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“Leak Current” correction for critical current measurement of no-insulation HTS coil

Jung-Bin Song[a] , **and Seungyong Hahn**[*,b]

[a] *Laboratoire National des Champs Magnétiques Intenses, CNRS, Grenoble 38000, France*
[b] *Department of Electrical and Computer Engineering, Seoul National University, Gwanak-ro 1, Gwanakgu, Seoul 08826, Korea*

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Abstract

Discrepancy between a power supply current and an actual “spiral” coil current makes the conventional 4-probe measurement of a critical current (I_C) of a no-insulation (NI) high temperature superconductor (HTS) coil *inaccurate* and *time-consuming*. This paper presents a fast and accurate approach for I_c measurement of NI HTS coils. With an NI HTS coil energized at a constant ramping rate, a complete analytic expression for the spiral coil current was obtained from a first-order partial differential equation that derived from an equivalent circuit model of the NI coil. From the analytic solution, both spiral coil current and radial leak current can be obtained simultaneously, which enables fast and accurate measurement of the NI coil I_c. To verify the proposed approach, an NI double-pancake (DP) coil, wound with GdBCO tapes of 6 mm × 0.1 mm, was constructed and its I_c was repeatedly measured with various ramping rates in a bath of liquid nitrogen at 77 K. The measured results agreed well with the calculated ones, which validates the proposed approach to measure I_c of an NI HTS coil.

Keywords: Critical current measurement, HTS coil, Leak current, No-insulation

1. INTRODUCTION

Firstly, reported in 2011 [1], the no-insulation (NI) high temperature superconductor (HTS) winding technique has been demonstrated to be effective to make an NI HTS coil significantly more compact, stable, and mechanically robust than its conventional insulated counterpart. The key idea is to “automatically” bypass a quench current through turn-to-turn contacts, which essentially makes an NI HTS coil self-protecting [2, 3]. To date researches on the HTS NI technique, experimental and analytic, have been actively conducted to better understand the NI coil behaviors [4–16]. One of the fundamental challenges on NI coil researches is to accurately measure a critical current (I_c) of an NI coil. Due to turn-to-turn shorts, an NI HTS coil has a “leak” current in addition to a “spiral” one that generates a target magnetic field. As a result, when an NI HTS coil is ramping, the leak current leads to a discrepancy between a power supply current and the actual spiral coil current, which makes it challenging to accurately measure a critical current (I_c) of the NI coil with the conventional 4-probe method. An alternative to measure an NI coil I_c is a “ramp-and-hold” method. When a power supply current holds during a ramping test, the leak current decays and thus the power supply current gradually matches to the actual spiral coil current. This provides a relatively accurate approach to measure an NI coil I_c but requires multiple trial-and-errors that take a significant amount of time particularly for an NI coil having a charging delay.

Combined with the 4-probe method, this paper proposes a new approach for fast and accurate measurement of an NI coil I_c. To verify the proposed approach, an NI double pancake (DP) coil was wound with 6 mm wide and 0.1 mm thick GdBCO tapes manufactured by SuperPower, and its I_c was repeatedly measured using the proposed approach with various power supply ramping rates in a bath of liquid nitrogen at 77 K.

2. PROBLEM IDENTIFICATION IN CONVENTIONAL 4-PROBE I_c MEASUREMENT

2.1. Preparation of Coil

Fig. 1 shows a photograph of an NI double-pancake (DP) coil wound onto a stainless steel inner band to prevent HTS tape buckling during winding [17]. The inner and outer diameters of the coil are 91.0 and 119.9 mm, respectively, and

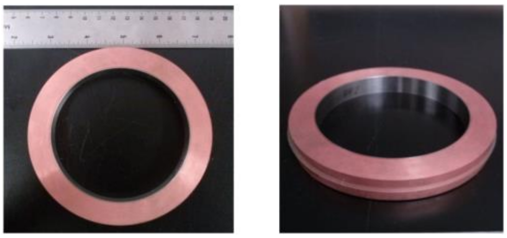
(a) (b)

Fig. 1. Photograph of an NI GdBCO DP coil for test; (a) a top view and (b) a side view.

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*Corresponding author: hahnsy@snu.ac.kr

[a,b] A part of works were performed at the authors' former institute: the Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, US

TABLE I
SPECIFICATIONS OF THE NI DP TEST COIL.

