A Flux Pumping Method Applied to Magnetization of YBCO Superconducting Coils: Frequency, Amplitude and Waveform Characteristics

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A Flux Pumping Method Applied to Magnetization of YBCO Superconducting Coils: Frequency, Amplitude and Waveform Characteristics

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Abstract — This paper presents a flux pumping method and the results gained when it was used to magnetize a range of different YBCO coils. The pumping device consists of an iron magnetic circuit with eight copper coils which apply a traveling magnetic field to the superconductor. The copper poles are arranged vertically with an air gap length of 1 mm and the iron core is made of laminated electric steel plates to minimize eddy-current losses. We have used this arrangement to investigate the best possible pumping result when parameters such as frequency, amplitude and waveform are varied. We have successfully pumped current into the superconducting coil up to a value of 90% of Ic and achieved a resultant magnetic field of 1.5 T.

1. Introduction

High temperature superconducting (HTS) magnets are one of the promising applications of superconductivity. However, HTS magnets suffer magnetic field decay when operating in persistent current mode because of a low n-index value [1, 2] and high joint resistance when compared to LTS. So the method for maintaining the field strength is regarded as a crucial problem [3]. A flux pump is one of the most effective methods to compensate the field decay for HTS superconductors [4] and has the advantage of not requiring current leads so has a low thermal overhead. To date, a variety of HTS flux pump devices have been developed, including rotating type with electromagnets [5-7] or permanent magnets [8-10] and the rectifier type [1,11-13].

This paper introduces a linear flux pumping method using electromagnets made of copper coils with laminated electric steel plates to magnetize different superconducting coils. Unlike a rotating travelling wave flux pump using permanent magnets, a linear pumping method can work with varying field strength and without vibrations and noise due to rotor unbalance [14,15]. The operational principle of rotating type flux pump is different from that of rectifier flux pump. Usually, rectifier type requires a more complex structure to control superconducting switches. The charging time also depends on the switching speed, and the switch often suffers from thermal runaway and instability in a faster speed. In our linear electromagnetic pump, current-source driver circuits were used rather than voltage-source driver circuits to control the current through the copper coils of the electromagnets. Hence, the current-source driver circuits output the current, applied field to the superconductor, independent of the load. During the experiment, unipolar sinusoidal waves, trapezoidal waves and triangular waves were all applied. Based on the previous flux pump research [5], the maximum value of applied field strength used for charging the superconducting coil with this new device was greatly increased to 0.8 T and solder skill was improved in order to minimize the connecting joint resistance between superconducting tape and superconducting coil. Moreover, compared with previous flux pump equipment [5], the new device is smaller in dimension and also designed to have smaller flux leakage and inductance of copper windings. In this experiment, several kinds of superconducting coil with and without iron core have been made to explore the frequency and amplitude characteristics of pumping.
2. Experimental configuration

2.1 Structure of magnetization system

Fig. 1 3D structure graph of magnetization system. Linear flux pump is composed of eight copper coils, iron cores, iron frame. The superconducting tape is positioned between the air gap of magnetic poles and superconducting coil is fixed on the supporting plate.

Fig. 1 shows the structure of the magnetization system. The magnetic poles comprise 4 upper copper-coils and 4 lower copper-coils with laminated iron cores inside, which are fixed in a supporting iron frame. The number of turns of each copper coil was 140 wound using copper wire with a diameter of 0.6 mm. Each upper coils was connected in series to the coil directly below it and the applied field that they provided was controlled by a driver circuit. The four driver circuits were current source circuits, which were designed based on the power operational amplifier LM3886 and the output current was stable without the effect of load change. The gap between the upper and lower coils was 1 mm. The resistance of each copper coil was 2 +/- 0.2 Ω in room temperature. The resistance decreased to less than 0.6 Ω in 77 K. The inductance of each copper coil was 10 +/- 1 mH. Four strips of 80 mm × 12 mm superconducting tape (Superpower SF12100) shorted the two ends of the superconducting coils (Superpower SCS6050) using solder method and each tape was placed in the air gap between the magnetic poles. The critical current of SF12100 is 365 A in self-field. The soldering method proposed by MIT magnet laboratory [16] is used to make the resistive joints which are expected to have a total parallel joint resistance less than 100 nΩ. During the measurement, the whole magnetization system was immersed in a liquid nitrogen bath at 77 K. One cryogenic Hall probe was placed on the surface of the superconducting tape to measure the accumulation of applied field and trapped field of superconducting tape. Another was installed close to the superconducting coil to measure the pumping current.

