Characteristics of a Persistent Current Compensator for Superconducting NMR Magnets Using Linear Type Magnetic Flux Pump

Yoon Do Chung, Itsuya Muta, Tsutomu Hoshino, and Taketsune Nakamura

Abstract—**This paper describes the characteristics of a linear type magnetic flux pump for compensating current in a superconducting coil with 10 A operating current. The linear type flux pump has been fabricated to use for compensating persistent current decay of HTS applications such as NMR and MRI systems. Pumping current of the linear type magnetic flux pump mainly can be controlled by frequency of AC current. In the experiment, it has been demonstrated that the linear type magnetic flux pump can effectively charge and discharge the current in the load coil of 543 mH for various frequencies with the DC bias of 10 A and the AC of 5 A_{rms}. Moreover, experimental results of temperature distribution of a slow response PCS have been compared with simulation.**

Index Terms—**Linear type magnetic flux pump, Nb foil, persistent current compensator.**

I. Introduction

MOST recently, the application for the superconducting power supply is very promising in high-Tc superconducting (HTS) coil applications such as magnetic resonance image-CT (MRI-CT) and nuclear magnetic resonance spectrometer (NMR) used for life science fields [1]–[3]. Compared with low-Tc superconductors (LTS), since HTS coils have a low n-index value, HTS coils could not keep the persistent current constant [4]–[6]. Superconducting flux pumps are mainly classified into rotating type and rectifier type. In this paper, we originally proposed linear type magnetic flux pump which makes less vibration and electric noise than the early-developed flux pump and can control pumping current by frequency of AC current [7], [8]. Consequently, a static linear type magnetic flux pump would be thought to be most suitable to compensate the persistent current decay.

In this experiment we observed pumping rate of the load coil to measure small quantities of pumping current using a hall sensor. We determined the ramp-up rates of pumping current in the load coils with DC bias current of 10 A, 3-phase AC current of 5 A_{rms} and operating current of 10 A. In addition to, experimental results of a temperature distribution of a slow response persistent current switch (PCS) have been compared with simulations.

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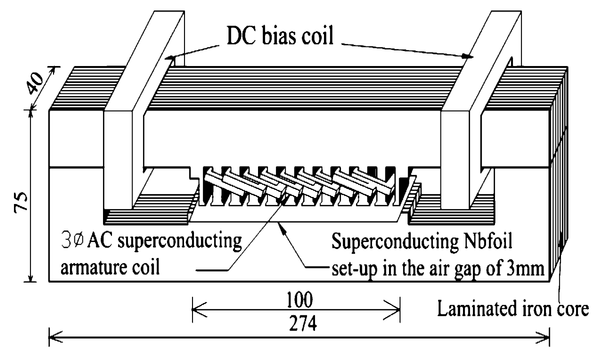

Fig. 1. Schematic diagram of the linear type magnetic flux pump.

II. Structure and Operational Principle

A. Structure

The linear type flux pump is mainly composed of four components as follows:

1) Laminated core
2) DC bias coil
3) 3-phase AC armature coil
4) Nb foil.

Fig. 1 shows a schematic diagram of the linear type magnetic flux pump that is connected to a 6-coil toroidal load magnet for the test. The Nb-Ti conductor of ϕ 0.9 mm is used for the DC bias magnet coil and the load coil of the flux pump. The Nb-Ti twisted multifilament conductor of ϕ 0.6 mm is used for 3-phase AC armature coils. A sheet of superconducting Nb foil of 20 μm thick, 60 mm wide and 120 mm long, is installed in the air gap of 3 mm. The Nb foil is sandwiched with translucent aluminum nitride ceramic thin plate with high thermal conductivity. The connection between the load coil and the Nb foil is done by spot welding method. Table I provides parameters for DC coil, 6-coil toroidal load magnet and 3-phase AC coil.

