Title: Study on stabilization and quench protection of coils wound of HTS coated conductors considering quench origins– Proposal of criteria for stabilization and quench protection

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Abstract

It has been considered that HTS coils are hard to be quenched because of high quench energy due to high critical temperature and high specific heat of HTS wires. Therefore, attention to quench protection was not much paid. However, HTS coils still have possibility to be quenched during operation by mainly the following two origins, a) presence of non-recoverable local defects in the conductors and b) temperature rise of long part of the conductor. Actually, severe quench accidents, such as burning coils, are occurring in various places as scales of HTS increased. Purposes of this paper are to study on behaviors of normal zone and hot spot temperature of wires during quench detect / energy dump sequence and to find criteria for the stability and quench protection. In the paper, criteria are proposed for stability and quench protection of HTS coils. A criterion for the stability is that a coil can be operated stably without a quench against defects in coil windings and that for quench protection is that a coil can be safely protected from damages caused by a quench due to temperature rise of long part of coil wires. The criteria are used as design rules for HTS coils.

Key words: HTS coil, stability, quench protection, coated conductor, criteria

1. Introduction

In recent years, HTS conductors and wires are commercially available and projects to develop practical apparatuses using HTS coils, e.g. generators and motors, NMR and SMES, are conducted in various countries. In those projects, importance of quench protection is recognized. It has been considered that HTS coils are hard to be quenched because of high quench energy due to high critical temperature and high specific heat of HTS wires. Therefore, attentions to quench protection have been not much paid. This is true for small scale experimental models. However, it is found that as scales of HTS apparatuses increase damages in coils caused by quenches become severer. Actually, severe quench accidents, burning coils, have occurred in various places, though few of them are reported openly [1].

Quenches caused by transient disturbances such as conductor motions which are most common in LTS magnet are very rarely in HTS coils. However, HTS coils still have possibility to be quenched in operation by mainly the following two causes;

- a) Non-recoverable local defects in the conductors which exist originally in HTS wires and is enlarged by fatigue effect due to repeated mechanical stresses during operation.
- b) Temperature rise of long part of the conductor due to malfunction of cryogenic system and electromagnetic losses generated by changing magnetic field, for example.

In the case of quench by the cause a), generally the coil cannot be reused if the coil current does not reach the rated operation current because the defects causing quench is permanent and training effects, as are observed in LTS coils, are not expected. On the other hand, in the case of quench by cause b) coils can recover the superconducting state and be reused when the coils are properly protected from the quench.

Coils wound of HTS wires are stabilized by attaching low resistive normal metals such as Cu (and/or Ag) to suppress Joule heating in resistive zone. If the wire is not stabilized, a coil is easily quenched and damaged when resistive zone appears in the wire during operation. Spreading velocity of resistive zone in

HTS wire is generally less than several cm/s and much lower than that of LTS wire. Therefore, Joule heating concentrates in the narrow resistive zone where a hot spot appears during quench protection sequence and the maximum temperature of the hot spot (T_{HS}) tends to be high. By attaching Cu stabilizer to wires, coils can be protected from damages suppressing T_{HS} below safe level. Most works on the quench issues are devoted to protection and stabilization of quenches by the cause a) [2]-[8]. In those works, however, relation between size of defects in HTS of coil wires and amount of the stabilizer is not well studied and criteria for stabilization relating to size of the defects are not clarified. Protection against quenches by the cause b) is not well studied though there is a work on this subject [9].

Amount of the stabilizer should be determined not to be excessive because large amount of the stabilizer greatly spoils merit of HTS coils. In a case of a coil wound of HTS coated conductors (CCs) a calculation shows that necessary thickness of copper stabilization layer is around 400 μm to keep T_{HS} below 300K, if CCs are adiabatic [9]. This thickness is beyond a practical level spoiling the merit of use of HTS, because current density of winding pack of coils is much reduced. According to opinions of R&D engineers, thickness of Cu layer should be less than $\sim 150 \mu\text{m}$ for practical applications such as field coils of ship propulsion motors, NMR and SMES [10]. The amount of the stabilizer can be reduced by improving cooling condition of coil wires by making coil winding structure so that the CCs contact directly to coolant. However, this is also impractical because rigidity and current density of the coil windings are much spoiled. In most common cases, HTS coils are tightly wound and conduction cooled to make the coils rigid and of high current density, which means that cooling condition is poor.

