Current Behaviors of NI REBCO Pancake Coil Wound with Multi-Bundled Conductors During Charging and Against Local Normal-State Transition

Kazuma Kodaka and So Noguchi

Abstract—**No-insulation (NI) Rare-Earth Barium Copper Oxide (REBCO) pancake coils can generate high magnetic fields and have the high thermal stability against normal-state transition due to allowing currents to radially bypass a local normal-state region through the turn-to-turn contacts. Despite these merits, no turn-to-turn insulation causes a charging delay. To solve this charging delay problem, an NI REBCO coil wound with multi-bundled (MB) conductors was proposed. As an experimental result, a charging delay was improved because the inductance per tape of MB coil is smaller than that of single-tape NI coil. Meanwhile, the current behaviors of MB coils are complicated and has not been clarified. We have investigated the current and thermal behaviors of MB REBCO coils during charging and against normal-state transition, comparing with and without turn-to-turn insulation. As the result, it is shown that the MB coil can be operated stably, and no pessimistic temperature rise is observed. However, the operating current of MB coils with turn-to-turn insulation may concentrate on one tape when the normal-state transition occurs. Therefore, MB coils without turn-to-turn insulation seems to be desirable.**

Index Terms—**Charging delay, high magnetic field generation, multi-bundled REBCO tape, no-insulation winding technique.**

I. Introduction

In recent years, higher magnetic fields are required for higher performance in various fields: medicine (magnetic resonance imaging; MRI) [1]–[3], pharmacy (nuclear magnetic resonance; NMR) [5], particle accelerators [5], [6], and fusion devises [7], [8]. In 2019, it was reported that an insert magnet called "LBC3" wound with Rare-Earth Barium Copper Oxide (REBCO) coated conductor (CC) generated 14.4 T inside a 31.1-T resistive background magnet [9]. However, this world record is smaller than an expected potential of REBCO CCs.

The LBC3 has no turn-to-turn insulation using a no-insulation (NI) winding technique proposed by Hahn, *et al.* [10], [11]. It enables to drastically enhance the thermal stability of REBCO pancake coils. When a local normal-state transition occurs in an NI REBCO pancake coil, the current bypasses the normal-state region through the turn-to-turn contacts. The NI winding technique makes REBCO magnets compact and increases the engineering current density. From these advantages, NI REBCO pancake coils are promising for practical ultra-high magnetic field (> 30 T) applications.

One issue on NI REBCO pancake coils is a charging delay due to no turn-to-turn insulation [12], [13]. To overcome this issue, the multi-bundled (MB) REBCO CC winding technique without insulation between bundled CCs was proposed [14]. It was reported that the charging delay was improved in experiments. This is because the inductance per one tape of MB coils is smaller than that of conventional NI coils wound with single tape. Furthermore, MB REBCO coils are expected to have high engineering current density since they are thermally stable by sharing an operating current with not-normal-state-transitioned bundled tapes when a local normal-state transition occurs on one REBCO CC. Meanwhile, the current behavior of MB REBCO coils is complicated, and it has not been clarified yet. It is pointed out that an operating current may not be evenly distributed in each tape due to their different inductances. The thermal stability against normal-state transition must be clarified. We have investigated the current and thermal behaviors of MB REBCO coils during coil excitation and against normal-state transition by numerical simulation. Furthermore, two cases of MB REBCO coils with and without turn-to-turn insulation are compared and their stability is discussed.

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II. Simulation Method and Models

A. Current Simulation

We adopt the Partial Element Equivalent Circuit (PEEC) method [12] to obtain the detailed current distribution of MB REBCO coils. The PEEC method has been shown to be effective in many NI REBCO pancake coil studies, e.g. [12], [15], and [16], even for bundled conductors [17]. Since an MB REBCO coil is modeled by dividing it in the circumferential and radial directions in the PEEC method, it is possible to observe the local phenomena inside the coil. Fig. 1 shows the equivalent circuit of applying the PEEC method to a pancake coil wound with three-bundled REBCO CCs. The circuit equations constructed from this model by Kirchhoff's first and second laws are as follows:

$$I_{sc}^{i} + I_{st}^{i} + I_{r}^{i} = I_{sc}^{i-n} + I_{st}^{i-n} + I_{r}^{i-1} \quad (1)$$

