Analysis on Solenoidal High Temperature Superconducting Magnet using COMSOL MultiPhysics®

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Abstract

Superconducting tapes are one of the advanced materials which show their candidacy in almost every electrical engineering applications starting from the energy/power generation (Superconducting Generators) to the household/industrial distributed systems (Superconducting Transformers). Also, superconducting tapes are being exploited in energy storage applications where such tapes can be wound to form a solenoidal or toroidal shaped magnet. It has been found that solenoidal magnet consumes less superconducting material compared to toroidal thus in the present analysis solenoidal configuration has been considered where an attempt has been made to design a magnet that can store 600kJ of energy. The magnet is designed to be cooled at 20K using conduction cooling. 1st Generation HTS tape (BSCCO-2223) has been considered whose critical current at 20K is found to be 480A. Analysis shows that it will be useful to use higher currents in order to minimize the total length of the superconducting wire needed to store 600kJ of energy. A reference field of 3.5T has been employed in the design of 600kJ HTS SMES having 297mm bore diameter and inductance of 1.296H. Also, it has been assumed that the evaluated perpendicular magnetic flux density should not exceed 3T.

Keywords: YBCO superconductors, HTS SMES, Lorentz force, Solenoidal Magnet, Superconducting Magnetic Energy Storage.

Introduction

There are numerous commercial energy storage systems such as mechanical, electro-chemical, thermal, electrical and chemical storage systems. However, these energy storage systems have their own constraints related to cost, storage capacity, power density and response time. To conquer such challenges, development of Superconducting Magnetic Energy Storage (SMES) technology is one of the solutions. Possible applications of SMES include load leveling, dynamic stability, transient stability, voltage stability, frequency regulation, transmission capability enhancement, power quality improvement, automatic generation control, uninterruptible power supplies, etc [1]–[10]. The one major advantage of the SMES coil is that it can discharge large amounts of power for a small period of time. Also, unlimited number of charging and discharging cycles can be carried out. After considering all the merits of SMES systems, an attempt has been made in the present study to evaluate the electromagnetic behavior of a 600kJ of SMES. The effect of maximum current on the inductance has been evaluated. Also, it has been found that there is no effect of the number of tapes stacked one over the other on the length of the superconductor if same maximum current is flowing through each.

HTS Tape specifications

In the present work, solenoidal configuration has been employed in the development of 600kJ SMES Magnet using 1G BSCCO-2223 tape [11]–[15]. The superconducting tape has been cooled at 20K using conduction cooling as it does not involve any multiphase heat transfer problems. For this study it has been assumed that the perpendicular field will not exceed 3T. This means it is possible to send 336A of current through single tape when 70% of load factor is taken into account. In order to have lower inductance (1.296), higher current of magnitude 1008A has been by staking three HTS tapes one over the other in order to store 658kJ of maximum energy.

Table 1 shows the variation in coil inductance and maximum storable energy (Emax) with respect to the magnitude of total maximum current while keeping minimum current and deliverable energy as constant.

$$E_{max} = \frac{1}{2} L\, I^2_{max} \qquad (1)$$

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

Table 1. Effect of Maximum Current on Emax and Inductance of the Coil

Imax (A)	336	672	1008
Imin (A)	300	300	300
Emax (MJ)	2.96	0.75	0.658
Deliverable Energy (kJ)	600	600	600
Inductance (H)	52.41	3.319	1.296

Analysis on HTS SMES

An electromagnetic analysis has been performed using COMSOL MultiPhysics® 5.2 on HTS SMES, having bore diameter of 297mm and aspect ratio of 6. Since the tape width is 4.5mm thus 396 Single Pancake Coils (SPCs) are arranged one over the other in axial direction of the solenoid. It has been assumed that the axial gap between the SPCs kept to zero. The model is symmetric about *r=0* and the parameters for axisymmetric model have been enlisted in following Table 2. Time dependent analysis has been done on the SMES where Faraday's Law (Equation 3 and Equation 4) has been incorporated on the both domains which estimate the magnetic flux linking to it.

Superconducting Coil acts like an inductor, therefore steady state current can be achieved after few time constants. Therefore, time dependent studies are needed to be performed in order estimate the magnitude of magnetic flux densities. Figure 1 shows the axisymmetric model of the HTS SMES having a bore diameter of 297mm and height of 1780mm.

$$E = \rho (\nabla \times H - J_e)$$
$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (3)$$

$$E = E(\nabla \times H)$$
$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (4) \text{ and}$$
$$E = E_o \left(\frac{J}{J_c} \right)^{\alpha}$$

Where α is the index and for this analysis its value is 21.