Purposes of this paper are to study on the following questions:

- i) Can HTS coils be stabilized and protected from damages caused by quenches with practical amount of stabilizer in a poor cooling condition of conduction cooling?
- ii) What are criteria for stabilization and quench protection to get rid of quench damages in those constraints?

In this paper, to clarify points of the issues, it is assumed that coils are wound of CCs and conduction cooled. The results of the studies are easily extended to Bi/Ag-sheathed wires. For this study origins of quenches should be taken into consideration. In the paper necessary amount of Cu stabilizer to stabilize and protect a coil from damages caused by quenches are studied considering characters of origins of quenches by simulation studies and criteria for stabilization and quench protection are proposed.

There are works to improve thermal stability of HTS coils using non-insulation winding method [11]. The authors consider that this method is effective to DC or quasi-DC coils but is not applicable to field coils of rotating machines and SMES where frequent changes of coil currents are required. HTS wires of those coils need insulation and attention to the stability and quench protection needs to be paid.

2. Analytical model

2.1 Structure of CC and equivalent circuit of current distribution in CC

Structure of a model conductor used in the analysis is illustrated in Fig. 1, where w is the width of the conductor and d_{Cu} , d_{Ag} , d_s , d_b , and d_{sub} are thicknesses of the copper, silver, YBCO, buffer, and substrate layers, respectively. The copper stabilization layer is plated to the silver protection layer on the YBCO

layer.

When the temperature of the conductor carrying transport current I_t rises, the critical current of the superconducting layer I_c decreases and if I_c becomes lower than I_t , sharing currents start to flow in the silver and copper layers. Current-sharing part of the conductor becomes resistive and dissipates heat. Temperature dependence of I_c is approximated as follows. **In the analysis here, I_c is defined at $V_0=1\mu\text{V/cm}$.**

$$I_c = \begin{cases} I_{c0} \frac{T_c - T}{T_c - T_{op}} & T_{op} \leq T \leq T_c, \\ 0 & T > T_c \end{cases} \quad (1)$$

where T and T_{op} are the conductor temperature and operation temperature of the coil, respectively. I_{c0} is the critical current of the YBCO layer at T_{op} . The critical temperature T_c is assumed to be 44.3 K in the calculation. Assuming that distributions of currents in the silver, copper layers and superconducting layer are uniform in the cross sections of the corresponding layers and dividing the CC in small sections in the longitudinal direction, an equivalent circuit model for current distributions in layers of the CC can be formed as shown in Fig. 2, where $I_{Cu}[i]$, $I_{Ag}[i]$ and $I_{Su}[i]$ are currents in Cu, Ag and HTS layers in the i th section, respectively and $R_{Cu}[i]$, $R_{Ag}[i]$ and $R_{Su}[i]$ are resistances of Cu, Ag and HTS layers in the i th section. R_{Su} is given by the following equation based on the n value model,

$$R_{Su}[i] = V_0 I_t^{n-1} / I_{ci}^n, \quad (2)$$

where I_{ci} is critical current of i th section defined at $V_0=1\mu\text{V/cm}$.

2.2 Thermal equilibrium equation

The following one dimensional thermal equilibrium equation is formed for CC.

$$C_p \frac{\partial T(x,t)}{\partial t} = \frac{\partial}{\partial x} \left\{ K \frac{\partial T(x,t)}{\partial x} \right\} + P - h(T - T_{op}) \quad (3)$$

where K [Wm/K] and C_p [J/mK] are the thermal conductivity and heat capacity per unit length of the conductor given by composition rule, respectively. P [W/m] is joule heat per the unit length of the conductor and $P=0$ for $I_t < I_c$ and $P=V_t I_t$ for $I_t > I_c$ where V_t [V/m] is voltage per the unit length of CC across the region of $I_t > I_c$. h [W/mK] is heat transfer factor, that is, the heat transfer per the unit length of the conductor per unit temperature differences to neighboring layers and a cooling plate. Time evolutions of conductor temperature profile can be numerically calculated by combining the equivalent circuit equation of Fig. 2 and Eq. (3). Details of calculation method are the same as in described in the reference [7]. T_{HS} is estimated from the calculated time evolutions of conductor temperature profile during sequence of quench detection and energy dump.

