Fast Current Regulation and Persistent Current Maintenance of High-Temperature Superconducting Magnets With Contact Power Supply and Flux Pump

Chenghuai Wu, Wei Wang, Run Long, Hong Li, Li Zhou, and Peng Liu

***Abstract*—Due to the properties of high-temperature superconducting (HTS) materials, current attenuation is inevitable during the closed-loop operation of HTS magnets. When a contact dc power supply is used to supplement this attenuation, it inevitably creates a huge thermal burden on the cryogenic system. The flux pump is a revolutionary new power source that can charge closed-loop HTS magnet wirelessly. However, for HTS magnets with a large inductance, the flux pump cannot fast adjust the dc current of the magnet due to its small dc output voltage. Here, we present a method to fast regulate the current in a closed-loop HTS magnet using a contact dc power supply and persistent current switch. After current regulation, the HTS magnet is operated in the persistent current mode with a flux pump. Applying the "four-quadrant" control theory of the flux pump allows the current in the HTS magnet to be controlled with high stability. The study provides a power strategy for the fast current regulation and maintenance of persistent current in the HTS magnet, enabling the industrial applications of flux pumps for HTS magnets with large inductance.**

***Index Terms*—Flux pump, persistent current mode (PCM), superconducting magnet, wireless power transfer, yttrium barium copper oxide (YBCO) wire.**

I. Introduction

COMPARED with low-temperature superconducting (LTS) wires, the second-generation high-temperature superconducting (HTS) wire is more suitable for generating strong magnetic fields due to its higher upper critical magnetic field, higher critical temperature, and higher critical current density [1], [2]. In recent years, significant progress has been made in various fields, such as superconducting magnetic energy storage [3], [4], [5], [6], particle accelerators, high-field magnet [7], [8], NMR/MRI [9], [10], [11], magnetic levitation vehicles [12], [13], and superconducting motors [14], [15], [16], thanks to the widespread use of yttrium barium copper oxide (YBCO) coated conductors for constructing HTS magnets. However, HTS magnets cannot operate in a closed loop, or in the persistent current mode (PCM) like LTS magnets, due to the inevitable soldering resistance [17] and the low n value in its superconducting E–J power relationship [18], [19]. If the traditional contact dc power supply is used to maintain the operation current, the presence of current leads causes huge heat leakage into the cryogenic system, and its own resistance also generates extra joule heat, resulting in the extremely high energy consumption. One potential solution to address this issue is the utilization of HTS flux pumps. These flux pumps can transfer dc current through wireless power transfer to maintain PCM in HTS closed-loop magnets, thus eliminating the need for current leads and contact power supply, thus decreasing the energy consumption by several orders of magnitude compared with the conventional contact dc power supply.

Over the past decade, a variety of HTS flux pumps have been developed to wirelessly charge HTS magnets, including HTS dynamo [20], [21], [22], [23], linear-motor-type flux pumps [24], [25], [26], linear-pulse field flux pumps [27], [28], [29], and transformer–rectifier flux pumps [30], [31], [32], [33], [34]. Of these, linear-motor-type flux pumps, HTS dynamo, and linear-pulse field flux pumps are categorized as traveling wave flux pumps [35]. Despite the prevalence of traveling wave flux pumps, the origin of their dc output has remained a theoretical challenge since their discovery. This is because it cannot be clearly explained by the induction law. Inspired by Giaever's "dc transformer" experiment [36], [37], Wang and Coombs [38] proposed macroscopic magnetic flux coupling theory to explain the source of the dc electromotive force of the traveling wave flux pump. The theory explains that the moving magnetic pole generated by the traveling wave flux pump can couple a large number of vortices on the superconducting films and drag the vortices to move in a predetermined direction, thereby generating a dc electromotive force, given as follows:

$$\vec{E} = \vec{B} \times \vec{v}_f \tag{1}$$

here, $\vec{B}$ denotes the magnetic flux density of the coupled vortices, while $\vec{v}_f$ represents the velocity of the traveling magnetic pole.

Relying on (1), Wang et al. [26] presented a "four-quadrant" control strategy to precisely regulate the dc output of HTS traveling wave flux pumps. By controlling the direction of the traveling magnetic wave or the dc bias magnetic field, the accurate control of the pumped current in the magnet is achieved, making the method promising for applications where high-current accuracy is crucial. For example, in a reported 14 T MRI, 1400 A of current needs to be passed to a superconducting magnet with a 300 H

Manuscript received 2 September 2023; revised 29 November 2023; accepted 7 December 2023. Date of publication 13 December 2023; date of current version 16 February 2024. This work was supported in part by the National Natural Science Foundation of China under Grant 51877143 and in part by the Science and Technology Project of Sichuan Province, China, under Grant 2021YFS0088. Recommended for publication by Associate Editor F. COSTA. *(Corresponding author: Wei Wang.)*

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TPEL.2023.3342471.

Digital Object Identifier 10.1109/TPEL.2023.3342471

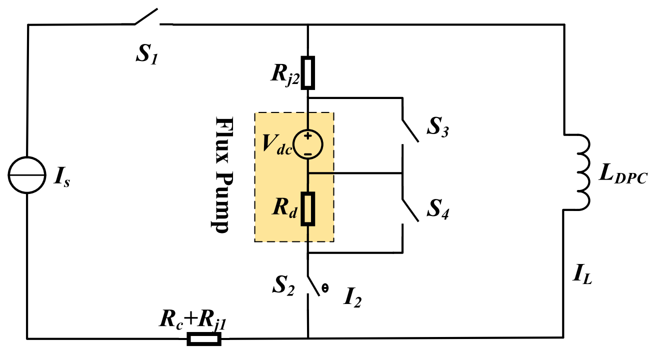

Fig. 1. Equivalent circuit diagram of the fast current regulation and PCM operation of an HTS magnet. When the flux pump is turned ON, a DC voltage and additional internal resistance will be generated in the loop.

inductance, and the current ripple cannot exceed 1 ppm [39], [40]. In this study, we controlled the switch of the dc bias coil of the flux pump via feedback, allowing to maintain PCM at any value in both directions below the maximum output current value of the flux pump. The current ripple is less than 5‰, making it suitable for most applications involving superconducting magnets. These results validate the viability of the "four-quadrant" control theory for achieving high-precision control of current ripple in traveling wave flux pumps.