B. Operational Principle

As is well known, a three-phase winding produces a traveling magnetic field in the air gap of Fig. 1 where a Nb foil is installed. Its magnitude is adjustable by the amplitude of the three-phase current, and its traveling speed depends on the frequency of applied power source. On the other hand, two DC bias coils in

TABLE I
PARAMETERS OF COILS

DC COIL	
Wire	Nb-Ti /Cu (1/3.3)
Wire diameter [mm]	0.9
Turns / coil	132
Length / coil [m]	23
Inside dimension [mm^2]	3×4.6
Outside dimension [mm^2]	4.8×6.2
LOAD COIL	
Wire	Nb-Ti /Cu (1/3.3)
Wire diameter [mm]	0.9
Turns / coil	142
Length / coil [m]	72
Inside dimension [mm]	$\phi 40$
Outside dimension [mm]	$\phi 80$
Inductance [mH]	1.3
3-PHASE AC COIL	
Wire	Nb-Ti
Ic @ 4.2K, 50 Hz [A_{peak}]	42
Wire diameter [mm]	0.6
Turns / phase	40
Total length / phase [m]	25

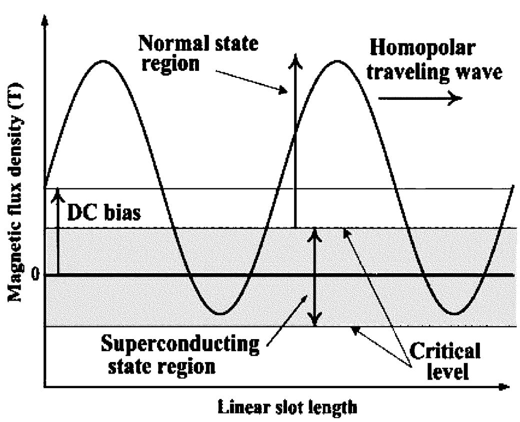

Fig. 2. Homopolar traveling wave for DC bias and 3-phase AC excitations in the air gap.

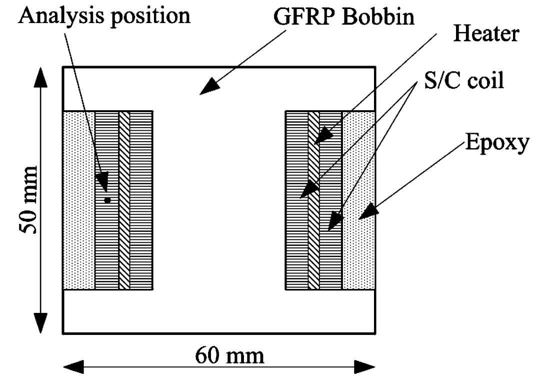

Fig. 3. Structure for slow response PCS and marked analysis position.

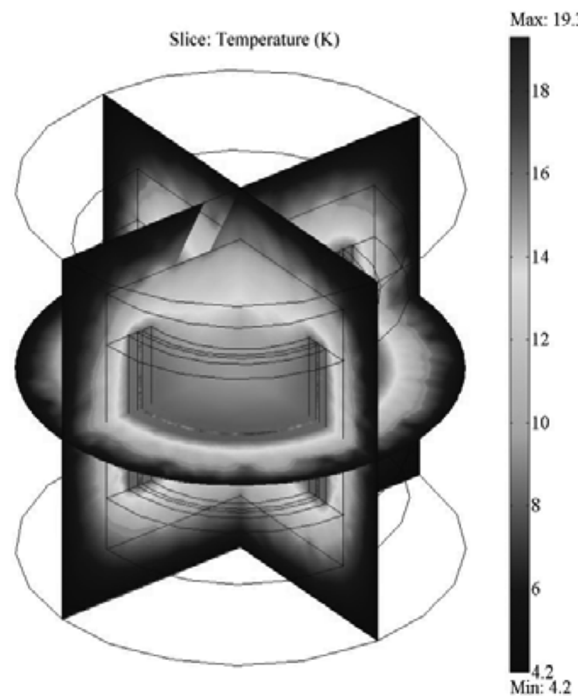

Fig. 4. Simulated result for the PCS by heater transfer analysis of heating current of 80 mA during 20 seconds.

Fig. 1 play a role in producing a homopolar magnetic field in such an air gap. Fig. 2 illustrates the ideal homopolar traveling magnetic field with 3-phase AC excitation, and DC bias. Under this condition, the Nb foil installed in the air gap is superconducting for part of a cycle, and extends the normal state when the critical field is exceeded.

