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EFFECT OF MECHANICAL DESIGN OF SUPERCONDUCTING COIL

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ABSTRACT

Superconducting Magnetic Energy Storage (SMES) systems have been identified as possessing advantages over other energy storage systems due to its ability to provide much greater power densities and superior reaction times compared to bulk energy storage systems such as hydro and CAES. This dissertation examines the potential designs of Superconducting Magnetic Energy Storage (SMES) systems, with a focus on categorizing the prior advancements in SMES design at both national and international levels. The identification of the high temperature superconducting tape is based on the assessment of manufacturers' offerings and the tape's current carrying capabilities. The tape selected for the current investigation has a substrate material that is not magnetic. Moreover, a comprehensive investigation has been conducted on the mechanical design of the 1 MJ Superconducting Magnetic Energy Storage (SMES) systems operating at a temperature of 77 K. This study encompasses the identification of all design parameters, as well as the constraints and input factors associated with the design process. The investigation has opted for a solenoidal magnet arrangement, with a reference field strength of 3 Tesla selected for the design.

KEYWORDS: Mechanical Design, Superconducting Coil, Superconducting Magnetic, energy storage systems, high temperature.

INTRODUCTION

A superconducting magnet has many sub-systems, including the primary superconducting coil, current leads, cryogenic setup, and supporting structure. Numerous research institutions have conducted investigations pertaining to the structural, thermal, and magnetic aspects of the Superconducting Magnetic Energy Storage (SMES) system. The following sections provide an extensive analysis of the global and domestic standing of superconducting magnets.

Literature Survey (International Status)

The commercialization of superconducting magnetic energy storage technology has been delayed owing to economic restrictions, resulting in its current status as a technology in the development phase. The installation of the most renowned superconducting magnet experiment, using a NbTi superconductor, has taken place at CERN in Geneva. In this experiment, the magnet is subjected to a cooling process employing superfluid Helium, maintaining a temperature of 1.9 K. The use of Low Temperature Superconductors (LTS), namely NbTi and Nb3Sn, has been extensively exploited in the fabrication of magnets. Following the discovery of High Temperature Superconductors (HTS), the scientific community has used these materials for energy storage purposes due to their cost-effectiveness in comparison to Low Temperature Superconductors (LTS). Additionally, HTS materials have shown the ability to create stable magnetic fields with high energy densities and compact dimensions, surpassing the capabilities of LTS materials. Numerous scholars have conducted simulations pertaining to the structural characteristics of high-temperature superconducting (HTS) superconducting magnetic energy storage (SMES) systems, including considerations such as magnet form and configuration. Different types of configurations, such as solenoidal, toroidal, D-shaped, and racing track coils, have been used in the creation and advancement of the high-temperature superconducting (HTS) magnet.

The HTS technology utilizes two primary kinds of HTS tapes for the advancement of SMES, namely 1st Generation (1G) HTS Tapes (BSCCO-2212 and BSCCO-2223) and 2nd Generation (2G) HTS tapes, namely Yttrium Barium Copper Oxide (YBCO). The literature indicates that both 1G and 2G tapes have been used in the construction of high-temperature superconducting (HTS) magnets. However, it has been observed that 2G tapes exhibit superior performance compared to 1G tapes in terms of their ability to carry higher currents and give enhanced mechanical strength. Numerous research endeavors are dedicated to the computational advancement of high-temperature superconducting magnetic energy storage (HTS SMES) systems. Several research institutions, such as 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 achieved successful development of their prototypes.

Literature Survey (National Status)

In India, endeavors have been undertaken to cultivate such systems via the use of Low Temperature Superconducting technology (below 10K) at IIT Kharagpur and Variable Energy Cyclotron Centre (VECC) in Kolkata, operating at Liquid Helium temperatures. Limited research has been documented beyond our prior work, which focused on the integration of high temperature superconducting tapes in the advancement of Superconducting Magnetic Energy Storage (SMES) devices in India. Tables 3.1 and 3.2 provide a comprehensive overview of the theoretical and experimental investigations conducted on Superconducting Magnetic Energy Storage (SMES) systems with diverse energy capacities.

This chapter primarily focuses on the design of a superconducting coil, specifically highlighting the identification of design criteria and restrictions related to HTS tape before to commencing the actual design process. The following sections provide a comprehensive explanation of the procedural steps involved in the electromagnetic design of a magnet coil.

