Feedback Control of a Rectifier Type HTS Flux Pump: Stabilizing Load Current With Minimized Losses

Jianzhao Geng, Bin Wang, Mehdi Baghdadi, Jing Li, Boyang Shen, Heng Zhang, Chao Li, Xiuchang Zhang, and Tim A. Coombs

***Abstract*—Flux pumps are able to compensate slow current decay in high-T_C superconducting (HTS) magnets through noncontact approaches. It is a promising alternative for power sources and thick current leads in operating HTS coils. Following the previous work of a rectifier flux pump, we developed a feedback control system to achieve flexible control of load current. Experimental results show that the flux pump can stabilize load current at a preset level with the help of the control system. Power loss of using the flux pump is also compared with that of using current leads.**

***Index Terms*—Feedback control, flux pump, high-T_C superconducting (HTS), minimized loss.**

I. Introduction

HIGH T_c superconductors normally have much higher upper critical field than low $\boldsymbol{T}_\mathrm{c}$ superconductors, which makes them ideal for high field magnets [1]. HTS coils made of Coated Conductors (CCs) have much better mechanical properties than HTS bulks and are more flexible than stacked tapes. These advantages make CC coil suitable in the application of NMR inserts [2] and motor windings [3]. DC CC coil can either be powered by external current source together with current leads or alternatively operate as a closed circuit [4]. Due to the fact that high $\boldsymbol{T}_\mathrm{c}$ superconductors always have a low n value [1], closed HTS circuit carrying a direct current is dissipative even without a joint. Moreover, when a DC carrying HTS coil is under external AC field, loss is much more evident [5], [6]. To cope with the problem, HTS flux pumps have been developed. Nakamura [7] and Bai [8] exemplified using linear travelling wave to achieve flux pumping. Hoffmann [9] developed a rotating magnets based flux pump, which has been followed by many researchers [10], [11]. In our recent work, we proposed two transformer-rectifier flux pumps. One is based on automatically driving the superconductor into flux flow region [12], and the other is based on AC field triggered flux flow [13], [14]. In the following, we mainly focus on the latter.

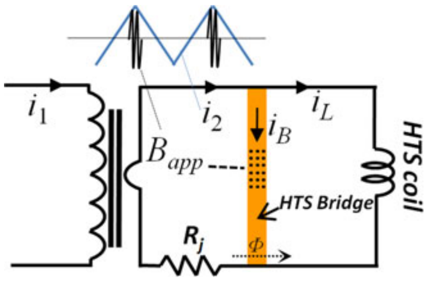

Fig. 1. Schematic drawing of an AC field controlled superconducting bridge based transformer-rectifier flux pump [13], [14]. A transformer induces high alternating current in its secondary winding and an HTS bridge. An AC field B_app is applied to the bridge to control flux flow. In the figure R_j represents joint resistance.

As shown in Fig. 1, the flux pump uses a transformer to generate high alternating current with low frequency i_2 in its secondary winding which is shorted by a superconducting bridge (a piece of YBCO tape). An AC field with high frequency B_app is intermittently applied to the tape wide surface when the bridge current i_B is positive. The applied ac field interacts with the transport current in the bridge superconductor, resulting in a net flux flow across the bridge. The net flux flow direction is only determined by the direction of i_B. Therefore, during each cycle of i_2, if the field is always applied when i_B is positive, the net flux flow will accumulate in the load, ending up with a high direct current in the load [13].

There are two main advantages of the proposed flux pump over existing ones: the first is that the magnitude of the bridge AC field required can be lower than full penetration field of the bridge superconductor, which is about 50 mT for a 12 mm width YBCO tape [14]; and the second is that the dynamic resistance of the bridge is nearly independent of bridge current, which allows a linear control. Our previous work focuses on the principle [13] and operational characteristics [14] of the flux pump, which is actually open loop operation. To make the flux pump suitable for application, it is important to achieve closed-loop control to adjust the load current as required.

