Three-Dimensional Thermal Analysis of an SFCL REBCO Coil Immersed in Liquid Nitrogen

Kezhen Qian¹, Toshiki Shiratani², Yutaka Terao³ and Hiroyuki Ohsaki²

¹ Graduate School of Engineering, The University of Tokyo, Tokyo 113-8654, Japan
² Graduate School of Frontier Sciences, The University of Tokyo, Kashiwa 277-8561, Japan
E-mail: qiankezhen@ohsaki.k.u-tokyo.ac.jp

Abstract. A resistive type superconducting fault current limiter (SFCL) using REBCO tapes has shown its advantages in power applications. However, the hotspot problem, which can be caused by the uniformity of critical current density $J_c$ over long-length of REBCO tapes, is still a threat to the SFCL safety. In this paper, we have studied the limiting performance and transient temperature rise distribution of a nonintersecting type non-inductive solenoidal SFCL REBCO coil using three-dimensional electromagnetic and thermal coupled FEM analysis. Firstly, we modelled a local degradation of $J_c$ and studied its influence on the transient temperature rise distribution during the over current. The results indicated that a narrow and severe $J_c$ degradation leads to the concentration of current and heat generation in the normal $J_c$ area, which is opposite to the case of a relatively wider and slighter $J_c$ degradation area. Furthermore, REBCO tapes with different thickness of substrate and Ag over-layer were analysed to study the influence on limiting performance and temperature rise. A thicker substrate leaded to a slower temperature rise because of its higher heat capacity, and the Ag over-layer of 4 μm showed better limiting performance and thermal stability because of its better thermal conductivity as well as uniform temperature rise and SN transition.

1. Introduction
A resistive type superconducting fault current limiter (SFCL) using REBCO tapes has shown its advantages in limiting fault currents and improving the reliability of a power system for its compactness and rapid increase in resistance [1]–[4]. However, critical current density ($J_c$) uniformity over long-length of REBCO tapes may lead to a local overheating and burning of the tapes, which are called as the hotspot phenomenon. In the previous research, two types of non-inductance solenoidal coils for resistive type SFCL were studied on their current limiting properties and recovery characteristics [5]. In addition, the electrical and thermal behaviours of several types of REBCO tapes during the fault current limitation were analysed and evaluated with a simulation model, consequently, tapes with no stabilizer were considered more suitable for constructing SFCLs [6]. In reference [7], a 2D $J_c$ distribution map of such REBCO tape with no stabilizer was measured using the scanning hall probe microscopy (SHPM).

In this paper, we have studied the thermal characteristics of an REBCO coil for SFCL use during the fault current limitation with the electromagnetic and thermal coupled FEM analysis. The nonintersecting type non-inductive solenoidal winding [5] consisting of the stabilizer free REBCO tape was assumed for the REBCO coil, which concept is shown in figure 1. This coil consists of an inner and an outer winding that are wound bifilarly and connected in series to reduce the inductance of the coil. A local...
2. Numerical Analysis Method and Conditions

2.1. Numerical Analysis Method
Electromagnetic and thermal coupled analysis was utilized for the numerical analysis of SFCL REBCO coil, because the operating characteristics of REBCO tapes are strongly affected by the temperature rise. In the electromagnetic analysis, the finite element method based on current vector potentials was used [8]. The governing equation of current vector potential \( T \) defined by \( J = \nabla \times T \) (\( J \): current density) is given by the following equation:

\[
\nabla \times (\rho \nabla \times T) = -\frac{\partial B}{\partial t}
\]

(1)

where \( \rho \) is the electric resistivity, and \( B \) is the magnetic flux density. A thin-plate approximation was employed for computing the current distribution in the REBCO tapes considering its high length-thickness ratio.

