Study on optimal thickness of copper layer of REBCO-coated wire for quench protection

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Abstract. The most probable cause of quench damage of REBCO coated wire is localized over-heating at a hot-spot in the coil wire during the quench protection sequence. To reduce the hot-spot temperature, it is effective to increase the thickness of the Cu layer of the coated wire. However, the thick Cu layer deteriorates the overall current density of the wire. The wire with thin Cu layer may be damaged by a quench at low operational current. For a coil of a real application it is important to increase the current density of the winding pack of the coil at operating condition. Increase of the overall current of the wire itself by reducing thickness of the Cu layer is not necessarily to increase the winding pack current density considering quench protection. In the paper, the optimum value of the thickness of the Cu layer is analytically studied based on a thermal model of the winding pack to maximize the winding pack current density, while the coil is safe from the damage caused by quench.

1. Introduction

It is widely understood that a coil wound with insulated high-temperature superconducting (HTS) wire quenches, despite the high quench margin of the HTS wire itself, and a quenched coil is easily damaged if proper measures are not taken, especially when the coil is wound with high-current-density rare earth–barium–copper oxide (REBCO) coated wire (RE wire in short).

There is a way to improve the thermal stability of HTS coils using the no-insulation (NI) winding method [1,2]. This method is effective for direct current (DC) or quasi-DC coils. Therefore, the NI method is not appropriate for HTS coils intended for applications in which they are subjected to frequent and rapid magnetic field changes, i.e., superconducting magnetic energy storage (SMES) [3,4], rotating machines [5,6], and nuclear magnetic resonance/magnetic resonance imaging (NMR/MRI) [7], because such rapid magnetic field changes cause significant losses and NI magnets cannot rapidly respond to changes in the coil current. Therefore, coils wound with insulated wires are necessary for such applications.

The most probable cause of quench damage in insulated RE wire in a coil is localized overheating at a hot spot in the coil wire that causes the hot spot temperature $T_{HS}$ to exceed a safe limit $T_{HSs}$ during the quench protection sequence. An effective method of reducing the hot spot temperature is to increase the thickness of the Cu layer of the coated wire. However, a thick Cu layer reduces the overall current density of the wire. A wire with a thin Cu layer may be damaged by a quench at a low operational current. The safe limit $I_0s$ of the operational current $I_0$, below which the coil survives the
quench damage, increases as the thickness $d_{Cu}$ of the Cu layer increases. The limiting current density of the winding pack of the coil at $I_0$, can be defined as $\rho_{wp} = \frac{I_0}{S_{sw} + S_I}$, where $S_{sw}$ and $S_I$ are the cross-sectional areas of the wire (including those of the Cu layer and substrate) and the insulation layer between the wires, respectively. When reinforcing material is inserted between the wires, its cross-sectional area per layer is included in $S_I$. For a coil intended for practical applications, it is important to increase the value of $\rho_{wp}$ while not increasing the current density of the wire itself. It is shown in the authors’ previous experiments a RE wire with a thicker Cu layer can survive quench damage at a higher operational current. In the experiment using small-scale test coils wound with RE wires of $d_{Cu} =$ 40 and 100 μm, the coil with $d_{Cu} = 100 \mu m$ had higher $I_0$ and $\rho_{wp}$ values [8].

In the present study, the optimal value of $d_{Cu}$ was investigated via numerical simulation using a thermal model of a winding pack composed of insulated RE wires.

2. Detect-and-dump quench protection method

Figure 1 shows a circuit of the detect-and-dump quench protection method, which is commonly used for insulated RE wire coils. When the voltage $V_s$ across a spreading resistive zone in the coil exceeds a certain limit $V_q$, the quench protection sequence starts opening the switch $S$. In this paper, an event when $V_s$ exceeds $V_q$ is defined as a quench, and $V_q$ is termed the quench detection voltage. During the quench protection sequence, the energy stored in the coil is dumped into the resistor $R$, and the coil current $I(t)$ decays with a time constant of $\tau = L/R$, where $L$ is the inductance of the coil. The peak voltage $V_{cp}$ between the coil terminals is given by

$$V_{cp} = LI_0/\tau. \quad (1)$$

where $I_0$ is the operational coil current when the quench protection sequence starts. To protect the coil from damage caused by a quench, the values of $V_q$ and $\tau$ should be set to maintain the hot spot temperature $T_{HS}$ below its limit $T_{HSs}$ and $V_{cp}$ below the coil withstand voltage during the quench protection sequence.

