# Current Behaviors Of NI REBCO Coil Wound With Multi-Bundled Conductors During Charging And Normal-State Transition

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## 1. Introduction

No-insulation (NI) REBCO pancake coils can generate high magnetic fields and have the high thermal stability against normal-state transition. Despite these merits, no turn-to-turn insulation causes a charging delay. To solve this problem, an NI REBCO coil wound with multi-bundled (MB) conductors was proposed. As an experimental results, a charging delay was improved because the inductance per tape of MB-NI coil is smaller than that of single-tape NI coil. However, the current behaviors of MB-NI coils are complicated and has not been clarified. Also, the thermal stability against normal-state transition is unknown. In this study, we investigated the current behaviors and thermal distribution of MB-NI coils during charging and normal-state transition.

## 2. Simulation Method

For the current analysis, a Partial Element Equivalent Circuit (PEEC) method is used to obtain the detailed current distribution. The equivalent circuits are built by dividing the MB-NI coil in the circumferential and radial directions. The electrical resistance of the REBCO layer is approximated with the n-index model which has strong nonlinearity. For the thermal analysis, the Finite Element Method (FEM) is employed. The heat generation in each component is computed from the obtained current distribution, and the thermal distribution is calculated with FEM. The governing equation is shown in equation (1), where ρ, c, T, t, λ, and Q are the specific heat, the mass density, the temperature, the time, the thermal conductivity, and the heating per volume, respectively.

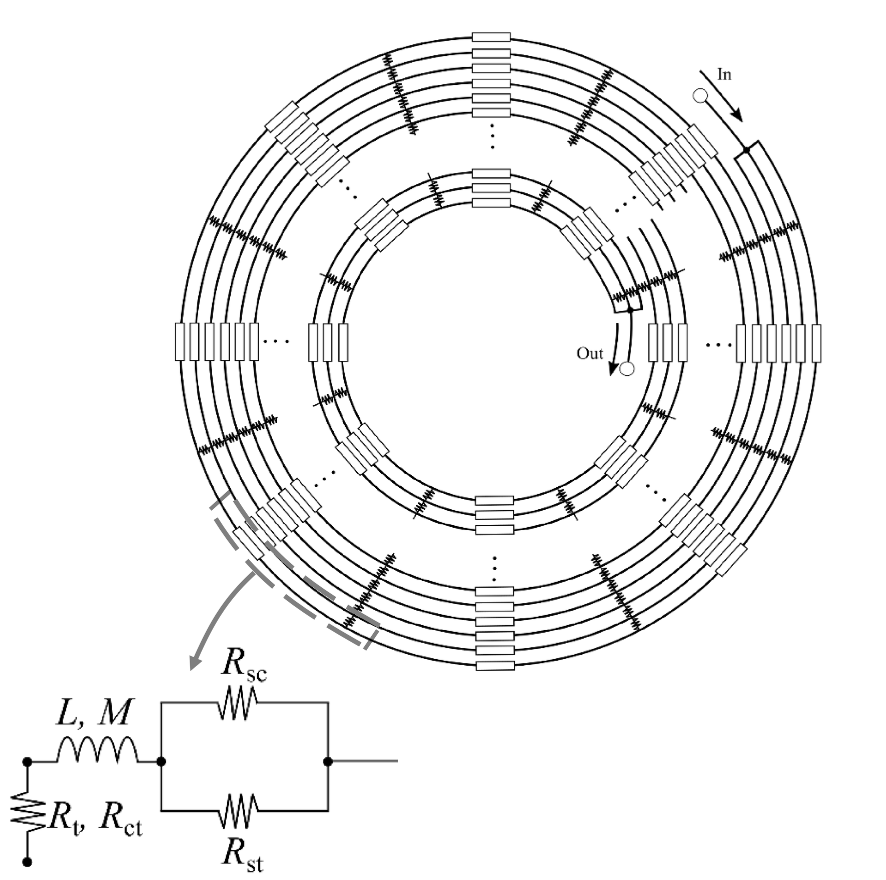


Fig. 1. The PEEC model extended to a MB NI coil

Governing Equation in FEM

$$\rho c \frac{\partial T}{\partial t} = \lambda \Delta T + Q \qquad (1)$$

## 3. Simulation Model

The parameters of simulated models are listed in Table 1. In this study, we examined 3 cases of REBCO pancake coils. All the coils are supposed to be wound with the SuperPower 2G-HTS tape wires. The Single-NI coil is the conventional NI REBCO coil wound with single-tape. The MB-NI coil is wound with 3-bundled tapes without turn-to-turn insulation. The MB-Insulated coil has a turn-to-turn insulation (with no-insulation between bundled tapes). Here, each bundled tape is called Tape 1, 2, and 3 from outside of the coil.