J. Geng, J. Li, B. Shen, H. Zhang, C. Li, X. Zhang, and T. A. Coombs are with the Electrical Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K. (e-mail: jg717@cam.ac.uk; jl908@cam.ac.uk; bs506@cam.ac.uk; hz301@cam.ac.uk; cl644@cam.ac.uk; xz326@cam.ac.uk; tac1000@cam.ac.uk).

B. Wang is with the Department of Electrical Engineering, Tsinghua University, Beijing 100084, China (e-mail: binw_ee@mail.tsinghua.edu.cn).

M. Baghdadi is with the Faculty of Engineering and Science, University of Greenwich, London SE10 9LS, U.K. (e-mail: mb876@cam.ac.uk).

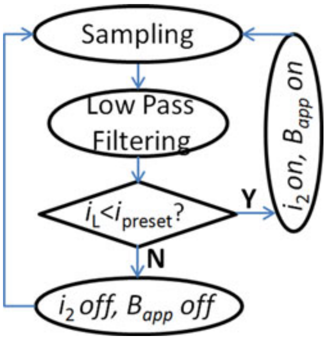

Fig. 2. Logic diagram of feedback control Strategy 1 of the flux pump.

In this paper, we present the feedback control of the proposed flux pump to achieve a stabilized load current. The control system is firstly described, different control schemes are proposed and the corresponding experimental results are presented. Loss comparison is also made between using the flux pump and using current leads in maintaining a stabilized load current.

II. EXPERIMENT

A. Experimental System

The schematic of our previously proposed flux pump is shown in Fig. 1. The HTS load is a double pancake coil made of YBCO coated conductor, which has an inductance of 0.388 mH. Other specifications of the coil and the tape can be found in Ref. [15]. Other parameters of the flux pump can be found in Ref. [14], except the joint resistance of the load is intentionally enlarged to 1.2 $\mu\Omega$ to make the current decay more evident. The load current is measured by a Hall sensor mounted in the center of the load coil. And the signal is acquired by an NI-6002 DAQ card with a sampling frequency of 1 kHz. A LabVIEW program was written to achieve real time feedback control logic. The load current is firstly low-pass filtered by averaging samples over 1s. Then the filtered load current is compared with a preset current i_{preset}. If the load current is lower than the preset value, the flux pump remains at an on state, in which the DAQ card outputs desired analogue waveform to control secondary current i_2 and bridge field B_{app}. If the load current is over the preset value, two Strategies are proposed: Strategy 1 is to set the controlling signals of i_2 and bridge field B_{app} both zero, as shown in Fig. 2, Strategy 2 is to set controlling signal of i_2 zero and leave controlling signal of B_{app} as in flux pump mode. In the following we will show the results of these two control strategies.

B. Results

Fig. 3 shows the result using control Strategy 1. The preset load current level is 20 A. The top figure shows load current, the middle figure is secondary current of the transformer, and the bottom figure is the applied field. In the beginning, the load current was pumped up from nearly zero to up to slightly above 20 A. Then the flux pump was stopped by setting the transformer secondary current and the applied field zero. Without the flux pump the load current gradually decayed until the current was lower than 20 A. Then the flux pump was triggered again, and the current was pumped up to over 20 A again. This process was repeated and the load current was stabilized at about 20 A. The details of waveforms during one start-up in Fig. 3 are shown in Fig. 4. The flux pump started up for about two seconds. During each cycle of the secondary current, the field was applied 10 cycles and the load current increased by about 1A. The flux pumped to the load during each field cycle was about 38 μWb. This value can be further reduced by reducing magnitude of i_2 or B_{app}.

