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A Review of Designing Aspects of SMES an Ideal Energy Storage for Renewable Energy

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Abstract- This paper outlines a systematic procedure for the design of Superconducting Magnetic Energy Storage System. The SMES covers many utility, industrial, and military applications. Both toroidal and solenoidal configurations were analyzed to determine physical dimensions, heat loads and cost of major components. Among the effects considered were the impact of critical current density on feasible configurations, mass of conductor, and cost; the effects of magnetic field and strain limits on physical parameters and structural mass; and the savings in refrigeration from operating at higher temperature. The design of the HTS, stability criteria, and coolant selection are also discussed.

Keywords: Superconducting magnetic energy storage (SMES), HTS, LTS, Solenoid, Toroidal, CCR.

1. INTRODUCTION

Recently the properties of high temperature superconducting (HTS) conductors have been improved. Various HTS magnets have been designed and fabricated. Magnet size and volume are expected to be reduced by using the HTS conductors, since they have better properties at high magnetic field than the LTS conductors [1]-[4]. High temperature superconductors (HTS), many predictions have been made for savings in the cost or performance of superconducting technologies for electric utility systems. One such technology, Superconducting Magnetic Energy Storage **(**SMES), is presently being developed to provide power for a number of applications. A SMES system is designed to store energy inductively in the magnetic field of a superconducting coil for use when needed by an electric utility or customer system. Current SMES designs use conventional metallic superconductors. The higher operating temperature of HTS materials could mean the use of less expensive cryogens, such as liquid nitrogen, higher refrigeration efficiencies, greater reliability, and easier acceptance within the utility community. The significance of such improvements depends on the application and other characteristics of the system. Also, today's HTS materials have some negative features, including lower critical current density and greater brittleness compared to conventional metallic superconductors [5]. The purpose of this study was to determine the potential advantages and development needs of HTS-SMES, taking into account both positive arid limiting features of today's HTS materials. A SMES system is designed to provide power for a relatively short period of time and is characterized by rapid response and high efficiency. A SMES unit has both a power rating and a storage capacity. 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. DESIGN CONCEPTS:

2.1. Coil:

SMES consists of a high conductance coil which can be treated as a constant current source. Due to its superconducting nature, energy can be stored for a long duration of time without leakage and may then be used to inject active power into the grid whenever there is a disturbance. Niobium-Titanium (NbTi) is the material commonly used to mould the superconductor [6].
There are three factors which affect the design and the shape of the coil

- Inferior strain tolerance
- Thermal contraction upon cooling
- Lorentz forces in a charged coil

Among them, the strain tolerance is crucial not because of any electrical effect, but because it determines how much structural material is needed to keep the SMES from breaking. For small SMES systems, the optimistic value of 0.3% strain tolerance is selected.

2.1.1. Geometries used in SMES designing:

- Solenoid Geometry
- Toroidal Geometry

2.1.1.1. Solenoid Geometry:

For small SMES, solenoids are usually used because they are easy to coil and no pre-compression is needed. 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.

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Another study [7] 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, 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 1. 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.

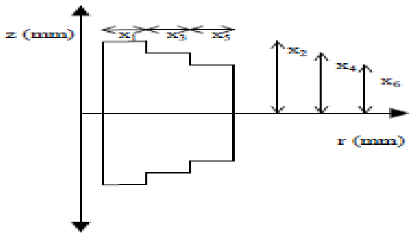

Figure:1- Stepwise superconducting coil

Fundamental Equations

The basic equations that relate the inductance of a coil to its geometrical characteristics are as follows. These are expressed in terms of three physical quantities for each system.

$$L = \mu_0 R \left(1-\sqrt{(1-\beta_s^2)}\right)$$

$$B_m = \left((\pi/\beta_s) + \text{In}(2\pi/\beta_s)\sqrt{\mu_0 E/(2\pi R a(\beta_s))}\; / (2\pi R)\right)$$

$$F_r = E\,(a(\beta_s)+1) / (a(\beta_s)\, R)$$

$$Q_s = E^{2/3} B_m^{-1/3}\, 4\pi \left[(1/2 + (\beta_s/2\pi)\, \text{In}(2\pi/\beta_s)) / (4\mu_0 \beta_s (\text{In}(4/\beta_s)-1/2)^2\right]^{1/3}$$

Were

B_m = peak field
R = major radius
β_s = aspect ratio (ratio of height to diameter)
$a(\beta_s)$ = function of β_s

The peak field in a solenoid occurs at the ends, but with minor modifications to separate the end turns, it is possible for the peak field to equal the mid plane field. In our analysis we assume B_s is both peak and mid plane field for the solenoid.

