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R L Thompson

Christopher J. Hawley
hawley@uow.edu.au

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

Steve Gower

Frank Darmann

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Abstract

The University of Wollongong (UoW) has received funding for the research and development of a high transition temperature (HTS) superconducting magnetic energy storage (SMES) device designed to operate at 40 K. This paper provides an update on work previously reported at AUPEC (2001) and summarises progress in the areas of computer assisted modelling, electromagnetic and thermal coil design, electronic control system, current leads and the cryogenic system. The proposed coil design for the SMES will be evaluated and discussed with respect to its advantages and limitations.

Keywords

wollongong, university, australia, work, current, smes, state

Disciplines

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CURRENT STATE OF SMES WORK AT THE UNIVERSITY OF WOLLONGONG, AUSTRALIA

R. L. Thompson[1], C. Hawley[1], F. Darmann[2], C. D. Cook[1] and S. A. Gower[1]

1. School of Electrical, Computer and Telecommunications Engineering
University of Wollongong, Northfields Ave, Wollongong, 2522
2. Australian Superconductors

Abstract

The University of Wollongong (UoW) has received funding for the research and development of a high transition temperature (HTS) superconducting magnetic energy storage (SMES) device designed to operate at 40 K. This paper provides an update on work previously reported at AUPEC (2001) and summarises progress in the areas of computer assisted modelling, electromagnetic and thermal coil design, electronic control system, current leads and the cryogenic system. The proposed coil design for the SMES will be evaluated and discussed with respect to its advantages and limitations.

1. Introduction

This paper will present the current status of SMES research at the University of Wollongong. This work has been reported on previously [1] and aims to design and build a commercially realisable HTS SMES. The SMES is designed to maintain supply to an industrial load for a period of 200 ms. The SMES discussed will also act as a blueprint for a larger SMES system designed to store 20 kJ of energy and provide levelling of short time (10 cycles) voltage drops in the 3 phase power supply to a typical 100 kVA industrial load.

This paper summarises progress to date in the following areas;

- finite element modelling (FEM)
- electromagnetic and thermal coil design
- electronic control system design
- current lead design and
- cryogenic system.

2. Finite Element Modelling

FEM has been used to determine the optimal coil configuration for the HTS SMES. This kind of modelling solves the overall problem (i.e. energy stored and magnetic field strength) for a number of smaller elements, which when added provide the total solution. The software used, ANSOFT’s Maxwell 3D, solves the problem iteratively with successively smaller elements until the “accuracy” of the result reaches a preset level - usually less than a 2 % difference from the previous answer. In our case, an optimal coil design is one that provides maximum energy storage for a given current and length of superconductor whilst taking into account constraints such as magnetic field strength in the vicinity of the superconductor.

FEM has been used to compare solenoids with cross sections of varying shapes. Some shapes tested were rectangular, triangular, trapezoidal and stepped [1]. Each design tested used the same length of superconductor and had the same inner diameter and height. As a result of these tests, it has been determined that a solenoid with a rectangular cross section is the optimal shape. Previous work [1] determined that the optimal shape was stepped. However, further analysis has determined that the maximum perpendicular magnetic field is located on the top edge of the inner surface of the coil, not towards the outer edge as postulated. This being the case, there is no advantage in having a stepped coil.

3. Electromagnetic Coil Design and Thermal Modelling.

The UoW SMES project has available 2500m of BSCCO-2223 tape from which, 2000m will be used for the coil and 500m will be used to construct the persistent mode current switch (PMCS) discussed in Section 4.2.

3.1 Electromagnetic coil design

Optimising the coil dimensions using FEM analysis resulted in a coil with the following dimensions; total tape length 1990m, 0.375m inner diameter, 0.4394m outer diameter and 0.0527m high. The final operating temperature of the coil has not been determined but is expected to be approximately 25K so the characteristics of the coil operating at 20, 25 and 30 K are presented in Table 1. The calculated inductance of the coil is 0.341H

Operating Temperature	20 K	25 K	30 K
Energy (kJ)	4.37	3.35	2.46
Current (A)	160	140	120

Table 1: Characteristics of the optimal SMES coil fashioned from 2 km of HTS tape.