TABLE I
PARAMETERS OF SIMULATED MODELS

| Parameters | Values | | |
|---|---|---|---|
| Coil models | Single-NI | MB-NI | MB-Insulated |
| REBCO tape | | | |
| Tape width[mm] | | 4.0 | |
| REBCO tape Thickness [mm] | | 0.1 | |
| Copper stabilizer thickness [μm] | | 20.0 | |
| REBCO layer thickness [μm] | | 2.0 | |
| Ic @ 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, 141.12 |
| Number of tapes | 1 | 3 | 3 |
| Number of turns | 69 | 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 | Insulation |
| Magnet | | | |
| Number of double pancakes | | 3 | |
| coil height [mm] | | 29.0 | |
| Inductance [mH] | 56.36 | 56.36 | 56.36 |

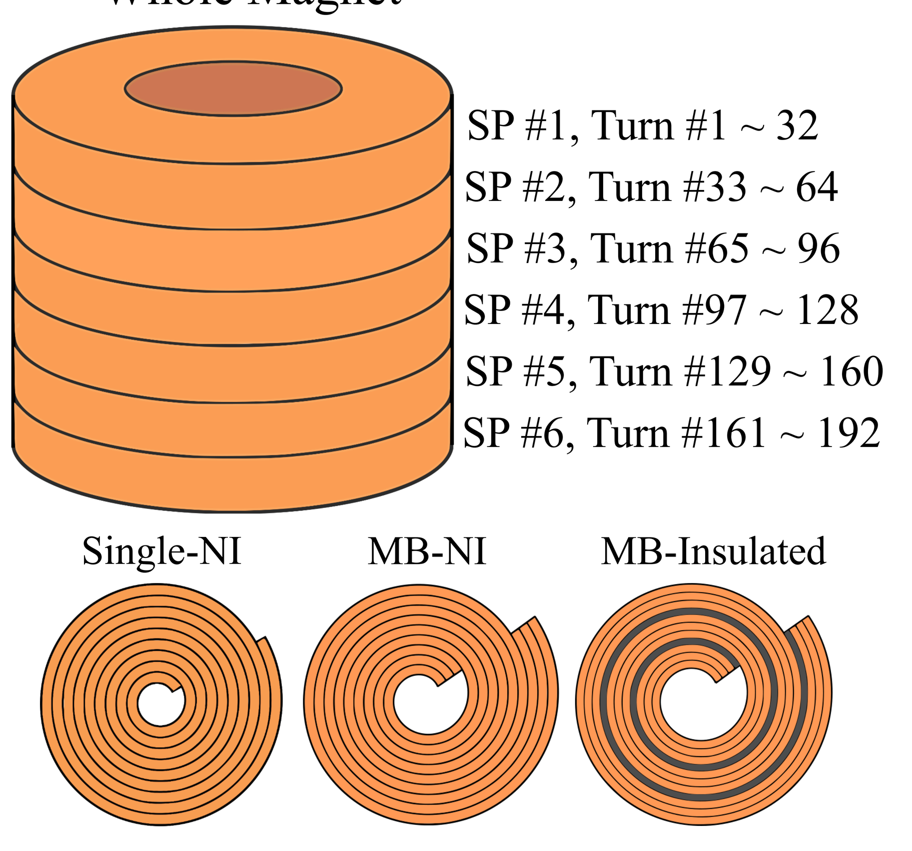


Fig. 2. Schematic drawings of simulation model.

## 4. Charging Simulation

As a previous study shows, during charging a Single-NI coil, the circumferential current of Single-NI coils is suppressed due to a large inductance, and the part of operating current flows in the radial direction. It is a 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 during charging MB coils, we simulated that the operating current increases with 1 A/s and stays for 50 s after reaching 200 A per tape. These results show that MB-NI and MB-Insulated coils are effective for improve charging delay and able to increase operating current stably.