Table 2. Parameters of HTS SMES

Parameter	Value
Inner bore radius, r1	148.5mm
Thickness of Solenoid, (r2-r1)	44.74mm
Energy Stored, Emax	658kJ
Deliverable Energy	600kJ
Inductance of the Coil	1.296H
Load Factor	0.7
Minimum Current, Imin	300A
Number of SPC	396
Number of Turns of SC Tape (Approx.)	4922
Number of turns/SPC (Approx)	37
Maximum Current, Imax	1kA
No. of SC tape used to support Imax	3
Critical Current Density, Jc	6.23E7
Resistivity of Vacuum (ohm*m)	0.001
Total Length of single SC Tape	15.82km

Figure 2 indicates the magnetic flux density distribution (normB component) for the solenoidal magnet and it can be noticed that a magnetic field of 3.538T has been achieved for a circulation current of 1008A. Figure 3 shows the perpendicular magnetic flux distribution for the solenoidal magnet and it has been found that the perpendicular component is restricted to 2.45T which is it is far below 3T, thus it implies that the design is safe.

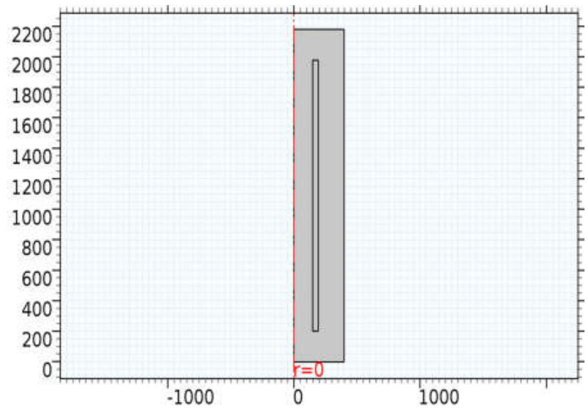

Figure 1 2D Axisymmetric Model

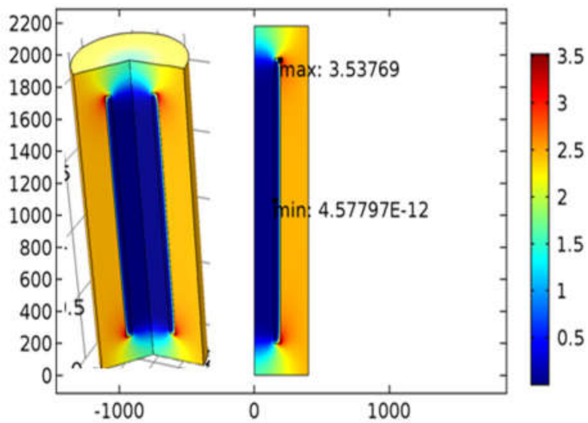

Figure 2 Magnetic Flux Density Distribution (normB component) (T)

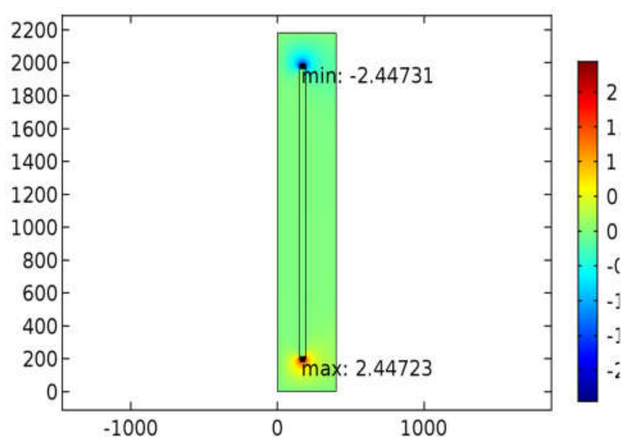

Figure 3 Perpendicular Magnetic Flux Density (T)

Conclusions

In the present work, electromagnetic analysis on 600kJ of HTS SMES has been done using axisymmetric 2D model. It has been found that the perpendicular magnetic flux is limited to 2.45T, thus the design is safe as the chosen field was 3T.

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