University of Wollongong

Research Online

Faculty of Informatics - Papers (Archive)

Faculty of Engineering and Information Sciences

1-6-2005

# Design and preliminary results of a prototype HTS SMES device

Christopher J. Hawley
hawley@uow.edu.au

S. A. Gower
*University of Wollongong*

Follow this and additional works at: https://ro.uow.edu.au/infopapers

Part of the Physical Sciences and Mathematics Commons

Recommended Citation
Hawley, Christopher J. and Gower, S. A.: Design and preliminary results of a prototype HTS SMES device 2005.
https://ro.uow.edu.au/infopapers/2

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

# Design and preliminary results of a prototype HTS SMES device


## Abstract

The University of Wollongong (UOW) has developed the design for a 20 kJ high transition temperature Superconducting Magnetic Energy Storage (SMES) device, and constructed a nominally 2.5 kJ prototype. The coil for the prototype was wound using High Temperature Superconducting (HTS) BSCCO-2223 tape. It was refrigerated to 20 K using a gaseous helium cold head cryocooler. The SMES device has been constructed as a prototype for a larger commercially realizable system, and hence is capable of supplying a 3-phase load during voltage sags or short (s) power interruptions. This paper discusses the modeling and design of the electromagnetic and thermal aspects of the coil, the Power Control Circuit (PCC), current leads and cryogenic system. Also presented are preliminary results of the SMES coil, cryogenics, and system energy storage and delivery capabilities.



## Keywords

Energy, high-temperature, magnetic, storage, superconducting


## Disciplines

Physical Sciences and Mathematics


## Publication Details

This article was originally published as: Hawley, CJ, Gower, SA, Design and preliminary results of a prototype HTS SMES device, IEEE Transactions on Applied Superconductivity, June 2005, 15(2),1899-1902. Copyright IEEE 2005.



This journal article is available at Research Online: https://ro.uow.edu.au/infopapers/2

# Design and Preliminary Results of a Prototype HTS SMES Device

C. J. Hawley and S. A. Gower

***Abstract*—The University of Wollongong (UOW) has developed the design for a 20 kJ high transition temperature Superconducting Magnetic Energy Storage (SMES) device, and constructed a nominally 2.5 kJ prototype. The coil for the prototype was wound using High Temperature Superconducting (HTS) BSCCO-2223 tape. It was refrigerated to 20 K using a gaseous helium cold head cryocooler. The SMES device has been constructed as a prototype for a larger commercially realizable system, and hence is capable of supplying a 3-phase load during voltage sags or short (<1 s) power interruptions.**

**This paper discusses the modeling and design of the electromagnetic and thermal aspects of the coil, the Power Control Circuit (PCC), current leads and cryogenic system. Also presented are preliminary results of the SMES coil, cryogenics, and system energy storage and delivery capabilities.**

***Index Terms*—Energy, high-temperature, magnetic, storage, superconducting.**

## I. Introduction

THE term power quality refers to the to maintenance of near perfect sinusoidal voltage waveforms for power distribution systems [1]. Distortion of the sinusoidal wave can occur as a result of the introduction of harmonic distortion, fault currents, voltage sags, voltage swells, power interruptions or resonance into the system.

Voltage sags, defined as a transient reduction in the rated AC voltage of a line with a duration of less than one second, are one of the most important power quality issues of concern to end users of electricity [1].

Momentary interruption or significant reduction in the line voltage of a system can cause sensitive equipment to fail or shutdown. This issue is of particular concern to industrial manufacturers who run continuous processes or consumers who require 100% reliability for electronically sensitive applications such as server farms.

A range of power conditioning devices have been developed that are capable of allowing a load to ride through a voltage sag or even complete power interruption. These include motor-generator sets, constant voltage transformers, static voltage compensators, tap changing regulators and uninterruptible power supplies.

This paper details the design and manufacture of a HTS SMES device. Other HTS SMES designs have been developed in the US by American Superconductors [2], and are in progress in Germany [3] and Korea [4].

Manuscript received October 3, 2004. This work was supported in part by the Australian Research Council SPIRT grant and Metal Manufactures.

The authors are with the School of Electrical Computer and Telecommunications Engineering (SECTE) at the University of Wollongong (UOW), NSW 2522, Australia (e-mail: hawley@uow.edu.au; steveg@uow.edu.au).