Parameters		**Values**
Conductor (GdBCO)		
Manufacturer		SuperPower
Width; Thickness	[mm]	6.0; 0.075
I_c at 77 K, self-field	[A]	210
Cu stabilizer thickness	[mm]	0.05 per side
Double Pancake (DP) Coil		
ID; OD; Height	[mm]	91.0; 119.9; 12.1
Turn per pancake		186
Coil constant	[mT/A]	4.44
Self inductance	[mH]	20.5
Total conductor length	[m]	120.7
V_c with 1 μV/cm	[mV]	12.1
V_c with 0.1 μV/cm	[mV]	1.21

the total number of turns is 372. The coil constant (axial center field, B_z at 1 A) and the self-inductance are calculated to be 4.44 mT/A and 20.5 mH, respectively. Table I summarizes key parameters of the NI DP coil.

2.2. Discrepancy between Power Supply Current and Actual Coil Current

Firstly, the coil was charged up to 72 A with three different ramping rates of 2.0, 6.2 and 9.0 A/min. Fig. 2 shows the test results: coil terminal voltages (solid symbols) and coil center fields (open symbols). Using the conventional 4-probe method, the I_c of the NI coil may be obtained: 52.7, 54.6, and 56.0 A using 0.1-μV/cm criterion and 69.4, 70.3, and 71.1 A using 1-μV/cm criterion with ramping rates of 2.0, 6.2, and 9.0 A/min. The basic assumption under these I_c evaluations is that the power supply current (I_p) matches exactly to the coil current, i.e., no currents "leak" through turn-to-turn contacts. In an NI coil, however, the intrinsic "current leak" exists and even varies as the ramping rate of power supply changes, which makes I_c measurement of the NI coil challenging. Table II summarizes the measured (B_m) and calculated (B_c) coil center fields, when the power supply current (I_p) reached the coil "I_c" at each ramping rate; B_c was calculated by multiplying I_c by the coil constant in Table I. In all cases, B_m is smaller than B_c, due to the current leak through turn-to-turn contacts. The discrepancy between B_m and B_c increased with increasing I_c voltage criterion and current ramp rate of power supply. The results indicate that the conventional 4-probe approach leads to an inaccurate I_c evaluation for an NI coil.

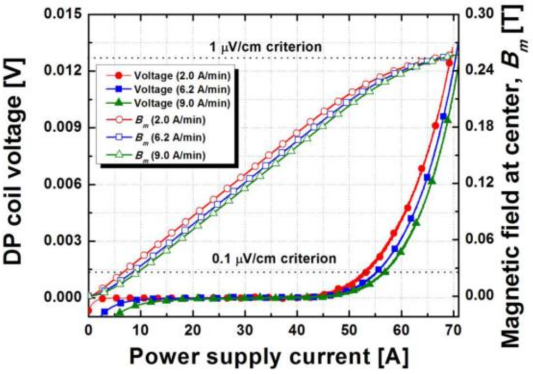

Fig. 2. *V-I* and magnetic field curves of the NI DP coil at three different ramping rates of power supply currents: 2.0, 6.2 and 9 A/min.

TABLE II
MEASURED (B_m) AND CALCULATED (B_C) COIL CENTER FIELDS WHEN A POWER SUPPLY CURRENT (I_P) REACHES THE COIL I_C, DETERMINED BY TWO CRITERIA OF 0.1 μV/cm AND 1 μV/cm, IN THREE DIFFERENT RAMPING-RATE CHARGING EXPERIMENTS.

Ramping rate [A/min]	**Measured (B_m) [T]**	**Calculated (B_c) [T]**
Voltage Criterion: 0.1 μV/cm		
2.0	0.224	0.232
6.2	0.225	0.243
9.0	0.225	0.249
Voltage Criterion: 1.0 μV/cm		
2.0	0.256	0.308
6.2	0.257	0.312
9.0	0.257	0.316

3. NEW APPROACH: CONSTANT RAMPING AND LEAK CURRENT CORRECTION

3.1. Equivalent Circuit Model for NI Coil

Fig. 3 shows an equivalent circuit model to characterize both spiral and leak current paths in an NI coil [1]. L_{HTS}, R_R, and R_θ represent, respectively, coil inductance, turn- to-turn contact resistance along the leak current path, and HTS index resistance along the spiral path. I_P, I_R, and I_θ are, respectively, power supply current and leak and spiral currents in the NI coil. By applying the Kirchhoff's voltage law, one may obtain:

$$L_{HTS}\frac{dI_\theta}{dt}+R_\theta I_\theta = R_R I_R \tag{1}$$

From the HTS index model [18], R_θ may be expressed:

$$R_\theta = \frac{V_c}{I_\theta}\left\{\frac{I_\theta}{I_c}\right\}^n \tag{2}$$

where, I_c is a coil critical current and V_c is the corresponding coil critical voltage, typically obtained by the coil conductor length (l_{coil}) multiplied by either 0.1 μV/cm or 1 μV/cm. From the Kirchhoff's current law, one may also obtain:

