Superconducting AC/DC Power Conversion using High-Temperature Superconducting Components

David A. Barton and George O. Zimmerman
Boston University, Boston, MA USA

Abstract--The trend towards DC transmission of power, especially when using superconductors, has made the conversion of power from AC to DC and DC to AC a critical element of many electrical systems. We designed and tested a AC to DC and DC to AC converter which used HTS cryotron switches. The superconducting elements were made from yttrium barium copper oxide, and the converter was operated at 77 Kelvin. Both AC to DC and DC to AC conversion has been demonstrated, and the conversion has been shown to be relatively independent of frequency over a wide range. The converter was tested with a current of a few amperes, but is upwardly scalable to thousands of amperes. At larger currents the converter is more efficient as much of the power loss occurs in a separate control circuit which carries a current that does not scale with the amount of current controlled. Significant sources of inefficiencies remain which make the initial device impractical for actual use; however, the proposed improvements in material and design should allow the converter to be used in practical applications and outperform conventional methods of conversion such as thyristors.

I. INTRODUCTION

A cryotron is a magnetically switched superconducting device that was invented by Buck in the early 1950s [1]. A cryotron consists of a superconducting pathway surrounded by a coil. A current less than the critical current is passed through the superconductor. The coil is used to switch the superconductor between its superconducting and normal states by passing a current through the coil. This current creates a magnetic field which causes the critical current of the superconductor to drop below the level of the current already present. (See Fig. 1) [2]

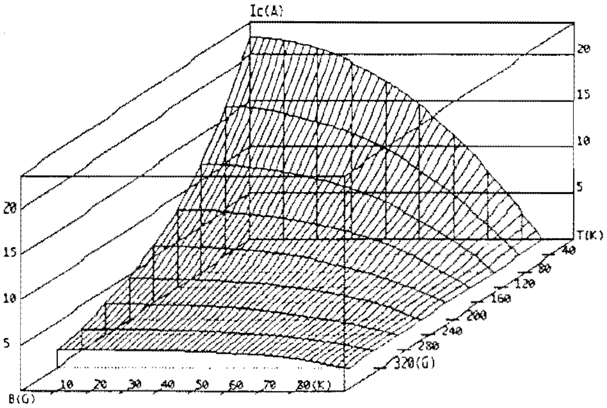

Fig. 1. Relationships of current, magnetic field, and temperature for different superconducting material.

This causes the superconductor to go into its normal state which creates resistance. Fig. 1 shows how critical current, magnetic field, and temperature are related for a typical high-temperature superconductor.

II. RESULTS

A. *Magnetic Testing*

The measured current and voltage characteristics under different levels of the magnetic field in our fiberspun YBCO rods are shown in Fig. 2.

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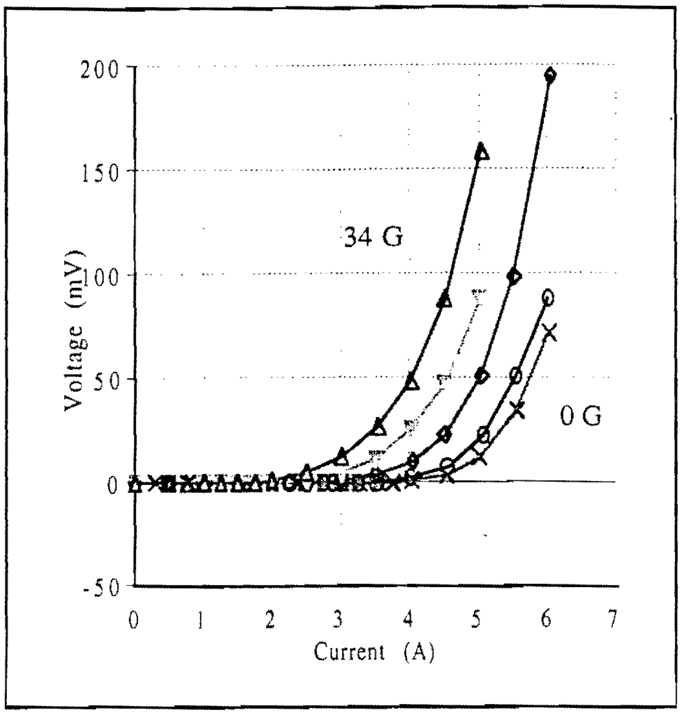

Fig. 2. Current and voltage measurements at magnetic field strengths from 0G to 34G.

One sees that, changing the magnetic field by a small amount can create a significant change in resistance. And as expected the critical current, the highest current at which zero resistance is observed, drops with increasing magnetic field.