$$R_{st}^{i} I_{st}^{i} - R_{sc}^{i} I_{sc}^{i} = 0 \quad (2)$$

$$\sum_{j=1}^{N} M_{i,j} \frac{dI_{sc}^{j} + I_{st}^{j}}{dt} + R_{st}^{i} I_{st}^{i} + R_{r}^{i+k} I_{r}^{i+k} = \sum_{j=1}^{N} M_{i+1,j} \frac{dI_{sc}^{j} + I_{st}^{j}}{dt} + R_{st}^{i+1} I_{st}^{i+1} + R_{r}^{i} I_{r}^{i} \quad (3)$$

where i and j are indices of the local winding elements from 1 to N (N is the total number of elements). k is the number of bundled REBCO CCs. $M_{i,j}$ is the inductance between the elements i and j. I_{sc}, I_{st}, and I_r are the currents in REBCO layer, copper matrix, and radially through the CC-to-CC contact, respectively. R_{sc}, R_{st}, R_r are the electrical resistances of each element in REBCO layer, copper matrix, and CC-to-CC (R_{r1} and R_{r2} in Fig. 1) or turn-to-turn contact resistance (R_{r3} in Fig. 1), respectively. The REBCO layer resistance R_{sc} is approximated with the n-index model based on *I-V* characteristics [18]. Since the n-index model involves a strong nonlinearity, the Newton-Raphson method is employed as a non-linear solver. The turn-to-turn contact resistance R_{r3} changes to investigate the thermal stability at a normal-state transition.

B. Thermal Analysis

To investigate the detailed stability behaviors of MB REBCO coils, a thermal analysis is required. From the current distribution obtained with the PEEC method, the amount of heat generation at each element of electrical resistances can be calculated as an input of thermal analysis. The temperature distribution of MB REBCO coils is computed with a finite element method (FEM) [19]. The governing equation is

$$w\rho c \iint \frac{\partial T}{\partial t} r dr d\theta = w \iint \left(\lambda_r \frac{\partial^2 T}{\partial r^2} + \lambda_\theta \frac{\partial^2 T}{\partial \theta^2} \right) r dr d\theta + Q \quad (4)$$

where w, ρ, c, T, and Q are the REBCO tape width, the mass density, the specific heat, the temperature, and the heat generation per volume, respectively. λ_θ, λ_r, are the thermal conductivity in the radial and circumferential directions, respectively. In this study, the initial coil temperature is 20 K and it is assumed to be adiabatic to investigate the thermal stability at the worst scenario.

C. Simulation Models

Table I lists the parameters of simulation models. We examined 2 cases of MB REBCO pancake coils: (1) MB-NI coil which is wound with 3-bundled tapes without turn-to-turn insulation and (2) MB-INS coil which has a turn-to-turn insulation although there is no insulation between bundled tapes. A

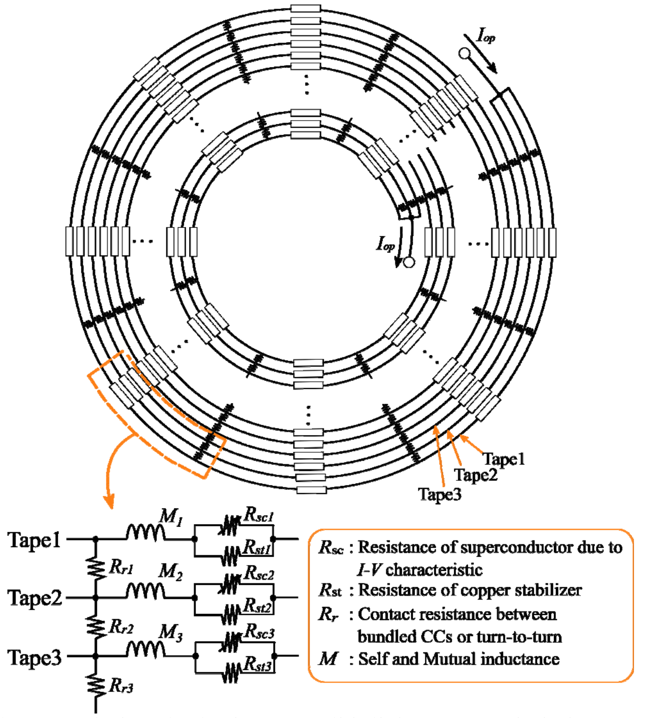

Fig. 1. Equivalent circuit of an MB coil built by PEEC method (three tapes bundled). R_{r1} and R_{r2} are the contact resistance between bundled tapes, and R_{r3} is the contact resistance between turns.

