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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

$$N_C = N/(R_2 - R_1)D \tag{2}$$

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),

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

Considering the filling factor K for practical design,

$$Nab = (R2 - R1)D \tag{4}$$

The total length of conductors S is given by

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

Energy storage of a coil is given by

$$E = \frac{1}{2}LI^2 \tag{6}$$

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

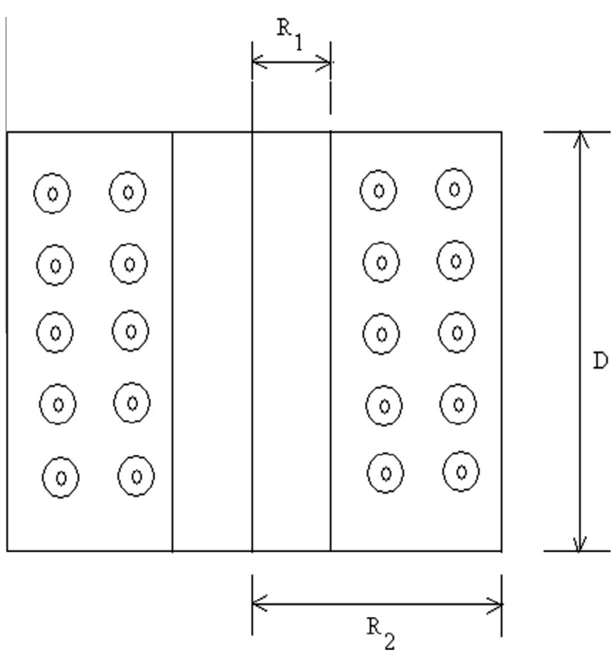

Fig. 1. Scheme of HTS solenoid coil.

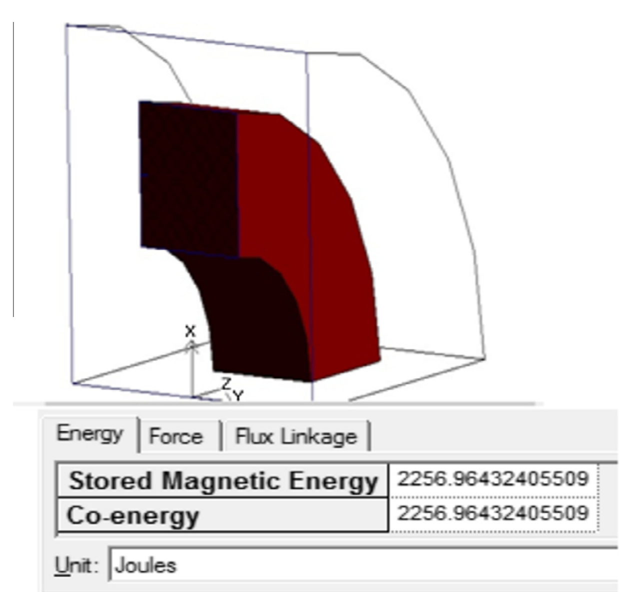

Fig. 2a. Energy storage of YBCO coil.

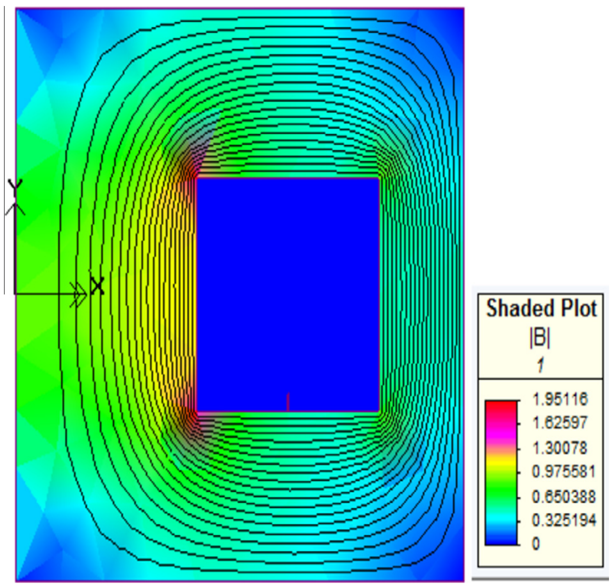

Fig. 2b. Magnetic flux density pattern of YBCO.