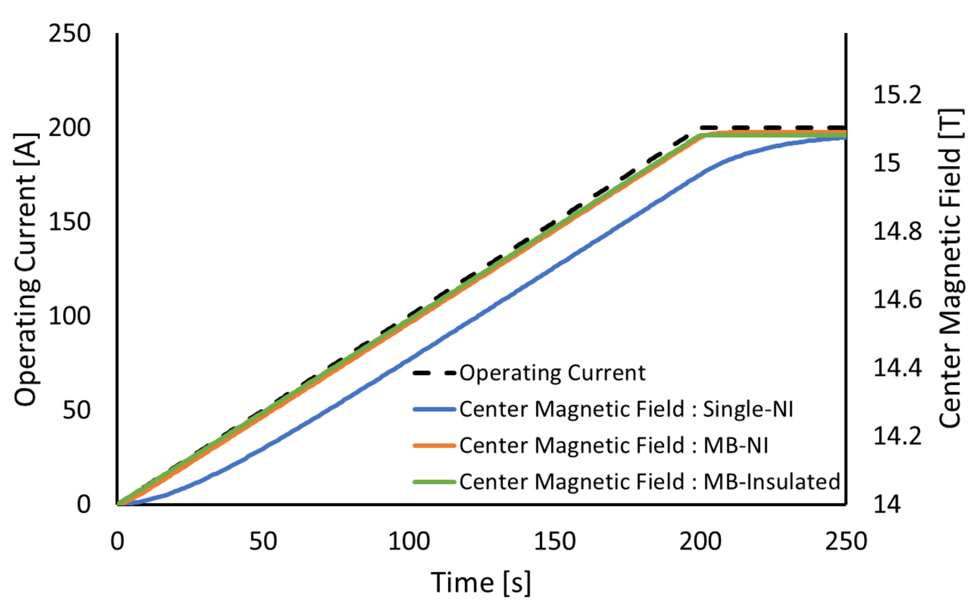


Fig. 3. Time variation of the operating current and magnetic field during charging coils.

- MB coils has good excitation characteristics as previous experimental results

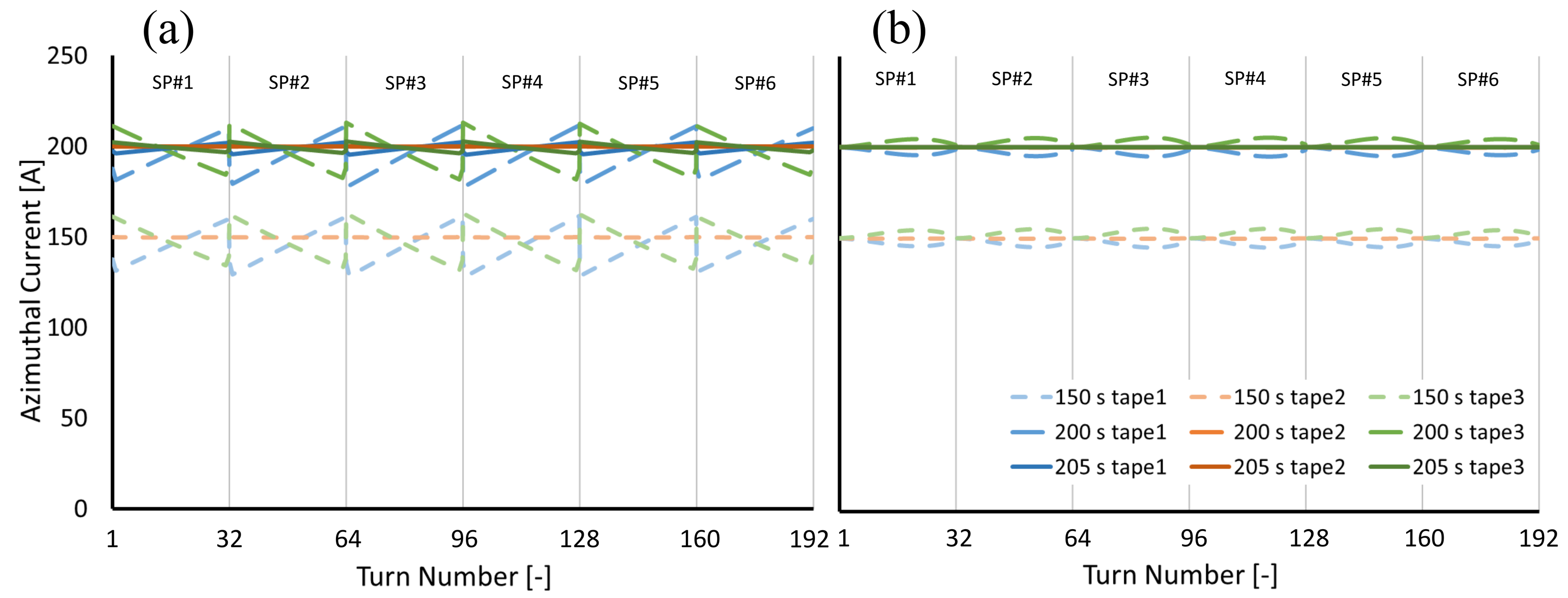


Fig. 4. Time variation of the current distribution during charging coils. (a) MB-NI, (b) MB-Insulated

- Some current differences were observed between bundled tapes in both coils to take the induced voltage balance at end to end of the tapes.
- These differences are disappeared rapidly, and little heat generation was observed after the end of excitation.

