Effectiveness of Filter Inductor of Rectifier Transformer Flux Pump in Energizing Multi-Stacked No-Insulation REBCO Pancake Coils

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Abstract. In recent years, strong magnetic field rare-earth barium copper oxide (REBCO) magnets are desired for various applications. For such magnets, since heat penetrating from current leads is undesirable, a flux pump is an attractive method to energize. However, it is difficult to apply a flux pump to a REBCO coil using no-insulation (NI) winding technique. Because, a large current flows into the radial direction due to a low contact resistance. Recently, a filter inductor installed into a rectifier transformer type flux pump (RTTFP) was proposed to effectively charge an NI REBCO single pancake coil. However, it is not sure whether it also works for multi-stacked NI REBCO pancake coils. Hence, we investigate the role of a filter inductor by a numerical simulation, and then we clarify the validity of filter inductor. As the result, the filter inductor accelerates the charging of multi-stacked NI REBCO pancake coils with low contact resistance.

1. Introduction

In recent years, strong field high-temperature superconducting (HTS) magnets are required in many applications, such as magnetic resonance imaging (MRI) [1], nuclear magnetic resonance (NMR) [2], and particle accelerators [3]. Also, they can be applied to the rotors of highly efficient motors [4]. The no-insulation (NI) winding technique [5] is promising, and it greatly improves the thermal stability of rare-earth barium copper oxide (REBCO) pancake coils. Recently, an NI REBCO magnet generated a world-record high DC magnet field of 45.5 T [6]. However, in the NI REBCO magnet, a little large heat was generated during charging due to Joule heat of radial current. Although the Joule heat cannot be avoided, in order to generate a high magnetic field, it is desired to reduce total heat generation as mush as possible. An attractive method to reduce heat in a magnet during charging is a flux pump [7, 8, 9]. A flux pump effectively increases a current in a closed loop made of superconducting wires without a large amount of heat penetration, because heat is prevented from penetrating through current leads.

Recently, it was reported that a rectifier transformer type flux pump (RTTFP) [8, 9] could energize an NI REBCO single pancake coil. The RTTFP performance was validated in the experiments. It was proposed that a filtering inductor improved the charging performance of an NI REBCO single pancake coil. An NI REBCO coil has a disadvantage of charging delay. It also deteriorates the charging performance using an RTTFP. However, the charging was accelerated using a filter inductor.
As a next development step, an RTTFP must be applied to more practical applications. Toward practical applications, it is necessary to investigate whether an RTTFP is effective in multi-stacked NI REBCO pancake coils; however the multi-stacked NI pancake coils have a large inductance. Therefore, the effectiveness of a filter inductor in multi-stacked NI pancake coils with a large inductance must be investigated further.

In this paper, an extended equivalent circuit model is used for multi-stacked NI REBCO pancake coils by connecting the equivalent circuit of NI pancake coils in series, and an adequate filter inductance for multi-stacked NI pancake coils is found by numerical simulation. The effectiveness of filter inductor is also investigated.

2. Analysis model and method

Figure 1 shows an equivalent circuit model of RTTFP. The current source generates a triangular wave current. The permanent current switch (PCS) is connected with NI pancake coils in parallel. The PCS works by applying an AC magnetic field perpendicularly to an REBCO tape [10]. The PCS turns on/off in synchronization with the triangular source current as shown in figure 2. When the PCS is off, the source carries a current into \( n \)-stacked NI REBCO pancake coils. In the case of a conventional RTTFP, the azimuthal coil current \( i_\theta \) of NI REBCO coils does not efficiently increase. When a filter inductor was installed in series, the charging performance of an NI REBCO single pancake coil was improved [9].

To numerically investigate the current behaviors of RTTFP with a filter inductor, the following equations (1)-(4) are solved:

\[
L_f \frac{di_L}{dt} + \sum_{j=1}^{n} R_{cj}i_{rj} = R_{dyn}i_B
\]  

(1)

\[
R_{ci}i_{ri} = \sum_{j=1}^{n} M_{ij} \frac{d\theta_j}{dt} \quad (i = 1, \cdots, n)
\]  

(2)

\[
i_L = i_{r1} + i_{r2} \quad (i = 1, \cdots, n)
\]  

(3)

\[
i_B = i_s - i_L
\]  

(4)

where \( L_f, i_L, R_c, i_r, R_{dyn}, i_B, M, \) and \( i_s \) are the filter inductance, the filter current, the contact resistance of each pancake coil, the radial current of pancake coil, the PCS resistance, the
Table 1. Coil specifications

| Parameters                        | Values |
|-----------------------------------|--------|
| Inner diameter (mm)               | 60.0   |
| Outer diameter (mm)               | 79.2   |
| REBCO tape thickness (mm)         | 0.96   |
| REBCO tape width (mm)             | 4.0    |
| Number of turns                   | 100    |
| Space between each pancakes (mm)  | 1.0    |
| Critical current at 77 K, self-field (A) | 140   |

1 single pancake coil
- Inductance (mH) 1.10
- Magnet constant (mT/A) 0.89

12-stacked pancakes coils
- Inductance (mH) 66.0
- Magnet constant (mT/A) 9.81

Table 2. Operating conditions

| Parameters                        | Values |
|-----------------------------------|--------|
| Operating temperature (K)         | 77     |
| Peak triangular source current $i_{\text{smax}}$ (A) | 120    |
| Frequency of source current (Hz)  | 0.5    |
| Maximum PCS resistance $R_{\text{dmax}}$ ($\mu\Omega$) | 458    |
| Ratio of PCS OFF duration to one cycle $T_{\text{OFF}}/T$ | 0.10   |

PCS current, the self- and mutual-inductance between pancake coils, and the source current, respectively. The self- or mutual-inductances of every pancake coil are computed from the relation of the magnetic vector potential and the current density in [11], assuming that currents flow uniformly in REBCO tape conductors.

