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Enhancing the design of a superconducting coil for magnetic energy storage systems

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ABSTRACT

Study and analysis of a coil for Superconducting Magnetic Energy Storage (SMES) system is presented in this paper. Generally, high magnetic flux density is adapted in the design of superconducting coil of SMES to reduce the size of the coil and to increase its energy density. With high magnetic flux density, critical current density of the coil is degraded and so the coil is wound with High Temperature Superconductors (HTS) made of different materials. A comparative study is made to emphasize the relationship between the energy storage and length of the coil wound by Bi2223, SF12100, SCS12100 and YBCO tapes. Recently for the construction of HTS magnets, YBCO tapes have been used. Simulation models for various designs have been developed to analyze the magnetic field distribution for the optimum design of energy storage. The design which gives the maximum stored energy in the coil has been used with a certain length of second-generation HTS. The performance analysis and the results of comparative study are done.

1. Introduction

Size and weight of the energy storage system are comparatively lesser in SMES than other energy storage systems [1]. SMES stores energy in the form of magnetic field. The invention of HTS in 1986 makes SMES as the hot research area. Recently for the construction of HTS magnets, YBCO tapes have been used [2–6]. Compared to other energy storage methods, SMES exhibits a better performance. The current density of SMES coil is about 10–100 times larger than the common coil because it has virtually no resistive losses. Consequently, the Energy with a higher density can be stored in a persistent mode until required. SMES system has superior features such as high efficiency, fast response and no performance degradation due to repetition of charging and discharging of the coil. The SMES system is expected to be used for power system stabilization, load fluctuation compensation and instantaneous voltage drop compensation [7]. A new advanced SMES consists of renewable energy resources, SMES coil and a hydrogen energy storage system. This system uses the renewable energy effectively [8,9].Therefore, a focus on more researches has been performed for practical use of SMES system [10–12].

The solenoid-type SMES coil is preferred due to its simple configuration and high energy storage capacity [13]. An effective method of reducing superconducting wire usage by considering the maximum magnetic flux density within the SMES coil has not been investigated effectively so far. In general, high magnetic flux density is adapted in the superconducting coil design to make the coil size to be smaller. However, critical current density of the superconducting coil is degraded when high magnetic flux density is adapted to the superconducting coil. High magnetic flux density is not only the criteria for reducing superconducting coil size it also depends on the J_C–B characteristics and the coil shape. In this paper, HTS solenoid coil design, its analysis and simulation results are studied.

2. HTS solenoid coil design

In this section, four HTS solenoid coils with different material tapes are designed and compared. Modeling has been carried out in MAGNET software package to design the coil. A common configuration of HTS solenoid coil is shown in Fig. 1. In practice, Bi-2223 or YBCO multifilament HTS tape conductor is chosen to design a HTS solenoid coil. Its main specifications are: width of 4.23 mm, thickness b of 0.23 mm, critical current I_C of 100 A (at 77 K), the critical current density J_C of 10 kA/C.

2.1. Computation of energy storage of SMES coil

Inductance of a superconducting coil is computed as follows [14].

$$L = 2\pi\mu_0 N_C 2R_1^5 T(p,q) \quad (1)$$

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where
$\mu_0 = 4\pi \times 10^{-7}$,
R_1 – Inner radius of the coil

$$N_C = N/(R_2 - R_1)D \quad (2)$$

where
R_2 – Outer radius of the coil
D – Depth of the coil
N – Number of coil turns
$T(p, q)$ – function of size ratio

$$p = \left(\frac{R_2}{R_1}\right), q = \left(\frac{D}{R_1}\right)$$

According to (1) and (2),

$$L = 2\pi\mu_0 R_1^5 T(p,q)\left[\frac{N}{(R_2 - R_1)D}\right]^2 \quad (3)$$

Considering the filling factor K for practical design,

$$Nab = (R2 - R1)D \quad (4)$$

The total length of conductors S is given by

$$S = N\left[2\pi\left(R_1 + \frac{R_2 - R_1}{2}\right)\right] \quad (5)$$

Energy storage of a coil is given by

$$E = \frac{1}{2}LI^2 \quad (6)$$

2.2. Design of HTS solenoid coil

For the practical design of HTS solenoid coil, inner radius R_1, outer radius R_2 and cross sectional area $(R_2–R_1)$ D are considered.

2.2.1. Comparison of Bi2223 and YBCO coil

Table 1 gives the main geometries of Bi2223 and YBCO coil. The computed value of size ratios (p,q) is (2,1) respectively. $T(p,q)$ of Bi2223 is computed as 0.3290 [15]. A solenoid coil having the size ratios (2, 1) is called as Brooks Coil and this coil gives the maximum inductance for a given length and volume of the conductor.

