# Design and Fabrication of a Conduction-Cooled High Temperature Superconducting Magnet for 10 kJ Superconducting Magnetic Energy Storage System

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***Abstract*—A high temperature superconducting (HTS) magnet for 10 kJ superconducting magnetic energy storage (SMES) system is designed by an improved optimal algorithm and cooled through GM cryocooler. In order to demonstrate the technology, a model HTS magnet made of Bi-2223/Ag tape to fabricate double-pancakes with the inner and outer diameters of 120 mm, 207.1 mm and height of 119 mm was fabricated and tested. The magnet is operating with GM cryocooler at 10 K. We have tested the Bi2223 HTS magnet at various ramping rates with 0.1–5.06 A/s. The experimental results show that the model HTS magnet is operating very stable. In the paper, we report the design of the HTS-SMES and fabrication technique for the model HTS magnet.**

***Index Terms*—Bi2223 high temperature superconductor, conduction-cooled, superconducting magnet energy storage system.**

## I. Introduction

SUPERCONDUCTING magnetic energy storage system (SMES) with the efficient energy storage capability, fast response and independent controllability over active and reactive power has the potential to be applied to load leveling and power system control. SMES is particularly suited in applications that rate high repetition rates (pulsating electrical loads). A central storage will be needed to ensure network stability and voltage support, and to allow quasisteady state operation of the generating units in presence of pulsating loads. SMES is a good candidate to fulfill the applications [1].

The critical current density of Bi-based superconducting tape is $J_C = 10^4 - 10^5\ \mathrm{A/cm^2}$ at the operating temperature of 20–30 K and self-field. The applications of HTS tapes for the superconducting magnet have been employed in fabrication of SMES system. An HTS-SMES can stably operate, consumes no power beyond refrigeration requirements, has no liquefying system to maintain, takes up less space, and costs less to purchase and operate than a lower superconducting magnet system [2]. The design and fabrication of a conduction-cooled HTS magnet for a 10 kJ superconducting magnet energy storage system are presented for the experimental research. The results of the electromagnetic and thermal analyses are discussed. The model high temperature superconducting coils have been fabricated and tested. The fabrication technology and the structure of the superconducting magnet are reported.

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TABLE I
MAIN PARAMETERS FOR BI-2223 TAPE

| Width of tape | 4.2mm ± 0.2 mm |
|---|---|
| Thickness of tape | 0.24mm ± 0.02 mm( with insulation thickness in 0.01 mm) |
| Length of each piece | 200 m |
| Filamentary number | 61 |
| Filling factor | 0.3 ~ 0.35 |
| Mass density | 4.5 g/cm$^2$ |
| Engineering current | ≥ 80 A ( 77 K, self field) |
| Max. tensile stress | 100 MPa (5 % $I_C$ degradation) |
| Max. tensile strain | 0.15 % (5 % $I_C$ degradation) |
| Min. bending radius | 30 mm (5 % $I_C$ degradation) |
| Critical temperature | 110 K |
| Insulator | Maylar |
| Breakout voltage | 300 V (10μm, 300 K) |
| Thickness of insulator | ≤ 10μm |

## II. Design of Bi-2223 High Temperature Superconducting Magnet

The parameters for the HTS tape are listed in the Table I. The optimal objective functions for HTS-SMES, that represents the total volume of double pancake coils needed in the HTS magnet, and the constraint equations are set as follows: volume minimum of coils. The storage energy more than 10 kJ is set. The constraint of the inner diameter in the magnet is $\phi$ 120 mm and the safety factor for the critical current $I_C$ of the magnet is 0.6. Because of the strong anisotropy of the HTS tape, the critical current $I_C$ in tape is sensitive to perpendicular field $B_r$, the critical current of the HTS magnet can be determined by the load curve derived from the maximum perpendicular field and its operating current of the HTS magnet and the perpendicular magnetic field performance curve of the HTS tape at 20 K.

A genetic optimal algorithm can deal with the constrained nonlinear optimization problems. However, some results have shown that the genetic optimal algorithm performs well for a global search, it is very poor in a localized search [3]. For practice applications in the design of SMES HTS magnet, we combined sequential quadratic programming with the genetic optimal algorithm. For the method, as the first step, the genetic optimal algorithm searches the global optimum in the whole solution region to obtain a quasioptimal solution, and then,