On the other hand, compared with the conventional contact dc power supplies, the traveling wave flux pumps have a relatively low output voltage [41], resulting in a relatively slow current regulation rate for HTS magnets with large inductance. However, in some application scenarios, fast excitation [42] and demagnetization [43], [44] or even fast current regulation [45], [46], [47] is necessary. For example, in the Tokamak device, superconducting magnets with a caliber of 10–20 m are required to be excited to the maximum field intensity of 3–10 T within 1–20 s. To cope with this problem, here, we propose a method to fast adjust the current in an HTS magnet operated in the PCM. During the current regulation stage, the contact dc power supply and persistent current switch (PCS) are used for fast current regulations. During the closed-loop operation phase, the flux pump is used to supplement the current attenuation caused by the soldering resistance. This method combines the advantages of contact dc power supplies and flux pumps, which can realize both the fast current regulation and PCM operation for HTS magnets. The research results of this work can provide a novel power strategy to enable the use of flux pumps for HTS magnets with large inductances, thus decreasing the energy consumption by several orders of magnitude. This, in turn, may accelerate the broad application of HTS magnets.

II. Working Principle

A. Process and Circuit Principles for Fast Current Regulation and Maintaining PCM Operation

The power strategy proposed in this work enables the fast switching between two operation modes: fast current regulation and the PCM operation. The equivalent circuit is shown in Fig. 1, which contains two circuit loops, the first is the current regulation loop composed of a contact dc power supply I_s and HTS coil L_{DPC}, the second is the PCM operation loop comprised of the flux pump, HTS bridge (stator), and the HTS coil L_{DPC}. The switching between the two operation modes is controlled by two switches S_1 and S_2, while S_2 is the PCS controlled by a heater, i.e., when the heater is switched ON, the HTS bridge becomes normal state, and the PCS is "open." R_{j1} and R_{j2} are the soldering resistances, R_c is the resistance of the current leads, and L_{DPC} is the inductance of the HTS DPC. I_L is the current through DPC and I_2 is the current through the bridge when switch S_2 is closed.

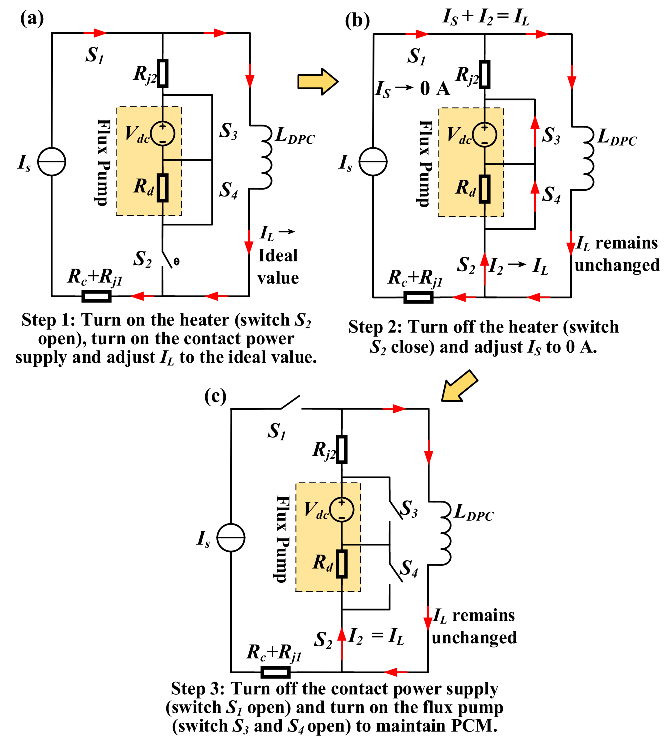

Fig. 2. Initiate fast excitation of the superconducting magnet using the contact power supply and then switch to the flux pump to maintain the PCM.

$\vec{V}_{\mathrm{dc}}$ and R_d [48], [49], [50], [51] are the dc electromotive force (EMF) and internal resistance generated by the flux pump, S_3 and S_4 are the switches of the dc bias coil and ac coil of the flux pump, respectively, i.e., based on (2) and (3), by switching on the dc bias coil and the ac coil of the flux pump, which is equivalent to S_3 and S_4 is "open," the dc EMF $\vec{V}_{\mathrm{dc}}$ is switched ON, and the current is pumped into the closed loop. It is worth noting that only when the dc bias coil of the flux pump and the ac coil are opened at the same time, the flux pump will generate dc EMF in the closed loop; only opening the dc bias coil will not generate dc EMF.

1) Fast Excitation and Maintaining PCM Operation: Fig. 2 shows the operation procedure and circuit principle of fast excitation and maintain PCM operation. First, turn ON the heater (open the switch S_2), turn ON the contact power supply (close the switch S_1), and adjust the current of the contact dc power supply I_s so that I_L can reach its ideal value. The reason for this operation is to use the contact power supply for fast excitation of the DPC. Second, after the fast excitation is completed, it is necessary to switch to the closed-loop operation mode. Turn OFF the heater (close the switch S_2) and slowly reduce the contact dc power supply I_s current to 0 A. In this process, $I_s + I_2 = I_L$, where I_L remains unchanged due to the inductance of DPC, I_s decreases to 0 A, I_2 becomes the same as I_L, and DPC

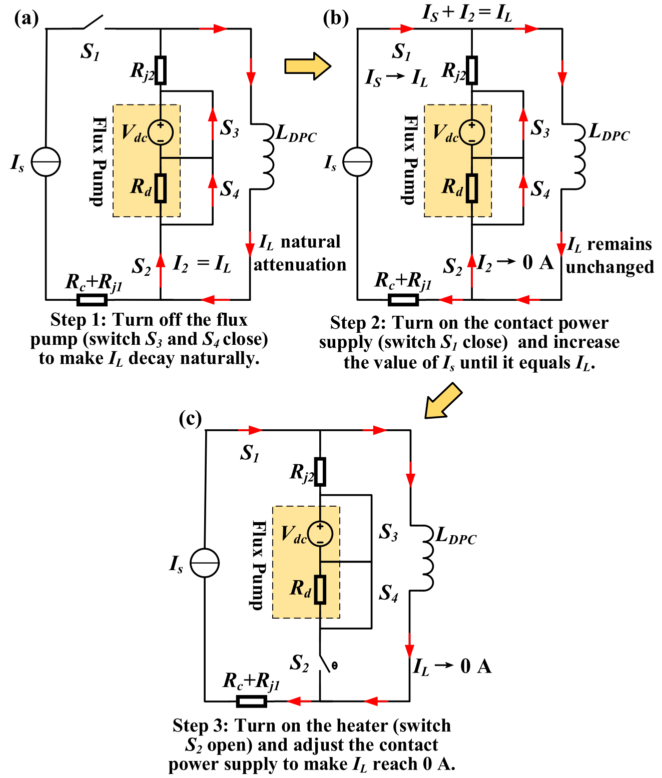

Fig. 3. Switching from the PCM maintained by the flux pump to the open-loop circuit maintained by the contact power supply and utilizing the contact power supply for fast demagnetization of the superconducting magnet.

