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Analytical and numerical simulation on charging behavior of no-insulation REBCO pancake coil

Huu Luong Quach[a], Ji Hyung Kim[a], Yoon Seok Chae[a], Jae Hyung Moon[a], Jung Hyup Ko[a], Hyung-Wook Kim[b], Seog-Whan Kim[b], Young-Sik Jo[b], and Ho Min Kim[*,a]

[a]*Department of Electrical Engineering, Jeju National University, Jeju, S.Korea*
[b]*Korea Electrotechnology Research Institute, Changwon, Korea*

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Abstract

This paper presents analytical and numerical simulation approaches on charging characteristics of no-insulation (NI) REBCO pancake coil by using the equivalent circuit model to estimate magnetic performance response in the coil. The analytical methods provide closed form or definite solution in the form of complete mathematical expressions but they are hard to solve the complex problems. Numerical methods have become popular with the development of the computing capabilities to solve the problems which are impossible or very hard to solve analytically. First of all, the equivalent circuit model are proposed to develop the simulation code for both analytical and numerical method. The charging test was performed under critical current to obtain magnetic field induced and terminal voltage through the radial as well as spiral current paths within the coil. To verify the validity of both proposed methods, the simulation results were compared and discussed with the experimental results.

Keywords: REBCO coated conductor, no-insulation pancake coil, charging behavior, analytical method, numerical method, equivalent circuit model

1. INTRODUCTION

The no-insulation (NI) winding technique [1] has recently attracted more attention of many researchers in applying to REBCO pancake coils for the use of MRI, NMR, and accelerator applications [2, 3]. The key idea is to completely remove turn-to-turn organic insulation layer within a REBCO pancake coil. Therefore, the NI REBCO magnet can achieve more compact, higher overall current density, higher thermal and electrical stability and lesser risk of partial quenching than the conventional insulated HTS magnet [4, 6]. It has been reported that the NI coil was successfully generated the target magnetic field as its conventional insulated coil in the steady state. In addition, when a local normal hot spot occurs in the NI coil, the excessive current automatically bypass the quench region to protect the coil from permanent damage even though the operating current (I_t) is twice more than the critical current (I_c) [1]. However, the major drawback of NI winding technique is charging delay of magnetic field. For conventional insulated coil, the I_t flows only in the spiral direction to generate expected design magnetic field. On the other hand, NI coil exhibited bypassing current through turn-to-turn contact resistance from its original spiral path during the charging process. Therefore, It takes long charging time for an NI coil to reach the designed magnetic field due to the charging delay [7, 8]. To date, the charging delay of an NI coil was presented by many research groups. A simulation method base on the equivalent circuit model was introduced to investigate the electromagnetic behavior of NI coil [9]. However, the detail charging delay time has not been clearly evaluated in the simulation studies.

This paper presents analytical and numerical methods to investigate the charging delay time of NI coil under critical current during the charging process. The simulation code for both analytical and numerical methods were developed base on the proposed equivalent circuit model using MATLAB. The simulated results were compared and discussed with the experimental results to evaluate the charging delay time of both simulation methods.

2. FABRICATION OF AN NI REBCO COIL

The specifications of REBCO coated conductor (manufactured by SuNAM Co., Ltd) and test coil used in this study are given in Table I. It was 4.1 mm wide and 0.15 mm thick. The minimum and maximum I_c of the REBCO tape were 245 A and 268 A, respectively under 77 K and self-field. The total length of 7.96 m was used to wound 30 turns with winding inner and outer diameters of 80 mm and 89 mm, respectively. The I_c of NI coil is 125 A at 77 K with the 1 μVcm^{-1} criterion. The axial magnetic field was measured using a Hall sensor (HGCT-3020 model) from Lake Shore Cryotronics Inc. and recorded by SCXI-1000, 1325, and 1328 model from National Instruments Corp. The picture of NI coil used in the experiment test is shown