B. *Frequency Doubling*

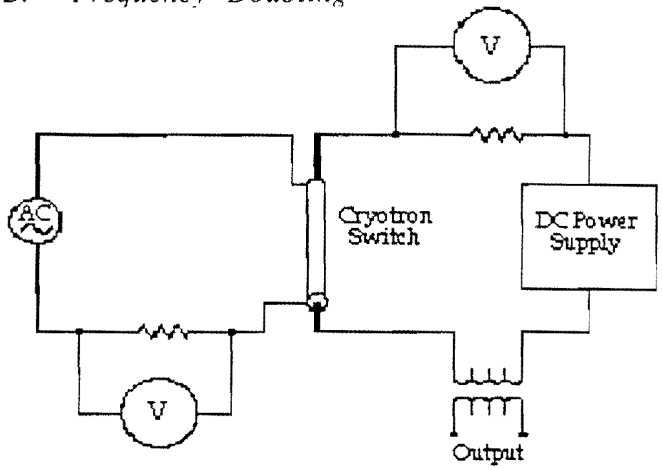

Fig. 3. Set up for frequency doubling using a cryotron circuit..

We performed our initial tests with a single cryotron in the circuit shown in Fig. 3. One interesting effect that we discovered was that it is very easy to double the frequency using a cryotron switch. The circuit was set up as seen in Fig 3., and the output was placed across the transformer.

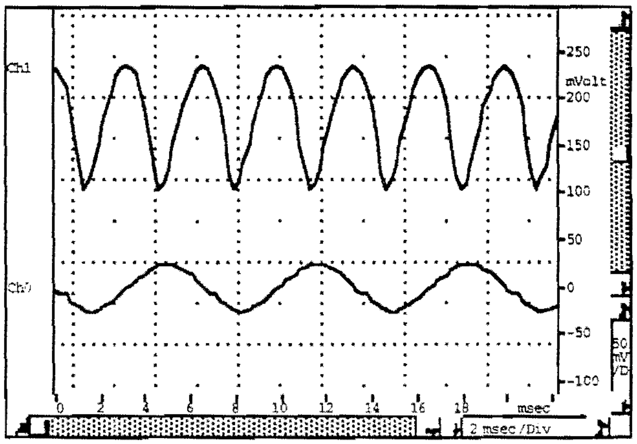

Fig. 4. Frequency doubling results.

Fig. 4 shows an ac output frequency (with a dc offset) at twice the frequency of the control circuit. This doubling of the frequency comes about because of the insensitivity of superconductors to the sign of the magnetic field. The critical current only depends on the strength and the orientation of the magnetic field. So the circuit behaves, in essence, like a fullwave rectifier.

C. *Conversion Design*

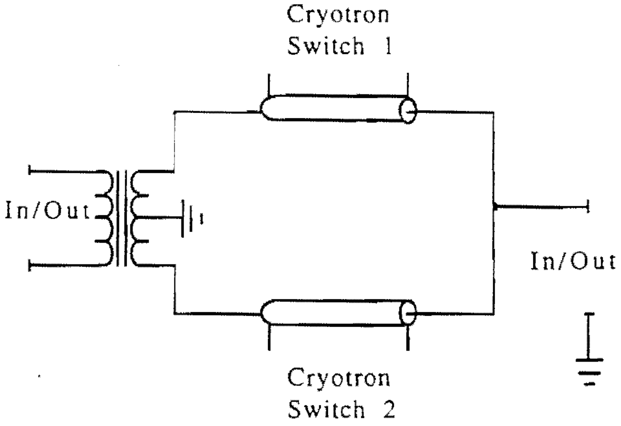

Fig. 5. Design of superconducting converter

The design of the ac/dc converter uses two cryotron switches in parallel as shown in Fig. 5. The signal is fed into the input and arrives at the parallel cryotron switches, which are switched alternately and out of phase with each other between their normal and superconducting states. This causes the current to flow alternately through one and then the other of the branches; thereby switching ac to dc and dc to ac. For ac to dc conversion the input is on the transformer side and for dc to ac conversion the input is on the opposite side.

D. DC to AC Conversion

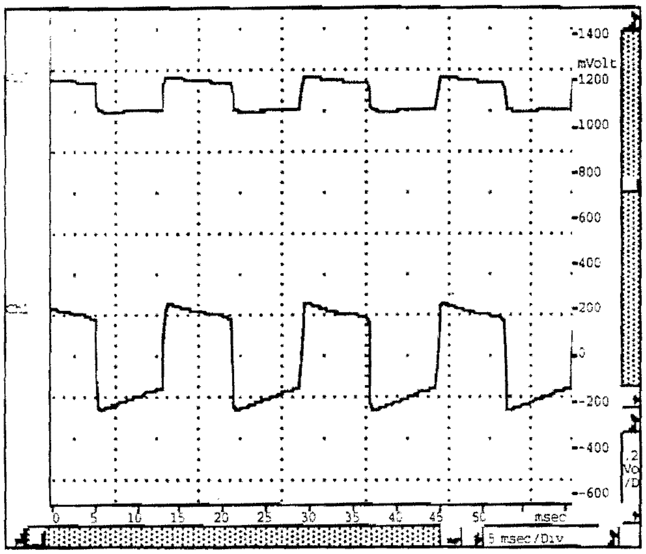

Fig. 6. Results for ac to dc conversion with a load of 511 ohms and frequency of 60 Hz.