This optimal coil design for a given length of tape (tested for tape lengths up to 5000m) had an inner radius of 0.20m and a coil thickness of approximately half its height. While coils with smaller inner radii stored more energy (the maximum energy being stored in the coil with r = 0.09m), energy stored was similar over a range of radii (0.08m to 0.20m). It was also found that the larger the inner radius, the smaller the maximum perpendicular magnetic field in the tape. Since this is the factor that limits the amount of current each tape can carry while remaining superconducting, the optimum design must be chosen taking the trade-off between inner radius and maximum perpendicular field into account. When the inner radius of the coil is 0.20m, the maximum perpendicular field is small enough that a small decrease in temperature allows an increase in the coil current leading to a large increase in energy stored.

American Superconductor Corporation (ASC) has previously designed and constructed an HTS SMES coil, as described in Kalsi et al. [2]. This coil uses approximately 5000m of superconducting tape and is comparable to a coil designed at UoW using a similar length of tape. The specifications and operating parameters of these coils are compared in Table 2.

	ASC coil	UoW coil
Tape Length (m)	4910	5000
Inner Diameter (m)	0.370	0.400
Outer Diameter (m)	0.447	0.494
Height (m)	0.1008	0.837
Inductance (H)	0.83	1.84
Current (A)	100	120
Energy (kJ)	4.85	13.27
Temperature (K)	25	25

Table 2. Comparing ASC coil to UoW coil of similar specifications

This quick comparison shows that the coil designs of ASC and UoW have similar dimensions. However, the coil designed at UoW has an inductance approximately twice that of the ASC coil. This has been achieved by using a tape with a higher critical current and by winding the coil with two tapes bundled together (instead of three bundled as used by ASC). This results in approximately three times the amount of energy stored by the UoW coil than the ASC coil.

3.2 SMES Thermal modelling

The thermal model of the SMES system must consider all sources of heat leak into the system and the temperature of the system internally at each point. To simplify analysis, the system will be broken up into a number of separate elements – the coil, the cryostat, the current leads and the control electronics. At this time, only static losses in the SMES system have been calculated.

In the steady state, the entire coil will be at the temperature of the cold head and will generate no heat. There will be no eddy currents losses so the entire heat leak will be due to; a) electrical losses generated by current in the leads b) conductive losses along the leads and c) radiation from the outside of the cryostat.

3.2.1 Current lead electrical losses

The losses in the current leads are summarised in Table 3 and were calculated using equation (2).

	Copper Section	BSCCO Section	Combined Leads
Electrical Loss (W)	9.88	0.005	9.89
Conductive Loss (W)	15.44	0.148	15.59
Total Loss (W)	25.34	0.153	25.48

Table 3: Heat leak in the current leads when the cold end is 20 K

3.2.2 Radiative Losses

The radiation exchange between two surfaces may be expressed as

$$q_{12} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where σ is the Stefan-Boltzmann constant, T_1 and T_2 are the temperatures of the outer and inner surfaces respectively, ε_1 and ε_2 are the emissivities of the outer and inner surfaces respectively, A_1 and A_2 are the areas of the outer and inner surfaces and F_{12} is the view factor. The view factor, $F_{12,}$ is defined as the fraction of the radiation leaving surface 1 that is intercepted by surface 2.

From equation (1) the heat leak between the outer casing and the copper heat shield has been calculated as 4.11 W. The heat leak between the copper heat shield (77 K) and the copper surrounding the coil (~20 K) is 5.4 mW, giving a total heat leak by radiation of 4.12 W.

