Development of Large-Bore Superconducting Magnet With Zero-Vapor Liquid Helium

Qiuliang Wang, Yinming Dai, Baozhi Zhao, Souseng Song, Shunzhong Chen, Ye Bai, Luguang Yan, and Keeman Kim

***Abstract*—A large bore NbTi superconducting magnet with liquid helium bath cooling has been developed for a micro-sized superconducting magnetic energy storage (SMES). The superconducting magnet has the clear bore of 480 mm, outer diameter of 550 mm and height of 500 mm. The magnet system is cooled in a compact cryostat with two GM cryocoolers. One of the cryocoolers is used to cool the thermal shielding. Another is used to re-condense the helium evaporation. A pair of high temperature superconducting current leads is used to reduce heat load to the cryostat. The operating current of the SMES system is rated at 325 A. Maximum energy storage is evaluated as 1.0 MJ at the rated operating current. Test results show that the stored energy can be dumped at the power of 7 kW to a dummy resistor load. This superconducting magnet system can be demonstrated as an Uninterruptible Power Supply (UPS). The superconducting magnet and the cryogenic system are described in this paper.**

***Index Terms*—Large-bore NbTi coil, SMES, zero-vapor.**

I. Introduction

A large bore superconducting magnet with high current density for SMES was initiated to generate a long duration output power through power electronic topology. In order to develop the superconducting magnets for UPS-SMES, a lot of superconducting magnet configurations such as single solenoid, toroidal and multipole superconducting coils have been proposed to evaluate their energy density, stray field and complexity as well as costs. The superconducting magnet with fast response to grid transient disturbance needs discharging high output power. The superconducting magnet can be manufactured with cooling channels inside the superconducting windings or cable-in-conduit-conductor to enhance the stability during fast discharging [1], [2]. The conductor for the superconducting magnet might adopt Rutherford cable, monolith conductor with high copper ratio, strands with aluminum stabilized matrix, or CICC. The cooling scenario for the superconducting magnet can be chosen as the liquid helium pool cooling, superfluid helium or supercritical helium force-flow cooling to keep effective thermal transfer between superconductor and the cryogen. Recently, the conduction cooled superconducting magnet is developed for UPS-SMES [3], [4].

In order to obtain a long duration pulse power for studying material characteristics, we have successfully developed a superconducting magnet system with 1 MJ stored energy, which suggests the use of NbTi superconducting strands. A special requirement for this SMES operation is the long duration of output power pulse. The operation of the superconducting magnet system has been tested with a satisfactory performance. The superconducting magnet can be charged to 1 MJ energy and discharged with an output power of 7 kW at a constant output voltage of 500 V. The cryogenic system of the SMES takes two GM cryocoolers to keep the superconducting magnet operated in the liquid helium bathe at the temperature of 3.8 K. The liquid helium in the cryostat is kept in a zero evaporation condition. The superconducting magnet system is controlled based on a personal computer with friendly protection and instrumentation interface. The details of the magnet design, fabrication and operating tests are described.

II. Design and Fabrication of Superconducting Magnet System

A. Design and Fabrication of the Superconducting Magnet

The superconducting magnet is designed based on the requirements on the total energy storage of 1 MJ and the maximum terminal voltage of 200 V. The stored energy is dumped out at the power of 7 kW through two-stage booster electronic circuit to maintain a constant output voltage in the range of 300 V–500 V. Due to the tests requirements on different discharging rate, the magnet coils are designed with high current density windings within which narrow liquid helium channels are arranged to enhance the cooling effect. To keep the operation stability and reliability, the SMES magnet has been designed with a superconductor which can sustain large disturbances without quench. Actually, we had to use several pieces of multi-filamentary NbTi/Cu superconducting wires in hand to wind the magnet coils. Parameters of these superconducting wires are characterized with the diameter of 1.3 mm, filament size of 45 μm and twist pitch of 15 mm. Critical current of the wires is 1920 A at 5 T and 4.2 K. Wire insulation is no less than 1.5 kV for the 0.02 mm thickness varnish coatings.