SELECTION OF HIGH TEMPERATURE SUPERCONDUCTING TAPE

High temperature superconducting (HTS) tapes may be classified into two distinct categories: the first generation and the second generation tapes. When comparing the two, it is seen that second generation high-temperature superconducting (HTS) tapes have the ability to support larger current densities under high magnetic fields and exhibit higher critical currents compared to first generation tapes at a temperature of 77 K. Yttrium Barium

Copper Oxide (YBCO) is a commonly used kind of second-generation tapes, whereby Yttrium (Y) is utilized as a rare earth metal owing to its superior attributes compared to first-generation tapes. The HTS tape produced by Superpower (SCS 12050) has been chosen for the current investigation because to its specific design for use in high magnetic field scenarios, such as magnets, and its non-magnetic substrate.

SELECTION OF MAGNET CONFIGURATION

The careful selection of the superconducting magnetic energy storage (SMES) magnet cross-section is a critical aspect in the magnet design process. The first prerequisites for the device are its strength, spatial considerations, and resilience, given the significant pressures often connected with such devices. In the existing body of literature, researchers have used several combinations so far in order to get an optimized design for the high-temperature superconducting (HTS) SMES device for energy storage.

Various efforts have been undertaken in the past to build economically viable and ecologically sustainable Superconducting Magnetic Energy Storage (SMES) magnets, starting with the Low Temperature Superconductors (LTS) such as Nb-Ti and Nb3Sn. Following the discovery of high temperature superconductors (HTS), scholars have shown a preference for HTS technology over low temperature superconductors (LTS) in the advancement of superconducting magnets. This inclination is primarily driven by considerations of economic viability and durability. During the first phases, magnets are being constructed using First Generation (1G) tapes, namely Bismuth Strontium Calcium Copper Oxide (BSCCO-2212 and 2223). The production of these superconductors involves the use of "Powder-in-Tube" technology. Nevertheless, recent findings have shown that Second Generation (2G) High-Temperature Superconducting (HTS) tapes, specifically coated conductors such as Yttrium Barium Copper Oxide (YBCO), have the capacity to transport higher levels of electric currents compared to their First Generation (1G) counterparts. In this investigation, YBCO tapes produced by Superpower® SCS12050 have been used for the construction of the superconducting magnet. Two different geometrical configurations are possible for the SMES, namely the solenoid and the toroid, as seen in Figure 3.2. According to literature, it has been determined that the solenoidal configuration is more straightforward to produce and facilitates the management of mechanical stress with more ease. Furthermore, in the case of isotropic superconductors, the use of a solenoid structure not only minimizes wire consumption but also represents the most economically efficient approach.

However, it should be noted that 2G HTS coated conductor’s exhibit anisotropic behavior. However, for the purposes of this study, only the isotropic features of these conductors have been taken into account. Although the large stray field is a limitation, solenoidal geometry has been used in previous instances for the advancement of full-scale SMES (Superconducting Magnetic Energy Storage) systems using low temperature superconductors. In recent times, solenoidal geometries have also been used in the advancement of Superconducting Magnetic Energy Storage (SMES) systems using first generation High-Temperature Superconducting (HTS) wires. In the context of 2G HTS materials, it is often believed that a toroidal geometry is used. The use of toroidal geometry results in a reduction of the perpendicular component of the magnetic field acting on the conductor. Consequently, this reduction leads to an anticipated decrease in the material need. This is mostly due to the significant influence of the direction of the magnetic field on the critical current density (Jc) against magnetic field (B) performance.

It is reasonable to anticipate a decrease in AC losses as a result of the reduced perpendicular field. Nevertheless, an increase in the overall dimensions of the toroidal Superconducting Magnetic Energy Storage (SMES) system will lead to an augmentation in the external heat loads caused by radiation. Indeed, it can be seen that the surface area of the toroidal magnet is about three times greater than that of the solenoidal magnet. Moreover, the inclusion of a more intricate support system is necessary to effectively secure the pancakes, thereby leading to an escalation in the total expenditure associated with manufacture.

DESIGN VARIABLES AND CONSTRAINTS

The design of a superconducting magnet encompasses several aspects that may influence the magnet's geometrical configuration. The key geometric factors for a solenoidal magnet are the diameter of the hole, the aspect ratio, the number of turns or thickness of the coil, and the characteristics of the supporting structure. Taking into consideration the various design variables such as bore diameter, the number of single or double pancake coils, and the number of winding turns of the superconductor, as well as the constraints imposed by the stray magnetic field, critical magnetic field, and total length of the superconductor, an HTS tape with a critical current (Ic) of 330 A has been selected for the purpose of energy storage. Additionally, higher load factors have been taken into account in order to minimize the length of the HTS tape, thereby maximizing the amount of energy that can be stored within the specified design constraints. The selection of a minimum length is motivated by the consideration of the superconductor's cost, which in turn impacts the economic limitations. The achievement of an optimal energy storage design necessitates the careful selection of design constraints and variables. However, the optimization of the magnet settings has not been taken into account in the current work.