The total heat loss in the static state is therefore calculated to be approximately 29.6 W at 20 K. From Figure 1, we can see the cryocooler will provide 20

W of cooling power at 20 K. It will therefore be necessary to operate the coil at a higher temperature. When the coil is operating at 25 K, the static losses are 27.3 W and the cooling power of the cryocooler is 33 W. However, this figure neglects some of the losses during charging and discharging of the coil. The transient losses may well exceed the 6 W spare cooling power at 25 K. Therefore, operating the coil at 30 K, where the cryocooler can remove up to 45 W of heat, must be considered.

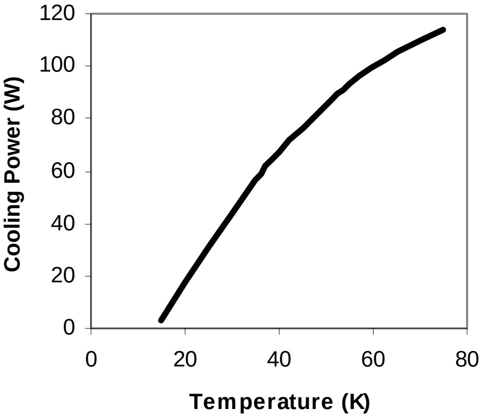

Figure 1. Cooling power of the Coolpower 120T

4. Electronic Control System

The function of the SMES electronics is to efficiently store the energy in the SMES coil, detect faults in the mains and discharge the stored energy to the load.

The SMES system is specified to be able to support a load for a duration of 200ms. The electronics must be able maintain the DC bus voltage to within 10% of the nominal value, and respond to events by returning the voltage to the nominal voltage within 20ms.

4.1 SMES Circuit Topology

Various circuit topologies were researched and considered during the design of the SMES. When designing a SMES there are two main decisions that must be made.

The first decision is the choice of inverter configuration; to use a Voltage Sourced Inverter (VSI) or a Current Sourced Inverter (CSI). Inherently the SMES coil acts as a current source, hence the immediate thought is to choose a CSI configuration. However, after examining previous implementations of SMES devices and the theoretical arguments regarding the choice of inverter type, the VSI configuration was chosen. This was mainly due to the smaller amount of low order harmonics produced by the VSI, but also the introduction of the capacitance on the DC bus means that the system has a much faster response and is not hampered as much by the large inductance of the SMES coil [5].

The second decision to be made was whether to install the SMES circuit in series with the mains supply or to attach it as a parallel supply. The major benefit of the parallel configuration is that all the devices need only be rated to perform during a mains fault event (for the majority of the time, the SMES remains idle).

However, the series configuration was chosen, as the cost of fully rated devices was a small consideration in the project design. Also the series system has a simpler switching configuration and it also means that all of the power is directed through the SMES inverter, so impurities in the waveform generated further up the line can be removed [5].

The complete SMES circuit design is shown in Figure 2, incorporating the series configuration and VSI.

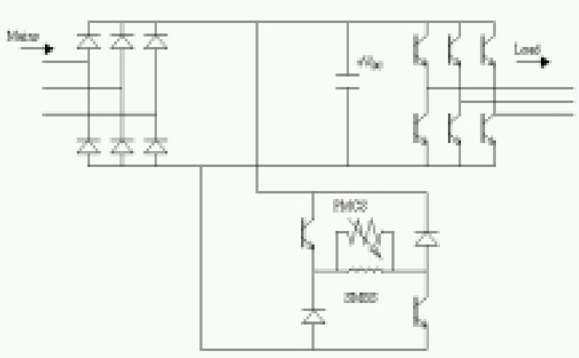

Figure 2. Complete SMES Circuit

4.2 Alternative Technologies

Storing energy requires large coil currents, thus any source of voltage drop in the current circulation path can lead to a large loss of stored energy. These voltage drops increase the frequency with which one needs to top up energy from the mains and can also result in a reduction in the stored energy available in the coil. Reducing the energy lost due to the circulation of current in the coil can significantly increase the stored energy and efficiency of the SMES device. The major source of circulation losses are the semiconductor devices used to charge and discharge the coil.

