Experimental research on pulse forming based on high-temperature SMES applied in pulsed power

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Abstract. To research the key problems of storage energy and pulse forming in pulsed power, a pulse magnet made of Bi2223/Ag high-temperature superconducting (HTS) tapes applied in pulsed power experiment was developed. After determining electromagnetic characteristics of the magnet, a pulse forming network was designed. HTS magnet was immersed in liquid nitrogen bath, experiments were carried out about discharging pulse current to resistance load based on HTS magnet energy storage (SMES). The results show that pulse current waves were obtained through adjusted circuit construction and magnet parameters by acting delay of switches in the pulse forming network. The technical schemes about pulse forming based on SMES were presented.

1. Introduction

The key problems of high pulsed power technology are energy storage systems which can support high density of energy storage and power, discharge pulse current wave well controllable and repetitive, satisfy different load required, and require simple composing of system. Thus improving energy storage density, repeated frequency, making the devices light, miniaturization and practicality, these are the developing direction in the future. Superconducting magnet energy storage (SMES) provides advantages of high-efficiency storage, high density storage, fast discharge energy and easy control [1].

Low-temperature superconducting technology was applied to produce some strong magnetic-field and storage energy [2], high-temperature superconducting (HTS) tape of Bi series can work at 5-10T under 30 K temperature, more lower the temperature, more stronger the working magnetic-field [3], the stronger magnetic-field can be obtained at higher temperature range by Y series high-temperature superconductor. The sufferance energy density of high-temperature superconductor are more several amount levels than low-temperature superconductor’s [4], high-temperature superconducting magnet has better resisting ability to disturb than low-temperature superconducting magnet [5], such as disturbing in normal run, magnet charging and discharging [6]. The capability of high-temperature magnet can be improved by augmenting thermal capacity of superconducting coil under a well cooling condition [7]. Some researches on high-temperature SMES applied in pulsed power have been
reported [8, 9]. The authors’ former investigation has discovered the high-temperature superconductor a good characteristic for pulse over-current [10, 11]. Therefore the application of HTS for future pulsed power would be very promising.

To discuss methods on pulse forming based on high-temperature SMES, a pulse magnet made of Bi2223/Ag high-temperature superconducting tapes applied in pulsed power experiment was developed. After determining electromagnetic characteristics of the magnet, a pulse forming network was designed. HTS magnet was immersed in liquid nitrogen bath, experiments were carried out about discharging pulse current to resistance load based on HTS magnet energy storage. The results show that pulse current waves were obtained through adjusting circuit construction and magnet parameters, the technical schemes about pulse forming based on SMES were put forward.

2. Experimental HTS pulse magnet

2.1. Magnet Structure

Hollow single-solenoid HTS pulse magnet is shown in figure 1, HTS double-pancake coil is shown in figure 2, and the specifications are shown in table 1. Double-pancake coil was formed framework with copper-coil, the insulated Bi2223/Ag HTS tapes were enlaced on the framework, and double-pancake coils were piled up to be a single-solenoid coil. To avoid short circuit effect at transformer subaltern side, the cooper-coil is cracking little, and the brim is protruding at the top and concave at the below along inside copper-coil, buttoning one another along coaxial, so that improve the whole magnet resisting machine stress effect. The magnet exterior-diameter is 272 mm, the inner-diameter 142 mm, height 100 mm. Use 1 mm epoxy board to insulate and exchange heat. The magnet is linked upper and nether flange and 6 heat exchange pieces of epoxy between two coils, and by using 8 radixes of steeliness heat exchange poles. The length of heat exchange pole is 130 mm, its diameter is 12 mm, the passing aperture are all 13 mm, the gaps is crammed with indium to insure the heat exchange well.

![Figure 1. Experimental HTS pulse magnet](image1)

![Figure 2. HTS double-pancake coil](image2)

To consider the requirement of research on pulse forming method based on high-temperature SMES and electromagnetic characteristics of single double-pancake coil, there are 5 tie-ins in magnet, each double-pancake coil was designed alone current lead, each current lead was fetch out by copper down-lead (Using two voluble copper leads with 150 mm length and 3 mm diameter) to provide experimental connection. The current lead was made of copper bar, the same width with the tape, which is fixed on the epoxy bracket, and the bracket board is fixed on magnet flange. Two superconducting taps of each double-pancake coil and the jointing length of current down-lead are all 5 cm, jointing well. There are two voltage detection taps in each double-pancake, and the distance between voltage detection tap and the jointing point is 8 cm, so that it avoids detection error because of jointing superconducting tape over temperature to damage.
Table 1. Specifications of HTS double-pancake coil

| Specification                          | Parameter                                      |
|----------------------------------------|-----------------------------------------------|
| Tape manufacturer                      | Beijing Innao ST,Ltd.                         |
| Tape                                   | Bi-2223/Ag tape                               |
| Width                                  | 4.2 mm                                        |
| Thickness                              | 0.23 mm                                       |
| Tape critical current                  | 68.7 A (77 K, self-field)                     |
| Length of double-pancake coil tape     | 231.25 m                                      |
| Coil inner diameter                    | 150 mm                                        |
| Coil exterior diameter                 | 272 mm                                        |
| Coil(double-pancake) circle number     | 176×2 circles                                 |
| Critical current of coil               | 28.7 A (77 K, self-field)                     |
| Insulation between pancakes            | 0.5 mm epoxy                                  |
| Diameter of inside heat exchange canister | 145 mm                                    |
| Thickness of inside heat exchange canister | 3 mm                                      |
| Outboard insulation of inside heat exchange canister | 2 mm solidify apoxy |
| Double-pancake coil self-induction     | 123 mH                                        |