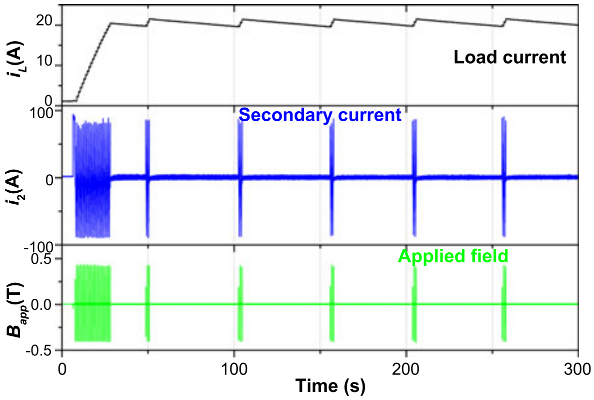

Fig. 3. Experimental result on stabilizing load current using control Strategy 1 described in Fig. 2. The top figure shows the load current curve where the load current i_L is pumped up and then stabilized at around 20 A, the middle figure shows the waveform of the transformer secondary current i_2, and the bottom figure shows the waveform of applied field B_{app}.

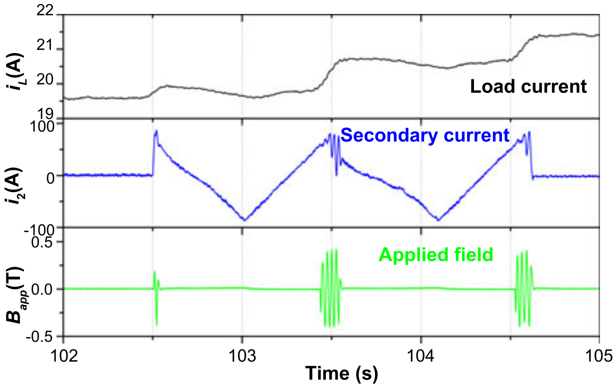

Fig. 4. Details of the waveforms in Fig. 3.

Fig. 5 shows the result of load current with different preset levels, together with a load current curve under no feedback control. All curves nearly overlap in the beginning of charging. Each curve stabilizes at the preset level. The flux pump starts more frequently when the preset current level is higher. This is because the load current decays faster when it is at a higher value. Control Strategy 1 is suitable for stabilizing the load current from a lower level to a higher level. However, it is not suitable for changing load current from a higher level to a lower level, because it cannot pump flux out of the load. To deal with the problem, control Strategy 2 is proposed. When the load current value is lower than the preset level, the flux pump is started, which is the same as that described in Strategy 1.

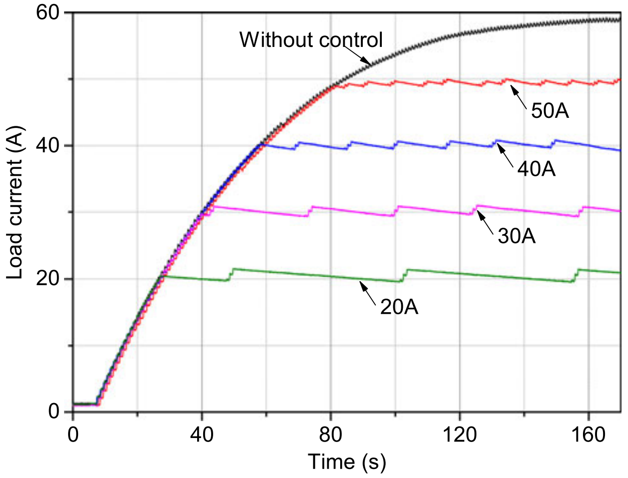

Fig. 5. Plots show the load current curves with various preset levels, together with a load current curve under no feedback control for comparison.

When the load current value is higher than the preset value, the secondary current i_2 is set zero, but the field is still applied to the bridge superconductor. The applied field induces a flux flow outside the load, thus reducing the load current quickly. The waveforms of using Strategy 2 are shown in Fig. 6. Fig. 7 shows a comparison between these two control strategies in stabilizing load current from a higher level to 45 A. We can see that Strategy 2 stabilizes the load current much faster. The load current has to be reduced by the joint resistance of the coil for Strategy 1. Strategy 2, however, has much higher operating loss than Strategy 1, because the field is applied all the time.