The present test rig is placed inside a liquid-nitrogen bath or a cryostat. This configuration has a drawback; thermal losses are caused by Joule heating of copper windings and iron-core hysteresis. The field strength is, however, greatly enhanced with a smaller length of air gap, and the resultant charging time is much shorter. Those losses can be eliminated by applying a field from the outside of the cryostat as in [13]. The AC losses are also inevitable in the superconducting tapes. However, they are much smaller than the heat leak due to copper current leads with conduction cooling [17] and do not greatly influence the total cooling capacity.

Firstly, the magnetization system was applied to charging three kinds of superconducting coils including pancake coil, rectangle coil and rectangle coil with iron core. These coils are shown in Fig. 2. The pancake and rectangular coils were made from 6mm wide superconducting wire (SCS6050) wound around G-10 fiberglass bobbins (Figs. 2(a) and 2(b)). The rectangular coil was also placed around an iron core to enhance the field strength and the coil inductance (Fig. 2(c)). The iron core was made from laminated electric steel plates and had an air gap of 1 mm at the central pole of E core. In order to obtain the critical current of each coil, the 4-point method was used to measure current versus
voltage characteristics of those three coils and the results are shown in Fig. 3. The three coils have similar current versus voltage characteristics to one another, and the measured critical current and details of those three coils are shown in Table 1. The rectangular coil has the critical current of about 100 A with and without the iron core. The iron core certainly enhances the field strength, however, it doesn't greatly influence the critical current of the superconducting coil. This is because only a small amount of leakage flux is applied to the coil. Usually, the critical current of coil decreases as the number of turns increases. Hence, the critical current of pancake coil is smaller, only 77 A.

![Fig.2 Photograph of pancake coil, rectangular coil and rectangular coil with iron core](image)

**Fig.2 Photograph of pancake coil, rectangular coil and rectangular coil with iron core**

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>SPECIFICATIONS OF SUPERCONDUCTING COILS</th>
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<tbody>
<tr>
<td>Core</td>
<td>I_c (A)</td>
</tr>
<tr>
<td>Pancake</td>
<td>air</td>
</tr>
<tr>
<td>Rectangle</td>
<td>air</td>
</tr>
<tr>
<td>Rectangle</td>
<td>iron</td>
</tr>
</tbody>
</table>

![Fig.3 I-V characteristics of superconducting coils including pancake coil, rectangular coil and rectangular coil with iron core](image)

**Fig.3 I-V characteristics of superconducting coils including pancake coil, rectangular coil and rectangular coil with iron core**
2.2 Current-source driver circuit

The four pairs of copper solenoids are each connected to identical driver circuits to produce AC applied field. The design of the driver circuits is based on the power operational amplifier LM3886, and the output current does not depend on the load in theory. The circuit mainly comprises a signal source, resistors, a ±24V DC power supply and an amplifier.

![Circuit Diagram](image)

Fig.4 The circuit diagram of a current-source driver circuit including a signal source, resistors, a DC power supply and an power amplifier LM3886.

Fig.4 shows the driver circuit diagram. In order to calculate the current of solenoid $I$, we make two assumptions:

1) $V_+ = V_-$
2) $I \approx I_2$ (Since $R_1 + R_2$ is much larger than $R_3$, $I_1$ is much smaller than $I_2$)

By using the Kirchhoff's Law, $V_+$ and $V_-$ are expressed in terms of $V_{in}$ and $I$, and then are substituted into the assumption 1). We can then obtain the current of solenoid $I$:

$$I = \frac{R_2}{R_1 R_3} V_{in} \quad (2.2.1)$$

Hence, the current just depends on the input signal since the values of $R_1$, $R_2$ and $R_3$ were defined. On the other hand, copper solenoids have resistance $R$ and self-inductance $L$. From the Ohm’s law, the amplifier output $V_{out}$ can be expressed as follow:

$$V_{out} = (R + j \omega L + R_3)I \text{ with } I \approx I_2 \quad (2.2.2)$$

Since the supply voltage of LM3886 is 24 V, $V_{out}$ should be no larger than 24 V.