A nonlinear \( E-J \) relation (\( E \): electric field) based on the power law (2) was used for modelling the electromagnetic property of superconductors [8]. Temperature and magnetic flux density dependence of the critical current density \( J_C \) was expressed by (3) [9, 10], where \( T \) is the temperature and \( B \) is the component of magnetic flux density parallel to the surface of REBCO tape. The perpendicular magnetic field component is negligible because of the bifilar winding (figure 2). The magnetic flux density dependence was considered because the magnetic flux between the outer and inner winding cannot be...
cancelled out, even though the non-inductive solenoidal winding was employed for the REBCO coil in this paper. Furthermore, flux density $B$ was calculated according to the calculated circuit current and the linear relation between the current and the magnetic flux density because of the coil’s nonmagnetic property. Additionally, the linear relation was obtained from the static electromagnetic analysis using JMAG (figure 2).

$$E = E_C \left( \frac{I}{I_{C0}} \right)^n \quad (2)$$

$$J_C(T) = J_{C0} \left[ 1 - \left( \frac{T}{T_C} \right)^2 \right]^{3/2} \times \frac{1}{(1 + B/B_C)^{0.6}} \quad (3)$$

The governing equation of the three-dimensional thermal analysis was given by:

$$\rho c \frac{\partial T}{\partial t} = \left[ \frac{\partial}{\partial x} (\kappa \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y} (\kappa \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z} (\kappa \frac{\partial T}{\partial z}) \right] + Q \quad (4)$$

where $\kappa$ is the thermal conductivity, $T$ is the temperature, $\rho$ is the mass density, $c$ is the specific heat, and $Q$ is the Joule heat. Additionally, the temperature dependence of $\kappa$, $\rho$, and $c$ were considered in the analysis [11]–[14]. The analysis region of the REBCO tapes coinciding with substrate, cooling characteristics of liquid nitrogen [8], and heat sources originated in Joule loss in the Ag and superconductor layer were given by the boundary conditions.

2.2. Analysis Conditions

The REBCO coil used in the numerical analysis is shown in figure 1, and the schematic diagram of over-current simulation circuit is shown in figure 3. The specifications of the simulation circuit and the REBCO coil are summarized in table 1 and table 2.

| Table 1. Specifications of simulation circuit and REBCO coil. | Table 2. Specifications of the REBCO tape used in the coil. |
|---|---|
| Power-supply voltage | 500 V |
| Circuit resistance | 0.05 Ω |
| Coil diameter | 31.8 cm |
| Number of turns for both windings | 5 |
| Number of tapes per turn | 1 |
| Coil pitch | 1.35 cm |
| Over current duration | 100 ms |
| REBCO tape | SuperPower SF12100 |
| Ag over-layer thickness | 2 μm |
| Substrate thickness | 100 μm |
| $I_C (J_{C0})$ @77 K, self-field | 468 A (3.9 × 10$^{10}$ A/m$^2$) |
| $E_C$ | 1 μV/cm |
| $T_C$ | 90 K |
| $B_C$ | 118.2 mT |

We explain the experiment results [7] and simulation results in the next chapter. In 3.1, a comparison is conducted between over-current experiment results [7] and simulation results, which are based on the same specifications: an over-current of 2000 A and one meter SF12100 tape. Meanwhile, the simulation specifications in 3.2 and 3.3 are shown in table 1. In 3.2, with the same macroscopic $J_C$ distribution in
3. Numerical Analysis

3.1. Comparison with experimental results
To examine the accuracy of the numerical analysis model, an over-current simulation was conducted with an over-current of 2000 A and one meter SF12100 tape. The simulation results (figure 4) show good agreement with the experimental results [7]. In addition, a local degradation of $J_C$ (85% of the rated $J_C$), which is the same as the experimental tape, was also modelled in the numerical analysis.

Figure 4. Over-current simulation results of 1 m SF12100 tape, which show good agreement with the experiment results [7].

Figure 5. Temperature distribution of the REBCO coil with a $J_C$ degradation (degrading to 25% of the rated $J_C$ in 63 mm$x$2.4 mm) at the rising phase of current $t = 0.725$ ms.

Figure 6. Temperature distribution of the REBCO coil with a $J_C$ degradation (degrading to 75% of the rated $J_C$ in 63 mm$x$7.2 mm) at the rising phase of current $t = 0.725$ ms.

Figure 7. Temperature distribution of the REBCO coil with a $J_C$ degradation (degrading to 85% of the rated $J_C$ in 63 mm$x$12 mm) at the rising phase of current $t = 0.725$ ms.