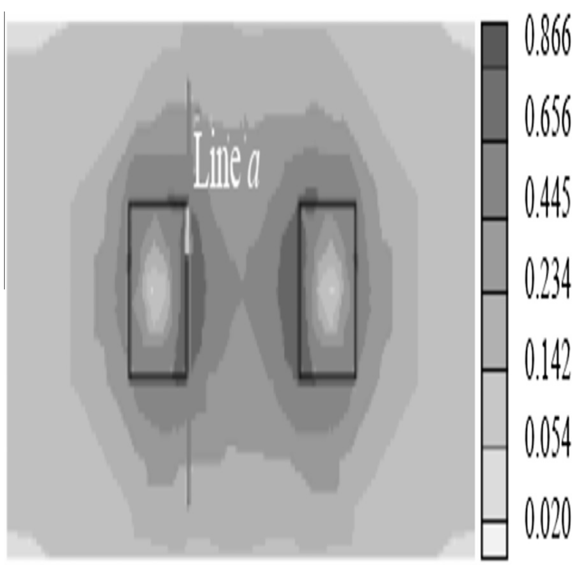

Fig. 2c. Magnetic flux density pattern of Bi2223 coil.

influence of critical current degradation due to increase of magnetic flux density is less than the influence of decreased size of superconducting wire due to increase of energy density. Therefore, adapting the maximum magnetic flux density of 1.9511 T is effective for reducing the size of the superconducting wire compared to Bi2223.

2.2.2. Comparison of SCS12100 and YBCO tapes

Practically, SCS12100 and YBCO HTS tapes are chosen to design a solenoid coil. In a solenoid configuration, pancake coils are stacked vertically. Table 3 lists the main geometries of SCS12100 and YBCO tapes. Super Power SF12100 tapes wound with pancakes, has the main specifications of width $a = 12$ mm, thickness $b = 0.10$ mm, critical current $I_C = 300$ A at the critical temperature of 65 K, critical current density $J_C = 2.5 \times 108$ (A/m^2). The inductance and the number of turns in SCS12100 tape are calculated as 26.67 mH and 46 respectively using Eqs. (3) and (4). Using Eq. (5), the total length of it is calculated as 0.17 km [17].

Table 3
Main geometries of SCS12100 and YBCO tapes.

Material	R_1 (cm)	R_2 (cm)	D (cm)	Length (km)	No. of turns
SF12100	4.5	6.8	2.4	0.17	460
YBCO	4.5	6.8	2.4	0.17	460

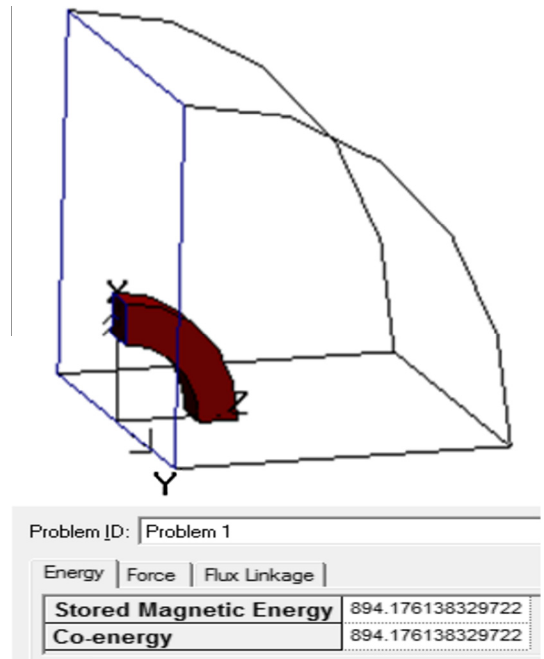

Fig. 3a. Energy storage of YBCO tape in comparison with SCS12100 tape.

