Study on conditions to reuse quenched HTS coil

H. Toriyama, A. Nomoto, T. Ichikawa, T. Takao, K. Nakamura, O. Tsukamoto and M. Furuse

1 Sophia University, 7-1 Kioi-cho, Chiyoda-ku, Tokyo, Japan
2 National Institute of Advanced Science and Technology, 1-1-1 Umezono, Tsukubashi, Ibaraki, Japan

E-mail: tsukamoto-osami-np@ynu.ac.jp, hifumitoriyama@gmail.com

Abstract. An HTS coil quenches despite of the high quench margin. Main origins of unexpected quench of HTS coils are non-reversible local defects, and training effects as in LTS coils are not observed in HTS coils. Therefore, when an HTS coil is quenched before the required coil performance is met, the coil cannot be reused unless the coil is safely protected from quench damage and its operating conditions are readjusted. This paper studies on the conditions to reuse the coil which experienced a quench and is not damaged by the quench to meet the required performance. The study is conducted based on the temperature and current dependences of the coil stability measures of the maximum allowable defect (MAD) and minimum propagating zone (MPZ).

1. Introduction
High-temperature superconductor (HTS) coils are used in various applications, such as HTS rotating machines [1, 2], superconducting magnetic energy storage (SMES) [3, 4], and magnetic resonance imaging MRI [5]. However, HTS coils quench and are easily damaged when the quench protection system does not work properly, even though the coils have a high quench margin [6, 7]. It is known that unexpected quenches of HTS coils are caused by non-reversible local defects, and that the training effects observed in low-temperature superconductor coils are not observed in HTS coils [8]. Therefore, to reuse quenched coils, it is important to protect coils from quench damage. It has been shown that quenched HTS coils can be protected from damage by adopting a commonly used detect-and-dump method with a properly selected quench detection voltage and current decay time constant [9, 10]. When a coil is prematurely quenched (i.e., before the required performance is met), it is necessary to adjust the operating conditions for the coil, such as the operating temperature and coil current.

Coils wound with rare earth–barium–copper oxide (REBCO) wires are more sensitive to quenching and easily damaged, especially those with a high winding pack current density, compared with coils wound with Bi2223/Ag-sheathed wires [7]. This study investigated the conditions required to reuse a coil wound with insulated REBCO wires that had experienced a quench without damage. The study was conducted based on the temperature and current dependences of two coil stability measures, namely the maximum allowable defect (MAD) and the minimum propagation zone (MPZ) [11, 12].

2. Analysis
The MAD and MPZ were calculated using a numerical simulation analysis of the behaviour of the resistive zone caused by a local defect in a coil wire. A local defect is defined as a part of the wire where the critical current $I_{cd}$ is locally lower than the critical current $I_c$ in the defect-free part. In the analysis, it is assumed that $I_{cd}$ is uniform in the defect area. Here, the deterioration factor $\eta$ for the defect is defined as

$$\eta = (I_c - I_{cd}) / I_c$$  \hspace{1cm} (1)

Analytical model

The numerical simulation analysis was conducted based on a thermal analytical model of a winding pack of a coil wound with REBCO wires. The MAD and MPZ depend on various parameters. In this study, the simulation analysis was conducted for the winding pack model shown in figure 1, which is similar to that used in the authors’ previous study [12]. In the model, thin Cu strips are inserted between the insulated REBCO wires to make a co-winding coil for highly sensitive quench detection [13], which is considered necessary for medium and large scale YBCO coils. The REBCO wires are insulated by Kapton tape (12.5 µm thick × 2). The winding pack is cooled by thermal conduction to the cooling blocks at the bottom of the pack. In figure 1, the layers of insulated REBCO wires are labelled consecutively as $w_{-n}$, ..., $w_0$, $w_1$, ..., $w_n$. In the model, it was assumed that there is a defect of length $l_d$ in layer $w_0$ and that the temperature of the cooling block $T_0$, which corresponds to the coil operating temperature, is kept constant. Values of MAD and MPZ depend on various parameters. In this study, the simulation analysis was conducted for a case similar to that used in the reference [12]. Specifications of the REBCO wire are summarized in table 1. The following heat equilibrium equation for a wire comprising the $i$-th layer of the winding pack was used in the analysis,

