Design of a high temperature superconductor magnetic energy storage systems

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DESIGN OF A HIGH TEMPERATURE SUPERCONDUCTOR MAGNETIC ENERGY STORAGE SYSTEM

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Abstract

The University of Wollongong (UoW) has received funding for the research and development of a 20 kJ high temperature superconducting magnetic energy storage device (HTS SMES). This SMES will be operated at 25 K in contrast to most existing HTS designs, which operate at 77K. This paper includes a literature review of the current technology for the configuration of the SMES coil and a summary of the work done at UoW to date. Solenoidal and toroidal coils designs are compared to determine which will provide the required level of energy stored for a minimum superconductor and device volume. The design for the proposed SMES is evaluated with respect to UoW’s requirements.

1. INTRODUCTION

This paper will present a study on current state of the art designs for SMES coils. A design is chosen and analysed as most suitable for our needs. The aim of this is ultimately to design and build a commercially realisable 20 kJ HTS SMES to be used to improve power quality for an industrial manufacturing site.

It has been determined, in a recent techno-economic study [1], that there is a need for a method of providing levelling of short time (10 cycles) voltage drops in the 3-phase power supply to a typical 100 kVA industrial load. Other possible energy storage mechanisms include compressed air, pumped hydro and battery based uninterruptible power supplies. However, SMES is attractive because of its high efficiency and rapid response time. This HTS SMES will operate at 25 K and has four times the energy density of LTS devices operating at 4 K. It will also have a simpler design and lower operating costs due to less rigorous refrigeration demands.

A 20 kJ HTS SMES has practical applications to Australian industry with the potential to provide energy and cost savings. Environmentally, SMES is desirable as it is potentially a clean energy storage medium with very high efficiencies. SMES can also be used to provide additional support for renewable energy generators and so have a positive impact on greenhouse gas emissions.

SMES consists of coils and its overall performance is very dependent on the precise configuration of these coils. Various configurations are presented for comparison. In particular, the field orientation effects on the critical current, and the effects on the total energy storage are examined.

2. TOROIDAL COILS

The main advantage of using toroidal coils is that the magnetic field is completely contained within the coil; therefore there are no problems with stray fields and no shielding requirements. Toroidal coils can be made in two ways – as a continuous helical winding or as a number of short solenoids connected in series.

2.1 Helical Toroids

A Japanese group is producing the state of the art in helical toroids. They have developed two new concepts for helical windings – the Force-Balanced Coil (FBC) [2] and the Stress-Balanced Coil (SBC) [3]. The FBC was initially proposed by Miura et al. [4], and was applied to SMES by Sato et al. [5]. The SBC is an improvement on the FBC and is designed to optimise large aspect ratio superconducting coils [3]. These coils are designed to balance the large electromagnetic forces generated by the high magnetic fields and currents used in SMES. The tensile stress caused by these forces can damage brittle superconductors. Nomura et al. [2] found that a helical coil optimised by the virial theorem can reduce the mass of the entire SMES structure by up to 75% of the Toroidal Field Coil while storing the same amount of energy. They expect the SBC to achieve the SMES design with the minimum amount of superconductor – about 17% of the ampere-
metres of the Toroidal Field Coil for the same energy.

2.2 Modular Toroids

Most toroid designs use coils formed from a number of short solenoids arranged symmetrically as a torus and connected in series.

The optimum number of modules in a toroid is one of the most basic design considerations. The number and size of the modules will influence the size of the overall SMES, but also will affect the ease of fabrication, which in turn helps determine the feasibility of the design. Borghi et al. [6] have used two methods – an objective weighting method and a fuzzy logic method – to optimise the SMES design for a given magnetic energy, with a minimum amount of superconductor and minimum overall device volume, $\Omega_D$. They have used the stray field and the parallel and perpendicular critical currents as constraints. This analysis was done for a multiple solenoid system as well as a modular toroid, however this will not be examined in this paper. The modular toroid configuration is shown in figure 1. Their optimisation method found two minima, one corresponding to a six-coil system, the other to a system of 97 coils. Both of these configurations used approximately half the amount of superconductor of any of the multiple solenoid systems.

![Fig 1. Toroidal system configuration [6]](image)

Another of the basic parameters of a toroid is the shape of the modules; for example are D-shaped coils more efficient, for a given length of superconductor with constant current, $I$, and magnetic field, $B$, than circular coils? This issue has been investigated by Birkner [7] who directly compared the effects of using either a circular coil or one in the shape of a ‘Princeton D’. He has discovered that the induction of a coil does not depend on its shape and that a SMES coil is optimised, for a given length of cable, with low inductance and high current. Birkner determined that although the Princeton D shape has higher maximum energy (18% higher) than a simple circle, it is unlikely that this difference would justify the added expense of fabricating the complex D.