The systems of equations is solved in each time step using a backward time difference method as every current is variable.

3. Simulation results

Figure 3 shows the charging times at different filter inductances for 1 single and 12-stacked single pancake coils. Here, the contact resistivity is supposed to be 70 $\mu\Omega \cdot \text{cm}^2$ [12] (i.e. contact resistance $R_c = 426 \mu\Omega$ for one single pancake coil). The convergence current is 108 A for both magnets, and the center magnetic field reaches to 0.10 T for 1 single pancake coil and 1.06 T for 12-stacked pancake coils, respectively. Table 1 shows the coil specifications, and table 2 lists the operating conditions, respectively. Without a filter inductor, the charging times of the single and the 12-stacked single pancake coils are 150.5 s and 4690 s, respectively. In the case of 12-stack,
Figure 3. Charging time as a function of filter inductance. Broken lines are the charging time without filter inductor.

the filter inductor does not work at any inductance value. Meanwhile, the RTTFP effectively charges the single pancake coil with a filter inductance in the range of 0.01-1.0 mH. From the simulation results, it is shown that the RTTFP with a filter inductor cannot effectively work for all kinds of NI REBCO pancake coils.

Hence, we have further investigated effective filter inductors as a function of the time constant $\tau$. For $n$-stacked single pancake coils, the time constant $\tau$ is given as follows:

$$\tau = \frac{L_{tn}}{nR_c}$$

where $L_{tn}$ is the total inductance of $n$-stacked coil. In addition, a reduction rate $\gamma$ of charging time of NI REBCO pancake coils is defined as follows:

$$\gamma = \frac{\alpha_{wof} - \alpha_{wf}}{\alpha_{wof}}$$

where $\alpha_{wof}$ and $\alpha_{wf}$ are the charging time without/with a filter inductor, respectively.

Figure 4 plots the reduction rate for different time constants by changing the contact resistance $R_c$ from 10 $\mu$Ω to 100 mΩ. Here, the filter inductor is constant at 0.2 mH, and the cross marks show the reduction rate at the contact resistivity of 70 $\mu$Ω·cm². From this figure, it is observed that a filter inductor is not effective when the time constant $\tau$ is small. Also, it is clear that when a magnet inductance is large (i.e. for a high field magnet), the small contact resistance is required for increasing the filter inductor effect. That is, for multi-stacked NI REBCO pancake coils, a contact resistivity lower than 70 $\mu$Ω·cm² is required.

To clarify and understand the detailed current behavior of NI REBCO pancake coils, figures 5 and 6 show the coil voltage and the azimuthal and radial current with/without a filter inductor in the cases of the contact resistance $R_c = 4.26$ mΩ and $R_c = 42.6$ $\mu$Ω, respectively. When the contact resistance is large ($R_c = 4.26$ mΩ), the coil voltage is applied for a very short time, like a pulse. The pulse-like voltage increases the azimuthal current $i_\theta$ in the both cases with/without a filter inductor. Meanwhile, in the case of low contact resistance ($R_c = 42.6$ $\mu$Ω), the pulse-like voltage without a filter inductor cannot effectively increase the azimuthal current $i_\theta$. Due to
Figure 4. Reduction rate $\gamma$ of charging time versus time constant $\tau$ for different number of NI REBCO single pancake coils. The cross marks show the reduction rate at the constant resistivity of 70 $\mu\Omega \cdot \text{cm}^2$.

Figure 5. Plots showing transient response of (a) Coil voltage $V_c$, (b) Azimuthal current $i_\theta$, (c) Radial current $i_r$, under contact resistance $R_c = 4.26 \text{ m}\Omega$ (contact resistivity $\rho_c = 700 \text{ m}\Omega$).

The low contact resistance, a large current escapes into the radial direction. On the other hand, the filter inductor keeps a voltage, and it increases the azimuthal current. As a result, a filter inductor works for a multi-stuck NI REBCO pancake coil with low contact resistance.
Figure 6. Plots showing transient response of (a) Coil voltage $V_c$, (b) Azimuthal current $i_\theta$, (c) Radial current $i_r$ under contact resistance $R_c = 42.6 \, \mu\Omega$ (contact resistivity $\rho_c = 7 \, m\Omega$)

4. Conclusion
In this paper, we model a rectifier transformer type flux pump (RTTFP) with multi-stacked NI REBCO pancake coils. And then, we investigate the validity of a filter inductor by numerical simulation. The RTTFP with filter inductor can improve the charging performance of multi-stacked NI REBCO pancake coils with low contact resistance. However, for high contact resistance, the large inductance of multi-stacked NI REBCO pancake coils prevents an effective charging even with a filter inductance.

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