Mechanical Damage Protection Method by Reducing Induced Current in NI REBCO Pancake Coils During Quench Propagation

Takanobu Mato, Seungyong Hahn, and So Noguchi

Abstract—**The no-insulation (NI) winding technique has been attracting attention, because NI Rare-Earth Barium Copper Oxide (REBCO) pancake coils have high thermal stability. It is an indispensable technology to generate an ultra-high magnetic field. In 2017, using the NI winding technique a world-record high magnetic field, 45.5 T, was generated by 12 insert single pancake coils with an outsert magnet, and it showed a high potential to generate 14.4 T inside a background field of 31.1 T. After the experiment, the REBCO tapes were mechanically damaged, so that the critical currents were deteriorated. A large current was induced in NI REBCO coils next to the quenched coil when one of multi-stacked NI REBCO pancake coils quenched, resulting in tape property degradation and irreversible mechanical damage. Therefore, in order to protect NI REBCO pancake coils during quench, it is desired to reduce the amount of induced current.**

To suppress an induced current, the idea of "magnetic dam" has been proposed previously. The idea is to use a copper pipe installed at the outside of NI REBCO pancake coils. However, the copper pipe just slowed the quench propagation. In this paper, we extended the method to decrease an induced current much more by installing extra NI REBCO windings instead of the copper pipe. The electromagnetic and stress behaviors of 6-stacked NI REBCO coils with extra windings are simulated when one of the stacked NI REBCO coils transitions into a normal state. The ability of mechanical damage protection from a strong stress by an induced current during quench propagation is demonstrated through simulations.

Index Terms—**magnetic dam, no-insulation technique, mechanical damage protection.**

I. Introduction

IN 2011, Hahn, *et al.* proposed the no-insulation (NI) winding technique, which has demonstrated the high thermal stability of a Rare-Earth Barium Copper Oxide (REBCO) single pancake coil through an overcurrent test [1]. When a local hot spot occurs in an NI REBCO pancake coil, the coil operating current bypasses into adjacent turns directly through turn-to-turn contact surfaces, known as a "survived" function [2]–[4]. The NI winding technique is promising for high magnetic field (> 10 T) applications, such as Nuclear Magnetic Resonance (NMR) [5], Magnetic Resonance Imaging (MRI) [6]-[8], and particle acceleration devices [9]-[11].

In 2019, it was reported that an insert NI REBCO magnet, called "LBC3," generated 14.4 T under a background field of 31.1 T generated by a resistive copper magnet [12]. After the 14.4-T generation, the mechanical damage and critical current degradation of REBCO tapes were observed. Large currents were induced in NI REBCO coils next to the quenched coil when one of 12-stacked NI REBCO pancake coils was transitioned into a normal state. Due to large induced currents, large stress is applied to the REBCO tapes, which resulted in tape property degradation and irreversible mechanical damage [13]. Hence, it is desired to reduce the amount of induced currents in NI REBCO pancake coils during quench propagation.

To decrease an induced current during quench propagation, an idea of "magnetic dam" has been proposed [14]-[16]. A copper pipe was placed surrounding NI REBCO pancake coils so that the copper pipe consumed the magnetic energy of quenched NI REBCO pancake coils by an induced current flowing in resistive copper. Although the magnetic dam just slowed the quench propagation velocity due to the large copper resistance, the induced currents could not sufficiently be absorbed. As a new "magnetic dam" concept to decrease the induced current much more, we substitute the copper pipe for extra NI REBCO windings. Extra NI REBCO windings are placed inside and outside main NI REBCO pancake coils. They are electrically isolated from the main coils, i.e., they are not charged. When one of the main pancake coils quenches, a current is not largely induced in the main coils, but in the extra windings. To confirm the validity of mechanical damage protection by the newly proposed magnetic dam, we simulated the behaviors of main NI REBCO pancake coils with extra NI windings with an equivalent circuit model and thermal finite element analysis (FEA). In this paper, the detailed mechanism of quench protection and the simulation results are presented.

II. New Magnetic Dam and Simulation Model

Fig. 1 shows the schematic view of the newly proposed magnetic dam. Extra windings which has a few turns with no-insulation technique are installed inside/outside every main NI REBCO pancake coil with electrical insulation between each

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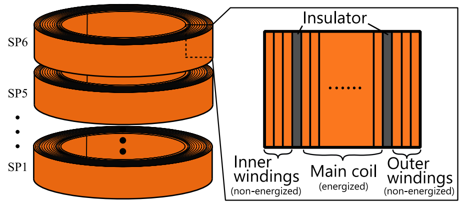

Fig. 1. Schematic view of newly proposed magnetic dam. Extra NI REBCO windings with a few turns are placed inside/outside main coils.