Digital Object Identifier 10.1109/TASC.2005.849328

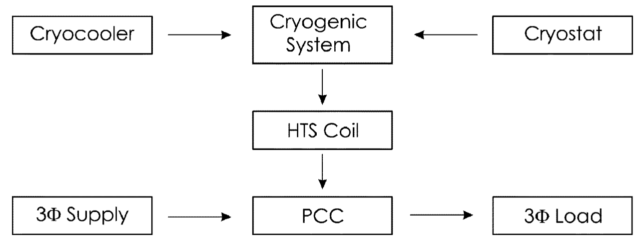


Fig. 1. Block diagram shows the components of the SMES system and their interaction.

## II. Design Overview

The design of the SMES system can be represented as several components that must be integrated to make up the whole system. Each component was designed to meet certain specification criteria in order to obtain a predefined level of performance and also improve the performance of the interdependent components. In this paper, these components are identified as the cryogenic system, the HTS coil and the PCC. The interaction of these components is shown schematically in Fig. 1.

## III. Cryogenic System

The cryogenic system was designed to allow the HTS coil to operate at a stable temperature of 25 K via the conduction cooling method. The cryogenics system consists of two components, the cryocooler and the cryostat. The cryocooler chosen was a Leybold 120T cold head supplied by a Leybold Coolpak 6000 gaseous helium compressor. This arrangement was specified to provide approximately 38 W of cooling power at a temperature of 25 K.

The cryostat was designed to house the coil in a vacuum chamber, using radiation baffles, super insulation wrapping and a LN2 buffer to reduce radiative heat loss. A line drawing of the cryostat design is shown in cross-section in Fig. 2.

The HTS coil former was placed directly on the copper cold plate so as to provide a direct thermal contact with the cryocooler cold head. The installation of the finished coil with the vacuum jacket removed is shown in Fig. 3.

The chamber inside the cryostat was pumped down to a pressure of 15 Pa, using a combination of a rotary roughing pump and a turbo molecular pump (this was prior to cooling and the cryo-pump effect reduced the pressure further). The chamber inside the cryostat was quite large, and the thermal mass of the copper in the design also quite substantial. However, the combination of the compressor and the 18 liter LN2 reservoir resulted

1051-8223/$20.00 © 2005 IEEE

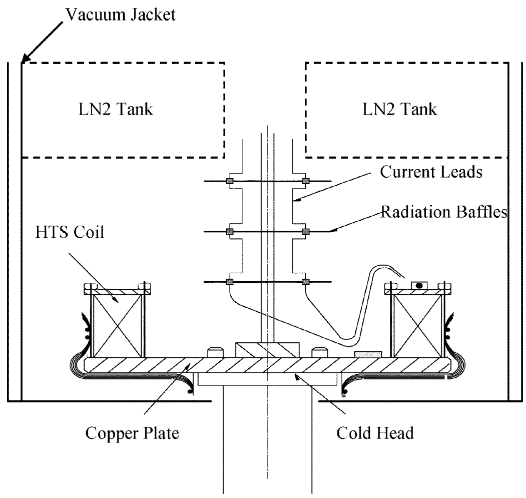


Fig. 2. Line drawing shows cross section of middle of cryostat. The placement of the radiation baffles and cold head are identified.

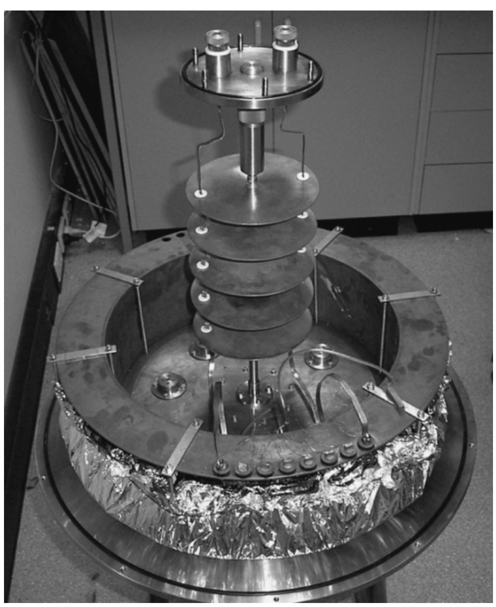

Fig. 3. Photo of actual HTS SMES coil installed in the cryostat, with the upper bell removed.