Main parameters of the superconducting magnet are listed in Table I. The inductance of the superconducting magnet is calculated as 18.9 H. The designed maximum operating current is decided as 325 A. When the operating current was decided, the maximum field in magnet windings is 5.32 T. Because the SMES magnet is wound with thin round wires onto a relatively large bore former, instabilities resulted from conductor motion

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TABLE I
MAJOR PARAMETERS OF NbTi SUPERCONDUCTING COILS

Superconducting magnet	NbTi/Cu
Inner diameter (mm)	480
Outer diameter (mm)	550
Height (mm)	500
Self inductance (H)	18.9
Operating current (A)	325
Total turns	7531
Layer number	20
Storage energy (MJ)	1
Maximum magnetic field (T)	5.32T

and other spot disturbances are expected. A safety margin of 56% is set considering the conductor critical performance. Actually, specifications of the round superconductor have a strong influence on the magnet stability and special care must be taken in the coil winding process. The design criteria of the SMES magnet were set with minimum superconducting materials to obtain the required energy storage of 1 MJ. As to the manufacture of magnet coils, a nonmetallic material, fiberglass reinforced plastic G-10 is used as the bobbin to avoid eddy current losses during fast discharge operation. In order to obtain good thermal transfer between superconducting strands and liquid helium, the magnet coil is manufactured with transparent windings and a large number of holes are drilled on the end flanges and the bobbin cylinder. The transparent winding structure is formed by laying FRP strips with equal intervals between adjacent layers. The FRP strip has a thickness of 0.5 mm and width of 10 mm. These measures may improve the cooling characteristics in the superconducting windings. Transient heat generation caused by disturbances such as wire motion can be removed by the liquid helium ventilation through the narrow channels. Moreover, radial channels are also made on the inner face of the two end flanges to help the evaporated helium gas passing through easily. Furthermore, the other structure materials for the coil reinforcing must not be conductive because of the high changing rate of magnetic field during discharging. Hence we applied the epoxy-resin wetted fiber-glass tapes to bind the coil windings. The solidified binding layer has the thermal contraction property which matches the coil windings during cooling-down process. The fiber-glass has also a satisfied mechanical strength. It causes a radial magnetic pressure of 11 MPa on the inner windings in Fig. 1. The superconducting magnet is wound with a pre-stress of 65 N/mm^2 to avoid possible conductor motions during the charging process.

B. Quench Detection and Protection of SMES

Quench detection and protection of superconducting magnet is one of the most stringent safety requirements for superconducting magnet with high storage energy. To make a sensitive detector which response to a very small resistance emerged at the start of a quench, while ignoring voltage spikes caused by power supply fluctuations and other environmental noises, it is necessary to use the signal balance circuits. In the manufacture process, voltage taps are set to divide the magnet windings into two sections, which can be connected in parallel with two resistors to form two voltage bridges. This arrangement makes it possible to detect a quench in each section with an equal sensitivity. The detection circuit is designed using three voltage taps

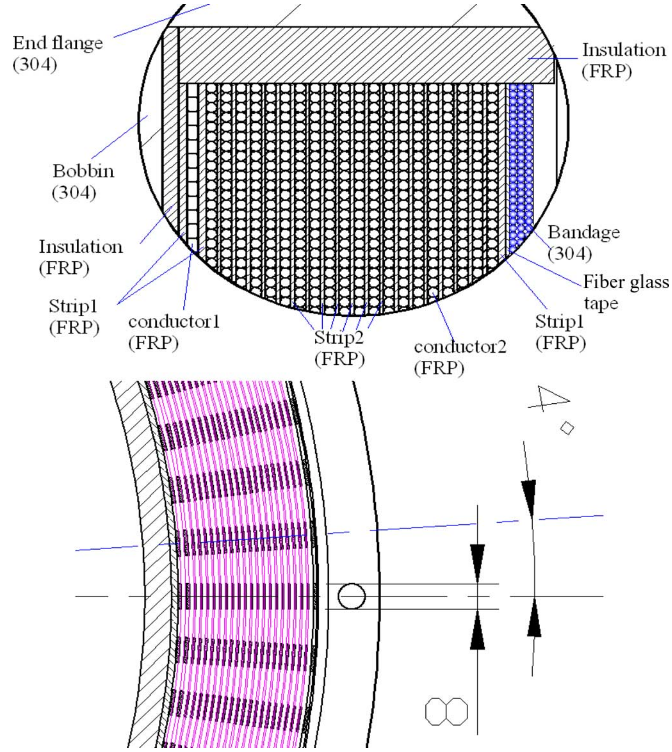

Fig. 1. Configuration of superconducting winding.