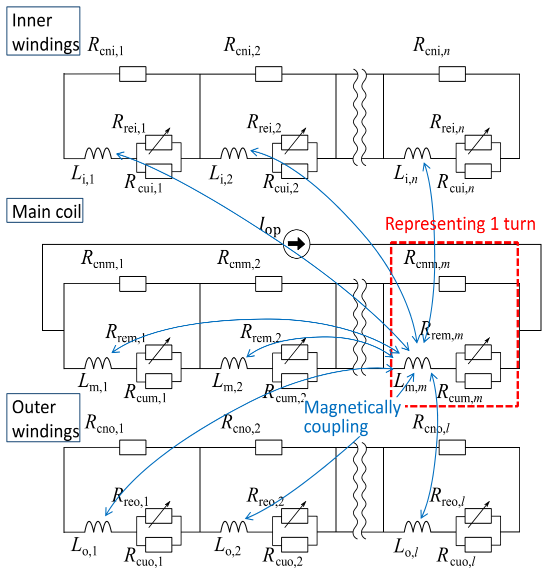

Fig. 2. Equivalent circuit model for the proposed magnetic dam. Each turn is modeled as one element circuit, and magnetically coupling with all element circuits.

TABLE I
PARAMETERS OF PANCAKE COILS AND REBCO TAPE

Number of SPs	6
Main coil i.d.; o.d. (mm)	79; 89
Coil height (mm)	29
Number of turns of main coils	50×6
Number of turns of inner winding turns	5×6
Number of turns of outer winding turns	5×6
Turn-to-turn contact resistivity (μΩ·cm^2)	70
Operating current (A)	500
Operating temperature (K)	10
Space between each pancake (mm)	1
Space between extra windings and main coil (μm)	10
Tape width (mm)	4.0
Tape thickness (μm)	96
Copper matrix thickness (μm) (each side)	20
Hastelloy thickness (μm)	55
REBCO thickness (μm)	1.0
Critical current at 77K, s.f. (A)	120
n value	25

windings and main coils. In this paper, we investigated the effectiveness of inner and/or outer extra windings of 5 turns on the stress reduction of main NI REBCO coils during quench propagation from the viewpoint of mechanical damage protection. The extra windings are electrically insulated from the main coils; however, they are magnetically coupling with the main coils. Hence, a large current can be induced in the extra windings; eventually, it is possible to protect the main coils from a large stress generated by induced current. Although the extra windings are not directly energized, the current is induced in them while charging the main coils. There is a possibility the induced current results in a charging delay. A charging delay must be also investigated.

Fig. 2 shows the equivalent electric circuit of proposed magnetic dam. Each turn is modeled as one element circuit [13], which is composed of the self and mutual inductances L, the equivalent REBCO layer resistance $R_{\rm re}$ the copper matrix resistance $R_{\rm cu}$, and the turn-to-turn contact resistance $R_{\rm cn}$. Here, $R_{\rm re}$ is obtained according to the index power model [17]. $R_{\rm cu}$ is computed using the copper resistivity shown in [18]. $R_{\rm cn}$ on the contact surface per one turn is derived from [13]

$$R_{\rm cn} = \rho_{\rm cn}/S \qquad (1)$$

where$\rho_{\rm cn}$ and S are the contact resistivity and the turn-to-turn contact surface on one turn, respectively.

By connecting all the element circuits of the main coils in series to the current source, we can obtain the entire equivalent circuit for the main coil. For the inner and outer extra windings, the equivalent circuits are not connected to the current source, as shown in Fig. 2. The inner and outer extra windings magnetically couple with the main NI REBCO coils. When one of main NI REBCO pancake coils is quenched, it immediately loses an azimuthal current generating an axial field, and then most of the induced current flows in the extra windings to compensate the axial field.

The electromagnetic analysis is conducted by solving the system of equations derived from the above-mentioned equivalent circuit using an in-house code. For the thermal analysis, the following thermal diffusion equation is solved with finite element method:

$$2\pi w\lambda \int_{r_{\rm in}}^{r_{\rm out}} r\frac{{\rm d}^2 T}{{\rm d}r^2}{\rm d}r + Q = 2\pi w\rho c\int_{r_{\rm in}}^{r_{\rm out}} r\frac{{\rm d}T}{{\rm d}t}{\rm d}r \qquad (2)$$

where w, λ, T, Q, ρ, and c is the REBCO tape width, the thermal conductivity, the temperature, the heat generation, the mass density, and the specific heat, respectively. The thermal properties are referred in [18] and [19], and their thermal dependencies are considered. Thermal resistance of contact surface is also considered [20]. The temperature is assumed to be uniform within each turn. The heat generation is obtained as the Joule heat generated on all the resistance component of PEEC model [21]. Here, an adiabatic condition is also assumed within a single pancake coil.