While in the normal state, some magnetic flux can definitely penetrate the Nb foil, traveling toward the superconductive circuit, which consists of the load coil connected to the Nb foil through superconducting wires. Since such a completely superconductive circuit should generally keep linkage flux constant according to Lenz's law, some persistent current must flow to keep them constant, resulting in pumping-up the persistent current. As a result, the continuously traveling homopolar magnetic flux continues to increase the persistent current in the positive or negative direction.

III. SLOW RESPONSE PCS

A. Structure

We fabricated a slow response PCS system to keep operating current at 10 A and made computer simulations of the temperature distribution for slow-response PCS with 3-D thermal transfer analysis. The PCS consists of four parts as follows: GFRP bobbin, superconducting Nb-Ti coil, NiCr wire of heater and Epoxy. The structure of the PCS with superconducting coil and marked analysis position are shown in Fig. 3. Fig. 4 shows 3-D thermal transfer analysis results for slow response PCS with heating current of 80 mA during 20 seconds heating. Fig. 5 shows the simulated result for temperature distribution at the superconducting coil marked position in Fig. 3. Under these conditions the maximum temperature of the superconducting coil reaches 17.8 K. As the critical temperature of Nb-Ti is around 9.2 K, The coil effectively begins to keep switch off state over 9.2 K. Table II provides parameters for the slow response PCS.

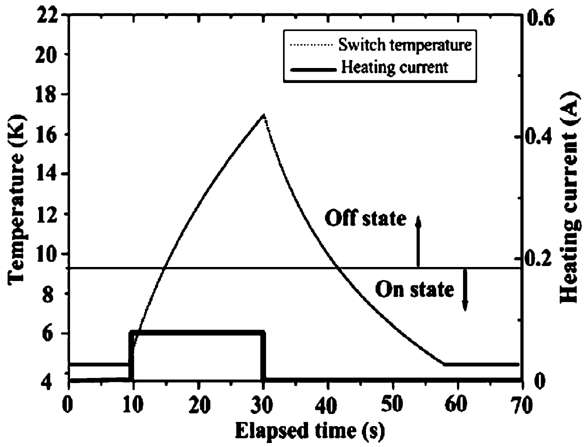

Fig. 5. Calculated temperature distribution at the center of S/C coil and outside layer with the heating current of 80 mA.

TABLE II
SPECIFICATIONS OF SLOW RESPONSE PCS

Wire	CuNi:Cu:NbTi = 2.88:0.35:1
Wire diameter [mm]	0.57
Filament number	9720
Filament diameter [μm]	2.5
DC critical current [A] / [T]	260 / 1
Heater thickness [mm]	0.05
Wide of heater [mm]	1
Length of heater (NiCr wire) [m]	2.5
Heater Resistance [Ω] @ 4.2 K	221
Length of NbTi coil [m]	18.2
I.O of the bobbin [mm]	40
Thickness of epoxy [mm]	6

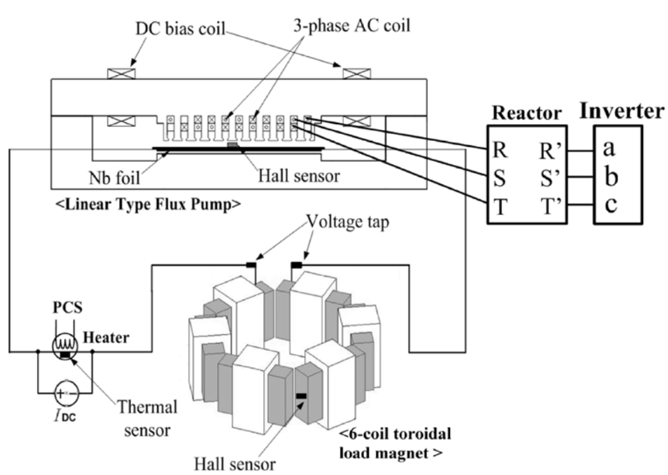

Fig. 6. Connection diagram for linear type magnetic flux pump system.

