A 30 kJ Bi2223 High Temperature Superconducting Magnet for SMES with Solid-Nitrogen Protection

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***Abstract*—A conduction-cooled high temperature superconducting (HTS) magnet system through a solid nitrogen protection with energy storage of 30 kJ was developed. The HTS magnet system is used to investigate fast discharging performances with a constant output voltage. The superconducting magnet consists of 14 double pancakes wound with Bi2223 tape with the length of 200 m. The magnet has an outer diameter of 212 mm and a clear bore of 108 mm. Cryostat for the HTS magnet system is designed and the coil is cooled with a GM cryocooler together with the solid nitrogen protection technology. The superconducting magnet is fabricated and tested. The operating current is about 155 A with raping rate of 5 A/s. It can generate a central magnetic field of 4.31 T at a temperature lower than 20 K. In this paper, the magnet design, coil fabrication and cryogenic system are presented. Experimental research of the superconducting magnet as a constant voltage power supply was carried out.**

***Index Terms*—HTS coil, SMES, solid-nitrogen.**

I. INTRODUCTION

A SUPERCONDUCTING Magnetic Energy Storage (SMES) technology is needed to improve power quality by preventing and reducing the impact of short-duration power disturbances. In a SMES system, energy is stored within a superconducting magnet that is capable of releasing megawatts of power within a fraction of a cycle to replace a sudden loss of line power. SMES has branched out from its application origins of load leveling to include power quality for utility, industrial, commercial and other applications. Because SMES has the ability to charge and discharge very quickly, thus supplying large amounts of current for very short durations. A SMES coil, for all practical purposes, can be cycled through the charge/discharge cycle infinitely many times. In applications such as pulsed power, where charge/discharge cycles occur often, the SMES could prove to be more reliable and have a much longer life expectancy then current technology such as batteries or flywheel energy storage [1]. It has also shown promise as a power supply for pulsed loads such as the electromagnetic aircraft launchers as well as for vital loads when power distribution systems are temporarily down. These new applications demand more efficient and compact high performance power electronics. The use of SMES for pulsed power applications is something that is unique to the special applications.

The entire SMES includes the superconducting coils, the cryostat, refrigeration, converter and control devices. We have developed and tested the laboratory scale high temperature superconducting magnetic energy storage (HTS-SMES) system with storage capacity of 30 kJ. The SMES is employed through the high superconducting coil with GM cryocooler immersed in solid nitrogen lower than 20 K to provide efficient thermal contact with the coolant. We also developed a cryogenic DC-DC converter, providing low losses in the stored energy and high operational efficiency. The fast charging and discharging power of HT-SMES was proved with constant output voltage.

II. SUPERCONDUCTING MAGNET

The important part of energy-storing unit in the SMES is a high temperature superconducting coil. We have designed and built a laboratory scale SMES device based on HTS coil (HT-SMES) to demonstrate the improving operation in constant output voltage load. In this part, the design and fabricate the HTS coils were presented.

A. High Temperature Superconducting Wire

The HTS superconducting coil consists of 14 double pancake coils. Each pancake coil is wound with a varnish coated Bi2223/Ag tape. The thickness of the varnish insulation is 10 micrometers. Fourth pieces of Bi2223/Ag tape with each has a length of 200 m are supplied by Innova Superconductor Technology Co. Ltd. The critical current of the Bi2223 high temperature superconducting tapes is 90 A at 77 K and self field. The break-down voltage of the varnish coating is guaranteed by the supplier as 300 V. Parameters of the superconducting wire are listed in Table I. Each of the 14 piece superconducting tapes is tested using a non-contact detection device to examine the structure uniformity.

B. HTS Coil Design and Manufacture

In order to test the discharging performance at different discharging rate, the magnet is designed to possess the magnetic energy storage over 30 kJ. The designed HTS magnet will be cooled down to 20 K with a GM cryocooler.