III. SIMULATION RESULTS

A. Induced Current Reduction and Current Behavior

Table I lists the REBCO tape parameters and the specifications of the 6-stacked single pancake (SP) coils, as shown in Fig. 1. The magnet is operated at 10 K. The critical current is calculated by an approximation formula presented in [22]. The operating current $I_{\rm op}$ is 500 A, and the load factor $I_{\rm op}/I_{\rm c}$ is 91% at the innermost turn of SPs 3 and 4. In the simulation, the turn-to-turn contact resistivity is 70 μΩ·cm^2 [23]. We have investigated the induced current behaviors of each SP when SP 2 wholly transitioned into the normal state at t = 0 ms.

Fig. 3 shows the maximum azimuthal current in each single pancake coil (a) without extra windings, (b) with outer extra windings, and (c) both inner and outer extra windings. In Fig. 3(a) and (b), SP 1 quenches immediately after SP 2 quenches at $t = 0$ ms, and then SPs 3, 4, 5, and 6 quench in sequence. A large current is induced in every pancake. In case that both inner and outer extra windings are attached, the simulation results are shown in Fig. 3(c). A small amount of induced current flows in SPs 1 and 3 after SP 2 quenches because a large current is induced in the extra windings. The induced current is dramatically reduced, compared with the results of Fig. 3(a) and (b). The sequential quench is avoided.

To investigate the mechanism of induced current reduction, the transition of the azimuthal current distribution in the main SP 3 coil is shown in Fig. 4; (a) without extra windings, (b) with outer extra windings, and (c) both inner and outer extra windings. In the case of no extra windings, the large currents are induced on both the inner and outer turns of SP 3 at the beginning of the normal-state transition ($t = 1$ ms). The induced currents propagate into the middle turns with time ($t = 3 – 8$ ms). The largest current is 1329 A on the 34th turn at $t = 8.5$ ms. The entire SP 3 transitions into the normal state at $t = 14$ ms.

When extra 5-turn windings are installed only outside the main coils, at the beginning of the quench, the induced current in the outermost turns of SP 3 is absorbed with the outer extra windings of SP 2, which is magnetically coupling with SP 2 the most. Fig. 5 shows the transient current on every turn of the outer extra windings. An extremely large current is induced in the extra windings, and it generates a large Joule heating since the current exceeds the critical current. Due to the increase in the temperature of extra windings, the current gradually decreases with time. Meanwhile, a large induced current can be seen at the innermost turns on Fig. 3(b), and it propagates from inner to outer turns. Finally, SP 3 reaches to entirely quench at 18 ms. Compared with the result of no extra windings as shown in Fig. 4(a), the quench propagation velocity is slow. However, the maximum current is almost the same, large enough to mechanically damage the main coil.

To reduce an induced current at inner/outer turns simultaneously, extra 5-turn windings are located not only outside but inside the main coils. The transient current on each turn is shown in Fig. 4(c). A large induced current is not observed. The maximum temperature rise in SP3 is 9.9 K. Since the inner/outer extra windings decrease the induced current of the main coils and suppress a large temperature rise, it can prevent the main coil from normal-state transition. Fig. 6 shows the time-transient current on each turn of the inner/outer extra windings of the initially quenched SP 2. Large currents are induced in both of extra windings, not in the main coil. The currents induced in the extra windings are

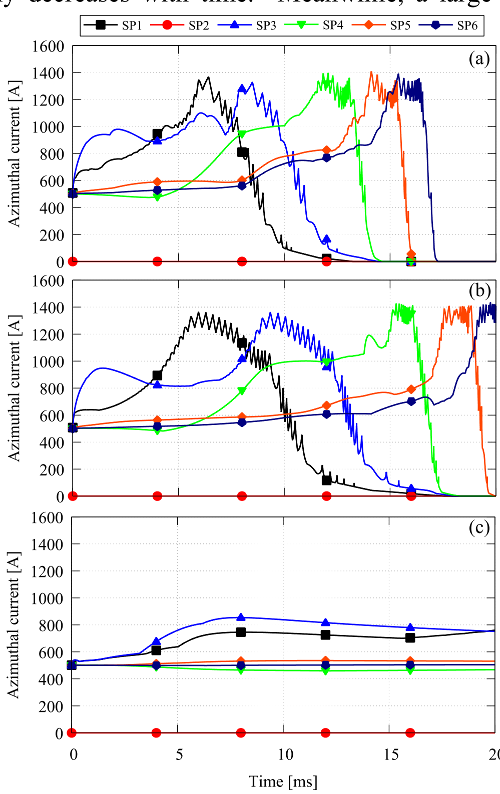

Fig. 3. Simulation results of maximum azimuthal current in each pancake coil; (a) without extra windings, and (b) with extra windings.