enters the closed-loop operation. Finally, disconnect the contact power supply (open the switch S_1) and turn ON the flux pump power supply (open the switches S_3 and S_4) to maintain PCM operation.

2) Fast Demagnetization: Fig. 3 shows the operation procedure and circuit principle of fast demagnetization. First of all, ensure that the closed-loop operation magnet is in the natural decay state. If the flux pump is turned ON, it needs to be turned OFF first (keep switches S_3 and S_4 close). Second, turn ON the contact power supply (close the switch S_1) and adjust the knob until the current I_2 is 0 A. In this process, $I_s + I_2 = I_L$, where I_L remains unchanged due to the inductance of DPC, I_2 decreases to 0 A, I_s becomes the same as I_L, and DPC enters the open-loop operation. Finally, turn ON the heater (open the switch S_2) and reduce the current of the contact power supply to 0 A so that $I_L = I_s = 0$ A; fast demagnetization is complete.

3) Fast Adjust the Current and Maintaining PCM Operation: Fig. 4 shows the operation procedure and circuit principle of fast adjust the current and maintaining PCM operation. First of all, ensure that the closed-loop operation magnet is in the natural decay state. If the flux pump is turned ON, it needs to be turned OFF first (keep switches S_3 and S_4 close). Second, turn ON the contact power supply (close the switch S_1) and adjust the knob until the current I_2 is 0 A. In this process, $I_s + I_2 = I_L$, where I_L remains unchanged due to the inductance of DPC, I_2 decreases to 0 A, I_s becomes the same as I_L, and DPC enters the open-loop operation. Third, turn ON the heater (open the switch S_2) and adjust the current of the contact power supply to the ideal

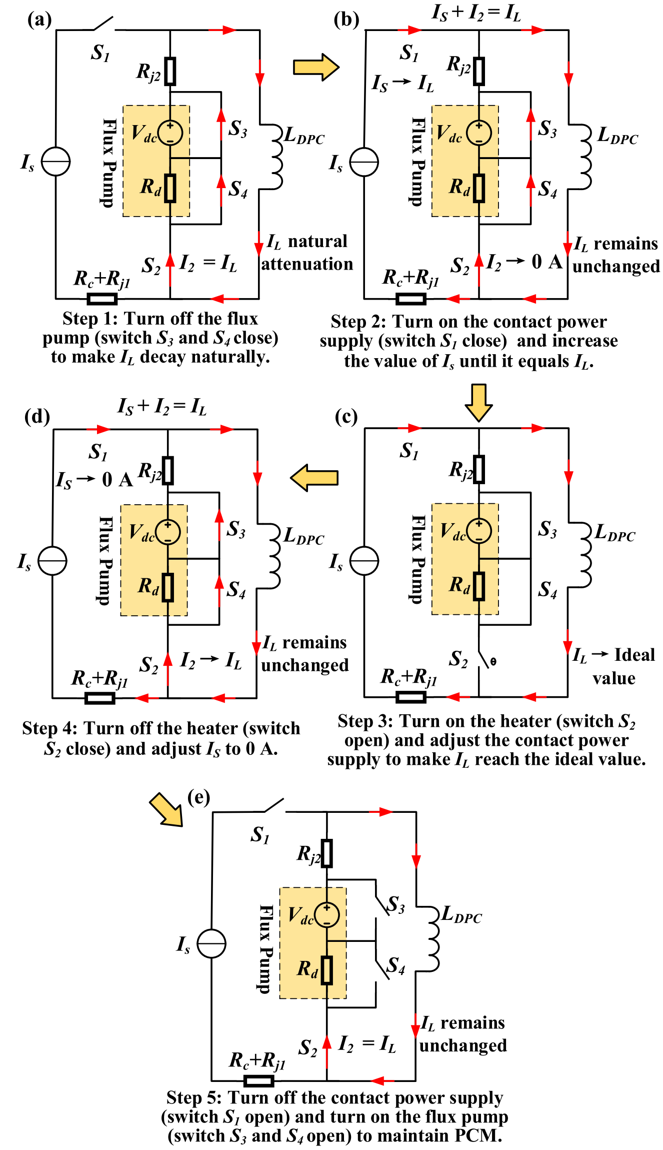

Fig. 4. Switching from the PCM maintained by the flux pump to the open-loop circuit maintained by the contact power supply. After performing fast current adjustment using the contact power supply, switch back to the PCM maintained by the flux pump.

value. In this process, $I_L = I_s$, completing the fast regulation of the current in the DPC. Fourth, turn OFF the heater (close the switch S_2) and slowly reduce the contact dc power supply I_s current to 0 A. In this process, $I_s + I_2 = I_L$, where I_L remains unchanged due to the inductance of DPC, I_s decreases to 0 A, I_2 becomes the same as I_L, and DPC enters the closed-loop operation. Finally, disconnect the contact power supply (open the switch S_1) and turn ON the flux pump power supply (open the switches S_3 and S_4) to maintain PCM operation.

