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Pumping-up Current Characteristics of Linear Type Magnetic Flux Pump

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Abstract—**The linear type flux pump aims to compensate a little bit decremental persistent current of the HTS magnet in NMR and MRI spectrometers. The flux pump mainly consists of DC bias coil, 3-phase AC coil and Nb foil. The persistent current in closed superconductive circuit can be easily adjusted by the 3-phase AC current, its frequency and the DC bias current. In the experiment, it has been investigated that the flux pump can effectively charge the current in the load coil of 543 mH for various frequencies in 18 minutes under the DC bias of 10 A and the AC of 5 A_{rms}. The maximum magnitudes of pumping current and load magnet voltage are 0.72 A/min and 20 mV, respectively. Based on simulation results by the FEM are proved to nearly agree with experimental ones.**

Keywords: linear type magnetic flux pump, NMR magnet system, persistent current compensator.

1. INTRODUCTION

Most recently, the application for the superconducting power supply has been expected to be very promising in high-*Tc* superconducting (HTS) magnet systems such as MRI-CT and NMR spectrometer in life science research fields [1], [2]. Compared with low-*Tc* superconductors (LTS), since HTS cnductors have a low *n*-index value, HTS coils could not keep the persistent current constant substantially [3], [4]. Typically, LTS conductor used for NMR magnets has a relatively high *n*-index value in 50-100 for Nb-Ti and 40-80 for Nb_3Sn. For HTS conductors available at the present time, *n*-index value typically ranges over 10-14. As some flux flow phenomena in HTS conductors intrinsically happen, a current compensator is needed to sustain persistent current mode [5]-[7].

From this point of view, the linear type magnetic flux pump presents an option to achieve the current compensator required for HTS magnet systems. This linear type magnetic flux pump does not have any mechanical vibrations and electric noises compared to the early-developed flux pump. Generally, HTS NMR and MRI systems are required in compensating rates of 10 μ A for one pumping shot. Also the size of HTS magnet is over 10 H [8]-[12]. The main purpose of this study is to obtain the design, manufacturing techniques and fundamental data as a current compensator. In this preliminary experiment, we examined the ramping-up rates of pumping current in the load coil of 543 mH for changing the frequency of the 3-phase AC current magnitudes, and the DC bias current magnitudes in 18 minutes. Also, the simulation results in the air gap using FEM have been compared with the experimental ones.

2. LINEAR TYPE MAGNETIC FLUX PUMP

2.1. Structure

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

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

Fig. 1 shows a schematic diagram of the linear type magnetic flux pump that is connected to 6-toroidal load magnet for the test. Nb-Ti conductor of ϕ 0.9 mm is used for DC bias magnet coil and 6-toroidal load magnet composed with 6 rectangular coils 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

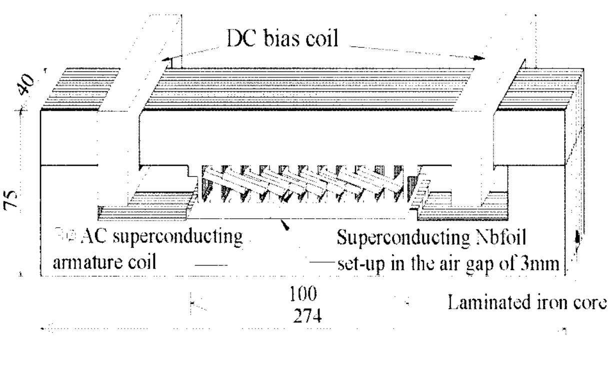

Fig. 1. Schematic diagram of the linear type magnetic flux pump.

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. Fig. 2 shows the schematic diagram of a 6-toroidal load coil wound around rectangular laminated silicon steel core. The air gap between each core is provided in at least 1mm to prevent the saturation of such cores.

Table I provides parameters for DC coil, 6-toroidal load coil and 3-phase AC coil. Table II presents the inductance value of an individual 6-toroidal coil.