From Table 3, it is clear that the parameters of SCS12100 and YBCO tapes are same. In YBCO tape, the critical temperature is 77 K. In case of proposed YBCO tape, the inductance and the number of turns are computed as 79.4 mH and 460 respectively. For the critical current of 300 A, the energy stored and the magnetic flux density pattern of YBCO tape are as shown in Figs. 3a and 3b. Maximum magnetic flux density of 2.9226 T is effective for reducing the size of the superconducting wire compared to SCS12100 Tape. Table 4 gives the comparison of SCS12100 and YBCO Tapes.

2.2.3. Comparison of super power's SF12100 tape and YBCO tape

Practically, SF12100 and YBCO taped conductors are chosen to design a HTS solenoid coil. Its main specifications are: width $a = 12$ mm, thickness $b = 0.150$ mm, critical current $I_C = 201$ A at the critical temperature of 77 K. The main geometries of SF12100 and YBCO tapes are given in Table 5. Using Eqs. (3)–(5), the inductance, the number of turns and the length of SF12100 tape are calculated as 20 mH, 266 and 100 m respectively [18]. The inductance and the energy stored in SF12100 and YBCO tapes are obtained as in Table 6. In case of proposed YBCO, the inductance value is 26.34 mH and the number of turns is 266. The total length of YBCO tape is 100 m. Energy stored and the magnetic field distribution of YBCO tape are as shown in Figs. 4a and 4b. It is clear from Table 6 that when the SMES coil is designed using YBCO wire, the length of coil decreases.

3. Optimal design of SMES coil

For the optimal design of SMES coil, the size ratios (p,q) for square, rectangular and stepped shaped coils are (2, 1), (1.5, 2)

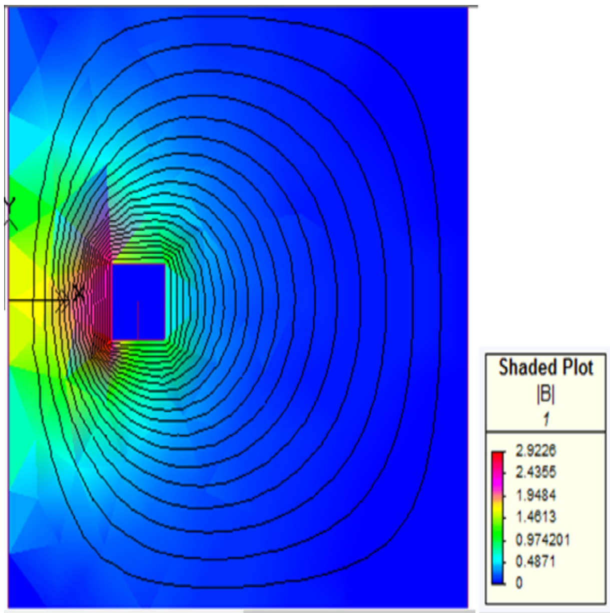

Fig. 3b. Magnetic flux density pattern of YBCO tape in comparison with SCS12100 tape.

Table 4
Comparison of SCS12100 and YBCO tapes.

Material	Inductance (mH)	Energy stored (kJ)	Magnetic flux density (Wb m^{-2})
SCS12100	26.67	1.7	1.91
YBCO	79.40	3.57	2.92

Table 5
Main geometries of SF12100 and YBCO tapes.

Material	R_1 (mm)	R_2 (mm)	D (mm)	Turns	Length (m)
SF12100	40	79.9	12	266	100
YBCO	40	79.9	12	266	100

Table 6
Comparison of SF12100 and YBCO tapes.

Material	Inductance (mH)	Energy storage (J)
SF12100	20	404
YBCO	26.34	532

and (1.5, 2) respectively. $T(p,q)$ for square, rectangular and stepped shaped coils are 0.3290, 0.2046, and 0.1901 respectively [15]. Main geometries of YBCO coil for various shaped coils are given in Table 7.