B. Working Principle of Linear-Motor-Type Flux Pump

The linear-motor-type flux pump is mainly composed of ac coil and dc bias coil, which produces a dc biased ac traveling magnetic wave in the air gap, as depicted in Fig. 5, which can be mathematically represented by a 1-D wave equation [52] as

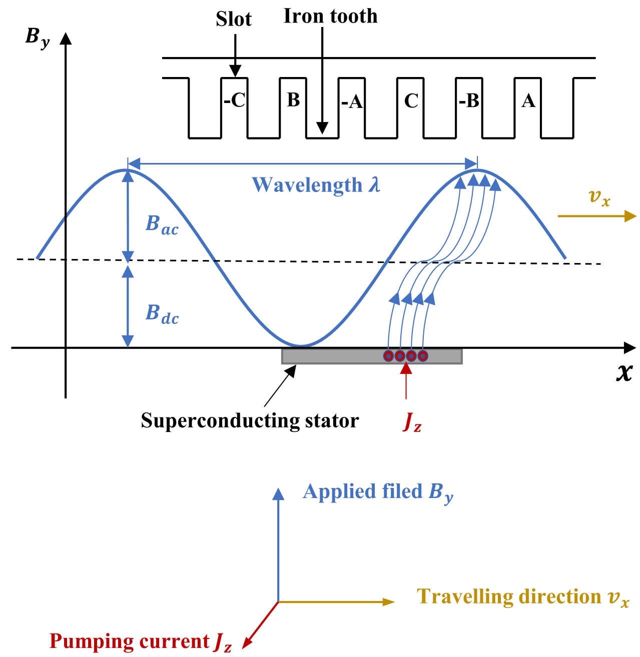

Fig. 5. Applied magnetic field $\boldsymbol{B_y}$ is perpendicular to the superconducting stator and the pumped current is perpendicular to the 2-D plane.

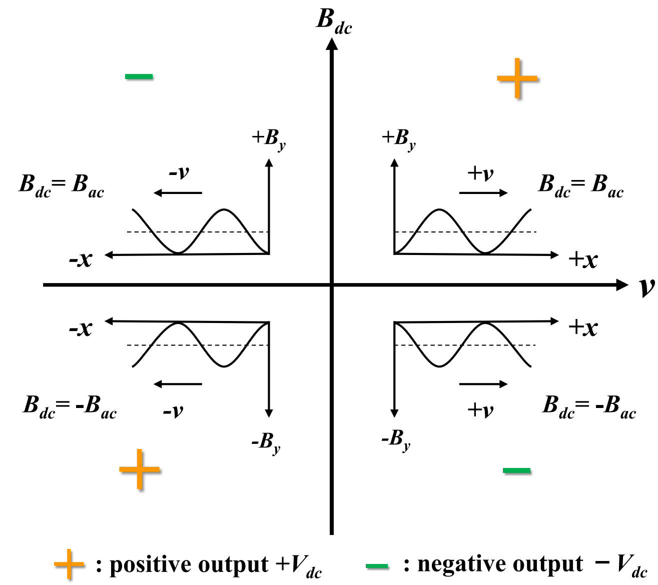

Fig. 6. Schematic diagram of "four-quadrant" control. This control method proposed by Wang accurately controls the DC output of HTS traveling wave flux pumps, based on the theory of macroscopic magnetic coupling effect.

follows:

$$B_y\ (x,t) = B_{\rm ac}\ \sin\left(kx + \omega t\right) + B_{\rm dc} \tag{2}$$

where $B_{\rm ac}$ is the amplitude of ac traveling magnetic wave, $B_{\rm dc}$ is the value of dc bias field, $k = \frac{2\pi}{\lambda}$ is the wavenumber, λ is the wavelength, $\omega = 2\pi f$ is the angular frequency, and f is the frequency.

The dc biased ac traveling magnetic wave generated by the traveling wave flux pump can couple a large number of superconducting vortices on the superconducting stator and drag the vortices to move in a predetermined direction. According to (1), the movement of vortices in a predetermined direction results in an output dc EMF, expressed as follows:

$$\vec{V}_{\rm dc} = l_{\rm eff}\ \vec{B}_y \times \vec{v}_x \tag{3}$$

where $\vec{V}_{\rm dc}$ is the averaged dc output EMF, $l_{\rm eff}$ is the effective length along the YBCO stator, $\vec{B}_y$ is the average flux density of coupled vortices, and $\vec{v}_x$ is the velocity of the traveling magnetic pole.

C. "Four-Quadrant" Control Theory Accurately Controls DC Output

Relying on (2) and (3), a "four-quadrant" control method was introduced by Wang et al. [26] to accurately control the dc output of HTS traveling wave flux pumps, as demonstrated in Fig. 6, i.e., by reversing either the direction of dc bias field $B_{\rm dc}$ or the traveling direction $\vec{v}_x$; the dc output EMF $\vec{V}_{\rm dc}$ can be reversed in the HTS traveling wave flux pumps. Based on the "four-quadrant" control method, we designed a feedback control algorithm to control the ON/OFF of the dc bias coil of the flux pump. We first run the flux pump at its maximum output capacity, i.e., ensuring $|B_{\rm dc}| = B_{\rm ac}$ [52]. Then, a feedback control program is used to control the dc bias coil of the flux pump to ensure that the pump current can be output at the preset current $I_{\rm preset}$ within an allowed fluctuation ΔI, which take any value and stabilize it, as shown in Fig. 7. To accomplish the target, the feedback program will track the difference between the output current and the preset current in real time, i.e., when the output current value is less than the preset value, the dc bias coil is turned ON for charging, and when the current value is greater than the preset value, the dc bias coil is turned OFF for attenuation.

III. Experiment

A. Experimental Setup

In the experiments, the entire closed-loop HTS coil, as shown in Fig. 8 is submerged in liquid nitrogen at 77 K. A contact dc power supply is connected to the terminals of the HTS coil by two current leads, as shown in Fig. 8, to fast excite or demagnetize the HTS coil. After fast current regulation, the flux pump is used to maintain the PCM operation of the superconducting magnet, and the heater is used to switch ON/OFF of the PCS. The 12-mm-wide YBCO wire made by *Shanghai Superconductor Technology Company* [53] is used as the stator in the air gap of the flux pump. An HTS closed loop is formed by connecting the DPC and the superconducting stator by soldering, while the measured soldering resistance is 30 nΩ. In addition, two Hall sensors are installed in the middle of the DPC and the C-shaped iron ring to measure the magnetic field. By calculating the measured magnetic field, the current in both the DPC and the stator can be obtained. The detailed parameters of HTS DPC, stator, heater, and flux pump are shown in Table I.