![Fig 2. Toroidal structure, alternating circular and “D” shaped coils. [8]](image)

While a toroidal coil has the advantage of a completely enclosed magnetic field, this can only strictly be applied to a helical coil. A modular coil will ‘leak’ its magnetic field outside the structure. To overcome this problem Vincent-Viry et al. [8] have proposed two new SMES coil configurations. The first configuration is an n-polygon group. This configuration consists of $n$ coils with a ‘D’ shaped cross section. The second configuration is a toroidal structure consisting of alternating circular and ‘D’ shaped short solenoids with the ‘D’ coils filling the ‘gaps’ between the circular coils as shown in figure 2. Both designs performed well in numerical simulation. In particular the n=4 polygon system (figure 3) showed very good performances in terms of energy storage and magnetic leakage.

![Fig 3. n = 4 polygon. Each coil of the structure has a “D” cross section. [8]](image)
3. SOLENOIDAL COILS

A Slovakian group has done extensive research into HTS SMES, particularly into optimising single solenoids. One study, Pitel et al. [9], did a theoretical study on the influence of the number of pancake coils in a magnet on the critical current. They found that above 10 pancakes the critical current of the system remained constant. A decrease in operating temperature from 77 K to 4.2 K resulted in an order of magnitude increase in the critical current. Another study [10] involved keeping the same length of tape while determining the influence of operating temperature and winding geometry. In this study they discovered that the optimal winding geometry was different at different temperatures. At higher temperatures the best shape was one double pancake. For a given length of tape, changing the inner diameter made little difference to the maximum energy stored and increasing the number of pancakes decreased it. In general, at this temperature, the energy behaves like the critical current. At lower (liquid helium) temperatures, the energy dependence on the number of pancake coils and the inner winding diameter is quite different, and the energy behaves much more like the self-inductance than the critical current.

While the traditional shape of the cross-section of a solenoid is rectangular, Noguchi et al. [11] suggest using a coil whose cross-section is step-shaped – that the coil consists of a number of coaxial coils with different lengths. This configuration is illustrated in figure 4. This design will reduce the winding volume to 67% of that of the rectangular coil while still producing the 12 T magnetic field they required. This configuration also reduces the effect of the magnetic field at the ends of the coil on the superconductor, hence increasing the critical current.

4. WORK TO DATE AT UOW

Preliminary work on the design of the 20 kJ SMES has been done in the form of the design, modelling and building of a 200 J SMES system. This SMES consists of 3 pancake coils in a stack, a cryostat and a power conditioning system to interface the coil to the power supply and load. Bi-2223/Ag was used for the coils, with the final dimensions being 435 mm (outer radius) and 200 mm (inner radius). A cruciform iron core surrounds the coils. The cryostat is a polystyrene box that follows the shape of the coils closely but does not surround the iron core. This leads to a great saving in the amount of cryogen used. The cryogen chosen for this coil was liquid nitrogen. The power conditioning system was designed and built by UoW, and has been described elsewhere [12].

The small SMES (200 J) was modelled using finite element analysis (figure 5). Full results have been reported in Josh [12]. It was estimated that the energy storage of this system would be 150 J. It was calculated to be 133.6 J. The system is currently undergoing tests to determine the actual energy storage, however, preliminary testing indicates it will perform as expected.

The coil design to be chosen for the large SMES must fulfil a number of constraints. The SMES is required to store 20 kJ of energy while operating at 25 K. It will be cooled by a cryocooler that will provide at least 15 W cooling power at 20 K. This in turn requires the loss level of the device to be less than 15 W. Ideally, the total device volume will be as small as possible, with a maximum volume of 1 m³.
The Bi-2223 tape for this SMES is being provided by Australian Superconductors. The critical current of the tape will be assumed to be $I_c = 50$ A.

With these constraints, the stepwise solenoid proposed by Noguchi et al. [11], and shown in figure 4, is the chosen design for this SMES. The basic solenoid shape is chosen to provide the greatest energy storage for a given superconductor tape length. Various studies have shown that, due to anisotropy, the critical current in a superconducting tape is a maximum when the magnetic field is parallel to the tape and a minimum when the magnetic field is perpendicular to the tape (figure 6). In a solenoid, the magnetic field is parallel to the tape everywhere except at the ends, where the field begins to spread out. This means that the outer corners of the solenoid will experience the greatest perpendicular component of the field, and therefore the greatest critical current reduction. The proposed configuration removes the windings that would be subject to the largest perpendicular field, resulting in a larger critical current. As a result, the same energy storage can be achieved using less superconductor leading to both cost and space savings.

![Fig 6. Bi-2223 tape showing 1) the parallel and 2) the perpendicular directions](image)

This design is very simple and easy to fabricate. To make it even simpler, plans have been made to use a stack of pancake coils with the same inner radius but varying outer radii to make the steps. Calculations and modelling to determine the final parameters on the pancakes are in progress.

### 5. CONCLUSIONS

This paper has examined the literature on the current state of the art in SMES design. A small, 200 J, HTS SMES has been designed, modelled and built. Testing is planned to determine the performance characteristics of this design. A coil configuration has been chosen for a 20 kJ HTS SMES. This design will be refined and modelled using finite element analysis in future work.

### REFERENCES

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