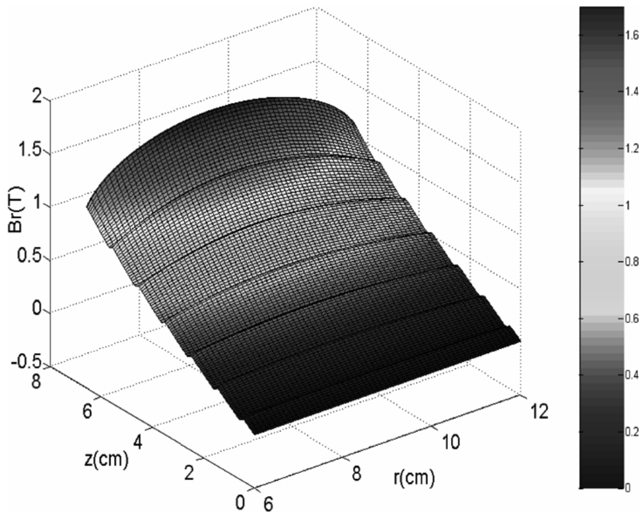


Fig. 1. Distribution of perpendicular field in HTS magnet.

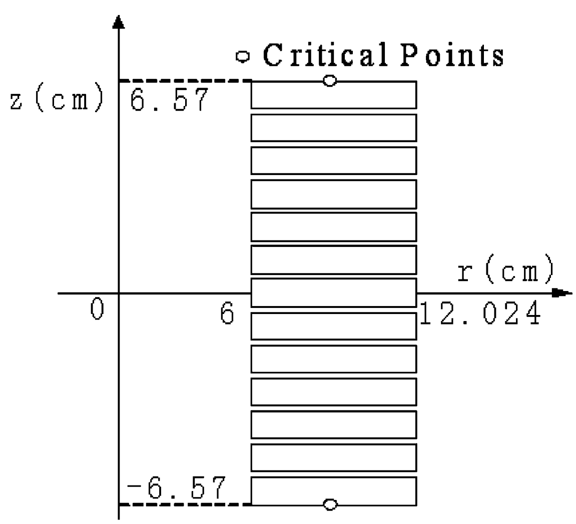


Fig. 2. Configuration of high temperature superconducting-SMES magnet.

the global optimal solution can be obtained by the sequential quadratic programming. The designing arguments are the thickness and height of the magnet. Because the height of each double pancake coils, as well as the thickness of each thermal conducting copper plate, is fixed, hence, the height of the magnet which is fabricated by coaxial double pancake coils will discretely change. Similarly, as the thickness of the HTS tape is a fixed value, the thickness of the magnet will also changes discretely for the reason that it is multiple to the thickness of the HTS tape. Considering the conditions, the genetic optimal algorithm utilizes binary code string to implement the encoding of these discrete variables. The sequential quadratic programming is used to make further optimization from the point as determined by the genetic optimal algorithm and the global optimal solution can be obtained. The distribution of the perpendicular field in the optimized magnet is shown in Fig. 1. Based on the computing results, thirteen double-pancake coils are needed to compose the HTS magnet. The configuration of the magnet is shown in Fig. 2 and the design results of the magnet are listed in Table II.

TABLE II
MAGNET DESIGN PARAMETERS

| Parameters | values |
|---|---|
| Number of double pancake coils | 13 |
| Operating temperature (K) | 20 |
| Inner diameter (mm) | 120 |
| Outer diameter (mm) | 240.5 |
| Height (cm) | 13.14 |
| Central field $B_0$ (T) | 3.2067 |
| Stored energy $E$ (J) | 17399.2 |
| Total turns of the magnet | 6526 |
| Inductance (H) | 4.6795 |
| Safety factor (%) | 60 |
| Operating current $I_{OP}$ (A) | 86.2348 |
| Critical current $I_C$ (A) | 143.72 |
| Maximum perpendicular field $B_{rmax}$ (T) | 1.6869 |
| $\theta$ angle of field and tape wide surface | 56.9382 |
| Filling factor (%) | 79.64 |
| Total volume of double pancake coils (cm$^3$) | 3990.9 |
| Volume of the HTS magnet (cm$^3$) | 4482.1 |
| Volume of the HTS tape needed in the HTS magnet (cm$^3$) | 3569.6 |
| Turns of a double pancake coils | 502 |
| Length of the HTS tape needed in a double pancake coils (m) | 285 |
| Length of the HTS tape needed in the magnet (m) | 3705 |