B. Power Supplies, Measurement, and Control System

The ac coil of the linear-motor-type flux pump is powered by a three-phase inverter. The operation frequency directly impacts the EMF $\vec{V}_{\rm dc}$ and internal resistance R_d. For instance, by

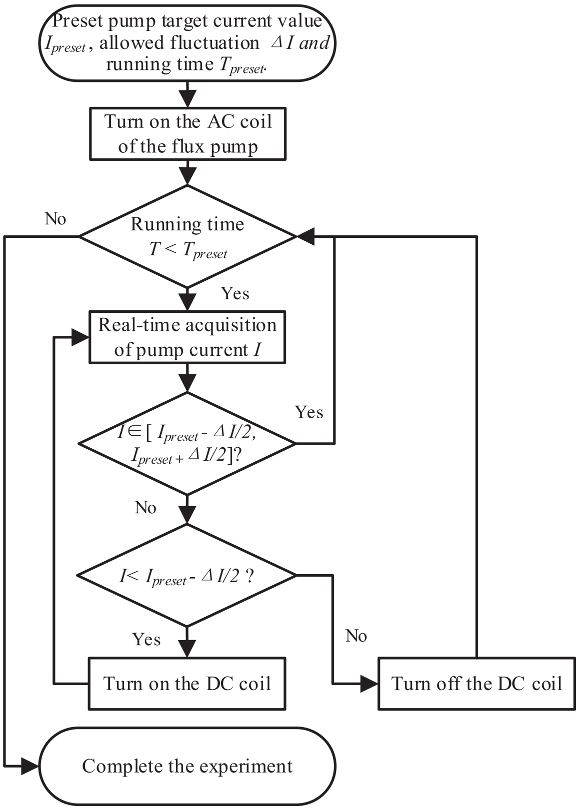

Fig. 7. Block diagram of feedback control. By comparing the difference between the pump current and the preset current, we perform a real-time feedback control of the pump current.

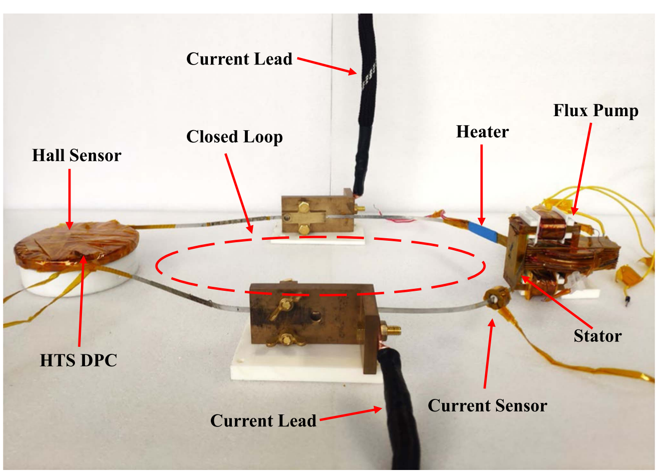

Fig. 8. Connection of the experimental apparatus. The current leads are used to fast adjust the current in the DPC, the heater is used as PCS, and the flux pump is used to maintain the HTS magnet's PCM operation.

increasing frequency f, based on (3), $\vec{V}_{dc}$ increases linearly since $v = \lambda f$. Meanwhile, the increase of frequency f also increases the ac losses, which increases the internal resistance R_d. In our previous experiments, the optimal output frequency of this flux pump is verified as 20 Hz [52], which is chosen as the operation frequency in this work. The dc bias coil of the linear-motor-type flux pump is powered by a programmable dc power supply.

TABLE I
MAIN SPECIFICATIONS OF EXPERIMENTAL SETUP

Parameters	Specification
HTS INS DPC	
Material/Manufacturer	YBCO/SSTC
Wire Width/Length	4.8 mm/50 m
Inner diameter/Outer diameter	50 mm/125 mm
Number of turns	88×2=176 turns
Inductance	2.52 mH
I_c@77k, Self-field	82 A
Stator	
Material/Manufacturer	YBCO/SSTC
Thickness/Width	220 μm/12 mm
Welding resistance	30 nΩ
I_c@77k, Self-field	325 A
Heater	
Size	10×93×0.25 mm
Heater resistance	12 Ω
Rated temperature	443 K
Flux pump	
Type	Linear-motor type [24],[25],[26]
Control method	Four-quadrant control [23]
Airgap	2 mm
Size	30×104×70 mm

The current leads are connected to a contact superconducting dc power supply (Keysight 6680A), which can output a maximum current of 875 A. The two Hall sensors, installed in the center of the DPC and C-ring to measure current, are powered by a precise dc current supply.

The data acquisition system is mainly composed of a data acquisition instrument (Agilent 34972A) and National Instruments PCI-4070 cards, which read the voltages from the two Hall sensors and calibrate to the value of pumped current. To accurately control the closed-loop current, the measured current data are transmitted to a LabView feedback control program. Based on the algorithm, as shown in Fig. 7, the LabView program controls the ON/OFF-state of the dc power supply connected to the dc bias coil of the flux pump.

IV. TEST RESULTS AND ANALYSIS

A. Fast Excitation and Maintaining PCM Operation

In order to visually reflect the effect of the flux pump in maintaining PCM operation, we used the contact dc power supply to fast excite the HTS magnet, then allowed current attenuation in the closed loop and used the flux pump to compensate the current losses, which enables the PCM of the closed-loop HTS magnet. The experimental operation and circuit principle of fast excitation and maintaining PCM operation are described in Section II-A. The experimental results are shown in Fig. 9. The blue line represents the measured load current after the HTS magnet is rapidly excited and switched to the closed loop. It can be seen that the closed-loop current decreases rapidly after switching to the closed loop due to the soldering resistance and flux creep. On the other side, the red line represents the measured load current when a flux pump is used to compensate this current decay, which has managed to maintain and stabilize the closed-loop current in the HTS magnet. It can be seen that the closed-loop current is maintained very stably with the support of the flux pump.