2.3 Quench protection sequence

It is assumed that the coil is protected by a commonly used sequence as follows. A quench in the coil is detected by monitoring the voltage across the resistive part of the conductor V_q using a bridge balancing

method. When V_q exceeds a threshold level V_{qs} , the power supply is disconnected from the coil and stored energy of the coil is dumped to the dump resistor R_D . Usually, there is a time delay t_d to start energy dump after detection of quench. Decay of the coil conductor current $I_t(t)$ is given by the following for $t > t_d$,

$$I_t(t) = I_{t0} \exp\{-(t - t_d)/\tau\}, \quad (3)$$

where I_{t0} is the value of I_t at $t = 0$ when the quench is detected and $\tau = L_c/R_D$ is the energy dump time constant (L_c is the inductance of the coil). To protect the coil from a damage caused by a quench, the conductor and quench protection system should be designed so that T_{HS} should not exceed a certain threshold.

3. Model conductor analysis

To obtain a value of T_{HS} , using the analytical model described in the previous section time evolution of temperature profile of the model CC is numerically calculated for various conditions of cooling, that is for various values of h in Eq. 3. Parameters of the model conductor are assumed as shown in Table I. Temperature dependencies of specific heats and resistivities of the conductor materials are taken into consideration in the calculation according to the data given in the reference [12]. In the calculation it is assumed that when a resistive zone caused by a) a local and non-recoverable defect or b) temperature rise of long part of conductor starts to spread at $t = 0$ and V_q grows to exceed V_{qs} , I_t decreases at time constant τ with time delay of t_d . In this analysis, the operation temperature T_{op} is assumed to be 37 K. Table II shows the assumed operating conditions of the model conductor and parameters of quench dump sequence.

3.1 Quench caused by local and non-recoverable defect and maximum allowable size of defect

T_{HS} is obtained for local defect of length L_d in the longitudinal direction of CC. It is assumed in the calculation that critical current in the defect area I_c' is 0 or 50% of I_{c0} . Calculations are done for practical values of d_{cu} less than 150 μm . Fig. 3 (a) and (b) shows T_{HS} vs. L_d for $I_c' = 0$ and 50% of I_{c0} , respectively in a case that $h = 0.4 \text{ W/mK}$, $V_{qs} = 0.1 \text{ V}$ and $d_{cu} = 50, 100, 150 \mu\text{m}$. Obviously from Fig. 3 there is a threshold value of L_d , L_{MAD} , where resistive zone caused by a local defect does not grow and V_q is kept much lower than V_{qs} for $L_d < L_{MAD}$, and for $L_d > L_{MAD}$ T_{HS} jumps well over 1000K sharply for both cases of $I_c' = 0$ and 50% of I_{c0} . Fig. 4 shows an example of time evolution of temperature profile of CC calculated for the case that $L_d > L_{MAD}$ and temperature of the CC goes quickly over 1000K in less than 1 s once the temperature starts to rise. There exists the threshold value L_{MAD} for the practical values of d_{cu} . We call L_{MAD} maximum allowable size of defect (MAD). MAD depends on h , I_c' , d_{cu} and operating conditions of a coil. Fig. 5 (a) and (b) shows L_{MAD} vs. h for $d_{cu} = 50, 100$ and $150 \mu\text{m}$ in the cases of $I_c' = 0$ and 50% of I_{c0} , respectively. Fig. 5 is obtained for $\tau = 10 \text{ s}$ and $t_d = 0.2 \text{ s}$. Calculations show that values of L_{MAD} are slightly dependent on τ and V_{qs} for defects of $I_c' = 0$ as shown Fig. 6 (The same calculation was conducted for $I_c' = 50\%$ of I_{c0} and the result was the same). It is considered that this is because temperature of CC rises quickly as shown in Fig 4 at the beginning of the quench dump sequence where I_t is not much decreased from I_{t0} and heating power at the beginning of the temperature rise of the CC which dominates value of

L_{MAD} is not much changed by the values of V_{qs} and τ .