2.2. Magnet Parameter

The HTS double-pancake coils are 5, the height of the superconducting magnet is 56 mm, the sum of coil circles: \(352 \times 5 = 1760\), the length of HTS Bi2223/Ag tape in magnet: \(231.25 \times 5 = 1156.25\) m, the quench voltage of magnet under DC current: 115.6 mV (criterion: 1 µV/cm).

Magnetic field result: under 77 K, current 20 A, radial magnetic field \(7.616 \times 10^{-2}\) T, axis magnetic field 0.3174 T, inductance 0.615 H, energy storage 123.0 J.

Immersed in liquid nitrogen bath, and self-field, the magnet critical current 19.4 A. The magnet resistance in room temperature 20.87 Ω (13 °C)

3. The DC characteristic of magnet

As a first step, to make sure electric characteristic of HTS magnet, immersed in liquid nitrogen bath and self-field, DC characteristic experiment of HTS magnet was carried out, the critical current of the magnet was determined.

The DC characteristic of magnet is shown in figure 3, use 1 µV/cm as criterion of quench, the total length of HTS tapes applied for magnet is 1156.25 m, quench voltage is 115 mV+230 mV (the resistance voltage of current copper lead between HTS double-pancake coils)=345 mV, corresponding current is 19.4 A. As is shown in figure 3, when the magnet doesn’t quench, the \(I-V\) curve of DC current flatness, the obtained voltage is resistance voltage of current lead (copper lead) between 5 double-pancake coils. When the magnet quench, the normal region enlarge rapidly, the normal resistance augment incessantly, the normal voltage augment rapidly, the \(I-V\) curve become cragged, therefore it shows that the critical current of magnet is 19.4 A under 77 K and self-field.
4. Pulse forming experiment

4.1. Experiment circuit.
As is shown in figure 4, the cooling condition of magnet is immersed in liquid nitrogen bath, \(L_{s1}, L_{s2}\) are two superconducting coils of HTS magnet, \(I_s\) is constant current source adjustable, \(D_1, D_2, D_3, D_4\) are diodes, \(R_1\) is energy consumption resistance of magnet protection (1.6 \(\Omega\)), \(R_2\) is load resistance (0.86 \(\Omega\)), \(F_1\) is DC diffuent implement (200A/75mV), \(F_2\) is coaxial diffuent implement, the resistance 3.1058 m\(\Omega\). There are three processes in the experiment, magnet charge, energy storage, and magnet discharge. The charge current and discharging load current are detected with oscillograph through \(F_1, F_2\) respectively. The magnet voltage and the load voltage are detected with oscillograph also.

![Figure 4. Experiment circuit of pulse forming based on SMES](image)

4.2. Magnet in Series Discharge
\(K_2\) is cut off, \(K_3\) and \(K_1\) are closed, superconducting coil \(L_{s1}\) and \(L_{s2}\) are charged in series. Close \(K_2\), cut off \(K_1, L_{s1}, L_{s2}\) storage energy. As discharge experiment, cut off \(K_3\), the two superconducting coils in series discharge to load. Figure 5 shows the obtained representative pulse current wave, the pulse current amplitude of load is 14.1 A, the attenuation time of the pulse current is 230 ms, the export maximal pulse power is 128.3 W.

4.3. Mixed Discharge of Magnet in Series and parallel
After two superconducting coils in series charged and storage energy, cut off \(K_2\) and \(K_3\) at the same time, the two superconducting coils in parallel discharge, or adjust the acting times of two switches,
change discharge circuit connection, the HTS magnet in series or parallel discharge to obtained load pulse current with different waves.

![Graph](image1)

**Figure 5.** Pulse current wave as two HTS coils in series discharge

Figure 6 shows the experimental results that $K_2$ delay cutting off $K_3$ 31.163 ms, the two load current peak value are 12.8 A and 13.1 A respectively, the current attenuation time is 101.6 ms, the two peak value of export pulse power are 107.8W and 106.4W. It shows that a good load pulse current wave can be obtained through adjusting switch action time to change the circuit or parameter of superconducting magnet discharging to load.

![Graph](image2)

**Figure 6.** Pulse current wave as two HTS coils in series and parallel discharge

5. **Conclusions**

A experimental HTS pulse magnet was developed, under the condition of immersed nitrogen bath and self-field, DC characteristic experiment on magnet was carried out. After determining the magnet critical current, the pulse forming circuit was designed. To discuss pulse forming method based on high-temperature SMES, pulse forming discharge experiment to 0.86 Ω resistance load was carried out after the magnet charged. The experimental results show that the HTS magnet has a good pulse discharge characteristic, pulse current waves can be generated through adjusting circuit construction
and magnet parameters by acting delay of switches in the pulse forming network. The technical schemes about pulse forming based on SMES would be very promising.

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