![Figure 1. Circuit of the detect-and-dump quench protection method](image)

3. Thermal model of winding pack and thermal equilibrium equations for simulation analysis

The numerical simulation analysis was conducted in this study considering that main origin of an unexpected appearance of resistive zone in a RE wire coil is a local defect in the wire. Figure 2 shows the thermal analytical model of a winding pack of a coil wound with RE wires used for the analysis. The RE wires are insulated by Kapton tapes (12.5μm thick×2). In the model, thin Cu strips are inserted between the insulated RE wires to make a co-winding coil for highly sensitive quench detection [8]. The winding pack is cooled by thermal conduction to the cooling blocks at the bottom of the winding packs. In figure 2, the layers of insulated RE wires are labeled consecutively as $w_0$, $w_1$, ..., $w_n$. In the model, there is a defect area of length $l_d$
with a critical current $I_{cd}$ in the layer $w_0$, where $I_{cd}$ is lower than the critical currents $I_c$ of the other areas, and it is assumed that these $I_c$ values are the same in all layers except the defect area. There is a glass-fiber-reinforced plastic (GFRP) sheet with a thickness of 0.2 mm between the bottom surface of the winding pack and the cooling block surface. In the analysis, the temperature of the cooling block $T_{CB}$ was kept constant.

The following heat equilibrium equation of the wire comprising the i-th layer of the winding pack was used in the analysis.

$$C_p \frac{\partial T_i(x,t)}{\partial t} = \frac{\partial}{\partial x} \left( K \frac{\partial T_i(x,t)}{\partial x} \right) + P_i(x,t) - h_i(2T_i - T_{i-1} - T_{i+1}) - h_b(T_i(x,t) - T_{CB}).$$  \hspace{1cm} (2)

where $T_i(x,t)$ is the temperature of the wire in the i-th layer and $K$ [Wm/K] and $C_p$ [J/mK] are the thermal conductivity and heat capacity per unit length of the wire, respectively. The heat capacity of the wire insulation layer and that of the Cu strip are included in the value of $C_p$. The Joule heat per unit length of the wire of the $i$-th layer, $P_i(x,t)$ [W/m], was calculated using the current sharing model, as explained in detail in a previous work [9]. The equation for $P_i(x,t)$ is given by

$$P_i(x,t) = V_i(x,t)I_i(t).$$  \hspace{1cm} (3)

where $V_i(x,t)$ [V/m] is resistive voltage per unit length of the RE wire at $x$ which is calculated based on the current sharing model and the $n$ value power law of voltage-current characteristics. Heat generated in the resistive zone is transferred to the neighboring wires and the cooling block. The heat transferred to the neighboring wires is considered proportional to the temperature differences between the wire with the resistive zone and the neighboring wires and expressed as $h_i(2T_i - T_{i-1} - T_{i+1})$, where $h_i$ [W/mK] is the heat transfer factors per unit length of wire. The heat transferred to the cooling block is proportional to the temperature differences between the wire and the cooling block and expressed as $h_b(T_i(x,t) - T_{CB})$, where $h_b$ [W/mK] is the heat transfer factors per unit length of wire.

The temperature behaviors of the RE wires in the coils during the quench protection sequence were investigated by numerically solving equation (2) by use of the multi-physics modeling software COMSOL® [10].

Figure 2. Thermal analytical model of winding pack of coil wound with RE wires.

4. Dependence of thickness of Cu layer on quench protection performance

Quench protection performance is dependent on many parameters. Therefore, the simulation study was conducted for an example case in this study. $T_H$ is the temperature $T_0(0, t)$ at the center of the defect area of the wire was calculated based on the specifications of the RE wire (yttrium barium copper oxide; YBCO wire) listed in table 1. The values of $C_p$ and $K$ were determined from data on the
temperature-dependent heat capacities and thermal conductivities of a Hastelloy substrate, Cu, and Kapton insulator [11-13]. It was assumed that $T_{CB}$ was 25 K and that the magnetic field vertical to the wide face of the wire was 4.2T. Value of $I_c$ dependent on temperature and magnetic field component vertical to wide face of YBCO wire was determined based on data of lift factor given the reference [14]. There do not exist directly measured data of $h_l$ and $h_b$ in the case of a RE wire winding pack. Therefore, the values of $h_l$ and $h_b$ were estimated based on the experimental values for a winding pack of Bi/Ag-sheathed wires [15]. The value of $h_l$ was assumed to be half of the value of the Bi / Ag sheathed wire winding pack because Cu tapes for co-wound coil for the quench detection are inserted and the heat transfer between the layers is dominated by the surface thermal resistance [15].