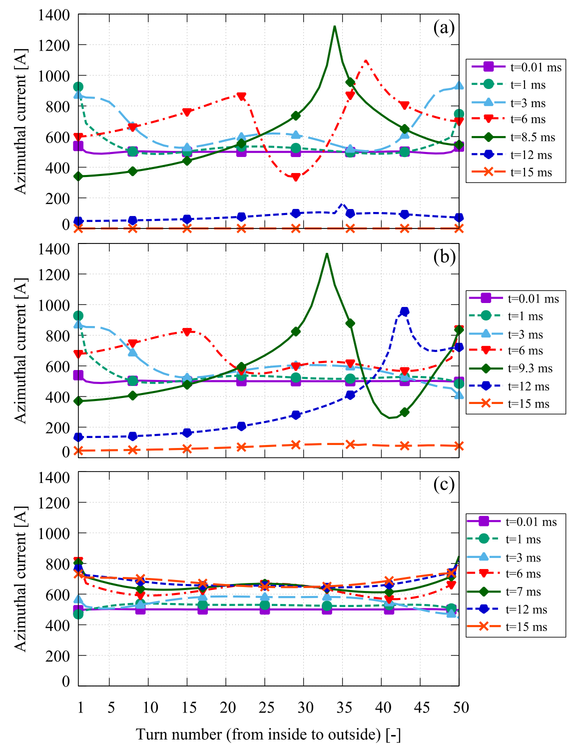

Fig. 4. Azimuthal current distribution of main coil after SP 2 quenches at $t = 0$; (a) w/o extra windings, (b) w/ outer extra windings, and (c) w/ inner and outer extra windings. The currents reach to maximum at (a)8.5 ms, (b)9.3 ms, and (c)7 ms.

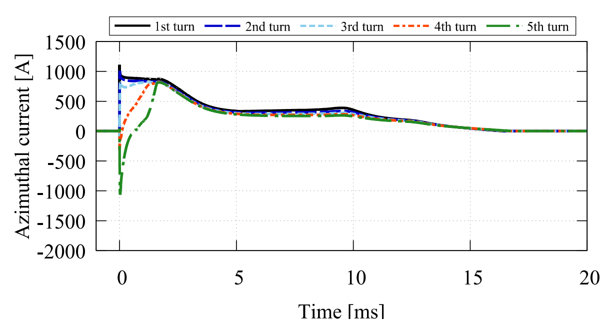

Fig. 5. Time-transient current behavior of extra windings of SP 2 when only outer extra windings are installed. Turn number is from inside to outside.

gradually reduced with the temperature raise, and most of the energy of SP2 dissipates in the inner and outer extra windings.

B. Charging time delay

A major concern of the extra winding installation is the prolongation of the charging time. Therefore, we simulated the charging of the NI REBCO pancake coils with magnetic dam. Fig. 7 shows the normalized center magnetic field without and with extra windings together with the charging current. Here, the operating current reaches up to 200 A with a ramp rate of 1 A/s. Although the normalized center magnetic field follows the operating current with a few second delay, the fields with or without inner and outer windings agree well each other. A main cause of the delay is the no-insulation structure of the main coils, not extra windings, because a part of current flows in the radial direction. Thus, it is concluded that the magnetic dam hardly affects the charging delay, because of the small number of turns of extra windings.

C. Hoop Stress

Fig. 8 show the maximum hoop stress transition calculated from the *BJR* relation [24]. Without extra windings, the stress peak is propagated sequentially from SP 3 to SP 6. The maximum stress is 533 MPa on SP 6. Meanwhile, in the case of the inner/outer extra windings, the maximum stress is decreased to 352 MPa on SP 3.

Next, Fig. 9 plots the maximum hoop stresses of inner and outer extra windings. The stronger hoop stress of the inner extra windings of SP 2 (596 MPa) appears than that of the main coils without extra windings (533 MPa). It is likely to cause a mechanical damage of the inner windings, such as I_c degradation [25]. Accordingly, the newly proposed "magnetic dam" needs to be replaced when the extra windings are damaged after working as a magnet protection. The extra windings cost is much smaller than the main coils, because of the small number of turns. The extra windings need to be designed as replaceable.