HTS coil should be wound with a certain insulating layer. The total width and the thickness of Bi2223 HTS conductor with insulating layer are 6 mm and 0.6 mm respectively. Therefore, a reasonable filling factor is 32.2%. Using Eqs. (3) and (4), the inductance and the number of turns in Bi2223 coil are calculated as 1 H and 2186 respectively. Total length of HTS coil is calculated as 1668 m using Eq. (5) [16]. Critical current through the Bi2223 coil is100 A.

In the proposed YBCO coil, the same filling factor of 32.2% is considered. The inductance and the number of turns in YBCO coil are 1.8 H and 2186 respectively. Using Eq. (5), the total length of YBCO coil is calculated as 1668 m. Table 2 gives the comparison of Bi2223 and YBCO coil. Inductance, energy storage and flux density are more in YBCO compared to Bi2223 coil.

The design of YBCO coil and its energy storage are shown in Fig. 2a. Assume that the center co-ordinate of magnetic distribution is (0, 0) and the coil is symmetrically placed around it. A line 'a' from (−100, −200) to (−100, 100) is added to analyze the flux density pattern. The magnetic flux density pattern of YBCO and Bi2223 coil are obtained as shown in Figs. 2b and 2c.

The usage of the superconducting wire is improved with the maximum magnetic flux density in YBCO. This means that the

Table 1
Main geometries of Bi2223 and YBCO coils.

Material	R_1 (mm)	R_2 (mm)	D (mm)	No of turns	Length (m)	Volume (m^3)
Bi2223	81	162	81	2186	1668	0.0005
YBCO	81	162	81	2186	1668	0.0005

Table 2
Comparison of Bi2223 and YBCO Coils.

Material	Inductance (H)	Energy storage (J)
Bi2223	1	5000
YBCO	1.8	9000

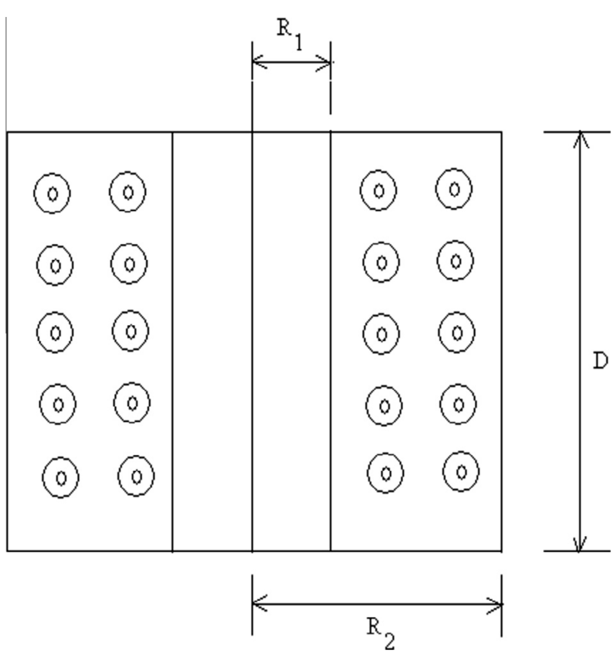

Fig. 1. Scheme of HTS solenoid coil.

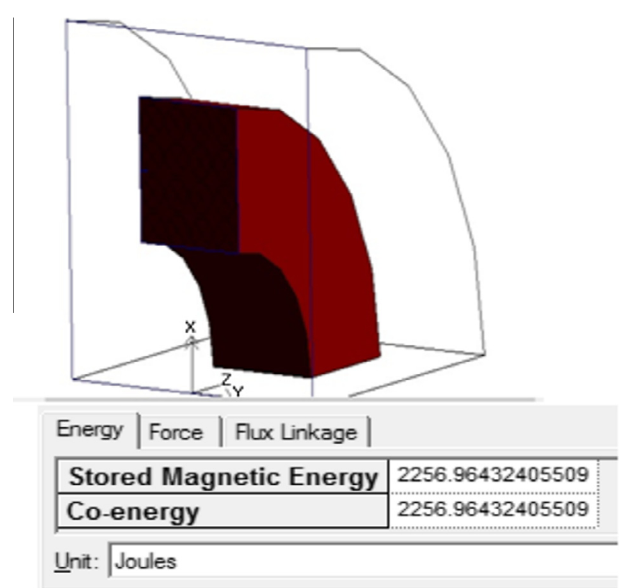

Fig. 2a. Energy storage of YBCO coil.