$$I \leq \frac{24}{R + j \omega L + R_3} \quad (2.2.3)$$

In the experiment, the largest current that we need apply to solenoid was 4.2 A. As the driver circuit worked at lower frequencies, the second term in the right side of (2.2.2), $j \omega L$, was small and the
limitation of output current (2.2.3) didn’t influence actual current through solenoid. However, as the frequency increased, the effects of the inductance \( j_0L \) would become larger and larger. This may lead to the set current (2.2.1) larger than the limitation of output current. Hence, the wave profile of current through solenoid is distorted with reduced amplitude at higher frequencies. In the test, as the frequency of input signal was larger than 30 Hz, the inductance term starts to distort the wave profile.

2.3 Soldering system

Based on the soldering method proposed by MIT magnet laboratory [16], we built a new soldering equipment to make the flux pump joints. We can precisely control the quantity of ribbon solder, the pressure exerted on joints and heating time using the new equipment. Moreover, all the joints can be heated uniformly and simultaneously instead of manual soldering. These joints are expected to have parallel joint resistance less than 100 nΩ. The superconductor soldering system contains a temperature controller, two 300 W cartridge heaters with aluminium holders, two Tufnol supporting plates, together with circular weights of 4.2 kg. The superconducting tapes are placed on the aluminium holder and heated by the heaters while being subjected to a pressure of 9.5x10^6 Pa from the circular weights. The aluminium holder is a slender bar with a central hole to accommodate the cartridge heater and is designed to maximize the rate of temperature rise. The solder (63SN37PB Ribbon, Indium Corporation of America) is a thin strip with thickness of 50 μm, and the soldering flux (CW8100, ITW Chemtronics) is based on rosin. The flux pump joints are made using the following steps: 1) Prepare four 12 mm width tapes and a superconducting coil made of 6 mm width tape 2) Clean the superconductor side surface of all tapes and both ends of the coil with sponge and acetone 3) Fix the two ends of the coil on the aluminum holder of cartridge heater via kapton tape 4) Apply soldering flux and eight pieces of solder (12 mm × 1 mm) on the superconductor side of the ends of the coil 5) Arrange the four 12mm tapes on the ends of the coil, fix them by Kapton tape, and place the tufnol plate and the weights on the joints 6) Switch on the temperature controller with the maximum output and wait for the temperature to rise up to 185 degrees centigrade (the solder melting point) in about one minute 7) Switch off the controller at the melting point and start cooling the joints by contacting an aluminum plate; the temperature rises up to 210 degree centigrade and naturally returns to the room temperature.

Three samples of the flux pump joints were made using the procedure described above. The total joint resistances of all the samples were measured by the conventional 4-point method. In the 4-point method, a current is supplied through the ends of the sample and the voltage across two points on the sample is measured by a voltmeter. Ohm’s law is used to calculate the joint resistance from the
measured voltage. The values of the total joint resistance were 42 nΩ, 55 nΩ and 71 nΩ respectively, which were less than 100 nΩ in all samples.

2.4 Operational principle and measurement procedure

The principle of our linear flux pump has been presented in previous work [5]. According to Faraday's Law, an electric field is induced in superconductor by the travelling magnetic field \( \Phi \) generated by copper solenoids. The strength and travelling speed of magnetic field depend on the amplitude and frequency of applied current to copper coils. Therefore, we can change the input signal of driver circuit easily to control \( d\Phi/dt \), i.e. the induced electric field.

At the start of each measurement the whole magnetization system was immersed in a liquid nitrogen bath for about 15 minutes. The liquid nitrogen level was maintained so that the whole magnetization system remained immersed during measurement. Secondly, the frequency, amplitude and duty cycle of applied field profile were set. The frequencies used in experiment were 5 Hz, 10 Hz and 15 Hz. The amplitude of applied current was 0.7 A, 1.4 A and 2.1 A. Rising percentage of triangular wave profile was changed from 15% to 95%. In a typical measurement the copper coils were actuated until saturation of induced current or trapped field strength in the superconducting coil occurred. The actuation was then switched off and we recorded the decay of current, which resulted from the joint resistance and superconducting resistance based on E-J Law.

