Feedforward current control of MRI magnet with power supply driven operation

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Abstract. We have been developing a conduction cooled 3T HTS(REBCO)-MRI system. The prototype system of 100 mm DSV (diameter spherical volume) was designed and made. The MRI image of a mouse fetus (25 mm long) was obtained successfully with 2.9 T under a power supply driven operation. However, the HTS(REBCO)-MRI magnet still had a considerable magnetic field fluctuation for clear MRI imaging due to a long-lasting attenuation of screening current induced on the superconducting tapes. To solve this problem, we introduced a power supply system consists of an exciter power supply and a small trimming current supply, which compensates the magnetic field deviation due to the screening current, in parallel. We measured and evaluated the magnetic field stability of a commercial 3T-LTS-MRI magnet under both the power supply driven operation with proposed system and the persistent current operation. The availability of the power supply system was discussed using an experimental HTS-MRI system.

1. Introduction
The LTS-MRI magnets cooled by a large amount of liquid helium (LHe) are widely used. However, LHe is rare and its price has gone up. Therefore, it is expected to develop a conduction cooled helium-free HTS-MRI magnets. And we study 3 T REBCO-HTS-MRI magnet, which is a candidate in updating existing 1.5 T LTS-MRI magnet. Helium free systems are also very attractive because they eliminate the requirement for risk management of the liquid helium vessel usually required for LTS MRI magnets.

It is necessary to produce a very stable magnetic field for clear MRI imaging. But there is a big problem of HTS(ReBCO)-MRI magnet. The problem is that the long–lasting attenuation of screening current induced on the ReBCO tapes has influence on the magnetic field stability [1]. To solve this problem, we must predict the behavior of the screening current, and do open-loop control because it is difficult to measure the magnetic field of the coil center at MRI imaging. The magnetic field stability and the electromagnetic behavior of HTS coils have been studied [2], [3].

Then we introduced a power supply system consists of an exciter power supply and a small trimming current supply, which compensates the magnetic field deviation due to the screening current,
in parallel. And we carried out the magnetic field stabilizing test at 1.5 T (224.3 A) under the proposed power supply system with a commercial 114 H LTS-MRI magnet.

2. Experimental apparatus

2.1. 3T LTS-MRI magnet

Fig. 1 shows 3 T LTS-MRI magnet provided by Mitsubishi Electric Co. The magnet contains the LHe vessel in the vacuum vessel which consists of the superconducting coil, and the persistent current switch (PCS), and the protection diode [4]. To minimize the evaporation of liquid helium, GM 4K refrigerator RDK-408D2 and Compressor Unit F-50H provided by Sumitomo Heavy Industries are quipped. The inductance of the magnet is 114 H.

![3 T LTS-MRI magnet](image)

2.2. High stabilized power supply system for excitation and holding current

We supposed that HTS MRI magnet is powered even during imaging operations, so a highly stable power supply system is required. Then we designed and made the high stabilized power supply system for a MRI magnet.

The system is composed of the excitation power supply, the holding current power supply, the protective resister, the quench detection unit and control unit. This power supply is combined with switching power supply and dropper constant current control. The control board in the power supply is kept at a constant temperature, therefore output current is highly-stabilized and low-noised.

The specification of the power supply for excitation and holding current is shown in Table 1, and the photograph is show in Fig. 2.

At the imaging, the coil current is kept constant for the highly stable magnetic field with precise current control of the power supply for holding current. The power supply for excitation is only used in the maintenance mode (charging or discharging) and can be removed in the imaging mode.

| Item                     | Excitation                        | Holding current       |
|--------------------------|-----------------------------------|-----------------------|
| Max output current       | 1000A                             | 300A                  |
| Output voltage           | ±15V                              | ±2V                   |
| Current stability        | 100ppm/hour                       | 1ppm/hour             |
| Output current ripple    | 100ppm                            | 10ppm                 |
| (peak to peak)           |                                   |                       |
| Cooling method           | Water cooling and forced air cooling | Forced air cooling   |
2.3. Small trimming current supply

Our goal is to reduce the current fluctuation of the power supply and to compensate the magnetic field deviation due to the screening current by a proper current control of the power supply. To achieve the goal, we introduced a small trimming current supply, which compensates the magnetic field deviation due to the screening current. Using this power supply, it is possible to current control on the order of µA.

The specification of the power supply is shown in Table 2, and the photograph is shown in Fig. 3.

| Table 2. Specification of the small trimming current supply |        |
|-----------------------------------------------------------|--------|
| Max output current                                        | 20mA   |
| Output voltage                                            | ±2V    |
| Current stability                                         | 10ppm/hour |
| Output current ripple (peak to peak)                      | 10ppm  |
3. Magnetic field stability experiment

3.1. Determination of control current amount by simulation

First, based on a free-run experiment of the LTS-MRI magnet (114 H), we simulated the experimental circuit by analysis program XTAP, and determined the amount of control current.