2.1.1.2 Toroidal geometry:

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 continuous helical winding or as a number of short solenoids connected in series.

2.1.1.2.1 Helical Toroids:

There are two new concepts for helical windings – the Force-Balanced Coil (FBC) [8] and the Stress-Balanced Coil (SBC) [9]. The SB is an improvement on the FBC and is designed to optimise large aspect ratio superconducting coils [9]. 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. 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.

2.1.1.2.2 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. [10] have used two methods – an objective weighting method and a fuzzy logic method – to optimize the SMES design for a given magnetic energy, with a minimum amount of superconductor and minimum overall device volume, 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 2. Their optimization 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.

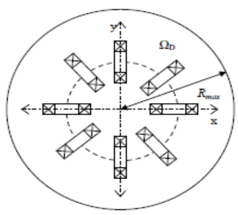

Figure:2- Toroidal system configurations

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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. The effects of using either circular coil or one in the shape of a 'Princeton D' were observed that the induction of a coil does not depend on its shape and that a SMES coil is optimized, for a given length of cable, with low inductance and high current. 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.

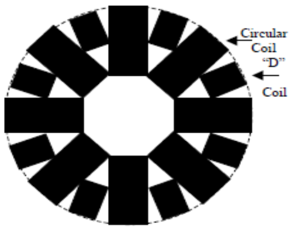

Figure:3- Toroidal structures, alternating circular and "D" shaped coils.

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 we have 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 3. Both designs performed well in numerical simulation. In particular the n=4 polygon system (figure4) showed very good performances in terms of energy storage and magnetic leakage.

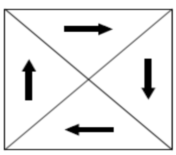

Figure:4- *n* = 4 polygon. Each coil of the structure has a "D" cross section.

Fundamental Equations

The basic equations that relate the inductance of a coil to its geometrical characteristics are as follows. These are expressed in terms of three physical quantities for each system.

For toroidal coil derived quantities are

$$L = \mu_0 R \left(1-\sqrt{(1-\beta_t^2)}\right)$$

$$E = (\mu_0 R/2)\left(1-\sqrt{(1-\beta_t^2)}\right) I_t^2$$

$$B_m = \mu_0 I_t / (2\pi R (1-\beta_t))$$

$$F_t = 2\pi^2 R^2 \beta_t (1-\beta_t)^2 B_m^2 / \mu_0$$

L = inductance

E = total energy

Q_t = quantity of conductor

F_t = Lorentz forces generated by the interaction of the current with the magnetic field

μ_0 = the permeability

I_t = the total current across the mid plan of the coil at the inner(R-r) and at outer (R+r) boundaries

$$I_t = 2\pi (R - r) B_m / \mu_0$$

Q_t quantity of superconductor in Amper-meters

$$Q_t = E^{2/3} B_m^{-1/3} 3[16\pi^2\beta_t^3 / \mu_0 (1-\beta_t)(1-\sqrt{(1-\beta_t^2)})^2)]^{1/3}$$

3. HTS COIL DESIGNING:

The HTS coil is a critical component of the SMES device, as is responsible for storing energy required to support the load during voltage sags. It is the component that characteristically sets the system apart from other conventional devices and drives the originality of the other system component integrated with it [5].

