HIGH TEMPERATURE SUPERCONDUCTING VECTOR SWITCH

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Abstract

A summary of previous results of a high temperature superconducting switch based on the principle of the Superconducting Vector Switch (SVS) is discussed. This switch exploits the anisotropy in electrical conductivities of the high temperature superconductors. Underlying the SVS mechanism is the ability to turn on/off large superconducting currents confined to the CuO_2 planes using lower currents flowing normal to the planes. Recent results using induced pulse currents to turn on/off the switch are discussed.

Introduction

Many superconducting switches have been proposed and tested in the past.[1,2] Switching from the superconducting to normal state is achieved by means of current, heat, or external magnetic field pulses. However, switches based on the high T_c materials may be superior to those based on conventional superconductors in view of their high normal state resistivity, low cooling cost, and anisotropy in conductivity. Of particular interest to the present work is the anisotropy for electrical conduction in the high temperature superconductors (HTSC). In this study, we discuss the feasibility of a switch based on the concept[3] of a Superconducting Vector Switch which exploits this anisotropy.

Principle of Switching Mechanism

The ceramic high temperature superconductors are characterized by the anisotropy in their electrical conduction due to presence of quasi-two dimensional copper oxide planes. As a result, they can support large critical currents in the a-b plane while the critical current normal to the plane is significantly lower. The anisotropy manifests itself especially in single crystalline materials or oriented bulk material. Hence, large superconducting currents flowing in the a-b plane (which we call the conduction current) can be switched off using a small normal current (described as the control current) that exceeds the critical current in the c-direction. This concept is evident from Figure 1, where $J_{c//}$ is plotted schematically against $J_{c\perp}$. We call this control technique "Superconducting Vector Switching" or SVS.[3]

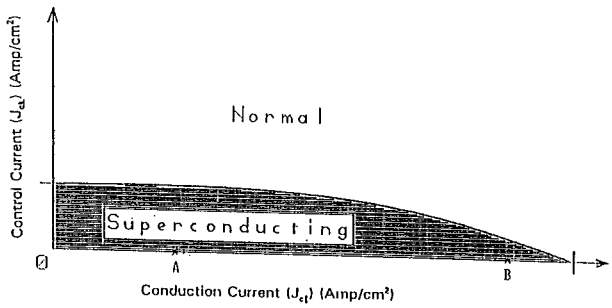

Fig. 1 The schematic plot of conduction current density (in a-b plane) versus control current density (in c-direction) of anisotropic high temperature superconductor. Due to the anisotropy large currents flowing in the conduction plane can be switched off using relatively small normal currents.

Summary of Method & Previous Results

A simple transformer method was used to introduce conduction currents in our HTSC samples. The details of which are discussed in Reference 4. In this method, the superconducting sample, shaped in the form a ring, is mounted inside a ferrite core transformer. An alternating current (I_p) was passed through the primary. The conduction current was induced in the ring by the primary. Two different methods were used to generate the required control current, I_n, in a direction perpendicular to the conduction currents. In the first method, it was induced via a toroidal coil wrapped around the superconducting ring. The second method of creating I_n was to pass a direct current through ohmic contact leads attached to the top and bottom of the ring. Using the above conduction and control currents, the feasibility of a HTSC switch based on the SVS mechanism was demonstrated. A summary of these results is described below.

A series of measurements were performed where the material is switched between normal and superconducting states using the induced and direct control current (I_n). As discussed in Reference 4, the value of the toroidal control current decreased according to the SVS principle as I_c is increased. We confirmed, using direct control currents that at higher conduction currents smaller I_n were required to suppress superconductivity in accordance with the SVS principle.

The following sections describe new results that provide further insight into characteristics of the switching transition.

Present Experiment & Results

The focus of the present tests is to determine the parameters needed to achieve the switching action, and to characterize the properties of both the switch and the high T_c ring during the switching transition. These properties must be determined in order to develop appropriate design tools and guidelines for the switch.

For these tests, the induced currents in the ring are generated using only the primary power windings; thus, eliminating the variables introduced by the control winding. When the ring enters the resistive mixed state prior to complete ohmic condition, currents in the ring dissipate, generating heat and reducing the current present. To minimize these effects, pulsed primary currents were utilized. This permitted dI_c/dt to be as large as possible, minimizing the time available for dissipation to occur. This enabled us to measure the impulse response of the SVS mechanism, and to determine the resistivity of the ring as a function of both time and applied currents.