3.3. longitudinal direction, 3 cases with different $J_C$ degradation area in width direction are analysed to study the influence on the temperature rise. In 3.3, several cases with different thickness of substrate and Ag over-layer are analysed to study the influence on limiting performance and temperature rise.
3.2. Influence of $J_C$ degradation area

To study the influence of different $J_C$ degradation area in width direction on the temperature rise distribution during the over current, 3 cases of thermal analysis were carried out in the assumptions that the macroscopic $J_C$ distribution in longitudinal direction is the same in all 3 cases but the widths of $J_C$ degradation area are different (figure 5–7). According to the analysis results, the difference mainly appears during the rising phase of current. As in the case of narrow and severe $J_C$ degradation (degrading to 25% of the rated $J_C$ in one-fifth of the tape width, figure 5), the temperature rise in the $J_C$ degradation area is lower than that in the normal $J_C$ area, which indicates that the current bypasses the $J_C$ degradation area and flows through the normal $J_C$ area. Therefore, in this case, the hotspot is more likely to occur in the normal $J_C$ area.

On the other hand, in the case of wide and slight $J_C$ degradation (degrading to 75% of the rated $J_C$ in three-fifth of the tape width, figure 6), the temperature rise in the $J_C$ degradation area is higher than that in the normal $J_C$ area. Because the current cannot completely bypass the $J_C$ degradation area, meanwhile, the current through the $J_C$ degradation area generates more Joule heat. In this case, a hotspot is more likely to occur in the $J_C$ degradation area.

With the development of temperature rise and heat conduction, the heated area expands from the $J_C$ degradation area (figure 8). However, different widths of $J_C$ degradation area show little influence on the temperature rise along longitudinal direction or the peak temperature of the tape during the over current.

3.3. Influence of different thickness of REBCO tape layers

![Figure 9](image1.png)

**Figure 9.** Maximum temperature of the REBCO coils with different substrate thickness.

![Figure 10](image2.png)

**Figure 10.** Temperature distribution along the REBCO tape with 50 μm substrate in longitudinal direction, which starts from the outer terminal of the outer winding, at different times.
3.3.1 Influence of substrate thickness. Three cases with substrate thickness of 50 μm, 75 μm, and 100 μm were analysed to study the influence on current limiting performance and temperature rise. The maximum temperature of the REBCO coil during the over current is shown in figure 9. The temperature distribution along the REBCO tape of outer winding in longitudinal direction at different times, which is 5 meters long and from the outer terminal to the connection of two windings, is shown in figure 10–12. Thinner substrate leads to a higher temperature rise because of its lower heat capacity, yet, the thickness of substrate has less influence on the limited current. Therefore, considering the heat capacity and thermal stability as well as mechanical strength, a relatively thicker substrate is favourable.

3.3.2 Influence of Ag over-layer thickness. Six cases with Ag over-layer thickness of 2 μm, 3 μm, 4 μm, 6 μm, 8 μm, and 10 μm were analysed to study the influence on current limiting performance and temperature rise. According to the results, the temperature distribution with an Ag over-layer of 2 μm is quite different from other cases (figure 13–16). In figure 13, a significant hotspot occurs at the $J_c$ degradation area because of the poor thermal conductivity and high resistance of a thin Ag over-layer. As in the cases with Ag over-layer of 3 μm or higher, the hotspot phenomenon and the maximum temperature (figure 19) are both suppressed with the thicker Ag over-layer, meanwhile, a nearly uniform temperature rise along the REBCO tape in longitudinal direction is observed. Therefore, the limited currents rise even lower with the Ag over-layer of 3 μm and 4 μm that have higher overall resistances (figure 17, 18). In comparison with the case of 2 μm, a REBCO tape with 4 μm Ag over-layer shows

Figure 11. Temperature distribution along the REBCO tape with 75 μm substrate in longitudinal direction, which starts from the outer terminal of the outer winding, at different times.

Figure 12. Temperature distribution along the REBCO tape with 100 μm substrate in longitudinal direction, which starts from the outer terminal of the outer winding, at different times.

Figure 13. Temperature distribution along the REBCO tape with 2 μm Ag over-layer in longitudinal direction, which starts from the outer terminal of the outer winding, at different times.