IV. Experimental Setup

The connection diagram of the flux pump system is shown in Fig. 6. In the flux pump system, two Hall sensors and one thermal sensor are used at the following positions: in the central air gap of the flux pump, a transverse type Hall sensor measures magnetic flux density generated by the DC bias and measures temperature distribution in the PCS. The reactor is installed between 3-phase AC coil and inverter, to produce AC excitations in the air gap between two toroidal cores, an axial type Hall sensor calibrates the pump-up current in the Nb-Ti load coil, on the superconducting coil, a thermal sensor measures temperature distribution in the PCS. The reactor is installed between

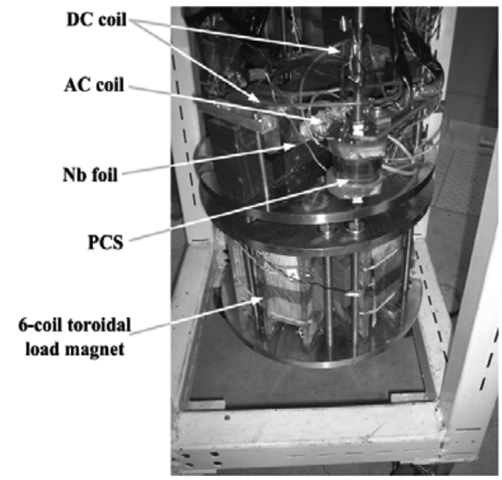

Fig. 7. Photograph of the linear type magnetic flux pump system.

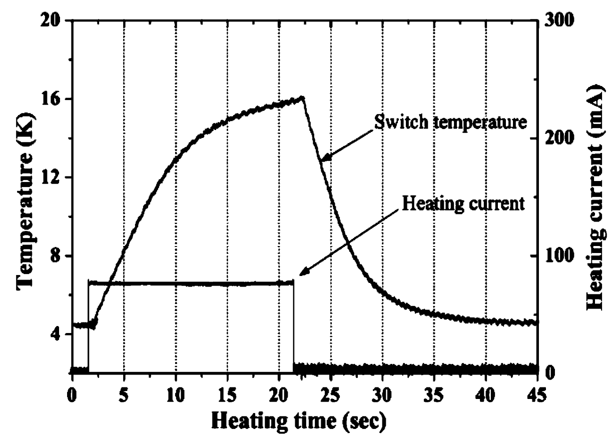

Fig. 8. Measured temperature distribution for PCS in the S/C coil with heating current 80 mA during 20 seconds.

3-phase AC coil and inverter to produce clear sinusoidal wave of 3-phase AC current from inverter. The resistance values of R-R′, S-S′ and T-T′ in the reactor are 38.2, 37.9 and 38.5 Ω, respectively. Fig. 7 shows a photograph of whole assembly flux pump system.

All signals are automatically recorded and monitored through the data acquisition system at the same time.

V. Results and Discussions

In this experiment, we measured the pumping current for the DC bias of 10 A and the 3-phase AC of 5 A_{rms} of 10, 15 and 20 Hz as well as the temperature distribution for slow response PCS. Fig. 8 shows the experimental results for temperature distribution of slow response PCS with heating current of 80 mA and heating time of 20 seconds. Under this condition, the maximum temperature of the superconducting coil reaches 16.1 K. Fig. 9 shows the experimental results for magnetic flux density at center of the linear core with the DC bias of 10 A and the 3-phase AC of 5 A_{rms} at 10, 15 and 20 Hz. It has been measured that the maximum and minimum magnetic flux densities are about +0.10 T and −0.02 T, respectively. The measured pump-up and -down current with DC of 10 A and AC of 5 A at 10 Hz, 15 Hz and 20 Hz are shown in Figs. 10, 11 and 12. The maximum pump-up currents at 10 Hz, 15 Hz and 20 Hz during 15 minutes reach 10.75, 11.32 and 11.78 A, respectively.

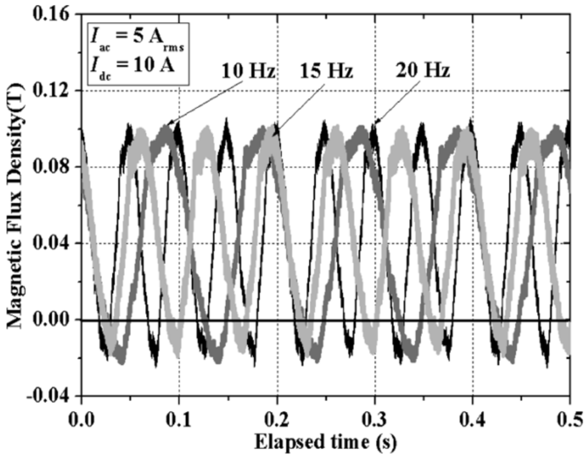

Fig. 9. Measured magnetic flux density at the center of the linear core with DC bias of 10 A and 3-phase AC of 5 A_{rms}.