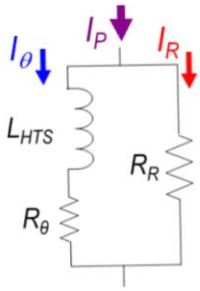

Fig. 3. Equivalent circuit model for an NI HTS coil [1].

$$I_\theta + I_R = I_P \tag{3}$$

3.2. Charging Analysis of an NI Coil with a Constant Ramping Rate

With a constant ramping rate of α, $I_P = \alpha t$ and (1) becomes:

$$L_{HTS}\frac{dI_\theta}{dt} + (R_\theta + R_R)I_\theta = R_R\alpha t \tag{4}$$

In most cases, $R_R \gg R_\theta$ especially $I_\theta < I_c$. Then, (4) may be simplified to:

$$L_{HTS}\frac{dI_\theta}{dt} + R_\theta I_\theta = R_R\alpha t \tag{5}$$

The solution of (5) can be obtained analytically with a boundary condition of $I_\theta|_{t=0} = 0$:

$$I_\theta(t) = \alpha\tau_c(e^{-\frac{t}{\tau_c}} - 1) + \alpha t \tag{6}$$

where, τ_c is the charging time constant defined as $\tau_c = L_{HTS}/R_R$. Here, R_R is also defined as “characteristic resistance” of an NI coil, often denoted by R_c.

3.3. Characteristic Resistance (R_c) Estimation

Though an analytic approach to estimate R_c was previously proposed [14, 19], R_c of an NI coil may be obtained more accurately from (6) and a constant ramping test, where power supply currents, $I_p(t)$ and coil center fields, $B_m(t)$ are simultaneously measured. At $t \gg \tau_c$, (6) may be simplified to:

$$I_\theta(t) \cong \alpha(t - \tau_c) = \alpha(t - L_{HTS}/R_c) \tag{7}$$

With a coil constant set to κ (unit: T/A), $I_\theta(t)$ may be expressed as:

$$I_\theta(t) = B_m(t)/\kappa \tag{8}$$

Thus, R_c may be expressed as:

$$R_c = \frac{\alpha\kappa L_{coil}}{\alpha\kappa t - B_m(t)} \tag{9}$$

To validate (9), the NI coil in Table I was charged at a constant ramping rate of 1 A/min and the results are presented in Fig. 4. At $t = 600$ s, the measured field, B_m was 42.2 mT. From (9), R_c may be calculated to be 727.0 μΩ. To validate the estimated R_c, I_θ was calculated from (5), and then the coil center fields, B_c, was calculated using κI_θ. In Fig. 4, B_c agreed well with B_m, which validates our approach to estimate R_c of the NI coil using (9).

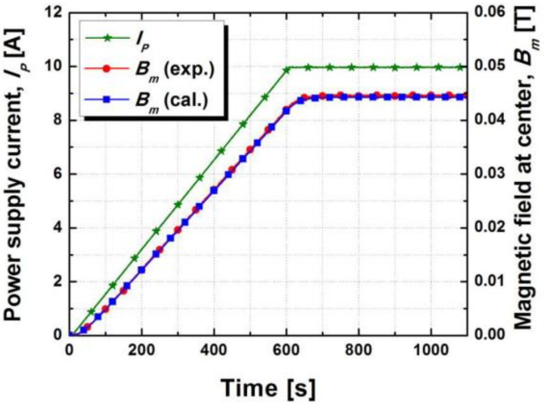

Fig. 4. I_{op} and B_z traces, experimental and analytical, of an NI DP coil at ramping rate of 1 A/min.

3.4. Leak Current Correction for Critical Current Measurement

In general, $\tau_c \ll I_c/\alpha$. Then, (6) may be simplified to:

$$I_\theta|_{t=I_c/\alpha} \cong I_P - \alpha L_{HTS}/R_c \tag{10}$$

(10) indicates that, to obtain the actual coil current of I_θ, $\alpha L_{HTS}/R_c$ should be subtracted from I_P that may be obtained from the conventional 4-probe I_c test with a given electric field criterion, typically in a range of 0.1-1 μV/cm.