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

where $T_i(x, t)$ is the temperature of the wire at $x$ in the $i$-th layer and $C_p$ [J/mK] and $K$ [W/mK] are the heat capacity and the thermal conductivity per unit length of the wire, respectively. The heat capacity of the wire insulation layer is included in the value of $C_p$. $P_i(x, t)$ [W/m] is the Joule heat per unit length of the wire in the $i$-th layer and is given by $P_i(x, t) = V_i(x, t)I_{1}(t)$, where $V_i(x, t)$ [V/m] is the resistive voltage per unit length of the REBCO wire at $x$ calculated based on the current sharing model and the $n$ value power law for the voltage-current characteristics. $h_l$ [W/mK] and $h_b$ [W/mK] are the heat transfer factors from a layer to neighboring layers and the cooling block per unit length of wire, respectively. The temperature dependences of $C_p$, $K$, $h_l$, and $h_b$ were taken into consideration in this analysis. Details of the parameters in equation (2) are in the reference [12]. The value of $I_c$, which depends on the temperature and the magnetic field component vertical to the wide face of the YBCO wire $B_{\perp}$, was determined based on data for the lift factor given in the reference [14]. In the calculation, it was assumed that the centre of the defect part is located at $x = 0$, and that the highest temperature $T_{HS}$ in the resistive zone (hot-spot temperature) is equal to $T_0(0, t)$. 


Figure 1. Thermal analytical model of winding pack of coil wound with REBCO wires.

The behaviour of the resistive zone that originated at the defect in the winding pack was investigated by numerically calculating $T_{HS}$. This was done by solving Eq. (2) for a model coil with the winding pack structure shown in figure 1 using the multi-physics modelling software COMSOL® [15]. The model coil was composed of 8 double-pancake coils, whose specifications are shown in table 2. The critical current for the model coil wire $I_c$ and the highest value of $B_\perp$ of the model coil versus the model coil current $I_0$ are shown in figure 2.

### Table 1. Specifications of REBCO wire.

| Wire                        | YBCO tape                  |
|-----------------------------|----------------------------|
| Material                    | YBCO tape                  |
| Width                       | 4.0 mm                     |
| Thickness                   | -Substrate: 75 µm          |
|                             | -Cu layer: 40 µm           |
|                             | -Ag layer: 3.8 µm          |
|                             | -Total: 120 µm             |
| Critical current (77 K, self-field) | 165 A                     |
| Thickness of Kapton insulation layer | 25 (12.5×2 half-wrap) µm |
| Cu tape for co-winding coil | Width 4.0 mm
|                             | Thickness 40 µm            |

### Table 2. Specifications of model coil.

| Sub-coil        | Double-pancake coil        |
|-----------------|----------------------------|
| Type            | Double-pancake coil        |
| I. D.           | 600 mm                     |
| O. D.           | 884 mm                     |
| Number of turns | 1354                       |
| Composed coil   |                            |
| Number of Sub-coils | 8                        |
Analytical results

2.1.1. Behaviour of resistive zone - MAD and MPZ. The MAD length, $l_{\text{MAD}}$, at a coil operational current $I_0$ is defined as follows. When $l_d > l_{\text{MAD}}$, the resistive zone in the wire that originated at the defect area keeps spreading, eventually leading to coil quenching, and when $l_d < l_{\text{MAD}}$, the coil can be operated free from quenching [12]. MAD is explained in figure 3, which shows examples of numerically calculated time traces of the hot-spot temperature $T_{\text{HS}}$ for the cases of $l_d = 5.85$ and $5.86$ cm with $I_0 = 140$ A, $T_0 = 25$ K, and $\eta = 60\%$. As shown, for $l_d = 5.85$ cm, $T_{\text{HS}}$ is steady. However, when $l_d$ is slightly increased to $5.86$ cm, thermal runaway occurs, with $T_{\text{HS}}$ suddenly and sharply rising, which may damage the wire. $l_{\text{MAD}}$ can thus be estimated to be a value between $5.85$ and $5.86$ cm.