The comparison between the two experiments shows that the operation strategy of using a contact power supply for fast

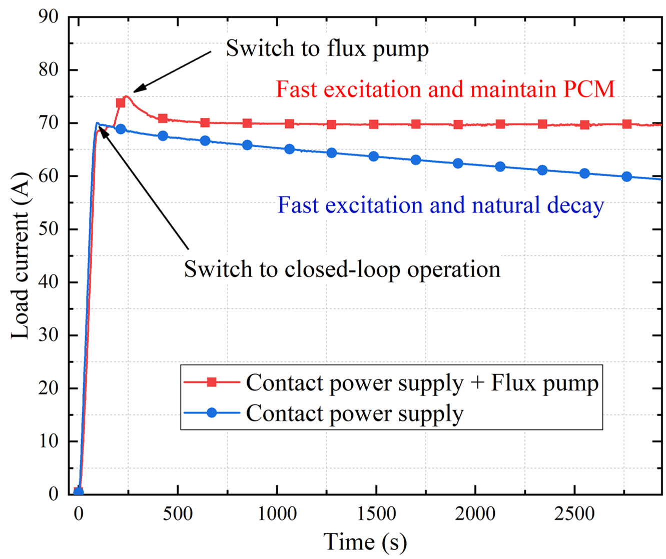

Fig. 9. Experimental results of fast excitation and maintaining PCM operation experiment. The flux pump was used to maintain PCM operation experiment, no current attenuation was observed. However, the current decayed rapidly in the experiment without a flux pump to maintain PCM operation.

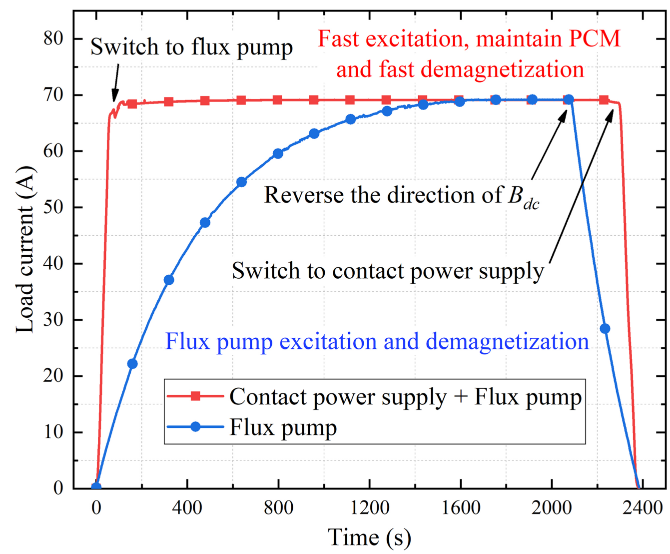

Fig. 10. Comparison of excitation and demagnetization speed between two power supplies. The excitation speed of the contact power is 16 times faster than that of the flux pump, and the demagnetizing speed is 4 times faster.

excitation, and subsequently, employing a flux pump to maintain PCM operation is an ideal solution for HTS magnets with large inductances that enables both fast excitation and maintenance of PCM operation.

B. Comparison of Excitation and Demagnetizing Speeds

According to the "four-quadrant" control theory, as depicted in Fig. 6, the dc output EMF $\vec{V}_{\rm dc}$ in the HTS traveling wave flux pumps can be reversed by altering the direction of the dc bias field $B_{\rm dc}$. Therefore, when the HTS magnets need demagnetization, the current in the HTS magnets can be reverse charged to 0 A by reversing the direction of dc bias field $B_{\rm dc}$. Subsequently, we designed experiments to compare the excitation and demagnetization speeds of the proposed power strategy that combines a contact power supply and flux pump, with the strategy of using only a flux pump. The experimental operation and circuit principles of fast excitation, maintain PCM operation, and fast demagnetization are described in Section II-A.

Fig. 10 shows the experimental results. The red line represents the measured load current to use the contact power supply for fast excitation, then switched to the flux pump for PCM maintenance, and finally switched to the contact power supply for fast demagnetization. The blue line represents the measured load current while only using the flux pump for excitation, PCM maintenance, and demagnetization. It can be seen that it only takes 98 s to use the contact power supply to charge the closed-loop current of the HTS magnet to 69 A, while the flux pump takes 1614 s. It takes 68 s to demagnetize the closed-loop current of the HTS magnet from 69 to 0 A using a contact power supply, compared with 299 s for a flux pump. The excitation speed of the contact power supply is more than 16 times larger than the flux pump, and the demagnetization speed is more than 4 times. The main reason for this difference is that the output voltage of the flux pump is relatively small, and it cannot quickly excite and demagnetize the HTS magnet with a large inductance. On the other hand, the contact power supply can have a much larger output voltage, which is more suitable for fast excitation and demagnetization of the HTS magnet. Therefore, with the help of a contact dc power supply, the excitation and demagnetization speed of the HTS magnets can be greatly improved.

The inductance of the HTS magnet used in this experiment is only 2.52 mH, but the excitation speed of the HTS magnet with the flux pump is 16 times slower than that of the contact power supply. If the flux pump is used to excite an HTS magnet with a large inductance, the excitation and demagnetizing speeds of flux pump are difficult to meet the industrial requirements. For instance, in the cyclotron magnet, the superconducting magnet is required to be excited smoothly to 4–6 T within 1–10 s, and in international thermonuclear experimental reactor (ITER) magnets, fast demagnetization is required [42], [43]. The proposed combined power strategy may have the capability to solve this problem.

C. Fast Bipolar Excitation and Maintaining PCM Operation

The above experiments demonstrate that the use of both contact dc power supply and flux pump can achieve fast excitation/demagnetization while maintaining the PCM operation of the HTS magnet after current regulations. In applications, the load current in the HTS magnet needs to be controlled to a preset value with certain accuracy, in which case the feedback control of the flux pump's output current is required.

Based on the "four-quadrant" control theory, the output current can be controlled by the ON/OFF states of the dc bias coil or ac coil, while the control flowchart is shown in Fig. 7. In this section, the flux pump's feedback current control is employed to ensure that the PCM operation is maintained following rapid current regulation.