To reduce circulation losses, the use of various alternative switch technologies has been investigated. The first of these is to employ cryogenically cooled semiconductor devices. These devices are placed in a secondary cryogenic environment of liquid nitrogen. Studies done at UoW have shown that for smaller power requirements where MOSFETs are a suitable switching device, the forward voltage drop V_{CE} (and hence the power loss) can be reduced by a factor of ten by cryogenically cooling the device. However, the results for larger devices such as IGBTs are inconclusive [6].

The second alternative technology investigated is the use of a Persistent Mode Current Switch (PMCS). These devices are made from coils of superconductors and exhibit zero conduction losses when closed. To open the switch, the superconducting coil must be forced to leave the superconducting state and become resistive. This can be done a number of ways however the fastest method (and the only one suitable for a SMES application) is by pulsing a large, high frequency current through the PMCS coil. This method has proved to switch open within 50μs, and reach full impedance in less than 50ms [7].

Once the PMCS has become resistive, the current path is altered and the current is forced to discharge to the load. Opening the PMCS during discharge introduces into the circuit a resistive element that accounts for the entire 600 V (DC bus) voltage drop. This increases the dynamic losses of the system. These losses are not as significant at higher energy storage levels but are proportionately very large for lower power applications.

To broaden the scope of the SMES demonstration, it is planned that the power conditioning circuit of the SMES will be run at a lower variable voltage than the DC bus. By reducing the voltage, the efficiency of the PMCS is increased. This also increases the current required by the SMES so it cannot be discharged as far, as shown in Figure 3. The variable voltage level will allow the capabilities of both the PMCS and the energy delivery of the SMES to be demonstrated.

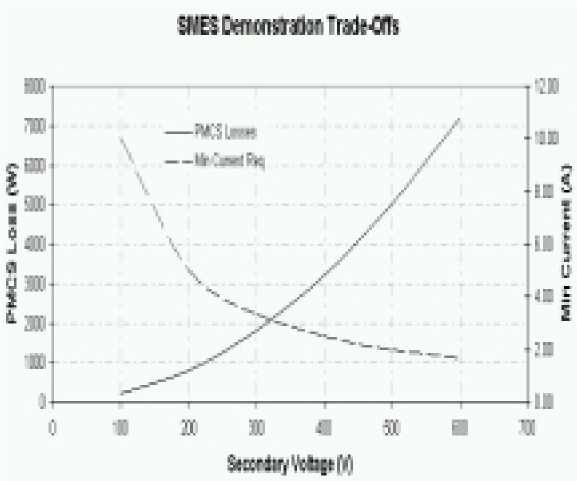

Figure 3. SMES Demonstration Trade-Offs

5. Cryogenics

The coil will rest inside the cryostat on a copper plate, which is connected to the cold head of the cryocooler. A Leybold Coolpower 120 T cryocooler with a single stage cold head will provide cooling as shown in Figure 1. The coil will be wound onto a copper former, and will be surrounded by a copper cylinder. The former and the cylinder will be connected to a copper annulus acting as a lid over the coil. Thus, the coil will be completely surrounded by copper that is constrained to be at the temperature of the cold head.