3.1 Initial Coil Design:

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 made welded copper plate and tube [11]. It is well known that the energy storage capacity of a coil is dependent upon the current and inductance characteristics as describe by equation 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 made welded copper plate and tube [11]. It is well known that the energy storage capacity of a coil is dependent upon the current and inductance characteristics as describe by equation.

$$E = \frac{1}{2} L I^2$$

Where

E is the coil energy capacity (J)

L is the coil inductance value (H)

I is the coil current rating (A)

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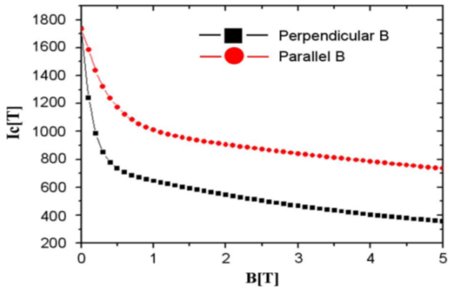
HTS materials exhibits a different critical current (Ic) depending upon the operating temperature and perpendicular magnetic field. The performance of the



material is dependent primarily upon the manufacturing process and it is necessary to characterize each batch of tape to be able to model its behavior [5].

Figure:5- Estimated Ic-B curve of HTS coil

It can be seen from this figure that the perpendicular field strength has a much greater effect on the Ic value of the HTS tape then the parallel field especially in the range of (0-1000mT).The coil and former design was modeled using the Finite Element Modeling (FEM).The FEM was used to evaluate the electromagnetic behavior of the coil and define the magnetic flux density, field intensity, force and resulting inductance. These FEM model results predicted that maximum perpendicular field intensity in the coil would be 695mT and that the coil should have an inductance of 285mH.To confirm the inductance value given by the FEM modeling. Calculations were performed using a technique outlined by F.W.Grover to determine the inductance of a short fat solenoid. The expression is defined in equation.

$$L = 0.019739\left(\frac{2a}{b}\right)N^2 aK'$$

Where

L = the coil inductance ((H)

N = the No. of turns

a = the mean radius of the turn (cm)

b = the axial dimension length of winding (cm)

c = radial dimension depth of winding (cm)

K' = defined by equation

$$K' = (K - k)$$

Where

K is a function of Nagoka's formula dependent upon the ratio of the b/2a K is a function of the decrease in current due to the separation of the turns in a radial direction, dependent upon the ratio of c/2a and b/c. It was also necessary to include a correction factor to represent the effect of the insulation material used in winding the coil. The correction factor is included using equation.

Where

ΔL is the correction factor defined by equation

$$\Delta L = 0.004\,\pi\, a\, N\left[\log_e\left(\frac{\rho}{\partial 1}\right) + 0.1381 + E\right]$$

Where

E is the constant based upon the number of layer, and the number of turns per Layer, as per defined in table since in most case ΔL is relatively small, E is assumed to be 0.017 in the general case.

The BSSCO-2223 taps used had a nominal critical (I_c) of 40A (@ 77K) in zero perpendicular field. Specified by the supplier using the estimated maximum I_c and assuming a final operating temperature of 25k, the maximum perpendicular magnetic field strength was predicted to be 65mT (using an iterative FEM process). The relationship determined from experimental characterization of the tap was used to determine when the calculated perpendicular field was equal to the critical field of the tape for the given current and temperature. Two tapes were wound in parallel to increase the I_c and the net result was a predicted effective I_c of 140A (@ 25 K).The HTS tape was wound on a copper former will voltage tapes incorporate at six point along the winding length so that the integrity and performance of sections of the coil could be assessed and monitored [11] . Kapton insulation was used between the turns and layers to avoid an electrical short and the entire coil was cured in an autoclave at 120^0C and 100kPa for 550 minutes to reduce the possibility of displacement of the layers due to magnetic hoop stresses.

3.2 Experimental Coil Characterization:

3.2.1 I Characterization:

To determine the I_c of the coil, it was tested using a four wire contact I-V method with the threshold voltage set to 1µV/cm to verify the design. The first step was to conduct the test in a LN_2 bath, both across the whole length and at each of the voltage taps to ensure uniformity along the coil (the voltage taps were placed 200m/15 layers apart with 1 being the inner tap) [11].