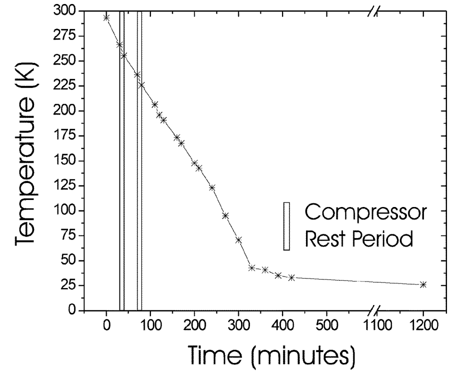


Fig. 4. Plot of temperature versus time of SMES cryostat chamber during cool down from 300 K to minimum 23.8 K. Compressor rest periods have been highlighted with temperature measurements made either side.

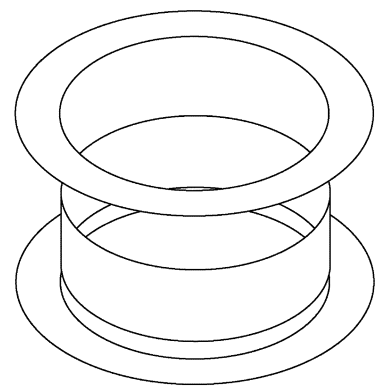

Fig. 5. Assembly drawing showing the design of the former in three parts, the center piece made of fiberglass resin and the two outer copper sleeves.

TABLE I
SMES COIL DESIGN CHARACTERISTICS

| Parameter | Value |
|---|---|
| Inner Diameter | 0.380 m |
| Outer Diameter | 0.436 m |
| Height | 0.116 m |
| Tape Length | 2000 m |
| Critical Current in Field at 25K | 120 A |
| Maximum Perpendicular Field | 695 mT |
| Inductance | 0.345 H |
| Energy Stored | 2.48 kJ |

Table shows parameters used in design and modeling phase of the coil and estimated resultant energy and critical current values.

in the coil being cooled to a minimum temperature of 23.8 K within 17 hours on the first run. The first cool down was conducted conservatively so as to not overheat the compressor. Subsequent cool downs have improved this time to less than 9 hours. Fig. 4 gives the temperature inside the chamber as a function of time and is representative of the typical cooling curves obtained.

It should be noted that temperature readings were taken either side of the rest periods and the temperature continued to fall even whilst the compressor was switched off. This demonstrated the thermal inertia in the system during cooling that stabilizes once a minimum temperature is reached.

Whilst the minimum temperature value was found to be 23.8 K, it was observed that the temperature rose to 30.4 K when the current leads were connected to the power supply whilst conducting the current-voltage (IV) tests.

## IV. HTS COIL

The HTS coil was designed to incorporate BSSCO-2223 HTS tape and a former in an air-core coil arrangement. The coil was designed in a solenoid fashion, and the former designed in three pieces. The center of the former, as shown in Fig. 5, was built from a fiberglass resin to minimize any magnetic coupling inside the center of the coil field, and the two sleeves manufactured from copper to aid with heat transfer to the cold head.

The coil itself was designed using Finite Element Modeling (FEM) analysis, by which the magnetic field strengths, inductance and electromagnetic losses could be predicted. The design characteristics for the coil are shown in Table I.

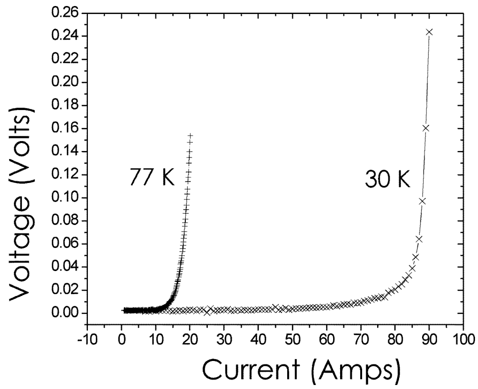


Fig. 6. IV curves for SMES coil obtained experimentally at 30 K and 77 K.