Figure 14. Temperature distribution along the REBCO tape with 3 μm Ag over-layer in longitudinal direction, which starts from the outer terminal of the outer winding, at different times.
4. Conclusion
In this paper, we have built a three-dimensional electromagnetic and thermal coupled FEM analysis model. Using this model, a nonintersecting type non-inductive solenoidal REBCO coil for SFCL use was modelled, and its thermal characteristics during the over current were analysed with different $J_C$ degradation area and thickness of REBCO tape layers. The development of temperature rise distribution better limiting performance and thermal stability in this analysis.
and heat conduction was investigated, and indicated that a narrow and severe \( J_C \) degradation leads to the concentration of current and heat generation in the normal \( J_C \) area, which is opposite to the case of a relatively wider and slighter \( J_C \) degradation area. Then, several cases with different thickness of substrate and Ag over-layer were analysed. A thicker substrate led to a slower temperature rise because of its higher heat capacity, and the Ag over-layer of 4 \( \mu \)m showed better limiting performance and thermal stability in this analysis because of its better thermal conductivity as well as uniform temperature rise and SN transition.

References

[1] Morandi A 2013 State of the art of superconducting fault current limiters and their application to the electric power system *Physica C: Superconductivity* 484 242–7

[2] Ruiz H S, Zhang X and Coombs T A 2015 Resistive-Type Superconducting Fault Current Limiters: Concepts, Materials, and Numerical Modeling *IEEE Transactions on Applied Superconductivity* 25 1–5

[3] Neumüller H W et al. 2009 Development of Resistive Fault Current Limiters Based on YBCO Coated Conductors *IEEE Transactions on Applied Superconductivity* 19 1950–5

[4] Noe M and Steurer M 2007 High-temperature superconductor fault current limiters: concepts, applications, and development status *Supercond. Sci. Technol.* 20 R15

[5] Liang F, Yuan W, Zhu J, Zhang M, Venuturumilli S, Li J, Patel J, Zhang G and Zhang Z 2017 Experimental Test of Two Types of Non-Inductive Solenoidal Coils for Superconducting Fault Current Limiters Use *IEEE Transactions on Applied Superconductivity* 27 1–5

[6] Majka M, Kozak J and Kozak S 2017 HTS Tapes Selection for Superconducting Current Limiters *IEEE Transactions on Applied Superconductivity* 27 1–5

[7] Kar S, Li X-F, Selvamanickam V and Rao V V 2017 Current distribution mapping in insulated (Gd,Y)BCO based stabilizer-free coated conductor after AC over-current test for R-SFCL application *IOP Conf. Ser.: Mater. Sci. Eng.* 171 012118

[8] Ohsaki H, Sekino M and Nonaka S 2009 Characteristics of Resistive Fault Current Limiting Elements Using YBCO Superconducting Thin Film With Meander-Shaped Metal Layer *IEEE Transactions on Applied Superconductivity* 19 1818–22

[9] Matsushita T, Wada H, Kiss T, Inoue M, Iijima Y, Kamimoto K, Saitoh T and Shihohara Y 2002 Critical current properties in superconducting Y-123 tapes *Physica C: Superconductivity* 378–381 1102–7

[10] Zermeño V M R and Grilli F 2014 3D modeling and simulation of 2G HTS stacks and coils *Supercond. Sci. Technol.* 27 044025

[11] Lu J, Choi E S and Zhou H D 2008 Physical properties of Hastelloy® C-276™ at cryogenic temperatures *Journal of Applied Physics* 103 064908

[12] Fujishiro H, Ikebe M, Naito K, Kohayashi S and Yoshizawa S 1994 Anisotropic Thermal Diffusivity and Conductivity of YBCO(123) and YBCO(211) Mixed Crystals *Jpn. J. Appl. Phys.* 33 4965–70

[13] Zhang M, Matsuda K and Coombs T A 2012 New application of temperature-dependent modelling of high temperature superconductors: Quench propagation and pulse magnetization *Journal of Applied Physics* 112 043912

[14] Smith D R and Fickett F R 1995 Low-Temperature Properties of Silver *J Res Natl Inst Stand Technol* 100 119–71