3.1. Square coil

In the design of square shaped coil, total width and the thickness of YBCO HTS conductor with insulating layer are 6 mm and 0.6 mm, respectively. Therefore, a reasonable filling factor is 32.2%. Using Eq. (3) and (4), the inductance L_1 and the number of turns N_1 are calculated as 1.8 H and 2186 respectively. Using the Eq. (5), the total length of HTS wires S_1 is computed as 1668 m. The current I_1 through the designed coil is 100 A. The magnetic flux density pattern of the square coil is as shown in Fig. 2b.

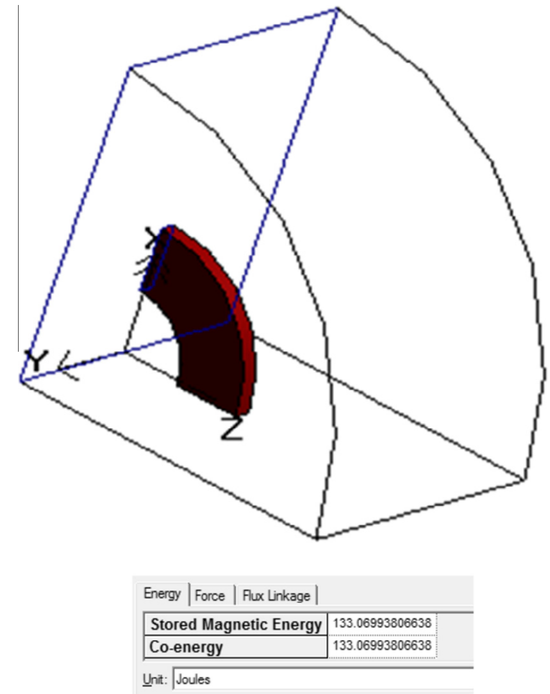

Fig. 4a. Energy storage of YBCO in comparison with SF12100 tape.

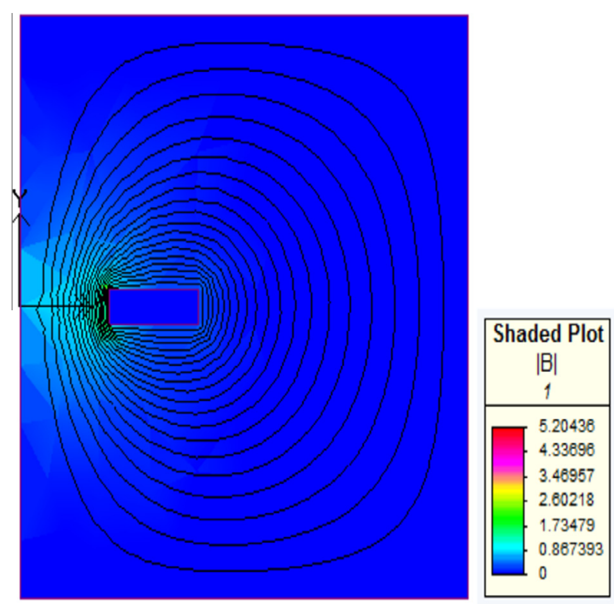

Fig. 4b. Magnetic flux density pattern of YBCO in comparison with SF12100 tape.

Table 7
Main geometries of YBCO tape for the optimal design.

R_1 (mm)	R_2 (mm)	D (mm)	Shape
81	162	81	Square
81	121.5	162	Rectangular
81	121.5	162	Stepped

3.2. Rectangular coil

The filling factor K_1, the length of HTS wires S_1 and the current I_1 in square coil are used to design the rectangular coil with an aim to optimize the design of Superconducting Coil. Using Eqs. (3) and (4), the inductance L_2 and the length of YBCO conductors S_2 in rectangular coil are calculated as 1.07 H and 1390 m respectively. Energy storage and the magnetic flux density pattern of the rectangular coil are shown in Figs. 5a and 5b respectively.

3.3. Stepped coil

The filling factor K_1, the length of HTS wires S_1 and the current I_1 in square coil are used to design stepped coil with an aim to optimize the practical inductor design. Using Eqs. (3) and (4), the inductance L_3 and the length S_3 of YBCO conductors in stepped coil are calculated as 1.41 H and 1250 m respectively. Energy storage and the magnetic flux density pattern of the stepped coil are shown in Figs. 6a and 6b respectively.