The neighboring layer are heated by heat generated in the defected layer and become resistive to generate heat. We found by a calculation taking this effect into consideration that influence on this effect on values of L_{MAD} were negligibly small, though that accelerates temperature rise of the defected layer. Therefore, this effect is neglected in the above calculation.

From the above study the following conclusion is obtained. Value of L_{MAD} of CCs can be calculated knowing parameters of CC's and operating conditions of a coil and a coil can be stably operated at given operating conditions when sizes of defect parts are smaller than L_{MAD} regardless for defects originally existing or expanded by mechanical stresses during operation.

3.2 Quench caused by temperature rise of long part of conductor

When temperature of a part of a coil increases due to malfunction of cooling system, for example, coil conductor there becomes resistive in the range where I_t exceeds I_c . When the voltage across the resistive region V_q exceeds V_{qs} , a quench is detected and quench protection sequence starts. In the calculation it is assumed for the simplicity of the study that the conductor temperature distribution in the resistive region is uniform and **temperature of other non-resistive part is at the temperature of normal operation when the quench protection sequence starts (that is this temperature distribution is assumed as the initial condition of the wire temperature calculation)**. Fig. 7 shows a graph of T_{HS} vs. length of resistive zone of the conductor L for the operating condition of Tab. II in the case of $d_{Cu} = 50, 100, 150 \mu m$ and $h = 0.4$ W/mK. As seen in Fig. 7, for L below a certain critical length L_{MALRZ} T_{HS} sharply increases well over 1000 K. Fig. 8 shows a time evolution of temperature profile of CC in a case that L is shorter than L_{MALRZ} . When L exceeds L_{MALRZ} T_{HS} is slightly above current sharing temperature T_{sh} at which I_t equals to I_c when a quench is detected, and after the energy dump the coil recovers the superconducting state and is safely protected. We call this threshold L_{MALRZ} minimum allowable length of resistive zone (MALRZ). Fig. 9 shows curves of L_{MALRZ} vs. h for $d_{Cu} = 50, 100, 150 \mu m$ in the case of $\tau = 10$ s and $V_{qs} = 0.1$ V. **When h is high, the CC is well cooled. For the higher value of h the higher dissipation in the CC is necessary for its temperature to reach threshold that the voltage across the resistive zone to exceed V_{qs} . Therefore, the higher dissipation causes the higher voltage per unit length of the resistive zone and MALRZ becomes the shorter as shown in Fig. 9.** It is found by a calculation changing τ for $V_{qs} = 0.01$ and 0.1 V that dependence of L_{MALRZ} on τ is very small for $\tau > 10$ s as shown in Fig. 10. This result is because the temperature of CC rises quickly at the beginning of the quench dump sequence as shown in Fig. 8 where I_t is not much decreased from I_{t0} and heating power at the beginning of the temperature rise of the CC is not much changed by τ . An experiment was conducted by a Sumitomo Electric Industry group where operating temperature of a coil of Bi/Ag sheathed wire was increased gradually until resistive voltage of the coil exceeded V_{qs} to start quench dump sequence and damages in the coil were observed [13]. A result of the experiments supported the simulation result that L_{MALRZ} is not dependent on τ . If d_{Cu} is large enough, a value of L_{MALRZ} is dependent on τ . The dependence on values of V_{qs} is significant. L_{MALRZ} for $V_{qs} = 0.01$ V is smaller than that for $V_{qs} = 0.1$ V by almost one order of magnitude. This result means that sensitive quench detection of $V_{qs} = 0.01$ V can protect a coil where appears a resistive zone much shorter, by one order of magnitude, than the limit of

length of the resistive zone for quench detection of $V_{qs} = 0.1V$.

To obtain the above results, effect of heat generation in the layers neighboring to the temperature rising parts is neglected, because they are still in superconducting state when a quench is detected. Fig. 8 is an example of time evolution of temperature profile of the model CC for $L < L_{MALRZ}$ and temperature of the CC rises quickly well over 1000K in about a half second. This is a reason that dependence of the curves on τ is very small. Obviously from Figs. 6 and 7, L_{MALRZ} is larger as d_{Cu} is larger. This is because L is longer and temperature of the CC in the resistive zone higher in the case of higher d_{Cu} when a quench is detected.

From the above study, it is concluded that if a long resistive zone appears in a weak part of poor cooling condition or in a part of low critical current is longer than L_{MALRZ} a coil can be protected and that, otherwise, the coil is damaged when it is **quenched**.