Fig. 5 shows measured (blue squares) and calculated (green triangles) results for I_θ of the coil; the calculated $I_{\theta,cal}$ was obtained from (10) with R_c of 727.0 μΩ, while the measured $I_{\theta,exp}$, the actual coil current, was obtained from the measured field, B_m divided by the coil constant, κ. The saturation of $I_{\theta,exp}$ is an intrinsic NI characteristics, commonly observed in other NI coils. With a 0.1-μV/cm criterion, the power supply current (I_P), a critical current from the conventional 4-probe method, was 54.6 A. With $\alpha L_{coil}/R_c$ of 2.914 A subtracted from I_P, $I_{\theta,cal}$, I_c determined

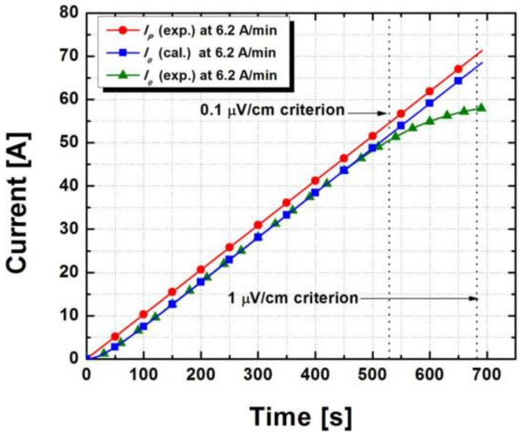

Fig. 5. Red circles: measured power supply currents (I_P); green triangles: actual coil currents (I_θ) obtained from the measured fields (B_m) divided by the coil constant κ; blue squares: calculated coil currents from (1). The ramping rate of the NI coil was 6.2 A/min.

TABLE III
SUMMARY OF CRITICAL CURRENTS: CONVENTIONAL 4-PROBE METHOD (I_P); PROPOSED NEW METHOD ($I_{\theta,cal}$); ACTUAL COIL I_c ($I_{\theta,exp}$).

Ramping rate [A/min]	**I_P [A]**	**$I_{\theta,cal}$ [A]**	**$I_{\theta,exp}$ [A]**
Voltage Criterion: 0.1 μV/cm			
2.0	52.7	51.8	50.6
6.2	54.6	51.7	50.8
9.0	56.0	51.8	50.9
Voltage Criterion: 1.0 μV/cm			
2.0	69.4	68.5	57.8
6.2	70.3	67.4	57.8
9.0	71.1	66.9	58.0

by the proposed approach, was 51.7 A, while $I_{\theta,exp}$, the actual I_c of the coil, was 50.8 A. With 1 μV/cm, I_P, $I_{\theta,cal}$, $I_{\theta,exp}$ are, respectively, 70.3, 67.4, and 57.8 A. The results are summarized in Table III together with those of the other two ramping rate cases, 2.0 and 9.0 A/min. In the table, I_P and $I_{\theta,cal}$ represent critical currents by the conventional 4-probe method and the proposed new approach, while $I_{\theta,exp}$ was the actual coil critical current.

Overall, from these results, this study suggests that, for estimating accurate I_c of an NI coil, it should be measured by the following four steps: 1) obtain R_c of an NI coil, 2) calculate the leakage current values of NI coil with various ramp rates by an equivalent circuit model to optimize charging conditions, 3) investigate the *V-I* characteristics of the NI coil under selecting condition, and 4) estimate the I_c value at 0.1-μV/cm criterion through comparing empirical and numerical analyses.

4. CONCLUSION

In this study, no-insulation (NI) double pancake (DP) coil's actual current (I_{sc}) flowing through GdBCO superconducting layer was investigated, experimentally with various charging conditions and analytically with an electric circuit model. Based on the test results, we may conclude that:

- The NI DP coil's critical current (I_c) value determined by conventional method is estimated inaccurately because its value includes current flowing through the radial direction as well as the spiral direction.
- The I_{sc} could perfectly flow through spiral direction before generated resistance of GdBCO superconducting layer, and afterward a portion of the excess current was bypassed through the turn-to-turn contacts, which consequently led to the saturation of the I_{sc}. Therefore, the 0.1-μV/cm criterion was more appropriate than 1-μV/cm criterion to determine the I_c of an NI coil in terms of the error by the I_{sc} saturation and heat generation due to the bypassing current.
- The I_{sc} also flows constantly below the 0.1-μV/cm criterion regardless of ramp rate because the current (I_r) flowing through radial directions almost increases with increasing ramp rate. This increased I_r with increasing ramp rate is well explained by a proposed equivalent circuit model.

Using the proposed approach based on an equivalent circuit model, I_{sc} and I_r flows of NI coil with various ramp rates could be quantitatively estimated, which enables obtaining reasonably I_c value of an NI coil to be utilized in practical superconducting magnet applications.

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