The system operates in a vacuum and is conduction-cooled via two-stage GM cryocooler with a nominal operating temperature of 10–20 K. The HTS conductor is made of Bi-2223 tape, and each coil is reinforced by the stainless steel tapes. The HTS magnet has about 3800 meters of superconducting tape. The HTS current leads were designed to improve resistance. The current leads were designed to operate with the warm end at about 40–50 K and the cold end at 20 K. The HTS magnet, current leads, and thermal shield are supported by G-10 tubes and hung from the lid of the vacuum vessel. The cryocooler is mounted on the vessel lid and connected to the thermal shield top plate and the magnet cooling plate with flexible links to provide vibration isolation. The first stage of the cryocooler cools the thermal shield and the heat pipe thermal intercepts. The heat pipe thermal intercepts combine the high thermal conductivity with good electrical insulation and ensure that the upper end of the HTS portion of the current leads is adequately cooled. The second stage of the cryocooler cools the HTS magnet and the bottom of the HTS current leads. The bottom of the leads is connected to the cooling plate by copper slice. The magnet is bolted to the cooling plate. The bottom plate of the HTS magnet and the magnet bore tube are made of copper and provide the conductive path into the windings for cooling. The magnet consists of individual double pancake windings stacked on the copper bore tube. Current lead mounting pads are provided to bolt the current leads to the magnet.

For the turn-to-turn coil insulation, a coating of 0.01 mm in thickness was applied to the Bi-2223 tape as the tape was being wound into its double pancake coil. The double pancake coil was separated from its winding mandrel and spiral wrapped with glass insulation. The wrapped pancake coil was then placed on top of a copper sheet. The purpose of the copper sheet was to improve axial thermal conduction. The double pancake coil and its copper insert were then epoxy impregnated. After epoxy resin DW-3 impregnation, the double pancake coils were stacked and spliced together on the inner diameter to form a continuous double pancake coil. The double pancakes were then stacked

TABLE III
TOTAL AC LOSSES IN CONTINUOUS RAMPING RATE OF HIGH TEMPERATURE SUPERCONDUCTING MAGNET

| Charging time | | 60 s | 6 s |
|---|---|---|---|
| Copper flake | | 0.0711 W | 7.11 W |
| Bobbin | Former | 0.017 W | 1.7 W |
| | Flange | 0.0208 W | 2.08 W |
| HTSC tape | Parallel magnetic field | 1.978 W | 19.78 W |
| | Perpendicular magnetic field | 2.046 W | 20.46 W |
| | Eddy losses | 0.0003 W | 0.03 W |
| Total AC losses power | | 4.13 W | 51.16 W |

in a precision fixture and subsequently spliced at the outer diameter using a copper transition piece.

AC losses in the HTS magnet consist of losses in copper flake for thermal linking, bobbin with material of bronze, flange and Bi2223 tapes. The penetration field for the HTS tape is about $B_{\mathrm{p}} = 0.091$ T in parallel magnetic field, the penetration field is much smaller than averaged field of 0.65 T, the hysteresis losses can be calculated as peak field $\boldsymbol{B}_m$, $\beta = B_m/B_p \gg 1$, the hysteresis losses for HTS tape can be calculated as:

$$Q_{\parallel} = \frac{2B_p^2}{3\mu_0}\left[\frac{B_m}{B_p}(3+i^2) - 2(1-i^3)\right] \tag{1}$$

where $i$ is the operating current and its critical current ratio, $B_m$ is the maximum magnetic field, $\mu_0$ is the magnetic permeability in vacuum. The penetration field in tape in the perpendicular magnetic field, is about $B_{\mathrm{p}} = 1.3$ T, the penetration magnetic field is larger than averaged field, the total hysteresis is:

$$Q_{\perp} = \frac{2B_p^2}{3\mu_0}\left[\left(\frac{B_m}{B_p}\right)^3 + 3\frac{B_m}{B_p}i^2\right] \tag{2}$$

The eddy losses of HTS tape with width in $\boldsymbol{b}$ and thickness in $\boldsymbol{c}$ and peak field $B_m$, the AC losses is expressed as:

$$P = \int pdl = \sum_{j=1}^{n} 2\pi r_j p = \frac{\pi b^3 c}{6\rho}\left(\frac{dB_m}{dt}\right)^2 \sum_{j=1}^{n} r_j k_j^2 \tag{3}$$

where $\boldsymbol{n}$ is turn number of coil, $\boldsymbol{r}_j$ is the radius in $\boldsymbol{j}^{th}$ turn, $\boldsymbol{\rho}$ is the resistivity of silver. The total AC losses for various ramping rate are listed in Table III. Under adiabatic condition, the HTS magnet is operating at 20 K, the maximum temperature rise in coil is about 1.35 K for 6 s charge time, if the total losses are absorbed by HTS magnet.