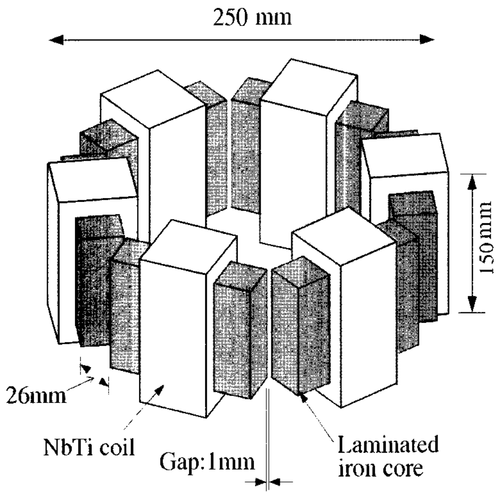

Fig. 2. Schematic diagram of 6-toroidal load coil made of Nb-Ti.

TABLE I.
PARAMETERS OF COILS

DC COIL	
Wire	Nb-Ti / Cu (1/3.3)
Wire diameter	0.9 mm
Turns / coil	132
Length / coil	23 m
Inside dimension	3 mm× 4.6 mm
Outside dimension	4.8 mm× 6.2 mm
DC critical current	930 A/1 T, 620 A/2 T, 310 A/4 T, 250 A/5 T
6-TOROIDAL LOAD MAGNET	
Wire	Nb-Ti / Cu (1/3.3)
Wire diameter	0.9 mm
Turns / coil	540
Length / coil	180 m
Laminated iron core	60 mm×84 mm×24 mm
DC critical current	930 A/1 T, 620 A/2 T, 310 A/4 T, 250 A/5 T
3-PHASE AC COIL	
Wire	Nb-Ti
I_c @ 4.2K, 50 Hz	42 A_{peak}
Wire diameter	0.6 mm
Turns / phase	40
Total length / phase	25 m

TABLE II.
INDUCTANCE OF 6-TOROIDAL LOAD MAGNET @ 4.2 K / 60HZ

No.1 coil	46 mH
No.2 coil	45.8 mH
No.3 coil	45.7 mH
No.4 coil	45.9 mH
No.5 coil	45.4 mH
No.6 coil	45.8 mH
Total inductance in series	543 mH

2.2. Operational principle

As well known, a three-phase winding produces a traveling magnetic field in the air gap of Fig. 1 where one Nb foil is installed. Its magnitude is adjustable by the amplitude three-phase current, and its traveling speed depends on the frequency of applied power source. On the other hand, two DC bias coils in Fig. 1 play a role in producing homo-polar magnetic field in such an air gap. Fig. 3 illustrates the ideal homo-polar traveling magnetic field of three-phase AC excitation, also biased with use of the DC bias excitation. Under this condition, the Nb foil installed in the air gap of 3 mm still keeps superconductive state between its critical magnetic flux density levels, while it has normal state over the critical level. These normal spot areas are produced as shown in Fig. 4. In each normal spot, some magnetic fluxes can definitely penetrate

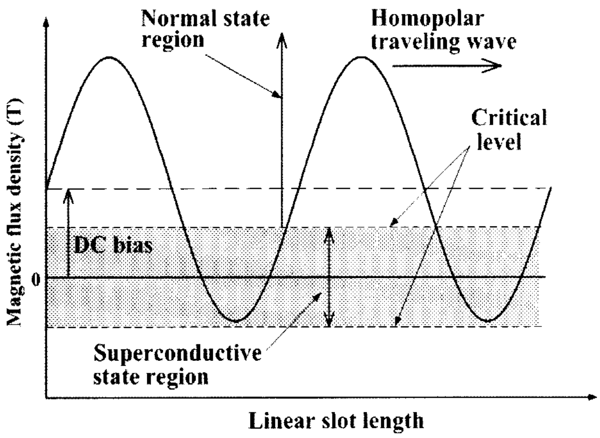

Fig. 3. Theoretical homopolar traveling wave for DC bias and 3-phase AC excitations in the air gap.

