Torque Simulation on NI REBCO Pancake Coils during Quench

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Abstract. This paper presents the unbalanced torque generated in No-Insulation (NI) REBa2Cu3Ox (REBCO, RE = Rare Earth) pancake coils after a normal-state transition. The NI REBCO pancake coil has a high thermal stability, and it is desired to apply to ultra-high field magnets. When an NI REBCO pancake coil locally transitions into a resistive state, the operating current bypasses a normal-state-transitioned turn to adjacent turns in the coil-radial direction, and the amount of heat generation can be reduced. That is an inherent feature of NI REBCO pancake coils. However, when a radial current flows in a magnetic field, a Lorentz force is generated toward the coil-circumferential direction, i.e. torque. In case that the coil radius and the external magnetic field are very large, the extremely large torque is generated, and it could damage the magnet itself and/or the joints to terminals with a mechanical factor. Therefore, it is necessary to investigate the behavior of the torque generated in the NI REBCO pancake coil after the quench.

In this paper, we present the numerical simulation results of the behaviors of the torque generated in the NI REBCO double pancake coil after quench. Their current, thermal, and mechanical behaviors are simulated by a partial element equivalent circuit (PEEC) method and 2-D thermal finite element method (FEM). The behaviors are different depending on the coil size. In addition, the behavior is presented when the operating current is suddenly shut down after quench.

1. Introduction
REBa2Cu3Ox (REBCO, RE = Rare Earth) pancake coils using a no-insulation (NI) winding technique [1, 2] has received attention very much. The NI winding technique greatly enhances the thermal stability of REBCO pancake coils, and it is desired to be applied to high magnetic field NMR/MRI magnet, etc. [3, 4]. The high thermal stability of NI REBCO magnets was confirmed in many experiments and numerical simulations, even though any accident caused a quench of NI REBCO magnets due to mechanical or thermal factors. When NI REBCO pancake coils locally transition into a normal state, an operating current bypasses resistive turns to adjacent turns in the radial direction. It reduces the amount of heat generation, and it brings on a high thermal stability. That is an inherent feature of NI REBCO pancake coils. However, when a radial current flows in a magnetic field, a Lorenz force is generated. The force works toward circumferential direction, i.e. torque. In the case that a large-bore coil operates at a large amount of current in a large magnetic field, a strong torque can be generated after quench, as shown in Fig. 1. In such a case, coils or joints may be damaged by unbalanced torque.
So far, an overcurrent test or quench test of NI REBCO pancake coils under a magnetic field higher than 10 T has not been reported. Hence, there is no report about unbalanced torque generated in NI REBCO pancake coils. In this paper, we will discuss unbalanced torque of NI REBCO pancake coils in high magnetic field after quench.

In order to investigate the torque behavior, the numerical simulation is performed. In this paper, the current, thermal, and mechanical behaviors of the NI REBCO double pancake coil are simulated by a partial element equivalent circuit (PEEC) method and a 2-D thermal finite element method (FEM) [5, 6, 7]. The coil size affects the unbalanced torque behavior. The torque behavior is also shown when an operating current is cut off after quench.

2. Simulation Method and Models
In this paper, the current, thermal, and mechanical behaviors of NI pancake coil were simulated by a PEEC method and a 2-D thermal FEM [5, 6, 7]. Firstly, with the PEEC method, the current and electromagnetic behaviors are obtained. It derives the amount of Joule heating in the NI coil, and then the thermal behavior is simulated with the 2-D thermal FEM.

The circumferential Lorentz force generated in one partial element $F_\theta$ is calculated by the following equation:

$$ F_\theta = I_r B_z l_t $$

where, $I_r$, $B_z$, and $l_t$ are the radial current flowing in a partial element, the axial magnetic field, and the length of the partial element in the radial direction, i.e. the REBCO tape thickness, respectively. The torque is the sum of the products of the radial coordinate and $(1)$.

Table 1 lists the parameters of NI pancake coil model. The simulated model is a double pancake coil wound with SuperPower 2G HTS tape [8] using the NI winding technique, and each pancake coil has 100 turns. The equivalent circuit model of double pancake coil consists of two single pancake coils connected at innermost with a crossover turn as shown in Fig. 2. The single pancake coils are electrically and thermally insulated each other, however the heat diffuses via the crossover turn.

In the thermal simulation, an adiabatic condition is supposed. Since the magnitude of the torque varied depending on the bore diameter of coil, the simulation was performed on four different coils with radii of 50, 100, 500, and 1000 mm. Table 2 lists the simulation condition. It is supposed that the whole lower pancake coil transitions into a normal state, operating at 20 K. The magnet is operated at 500 A, and an axial external magnetic field of 10 T is applied by an outsert magnet.

Table 1. Parameters of REBCO tape and double pancake coils.

| Parameters                  | Values  |
|-----------------------------|---------|
| REBCO tape width (mm)       | 4.0     |
| REBCO tape thickness (mm)   | 0.096   |
Copper stabilizer thickness (µm) 20.0
REBCO layer thickness (µm) 1.0
$I_c$ @ 77 K, self-field (A) 115.0
Coil inner radius (mm) 50, 100, 500, 1000
Number of turns (each pancake coil) 100
Coil thickness (mm) 9.6
Turn-to-turn contact resistivity ($\mu\Omega\cdot$cm$^2$) 70.0 [9]

Table 2. Simulation conditions.

| Parameters                           | Values |
|--------------------------------------|--------|
| Simulation time step (s)             | 0.1    |
| Simulation end time (s)              | 50     |
| Operating current (A)                | 500    |
| Axial & radial external magnetic field (T) | 10.0, 0.0 |
| Operating temperature (K)            | 20.0   |

3. Simulation Results

In this section, the simulation results of NI REBCO pancake coils after quench are presented. Since the results show different behaviors depending on the coil size, the results will be explained individually by the coil radii.