## III. MODEL HIGH TEMPERATURE COILS AND CRYOSTAT

In order to develop the 10 kJ HTS SMES, a model HTS magnet with twelve double pancakes was fabricated and tested for the technique and characteristics research in first step. The main parameters of the HTS magnet are listed in Table IV. The configuration of the HTS magnet is shown in Fig. 3. The cryostat for the model HTS magnet has the outer diameter of 650 mm and the height of 805 mm and the weight of 160 kg. The cryostat has a penetrating room temperature bore of 61 mm in diameter. The two-stage GM cryocooler was mounted on one side of the cryostat. In order to improve cooling capacity, the HTS magnet is cooled down by high purity copper braid for a flexible thermal link that connected magnet with second stage. 15 layers super-insulation were provided around the superconducting coil to minimize thermal losses. Coil terminals were cooled through pieces of AlN chips [4]. The magnet was protected with diode and resistor. A pair of copper current leads was anchored between the room temperature and the first stage of cryocooler. A thermal radiation shield was mounted to flange of the first-stage to reduce heat radiation to the coils and HTS current leads. The thermal radiation shield has a silted configuration to decrease eddy current losses, and two reinforcements with stainless ring were mounted to the two ends of the thermal radiation shield. The heat load at the first cool head of cryocooler is about 11.08 W and the heat load at second-stage cool head is about 2.075 W. The cooling capacity of the cryocooler as a function of temperature was obtained from the commercial manufacturer, and at 20 K the cooling capacity is over 20 W.

TABLE IV
MODEL HTS MAGNET PARAMETERS

| Design Parameter | Value |
|---|---|
| Peak radius $B_r$-field | 1.72 T |
| Central B-field ($B_{op}$) | 3.24 T |
| Operating current ($I_{op}$) | 120 A |
| Operating temperature($T_{op}$) | 10 K |
| HTS conductor | Bi-2223 PIT |
| No. of double pancakes | 12 |
| Length of the HTS tape needed in a double pancake coils (m) | 200 |
| Total conductor length (km) | ~2.4 |
| Coil height (mm) | 119 |
| Coil inner diameter (mm) | 120.0 |
| Coil outer diameter (mm) | 207.1 |

Fig. 3. Configuration of model high temperature coils.

## IV. FABRICATION AND TEST OF MODEL HTS COILS

The Bi-2223 tape was arranged on a winding spool and was wound from the midpoint of the whole length of the tape.


Fig. 4. Configuration and assembled the model HTS coils in cryostat.

Bi-2223 tape with length of 200 m was wound into a double pancake coil of 380 turns for the model HTS magnet. To avoid the tape displacing under electromagnetic force, a cryogenic resin was impregnated uniformly in every layer while winding the coils, and then the coils were heated at 60°C for 8 hours to make the resin solid completely. The configuration and fabrication of high temperature superconducting coils are shown in Fig. 4.

The model HTS magnet is tested by conduction-cooled methods. The cooling processing of HTS magnet is shown in Fig. 5. The superconducting coil is cooled to its operating temperature takes about 24 hours. The operating characteristics of the coils were measured in operating temperature of 10 K. In order to test the HTS magnet, various ramping rates for the HTS are studied. The operating current of the coil was measured to be 120 A and center field of 3.22 T at the temperature of 10 K with ramping rates from 0.1 A/s to 4.6 A/s. The operating current of 100 A with ramping rates from 0.1 A/s to 5.06 A/s is obtained.

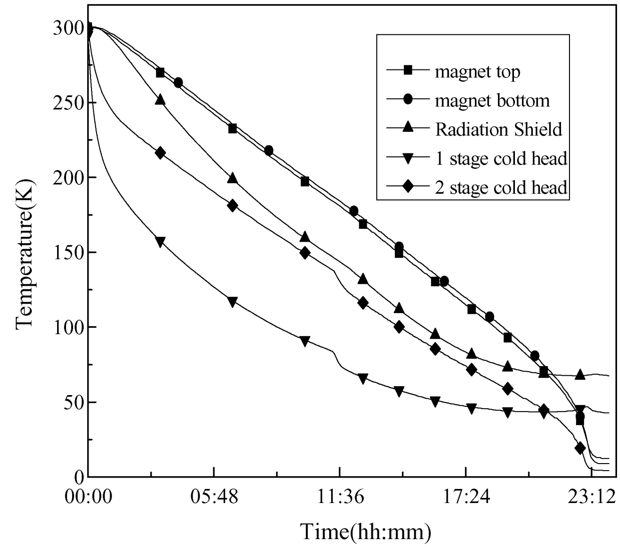


Fig. 5. Cooling processing of model high temperature superconducting coils.

## V. Conclusion

A conduction-cooled 10 kJ HTS SMES is designed based on the optimal algorithm. In order to demonstrate the fabrication technique and study operating characteristics, the model conduction cooled high temperature superconducting magnet was fabricated and assembled in the cryostat and linked with cryocooler. The magnet has been fabricated and tested. The model HTS magnet is tested in 10 K, and it can be stably operated over than 120 A with various ramping rates current to generate the center field in 3.22 T.

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