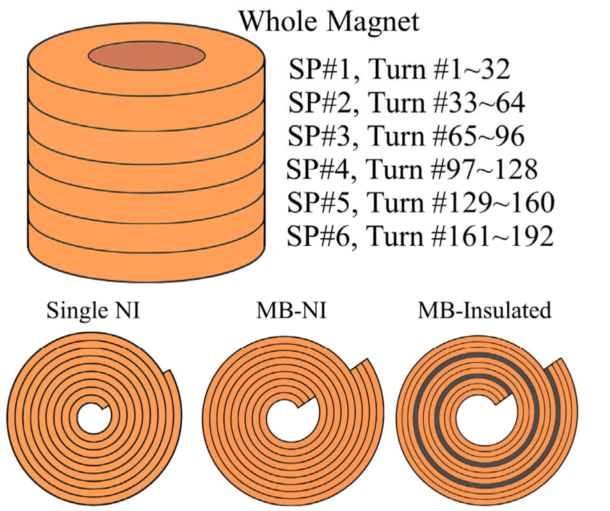

Fig. 2. Schematic drawings of simulation model. The turn numbers are serially assigned in order from SP #1 to #6.

conventional NI REBCO pancake coil wound with single tape, named Single-NI coil in this paper, is also examined for comparison. Fig. 2 shows all the examined pancake coils. All these coils are supposed to be wound with SuperPower 2G-HTS tapes. The contact resistivities between bundled tapes and between turns in the case of MB-NI are supposed to be 70 μΩ·cm² based on an experiment result [20]. In this paper, each bundled tape is numbered Tapes 1, 2, and 3 in order from the outside of the MB pancake coils. The magnet consists of 6-stacked single pancake coil, as shown in Fig. 2.

TABLE I
PARAMETERS OF SIMULATION MODELS

Parameters / Coil models	Single-NI	MB-NI	MB-INS
REBCO Tape			
Tape width [mm]		4.0	
REBCO tape thickness [mm]		0.1	
Copper matrix thickness [μm]		20.0	
REBCO layer thickness [μm]		2.0	
I_c @ 77 K, self-field [A]		120.0	
Single Pancake Coil			
Coil i.d; o.d [mm]	120.0; 139.2	120.0; 139.2	120.0; 141.1
Number of bundled tapes	1	3	3
Number of turns	96	32	32
Contact resistivity (tape-to-tape) [μΩ • cm^2]	-	70.0	70.0
Contact resistivity (turn-to-turn) [μΩ • cm^2]	70.0	70.0	Infinity
Magnet			
Number of single pancakes		6	
Coil height [mm]		29.0	
Coil Inductance [mH]		56.36	

TABLE II
SIMULATION CONDITIONS OF CHARGING COILS

Coil models	Single-NI	MB-NI, MB-INS
Outsert magnetic field [T]	14.0	
Operating temperature [K]	20.0	
Operating Current [A]	0 to 200	0 to 600
Charging speed [A/s]	1.0	3.0

III. CHARGING SIMULATION

As a previous study showed [13], during charging a Single-NI coil, a portion of operating current flows in the radial direction. It is the cause of the charging delay. Whereas MB coils are expected to improve the charging delay, the operating current may not evenly be distributed in each tape. To investigate the current distribution, MB coils are charged with the operating current with 1 A/s ramp rate per tape and stays for 50 s after reaching 200 A in Single-NI coil and 600 A in MB coils. Table II lists the simulation conditions.

Fig. 3 shows the current and center magnetic field with time. Consistently with the previous experimental results, the simulation results shows that the MB coils, MB-NI and MB-INS, have a good excitation characteristic without charging delay. Fig. 4 shows the time-transient current distribution of MB-NI and MB-INS, where the turn numbers are serially counted from SP #1 to #6 as shown in Fig. 2, and they are numbered from the outside to the inside of each pancake coil. Some current differences between bundled tapes can be seen in both MB coils. It happens so as to take the voltage balance between the ends of the REBCO tapes. Since the current difference is only ~20 A at largest in the MB-NI coil, it is not expected to have a significant impact on the operating condition of MB coils. These differences disappear immediately after the excitation. Fig. 5 shows the temperature distributions at the end of excitation. The temperature rise can be observed in the case of

