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A STUDY OF MECHANICAL DESIGN OF SUPERCONDUCTING COIL

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ABSTRACT

The design of a superconducting magnet has been investigated in this study at both 77 K and 14 K. The superconducting tape has been categorized into its first and second generation configurations. The critical current of the tape at 77 K and 14 K is taken into account throughout the selection process. The influence of working temperatures has also been discussed. Although there are a variety of magnet designs to choose from, this one was selected because it uses the least amount of surface area and has the potential to employ the shortest possible length of superconductor for energy storage. For the electromagnetic design of a superconducting magnet, the design, input, and constraint variables have been determined. The hole diameter, magnet height, magnet thickness, and number of turns on the pancake coil have all been measured and analyzed using analytical correlations. The topology of the magnet has been analyzed, taking into account the effects of current and solenoid thickness. A study comparing the magnet's design at 14 K and 77 K found that cooling the magnet at low temperatures cut down on the need for as much superconducting tape.

KEYWORDS: Mechanical Design, Superconducting Coil, superconducting magnet, energy storage, electromagnetic design

INTRODUCTION

There are several components that work together to form a superconducting magnet, including the primary superconducting coil, current leads, cryogenic setup, and supporting structure. The structural, thermal, and magnetic design of the SMES has been a collaborative effort amongst several academic institutions. In the parts that follow, we will delve more into the national and international standing of the superconducting magnet.

Literature Survey (International Status)

Due to financial restraints, superconducting magnetic energy storage technology is still in the research and development phase. Superfluid helium (Helium-3) is used to cool the world's most famous superconducting magnet (NbTi superconductor) to a temperature of 1.9 K at CERN in Geneva. NbTi and Nb3Sn, two types of Low Temperature Superconductors (LTS), have been frequently used in the magnets' production. High-temperature superconductors (HTS) have been widely used in energy storage applications since their discovery, thanks to their low cost, high energy density, and small footprint in comparison to low-temperature superconductors. Many scientists have used computer simulations to study the structural features of HTS SMES, such as the magnet's structure or arrangement. The HTS magnet has been created using a number of different coil shapes, including solenoidal, toroidal, D-shaped, and racing track coils.

First generation (1G) HTS tapes (BSCCO-2212 and BSCCO-2223) and second generation (2G) Yttrium barium copper oxide (YBCO) (HTS) tapes are the two main kinds of HTS tapes used in the creation of SMES. Both tapes have been used in the construction of HTS magnets; however 2G tapes are preferred due to their higher current carrying capacity and superior mechanical strength. The computational advancement of HTS SMES is the subject of several investigations. The Korea Electro-Technological Research Institute (KERI) in Korea, Kyushu Electric Power (KEP) in Japan, and the China Electric Power Research Institute (CEPRI) in China have all created successful prototypes of their own.

Literature Survey (National Status)

The Indian Institute of Technology (IIT) in Kharagpur [and the Variable Energy Cyclotron Centre (VECC) in Kolkata [98] have both made efforts to construct such devices using Low Temperature Superconducting technology (below 10K). Only our prior study has documented the use of high temperature superconducting tapes in the design of SMES devices in India at all.

This study focuses only on the design of superconducting coils, when the HTS tape's design and limitations characteristics have already been defined. The next sections elaborate on the technique for electromagnetic design of a magnet coil.

SELECTION OF HIGH TEMPERATURE SUPERCONDUCTING TAPE

First-generation HTS cassettes and second-generation HTS tapes are distinguished in Study 2. Second-generation HTS tapes have larger critical currents at 77 K and can handle greater current densities in a strong magnetic field than first-generation tapes. Yttrium barium copper oxide (YBCO) is one of the most popular 2G tapes because of the benefits it offers over 1G tapes; Yttrium (Y) is a rare earth metal. Because of its non-magnetic substrate and general design for use in high magnetic field applications like magnets, SuperPower HTS tape (SCS 12050) [138] was chosen for this investigation. The non-magnetic substrate material (Hastelloy), YBCO layer, and stabilizer (silver) layer that make up the proposed HTS tape measure 12 millimeters in width and 0.1 millimeters in thickness.

