Test results of HTS magnet for SMES application

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Abstract. The magnet for a superconducting magnetic energy storage system (SMES) conducting cooled by SRDK-408 cryocooler is described in this paper. The superconducting magnet consists of 7 double-pancake coils made of Bi-2223 HTS tape with the inner and outer diameters 210 mm, 315 mm respectively and height of 191 mm. The inductance of the magnet is approximately 1 H. In this paper we report the design improvements and the measurement results taken at the cooling of the magnet.

1. Introduction
Superconducting magnetic energy storage system (SMES) is a device for storing electric energy in a form of the magnetic field, with capability of the instantaneous discharge of large quantities of power. SMES technology is needed to improve power quality by preventing or reducing the impact of short-duration power disturbances. The magnetic field is created by the flow of DC current in a superconducting coil. Relatively high power capacity, fast time response and high efficiency are the main advantages of SMES over different energy storage systems. The HTS superconducting magnet of the SMES needs a cryogenic system operating under the liquid nitrogen or lower temperature (77.4 K or less). Such operating condition may be assured by the cooling system based on a cryocooler.

2. Design and construction of the SMES HTS magnet
The most important element of SMES system is superconducting magnet which stores electric energy in the form of magnetic field [1], [2]. Basic technical and electrical parameters of magnet like: inductance of winding, magnetic flux density, inner and outer radii of the winding as well as operating current and stored energy were defined by a number of magnet pancake coils, number of layers and number of turns. Changing initial technical and electrical parameters resulted in several construction solutions depending on the number of pancake coils of the superconducting magnet. FLUX 2D software [3] was used in design and optimization of magnet winding. We have chosen the magnet consisting of 14 coils connected in series [4], [5]. Table 1 shows the specification of the HTS SMES magnet. Besides temperature, critical current of the HTS tape in a pancake coil is primarily determined by the magnetic field perpendicular to the wide face of the tape (figure 1). The value of the current may be also increased by lowering the operating temperature of the magnet. The operating current in a superconducting magnet must be safely lower than the critical current of a wire [6]. The expected values of stored energy depending on the value of the maximal current and operating temperature are given in table 2.
Figure 1. $I_c - B$ characteristics of Bi2223/Ag HTS tape with the perpendicular and parallel field components [6].

| Parameter                          | Value     |
|------------------------------------|-----------|
| Inner diameter of coil             | 210 mm    |
| Outer diameter of coil             | 310 mm    |
| Distance between coils             | 8.6 mm    |
| Number of coils / pancakes         | 14        |
| Number of double-pancake coils     | 7         |
| Height of magnet                   | 191 mm    |
| Weight of magnet                   | 53 kg     |
| Length of HTS tape in the magnet   | 1621 m    |
| Width / thickness of HTS tape      | 4.2 mm / 0.31 mm |
| Critical current of HTS tape at 77 K | 125 A     |

Table 2. Values of the stored energy of the SMES [4], [5].

| Temperature (K) | Max. Current (A) | Max. stored energy (kJ) |
|-----------------|------------------|-------------------------|
| 77              | 25               | 0.31                    |
| 64              | 50               | 1.25                    |
| 35              | 180              | 16.20                   |
| 13              | 264              | 34.80                   |
2.1. Construction of the magnet

The magnet consists of 7 double-pancake coils, each one made of 14 pieces of HTS Bi2223/Ag high strength stainless-steel laminated tape – each roughly 100 m in length. The tape was made by American Superconductor. The magnet support is made of aluminium alloy 6063. Coils are insulated by Kapton and impregnated using epoxy resin. The total length of the HTS tape is 1621 m. Table 1 presents the specification of the HTS SMES magnet [4], [5]. The schematic view of the magnet is shown in figure 2a and the double pancake is depicted in figure 2b.