The available Bi2223 superconducting wire in the laboratory is 2800 meters which is in 14 equal pieces. So we decide to design the magnet with 14 double pancake coils. Each pancake coil has an inner diameter of 120 mm and an outer diameter of 212 mm. The thickness of the pancake coil is 9 mm. The Bi2223 superconducting tape is wound directly onto a brass former. In order to reduce eddy current during magnet discharging, the brass former is slit axially. The inner diameter of the brass former is 108 mm, outer diameter is 120 mm. Axial length is 15 mm. Each piece of superconducting tape can be wound as

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TABLE I
MAJOR PARAMETERS OF BI-BASED HIGH TEMPERATURE TAPE

	Parameter
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

Fig. 1. Coil former and pancake coil.

double pancake coil with 364 turns. The inductance of each pancake coil is 28 mH. The brass former and the finished double pancake coil are displayed in Fig. 1. In order to improve the thermal conduction properties of the HTS magnet, eighteen copper plates are placed between the adjacent two pancake coils. The thickness of the copper plate is set as 1 mm. The 18 copper plates are each radial slit and surface insulation coated.

The 14 double pancake coils are stacked between two brass end plates and fastened with 6 stainless steel bolts. After joints manipulation, binding is applied onto the magnet with glued fiber-glass tapes. The finished HTS magnet has an inner diameter of 108 mm and height of 220 mm. Inductance of the magnet is calculated about 2.5 H. The load line of the magnet is shown in Fig. 2. The magnetic field distribution along the axis is shown in Fig. 3. The magnetic energy storage is expected about 25 kJ during the operating current in 144 A. The magnet is designed to test its fast discharging performance with a constant voltage output. At the constant output voltages of 100 V, 200 V, 300 V, 400 V and 500 V, the HTS magnet has the discharging times of 4.5 s, 2.28 s, 1.52 s, 1.14 s and 0.91 s respectively. The main parameters of the HTS magnet are listed in Table II.

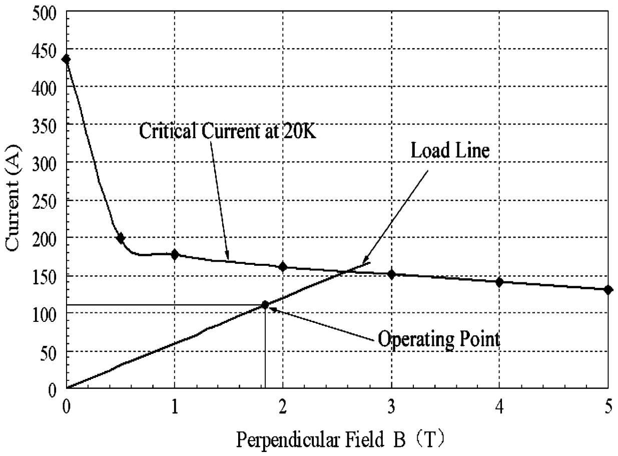

Fig. 2. HTS magnet load line.

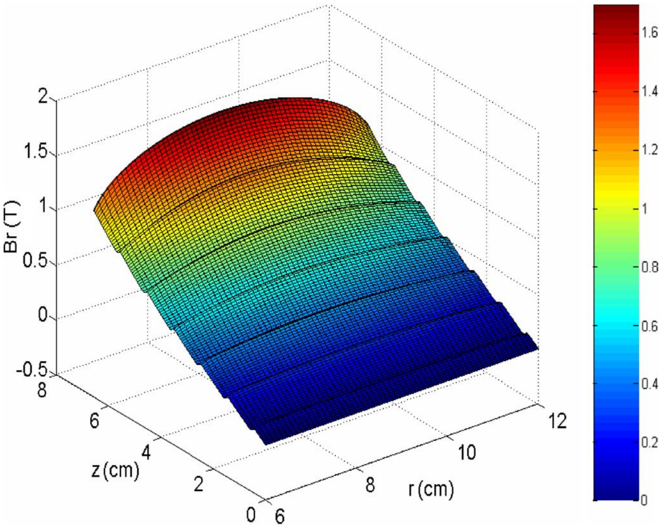

Fig. 3. Magnetic field distribution in the superconducting coils.

