Use of a High-Temperature Superconducting Coil for Magnetic Energy Storage

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Abstract. A high temperature superconducting magnetic energy storage device (SMES) has been realised using a 350 m-long BSCCO tape wound as a “pancake” coil. The coil is mounted on a cryocooler allowing temperatures down to 17.2 K to be achieved. The temperature dependence of coil electrical resistance R(T) shows a superconducting transition at T = 102.5 K. Measurements of the V(I) characteristics were performed at several temperatures between 17.2 K and 101.5 K to obtain the temperature dependence of the critical current (using a 1 µV/cm criterion). Critical currents were found to exceed 100 A for T < 30 K. An electronic DC-DC converter was built in order to control the energy flow in and out of the superconducting coil. The converter consists of a MOS transistor bridge switching at a 80 kHz frequency and controlled with standard Pulse Width Modulation (PWM) techniques. The system was tested using a 30 V squared wave power supply as bridge input voltage. The coil current, the bridge input and output voltages were recorded simultaneously. Using a 10 A setpoint current in the superconducting coil, the whole system (coil + DC-DC converter) can provide a stable output voltage showing uninterruptible power supply (UPS) capabilities over 1 s.

1. Introduction
Superconducting magnetic energy storage (SMES) is a remarkable application of superconducting magnets [1-4]. The potential utilization of high-temperature superconducting materials is especially promising in order to obtain devices showing high efficiency and lifetime for uninterruptible power supplies (UPS) [5, 6]. In this paper, we characterize the physical properties of a Bi-2223 coil used to build such as SMES prototype based to a home-made DC-DC converter and we present test results showing the UPS capability of this system at low temperatures.
2. Experimental setup

2.1. Coil design
The pancake coil is made of 350 m multifilamentary silver-sheated BSCCO tape purchased from Nordic Superconductor Technologies (NST). Characterization of 1 cm long samples have been previously performed [7, 8]. The cooling of the coil is achieved by using a cryocooler (see Sect. 2.2 below). In order to allow for sufficient cooling by conduction, the coil support is made of aluminium. Temperature, voltage and Hall sensors are mounted on the coil.

2.2. Cryogenic device
The superconducting coil is mounted in a home-made cryostat based on a cryocooler from CTI-Cryogenics using a Cryodyne cold head. The cryostat consists of a double wall enclosure with intermediate super-insulation. The inner and outer diameters of the inner chamber are 480 mm and 605 mm respectively. The inner chamber contains the coil fixed on a tray connected to the cryocooler cold head. In order to improve the thermal exchange between the superconducting coil and the cold head, the inner part is filled with helium gas (pressure ranging between 1 and 10 mbar). The vacuum in the outer chamber of the cryostat is around $10^{-7}$ mbar to achieve a sufficient thermal insulation.

Brass current leads are thermally anchored to the first stage of the cold head in order to reduce conduction heat losses between the power electronic circuits and the coil itself. The current lead diameter was calculated in order to keep both conduction losses and Joule losses as small as possible; a diameter of 8 mm was used. The temperature of the tray is monitored with a silicon diode and regulated with two heaters using a Lakeshore DCR-91C controller.

2.3. Electronic circuit
The electronic circuit for the SMES control is based on a 4-MOS transistor bridge allowing for a bi-directional power flow from and towards the superconducting coil (cf. figure 1). The bridge switches at a 80 kHz frequency and is controlled by Pulse Width Modulation (PWM) techniques.

When the energy has to be stored in the coil, the left hand side half-bridge (transistors 1 and 2) switches between the so-called “charge” and “persistent” states. In the “charge” state, the input voltage is applied to the coil, leading to a linear increase of the current, whereas in the “persistent” state, the current flows in an ideally resistanceless loop (cf. figure 1). In practice, the total loop resistance including the superconducting coil, both current leads and the circuit ground is less than 1.5 mΩ at $I=100$ A. The coil current is determined from the magnetic field measured in the center of the coil using a Hall sensor.

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**Figure 1.** Schematic of the 4-MOS transistor bridge. The dotted arrow represents the current loop in the “persistent” state.

**Figure 2.** Superconducting transition of the coil.
When the energy has to be extracted from the coil, the right hand side half-bridge (transistors 3 and 4) switches between the “persistent” state and the “discharge” state. In the latter, the current flowing in the coil is injected into the load. A PI control of the right hand side half-bridge duty cycle allows to feed the load under a constant output voltage.

3. Results

3.1. Superconducting properties
Figure 2 shows the resistance temperature dependence of the superconducting coil. The injected current was 1 A. In self-field, the temperature at which the resistance drops below the noise level is 102.5 K.

Our system allows us to achieve temperatures down to 17.2 K. In order to determine the temperature dependence of the critical current on the whole coil, V(I) characteristics were measured at several temperatures ranging between 17.2 K and 75.8 K. Results are shown on figure 3. All curves can be fitted by power law curves $V = V_0 (I/I_c)^n$ where $I_c$ denotes the critical current determined using a $V_0$ voltage criterion. The $V_0$ value is taken to be 35 mV, which corresponds to a 1 µV/cm electric field. Figure 4 shows the critical current values obtained at several temperatures. As can be seen, the critical current exceeds 100 A for $T < 30$ K. The temperature dependence is roughly linear in the investigated temperature range.

3.2. UPS capabilities
Figure 5 demonstrates the operation of the SMES at 17.2 K and with a persistent current of 10 A (limited value due to the wire diameter between the transistors) in order to supply a stable voltage of 30 V. In this experiment, the input voltage is a 0-30 V square wave at a frequency of ~0.4 Hz.

When the input voltage is 30 V, the excess of input power is used to inject a 10 A current in the coil by chopping the input half-bridge at 80 kHz between the “charge” and the “persistent” states (cf. figure 1). When the input voltage is 0 V, the magnetic energy stored in the SMES is used to provide the power needed to keep the output voltage at 30 V (cf. figure 5, open symbols). With the current used, the time during which the SMES is able to efficiently regulate the output voltage is larger than one second.
Figure 5. UPS capability of the SMES with a persistent current set equal to 10 A. Solid symbols: input voltage, open symbols: regulated output voltage.

4. Conclusions
We have built a prototype of SMES cooled with a cryocooler which allows us to measure the properties of the coil and to carry out operational tests between 17.2 K and room temperature. Resistive transition and V(I) curves have been obtained on the superconducting coil, demonstrating that currents above 100 A can flow below 30 K. An electronic power converter was used to control the SMES operations using a persistent current of 10 A; the system is able to supply a 30 V voltage for more than one second.

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