2.5 Applied wave profile

![Fig. 6](image1.png) Fig. 6 Applied triangular wave profiles in four-pair magnetic poles with 5-Hz frequency, 2.1-A amplitude and 60-degree phase shift between adjacent poles.

![Fig. 7](image2.png) Fig. 7 Effects of unipolar sinusoidal wave, trapezoidal wave and triangular wave at 5-Hz frequency and 2.1-A copper coil current for magnetizing rectangular coil

<table>
<thead>
<tr>
<th>Copper coil current (A)</th>
<th>Field strength between the pole gap (T)</th>
</tr>
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<tbody>
<tr>
<td>0.7</td>
<td>0.1725</td>
</tr>
<tr>
<td>1.4</td>
<td>0.34</td>
</tr>
<tr>
<td>2.1</td>
<td>0.497</td>
</tr>
<tr>
<td>2.8</td>
<td>0.635</td>
</tr>
<tr>
<td>3.5</td>
<td>0.73</td>
</tr>
<tr>
<td>4.2</td>
<td>0.77</td>
</tr>
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</table>
For this configuration, three wave profiles including sinusoidal, trapezoidal and triangular waves were applied to energizing the superconducting coils. Fig. 6 shows the applied wave profiles of four-pair magnetic poles with 5-Hz frequency, 2.1-A amplitude and 60-degree phase shift between adjacent poles. For applied triangular wave, it is an asymmetric wave profile with slow positive ramp and steep decay. The percentages of positive ramp and decay in one period are usually 85% and 15%. That is because we found the applied field strength should rise slowly and fall rapidly in order to improve the pumping speed and the maximum current after a series of measurements. As applied current value reach to 2.1 A, the applied field strength between the pole gap is almost 0.5 T. The details of applied field strength with different current amplitude are shown in Table.2.

Of the three waveforms tested the triangular wave is the most effective for pumping superconducting current. Fig. 7 shows the experimental results comparing the three wave profiles for magnetization of the rectangular coil with frequency and copper coil current set at 5 Hz and 2.1 A respectively for all of the wave profiles. The latter part of this paper only shows the frequency characteristics and amplitude characteristics with triangular waves for charging different superconducting coils.

3. Experimental results of three kinds of superconducting coils

3.1 Experimental results for magnetizing pancake coil

Fig. 8 Effects of applied frequency for pancake coil  Fig. 9 Effects of field strength for pancake coil

Fig.8 and Fig.9 show the experimental results for the pancake coil when it was charged up by the linear flux pump. Fig. 8 shows the effects of applied frequency on pumping the superconducting current as the amplitude of applied field strength was 0.34 T. The maximum induced current increased with applied frequency and reached about 70 A at 15 Hz, 91% of the critical current of pancake coil. The charging time decreased with applied frequency, and the shortest time was about 27 s at 15 Hz. The pumped current was also influenced by strength of the applied field as shown in Fig. 9 The saturation current increased with field strength, up to 2.1 A of copper-coil current. After the saturation of pumping current, the travelling magnetic field was removed and then the decay caused by superconducting resistance and joint resistance was recorded in every measurement. Hence, the results shown in Fig.8 and Fig.9 contain the whole changing process of superconducting current, which consists of pumping, saturation and decay. The following results for magnetizing other superconducting coils were presented in the same way.
3.2 Experimental results for magnetizing rectangular coil

Fig. 10 Effects of applied frequency for rectangular coil

The flux pump was also applied to the rectangular coil with an air core. The inductance of this coil is the minimum among the three coils and was expected to require the shortest charging time. The pumping speed and the maximum current both increased with applied frequency in Fig. 10. The maximum current reached about 87 A, 92% of the critical current, and the shortest charging time was about 15 s. The effects of field strength on the pumping current were also examined and were shown in Fig.11. The applied coil current of 1.4 A was the most effective, which is different from the pancake coil. The charging time of the rectangular coil was shorter than that of the pancake coil as was expected.