3.1. Small-Size Coils

Fig. 3 shows the total torque and the average circumferential current transition of each pancake coil at inner radii of (a) 50 and (b) 100 mm. In the graph, a counterclockwise direction is defined as positive.

In the quenched lower pancake coil, since almost of current flows toward the radial direction, the torque is generated immediately after the quench, and the strength of torque maintains afterward. The large torque appears as the coil radius is larger.

In the upper pancake coil, the torque is generated in the same direction as the lower one at the first time. This is why the current in the upper pancake coil is induced in the same radial direction as the radially-bypassing current in the lower pancake. Therefore, with the decrease of the induced current, the torque gradually decreases. The smaller the coil radius is, the faster the decay speed of torque, because the contact resistance is larger. In addition, for the 50-mm-radius pancake coils, the torque gradually increases in the counterclockwise direction after it becomes zero once.
Figure 3. Torque and average circumferential current transition when inner radius is (a) 50 and (b) 100 mm. In graph, a counterclockwise direction is positive.

Fig. 4 shows the distributions of the circumferential Lorenz force in the NI pancake coils with an inner radius of 50 mm, at (a) 10 s and (b) 100 s after the appearance of normal-state transition. At 10 s, the Lorenz forces act in the same direction in both the upper and lower pancakes; however, at 100 s, the force direction oppositely changes in the inner turns of the upper pancake. This is because the normal-state transition occurs due to an induced current in the upper pancake.

Figs. 5 and 6 show the radial current distribution and the temperature distribution at 100 s, respectively. The temperature rise can be seen at the inner turns of the upper pancake. Thus, the normal-state transition occurs in the region where the radial current flows toward the inside of the coil. Thereat, the large Lorentz force is generated in the positive direction. The heat propagates from inside to outside in the upper pancake, and the torque in the positive direction increases. That is the reason of the positive torque generation. Moreover, the radial current in the lower coil concentrates into the outer current terminal, so that the Lorentz force concentrates there. Since an electric terminal is mechanically weak, a locally strong Lorentz force would deteriorate the mechanical stability.

3.2. Large-Size Coils
Fig. 7 shows the total torque and the average circumferential current as a function of time in the cases that the inner radii are (a) 500 and (b) 1000 mm, respectively, where “positive” also means the counterclockwise direction. For these large-size coils, since the torque exceeds 20 Nm, the mechanical stability of coils would decrease. Compared with small-size pancake coils presented above, the torque generated in the upper pancake decays more slowly. However, when the coil radius is 1000 mm, the sudden inversion of torque can be seen.
Figure 4. Distribution of circumferential Lorentz force applied in NI pancake coils when inner radius is 50 mm at (a) 10 s and (b) 100 s after appearance of normal-state transition (not to scale).

Figure 5. Distribution of radial current density when inner radius is 50 mm at 100 s after appearance of normal-state transition (not to scale).

Figure 6. Distribution of temperature when inner radius is 50 mm at 10 s after appearance of normal-state transition (not to scale).

Next, Fig. 8 shows the circumferential current distributions at a coil radius of 1000 mm, on the same conditions in Fig. 4. In the upper pancake, the Lorenz force works in the negative direction at
10 s, however it entirely changes in the positive direction at 100 s. Figs. 9 and 10 present the radial current density and temperature distributions at 100 s, respectively. When the coil radius is very large, the current straightly flows from the outer terminal to the inner crossover turn, and the Joule heat concentrates there. When a normal-state transition occurs transversely from outside to inside, the current does not circumferentially carry in the rest area of the superconducting state. As a result, the radial current toward the inside increases in the coil, and the torque direction changes immediately after a local normal-state transition.

4. Conclusion
This paper shows a risk of torque generated in high magnetic field NI REBCO pancake coils during quench. A radial current in an NI pancake coil invokes a circumferential Lorentz force. Thereby, a rotational force is generated in the NI coil. When a magnet has a large bore radius and is operated in large magnetic field, it is possible that a torque large enough to cause damage to magnet is generated.

We also performed the numerical simulation of an NI double pancake coil after a quench by PEEC and 2-D FEM. When a quench occurred, a torque was generated in coils not quenched too, due to the induced current. It gradually decreased with the decrease of induced current. The faster the decay speed of torque, the smaller the coil radius was. Here, a normal-state transition occurred due to heating by the induced current. For a small-size coil, the torque in the direction opposite to the torque initially generated was gradually generated. For a large-size coil, the sudden inversion of torque was generated.

When the current was shut off immediately, the distribution of Lorentz force changed immediately, but the total strength of them did not change at that time. Thus, it was considered that a sudden shutdown was hardly caused to break a coil.
Figure 8. Distribution of circumferential Lorentz force applied in NI pancake coils when inner radius is 1000 mm at (a) 10 s and (b) 100 s after appearance of normal-state transition (not to scale).

Figure 9. Distribution of radial current density when inner radius is 1000 mm at 100 s after appearance of normal-state transition (not to scale).

Figure 10. Distribution of temperature when inner radius is 1000 mm at 10 s after appearance of normal-state transition (not to scale). Temperature near terminal is lower than around since it is connected with copper lead which is low temperature.
Figure 11. Transition of torque when current is cut off at 3 s after appearance of normal-state transition. Coil inner radius is 1000 mm.

Figure 12. Distribution of circumferential Lorentz force at 3 s from current interruption. Coil inner radius is 1000 mm (not to scale).

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