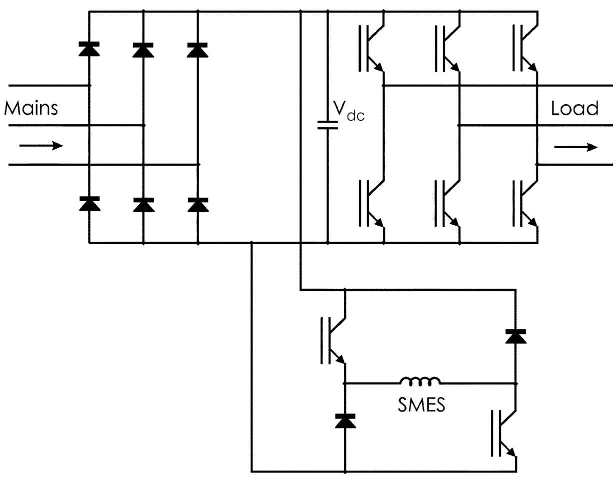


Fig. 7. Circuit diagram representation of SMES PCC. The diagram identifies the SMES coil, mains supply, load, and DC link bus.

The BSSCO-2223 tape used had a nominal critical current $(I_c)$ of 20 A (@77 K), by estimating the maximum perpendicular magnetic field strength to be 695 mT (using FEM) and assuming a final operating temperature of 25 K, the effective $I_c$ of the coil could be predicted using the relationship determined from experimental characterization of the tape. The coil was wound with two tapes in parallel to increase the predicted effective $I_c$ to the specified value of 120 A (@25 K).

The coil was then tested using a four-wire contact IV method with the threshold voltage set to $1\ \mu V/cm$ to verify the design. The experiment was conducted in a LN2 bath and then replicated at 30 K so that the ratio between the $I_c$ values could also be observed. The resulting IV curves are shown in Fig. 6.

It was found and can be seen from Fig. 6, that the $I_c$ value of the coil for 77 K and 30 K was 19.1 A and 90.2 A respectively. The ratio between the two values was 4.7:1, which is greater than the 4:1 ratio predicted. However, the $I_c$ was lower than expected and reduced the energy storage available to 1.39 kJ.

## V. Power Control Circuit

The PCC is an integral part of the design of any SMES system. The PCC must be able detect faults in the mains power then discharge the stored energy in the coil to the load at a controlled rate and within a specified period. It must then recharge the coil from the mains once the fault event has passed.

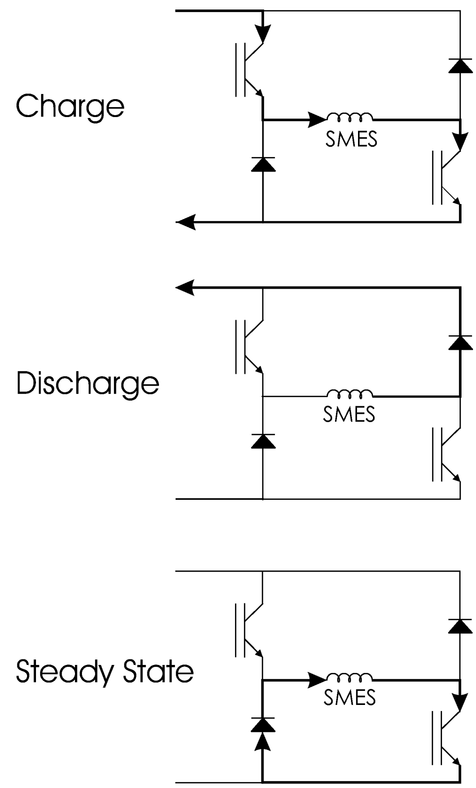


Fig. 8. Diagram shows the three different modes of the chopper control.

The PCC configuration chosen for the SMES system incorporated a Voltage Sourced Inverter (VSI) placed in series between the source and the load. The layout is shown in Fig. 7.

The advantages of placing the PCC in series with the mains are that detection of voltage sags is less complicated than having 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.