Table 8 gives the comparison of different shaped YBCO coils. Brooks coil is chosen to obtain the maximum value of inductance

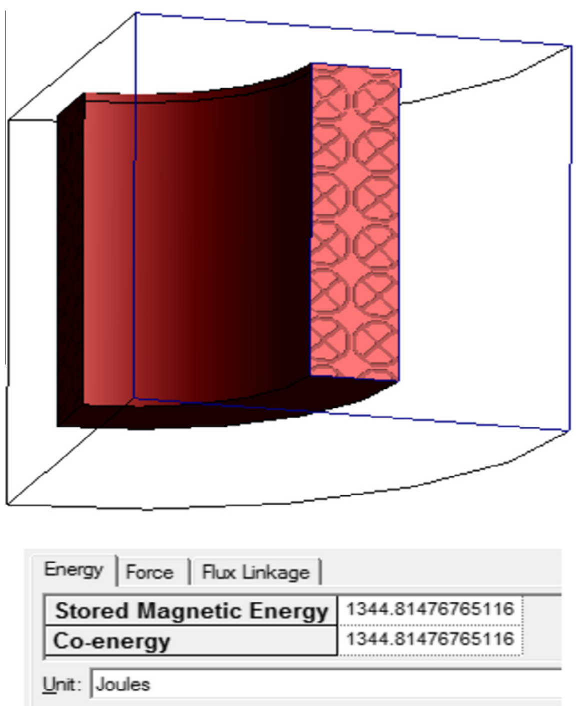

Fig. 5a. Energy stored in rectangular coil.

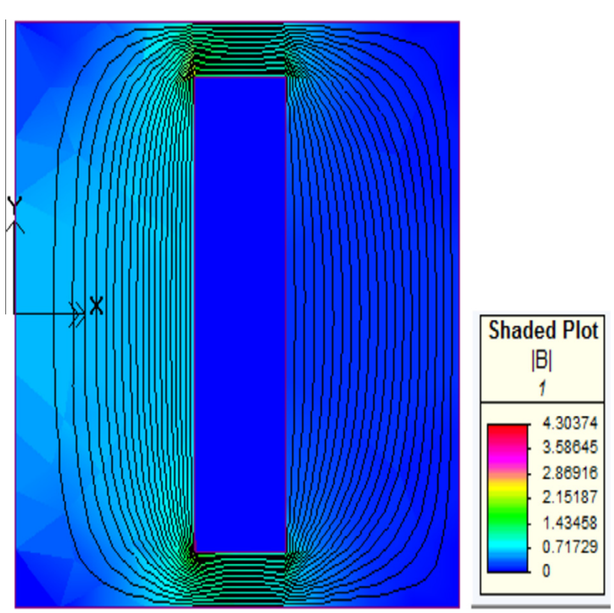

Fig. 5b. Magnetic flux density pattern of rectangular coil.

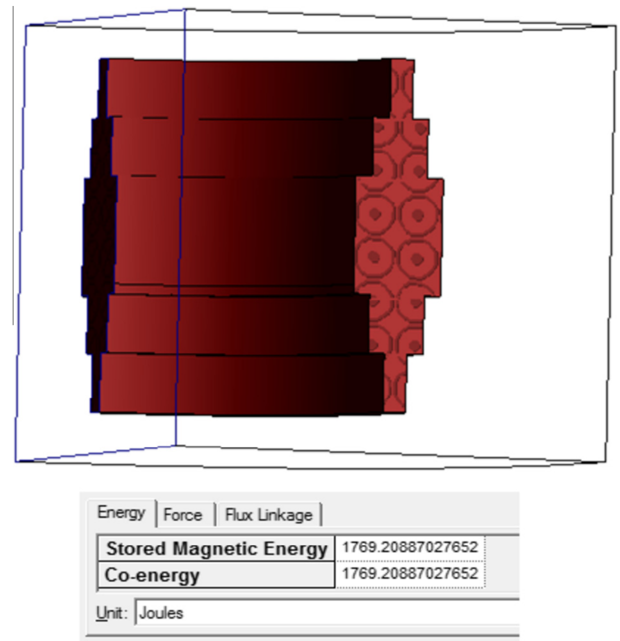

Fig. 6a. Energy stored in stepped coil.