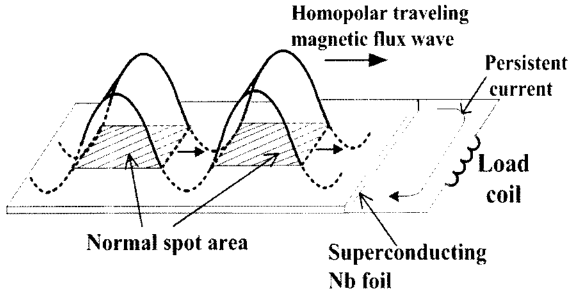

Fig. 4. Principle illustration for pumping-up current mechanism.

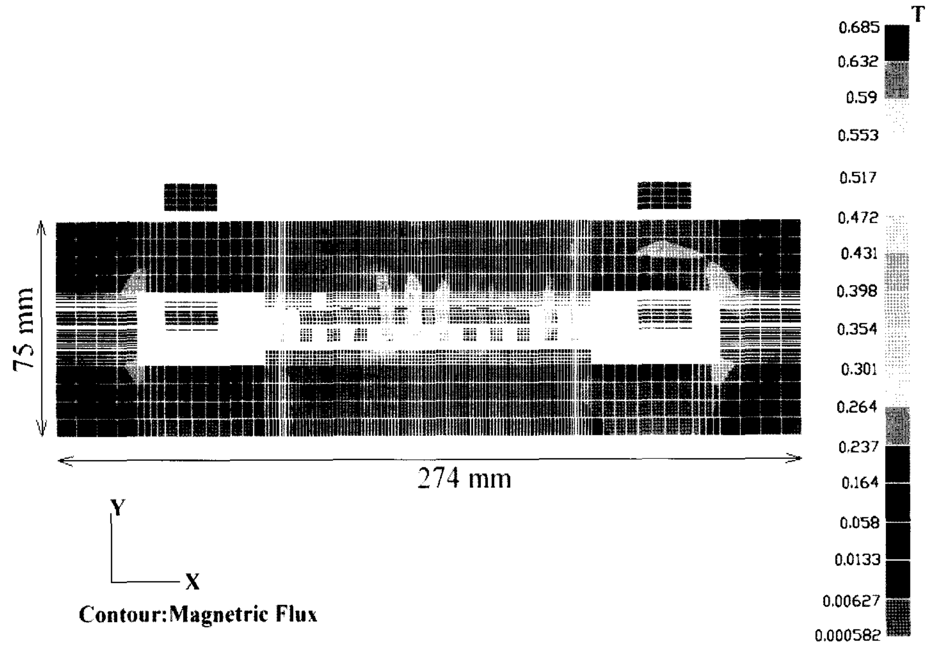

Fig. 5. Magnetic flux density distributions for DC bias of 10 A and 3-phase AC of 5 A_{rms} excitations.

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 fluxes constants according to Lentz's law, some persistent currents 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.

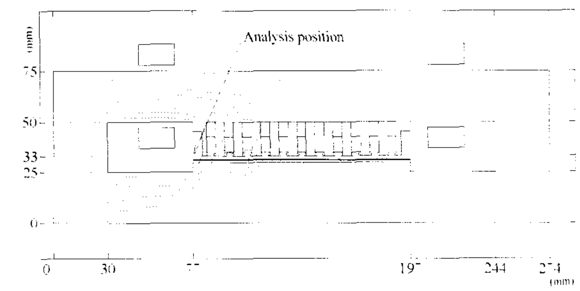

Fig. 6. Magnetic potential distributions for DC bias of 10 A and 3-phase AC of 5 A_{rms} excitations.