SELECTION OF MAGNET CONFIGURATION

The cross section of the SMES magnet is a crucial design consideration. Due to the high pressures involved, the device's strength, size, and resilience are prerequisites. In order to create an efficient design for the HTS SMES device to store energy, several different combinations have been used so far in the literature. Several efforts have been made in the past to build an affordable and ecologically sound SMES magnet, beginning with the Low Temperature Superconductors (LTS) such as Nb-Ti, Nb3Sn etc. Since the discovery of high temperature superconductors, HTS technology has been favored over LTS for use in the creation of superconducting magnets for reasons including cost and durability. Tapes made from Bismuth Strontium Calcium Copper Oxide (BSCCO-2212 and 2223) are used to create magnets in the first generation. The "Powder-in-Tube" method is used to create these superconductors. Second Generation (2G) HTS tapes, which use coated conductors (Yttrium Barium Copper Oxide-YBCO), have been shown to be capable of carrying higher currents than their predecessors, 1G tape. Therefore, in this research, a superconducting magnet was created using YBCO tapes.

The SMES may be constructed in either a solenoid or a toroidal geometry. According to the available literature, the solenoidal configuration is less complicated to produce and better able to deal with mechanical stress. The solenoid arrangement is also the most cost-effective since it requires the least amount of wire for isotropic superconductors. Due to the anisotropy of 2G HTS coated conductors, only isotropic characteristics have been taken into account in this study. Solenoidal geometry has been used in the past to construct large-scale SMES devices using low-temperature superconductors despite the disadvantage of a high stray field. SMES based on first-generation HTS wires with solenoidal shapes have been developed more recently. In contrast, toroidal geometry is often assumed when 2G HTS materials are being studied. Due to the strong reliance of its Jc vs. B performance on the orientation of the field, the material demand may be predicted to be reduced when the toroidal geometry is applied to the magnetic field on the conductor. Since the perpendicular field would be less, AC losses should be reduced as well. However, increased external heat loads from radiation would be experienced by a toroidal SMES of greater overall size. The area of a toroidal magnet is around 300% more than that of a solenoidal magnet. The complexity of the structure required to hold the pancakes also contributes to an increase in the price of production. Energy is stored using a solenoidal magnet because of this suggested technique.

DESIGN VARIABLES AND CONSTRAINTS

There are several factors that may change the magnet's geometry in a superconducting magnet's design. The bore diameter, aspect ratio, number of turns/thickness of the coil, and supporting structure are all crucial geometrical characteristics for a solenoidal magnet. HTS tape with Ic 330 A has been selected to store energy, and higher load factors have been considered for keeping the length of the HTS tape as minimal as possible so that maximum energy can be stored within the definable limits of the design (bore diameter, number of single or double pancake coils, number of winding turns of superconductor, total length of superconductor, etc.). The lowest length that can yet provide the desired performance is selected due to economic considerations connected to the high price of the superconductor. Careful selection of design restrictions and variables allows for an optimal energy storage system. However, optimizing the magnet settings was not a focus of this investigation.

3.5 Electromagnetic Design of HTS Magnet

For the 1 MJ HTS magnets, solenoidal geometry was examined. The solenoid consists of a number of pancake coils stacked atop one another along the axial axis. Pancake coil arrangement, current leads, supporting structure, vacuum shell, non-metallic structure, and cryocooler ports for cooling operations or liquid nitrogen inlet/outlet ports are just few of the numerous sub-systems that make up a whole SMES system. Since the critical temperature of ReBCO tapes is more than 77 K, liquid nitrogen is often used to cool 2G HTS magnets.

The following analytical relations allow for the construction of Solenoidal HT-SMES:

1. First, using the energy reference field (Bref), the bore volume (Vbore) of the solenoid may be calculated using the following relation [168].

$$V_{bore} = 2\mu_o \Delta E / B_{ref}^2; \quad D_{sol} = \left(4V_{bore} / a\pi\right)^{1/3}; \quad H_{sol} = aD_{sol} \qquad 1$$

In this equation, a represents the aspect ratio, Dsol the bore diameter, and Hsol the solenoid's height.

2 2Maximum current density in the SC conductor is calculated using the formula Jmax =c Jc, where c is the maximum permissible value of J and Jc, respectively. Using Jmax, we can calculate the maximum safe field in the solenoid's core, Bmax. From this, we can also calculate the maximum energy that the solenoid can store, Emax.