TABLE II
SIMULATION CONDITIONS OF CHARGING COILS

| Parameters | Values | |
|---|---|---|
| Coil models | Single-NI | MB-NI, Insulated |
| Simulation Condition | | |
| Time step [s] | 1.0 | |
| Simulation time [s] | 250.0 | |
| Outserted 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 |

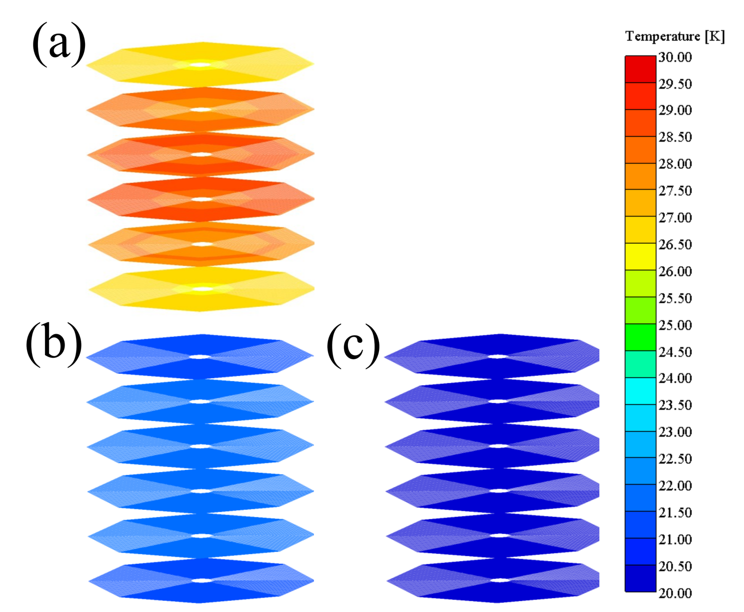


Fig. 5. Thermal distribution at 200 s
(a) Single-NI, (b) MB-NI, (c) MB-Insulated

## 5. Normal-State Transition Simulation

In REBCO tapes, a part of the tape may turn a normal-state transition due to local *Ic* deterioration caused by defects. The Single-NI coil was reported that it had the high thermal stability against normal-state transition. Meanwhile, the thermal stability of MB coils have not been clarified. We conducted 2 cases of simulation. The operating current is 600 A in case A, and 1350 A in case B. One element in mid-turn of outer tape (Tape 1) of SP #3 is transitioned into the normal-state at 0 s. The operating current is unchanged after transition. The simulation results show that MB-NI and MB-Insulated coils have high thermal stability against normal-state transition.

TABLE III
SIMULATION CONDITIONS OF NORMAL-STATE TRANSITION TEST

| Parameters | Values |
|---|---|
| Coil models | MB-NI, Insulated |
| Simulation Condition | |
| Time step [s] | 0.001 |
| Simulation time [s] | 0.2 |
| Outserted Magnetic Field [T] | 14.0 |
| Operating temperature [K] | 20.0 |
| Operating current [A] | 1350 |

