switch and still keep the self field low, the diameter must be increased. While this is a possibility, we believe that highly textured oxide superconductors offer more promise for high current opening switches. Highly textured materials are available with high current carrying capabilities as well as the ability to withstand intense magnetic fields, all at liquid nitrogen temperatures. Using these materials a 10,000 A switch could be reduced to a piece of material with a cross section of one square centimeter rather than a hollow cylinder of twenty or more centimeters in diameter.

**Conclusion**

We have successfully tested a polycrystalline YBCO hollow cylinder for use as an explosive opening superconducting switch. The switch opened over an interval of 160 μs while carrying a peak current of 95 A. These conditions resulted in a voltage pulse of over 960 V which would be available to commutate current into a load. The opening time of the switch could be shortened by the addition of a layer of plastic foam on the cylinder surface to provide a greater acoustic impedance mismatch so that more of the shock wave would be reflected back into the cylinder. The use of highly textured materials would result in significant device improvement. Highly textured materials have demonstrated a two order of magnitude increase in critical current density, at high magnetic fields, over the polycrystalline material. This would allow the size of the switch to be reduced. In addition, their fragility would allow the use of exploding wires or foils to open the switch, obviating the need for explosives in certain applications.

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