TABLE II
MAJOR PARAMETERS OF BI HIGH TEMPERATURE COIL

	Parameter
Inner Diameter	108mm
Outer Diameter	250mm
Height	172 mm
Number of double pancake	14
Turns	5096
Self inductance	2.5H
Operating temperature	10
Operating current	155 A
Center field B_0	4.31 T
Energy storage	30 kJ

In order to compare stability of HTS coil with and without the solid nitrogen protection in HTS coil. The hot-spot temperature rise has been analyzed through a numerical code. We consider a scenario with maximum fast pulsed current of 12 A/s and maximum operating current at 110 A through the HTS coil. Due to the AC losses in superconducting coils and structure, the temperature of high temperature superconducting coils will increase. Fig. 4 illustrates the profiles of the hot-spot temperature in superconducting coils cooled by GM cryocooler and with and without the solid nitrogen protection. The calculated results show that the solid nitrogen protection and GM cryocooler can significant press the maximum temperature rise in the coil with the same operation condition.

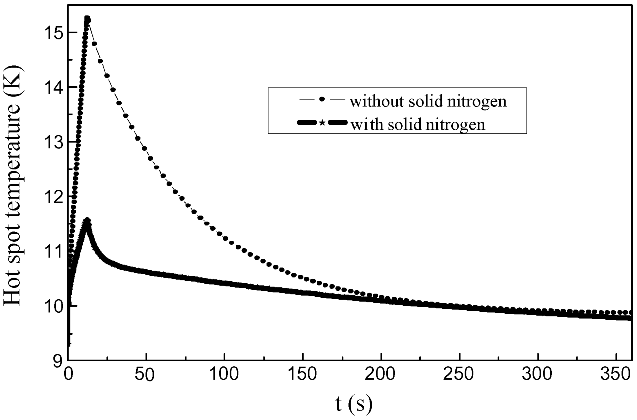

Fig. 4. Temperature profiles for HTS coils with and without solid nitrogen protection.

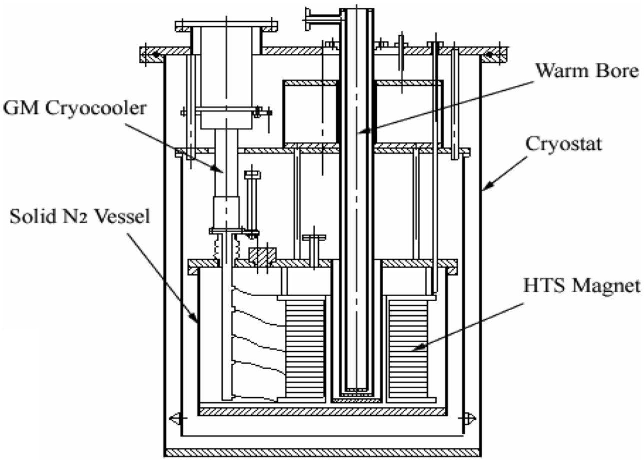

Fig. 5. Overall structure of the HTS magnet system.

III. CRYOGENIC SYSTEM

The HTS superconducting magnet is operated at 20 K with one two-stage GM cryocooler to cool down the magnet. To acquire experiences of stand-alone operation of the HTS magnet system, the solid nitrogen is used to keep the magnet temperature during the cryocooler to be shut down.

Cryogenic system of the HTS coil consists of a vertical cryostat, a solid nitrogen vessel, a liquid nitrogen vessel, a thermal shielding, current leads and a GM cryocooler. The thermal shielding with superinsulation is connected to the first stage of the GM cryocooler inside the cryostat. The liquid nitrogen vessel is also connected to the first stage of the cryocooler. In this case, the thermal shielding can be anchored to the liquid nitrogen temperature when the magnet system is operating at the stand-alone condition. Fig. 5 shows the overall structure of the HTS magnet system.

The cryostat has an outer diameter of 510 mm and a height of 810 mm. A ϕ34 mm warm bore is designed for further magnetic separation experiments. The HTS magnet is located inside the solid nitrogen vessel. The solid nitrogen vessel is made of stainless steel. It has an outer diameter of 445 mm and a height of 276 mm. Total volume is 26 liters. It is expected to contain 18.5 liters liquid nitrogen for solidification.

The liquid nitrogen vessel is on the top plate of the thermal shielding. Good thermal contact is guaranteed by bolt fastening with the top plate. The diameter of the liquid nitrogen vessel is 290 mm and the height is 120 mm. Total volume of the vessel is 7.25 liters. It is expected to host 5 liters liquid nitrogen to keep the thermal shielding at 77 K when the magnet system is in stand-alone condition.