When $l_d$ is equal to $l_{\text{MAD}}$, the resistive zone around the defect area (i.e., the area around the hot-spot) is the MPZ. In figures 4(a) and 4(b), the temperature distribution in the wire in the direction of the wire length ($x$-direction) and the layer ($y$-direction) around MPZ, respectively, are shown. As an example, figure 5 shows time traces of the voltage across the resistive zone $V_s$ for the cases shown in figures 3 and 4. The voltage $V_{\text{MPZ}}$ across the MPZ is estimated to be $6.9$ mV from figure 5. If $V_s$ appears during the operation of a coil whose winding configuration is that shown in figure 1, the coil will not quench for $V_s < V_{\text{MPZ}}$, but will quench for $V_s > V_{\text{MPZ}}$. Therefore, if a resistive voltage larger than $V_{\text{MPZ}}$ appears between the coil current terminals, the coil will be damaged unless a proper quench protection measure is taken.

Figure 2. $I_c$ and $B_{\perp}$ versus model coil current $I_0$.

Figure 3. Time traces for $T_{\text{HS}}$ at $I_0 = 130$ A for $l_d = ??$ and ?? cm.
Figure 4. Temperature distribution in wire in directions of (a) wire length (x-direction) and (b) layer (y-direction) around MPZ for $l_d$ close to $l_{\text{MAD}}$.

Figure 5. Time traces of voltage across resistive zone $V_s$ for cases shown in figures. 3 and 4.

2.1.2. Dependence of MAD and MPZ on temperature and current in coil. In figures 6(a)-(c), $l_{\text{MAD}}$ as a function of $I_0$ is plotted for various values of $T_0$ and $\eta = 60, 80,$ and 100%, respectively. As shown, $l_{\text{MAD}}$ increases as $T_0$ decreases for given values of $I_0$ and $\eta$, except for the case with $I_0 = 145$ A at $T_0 = 30$ K and 35 K, where $l_{\text{MAD}} = 0$ regardless of the value of $\eta$ because the load factor $\alpha = I_0 / I_c$ exceeds 100% (where $I_0$ is the critical current for the wire in the coil at $T_0$). When a coil quenches at $I_0 = I_{01}$ and $T_0 = T_{01}$, the results in figure 6 suggest that $l_d$ is higher than the value of $l_{\text{MAD}}$ at $I_0 = I_{01}$ and $T_0 = T_{01}$, and that the coil can potentially be reused if $T_0 < T_{01}$ and/or $I_0 < I_{01}$ are set to increase the value of $l_{\text{MAD}}$.

In figures 7(a)-(c), $V_{MPZ}$ is plotted as a function of $I_0$ for various $T_0$ and $\eta = 60, 80,$ and 100%, respectively. As shown, $V_{MPZ}$ increases as $T_0$ and $I_0$ decreases for given values $\eta$, which also indicates that the stability of the coil can be increased and reused by decreasing the values of $T_0$ and/or $I_0$. 

[Graphs and figures described in the text are not included in this text representation.]
3. Conditions required for coil reuse

If a coil that is prematurely quenched is not damaged, there is a possibility that it can be reused, as mentioned above. In the following, the conditions required to reuse a quenched coil are studied by taking two cases of a model magnet, whose specifications are shown in table 1.