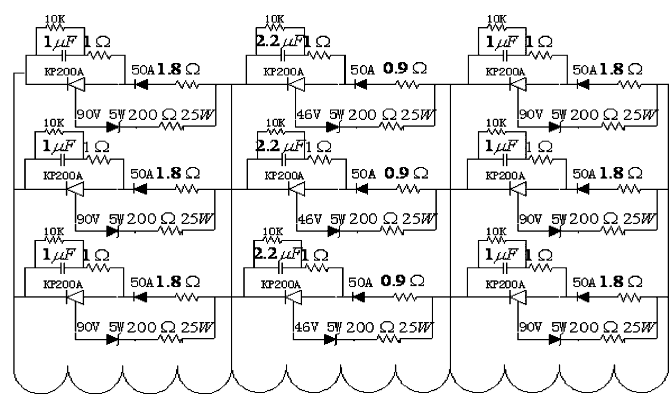

Fig. 2. Protection circuit for superconducting magnet.

in the magnet windings. Normal zone emerged in any sections can produce the out-of-balance voltage signal, which can trigger the turning off of the power supply. By adjusting the resistance ratio equal to the induced section voltage ratio during charging process, the two voltage bridges can be balanced.

The hot-spot temperature of the superconducting magnet will be increased when a local quench occurred due to the high current density in the superconducting windings. It may result in very high local temperature rise and insulation damage in case of protection failed. To protect the superconducting magnet, the stored energy should be released as soon as possible when a quench signal is detected. For the protection, the current decay is dominated by the magnet inductance and dump resistor resistance. To shorten the decay time constant by employing bigger dump resistance, the superconducting magnet can be effectively protected but at the expense of terminal over voltage. Finally we decided the protection dump resistor at the values to limit the magnet terminal voltages no more than 500 V. The basic parameters of quench protection circuit are illustrated in Fig. 2. The

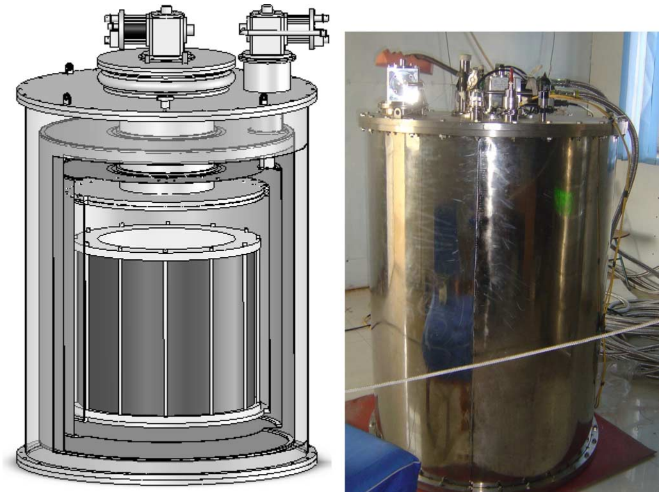

Fig. 3. Overall structure of the cryostat and magnet system.

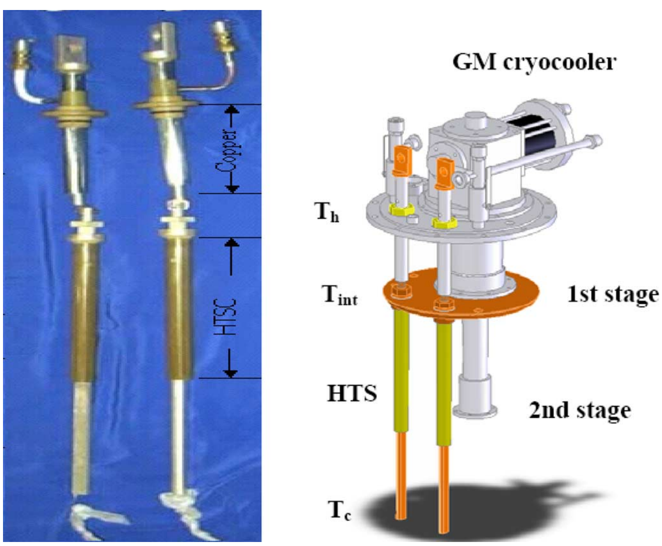

Fig. 4. High temperature current lead for the superconducting magnet.

protection circuit includes the dump resistor connected in series with a diode and a thyristor. In the case of the magnet quench, the quench detection circuit triggers the power supply turned off, the induced voltages over the magnet terminals trigger the thyristor turned on, the stored energy is to be dumped to the resistor.