TABLE III
THERMAL LOSS ESTIMATION ON THE CRYOGENICS SYSTEM

First stage of GM crycooler	50W/50K
Copper current lead	15W
Radiation loss	1.48W
Supporting structure	0.26W
LN2 transfer tube	2.06W
Total	18.8W
Second stage of GM cryocooler	20W/15K
N index losses	1.08W
Splice	0.058W
Radiation loss	0.021W
HTS current leads	0.05W
Supporting structure	0.06W
LN2 transfer tube	0.052 W
Instruments wire	0.005W
total	1.37 W

The thermal radiation shielding of cryostat is made of copper material. Dimensions of the thermal radiation shielding are designed with an outer diameter of 490 mm and a height of 556 mm. The inner shielding tube is set as 82 mm in diameter, which is installed between the warm bore and the solid nitrogen vessel.

The current leads for the HTS magnet system are designed as a hybrid structure, which is constructed with copper section, Bi2223 HTS bulk lead and Bi2223/Ag tapes. The copper section is in the form of copper tape for flexible installation. The copper section has a cross sectional area of 12 mm^2. The length is 600 mm. The copper section is located between the top flange of the cryostat and the top plate of the thermal shielding. It will introduce the operating current from 300 K to the 50 K thermal shielding temperature in the cryostat. The Bi2223 bulk current lead is located between the first stage of the GM cryocooler and the solid nitrogen vessel. The lower end of the bulk HTS lead will be anchored to the second stage of the GM cryocooler. The Bi2223/Ag tapes will be connected from the lower end of the bulk lead to the magnet passing through the solid nitrogen vessel. Special sealing structures are developed to keep the solid nitrogen vessel isolated with the surrounding vacuum. The solid nitrogen vessel is suspended by four FRP rods which can sustain the 125 kg cold weight. The GM cryocooler has a cooling capacity of 1.5 W at 4.2 K. The thermal load estimated on the cryogenic system is listed in Table III.

It can be seen from Table III that there is considerable cooling capacities for the GM cryocooler to cool down the magnet to a temperature lower than of 20 K, enhancing the magnet to be operated at a current higher than 155 A.

IV. CONVERTER FOR HTS-SMES CHARGING AND DISCHARGING TEST WITH CONSTANT OUTPUT VOLTAGE

The HTS-SMES system is operated for fast charge and discharging experiment. The fast discharging tests will be done by controlling the voltage at different levels. A two-stage booster device is connected to the magnet. HTS-SMES quench detection and protection are also integrated into the booster device. The booster device is composed of an input chopper stage and

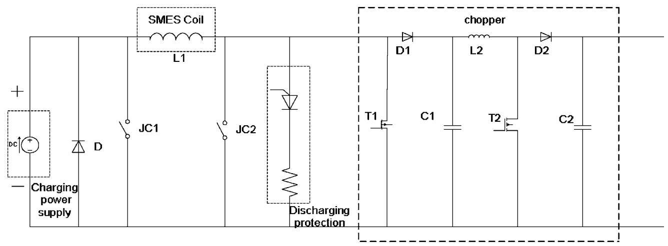

Fig. 6. Topology structure in converter with a two-stage booster.

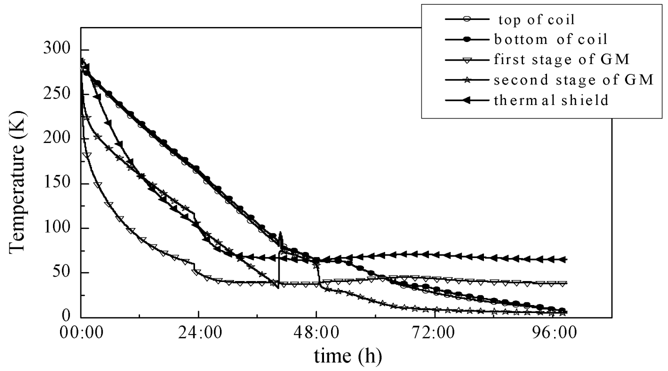

Fig. 7. Profiles of temperature with respect to time in the superconducting magnet cooled.