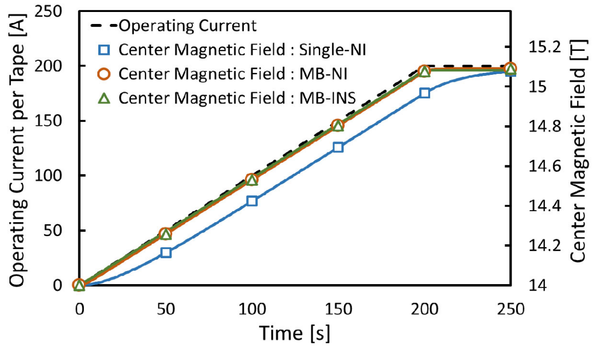

Fig. 3. Time variation of the operating current and magnetic fields during charging Single-NI, MB-NI, and MB-INS coils.

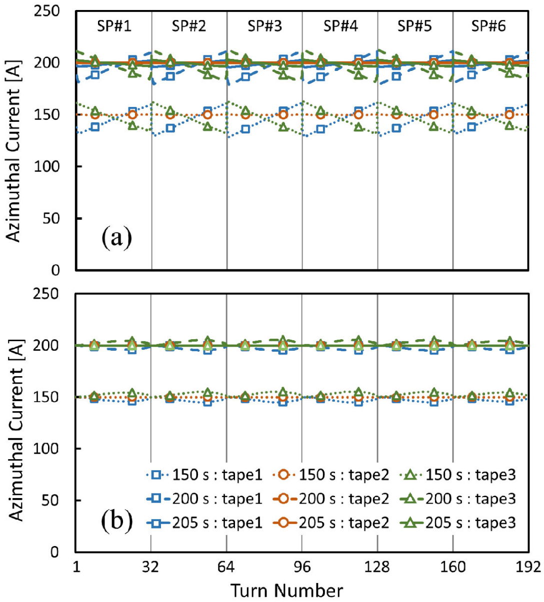

Fig. 4. Current distribution during charging MB coils: (a) MB-NI and (b) MB-INS, at 150, 200, and 205 s.

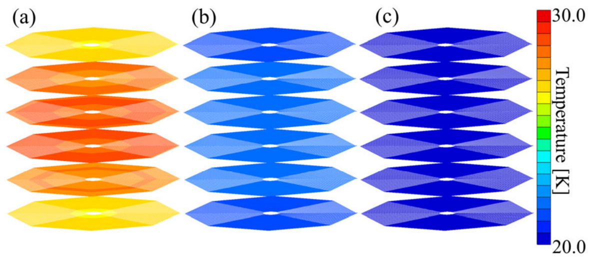

Fig. 5. Temperature distributions at 200 s: (a) Single-NI, (b) MB-NI, and (c) MB-INS.

Single-NI, and a little heat generation in both MB coils. Consequently, the MB-NI and MB-INS coils are effective for improvement of the charging delay and the thermal stability.

IV. NORMAL-STATE TRANSITION SIMULATION

A. Simulation Conditions

In REBCO CCs, a local normal-state transition may happen due to local critical current (I_c) deterioration caused by defects. It is well known that Single-NI coils have high thermal stabil-