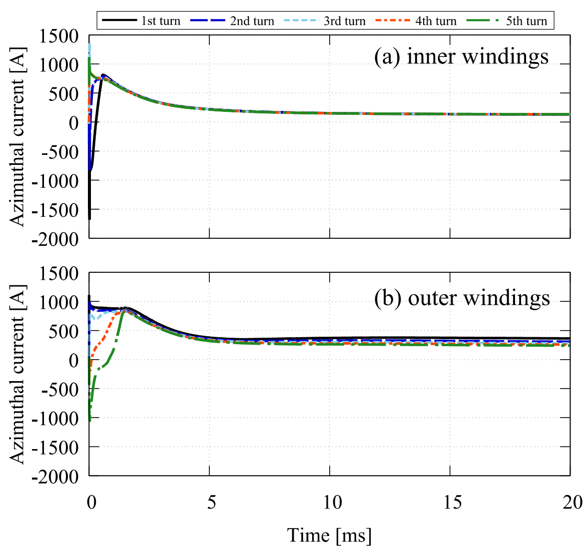

Fig. 6. Current transition of extra windings of SP 2 when inner and outer extra windings are installed; (a) inner and (b) outer windings.

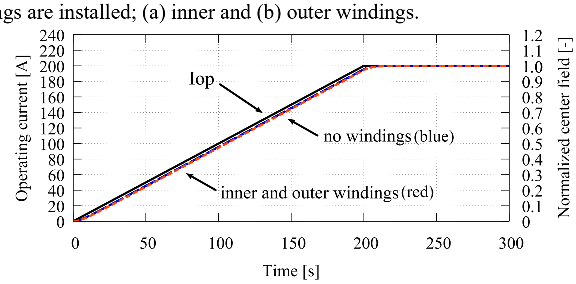

Fig. 7. Operating current and normalized center field versus time. Charging delay due to extra windings is ignorably small.

IV. Conclusion

In this paper, we have proposed a new "magnetic dam" of extra NI windings placed inside and outside the main coils, and the extra NI windings are electrically insulated from the main coils. The current behavior was analyzed by electromagnetic analysis coupled with thermal FEA. From the simulation result, 5-turn inner and outer extra windings can avoid a large current induced in the main coils. The maximum hoop stress is decreased from 533 MPa to 352 MPa; however, a stress applied to the inner extra windings is large enough to mechanically damage the REBCO layer. It is also shown that the extra windings do not affect the charging time delay.

In the near future, we will confirm the ability of mechanical damage protection from large stress during quench propagation by the new "magnetic dam" through experiments.

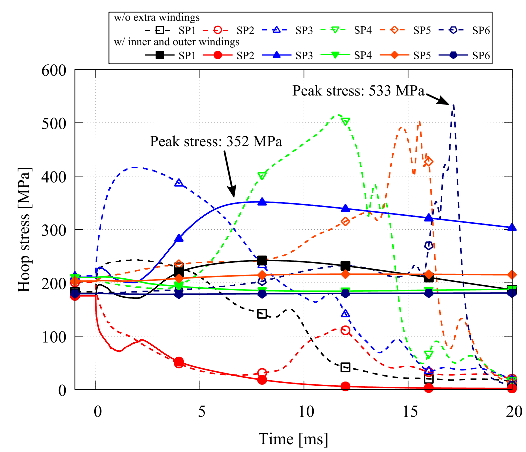

Fig. 8. Time transition of maximum hoop stress of main coils. Broken lines show the maximum stress without extra windings. Solid lines are the maximum stress with inner and outer extra windings. Maximum stress is decreased from 533 MPa to 352 MPa using extra windings.

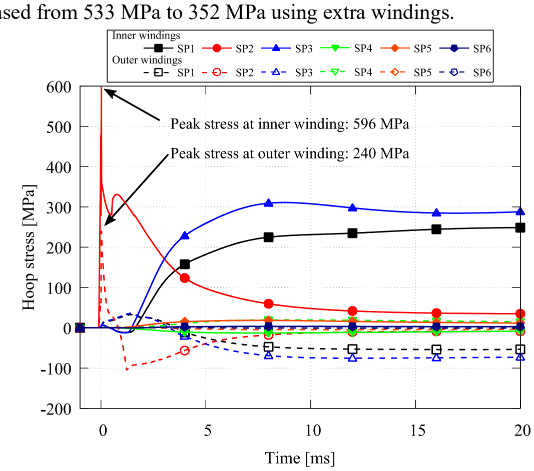

Fig. 9. Time transition of maximum hoop stress of extra windings. Large stress is applied to inner windings.

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