* Corresponding author: hmkim@jejunu.ac.kr

TABLE I
PARAMETERS OF REBCO CC TAPE AND NI TEST COIL

ITEMS	UNIT	VALUES
REBCO Tape		
Manufacturer	-	SuNAM Co. Ltd
Conductor Width	[mm]	4.1±0.1
Conductor thickness	[mm]	0.15
Max. I_c @77 K, self-field	[A]	268
Min. I_c @77 K, self-field	[A]	245
NI Pancake coil		
Number of turns	-	30
Inner diameter	[mm]	80
Outer diameter	[mm]	89
HTS wire length	[cm]	796
I_c @77K, self-field	[A]	125
Coil constant	[mT/A]	0.448
Coil inductance	[μH]	150
Decay time constant	[s]	2.5
Characteristic resistance	[μΩ]	60

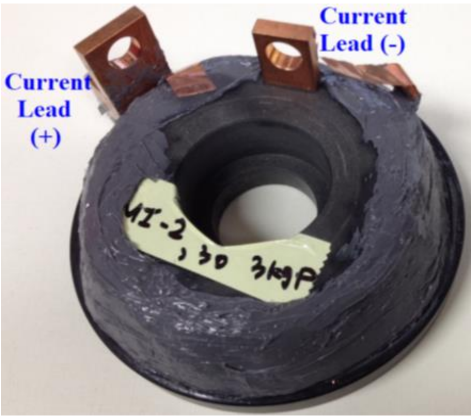

Fig. 1. Photograph of NI REBCO pancake coil.

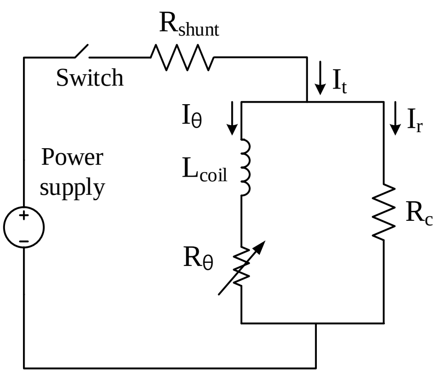

Fig. 2. Equivalent circuit model of NI coil for analytical method.

in figure 1. It was covered by encapsulant paste to compare the thermal stability with V_2O_3 insulation coil (in our previous study [10]) under quench test with over current charging. In this study, we utilized the charging results of NI coil as the preference to validate the proposed analytical and numerical methods.

3. EQUIVALENT CIRCUIT MODEL AND SIMULATION METHODS

3.1. Analytical Method

The proposed analytical method gives exact solution or closed form without the help of computational techniques. It can solve the problems with very limited effort. Therefore, the analytical solutions are very useful for checking the solutions obtained from the numerical methods.

Fig. 2 shows an equivalent circuit model of NI REBCO coil which consists of a DC power supply, a switch, a shunt resistor, and the NI test coil in cryogenic environment [5], [6, 9]. There are three main components in the NI coil model: L_{coil} (self-inductance), R_θ (azimuthal resistance including index loss and matrix resistance), and R_c (characteristic resistance mostly from turn to turn surface contact). To simplify calculation, R_θ was assumed to be zero because the NI test coil was conducted below the critical current and temperature. The equation of circuit model in the charging test can be given as follows:

$$L_{coil}\frac{dI_\theta}{dt}=\left(I_t-I_\theta\right)R_c \qquad (1)$$

In the static condition (i.e., $dI_\theta/dt = 0$), the I_t flows only through the superconducting layer in the spiral direction. However, under the time-varying condition (i.e., $dI_\theta/dt \neq 0$), I_t flows not only in the spiral direction but also in the radial direction due to the absence of insulation within the coil. The current values flowing in the superconducting layer (I_θ) with respect to I_t can be calculated by solving the first order differential equation (1). The analytical solution can be denoted as follows [11]:

$$\begin{cases} I_\theta = h\left[t-\tau\left(1-e^{-t/\tau}\right)\right], & 0\le t\le t_1 \\ I_\theta = t_1 h+\left[\tau h\left(1-e^{t_1/\tau}\right)e^{-t/\tau}\right], & t_1\le t\le t_2 \end{cases} \qquad (2)$$

where h, t, t_1, t_2 and τ represent current ramping up rate, time period respect to operating current, time location when the current ramping up reach maximum (I_{max}/h), remaining time of the maximum operating current, and decay time constant which can be obtained from the sudden discharge test with the normalization of B_z, respectively. The characteristic resistance of the magnet can be calculated by the following equation:

$$R_c=\frac{L_{coil}}{\tau} \qquad (3)$$

The center magnetic field distribution of the magnet can be obtained using the following equation [12]:

$$B_z(0,0)=\frac{\mu_0 NI}{2a_1}\left[\frac{\ln\left(a_2/a_1\right)}{\left(a_2/a_1\right)-1}\right] \qquad (4)$$

where μ_0, N, I, a_1, a_2 are permeability of free space, number of turns, current, inner radius, and outer radius, respectively.