3. SIMULATION RESULTS

Computer simulations on magnetic flux density distributions in the flux pump have been carried out, to verify its structural dimension magnitude of flux density. The FEM-2D analysis by using the FEMAP program for DC bias of 10A and 3-phase AC of 5 A_{rms}/60 Hz is shown in Fig. 5. The maximum magnetic flux density inside the laminated core is 0.685 T. Fig. 6 shows magnetic potential mapping in the X-Y plane of the flux pump. Fig. 7 shows the magnetic flux density in the air gap for DC bias of 10 A. Also, Fig. 8 shows 3-phase AC of 5 A_{rms}/60 Hz excitations. The DC bias of 10 A generates the rippled flux distribution between 0.049 T and 0.037 T due to slots and teeth of the core. The maximum and minimum for 3-phase AC excitation are +0.065 T and –0.065 T, respectively. As a result, it should be noted that the symmetric traveling magnetic flux is generated by the 3-phase AC excitation. Fig. 9 shows the resultant magnetic flux density for DC bias of 10 A and 3- phase AC of 5 A_{rms} / 60 Hz.

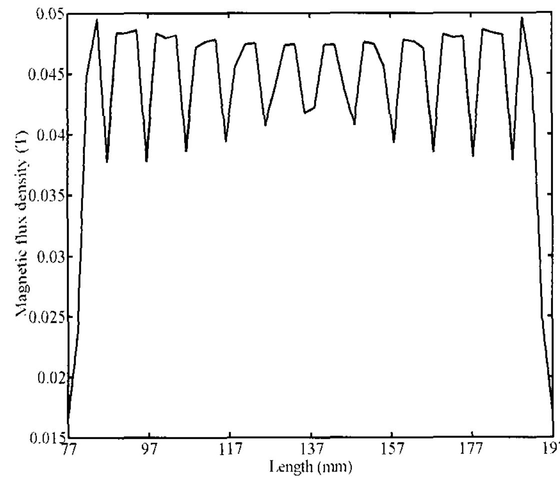

Fig. 7. Magnetic flux density distributions of the air gap for DC bias of 10 A .

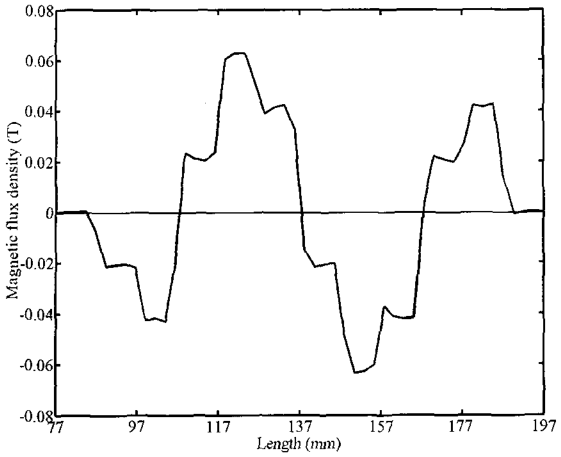

Fig. 8. Magnetic flux density distributions of the air gap for AC of 5 A_{rms} excitations, respectively.

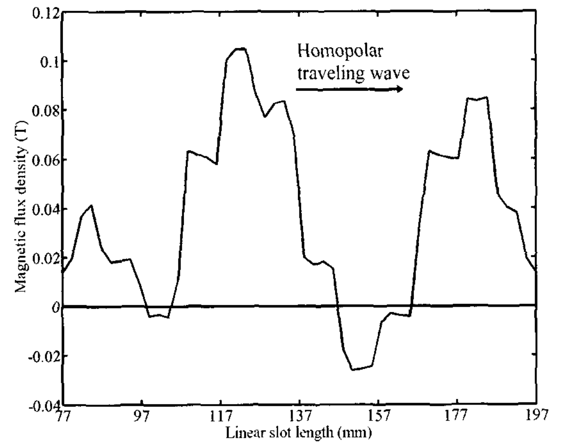

Fig. 9. Resultant magnetic flux density distributions of the air gap for DC bias of 10 A and AC of 5 A_{rms} excitations.