The experimental results for fast charging and maintaining the PCM operation are shown in Fig. 11. In the experiments, we preset the target current in the feedback control program, such as +10 A, +30 A, +50 A, and +69 A, respectively, then

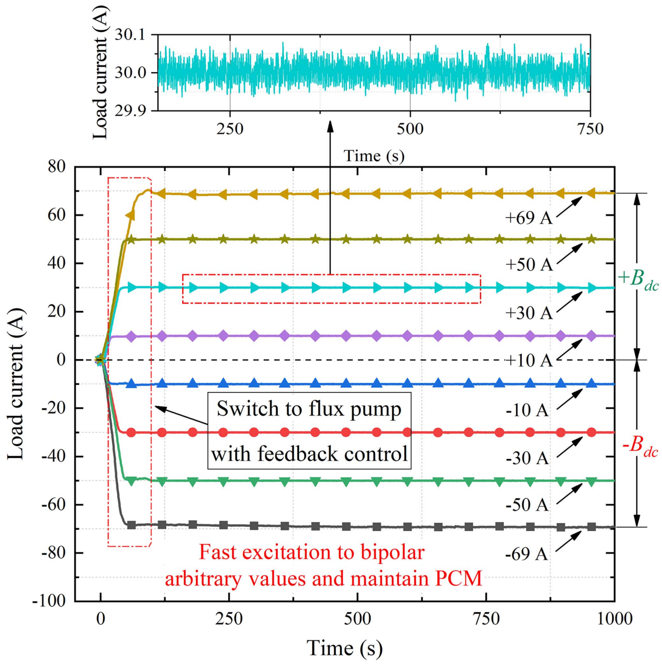

Fig. 11. Experimental results of fast excitation to bipolar arbitrary value and maintaining PCM operation. The flux pump can maintain the current of different polarities by adjusting the polarity of the DC bias magnetic field, and the current stability reached 5‰ when maintained at 30 A.

use the contact power to fast excitation to the target value, and then switch to the flux pump and open the feedback control program to maintain the target value to maintain PCM. For reverse charging, the operation process is the same as above, the only difference is to reverse the direction of the dc bias field B_{dc}. The procedure and circuit principle of fast excitation and maintaining PCM operation are described in Section II-A.

The experimental results show that the HTS magnets can be excited fast to any preset value in both directions by using the contact power supply and maintaining its persistent current by the flux pump based on a feedback control algorithm. In addition, we checked the current fluctuation when maintained at 30 A and found that the current fluctuation was only 0.15 A and the current stability reached 5‰, which is consistent with the preset accuracy. This experiment verifies that, with the feedback current control based on the "four-quadrant" control theory, the traveling wave flux pump can work as a bipolar power supply to maintain PCM operation with high current precision.

D. Fast Current Regulation and Maintaining PCM Operation

In several applications, such as the excitation coil of superconducting machine, and cyclotron magnet, fast regulation of the operation current is necessary. In this section, we demonstrate the switching from flux pump to contact power supply to enable fast current regulations, while the closed-loop current can be quickly changed or even reversed in the HTS magnet.

As shown in Fig. 12, a contact power supply is used to rapidly excite the magnet, and then switch to the flux pump to maintain PCM operation. After maintaining the persistent current for a period of time, the circuit is switched back to the contact power supply to fast adjust the current to any desired value. In the experiments, we demonstrate the fast adjustment to +50 A, +30 A, and +10 A, demagnetization to 0 A, and the reverse adjustment to −10 A, −30 A, −50 A, and −69 A. After the contact power supply fast adjusts the current, the circuit is switched to the flux pump with feedback control to maintain the persistent current in the PCM, with the current ripple less than 0.15 A. See Section II-A for the operating procedure and circuit principle of fast excitation, maintain PCM operation, and fast adjust the current.

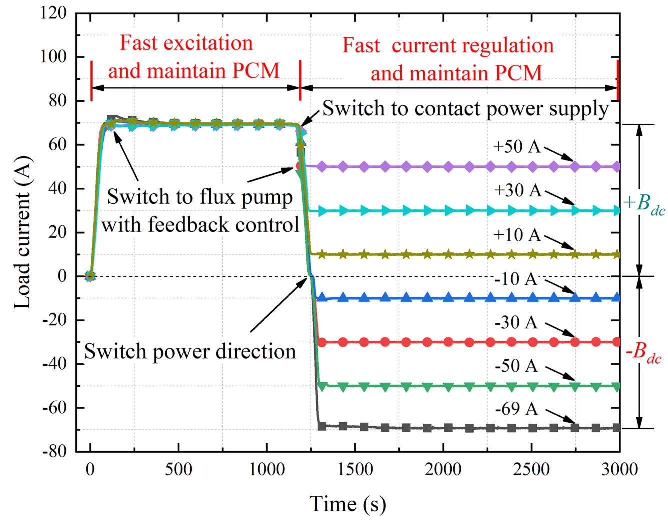

Fig. 12. Experimental results of fast adjust current to bipolar arbitrary values and maintaining PCM operation. Under the action of the contact power supply and the flux pump, the bipolar current of the large inductance superconducting magnet can be adjusted rapidly, and the closed-loop current of the magnet can be maintained without attenuation.

The above experiments provide evidence that the persistent current maintained by a flux pump in a closed-loop HTS magnet can be rapidly regulated with a contact power supply. Additionally, they demonstrate that the operation mode of the PCM and the fast current regulation mode can be swiftly switched. This indicates the feasibility of achieving efficient and flexible control over the magnet's current.

V. Discussion

A. Energy Consumption

The operation currents of HTS magnets typically range from hundreds of amperes to tens of thousands of amperes. If conventional contact power supplies are used to maintain the currents in the HTS magnets, the energy consumptions are extremely high, while the current leads bring heavy thermal load to the cryogenic system.