3.1 Case studies

3.1.1. Case 1: Model coil designed to operate at $I_0 = 135$ A and $T_0 = 35$ K. $I_0$ can reach 135 A without quenching if there are no defects in the wire, because $\alpha$ for the model coil wire is 95% at $I_0 = 135$ A and $T_0 = 35$ K (figure 2). However, if $V_s$ at $I_0 = 120$ A starts to increase rapidly and exceeds $V_{MPZ}$ while $I_0$ is gradually increased from 0 A, that suggests that there exists a defect with a length $l_d$ just exceeding $l_{dMAD} = 2.8 - 1.2$ cm dependent on $\eta = 60$-100% of the defect (see figures 6(a)-(c)). Figure 8 shows $l_{dMAD}$ versus $T_0$ for $\eta = 60$-100% at $I_0 = 135$ A. When the magnet is safely protected from quench damage, $I_0$ can be increased to 135 A without quenching by decreasing $T_0$ to lower than 30.4 K for $\eta = 60$ and 30.6 K for $\eta = 100$, because the values of $l_{dMAD}$ at 135 A for $\eta = 60$-100% are larger than those at 120 A at $T_0 = 35$ K (see figure 8). If the coil is quenched at $I_0 = 110$ A at 35 K, then $T_0$ needs to be decreased to lower than 26.8 K for $\eta = 60$ and 27.8 K for $\eta = 100$ for $I_0$ to reach 135 A, as seen in figure 8.
3.1.2. Case 2: Model coil designed to operate at $I_0 = 145$ A and $T_0 = 30$ K. $I_0$ can reach 145 A without quenching if there are no defects in the wire, because $a$ for the model coil wire is 93% at $I_0 = 145$ A and $T_0 = 30$ K (figure 2). However, if the coil is quenched at $I_0 = 120$ A due to $V_s$ exceeding $V_{MAD}$ at 30 K, there exists a defect with a length $l_d$ just exceeding $l_{dMAD} = 0.93 – 1.86$ cm dependent on $\eta = 60-100\%$ of the defect (see figures 6(a)-(c)). Then, $T_0$ needs to be decreased to lower than 22.8 K for $\eta = 60\%$ and 24.1 K for $\eta = 100\%$ for $I_0$ to reach 145 A, as shown in figure 9, where $l_{dMAD}$ versus $T_0$ for $\eta = 60-100\%$ at $I_0 = 145$ A is shown. When the coil is quenched at $I_0 = 130$ A, $I_0$ can reach 145 A if $T_0$ is decreased to lower than 25.8 K for $\eta = 60\%$ and 26.5 K for $\eta = 100\%$.

Figure 9. $l_{dMAD}$ versus $T_0$ for $\eta = 60-100\%$ at $I_0 = 145$ A.

3.2 Safe limit of quench detection voltage.

The safe limit of quench detection voltage $V_{qs}$ is defined as follows. When $V_q$ is smaller than $V_{qs}$, 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 $T_0$, $I_0$ and the current decay time constant $\tau$ during the quench protection sequence of the detect and dump method. A value of $\tau$ is determined so that the peak of the coil terminal voltage $V_{cp} = LI_0 / \tau$ ($L$: inductance of the model coil) is to be below the withstand voltage $V_{cps}$ of the coil. Values of $V_{qs}$ were estimated by calculating time traces of $V_q$ and $T_{HS}$ during the quench protection sequence of the detect-and-dump method based on equation (2) for the above cases 1 and 2. In the calculation, it was found that values of $V_{qs}$ were estimated lowest for at $\eta = 100\%$ and 8.2 mV for both cases of $I_0 = 135$ A at $T_0 = 35K$ and $I_0 = 145$ A at $T_0 = 30K$ assuming $V_{cps} = 1$kV ($\tau = 14.7$s for $I_0 = 135$ A and 15.8s for $I_0 = 145$ A), which means the coil can be safely protected from quench by setting $V_q < 8.2$ mV, regardless the value of $\eta$. 

Figure 8. $l_{dMAD}$ versus $T_0$ for $\eta = 60-100\%$ at $I_0 = 135$ A.
3.3 Discussions

As shown in the above analysis, the coil temperature $T_{0\text{re}}$ at which a quenched coil can be used to meet the designed value of $I_0$ is dependent on the value of $\eta$. Generally, it is difficult to know the value of $\eta$. In that case, the following procedure is taken to find proper value of $T_{0\text{re}}$ when a coil is quenched prematurely while setting $V_q$ smaller than $V_{qs}$ at the designed values of $I_0$ and $T_0$ for $\eta = 100\%$. $T_0$ is adjusted to lower than $T_{0\text{re}}$ which is estimated for $\eta = 100\%$ by the method explained above. When the coil prematurely quenches again, then $T_0$ is reduced repeatedly more until for $I_0$ to meet the required value. During this procedure, the value of $V_q$ is not necessarily changed, because $V_{qs}$ increases as $T_0$ decreases.

4. Conclusions

This paper studies on the conditions required to reuse a quenched coil wound with insulated REBCO wires that was quenched before the required performance was met were studied by calculating the temperature- and current-dependent values of $l_{\text{MAD}}$. A simple way to reuse the quenched coil is to degrade the required performance which is met at the coil current smaller than the quenched current, if possible. The other way is to readjust the operating temperature of the coil. When a coil quenched at a coil current $I_0$ at coil operating temperature $T_{01}$ and was protected from quench damage, the coil can be reused by lowering $T_0$ from $T_{01}$ and increasing the quenching current until $I_0$ reaches the required value. In this study, the value of $T_0$ at which the required value of $I_0$ can be reached was estimated from the curves of $l_{\text{MAD}}$ versus $T_0$.