3.3 Case study

MAD and MALRZ are calculated taking an example model of a conduction-cooled pancake coil. Cross section of the pancake coil is shown in Fig. 11. The coil is wound of the model CCs whose specifications are given in Table I and the parameters of quench dump sequence are given Table II. The CCs are twice half-wrapped with 12.5 μ m thick Kapton insulator. One sides of the edges of the CCs contact to a Cu cooling plate via Kapton insulator and 0.2 mm thick GFRP plate and the innermost layer contacts to the cooling plate also via Kapton tape insulator and 0.2 mm thick GFRP plate. The cooling plate is connected to a cold head of a cryocooler and it is assumed temperature of the cooling plate is fixed to 37K. Each of the coil layers is cooled by thermal conduction to the cooling plate at its edge and to neighboring layers through the Kapton insulator. Number of turns of the coil is 250 and $m=1,2,\dots,250$ denote the first, second, i -th, and 250th layer from the innermost layer, respectively. Fig. 12 shows heat transfer factor h of i -th layer estimated from the calculated temperature distribution assuming that i -th layer is heated. In the temperature calculation it is assumed that there is thermal surface resistance ρ_s [m^2K/W] at the boundary between the layers of CCs with Kapton insulator. The value of ρ_s varies depending on contact pressure between layers, operating temperature, impregnation material, etc. and $\rho_s = 0.008 m^2 K / W$ per layer is assumed in this study which is about 8 times of the thermal resistance of 50 μ m thick Kapton. This value of ρ_s is estimated by a preliminary experiment where a tape heater was inserted among a pack of Kapton insulated HTS wires cooled by conduction cooling using copper cooling plates. As seen in Fig 12, values of h is dependent on the position of the heated layer m . Exactly speaking, h depends also on value of heat dissipation P . However, the dependence is small in the temperature range to determine the value of MAD.

Fig. 13 (a) and (b) shows curves of L_{MAD} vs. m of the model coil of Fig. 11 for $d_{Cu} = 50, 100, 150\mu$ m in cases of $I_c \hat{=} 0$ and 50% of I_{c0} , respectively, which are determined from Figs. 6 and 12. As seen in Fig. 13, in a case of a defect of $I_c \hat{=} 0$, L_{MAD} of the CC in the outermost layer is smallest and 0.3 mm for $d_{Cu} = 50\mu$ m, which means that the coil operation can be continued without quench for $d_{Cu} = 50\mu$ m if the size of a defect is less than 0.3 mm. However, if a defect larger than 0.3 mm exists in the outermost layer, the coil is damaged by a quench. When a defect exists only in the innermost layer where a defect occurs most probably because generally mechanical stresses to CC is the highest in the coil winding, the coil is safe

against a defect of less than 0.8 mm. For a defect of $I_c' = 50\%$ of I_{c0} , L_{MAD} is 3 mm. When d_{cu} is increased to 100 μm , the coil can be operated stably if size of a defect of $I_c' = 0$ is less than 1.7 mm and in a case of a defect of $I_c' = 50\%$ of I_{c0} , the coil can be operated stably for a defect less than 8 mm, wherever the defect exists. In a case of $d_{cu} = 150 \mu\text{m}$ the coil is safe even for a defect of $I_c' = 0$ up to 12 mm.

L_{MALRZ} of the model coil can be estimated from Figs. 9 and 12 and 2.8 ~6.1 m for $d_{cu} = 50 \mu\text{m}$, 3.5~7.4 m for $d_{cu} = 100 \mu\text{m}$ and 4.0~7.8 m for $d_{cu} = 150 \mu\text{m}$ depending on where the resistive zone appears. L_{MALRZ} is shorter for the zone close to the innermost layer than that for the zone close to the outermost layer. For an example of a case of $d_{cu} = 50 \mu\text{m}$, if length of the resistive zone L is longer than 6.1 m when V_q exceeds $V_{qs} = 0.1$ V and quench dump sequence starts, the coil gets rid of damages wherever the resistive zone appears and if the resistive zone appears only in the inner most layer, the coil is safely protected from quench for L above 2.8 m.