We adopted a constant current source (rated for 20 amps at 20 volts at a maximum output frequency of 20 kHz) driven by a Wavetek function generator to generate the required pulses. Due to difficulties associated with the bandwidth of the power supply, only the leading and trailing edges of the pulse were used in the early stages of the analysis. The portion of the pulse leading edge that was used proved to be case dependent and ranged from 40 to 330 μs, while the total pulse period was set to 335 milliseconds.

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14. ABSTRACT
A summary of previous results of a high temperature superconducting switch based on the principle of the Superconducting Vector Switch (SVS) is discussed. This switch exploits the anisotropy in electrical conductivities of the high temperature superconductors. Underlying the SVS mechanism is the ability to turn on/off large superconducting currents confined to the Cu02 planes using lower currents flowing normal to the planes. Recent results using induced pulse currents to turn on/off the switch are discussed.

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Two different thicknesses (2.6 mm and 0.6 mm) of the superconducting ring with outer and inner diameters of 1.5 cm and 1 cm respectively were used. The primary power winding had 170 turns while there were 300 turns in the secondary.

Results From Thick Ring

Measurements on the thick ring indicated that in spite of inducing currents up to 2,736 amps (36,480 amps/cm^2) based upon the turns ratio, transition to the fully resistive state was not achieved. Using simple transformer theory, the resistance of the ring was computed in terms of the primary current, secondary voltage, and transformer parameters. The maximum resistance was 25 $\mu\Omega$ (resistivity = 0.5 $\mu\Omega$-cms). This value is very low and comparable to the resistivity of copper at 77 K. Hence, we conclude that the pulsed current densities utilized in this study are insufficient to drive the thick superconducting ring into the fully resistive state.

Results On Thin Ring

In the next series of tests, the same ring used in the previous study was thinned to 0.6 mm in order to support higher current densities. For increasing primary current amplitudes, the secondary voltage characteristics are shown in Figures 2 and 3. We believe that as the induced currents in the ring increases beyond the critical current, the resistance of the ring rises; thus, reducing the supercurrents in the ring. As a result, flux cancellation is incomplete, thus, giving rise to the increased secondary voltages shown in Figure 2. We find that up to a threshold primary current amplitude, the curves qualitatively resemble the results obtained from the thick ring. This behavior of the thinned ring suggests the occurrence of a similar mixed resistance state. However, above a threshold primary current, the characteristics of the secondary voltage are drastically different in comparison to the behavior below threshold. This distinct behavior may reflect the transformation of the ring to the fully ohmic state. These features are illustrated in Figure 3.

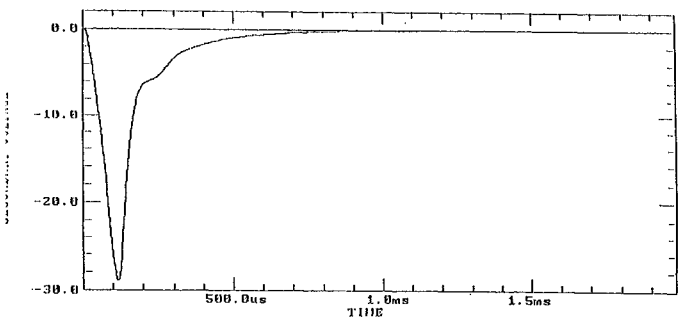

Fig. 2 The plot of the secondary voltage versus time just before the superconducting ring changed into ohmic state.

The final series of tests discussed here employed a new ring and different transformer parameters. The new ring had a minimum thickness of 0.55 mm, and the transformer secondary was reduced to 200 turns, thus reducing its sensitivity. We had overcome our difficulties with our power source, and were able to use data from the entire pulse, thereby enabling us to generate a complete curve of ring resistance versus time. Such a curve is depicted in Figure 4. This curve depicts the transition into the resistive state (peak resistivity = 24 $\mu\Omega$-cm, more than 100 times cryo-copper), followed by a relaxation back into the superconducting state when dI/dt approaches 0 at the top of the pulse. We are now proceeding with analysis to determine the current in the ring as a function of time, which will yield a current versus resistance plot.