This study was conducted using a winding pack of a model coil. However, the results can be generalized for other types of coil, if the structure of the winding pack is known because quenching originates at a local part of the coil wire.

Acknowledgements

This work is based on results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] B. Gamble, G. Snitchler, T. MacDonald et al., “Full Power Test of a 36.5 MW HTS Propulsion Motor,” IEEE Trans. Appl. Supercond., vol. 21, no. 3, p. 1083, Jun. 2011

[2] T. Yamamoto, M. Izumi, K. Unemoto et al., “Load Test of 3-MW HTS Motor for Ship Propulsion,” IEEE Trans. Appl. Supercond., vol. 27, no. 8, p. 5204305, Dec. 2017

[3] R. Gupta, M. Anerella, P. Joshi, J. Higgins et al., “Design, Construction, and Testing of a Large-Aperture High-Field HTS SMES Coil,” IEEE Trans. Appl. Supercond., vol. 26, no. 4, p. 5700208, Jun. 2016

[4] L. Ren, Y. Xu, W. Zuo et al., “Development of a Movable HTS SMES System,” IEEE Trans. Appl. Supercond., vol. 25, no. 4, p. 5701109, Aug. 2015

[5] S. Yokoyama, J. Lee, T. Imura et al., “Research and Development of High Stable Magnetic Field ReBCO Coil System Fundamental Technology for MRI,” IEEE Trans. Appl. Supercond., vol. 27, no. 4, p. 4400604, Jun. 2017

[6] Y. Terao, O. Ozaki, S. Kawashima, et al., “Analysis of an Abnormal Event in a 3-T MRI Magnet Wound with Bi-2223 Tape Conductors,” IEEE Trans. Appl. Supercond., vol. 24, no. 3, p. 4401105, Jun. 2016.

[7] S. Awaji, K. Watanabe, H. Oguro, et al., “First performance test of a 25 T cryogen-free superconducting magnet,” Supercond. Sci. Technol., vol. 30, no. 6 p.065001 (8p), 2017

[8] M. A. Green, “Quench Protection Solutions for Magnets Fabricated with Insulated HTS Tape Conductors,” IEEE Trans. Appl. Supercond., vol. 28, no. 3, p. 17534265, Apr. 2018

[9] T. Yamaguchi, E. Ueno, T. Kato, K. Hayashi, “Quench protection of DI-BSCCO coil”, Physics Procedia 65 (2015) 225 – 228
[10] T. Ariyama, T. Takagi, T. Takao, O. Tsukamoto, R. Matsuo, N. Matsuda, “Study on Hot-Spot Temperature Limits for YBCO Epoxy-Impregnated Coil to be Safe from Damages Caused by Quenches,” IEEE Trans. Appl. Supercond., vol. 27, no. 4, art. no. 4600504, Jun. 2017

[11] O. Tsukamoto, Y. Fujimoto and T. Takao, Sep.-Oct. 2014, “Study on stabilization and quench protection of coils wound of HTS coated conductors considering quench origins – Proposal of criteria for stabilization and quench protection”, Cryogenics, vol. 63, pp. 148-154.

[12] A. Kojima, Y. Fuchida, H. Toriyama, et al., “Study on optimal thickness of copper layer of REBCO-coated wire for quench protection,” IOP Conf. Series: Materials Science and Engineering 502 (2019) 012180

[13] T. Ariyama, T. Takagi, D. Nakayama, et al., “Quench protection of YBCO coils: co-winding detection method and limits to hot-spot temperature,” IEEE Trans. Appl. Supercond., vol. 26, no. 3, art. no. 4702205, Apr. 2016

[14] N. M. Strickland and S. C. Wimbush, Dec. 2016, “The Magnetic-Field Dependence Of Critical Current: What We Really Need To Know,” IEEE Trans. Appl. Supercond., vol.27, no. 4, Art. no. 8000505.

[15] COMSOL® Multiphysics Modeling Software http://www.comsol.com/