3.3 Experimental results for magnetizing rectangular coil with iron core

Fig. 12 Configuration of rectangular coil with iron core

Flux pump was also applied to charging the rectangular coil with an iron core. Fig.12 shows a configuration of rectangular coil with an iron core, and the core has an air gap of 1 mm length at the central pole of the E-core. A Hall sensor was placed at the gap to measure the trapped field strength. The iron core was used to enhance the field strength generated by the superconducting coil and the resultant inductance of the coil was 15 times larger than the original coil without the iron core. Fig.13
shows the effects of applied frequency on charging the coil. It was similar to the pancake coil and the rectangular coil with air core in that the charging speed increased with applied frequency. The maximum trapped field strength in the air gap reached about 1.35 T. This was equal to 90 A induced in superconducting coil, 92% of the critical current. The shortest charging time was about 160 s, which was much longer than preceding two coils because of the larger inductance value, and hence the large stored energy.

3.4 Comparison of charging time among three coils

In the preceding measurement results, the flux pump was used to charge three coils. Fig.14 compares charging histories of the three coils with a triangular wave profile at a frequency of 15 Hz and copper coil current of 1.4 A. The charging time is also expressed as a function of coil inductance in Fig. 15. From the Fig.15, we can find that the charging time is a linear function of coil inductance.

4. Improvement of trapped field strength

For a single coil arrangement, the maximum trapped field strength obtained was 1.35 T. In order to improve the trapped field, two superconducting coils were placed in an E-core loop and superconducting tape with double HTS layers (AMSC-Type 8612 Amperium wire with double HTS layers) was used to solder with them. We used same solder system, which was shown in previous part of the paper, to solder one side of superconducting tapes with upper coil and the other side with lower coil respectively. The critical current of type 8612 superconducting tape is 675 A. Parameters related to the superconducting coils were shown in Table.3. The photograph of assembled magnetization system was shown in Fig.16. The cryogenic Hall sensor was kept in the same position of E-core to measure the trapped field in the gap.

<table>
<thead>
<tr>
<th>TABLE 3</th>
<th>PARAMETERS OF SUPERCONDUCTING COILS</th>
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</thead>
<tbody>
<tr>
<td>Core</td>
<td>I_c (A)</td>
</tr>
<tr>
<td>Upper coil</td>
<td>iron</td>
</tr>
<tr>
<td>Lower coil</td>
<td>iron</td>
</tr>
</tbody>
</table>
Fig. 16 Flux pump with parallel superconducting coils

Fig. 17 and 18 show the frequency and amplitude characteristics of parallel rectangular coils. Due to the critical current of superconducting tape with double HTS layers (AMSC-Type 8612) being much larger than the original superconducting tape SF12100, we increased the applied field strength from 0.635 T to 0.77 T in the test. For this arrangement, we also tested the frequency characteristics from 5 Hz to 15 Hz. The results were similar to the single coil arrangement, the rate of rise of trapped field increased with frequency and the final trapped field strength reached to 1.5 T. The charging time was one quarter of the single iron-core rectangular coil arrangement, being only 40 seconds at 15 Hz. The applied field strength also influenced the charging time, reducing as larger field strength was applied.

5. Conclusion

Our linear flux pump was used to magnetize pancake coil, rectangular coil, rectangular coil with iron core and parallel rectangular coil with iron core. The pumped current in superconducting coils can reach more than 90% of Ic. The maximum trapped field strength of rectangular coil with iron core was 1.35 T. By soldering two rectangular coils with double HTS superconducting tapes, the resultant field strength was improved to 1.5 T. Usually, higher frequency and larger applied field strength can
obtain better pumping results and shorter charging time. The charging time also linearly depend on the inductance of superconducting coil.

For further work, we plan to investigate some other characteristics of charging superconducting coils such as phase shift between adjacent copper coils, temperature, position of superconducting tapes, etc. Moreover, a new racetrack bobbin with larger diameter of corner will be made to wind a new coil, which will increase the critical current of superconducting coil with identical turns instead of rectangular bobbin.

**Acknowledgement**

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**Reference:**

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