3.2. Numerical Method

Numerical method is mathematical algorithm that is used to find approximate solution of complicated mathematical problems where the analytical method is not available. Although numerical method can not give the solution in the form of mathematical expressions, it can handle a large system of equations or a system of nonlinear equations. Therefore, numerical method is common and frequently used in engineering practice.

There are many numerical methods (*i.e.*, Euler's method, Midpoint method, Taylor's method, Trapezoidal method, Rung-Kutta method (RK), etc) that can be used to solve (1) which is difficult or impossible to solve analytically. In this study, we developed a simulation code using the Runge–Kutta fourth order (RK4) [13, 14] to solve (1). RK is one of the commonly used method for solving differential equations. The higher order RK can be obtained higher accuracy but they suffer from the computation time. RK4 offers a good balance between the accuracy and cost of computation compared to other numerical methods. With better precision in the numerical approximation, the RK4 is expected to obtain the charging delay time with the small error which is very important in high power application to predict time delay of large coil.

4. RESULTS AND DISCUSSION

4.1. Sudden Discharge Test

A sudden discharge test was conducted in liquid nitrogen bath at 77 K to obtain the decay time constant (τ_d) then calculate the R_c of NI REBCO pancake coil. The experimental procedure of this test was described as follow. The NI test coil was charged to 87 A (~ 0.7 I_c) with the current ramp rate of 1 A/s, and then maintained in steady-state operation at 87 A for 40 s before the power supply current was immediately cut off. Fig. 3 shows the experimental results of normalized magnetic field with respect to time from the sudden discharge test of NI REBCO coil at 87 A. When the I_t was shut down, there was a time delay constant for the magnetic field of the NI coil exponentially decreasing to zero. This is because the remaining current in NI coil could flow through the superconducting layer in the spiral direction as well as turn to turn contact in the radial direction until it was dissipated as heat in the resistance. The τ_d value of NI coil which was determined at the normalized value of 0.37 (see the horizontal dashed line in Fig. 3) is about 2.5 s. The calculated self-inductance (L) of NI coil based on the relationship between inductance voltage and current ramp rate (*i.e.*, $V = L*di/dt$) is 150 μH. From the measured decay time constant and coil inductance, the R_c of the magnet was found to be 60 μΩ by (3).

4.2. Charging Test

In order to estimate the charging delay time of the NI REBCO pancake coil, the charging test was carried out in liquid nitrogen bath at 77 K. The operating current increased to 100 A (~ 0.8 I_c) at the charging rate of 1 A/s, and maintained at that level for 40 s during steady-state operation, then decreased to 0 A at discharging rate of 1