III. Loss Estimation

A. *Basic Assumption*

In the following we calculate the loss of the flux pump in maintaining current in a proper sized magnet, using control Strategy 1. The equivalent resistance of the load $R_{\rm L}$ is assumed to be 100 nΩ [9]. The load inductance is assumed to be $L = 1$ H, which is high enough so that the load current decay is very slow. The load current $I_{\rm L}$ is assumed to be 50 A. The bridge current experiencing applied field is $I_{\rm B} = 10$ A. The frequency of transport current in the transformer is 1 Hz. Applied field has a magnitude of 0.3 T and a frequency of 100 Hz. The load current variation allowed is 1 ppm (50 μWb).

B. *Loss Classification*

The total losses of the flux pumping system can be divided into two categories: losses in the superconducting circuit, and losses in electromagnets including the transformer. Three sources of loss contribute to the total loss in the superconducting circuit: transport AC loss in the secondary winding of the transformer, dynamic resistance loss of the bridge superconductor (loss caused by flux flowing across the bridge), and magnetization AC loss in the bridge superconductor (loss caused by field overcoming the threshold field [16] of the bridge). The losses in the electromagnets include copper loss of the transformer primary winding and the field magnet winding, and hysteresis loss in the transformer core and field magnet core.

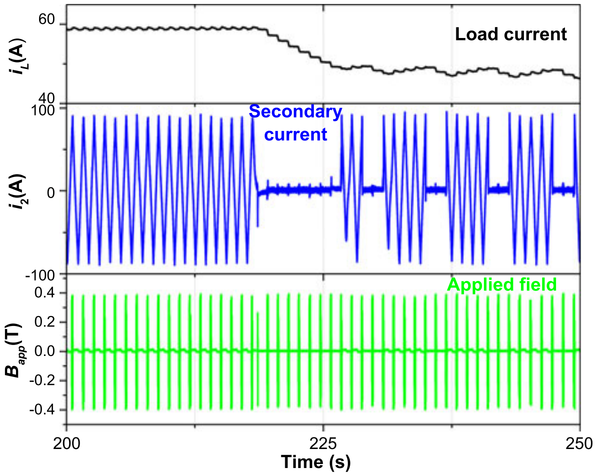

Fig. 6. Experimental result on stabilizing the load current using control Strategy 2 in chapter II. The top figure shows the load current curve where the load current decreases from around 60A to a stabilized value of about 45 A, the middle figure shows the waveform of the transformer secondary current i_2, and the bottom figure shows the waveform of bridge field $B_{\rm app}$.

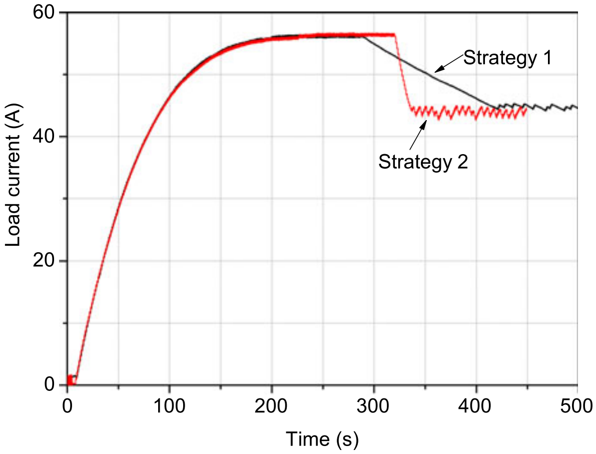

Fig. 7. Comparison between load curves under control Strategy 1 and Strategy 2.

C. *Loss Estimation in Superconducting Circuit*

The transport loss in the secondary winding: The length of the secondary winding is about 1m, the frequency of the transport current is 1 Hz, and the magnitude of the secondary current can be considered lower than 100 A. This loss is estimated to be less than 1 mW [17] if the current is continuous. The flux dissipation speed is $\mathrm{d}\Phi/dt = I_{\rm L}R_{\rm L} = 5\ \mu\mathrm{Wb/s}$. Considering the flux variation limit is 50 μWb, the flux pump only need to operate one tenth of the time. So the average loss of this item is 0.1 mW.