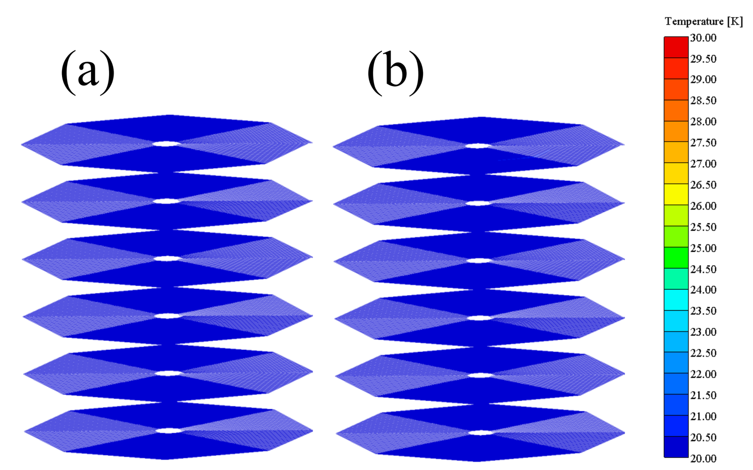


Fig. 7. Thermal distribution in case B at 0.1 s
(a) MB-NI, (b) MB-Insulated

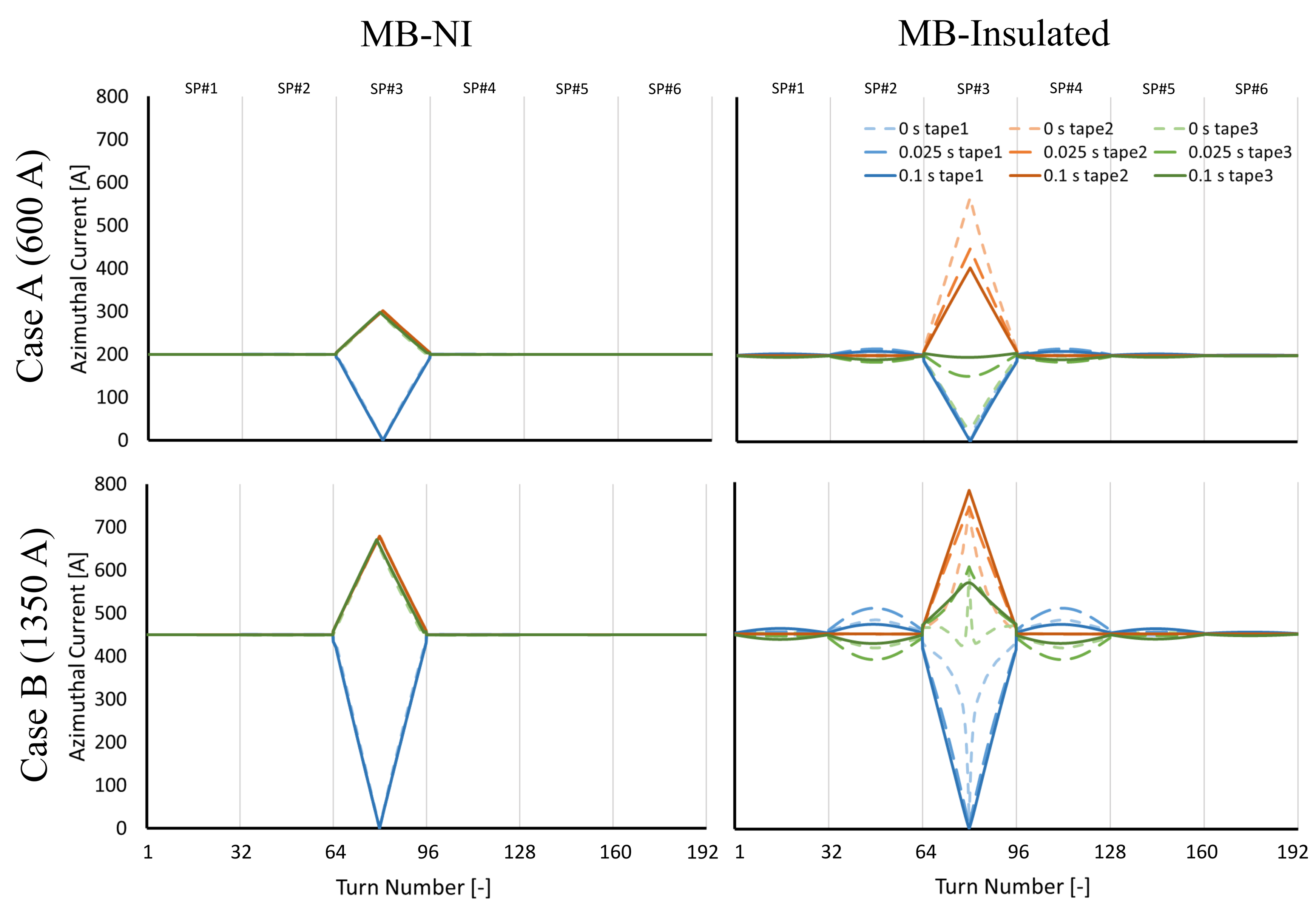


Fig. 6. Time variation of the current distribution against normal-state transition.

- In both cases, the current of MB-NI coils at the normal-state region in Tape 1 is transferred to the other tapes almost evenly.
- The operating current of MB-Insulated coils concentrated on Tape 2 due to the strong influence of inductance. And the current of Tape 3 increased to avoid the current of Tape 2 reaching critical current in case B.
- No rapidly temperature rise was observed in all cases.

## 6. Conclusion

- We investigated the current and thermal behavior of MB coils by numerical simulations using PEEC and FEM
- When the normal-state transition occurs, the operating current is almost evenly distributed in MB-NI coil and concentrated on one tape in MB-Insulated.
- MB-NI and MB-Insulated coils have high thermal stability during charging and against normal-state transition.
- Investigation of the optimal number of bundled tapes will be our future work.