Fig. 6 shows some of our results for dc to ac conversion. The load is 511Ω and the switching is done at 60Hz with an input of 4 Amps dc. Channel zero (the upper trace) shows the voltage across one branch of the converter and channel one is the output across the load. The voltage across the converter branch has a large dc portion which arises from two sources. Most of the dc voltage comes from the normal materials in the circuit. The junctions, transformer, and leads are all made from normal materials and as these have some resistance it will keep the closed switch from being completely resistanceless and so some current will flow through the open switch as well, reducing the efficiency. A second source of impedance comes from the load. While this effective resistance can be made small by using a transformer with a high turns ratio, it can never be completely eliminated.

E. AC to DC conversion

The ac to dc converter set up is nearly identical to the dc to ac set up. However, for ac to dc the converter is run in reverse. The input comes in at the transformer side and the load is on the other side. One thing that is very different from the dc to ac case is that the current can circulate in this loop made by the cryotrons and the transformer and never pass through the load. Therefore it is important that the resistance of the open switch be much larger than that of the load. We were not able to achieve this in our experiments. Because of this and also because of unwanted resistance in the circuit we have only minimal ac to dc conversion in our results.

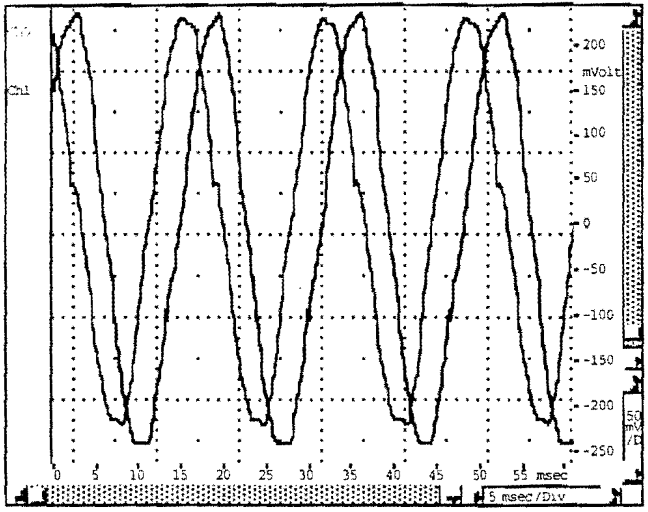

Fig. 7. Results of ac to dc conversion at 60 Hz

Fig. 7 shows two traces obtained using the ac to dc converter, with the voltages measured across the load. In one of the traces the switching is reversed such that the dc current flows in the opposite direction through the load. The load is a tenth ohm resistor and the inputs are 2.2 and 2.4 amps at a frequency of sixty hertz. The two traces are shifted slightly away from the zero level in opposite directions. We were able to achieve approximately a 9mV dc offset for each trace.

A simple calculation shows that in the ideal case (no resistance except in the load and the open cryotron switch) for our circuit the ratio of the power transmitted to the power lost during the conversion is equal to $R_0/4R_L$. Where R_0 is the resistance of the open switch and R_L is the equivalent load resistance.

F. *Frequency Dependence*

The frequency dependence of the converter was also checked. We found that the output was frequency independent with respect to voltage level over a range of 20 to 1000 hertz. While detailed measurements of the frequency response were not taken above 1000 Hz, there was mainly no voltage suppression up to several tens of thousands of Hertz, after which we noticed a decrease in voltage with increasing frequency.

III. FUTURE IMPROVEMENTS

There are several ways in which we hope to improve the efficiency of our converter. One of these is to make as much of the circuit as possible from superconducting materials. This would of course decrease the energy loss due to resistance, but more importantly would dramatically improve the action of the switches and thereby the conversion.

Another improvement we hope to make is to change to a different superconducting material, one more suited to our application. One material that looks very promising is BSCCO. This material is easier to form into wire and is more strongly affected by magnetic fields that YBCO. Both of these characteristics would be advantageous in making a practical and efficient superconducting converter.

IV. APPLICATIONS

Once an efficient superconducting converter was made, it would be a boon in many areas of the high power industry. One example is the area of power transmission. There are several long distance dc transmission lines in existence today, including one across the English channel, one in Malaysia, and one in New Zealand, and more are being built. Also all superconducting transmission lines need to be dc otherwise they will not be lossless. Because nearly all production and consumption of power is in ac mode there is a need for efficient ac/dc converters, and these areas of opportunity will only expand with the growth of the superconductor industry.

REFERENCES

[1] John Bremer, *Superconducting Devices.* Mc-Graw Hill Book Co. New York, 1962.

[2] W. J. Carr, Jr. *AC Loss and Macroscopic Theory of Superconductors.* Gordon and Breach Science Publishers: New York, 1983.