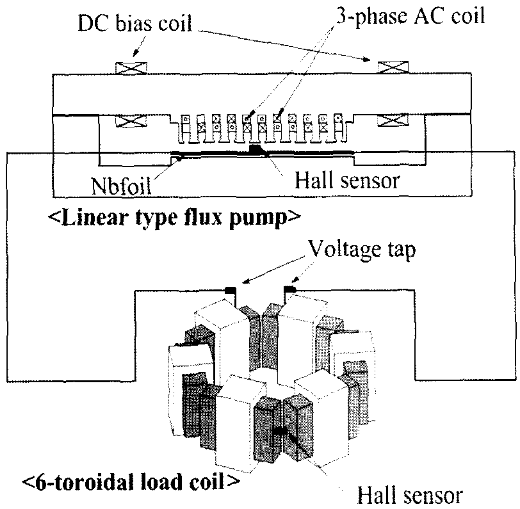

Fig. 10. Connection diagram in the flux pump system.

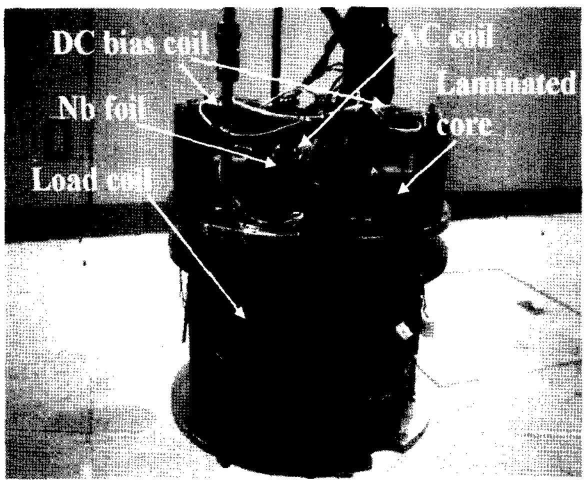

Fig. 11. Photograph of the whole assembly linear type magnetic flux pump system.

4. EXPERIMENTAL SETUP

The connection diagram of the flux pump system is shown in Fig. 10. In the flux pump system, two Hall sensors are used at the following positions: in the central air gap of the flux pump, transverse type Hall sensor to measure magnetic flux density generated by DC bias and AC excitations, and in the air gap between two toroidal cores, axial type Hall sensor to calibrate the pumping-up current in the Nb-Ti load coil. Also, voltage taps are installed in both ends of the load coil.

Fig. 11 shows a photograph of whole assembly flux pump system. In a thick iron plate is installed between the linear type flux pump and the 6-toridal coils in the system, because it prevents leakage flux influence from the load coil.

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

5. EXPERIMENTAL RESULTS

The pumping current and the magnet terminal voltage have been examined under the DC of 10 A and the 3-phase AC of 5 A_{rms} at 10, 15, 20, 40 and 60 Hz. The measured flux density variation in the central air gap under the DC bias of 10 A and the 3-phase AC of 5 A_{rms} at 10 Hz is shown in Fig. 12. The maximum and minimum magnetic flux densities are about 0.1 T and –0.02 T, respectively. Furthermore, the measured results of pumping current and load magnet voltage for DC bias of 10 A and 3-phase AC of 5 A_{rms} excitations are shown in Figs. 13 and 14. The pumping rates at 10, 15, 20, 40 and 60 Hz present about 0.38, 0.5, 0.72, 0.27 and 0.17 A/min, respectively. Under these conditions, the values of the load magnet voltage at 20 and 60 Hz reach about 20 and 14 mV, respectively. From these experimental results, it should be noted that the linear type magnetic flux pump continuously can control pumping-up current without saturation below 20 Hz of

3-phase AC current, and the AC excitation frequency successfully increases up to 20 Hz.