Fig. 13 demonstrates the two different operation modes, such as with the contact power supply and with the flux pump, respectively. As shown in Fig. 13(a), the PCM operation maintained by contact power supply has welding resistance R_j and current lead resistance R_c. The energy consumption required by contact power supply to maintain PCM operation is $W_c = I^2\,(R_{c1} + R_{c2} + R_j)$. As shown in Fig. 13(b), the PCM operation maintained by the flux pump has welding resistance R_j and internal resistance R_d of flux pump in the superconducting loop, so the energy consumption of the flux pump during operation is $W_{fp} = I^2\,(R_d + R_j)$. When a thousand or ten thousand amps of current is required, the resistance of the current lead is generally 4–6 orders of magnitude larger than the internal resistance of

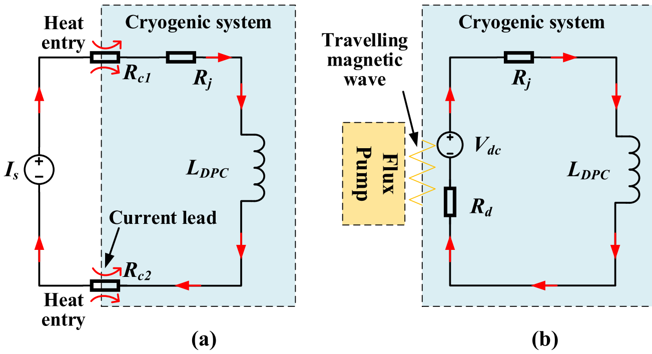

Fig. 13. Two ways to maintain PCM operation. (a) Using a contact power supply to maintain PCM operation, there are problems of heat leakage and large energy consumption of current lead resistance. (b) PCM is maintained by a flux pump, with only internal resistance and welding resistance causing energy consumption.

the flux pump. As a result, the energy consumption of the two power sources to maintain PCM operation differs by 4–6 orders of magnitude. And that does not take into account the extra heat that the current leads introduce. In practice, the current leads will also bring an additional heat burden to the refrigeration equipment as they pass through the low- and high-temperature environments, as shown in Fig. 13(a). The thermal conductivity of copper at 293 K is 397 W/m·K. In addition, the thermal conductivity power is related to the internal and external temperature difference and contact area. Superconducting magnets in Tokamak devices often require tens of thousands of amperes of current, the size of the current lead is very huge, and the heat leakage caused by it cannot be ignored. Therefore, the advantage of flux pump to maintain PCM operation is highlighted, which can maintain the closed-loop operation of high-current magnet without attenuation with very low energy consumption.

B. Current Ripple

Based on the "four-quadrant" control theory, we realized that the flux pump could maintain PCM operation at any value of positive or negative, with a ripple of 0.15 A and current stability of 5‰, as shown in Fig. 11. When the flux pump is applied to the MRI/NMR, the research direction is to make efforts to minimize the magnetic field ripple while compensating the magnetic field attenuation to meet the magnetic resonance system's requirements for magnetic field stability [39]. At present, because the output current is controlled only by switching ON/OFF the dc bias coil of the flux pump, the ac coil is always ON, which causes the superconducting wire to generate internal resistance under the action of the alternating magnetic field, and there will be large current ripple and decay of persistent current. Therefore, our next step is to control the ac coil and dc coil of the flux pump at the same time and realize the intermittent operation of the flux pump, which will greatly reduce the energy consumption of the flux pump and the ripple of the closed-loop current. This method has great application prospects in the fields that require high-current stability, such as MRI.

C. Fast Current Regulation

Due to the low EMF generated by the flux pump, the speed will be very slow if the industrial magnets with large inductances are charged by the flux pump. As shown in Fig. 10, for the magnet whose inductance is 2.52 mH used in this test, the excitation and demagnetization speeds of the flux pump are only 1/16 and 1/4 of the contact power supply, which cannot meet the industrial requirements to excite the magnet to the target magnetic field in a short period of time.

In order to solve this problem, this article proposes the use of contact power supply in excitation, demagnetization, and current regulation phase, and the use of flux pump in the PCM operation maintenance phase. As shown in Fig. 12, the current in the magnet can be fast adjusted by switching between the closed-loop operation mode of the magnet to the open-loop operation mode, which is very promising in many application scenarios. For instance, in proton heavy ion therapy, the current in the cyclotron magnet needs to be adjusted rapidly in order to kill cancer cells at different depths [47].

The successful experiment of this operation mode combines the advantages of both the contact power supply and the flux pump power supply, which cannot only fast adjust the current of superconducting magnets but also maintain PCM operation in an ultralow power consumption. It can meet the requirements of fast excitation, demagnetization, current regulation, and maintain PCM operation of industrial HTS magnets with large inductances.

D. Pluggable Current Lead

The existence of current leads will cause large heat leakage into the cryogenic system, even if the HTS magnet has been switched to the PCM with the help of a flux pump. Therefore, it is necessary to use "pluggable" current leads to disconnect this heat leakage during PCM, which will be the main concern in our next stage of work.

There are existing works focused on the pluggable current leads. For example, the Korea Basic Science Institute proposed a concept of detachable current leads for superconducting magnet systems in 2007 [54]. The room temperature end of these pluggable current leads utilizes the conventional copper conductors, while the low-temperature end employs current leads made of HTS materials. The two current leads are connected using plug-in intermediate blocks, and heat is intercepted at the first stage of the cooling system. Once the superconducting magnet is charged, the copper leads separate from the HTS leads without affecting the vacuum level of the refrigeration system. The pluggable current lead offers the benefit of no heat escape once the superconducting magnet operates within the PCM. In 2009, they actually applied the concept of the semi-retractable current lead to a high-field magnet system and achieved good testing results [55]. In the next stage, we will use the concept of pluggable current leads to design and construct our experimental system for the conduction-cooled HTS magnet [56].

VI. Conclusion

This article proposes the use of a flux pump to maintain PCM operation in HTS magnets, which are used in fields, such as accelerator physics, Tokamak devices, MRI/NMR, proton heavy ion therapy, and maglev trains. The use of flux pump greatly reduces the energy consumption of PCM operation because the resistance and heat conduction of the current lead of the conventional contact dc power supply will bring a huge heat burden to the cryogenic system. The ON/OFF of the dc bias coil of the flux pump is controlled by feedback so that the flux pump can maintain the PCM of the magnet in preset positive or negative values with high stability. The current stability is 5‰ and the current ripple is as low as 0.15 A, which can meet the industrial application of most HTS magnets.

In addition, for industrial magnets with large inductance, the speed of flux pump for current regulation is slow, so it is proposed to use contact dc power supply for fast excitation, fast demagnetization, and fast current regulation, while the flux pump is used to maintain the PCM operation after reaching the target current. This new operating mode combines the advantages of the contact dc power supply and the flux pump power supply, and can meet the requirements of fast current regulation and PCM operation maintenance of industrial HTS magnets with large inductance. This research results can provide a reference for fast current regulation and maintain PCM operation of HTS magnets and accelerate the wide application of HTS magnets and traveling wave flux pumps.

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