C. Cryogenic System for Superconducting Magnet

The cryogenic system can provide the necessary operating environment for the SMES magnet. The superconducting magnet is cooled in the liquid helium vessel. The cryogenic system is designed with helium zero evaporation. Two GM cryocoolers are adopted to cool the cryostat. The configuration of the cryostat for the SMES system is shown in Fig. 3. It consists of a vacuum vessel, a liquid helium vessel and a thermal radiation shield. The vacuum vessel is made of 304 stainless steel. The thermal radiation shield is made of OFHC material. The liquid helium vessel is made of 316L stainless steel. The Bi2223 high temperature superconducting current leads are used as shown in Fig. 4. The heat load of the current lead is about 28.12 W at the operating current of 325 A. The evaporated helium can be re-condensed by one of the GM cryocooler

TABLE II
HEAT LEAKAGE FOR CRYOSTAT IN THE FIRST AND SECOND STAGE OF GM CRYOCOOLER

First-stage Temperature of GM	First stage (W)				
	Radiation	Supporter bar	Neck pipe	Copper lead	Total
40K	14.98	0.079	1.58	32.54	37.6
50K	14.97	0.079	1.54	32.36	37.4
60K	14.96	0.079	1.47	32.16	37.1
70K	14.94	0.079	1.44	31.92	36.8
	Second stage (mW) 4.2 K				
	radiation	Supporter Bar	Neck pipe	HTS Lead	Total
40K	3.8	2.89	75	110	289
50K	9.3	2.89	115	110	329.8
60K	19.4	2.89	158	110	372.8
70K	36	2.89	211	150	465.8

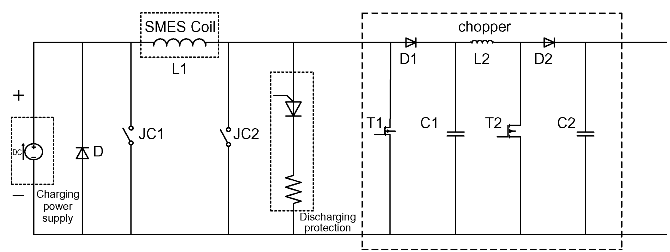

Fig. 5. Topology structure in converter with a two-stage booster.

during normal operation of the SMES magnet. Another GM cryocooler is used to cool down the thermal shield and helium vessel. The ripple pipe is employed to further reduce the heat leakage from room temperature to the liquid helium vessel. The total heat leakages to the first and second stages of GM cryocooler in the cryostat are summarized in Table II. Dimensions of the cryostat are with an outer diameter of 955 mm and a height of 1335 mm. After the superconducting magnet is fixed to the flange of the liquid helium vessel, the slot is welded in order to keep full airproof. During the normal operation of the cryogenic system, the pressure inside the liquid helium vessel can be kept at 0.07 MPa, which corresponds to a temperature of 3.85 K for the liquid helium.

D. The Principle of the Superconducting Converter Device

Fig. 5 shows the topology of the converter circuit for the SMES system. It consists of four main parts, i.e., the power supply for SMES charging, SMES magnet, discharging protection module and the chopper, which is designed to limit the magnet terminal voltage when the SMES magnet discharges.

For the converter device, there are three work modes. One is the charging mode, which the power supply can charge SMES magnet. The second mode is the persistent mode, which the DC current in SMES magnet continued in the close loop. The third mode is the discharging mode, which the SMES magnet can discharge through the chopper.

Fig. 6 shows the charging circuit. The switch JC2 is closed and the switch JC1 is opened. Fig. 7 shows the topology of a chopper for the SMES. It consists of the magnet L1, two diodes

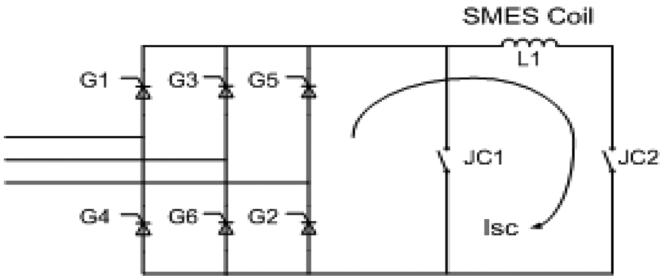

Fig. 6. Charging circuit for superconducting magnetic storage system.

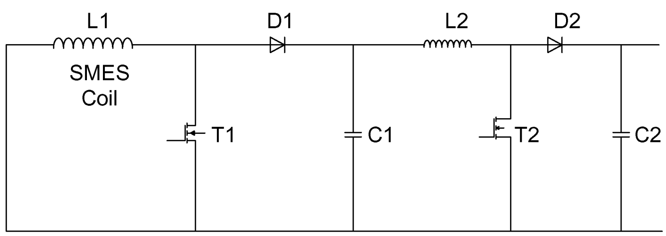

Fig. 7. Topology configuration of a chopper.

D1 and D2, two switches T1 and T2, and two capacitors C1 and C2.