![Figure 2. a) schematic view of magnet for SMES system, b) double pancake exploded view.](image)

![Figure 3. Assembly of the SMES magnet: a – instrumentation socket, b – vacuum connector, c – current leads, d – thermal bridge, e – temperature sensor, f – voltage taps, g – thermalisation aluminium block, h – connections between pancake coils, i – cold head of the cryocooler [5].](image)
The magnet is equipped with voltage taps used for monitoring the voltages on the coils and with temperature sensors. Initially, we used copper current leads to connect power supply to the magnet. The connections between double-pancakes are made by soldering of short pieces of HTS tape after magnet assembly. There are 13 interconnections in the magnet, the average interconnection resistance is 1.5 $\mu\Omega$ at cold. Total magnet resistance at room temperature is 54.66 $\Omega$. The resistance of each double-pancake coil is slightly different because of the uneven lengths of tape sections. Magnet situated in the vacuum cryostat is cooled by the cryocooler through the copper thermal bridge. Additionally, the heat was transferred by the aluminium support from both sides of the magnet. Figure 3 shows the SMES magnet with the cryocooler cold head, equipped with temperature sensors, voltage taps and current leads.

To meet project requirements, we expected to cool down the magnet at least to 35 K. Unfortunately, after 72 hours of cooling, we were able to obtain only 64 K because of problems with cryostat and thermal insulation. Temperature and resistance of the magnet winding during its cooling are shown in figure 4. Lack of thermal shield inside the cryostat and the poor vacuum quality (old vacuum pump) had the major impact on the magnet temperature [6].

![Figure 4. Temperature and resistance of the magnet during cooling process.](image)

2.2. Modification of the magnet assembly and thermal insulation

Temperature of the coils achieved during preliminary tests did not allow to fully verify the SMES magnet under the working conditions, since the critical current of the magnet equal 50 A was insufficient to obtain the required value of stored energy.

In order to solve this problem, we have introduced many changes in the construction, instrumentation and the magnet mount. Thermal insulation, both of the magnet and cryostat, was improved, what provided better utilization of the cryocooler cooling power.

Additional thermal copper shield, coupled with the 1st stage of the cryocooler cold head and the new cryostat, providing better vacuum insulation were used. Between 1st and 2nd stage of the cold head the HTS current leads were applied and the same magnet was suspended on the thermally low conductive carbon-fiber tubes. Each coil of the magnet was connected directly to the 2nd stage of the cold head using the individual thermal bridge. The SMES magnet after modifications is shown in figure 5. Figure 6 illustrates the copper thermal screen and the new vacuum cryostat of the SMES magnet. The new turbomolecular vacuum pump (Oerlikon Leybold Vacuum PT151) has been used to obtain $7 \cdot 10^{-8}$ mbar.

Applying mentioned above modifications, namely, the improvement of magnet cooling conditions, as well as better thermal insulation, made it possible to obtain the magnet temperature of 13 K after 66 hours of cooling (figure 7).
Figure 5. New configuration of the SMES magnet: a – instrumentation socket, b – cryocooler cold head, c – current connector, d – vacuum connector, e – cryostat cover, f – 1st stage of cold head, g – copper current leads, h – thermalisation aluminium block, i – thermal shield cover, j – 2nd stage of cold head, k – HTS current leads, l – carbon-fiber tubes, m – voltage taps, n – thermal bridges, o – connections between pancake coils.

Figure 6. Fully assembled SMES magnet: a – instrumentation socket, b – cryocooler cold head, c – current connectors, d – copper thermal shield, e – vacuum cryostat.

Figure 7. Temperature and resistance of the modified magnet during cooling process.
The temperature about 13 K allows the magnet to operate at the maximal (critical) current of 264 A, which gives the maximal storage energy of around 34.8 kJ. The maximal tested current, due to limitation of power supply unit, was 173 A \((T = 13 \text{ K})\), which gives the storage energy of 15 kJ. The magnet of this SMES will operate under control of the electronic power converter with limitation to 180 A that corresponds to 16.2 kJ.

3. Conclusions

Improvement of the cooling power usage and the upgrade of the thermal isolation of the superconducting device permitted to achieve stable working conditions even better than these assumed during conceptual stage of this project.

After putting into operation mentioned above modifications our magnet complies with project parameters with reasonable safety margin and it's ready for testing as the working SMES unit. 30 kVA electronic power converter has been already designed and constructed. It will couple the magnet with the test power grid 3 x 400 V, 50 Hz.

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