4. Discussions

Values of L_{MAD} and L_{MALRZ} can be adjusted to designed values by changing amount of copper stabilizer d_{cu} and heat transfer factor h by design of coil cooling structure, though there are limits to adjustable range considering practicability. A problem is to find how much possible values of L_d and L are.

Sizes of originally existing defects L_d in CCs as manufactured can be limited below sub-cm by screening test using a commercially available tester to measure local critical current and L_{MAD} can be set sub-cm. Most probable defects that newly appear during operation are caused by repeated stresses to CCs. From a result of SEM observation of CCs subjected to repeated stress it is estimated that L_d does not exceed 0.1 mm [14]. Therefore, originally existing defects are major ones to consider about. The smallest value of L_{MAD} of the pancake coil of the case study in the previous section is 8 mm for $I_c' = 50\%$ of I_{c0} and $d_{cu} = 100 \mu\text{m}$. Then, the pancake coil can be stably operated by making the coil using CCs of $d_{cu} = 100 \mu\text{m}$ without defects whose I_c' is lower than 50% of I_{c0} for more than 8 mm. Such CCs can be selected using a local critical current measurement tester. If $d_{cu} = 50 \mu\text{m}$, the minimum L_{MAD} is 0.3 mm for a defect of $I_c' = 0$ the coil has high risk to burn out because it is difficult from the stand point of the yield to make CCs without defects of 0.3 mm in the whole length of CC.

The length of resistive zone L can be estimated by investigating sizes of area where cooling can be weaker and area where perpendicular magnetic field component to wide face of CC is higher (critical current of CC I_c is lower there) than those in the surrounding areas. CCs in those areas become resistive earlier than those in the surrounding areas when coil temperature rises. If estimated value of L is longer than 7.5 m, the coil of the case study is safely protected from the quench damages for $d_{cu} = 100 \mu\text{m}$ wherever resistive zone appears.

As a conclusion, it is possible to make the pancake coil of the case study stable and free from quench damages using CCs of $d_{cu} = 100 \mu\text{m}$ by proper screening of CCs and designing cooling system to follow the criteria MAD and MALRZ.

A value of L_{MAD} can be increased and a value of L_{MALRZ} can be decreased by putting V_{qs} smaller. However, small V_{qs} makes quench detection system sensitive to noises and causes misdetection frequently. Generally speaking, V_{qs} is at least 0.1 V in real HTS apparatuses [15].

5. Conclusions

It is considered that a quench of an HTS coil is caused mainly by two origins, that is, a defect in coil wire where critical current is degraded and resistive zone appearing in long part of wire. By a numerical simulation study on a coil wound of model CCs, criteria for stability, MAD and for quench protection, MALRZ are proposed. Results obtained in this work are easily extended to a coil wound of Bi/Ag sheathed wire.

An HTS coil can be stably operated getting rid of quench even when defects appear in CCs, provided that sizes of the defects are smaller than L_{MAD} , a value of MAD. However, if a defect is larger than L_{MAD} the coil gets burned even when quench dump system functions properly. A coil is protected from damages caused by a quench due to temperature rise of long part of CC, provided that the length of resistive zone L caused by the temperature rise is larger than L_{MALRZ} , a value of MALRZ. If $L < L_{MALRZ}$, a coil also gets burned during quench / dump sequence.

There are other conceivable origins of quenches, an over current beyond a rated operation value and temperature rise of CCs due to electromagnetic losses caused by fluctuation of magnetic field. The former origin can be taken care by obtaining MAD for a possible value of an over current and the latter one by evaluating length of resistive zone caused by the electric magnetic losses and comparing it with L_{MALRZ} .

Values of L_{MAD} and L_{MALRZ} are determined based on knowledge on size and characteristics of possible defects by giving operating condition of a coil and parameters of quench protection system. Once values of L_{MAD} and L_{MALRZ} are determined, amount of copper stabilizer d_{cu} and heat transfer factor h can be determined. A value of h can be adjusted by design of cooling structure of a coil. To determine values of L_{MAD} and L_{MALRZ} more reliable and accurate, it is necessary to study about sizes and characters of defects, especially about defects which are created by repeated mechanical stresses. It is important from the engineering stand point to develop an instrument which can continuously measure local distribution of critical current with high resolution.