To construct a solenoid of thickness sol, we require a length of SC conductor equal to SSC, where SSC is the cross section of the conductor and Rm is the average radius of the solenoid (Rm = Dsol/2 + is assumed to unity). packing factor (b), density (sol/2)

$$length_{SC} = 2\pi R_m H_{sol} \delta_{sol} / S_{SC} \qquad 2$$

3 3Because of the magnetic field, the coil experiences a Lorentz force. This causes a stress pattern that the superconductor must be able to endure. In the case of a thick solenoid, the maximum tensile stress on the superconductor may be determined with the help of Equation 3-3, where r is the ratio of the outer to the inner diameter of the solenoid, and (r = 1 + 2sol/Dsol). From a purely mechanical standpoint, the constructed coil may be considered satisfactory if the maximum stress is much lower than the critical tensile stress of the superconductors.

$$\sigma_{max} = \frac{1}{2} J_{max} B_{max} D_{sol} \frac{1}{r-1} \left[\frac{2r(7r^2+r+1)}{9(r+1)} - \frac{5}{12}\left(2r^2 + r - \frac{3}{5}\right) \right] \qquad 3$$

4 4The last decision in solenoid design is the selection of the turn count (N). An accurate estimation of the inductance 'L' and, by extension, the solenoid's effectiveness, relies heavily on this value. Equations 3-4 and 3-5 [168] determine the maximum current Imax and the delivered energy E of the solenoid, respectively. These values are proportional to the solenoid's thickness sol and the number of turns N. Keep in mind that because L grows as N2, the greatest amount of energy that may be stored does not rely on N. A large number of turns, resulting in a high inductance L, is preferable for a solenoid with a certain thickness sol and maximum storable energy Emax since it indicates a lower maximum current Imax with decreased size and the heat load of current leads. With a reduced peak current, the DC/DC converter's switches may be made smaller.

$$I_{max} = J_{max} H_{sol} \delta_{sol} / N \qquad 3.4$$

$$\Delta E = \frac{1}{2} L\left(I_{max}^2 - I_{min}^2\right) \qquad 3.5$$

The following equation may be used to approximate the amount of energy that will be delivered:

$$\Delta E \approx \pi R_{sol}^2 H_{sol} B_{ref}^2 / 2\mu_o \qquad 6$$

The aforementioned analytical relations are then used to a study of the influence of current, solenoid thickness, and operating temperature on the magnet topology.

Self-field effects on Magnet topology for Single Pancake Coil

Superconducting tapes in a solenoidal or toroidal form may be used to store magnetic energy superconductingly. The current research proposes a solenoidal configuration for energy storage and assesses the impact of self-field on those parameters. It is possible to estimate the amount of energy that can be delivered from an inductor using, and to determine the maximum amount of energy that can be held in an inductor while a current of Imax flows through it using. The tape has an Ic of 330 A at a self-field of 0 T, and it draws an operational current of 270 A at an estimated load factor of 81%. It has been assumed that the critical current (Ic) and the load factor are constants, and that the minimal current (Imin) is the current running through a single tape. This requires a minimum deliverable energy of 1 MJ, an inductance of 0.784 H, and a maximum current through the tape of 1.62 kA (assuming six cassettes are stacked).

the superconductor length increases for the same delivery and maximum energy as the load factor decreases, suggesting that operating close to the critical current (high load factor) is preferable since less superconducting tape is required for energy storage that when the transport current is reduced, the inductance rises, indicating that more time is needed for the current to reach steady state. However, only a steady-state study (where the magnetic vector potential A/t 0) has been carried out here. When self-field effects are included, however, the tape's Ic drops to 275 A, which is much lower than the Ic (330 A) at 77 K @ 0 T. Operating current through a single tape dropped from 275 A to 225 A while maintaining the same load factor as without self-field effect. The fluctuation in superconductor length with operating currents with and without self-fields, after holding Emax and E constant. This indicates that more superconductor is needed to store the same amount of energy. With A and A1 standing for a load factor (LF) of 0.81 and E and E1 standing for an LF of 58%. The length of SC tape needed to store 1 MJ of energy is shown to grow from 12.8 km (Ic=330 A) to 15.4 km (Ic=275 A).

CONCLUSIONS

In this study, we look at the impact of the self-field on the critical current for magnet coils, taking into account different approximations to get over the challenges of computational modeling. Using the Kim model and a parameter P, we can guarantee the presence of the critical current on at least one tape out of 108 cassettes of a pancake coil, therefore identifying the self-field effects. It has been determined that self-field may greatly affect the magnet topology by affecting the critical current of the coil. Therefore, this factor has to be taken into account throughout the superconducting magnet's development. Input, design, and restrictions factors are analyzed, and the impact of operating current, solenoid thickness, and operating temperature on the magnet topology are investigated in this study, which focuses on the mechanical design features of the solenoid magnet. It may be deduced from the research that less superconducting tape is needed for energy storage if the operating temperatures are low since greater currents have a major influence on the length of the superconductor utilized for energy storage. Second, given the same total number of turns, it has been observed that the overall height and bore diameter may be reduced if greater solenoid thicknesses are employed for magnet design.

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