Initially the switch T1 is opened, the current of SMES magnet charge the capacitor C1 through diodes D1. When the voltage of C1 is reached 150 V, the switch T1 is closed and the DC current is circulated through T1. By controlling the switch T1 in the appropriate way, the magnet terminal voltage can be limited to 150 V.The converter is a typical booster circuit which can boost the voltage of C1 from 150 V to 500 V to the ultimate load.

III. Test Results and Discussion

The 500 A, 12 V DC power supply is used for the magnet testing. The superconducting magnet is connected to power supply through a vacuum circuit breaker and FL2-400 shunt resistor. The magnet protection circuit is connected to the magnet terminals and two current leading taps.

Before testing, helium gas is filled in the liquid helium vessel. The two GM cryocoolers are put into operation to pre-cooling the magnet with the help of gas helium convection. It takes about 80 hours to cool down the magnet into the superconducting state. The changing profiles of the system temperature and magnet resistance are shown in Fig. 8 during the pre-cooling process. Then, about 300 litters liquid helium are filled into the liquid helium vessel.

The superconducting magnet is charged with a ramping rate of 0.5 A/s to the maximum operating current of 325 A. The superconducting magnet can be stably operated in the charging and discharging process. The cryogenic system of the SMES magnet system has been operated continuously about one month. During this period, a lot of experimental tests have been done to testify the system performance, including charging and discharging at different ramp rates. No significant pressure rise was observed in the liquid helium vessel. Magnet discharge experiments through the converter show that the SMES system can produce a long duration pulse power of 7 kW at a constant output voltage of 500 V. The typical tests result on the discharging through converter is plotted in Fig. 9.

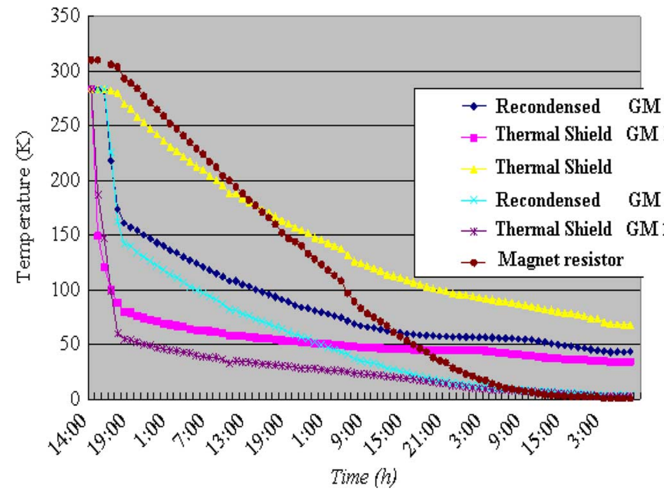

Fig. 8. Superconducting magnet cooled processing.

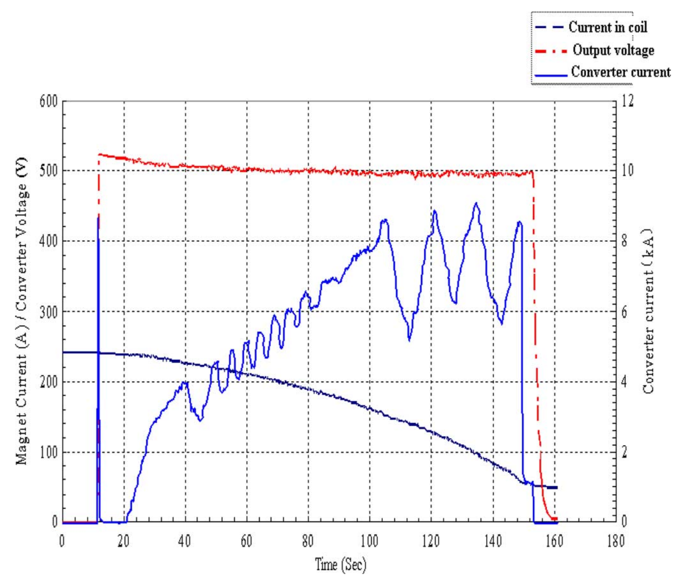

Fig. 9. Profiles of current, output voltage and power in SMES.

IV. Conclusion

A large bore superconducting magnet was designed, fabricated and evaluated for the development of UPS-SMES applications. The superconducting magnet is manufactured in the transparent winding structures. The cryogenic system adopts two GM cryocoolers with the cooling capacity of 3 W at 4.2 K. The compact cryostat demonstrates very good cryogenic performance which can be operated in the absolute zero evaporation condition. Experiment tests on the discharging through converter show that the SMES magnet system can produce a long duration power of 7 kW at a constant output voltage of 500 V.

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