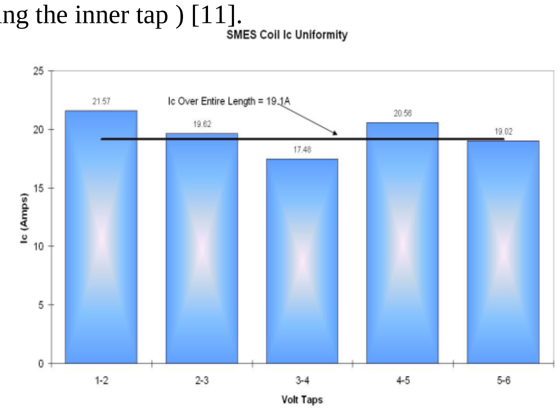


Figure:6- SMES Coil Ic uniformity graph

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Vol. 2, Special Issue 1, May 2015

It can be seen from fig. that the I_c value of the coil for 77K and 30K was 19.1A and 90.2A respectively. These I_c values are much less than originally predicted. This was partially because the cryostat was intended to operate at 25K. But was only capable of maintaining 30K, and also due to the number of joins present in the coil winding. These joins increased the resistive losses in the coil and hence also the amount of heat generated [5].

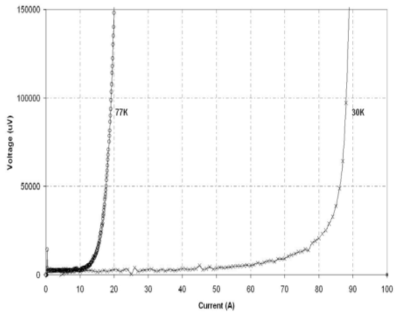

Figure:7 - HTS Coil I-V results at 77K and 30K

3.2.2 Inductance Characterization:

The inductance of the HTS coil was measured by observing the charge and discharge time of the coil. A current controlled power supply was connected across the terminals of the coil; the current in the coil was increased to 20A (at a temperature of 77K) and then the power supply was open circuited, a simplified diagram of this circuit is shown in figure:– 8

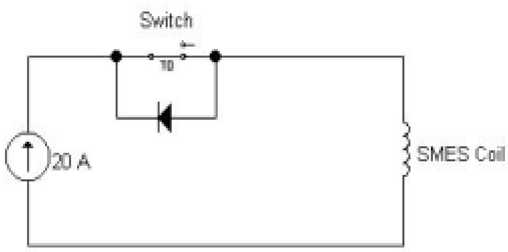

Figure:8 - Simplified coil inductance test circuit

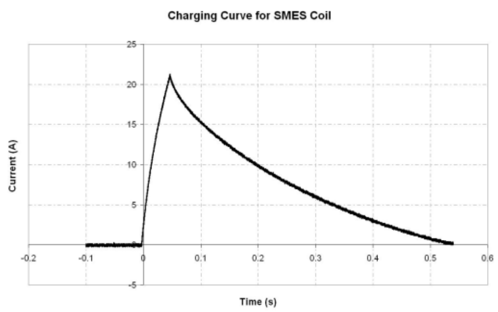

Figure:9 - Current in coil during charge and discharge test

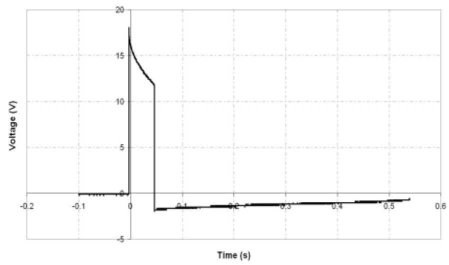

Figure:10 - Voltage applied to coil during charge and discharge test

The current in the coil charges to 20A and when the power supply is off, current discharges across the reverse diode inside the supply using the relationship described in equation. The inductance was found to be constant for both the charge and discharge component of the experiment at 42mH [12].

$$V = L\frac{\Delta I}{\Delta t}$$

Where

V is the voltage applied across the coil (V)

L is the coil inductance (H)

Δt is time elapsed (s)

ΔI is the change in coil current (A)

DC SMES electronic was connected to the coil and this time voltage observed during avoltage sag which caused the coil to discharge fully.