Table 1. Specifications of YBCO wire

| Wire                          | Width         | Thickness of YBCO layer | Thickness of Cu layer | Thickness of substrate (Hastelloy) | Thickness of protection layer (Ag) | Thickness of Insulating tape (Kapton) | $I_c$ (1 μV/cm) (at 77 K, Self field) | $I_c$ (1 μV/cm) (at 25 K, 4.2 T vertical field to wide face of wire) |
|-------------------------------|---------------|-------------------------|-----------------------|-----------------------------------|-------------------------------------|---------------------------------------|--------------------------------------|---------------------------------------------------------------------|
| Wire                          | 4 mm          | 1.3 µm                  | 40 ~ 100 µm           | 50 µm                             | 3.2 µm                              | 25 µm×2                               | 102 A                                | 191 A                                                                               |

**4.1. Maximum allowable defect length and minimum propagating zone**

Maximum allowable defect (MAD) length $L_{MAD}$ at coil operational current $I_0$ is defined as follows. When $L_d > L_{MAD}$, resistive zone in the wire due to the defect keeps spreading causing quench of the coil, and When $L_d < L_{MAD}$, the coil can be operated free from quench [16]. MAD is explained in figure 3 where examples of numerically calculated time traces of $T_{HS}$ are shown for the cases of $L_d = 1.72$ cm and 1.74 cm keeping $I_0 = 152$ A. In the calculation, it is assumed that $I_{cd} = 0$ A and $d_{Cu} = 60$ μm. As seen in figure 3, in the case of $L_d = 1.72$ cm $T_{HS}$ becomes steady state, but when $L_d$ slightly increases to 1.74 cm, $T_{HS}$ suddenly and sharply rises over 500 K and the wire is damaged [8]. Then, $L_{MAD}$ can be estimated to be a value between $L_d = 1.72$ cm and 1.74 cm. When $L_d$ is equal to $L_{MAD}$, the resistive zone around the defect area, that is the area around the hot spot, is the minimum propagating zone (MPZ) [17]. Figure 4 (a) and (b) show temperature distributions of wire in the directions of the wire length (x-direction) and the layer (y-direction) around MPZ, respectively for $L_d$ close to $L_{MAD}$, and the temperature distribution of figure 4 is nearly that of the MPZ. Figure 5 (a) and (b) show $L_{MAD}$ and voltage $V_{MPZ}$ across the MPZ versus $I_0$, respectively, for different values of $d_{Cu}$. As seen in figure 5, $L_{MAD}$ and $V_{MPZ}$ increases as $d_{Cu}$ increases for a given value of $I_0$, and a coil is safer from quench damage for larger value of $d_{Cu}$. 
4.2. Safe limit of winding pack current density and optimum value of Cu layer thickness

