Bi-2223 HTS winding in toroidal configuration for SMES coil

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Abstract. Energy can be stored in the magnetic field of a coil. Superconducting Magnetic Energy Storage (SMES) is very promising as a power storage system for load levelling or power stabilizer. However, the strong electromagnetic force caused by high magnetic field and large coil current is a problem in SMES systems. A toroidal configuration would have a much less extensive external magnetic field and electromagnetic forces in winding. The paper describes the design of HTS winding for SMES coil in modular toroid configuration consist of seven Bi-2223 double-pancakes as well as numerical analysis of SMES magnet model using FLUX 3D package. As the results of analysis the paper presents the optimal coil configuration and the parameters such as radius of toroidal magnet, energy stored in magnet and magnetic field distribution.

1. Introduction
In Superconducting Energy Storage System - SMES, the electric energy is stored in the magnetic field of the superconducting magnet. The scheme of SMES is shown in Figure 1.

The energy stored in d.c. inductor is given by:

\[ E = \frac{1}{2} \int V \mu H^2 \, dV \quad \text{and} \quad E = \frac{1}{2} LI^2 \]

where: \( H \) - magnetic field strength (A/m), \( E \) - energy (J), \( V \) - volume (m³), \( \mu \) - magnetic permeability (H/m), \( L \) - magnet inductance (H), \( I \) - operating current (A).

If the coil is wound by conventional wire such as copper, the magnetic energy would be dissipated...
as Joule heat due to the resistance and current. Superconducting wire have zero resistance to DC electrical current at low temperatures so the Joule heat dissipation is eliminated. The stored energy could have values up to $10^6 \, \text{J/m}^3$ depending on the parameters of superconductor.

The system of SMES consists of the superconducting magnet placed in the cryostat/(vacuum vessel), the power conditioning system, the cryogenically cooled refrigerator for cooling the magnet.

### 2. The design of SMES magnet

There are different design constructions of the superconducting magnet for SMES. In general there are three types of SMES coil: solenoid, multiple solenoid and toroid. The solenoid constructions are easy to design and easy to fabricate, but they cannot prohibit or confine stray fields. Multiple solenoid gives less stray fields, but the density of energy is relatively poor. The toroidal configuration can be a compromise proposal (Figure 2). A perfect toroidal coil makes no stray fields, but it’s more complicated to manufacture than solenoidal configuration. For the same parameters of SMES, toroidal coils require more wires than solenoidal coils, but less wire than multiple solenoidal coils [1].

In the large scale SMES device with energy storage range near several MJ, strong electromagnetic force caused by very high magnetic fields and coil current is a serious problem. In facing this problem the concept of the Forced-Balanced Coil (FBC) or Stress Balance Coil (SBC) has been proposed in a few investigations. FBC and SBC is helically wound toroidal coils (Figure 2b) [2].

![Figure 2. Shapes of SMES coil](image)

Modular toroid designs use coils formed from a number of short solenoids arranged symmetrically as a torus and connected in series. The number and size of modules in toroid are the most import design considerations. Other basic toroid parameter is the shape of the modules [4]. All these parameters determined the values of SMES energy as well as length of superconducting conductor used to manufacture wires and overall device cost.

In the presented investigation the modular toroid coil type was selected in consideration for the SMES magnet. We established the application of 7 double-pancake coils to the toroidal SMES magnet. The double-pancake coils were made of HTS Bi2223/Ag high strength stainless-steel laminated tape [5]. The tape was made by American Superconductor. The specifications of the HTS tape are shown in Table 1.

| Superconductor | HTS High Strength Wire Stainless Steel Laminated |
|----------------|-----------------------------------------------|
| Bi-2223 (Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10}$) | |

| Parameter     | Value  |
|---------------|--------|
| Thickness mm  | 0.31   |
| Width mm      | 4.20   |
| Min. bend diameter mm | 70.00 |
| Critical current A | 115.00 |
| Critical temperature K | 108.00 |

The coils bobbin is made of aluminium 6063. The coils are insulated by Kapton® and impregnated using epoxy resin. The total length of the HTS tape is 1621 m. Figure 3 presented the design of HTS double pancake coil.

The specifications of the assembled pancake coils are shown in Tables 2.
3. Numerical calculation of SMES toroidal magnet parameters

The numerical analysis of SMES magnet model was performed using FLUX 3D package. The model of HTS magnet was prepared under the assumption that the 7 existing double HTS pancakes [5] could be apply to build new toroidal configuration. The main objective of calculation was to find optimal radius of toroid type magnet to obtain the maximum storage energy. The magnetic field distribution was calculated by three dimensional numerical analysis, using finite element method in magnetostatic problem. The new magnet design and magnet geometry are shown in Figure 4.