As a conclusion of this study, stable and quench-damage free HTS coils can be made using CCs with practical thickness Cu stabilizer by designing them to satisfy the criteria MAD and MALRZ.

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TABLE I

DIMENSIONS OF MODEL YBCO COATED CONDUCTOR

w	Conductor width	$4.0 \times 10^{-3} \text{ m}$
d_{Cu}	Copper layer thickness	Variable
d_{Ag}	Silver layer thickness	$5.0 \times 10^{-6} \text{ m}$
d_s	YBCO layer thickness	$1.0 \times 10^{-6} \text{ m}$
d_b	Buffer layer thickness	$0.1 \times 10^{-6} \text{ m}$
d_{sub}	Substrate layer thickness	$50.0 \times 10^{-6} \text{ m}$

TABLE II

ASSUMED OPERATING CONDITIONS OF MODEL CONDUCTOR AND

PARAMETERS OF QUENCH DUMP SEQUENCE

Operating temperature T_{op}	37 K
Current sharing temperature T_{sh}	39.5 K
Critical temperature of conductor	44.3 K
Critical current of conductor at $T_{op} = 37\text{K}$	306 A
Operating coil conductor current I_{θ}	200A
Energy dump time constant τ	10 s
Time delay between quench detection and start of energy dump t_d	0.2 s
Threshold voltage for quench detection V_{qs}	0.1 V

Figure captions

Fig. 1 Model coated conductor (CC) with copper stabilizer.

Fig. 2 Equivalent circuit of model CC.

Fig. 3 Hot spot temperature T_{HS} vs. length of defect L_d .

(a) Critical current of defect area $I_d' = 0$

(b) Critical current of defect area $I_d' = 50\%$ of critical current of non-defected CC I_{c0} .

Fig. 4 Example of time evolution of temperature profile of CC calculated for the case that length of defect L_d exceeds threshold value L_{MAD} for $I_d' = 0$, $h = 0.4$ W/mK, $d_{cu} = 50\mu\text{m}$, $L_d = 1.5$ mm, $V_{qs} = 0.1$ V, $t_d = 0.2$ s and $\tau = 10$ s.

Fig. 5 Maximum allowable size of defect (MAD) L_{MAD} vs. heat transfer factor h for thickness of copper stabilization layer $d_{Cu} = 50, 100, 150$ μm ($\tau = 10$ s).

(a) $I_c' = 0$

(b) $I_c' = 50\%$ of I_{c0} .

Fig. 6 Dependences of L_{MAD} on τ and V_{qs} ($I_d' = 0$, $h = 0.4$ W/mK, $d_{cu} = 100\mu\text{m}$, $t_d = 0.2$ s)

Fig. 7 T_{HS} vs. length of resistive zone of the conductor L for the operating condition of Tab. II for $V_{qs} = 0.1$ V, $h = 0.4$ W/mK and $\tau = 10$ s in the cases of $d_{Cu} = 50, 100, 150$ μm .

Fig. 8 Example of time evolution of the model CC in a case of $L = 2.3$ m $< L_{MALRZ}$ for $d_{Cu} = 50$ μm , $h = 0.4$ W/mK, $V_{qs} = 0.1$ V and $\tau = 10$ s.

Fig. 9 Minimum allowable length of resistive zone (MALRZ) L_{MARZ} vs. h for $d_{Cu} = 50, 100, 150$ μm in the case of $\tau = 10$ s and $V_{qs} = 0.1$ V

Fig. 10 Dependence of L_{MALRZ} on τ and V_{qs} for $h = 0.4$ W/mK, $d_{cu} = 100\mu\text{m}$, $t_d = 0.2$ s.

Fig. 11 Cross section of conduction cooled model pancake coil for case study.

Fig. 12 Heat transfer factor h of i -th layer of conduction cooled model pancake coil

Fig. 13 L_{MAD} vs. m of model pancake coil of Fig. 9 for $d_{Cu} = 50, 100, 150$ μm ,

(a) $I_c' = 0$ and 50% of I_{c0} ,

(b) $I_c' = 50\%$ of I_{c0} ,

Fig. 1

Fig. 2

Fig. 3(a)

Fig. 3(b)

Fig. 4

Fig. 5(a)

Fig. 5(b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13(a)

Fig. 13(b)