Fig. 4 shows a XTAP simulation circuit. We determined PCS resistance and wiring resistance to fit the experimental results.

The LTS-MRI coil was excited up to 224.3 A (1.5 T) with 1 A overshoot by main power supply. The current sweep speed is 0.07 A/s. Fig. 5 shows the Current operation of main power supply. Power supply for Micro Current Control output the feedback controlled current to keep the coil current constant. The control target was a magnetic field of 500 s after the end of excitation.

Fig. 6 shows control current and magnetic field (with control), magnetic field (without control).
3.2. Experimental result

Fig. 7 shows the experimental result. The power supply for excitation feedback controls the current following through DCCT1, and the power supply for holding current feedback controls the current following through DCCT2. The small trimming current supply open-loop controls according to the corrected current command value from the PC.

Fig. 8 shows the experimental result of feedforward control with the control current determined by simulation, and Fig. 9 shows the enlarged result. The magnetic field is measured at the coil center with an NMR probe. The magnetic field fluctuation was reduced to 0.57 ppm/hour by micro current control. This stability is sufficient for clear imaging.

In the next chapter, we discuss whether clear imaging can be performed under power supply driven mode.

Fig. 6. Control current and Magnetic field (simulation)

Fig. 7. Experimental Circuit
4. Imaging under power supply driven mode

In order to investigate the difference between the imaging under the power supply drive mode and under the persistent current mode, we carried out an imaging test of rabbit formalin fixed sample with LTS-MRI magnet under both modes. Fig. 10 shows rabbit imaging sample (Φ13 cm × L256 mm).

Fig. 10. rabbit formalin fixed sample
Prior to the imaging test, we measured the magnetic field of the 3T LTS-MRI coil center under power supply without control. As a result, the magnetic field fluctuations were 7.14 ppm/hour (2 to 3 hours), 3.99 ppm/hour (3 to 4 hours), 1.59 ppm/hour (4 to 5 hours) and 0.73 ppm/hour (5 to 6 hours). The excitation start time is 0s.

4.1. Operation
We excited the LTS-MRI magnet up to 1.5 T (224.3 A) with High stabilized power supply system, and imaged the sample. After that, we made the shift to the permanent current mode and performed imaging. Fig. 11 shows the current operation. Imaging method is 3D spin echo and imaging time is 6.5min/image.

4.2. Result
Fig. 12 shows imagings of the lower part of the rabbit neck under power supply driven mode a) and under persistent current mode b). The white high-intensity part is the water component (90 %) of the formalin aqueous solution. Each imaging is considered to include a variation of measurement time 6.50 min. On the other hand, the imaging also includes an averaging effect. Fig. 12. a) was taken in 4 to 5 hours. The fluctuation of the magnetic field (4 to 5 hours) under the power supply driven mode is 1.59 ppm/hour.

Fig. 13 shows Phase difference image, which is obtained by a) — b). We highlight the range of phase angle 36 ° as the upper / lower limit. The green part shows a range of 19.5 Hz (1 pixel 195 Hz × 36 ° /360 ° , 0.3 ppm at 1.5T). It can be seen that it is almost green and the phase is aligned to about 0.03 ppm. The difference on the image between under the power drive mode and under permanent current mode is not observable.
As a result, the current source was very stable and micro current control can quickly stabilize the magnetic field, which is sufficient for imaging. It was confirmed that when the fluctuation of the LTS-MRI magnetic field under the power supply driven mode was 1.59 ppm/hour, the image was as clear as that under the persistent current mode. It took about 5 hours to reduce the magnetic field fluctuation to 1.59 ppm/hour without micro current control, but with micro current control, it took about 3 hours to reduce that to 0.57 ppm/hour. It can be said that the fluctuation of HTS-MRI magnet is larger than that of LTS-MRI magnet because of the influence of the shielding current, so the micro current control is effective to stabilize the magnetic field.

5. Conclusion
In developing the HTS-MRI magnet, it is one of the important issues to improve the magnetic field stability of the MRI magnet under the power supply driven mode.
We introduced a power supply system consists of a exciter power supply and a small trimming current supply, which compensates the magnetic field deviation due to the screening current, in parallel.

In conclusion, the micro current control (the magnetic field open-loop control), reduced the fluctuation to 0.57 ppm/hour which is sufficient for fine MRI imaging.

When the excitation pattern is fixed, the influence of the screening current on the magnetic field fluctuation can be almost predicted, so that it is possible to stabilize the magnetic field by determining a compensation current value in advance and adding a small-capacity power supply.

In the next step, the proposed current supply system will be verified by applying it to HTS-MRI magnets.

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