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Christopher J. Hawley  
hawley@uow.edu.au

Dominic Cuiuri  
*University of Wollongong*, dominic@uow.edu.au

Christopher D. Cook  
*University of Wollongong*, chris_cook@uow.edu.au

Steve Gower  
*University of Wollongong*

Timothy Beales

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Characterisation and Control of a Prototype HTS SMES Device

C J Hawley¹, D Cuiuri², C D Cook², S A Gower², and T P Beales¹

¹SC Power Systems, NSW, Australia
²University of Wollongong, NSW, Australia

chawley@scpowersystems.com

Abstract. A 2.79 kJ prototype high transition temperature Superconducting Magnetic Energy Storage (SMES) device has been constructed. The coil for the prototype has been wound using High Temperature Superconducting (HTS) BSCCO-2223 tape. The refrigeration system is a gaseous helium cold head cryocooler used to maintain the SMES coil at a temperature of 30 K, improving the Ic characteristic of the coil by a factor of 4.7 compared to that at 77 K. The SMES device is capable of supplying a 3-phase load during power interruptions, and has been constructed during a program to develop a larger 20 kJ system aimed at industrial applications.

1. Introduction
SMES devices are potentially an efficient way of storing electrical power to maintain a load during mains voltage sags [1]. The superconducting coil itself has a near loss-less current path and is very compact. SMES systems require no maintenance over many years and are environmentally friendly when compared with equivalent battery storage systems. This paper deals with the design of all the major components of a HTS SMES. In particular, this paper briefly discusses the experimental characterisation of the coil, and cryogenic system. Of particular interest is the design and construction of the Power Control Circuit (PCC), and this is the major focus of this paper. The PCC has a control algorithm designed to monitor the mains voltage and supply the load during voltage sags with a virtually instantaneous response characteristic.

This paper presents the design of the PCC and the characterization of the final PCC prototype. Aspects such as the SMES system energy storage, delivery capabilities and harmonic analysis are also described.

2. Coil and Cryogenic System
The HTS coil was designed to use BSSCO-2223 HTS tape in an air-cored coil arrangement. The coil was a solenoid and the former made from welded copper plate and tube. The BSSCO-2223 tape used had a nominal critical current (Ic) of 40 A at 77 K in zero perpendicular field specified by the supplier. By estimating the maximum perpendicular magnetic field strength to be 695 mT using Finite Element Modeling (FEM) and assuming a final operating temperature of 25 K, the effective Ic of the coil could be predicted using the relationship determined from experimental characterization of the tape. Two tapes were wound in parallel to increase the Ic, and the net result was a predicted effective Ic of 140 A at 25 K. The resulting coil design is summarised in Table 1.
Table 1. Design parameters for HTS coil.

| Parameter               | Value          | Parameter                             | Value   |
|-------------------------|----------------|---------------------------------------|---------|
| Inner Diameter          | 0.380 m        | Critical Current in Field at 25K      | 140 A   |
| Outer Diameter          | 0.436 m        | Maximum Perpendicular Field           | 695 mT  |
| Height                  | 0.116 m        | Inductance                            | 0.285 H |
| Tape Length             | 2000 m         | Energy Stored                         | 2.79 kJ |

The cryogenic system chosen for the prototype was a gaseous helium conduction cooling system, rather than the conventional LN2 bath. The main reason for this being that the gaseous helium system has the capability to cool the cryogenic environment to a temperature in the order of 10 K, whereas a LN2 bath is only capable of achieving 77 K (66 K under reduced pressure).

![Figure 1. HTS coil fitted into cryostat with bell removed.](image1)

![Figure 2. V-I curves for SMES coil obtained experimentally at 30 K and 77 K.](image2)

The cryocooler system was a Leybold 120T cold head supplied by a Leybold 6000 gaseous helium compressor. The cryostat was custom designed to utilise the 38 W of cooling power supplied by the cryocooler. The cryostat design housed the SMES coil in a vacuum chamber, using radiation baffles, super insulation wrapping and a LN2 buffer to reduce radiative heat loss. A photo of the SMES coil inside the cryostat is shown in Figure 1. The HTS coil former was placed directly on the copper cold plate to provide a direct thermal contact with the cryocooler cold head.