A coil can be operated at the coil current $I_0$ without quench when $l_d$ is smaller than $l_{\text{MAD}}$. However, during operation of the coil, there is a possibility that $l_d$ increases over $l_{\text{MAD}}$ due to excess mechanical stresses and fatigue effects caused by repeated mechanical stresses to the coil wire, for examples, and that the coil is quenched. When $V_q$ is smaller than a safe limit $V_{qs}$, the coil is protected from damage, but when $V_q$ is larger than $V_{qs}$, $T_{HS}$ exceeds the safe limit $T_{HSs}$ and the coil is damaged. Values of $V_{qs}$ are dependent of $d_{\text{Cu}}$, $I_0$ and $\tau$. Figure 6 shows curves of $V_q$ versus the safe limit $I_{0s}$ of $I_0$ for $\tau = 30$ s for various values on $d_{\text{Cu}}$ in the case that $l_d$ becomes 2 cm. For the values of $V_q$ and $I_0$ below the curves the coils are safe from quench damage. In figure 6, $l_{\text{MAD}}$ is 2 cm at the points denoted by \( \circ \). Obviously
from figure 6, $V_{qs}$ increases as $d_{Cu}$ increases for a given value of $I_0$, and the coil can be operated safely at a higher value of $I_0$ for larger value of $d_{Cu}$ for a given value of $V_q$. However, considering that increase of $d_{Cu}$ deteriorates winding pack current density, there is an optimum value of $d_{Cu}$ to maximize the value of $\rho_{wps}$. Figure 7 which is obtained from the data shown in figure 6 shows dependences of $\rho_{wps}$ on $d_{Cu}$ for $V_{qs} = 4, 6, 8 \text{ mV}$ in the case of $l_d = 2 \text{ cm}$. As seen from figure 7, the optimum value of $d_{Cu}$ is 80 μm, and for an example, $I_0$ can be increased up to 182 A ($\rho_{wps} = 222 \text{ A} / \text{mm}^2$) without quench damage for $V_{qs} = 6 \text{ mV}$ in the case of $d_{Cu} = 80 \mu\text{m}$, whereas $I_{0s} = 127 \text{ A} (\rho_{wps} = 191 \text{ A} / \text{mm}^2)$ in the case of $d_{Cu} = 40 \mu\text{m}$. As seen from this example, $I_{0s}$ and $\rho_{wps}$ can be increased by properly selecting $d_{Cu}$ from those values in the case of $d_{Cu} = 40 \mu\text{m}$ which is the thickness of Cu layer of widely used commercially available RE wires (for examples, Fujikura wires and SuperPower wires). In figure 8, values of $l_{dMAD}$ dependent on $d_{Cu}$ are plotted for $\rho_{wps} = 220$ and 230 A/mm$^2$, which shows that $d_{Cu} = 80 \mu\text{m}$ is also optimum to maximize $l_{dMAD}$.

As shown above, the optimum value of $d_{Cu}$ is 80 μm to maximize values of $l_{dMAD}$ and $\rho_{wps}$ for the example studied here.

![Figure 6](image1.png)

Figure 6. Safe limit $V_{qs}$ of $V_q$ versus the safe limit $I_{0s}$ of $I_0$ for $\tau = 30 \text{ s}$ for various values of $d_{Cu}$ in case of defect length $l_d = 2 \text{ cm}$.

![Figure 7](image2.png)

Figure 7. Dependence of safe limit of winding pack current density $\rho_{wps}$ on $d_{Cu}$ for $V_{qs} = 4, 6, 8 \text{ mV}$ in the case of $l_d = 2 \text{ cm}$.
Figure 8. $l_{MAD}$ dependent on $d_{Cu}$ for safe limit of winding pack current density $\rho_{wps} = 220$ and 230 A/mm$^2$

5. Concluding remarks

Dependence of thickness $d_{Cu}$ of Cu layer on quench protection characteristics of RE wire coils are studied by numerical simulation study assuming that a main origin of unexpected appearance of resistive zone initiating a quench is a local defect of the coil wire. Results of the study are as follows.

(a) When $l_d$ of a coil wire operating at $I_0$ is smaller than the length $l_{MAD}$ of MAD at $I_0$, the coil is not quenched.

(b) While $l_{MAD}$ increases as $d_{Cu}$ increases for a given value of $I_0$, $l_{MAD}$ becomes maximum at a certain optimum value of $d_{Cu}$ for a given value of the safe limit of the winding pack current density $\rho_{wps} = I_0s / (S_W + S_I)$.

(c) When $l_d$ of a coil wire operating at $I_0$ exceeds $l_{MAD}$, the resistive zone starts spreading and $V_s$ exceeds $V_q$, the coils is quenched. The coil is damaged unless values of $\tau$ and $V_q$ are not selected properly. For given values of $\tau$ and $V_q$, there is an optimum value of $d_{Cu}$ to maximize the value of $\rho_{wps}$ while the coil is safe from quench damage.

Summarizing the above results, it is shown in this analysis that a value of $d_{Cu}$ need to determine considering the quench protection and that increasing the winding pack current density of a practical RE wire coil is not increasing the overall current density of the wire itself by decreasing the value of $d_{Cu}$. There is an optimum value of $d_{Cu}$ to maximize the winding current density while protecting the coil from the quench damage. The optimum value of $d_{Cu}$ is dependent on various parameters of the quench protection system and the coil structure, but it can be estimated by use of the analytical method described in this paper for various cases.

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