To stabilize load field, the flux dissipation speed $\mathrm{d}\Phi/dt = I_{\rm L}R_{\rm L}$ should be equal to the flux flow speed across the bridge on average. The energy dissipation caused by the dynamic resistance is $I_{\mathrm{B}}\Phi$, and the average loss is:

$$\begin{aligned} P_d = {} & 2 \times d\left(I_B \Phi\right)/dt = 2 \times I_B d\Phi/dt = 2 I_B I_L R_L \\ = {} & 0.1 \text{ mW} \end{aligned} \tag{1}$$

This loss is considered twice because the amount of flux that flows into the loop formed by the secondary winding and the bridge should be equal to the amount of flux that flows across the bridge.

The loss caused by the magnetization loss on the bridge is much smaller than the loss caused by the dynamic resistance, because the applied field magnitude is much larger than the threshold field of the bridge superconductor.

Therefore the total loss in superconducting circuit of the flux pump is mainly contributed by transport loss in the secondary winding of the transformer and the dynamic resistance loss on the bridge, which is about 0.2 mW.

D. Loss Estimation in Electromagnets

The resistance of the transformer primary winding is 0.6 Ω @ 77 K, and the primary current has a 1A peak value to generate a 100 A secondary current. Considering the average operating time ratio is $1/10$, this loss is about 0.03 W.

The resistance of field magnet is 2.2 Ω @ 77 K, with a 1.5 A current to generate 0.3 T field. Ten cycles of field during each secondary current cycle are enough to compensate the flux decay (to inject flux of 50 μWb). So the average operating time ratio of the field magnet is $1/100$. This loss is about 0.025 W.

The transformer can be considered nearly shorted because the dynamic resistance value is very low. So the flux density in the iron core is very low, thus the hysteresis loss can be neglected.

The field magnet core is made of laminated silicon steel, which has a loss of about 0.4 watts per pound at 60 Hz, 1.5 T [18]. Considering weight of the core is about one pound, the field in it is only 0.3 T, and it operates $1\mathrm{cycle/second}$ on average. This loss is less than 6.6 mW.

Therefore, the total loss of electromagnets is mainly contributed by copper windings of the transformer and the field magnet, which is less than 0.1 W on average.

E. Loss Comparison With Current Leads or Rotating Magnet Based Flux Pump

The heat loss of using a pair of current leads to power the magnet in similar situation is about 2.5 W [19]. Using a rotating magnets based flux pump will incur a loss of more than 0.3 W [20], excluding the loss caused by the moving parts (continuous operation is considered because acceleration and deceleration of the motor would cause huge fluctuation in load current). In comparison, the proposed flux pump using feedback control only has a loss of 0.2mW in superconducting circuit, and a total loss of 0.1 W even if the electro-magnets are in liquid Nitrogen environment.

IV. CONCLUSION

We developed a feedback control system for a previously proposed transformer rectifier type flux pump. With the help of the feedback control system, the flux pump is able to stabilize superconducting load current of at a certain preset level. In maintaining load current, the loss of the flux pump is at least one order of magnitude lower than using current leads, even considering electromagnets are inside the cryogenic system. The proposed flux pump will be very promising in operating HTS coil magnets.

REFERENCES

[1] Y. Iwasa, “HTS magnets: Stability; protection; cryogenics; economics; current stability/protection activities at FBML,” *Cryogenics*, vol. 43, pp. 303–316, Mar. 2003.

[2] H. W. Weijers *et al.*, “High field magnets with HTS conductors,” *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 576–582, Jun. 2010.

[3] Y. Jiang, R. Pei, W. Xian, Z. Hong, and T. A. Coombs, “The design, magnetization and control of a superconducting permanent magnet synchronous motor,” *Supercond. Sci. Technol.*, vol. 21, Mar. 2008, Art. no. 065011.