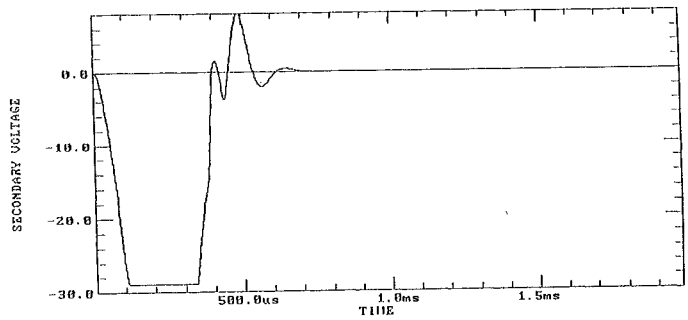

Fig. 3 The plot of the secondary voltage versus time just after the ring transformed into fully ohmic state.

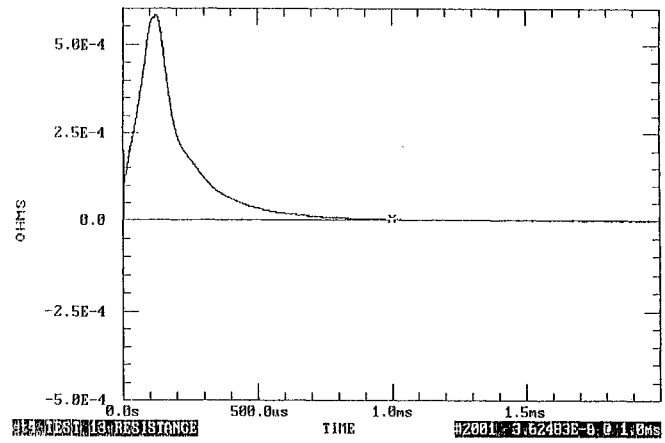

Fig. 4 Ring resistance versus time.

Circuit Element Considerations

In interpreting these results it is important to remember that the superconducting ring is functioning as a component of a circuit element, the SVS. The presence of the ring leads to some unusual properties in the SVS circuit element.

The test apparatus is a complete SVS, with an additional winding (the secondary winding) provided for data collection. In an operational SVS, the primary winding carries the power to be switched. When the SC ring is in the zero resistance state, the effective inductance of the primary winding is very nearly zero (within a factor set by the coupling coefficient). Therefore, the primary winding (ordinarily an inductive low pass filter) functions like an all-pass filter. In this state, the SVS switch is closed. When the SC ring is in a resistive state, either a mixed state or fully normal, the primary winding inductance is greater than zero, and the primary winding functions like a low pass filter. Thus, the SVS switch is partially or fully open. The frequency response pole of the

power winding can be shown to depend upon the resistance and inductance of the SC ring. Given that the resistance of the ring will vary over the course of one cycle, we have the peculiar condition of a power winding whose inductance at a given instant in time depends upon both the instantaneous current being passed, and the AC waveform. So long as the currents induced in the ring are below the critical current level, the resistance of the ring is zero and the currents generated in the ring through inductive coupling are persistent. Therefore, we find nearly perfect flux cancellation and symmetric behavior. However, when the current through the ring is sufficient to induce the beginnings of a resistive state, dissipation commences. dI/dt in the ring then consists of two terms: dI/dt+ which is contributed by the changing current in the control and power windings, and dI/dt- which is contributed by dissipation effects. When this happens, the current in the ring diverges from its original relationship to the currents in the control and power windings. Magnetic flux cancellation becomes imperfect, and the power winding begins to take on the characteristics of an inductor. If the current in the windings stops changing, or changes too slowly, the current in the ring will dissipate down to a level where resistance is zero, and the remaining current will persist. Thus, the effective inductance of the power winding will drop back to nearly zero and the switch will "fall closed." It is therefore clear that the SVS is current, waveform, and frequency sensitive.

Conclusions

In summary, we have extended our previous studies on the SVS to include pulsed currents. This was partially motivated to investigate the effects of high current densities in switching the circuit. Our preliminary results suggest that the switching into fully normal state can be achieved if sufficiently high current densities can be induced into the superconducting ring. These switches may find application in pulse forming networks.

References

[1] D.A. Tidman and Y.C. Thio, "A Superconducting Opening Switch," Technical Note 8706, GT-Devices, Inc., 5705A General Washington Drive, Alexandria VA 22312, August 12, 1987.

[2] O.K. Mawardi, "Cryogenic Switching Systems for Power Transmission Lines," US Patent No. 3,384,762, May 21, 1986.

[3] J. Barber, "High-Speed Superconducting Switch and Method," US Patent No. 4,942,378, July 17, 1990.

[4] B. Chelluri, J. Barber, N. Clements, and D. Johnson, R. Spyker, A.K. Sarkar, G. Kozlowoski; J. Appl. Phys. April 15, 1991.