4. DESIGNING OF CRYOGENICALLY COOLED REFRIGERATOR (CCR)

The Cryogenically cooled refrigerator used for cooling of SMES which maintains the SMES temperature below its critical temperature. The cryogenic system used to cool the SMES coil. The cryogenic system chosen for the prototype was a gaseous helium conduction cooling system, rather than the conventional LN2 bath. There are several reasons for this; the main one being that the gaseous helium system has the capability to cool the cryogenic environment to a temperature in the order of 10K, whereas a LN2 bath is only capable of achieving 77K (or 66K under pressure).This is important, because as the operating temperature decreases the current that can be carried by the HTS coil increases significantly [13]. The conduction cooling method also provides a 'dry' environment and reduces the thermal shock applied to materials in the cryogenic environment, because of a slower rate of cooling. The cryogenic system can be separated into two distinct components; the cryostat that provides the cryogenic environment and the cryocooler that removes the heat from the cryostat [14].

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Vol. 2, Special Issue 1, May 2015

4.1 Cryocooler

The cryocooler system chosen for the prototype was a Leybold 120T single stageGifford-McMahon cold head supplied by a Leybold 6000 gaseous helium compressor. The helium compressor, removes the heat by compressing the helium gas, reducing the temperature and then pumping it to the cold head. The cold head then uses a valve to expand the gas and return it to the compressor to complete the closed cycle. The compressor unit had a power requirement of 8.2kW at start up and 6.0 - 6.5kW when at the final operation temperature. In order to keep the compressor from overheating a constant flow of water coolant at a rate of at least 5l/min was required. The coolant required a certain level of purity otherwise the compressor was susceptible to corrosion over an extended period of time. The minimum coolant specifications supplied by the manufacturer, were compared to test results of the local water supply [13].

4.1.2. Cryostat

The cryostat was custom designed to utilize the 38W 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 radioactive heat loss. A line drawing of the cryostat design is shown in cross-section in Figure: 11The HTS coil former was placed directly on the copper cold plate to provide a direct thermal contact with the cryocooler cold head [14].

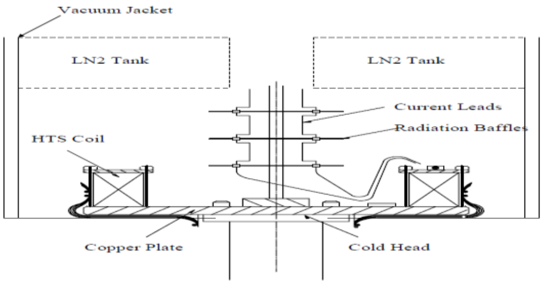

Figure:11- Line drawing showing cross-section of the cryostat

It was found that the radioactive and conductive losses contributed the major component of the heat leak. The resistive losses in the HTS coil were negligible and the convection losses zero due to the lack of air flow in the vacuum chamber [14]. The current leads were manufactured from a phosphorous deoxidized copper (C12200: Cu; 99.85% Min, P; 0.015 - 0.04%, O; <0.06%). This material exhibits a slightly lower electrical conductivity than other copper alloys, such as the electrolytic tough pitch copper (C11000: Cu; 99.9% Min, O; 0.04%) commonly used for electrical conductors; however it also has a much lower thermal conductivity, therefore reducing the heat leak through the leads. The outer vacuum jacket, manufactured from stainless steel, was fitted with valves to fill the 18litre LN2 tank and also act as a vent in the event that the LN2 pressure built up. It also had a NW40 vacuum valve mounted on the top to enable the cryogenic area to be evacuated.

5. CONCLUSION

This paper has examined the literature on the current state of the art in SMES design. A HTS SMES has been designed, modeled and built. Testing is planned to determine the performance characteristics of this design. A coil configuration of HTS SMES has been discussed. Different parts of Cryogenically Cooled Refrigerator have been discussed in this paper. This design will be refined and modeled using finite element analysis in future work.

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