[4] T. Tosaka, T. Kuriyama, M. Yamaji, K. Kuwano, M. Igarashi, M. Terai, “Development of a persistent current switch for HTS magnets,” *IEEE Trans. Appl. Supercond.*, vol. 14, no. 2, pp. 1218–1221, Jun. 2004.

[5] Y. G. Park *et al.*, “Experimental analysis on initial current decay characteristics of persistent-mode HTS coil by external alternating magnetic field,” *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art. no. 3601204.

[6] J. Geng, H. Zhang, C. Li, X. Zhang, B. Shen, and T. A. Coombs, “Angular dependence of direct current decay in a closed YBCO double-pancake coil under external AC magnetic field and reduction by magnetic shielding,” *Supercond. Sci. Technol.*, to be published, doi:10.1088/1361-6668/aa599b.

[7] T. Nakamura, M. Sugano, T. Doi, and N. Amemiya, “Flux pump effect of HTS films in a traveling magnetic field,” *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 1033–1036, Jun. 2010.

[8] Z. Bai, S. Ding, C. Li, C. Li, G. Yan, “A newly developed pulse-type microampere magnetic flux pump,” *IEEE Trans. Appl. Supercond.*, vol. 20, no. 3, pp. 1667–1670, Jun. 2010.

[9] C. Hoffmann, D. Pooke, and A. D. Caplin, “Flux pump for HTS magnets,” *IEEE Trans. Appl. Supercond.*, vol. 21, no. 3, pp. 1628–1631, Jun. 2011.

[10] S. Lee *et al.*, “Persistent current mode operation of A2G HTS coil with a flux pump,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 0606104.

[11] C. W. Bumby, A. E. Pantoja, H-J. Sung, Z. Jiang, R. Kulkarni, R. A. Badcock, “Through-wall excitation of a magnet coil by an external-rotor HTS flux pump,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 4, Jun. 2016, Art. no. 0500505.

[12] J. Geng and T. A. Coombs, “An HTS flux pump operated by directly driving a superconductor into flux flow region in the E–J curve,” *Supercond. Sci. Technol.*, vol. 29, no. 9, Jul. 2016, Art. no. 095004.

[13] J. Geng and T. A. Coombs, “Mechanism of a high-Tc superconducting flux pump: Using alternating magnetic field to trigger flux flow,” *Appl. Phys. Lett.*, vol. 107, no. 14, Oct. 2015, Art. no. 142601.

[14] J. Geng *et al.*, “Operational research on a high-Tc rectifier-type superconducting flux pump,” *Supercond. Sci. Technol.*, vol. 29, no. 3, Feb. 2016, Art. no. 035015.

[15] J. Geng *et al.*, “HTS persistent current switch controlled by AC magnetic field,” *IEEE Trans. Appl. Supercond.*, vol. 26, no. 3, Apr. 2016, Art. no. 6603304.

[16] M. P. Oomen *et al.*, “Dynamic resistance in a slab-like superconductor with *J*c(B) dependence,” *Supercond. Sci. Technol.*, vol. 12, pp. 382–387, Feb. 1999.

[17] M. Majoros *et al.*, “Transport AC losses in YBCO coated conductors,” *Supercond. Sci. Technol.*, vol. 20, pp. s299–s304, Feb. 2007.

[18] Selection of electrical steels for magnetic cores, 2007. [Online]. Available: http://www.aksteel.com/pdf/markets_products/electrical/mag_cores_data_bulletin.pdf

[19] S. S. Kalsi, *Applications of High Temperature Superconductors to Electric Power Equipment*, Piscataway, NJ, USA: IEEE Press, 2011, p. 53.

[20] Z. Jiang, K. Hamilton, N. Amemiya, R. A. Badcock, and C. W. Bumby, “Dynamic resistance of a high-Tc superconducting flux pump,” *Appl. Phys. Lett.*, vol. 105, no. 11, Sep. 2014, Art. no. 112601.