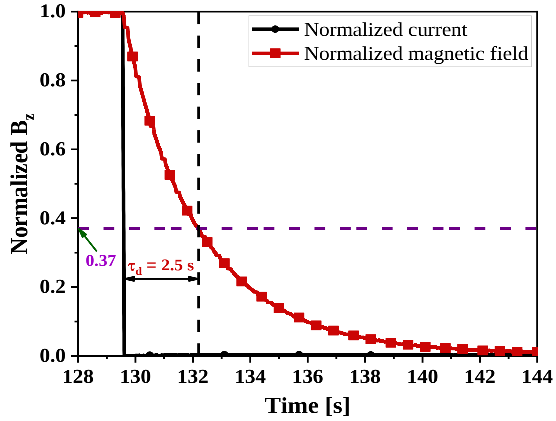

Fig. 3: Normalized B_z versus time during sudden discharge test at 77 K

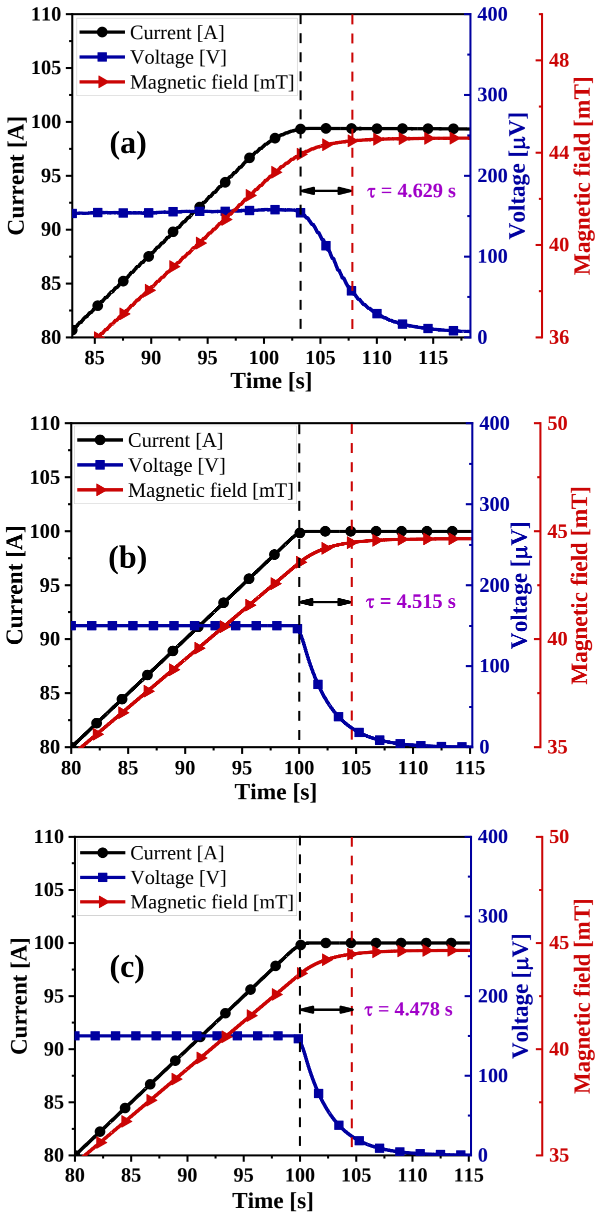

Fig. 4. Set of *I(t)*, *V(t)*, *and* $B_z(t)$ traces for NI coil during charging test at 100 A (~ 0.8 I_c) with ramping rate of 1 A/s: (a) experiment, (b) analytical simulation, and (c) numerical simulation.

A/s. A Hall sensor was placed at the center of NI coil to measure the center magnetic field. The coil constant was 0.448 mT/A which was obtained by operating current and center magnetic field during the steady-state operation of charging test (*i.e.*, $k = B_z/I_t$).

Fig. 4 shows the center magnetic field, terminal voltage, and operating current according to time among experiment (a), analytical simulation (b), and numerical simulation (c) of the NI coil during the charging test. The maximum center magnetic field and terminal voltage of both simulated results were virtually similar to those of experimental results which were found to be approximately 45 mT and 150 μV, respectively. The terminal voltage was similar to the inductance voltage (*i.e.*, $V = L*di/dt$) which caused the I_t bifurcate into radial and spiral direction, result in charging delay of NI coil. The charging delay time for the experiment, analytical simulation, and numerical simulation were 4.629s, 4.515 s, and 4.478 s, respectively. There is a small difference between numerical result (96.74 % of experiment) and analytical result (97.54 % of experiment). As expected, the delay time of the analytical result was closer to the experimental result than that of the numerical result. This is because the numerical method gives the approximate solution using arithmetic operations to solve the problem. However, these results demonstrated that both analytical and numerical methods using the proposed equivalent circuit model validate to characterize the charging behavior of NI REBCO coil.

4. CONCLUSION

The time-varying electromagnetic characteristic of NI REBCO pancake coil was carried out by experiment and both analytical and numerical simulations. Target field of the NI coil was obtained at the operating current of 100 A. Then charging delay time of the coil was calculated employing both analytical and numerical methods in the equivalent circuit model. As expected, the RK4 method, with high accuracy in numerically solving the differential equations, shows the charging delay time slightly lower than that of analytical solution. In engineering practice, the numerical method (especially RK4) is more frequency used than analytical method because it can solve the complicated problems that the analytical method can not or very hard to solve.

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