From the experimental measurements shown in Figure 2, the \( I_c \) values of the coil for 77 K and 30 K were found to be 19.1 A and 90.2 A respectively. These \( I_c \) values are much less than originally predicted. There were two reasons for this. Firstly, the cryostat was intended to operate at 25 K but was only capable of maintaining 30 K. Secondly, the number of joins present in the coil winding were greater than expected. This was caused by manufacturing constraints which are likely to afflict most practical SMES implementations. An additional and valuable lesson arising from coil testing showed that the coil design and subsequent prototype did not achieve the required specifications primarily because of inadequate thermal paths from all conductors to the cooling plate. The unfavourable characteristics exhibited by the coil and the lack of resources required to build a replacement resulted in a conventional copper inductor bank being used to complete the testing of the PCC.

3. PCC Design and Characterisation

The PCC configuration chosen for the SMES system incorporated a Voltage Sourced Inverter (VSI) placed in series between the source and the load. The circuit layout is shown in Figure 3. The advantages of placing the PCC in series with the mains are that detection of voltage sags is less complex in comparison to a parallel system, and the DC link bus capacitors provide a small buffer against voltage sags, compensating for any lag in reaction time of the SMES inductor and associated circuitry.
Of particular interest in this paper is the chopper and its control algorithm, primarily because it is the component responsible for the charge and discharge of the coil and the maintenance of voltage level at the load. The control algorithm must implement three modes of operation for the chopper; charge, discharge and steady state, these are represented in Figure 4 [2]. During steady state operation (where the mains supply is within normal operating limits), the coil current waveform was observed and it was shown that the current controller was able to maintain the current at the specified level. For example, the controller was used to set the current to 4 different levels: 10, 20, 30, and 40 A. The current waveform could then be observed over a range of nominal values, as shown in Figure 5.

The other waveforms (AC input, AC Output and DC voltages) were also measured during steady state conditions, with the system connected to a 1.06 kW per phase lagging load; in particular the AC output voltage waveform was analysed to determine the noise level generated by the SMES. The result of a Fast Fourier Transform (FFT) operation performed over 25 cycles sampled at a rate of 10 kHz and integrated over 20 Hz is shown in Table 2. The powers were then calculated as a percentage of the total power of the signal over the entire frequency range. These were found to be within relevant standard acceptable levels [3]. The operation of the SMES PCC during the sag event condition, i.e. when a voltage sag event occurs eventually reducing the DC bus voltage to less than the specified minimum value, was also verified. This test demonstrates the ability of the PCC to deliver the available energy in the coil to the load whilst maintain the DC bus voltage. The 100% depth sag experiments were performed by switching off the AC power supply to the SMES. The coil current was set to nominally 30 A and the minimum voltage trigger was set to 15% to provide a practical observation of the coil current being discharged while supplying the load.
Table 2. Harmonic power of output voltage.

| Harmonic | Power (%) |
|----------|-----------|
| DC       | 0.02      |
| 1        | 95.10     |
| 2        | 0.04      |
| 3        | 0.03      |
| 4        | 0.01      |
| 5        | 0.01      |
| 6        | 0.01      |
| 7        | 0.00      |
| 8        | 0.01      |
| 9        | 0.01      |
| 10       | 0.02      |
| 11       | 0.00      |

Figure 6. DC bus voltage.

Figure 7. DC coil current.

Figure 8. AC output voltage.

It can be observed from Figure 6 that as DC bus voltage passes below the 15% level, the current from the coil (Figure 7) is discharged to the bus to drive the voltage back up to 100%. The energy storage of the prototype system is relatively small, and in this embodiment it has the ability to supply the output load for 27 ms before dropping below the allowable voltage level. The last peak and gradual decline of the voltage is due to the capacitance on the DC bus. This is also reflected in the AC line to line output voltage, shown in Figure 8.

4. Conclusions

A SMES with solenoid coil was designed, built and tested. The coil’s performance of the constructed coil did not match the initial specification, for reasons discussed in Section 2. As a result of this process, new design techniques were developed to account for the number of joints likely to occur in practice, and the thermal difficulties involved in achieving homogenous cooling of all coils where a cold head is the only heat sink available. The PCC performed as designed by extracting all the energy from the SMES while maintaining a 3 phase AC waveform with acceptable harmonic content into a typical industry lagging power factor load.

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