![Figure 3. Double pancake coil design [5]](image)

Table 2. The parameters of HTS coils

| Double pancake coil | Number of turns | Length of tape (m) | $R$ (293 K) (Ω) | $I_c$ (77 K) (A) | Tested separately |
|---------------------|-----------------|--------------------|-----------------|-----------------|------------------|
| 1                   | 286             | 236.2              | 7.796           | 52.8            |                  |
| 2                   | 286             | 236.2              | 8.033           | 53.0            |                  |
| 3                   | 283             | 233.2              | 7.945           | 52.2            |                  |
| 4                   | 281             | 231.3              | 7.675           | 56.7            |                  |
| 5                   | 273             | 224.4              | 7.443           | 54.9            |                  |
| 6                   | 280             | 230.3              | 8.015           | 53.1            |                  |
| 7                   | 279             | 229.3              | 7.641           | 52.7            |                  |

3.1. The results of magnetic field calculation – current in magnet $I = 100A$

Figure 5 shows the distribution of total magnetic field density in toroid for two extreme values of toroid radius: $R=0.20$ m and $R=0.30$ m. The maximum value of total magnetic field density $B$ changes from 0.5 T for $R=0.20$ m to 0.38 T for $R=0.3$ m.
The changes of stored energy and maximal magnetic flux density values in relation to the toroid radius are shown in Figure 6.

Figure 6. The magnetic flux density and the energy stored in magnet vs. the radius of toroid for the magnet current $I = 100$ A.

Figure 6 shows the results of the stored energy computation in superconducting toroid and density of magnetic field. When the radius of toroid decrease the storage energy is higher.

3.2. The analysis of magnetic field distribution and the angle between flux density and tapes vs. the toroid radius

Figure 7 shows the area of the analysis of magnetic field distribution and the angle between flux density and tapes vs. the toroid radius

Figure 7. The area of the analysis

The distribution of magnetic field in area of analysis shows Figure 8. The maximum value of total magnetic field density $B$ in the examined area changes from 0.5 T for $R=0.20$ m to 0.38 T for $R=0.3$ m
The distribution of magnetic field in area of analysis shows Figure 8. The maximum value of total magnetic field density $B$ in the examined area changes from 0.49 T for $R=0.20$ m to 0.38 T for $R=0.3$ m.

The distribution of angle between flux density and tapes in area of analysis shows Figure 9. The critical characteristic of HTS tape Bi-2223/Ag for HTS SMES winding shows Figure 10.

![Figure 8](image1.png)
![Figure 9](image2.png)
![Figure 10](image3.png)

**Figure 8.** The distribution of magnetic field in area of analysis: toroid $R= 0.20$ m (a) and $R= 0.30$ m (b)

**Figure 9.** The distribution of angle between flux density and tapes in area of analysis: toroid $R= 0.20$ m (a) and $R= 0.30$ m (b)

**Figure 10.** Critical characteristic of HTS tape Bi-2223/Ag (Am Sc) for $B \perp J$ (a) and $B \parallel J$ (b)
The values of storage energy in coils were calculated vs. radius of toroid. The computation result indicates that the stored energy in coils increases when the radius of toroid decreases (Figure 12). Due to the critical characteristic of Bi-2223 tape the current in winding should be lower, when magnetic field density increases. The toroid with radius \( R = 0.22 \) m gives the maximum storage energy.

**Figure 12.** Energy of SMES vs. toroid radius and temperature magnet for th current \( I = 100 \) A

The toroidal coils can be made in two ways – as a continuous helical winding or as a number of short solenoids connected in series – modular toroid. The devices consist of seven double pancakes made with Bi-2223 HTS tape. Seven double-pancakes was a part of solenoidal magnet for HTS SMES which was design and built. In solenoidal configuration the expected maximum stored energy is \( E = 0.31 \) kJ at 77 K, \( E = 5.5 \) kJ at 50 K with the current \( I = 105 \) A and \( E = 16.2 \) kJ at 35 K with the current \( I = 180 \) A [5]. These existed coils could be applied to build new toroidal configuration.

4. Conclusion

The paper describes the results of calculation of the new toroidal model for SMES magnet. The main objective of calculation was to find optimal radius of toroid type magnet to obtain the maximum storage energy. Using FLUX-3D package the magnetic field distribution was calculated. The values of storage energy in coils were calculated vs. radius of toroid. The critical parameters of Bi-2223 tape and the angle between magnetic flux density and tape have been taken into consideration. The result of computation indicates that the energy stored in superconducting coils of SMES and density of magnetic field increase when the radius of toroid decreases. The current in superconductor should be lower, due to the critical characteristic of tape, when density of magnetic field increases. After analysis the toroid with radius \( R = 0.22 \) m gives the maximum storage energy.

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