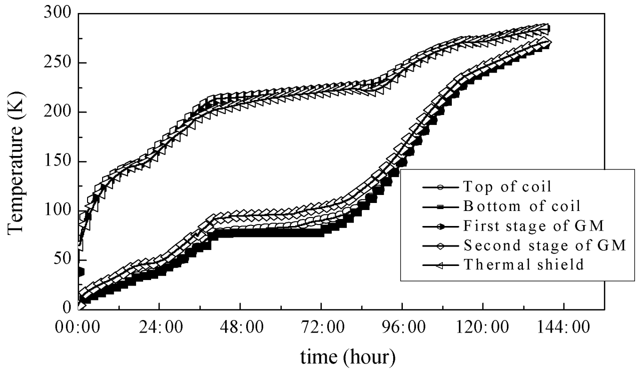

Fig. 8. Profiles of temperature with respect to time in the superconducting magnet system.

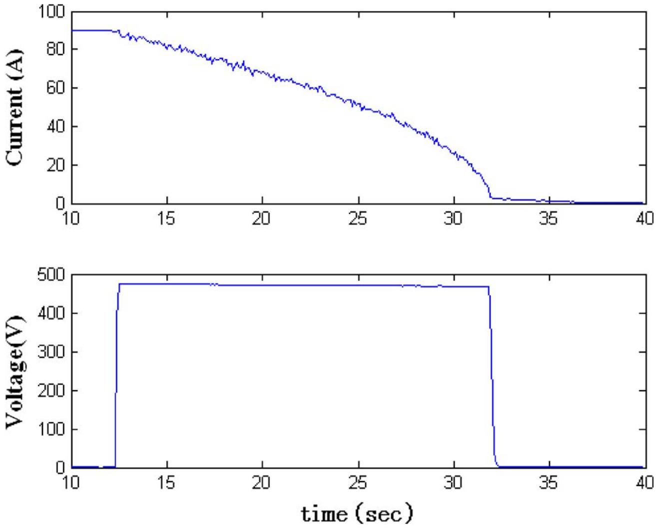

Fig. 9. Current of magnet and voltage in load with respect to time.

two booster circuits. For the discharging experiments, the energy stored in the HTS-SMES will be dumped to a resistive load. By controlling the chopper frequency and pulse width, it is expected to adjust the output voltage of the magnet from 100 V to 500 V. The magnet performances at different discharging rate can be examined. The basic electrical topology structure for the charging and discharge with quench protection is shown in Fig. 6.

The energy storage capabilities of the magnet are determined by the inductance and maximum rated current. Corresponding to operating current for the storage energy of 30 kJ is about 155 A. Before cooling the superconducting magnet, the gas pressure in the vacuum vessel is about 10^{-2} Pa. After that, the GM cryocooler started to work until to the temperature of HTS in about 77 K, the liquid nitrogen will be infused to the liquid nitrogen vessel and container of HTS coils. The cooling processing of HTS magnet is shown in Fig. 7. The superconducting coil is cooled to its operating temperature takes about 96 hours.

The resistance of joint for whole HTS coils measured is about 5.23×10^{-6} Ω. The operating characteristics of the coils were measured. In order to test the HTS magnet, various ramping rates for the HTS are studied. The maximum operating current of the coil was measured to be 144 A with ramping rates from 0.1 A/s to 4.6 A/s. The operating current of 110 A with ramping rates from 0.1 A/s to 5.06 A/s is obtained. During the whole test for the superconducting coil, the maximum temperature rise of the coil is lower than 1 K. Further, the operating characteristics in HTS coils after the switch off GM cryocooler were studied. Fig. 8 shows that the profiles of temperature in the superconducting magnet system.

The discharging characteristics for the HTS-SMES were studied through DC-DC converter with two-stage boosters to output constant voltage of 500 V. The load is with 1.2 kΩ resistor. The discharging time can be adjusted from 3 s to 20 s. Typical discharging current and output voltage for load with respect to time are shown in Fig. 9. The output power is about 200 Watt.

V. CONCLUSION

The design and fabrication for HTS-SMES with the solid nitrogen protection are developed. The magnet operating time when the cryocooler was shunt down with the solid nitrogen protected alone was about 40 hours. Finally, the device was connected to the converter, which is a charging power supply. The experimental results show that the HTS-SMES can output a constant voltage for load. The efficiency of the device reached more than 80% in rated load.

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