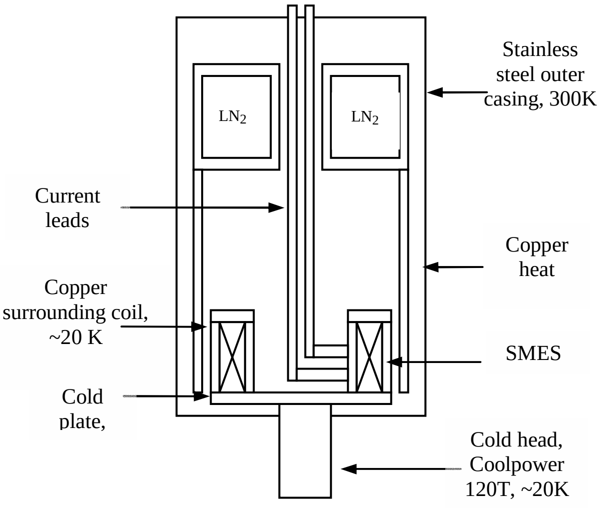

Figure 4: Schematic representation of the cryostat

The cryostat encompasses a volume of approximately 0.23 m^3 and is essentially a stainless steel cylinder that contains a liquid nitrogen reservoir, the coil, the cold plate and the current leads, as seen in Figure 4. The cryostat has been designed by Australian Superconductors in Wollongong Australia. The specifications of the cryostat are summarised in Table 4.

Outer Diameter	570 mm
Height	910 mm
Material	Stainless Steel
First Stage Cooling	LN$_2$ bath
Height of Bath	150 mm
Heat Shield	Copper

Table 4. Characteristics of the cryostat

6. Current Leads

A pair of current leads has been designed for UoW's SMES. The current lead design is based on equations in Mercouroff [3] and data for the thermal conductivity of BSCCO/AgAu4% from Putti et al.

[4]. Mercouroff states that the total heat leak along a current lead is given by Equation 2.

$$Q=\frac{1}{2}(\rho\frac{L}{A}I^2)+\frac{A}{L}\int_{T_0}^{T_1}\lambda(T)dT \text{ ....(2)}$$

where ρ is the resistivity of the current lead, L is the length of the current lead, A is the cross sectional area of the lead, λ(T) is the thermal conductivity and T_0 and T_1 are the temperatures at either end of the lead. From this equation, the minimum heat leak with respect to L/A can be found. The condition for minimum heat leak is

$$\rho\frac{L}{A}I^2=I\left[2\rho\int_{T_0}^{T_1}\lambda(T)dT\right]^{1/2} \text{ ....(3)}$$

Using Equation (2), a current lead can be chosen with L/A to provide minimum heat leak.

To reduce the heat leak to a minimum, the current lead has two sections. The first section will be made of copper wire and will operate between 300 and 77K. The second section will be made of BSCCO/AgAu4% and will operate between 77 K and the coil. The coil will be run at the minimum temperature possible with temperature depending on thermal losses. The minimum operating temperature of the cryocooler is 15 K. This will be discussed further in the Section 7.

The superconducting section of the current leads is constrained by the cross sectional area of the superconducting tape. The optimal length of the tape (which will minimize heat leak) is considerably longer than the actual length chosen. However, as the heat leak along the superconducting section is two orders of magnitude lower than from the copper section, the lead has been designed to minimize the amount of superconductor required. The current leads have been designed to carry a current of 200 A. Physical restraints require that each section of the leads be 0.3 m long. Other dimensions of the leads are summarized in Table 5. The total length of superconductor required is 3 m (1.5 m for each lead in the pair).

	Copper	BSCCO/AgAu4%
Losses (W)	25.34	0.154
Area(mm^2) / lead	12.99	6.00
# of tapes / lead		5

Table 5: Physical dimensions of 200 A current leads for the HTS SMES.

7. Future Work

The coil for the UoW SMES has been constructed. Testing of the coil at 77 K is now planned to confirm the modelling predictions. Once the cryostat has been delivered, the coil and the electronic control system will be integrated and the SMES will be fully tested and characterised.

Transient thermal calculations will be completed and a complete transient thermal analysis using FEM will be carried out. On completion of this work, the final operating temperature will be determined.

A general method to easily determine the optimal coil geometry for a given set of parameters (i.e. operating temperature, length of tape, operating current) will be developed. This method will be based upon the work described in this paper and in Causley et al. [1]

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