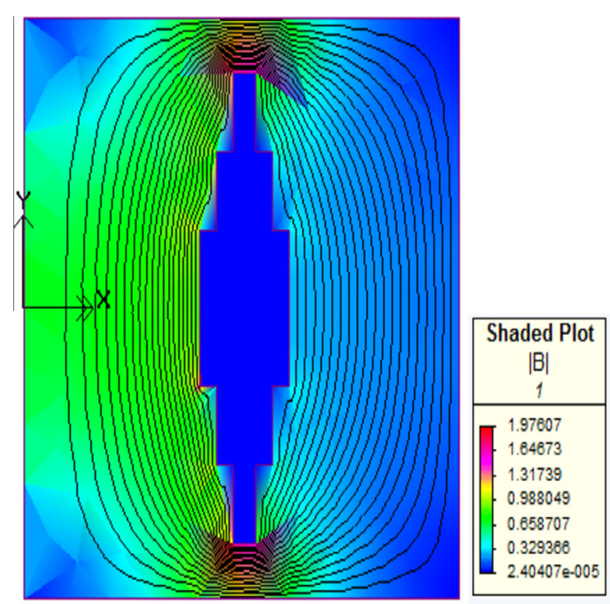

Fig. 6b. Magnetic flux density pattern of stepped coil.

Table 8
Comparison of YBCO tape with different shapes.

Shape	Volume (m)	Inductance (H)	Number of turns	Length (m)	Energy Stored (kJ)
Square	0.0005	1.8	2186	1668	9
Rectangular	0.0004	1.07	2186	1390	5.3
Stepped	0.0036	1.41	2186	1250	7.07

for YBCO conductors with a given length. The required length of the conductor for stepped coil is the lowest. Inductance in the rectangular coil is the lowest. The inductance and the energy stored in the square coil are very high among the other shaped coils with the minimum volume. So, the square shaped coil gives the optimum design.

4. Simulation results

4.1. Magnetic flux density pattern of YBCO in comparison with Bi2223 coil

Energy storage of the YBCO coil is shown in Fig. 2a. Simulation results for ¼th of the YBCO coil and Bi2223 coil are shown in Figs. 2b and 2c. The energy stored in YBCO coil is 2256.96 J. For the total coil, the energy stored is 9 kJ. Using Eq. (6), the inductance value is computed as 1.8 H.

4.2. Magnetic flux density pattern of YBCO in comparison with SCS12100 Tape

From Fig. 3b, energy stored in ¼th of the YBCO tape is 894.17 J for the design as shown in Fig. 3a. For the total tape, the energy stored is 3.57 kJ. Using Eq. (6), the inductance is calculated as 79.40 mH.

4.3. Magnetic flux density pattern of YBCO in comparison with SF12100 tape

From Fig. 4a, the energy stored in ¼th of the YBCO tape is 133.06 J for the design as shown in Fig. 4a. For the total tape, the energy stored is 532 J. Using Eq. (6), the inductance is calculated as 26.34 mH.

4.4. Simulation result for optimal design

From Fig. 5a, it is known that the total energy stored in ¼th of the rectangular coil is 5.3 kJ. Its flux density pattern is shown in Fig. 5b. Using Eq. (6), the calculated inductance value is 1.07 H. Fig. 6a shows that the total energy stored is 7.07 kJ in stepped coil. Flux density pattern of the stepped coil is shown in Fig. 6b. Using Eq. (6), the calculated value of inductance is 1.41 H.

5. Conclusion

A high temperature superconducting electromagnet design is analyzed in this paper using a three dimensional software MAGNET – 6.11.2. Performance of YBCO tape is compared with Bi2223, SCS12100 and SF12100 tapes. Based on the simulation results, it is clear that the maximum energy is stored in YBCO tape among the other tapes. With the optimal design of YBCO coil, the maximum energy is stored in it with the minimum volume. A prototype SMES with YBCO tape based on this study will be developed in the near future.

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