The inverter and all other circuitry were rated to 300 A, 1200 V to cater for the eventuality that the coil may be upgraded in the future. In addition to this, running the switching devices at much less than their rated current reduces the forward voltage drop across the devices, and hence the losses incurred. Experimental studies have been conducted into further reducing the losses across semiconductor devices using cryoelectronics [5] or HTS persistent mode current switches [6].

The operation of the SMES PCC and the behavior of the coil were modeled using the power systems modeling software PSCAD. In particular the behavior of the coil in response to the control the chopper was modeled in three different modes; charge, discharge and steady state. A graphical explanation of these modes is shown in Fig. 8.

The PCC was designed to limit any voltage sags for a period of up to 1 s depending on the depth of the sag. The graph in Fig. 9 shows the modeled DC link voltage and SMES current response to a voltage sag that has a depth of 30%. It can be seen that when the sag is initiated at 0.2 s, the SMES current begins to fall to maintain the DC link voltage to within 5% of the nominal supply voltage. The presence of the DC link capacitance ensures that the DC voltage does not fall below 95% whilst the SMES inductance is switched in.

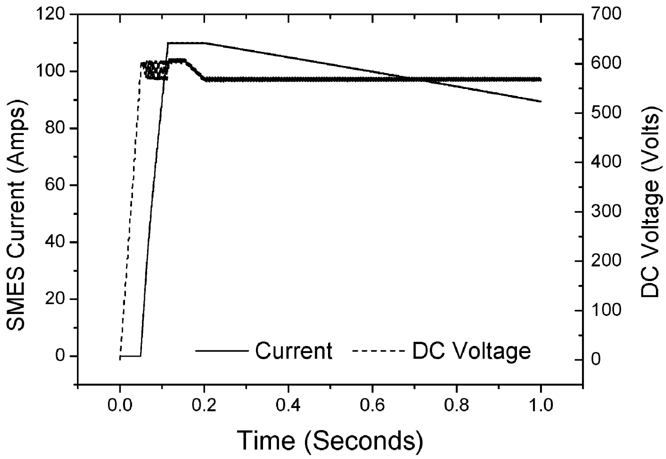


Fig. 9. Graph of DC link voltage and SMES current modeled in PSCAD.

## VI. Conclusion

A prototype HTS SMES coil and cryogenics system has been built. The control electronics enables the coil to discharge energy to a 3-phase AC load. The components of the system have been completed and the coil has been tested at 30 K, full integration of the electronics with the coil will be completed by the end of 2004.

## Acknowledgment

The authors thank F. Darmann and T. Beales from Australian Superconductors for their help in designing the cryogenics, M. Carapic and R. Fitzgerald for their assistance in designing the coil former, and S. Perera for his guidance in setting up the PSCAD model.

## References

[1] C. Radhakrishna, M. Eshwardas, and G. Chebiyam, "Impact of voltage sags in practical power system networks," in *Proc. Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, vol. 1, 2001, pp. 567–572.

[2] S. S. Kalsi, D. Aized, B. Conner, G. Snitchier, J. Campbell, R. E. Schwall, J. Kellers, T. Stephanblome, A. Tromm, and P. Winn, "HTS SMES magnet design and test results," *IEEE Trans. Appl. Supercond.*, vol. 7, pp. 971–976, 1997.

[3] R. Kreutz, H. Salbert, D. Krischel, A. Hobl, C. Radermacher, N. Blacha, P. Behrens, and K. Dutsch, "Design of a 150 kJ high-Tc SMES (HSMES) for a 20 kVA uninterruptible power supply system," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1860–1862, 2003.

[4] K. C. Seong, H. J. Kim, S. W. Kim, J. W. Cho, Y. K. Kwon, K. S. Ryu, I. K. Yu, and S. Y. Hahn, "Current status of SMES in Korea," *Cryogenics*, 2002.

[5] C. J. Hawley and S. A. Gower, "Cryoelectronics—an experimental examination of the behavior of power electronic devices at low temperatures," in *Proc. 20th Int Cryogenic Engineering Conf (ICEC20)*, Beijing, China, May 11–14, 2004.

[6] C. J. Hawley, D. Cuiuri, and S. A. Gower, "Preliminary design of a high $T_c$ superconducting persistent mode current switch," in *Proc. AUPEC 2003*, Christchurch, New Zealand, Sep 28–Oct 1 2003.