ELECTROMAGNETIC DESIGN OF HTS MAGNET

The use of a solenoidal shape has been taken into account in the conceptualization of a 1 MJ high-temperature superconducting (HTS) magnet. The solenoid consists of a series of pancake coils stacked vertically in the axial direction. Comprehensive superconducting magnetic energy storage (SMES) system has many subsystems, including a pancake coil configuration; current leads, supporting structure, vacuum shell, non-metallic structure, and cryocooler ports for cooling operations or liquid nitrogen inlet/outlet ports. In general, the cooling method used for 2G HTS magnets involves the utilization of liquid nitrogen due to the fact that the critical temperature of ReBCO tapes exceeds 77 K. Nevertheless, as previously mentioned, the current carrying capability of high-temperature superconducting (HTS) tapes is lower at 77 K in comparison to temperatures of 50 K, 20 K, or those achieved with liquid helium. Therefore, in order to operate at temperatures below 77 K, conventional methods such as the use of liquid hydrogen (20 K), liquid neon (27 K), liquid helium (4.2 K), or cooling systems based on cryocoolers have been applied. In the current investigation, it has been taken into account that the magnet is subjected to a cooling process at a temperature of 77 K by the use of liquid nitrogen.

Effect of Current on the Magnet Topology

This section examines the impact of electric current on magnet topological properties, including inductance, solenoid thickness, number of turns around pancake coils, and length of the superconductor. The study investigates the impact of varying the operating current via a single tape within the range of 170 A to 270 A on the design parameters of the magnet. In order to enhance the maximum current (Imax) and minimize the length of the superconductor required for storing 1 MJ of energy, a configuration including the stacking of six tapes is used. The lowest transport current of the tape has been seen to range from 170 A to 270 A, while the maximum transport current (Imax) has correspondingly ranged from 1020 A to 1620 A. The observed phenomenon is that the inductance of the coil decreases as the running current increases, in order to maintain a consistent level of deliverable energy (ΔE) and maximum energy (Emax).

Effect of Solenoid Thickness on Magnet Topology

This section examines the impact of different solenoid thicknesses, ranging from 5 mm to 35 mm, on key magnet design characteristics. These factors include the bore diameter, height of the solenoid, number of turns per unit length, number of solenoid per coil, and length of the superconductor. In order to assess the impact of solenoid thickness on magnet design parameters, a study was conducted on a set minimum operating current of 270 A running through a single high-temperature superconducting (HTS) tape. The study focused on a deliverable energy of 1 MJ and a fixed maximum energy.

Effect of Operating Temperature

In this study, it is assumed that the magnet is maintained at a temperature of 77 K. However, upon analyzing the characteristic curve B-T for the tape at a temperature of 14 K, it has been observed that the presence of a perpendicular magnetic field significantly influences the critical temperature of the tape. Specifically, at a self-field of 0 T, the critical temperature is approximately 330 A for a temperature of 77 K. At zero tesla self-field, the critical temperature of the tape is more than ten times that at 77 Kelvin. An endeavor has been undertaken to determine the ratio of critical currents (14K/77K) at varying perpendicular magnetic flux densities.

CONCLUSION

The mechanical design considerations of the solenoid magnet have been investigated, with a focus on evaluating input, design, and constraint factors. The impact of operating current, solenoid thickness, and operating temperature on the magnet's topology has been analyzed. Based on the findings of the research, it can be inferred that increased currents have a notable influence on the length of the superconductor used for energy storage, so suggesting that reduced quantities of superconducting tape would be necessary for energy storage at low operating temperatures. Additionally, while using larger solenoid thicknesses in magnet design, it is seen that the overall height and bore diameter drop while maintaining the same total number of turns. Based on the findings of the electro-thermal analysis conducted on the superconducting tape, it has been shown that an increase in the interfacial resistance of the superconducting-stabilizer layer may lead to an enhancement of the normal zone propagation velocity (NZPV). This enhancement in NZPV can be beneficial in regulating the quenching process of the tape. Nevertheless, as a result of the heightened interfacial resistance, there is a potential for amplified resistive losses. Consequently, more investigations are necessary to delve deeper into this matter.

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