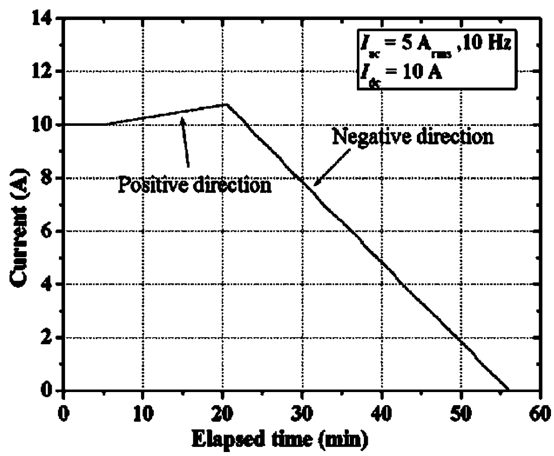

Fig. 10. Measured results for pump-up and -down current with DC of 10 A and AC of 5 A_{rms} at 10 Hz and operating current of 10 A.

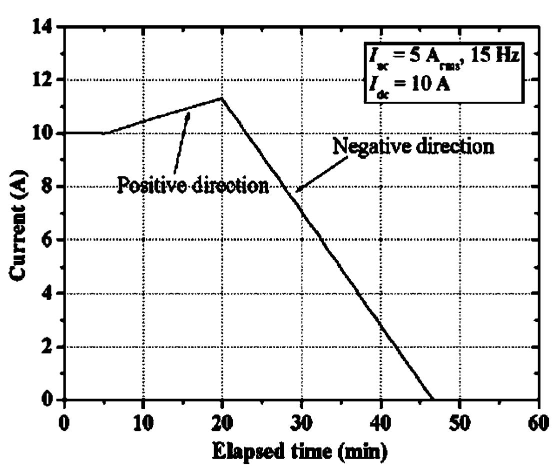

Fig. 11. Measured results for pump-up and -down current with DC of 10 A and AC of 5 A_{rms} at 15 Hz and operating current of 10 A.

Moreover, the pump-up current rates at 10, 15 and 20 Hz are 0.83, 1.47 and 1.98 mA/s, respectively. On the other hand, the pump-down current rates at 10, 15 and 20 Hz are −0.51, −0.69 and −10.8 mA/s, respectively.

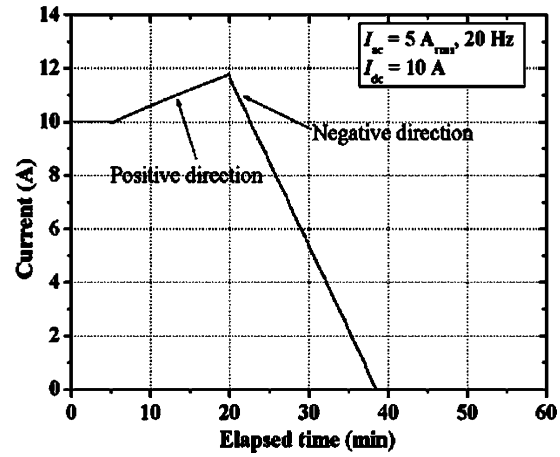

Fig. 12. Measured results for pump-up and -down current with DC of 10 A and AC of 5 A_{rms} at 20 Hz and operating current of 10 A.

From these experimental results, it should be proved that the linear type magnetic flux pump can effectively control the pump-up and -down current by the frequencies of AC current.

VI. Conclusion

Pump-up and -down currents characteristics for the linear type magnetic flux pump have been practically investigated with the operating current of 10 A. We observed that the flux pump can stably charge and discharge the current into the load magnet of 543 mH by frequency of AC current. The switch on-off operations were effectively measured. Moreover, the measured results agreed with simulated ones. Therefore, based on such experimental results, it is expected that the linear type magnetic flux pump as a stable persistent current compensator can apply for HTS magnets in NMR and MRI systems.

Furthermore, at the next stage, we will investigate whether the flux pump can compensate persistent current decay of 6-coil toroidal magnet using automatic feedback control circuit system.

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