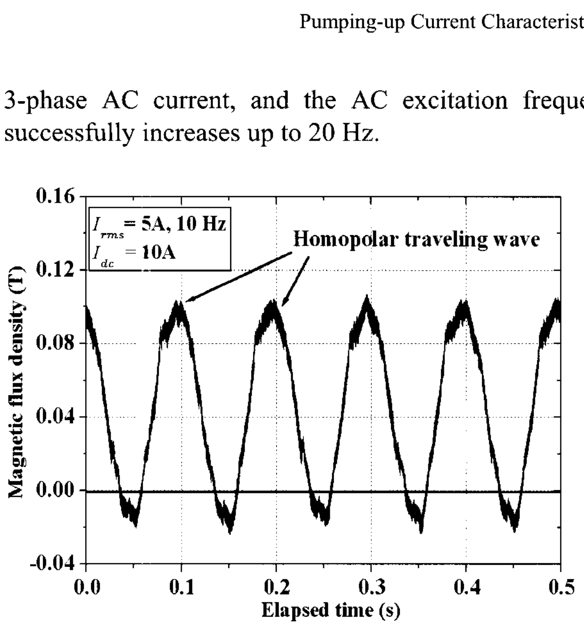

Fig. 12. Measured magnetic flux density at the center of linear core with DC bias of 10 A and 3-phase AC of 5 A_{rms} excitations.

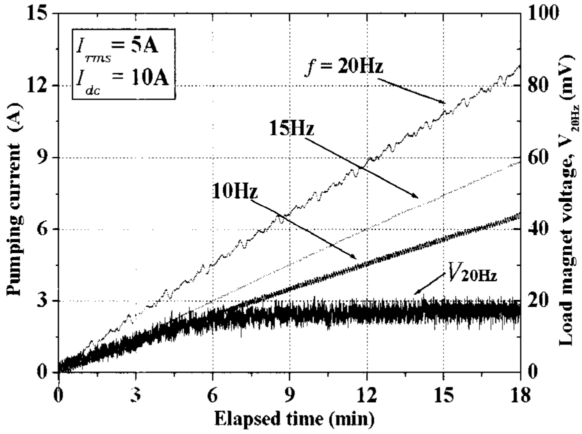

Fig. 13. Measured pumping currents at 10, 15 and 20 Hz, and load magnet voltage at 20 Hz.

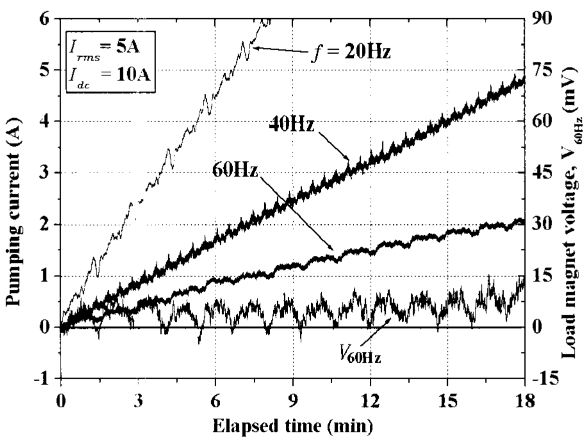

Fig. 14. Measured pumping current at 40 and 60 Hz, and load magnet voltage at 60 Hz.

The load magnet voltage value at 20 Hz was increasing until about six minutes. After this, the value was stably keeping. However, it was observed that for upper than 20 Hz, the pumping-up currents gradually saturate and go down as shown in Fig. 14. In the case of 40 and 60 Hz, the pumping-up current slightly increases. Also, the load magnetic voltage value at 60 Hz was fluctuating because of the saturation in the superconducting Nb foil. From these operational frequencies, it could be recognized that there are some optimal operation frequencies.

6. CONCLUSIONS

The fabrication, analysis and experiment of a linear type magnetic flux pump have been described for compensating a little decremental persistent current of HTS magnet. Also, as shown from the simulated results, the flux pump could be properly designed in terms of the size of the iron core, DC bias coil and 3-phase AC armature coil. Moreover, simulations results have been compared with experimental ones. Through the experimental observations, we investigated that the flux pump can practically charge the current into the load magnet of 543 mH. Pumping-up current rates were measured under the DC of 10 A and the AC of 5 A_{rms}. The maximum values of the pumping current and the load magnet voltage are 0.72 A/min and 20 mV, respectively. We observed that the flux pump could effectively control the pumping-up current by changing frequencies of 3-phase AC current and magnitudes of AC current in the load magnet of 543 mH.

Based on such various experimental results, it could be evaluated that the linear type magnetic flux pump can compensate a little decremental persistent current of HTS magnet such as NMR and MRI HTS magnet systems.

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