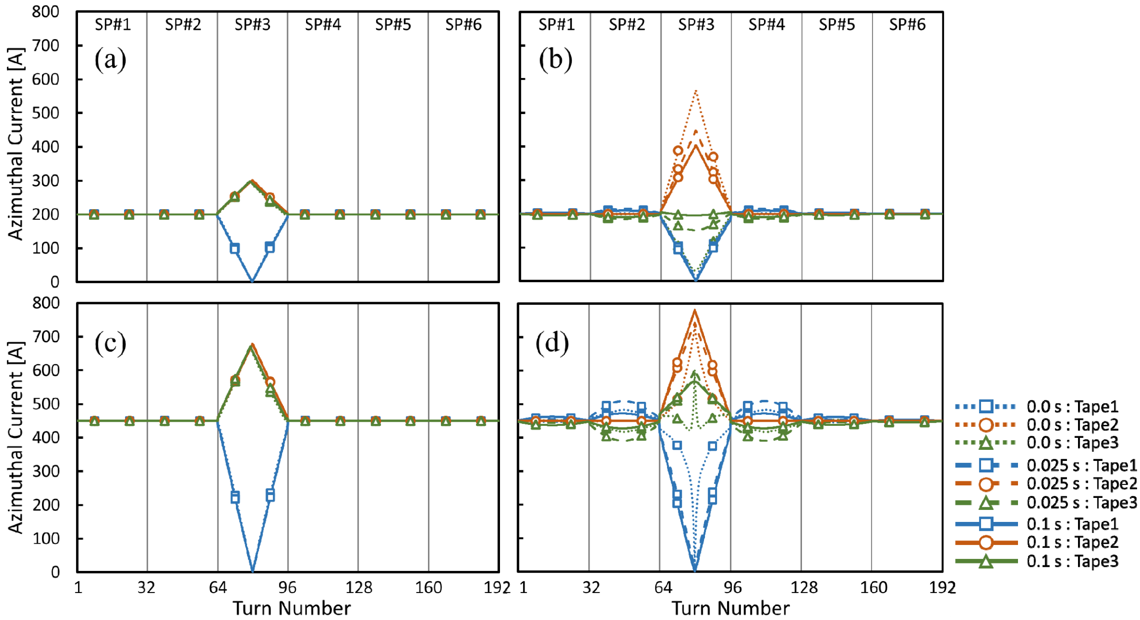

Fig. 6. Time variation of the current distribution against normal-state transition, (a) MB-NI in case A, (b) MB-INS in case A, (c) MB-NI in case B, (d) MB-INS in case B.

ity against normal-state transition by bypassing the normal-state region through turn-to-turn contacts. Meanwhile, the thermal stability of MB coils has not been reported. Therefore 2 different MB coils, MB-NI and MB-INS, are simulated at different operating currents of 600 A (case A) and 1350 A (case B). Here, 1350 A is too large for current leads and power supplies, but such a large value is tested to show a high thermal stability of coil itself. One element in mid-turn of outer tape (Tape 1) of SP #3 is transitioned into the normal state at $t = 0$ s in the simulation. The operating current is constant even after the local normal-state transition. Table III lists the simulation conditions.

B. Simulation Results

Fig. 6 shows the current distributions of MB-NI and MB-INS in the cases A and B. In case A of the MB-NI coil, the current of Tape 1 is almost evenly transferred to the other Tapes 2 and 3 to avoid the normal-state region immediately after the local normal-state transition occurs. Meanwhile, the transferred current concentrates on Tape 2 in the MB-INS coil. The turn-to-turn insulation prevents the current in Tape 1 from directly passing through to Tape 3. Then, as the current of Tape 1 flows to Tape 2, the current of Tape 3 is also transferred to Tape 2 due to the strong mutual inductance. Hence, in the MB-INS coil, most of the operating current is temporarily carried on Tape 2 after the appearance of a local normal-state transition.

In case B of the MB-NI coil, the current is almost evenly distributed like case A. In the MB-INS coil, the current is also concentrated in Tape 2, and the current in Tape 3 also increases around the normal-state region. The reason is probably to avoid the current of Tape 2 from exceeding the critical current (approximately 785 A around the normal-state region in SP#3). In addition, no rapid temperature rise is observed in all cases.

TABLE III
SIMULATION CONDITION OF NORMAL-STATE TRANSITION SIMULATION

Simulation cases	Case A	Case B
External magnetic field [T]	14.0	
Operating temperature [K]	20.0	
Operating Current [A]	600	1350

From these results, we can conclude that MB coils have a high thermal stability against a local normal-state transition, like a Single-NI coil. MB-INS coils may concentrate most of the operating current on one tape, and no unbalanced current occurs in MB-NI coils.

V. CONCLUSION

In this study, we investigated the current and temperature distributions of multi-bundled (MB) REBCO coated conductor (CC) winding coils by numerical simulation using the partial element equivalent circuit (PEEC) method and the thermal finite element method (FEM). We also investigated the effect of the different structure of the MB coil with and without turn-to-turn insulation. The findings from the simulations are summarized as follows:

- Multi-bundled REBCO CCs are effective for improving excitation characteristics.
- There is a small current difference between the bundled tapes during charging MB coils.
- When a local normal-state transition occurs, the operating current is almost evenly distributed in MB-NI coil, while it is concentrated on one tape in MB-INS coil.
- MB-NI and MB-INS coils have high thermal stability during charging and against local normal-state transition.

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