Quench protection of HTS coil composed of multiple Sub-pancake-coils by changing current distribution in sub-coils

Outline

- Background
- Proposed quench protection
- Effectiveness of proposed method - Case study
  - Magnetic field and circuit simulation
  - Hot-spot temperature analysis
- Concluding remarks
Background

HTS coils are key components of HTS applications. ⇒ For these sustainable operation, Quench protection is important.

Damage to HTS coil
→ Over heating at hot-spot during quench protection
→ Easily damaged if quench protection system does not work properly
Ordinary quench protection method

Detect-and-dump type method

For safe quench protection, values of quench detecting voltage $V_q$ and time decay constant $\tau$ should be as small as possible.

Reduction of the value of $\tau$ is restricted by a value of $L$ and withstand voltage of the coil.

\[ I_t = I_0 \left( -\frac{t}{\tau} \right) \]

\[ \tau = \frac{L}{R_1} \]

$L$: inductance of the coil

$R_L$: resistance of the dump resistor

\[ V_q \]

\[ I_t \]

\[ S_I \]

$R_{d\text{iode}}$

$R_I$

Dump resistor

DC

Coil 1

Coil 2

Coil 3

Coil 4

Cryogenic
Proposed method of quench protection

$B_r$: the perpendicular magnetic field component to wide faces of the wires

$B_r$ in the top and bottom sub coils are larger than those of middle sub coils.

$I_c$ of the wires of Sub-coils 1 and 8 are lower than those of Sub-coils 2 - 7.

Quench starts most probably in Sub-coils 1 or 8 that has lower $I_c$

if the current of Sub-coils 1 and 8 is transferred to Sub-coils 2-7 when quench occurs in Sub-coil 1 or 8, the $T_{HS}$ of Sub-coil 1 or 8 can be suppressed.
Proposed method of quench protection

Resistive-short method

Quench protection sequence

Quench is detected
Switch $S_1$ is opened
$S_2$ is closed to resistive short coils with resistance $R_2$

Current in Sub-coils 1 and 8 $I_t$ quickly decreases
Current in Sub-coils 2–7 $I_m$ increase temporarily due to magnetic coupling between coils
Joule heating in Sub-coils 1 or 8 is decreased for hot spot temperature to be suppressed

The value of $R_2$ is adjusted so that the increased of $I_m$ does not quench Sub-coils 2-7
Electric circuit and magnetic field analyses of proposed method - Case study

Calculation model

<table>
<thead>
<tr>
<th>Specification of model coil</th>
<th>Wire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Bi / Ag sheathed tape</td>
</tr>
<tr>
<td>Width</td>
<td>4.3 [mm]</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.23 [mm]</td>
</tr>
<tr>
<td>Critical Current</td>
<td>180 [A] (at 77 [K], self field)</td>
</tr>
<tr>
<td>Insulation</td>
<td>Kapton Double-wrap of 1.25 [μm]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>I. D</td>
</tr>
<tr>
<td>O. D</td>
</tr>
<tr>
<td>Number of turn</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composed coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of element coils</td>
</tr>
<tr>
<td>Inductances</td>
</tr>
<tr>
<td>-Self inductance</td>
</tr>
<tr>
<td>• Element coil</td>
</tr>
<tr>
<td>• Composed coil</td>
</tr>
<tr>
<td>Mutual inductance</td>
</tr>
<tr>
<td>• Between Coil 1 (or Coil 8) and Coil combined of Coil 2 – 7</td>
</tr>
<tr>
<td>• Between Coil 1 and Coil 8</td>
</tr>
</tbody>
</table>
Magnetic field of model coil

Distribution of perpendicular magnetic field component to the wide face of the wire $B_r$

- Peak values of $B_r$ in Sub-coils 1 and 8 are about 1.4 times higher than those of Sub-coils 2 and 7.
- $I_c$ of Sub-coils 2 - 7 are higher than those of Sub-coils 1 and 8 by about 38 % at 40 K in the case of Bi / Ag sheathed tape wires (Based on Sumitomo’s in-house data).
Current of model coil

$\tau = 10\ s, \ R_2 = 1.5R_1$

$\tau_1 = 0.07\ s, \ \tau_2 = 19\ s$

Sub-coils 1 and 8

$$I_t(t) = I_0 \left\{ A \exp\left(-\frac{t}{\tau_1}\right) + (1 - A) \exp\left(-\frac{t}{\tau_2}\right) \right\}$$

Sub-coils 2 - 7

$$I_m(t) = I_0 \left\{ B \exp\left(-\frac{t}{\tau_1}\right) + (1 - B) \exp\left(-\frac{t}{\tau_2}\right) \right\}$$

$\tau_1 < \tau < \tau_2$

$$\tau_1 = (1 + \alpha \beta) \frac{\tau}{2} + \frac{\sqrt{(1 + \alpha \beta)^2 L_{All}^2 - 4C\alpha}}{2R_1}$$

$$\tau_2 = (1 + \alpha \beta) \frac{\tau}{2} - \frac{\sqrt{(1 + \alpha \beta)^2 L_{All}^2 - 4C\alpha}}{2R_1}$$

$I_t$ decreases quickly and $I_m$ increases temporarily and decreases. The hot spot is suppressed by fast decreasing current of quenching coil.
Voltage of model coil

During the quench protection sequence with the resistive-short $V_0$ does not exceed that in the case of ordinary quench protection →the total voltage of the resistive short does not exceed that of ordinary method, even though coil currents of Sub-coils 1 and 8 change quickly

$\tau = 10$ s and $R_2 = 1.5R_1$

$V_0$: Sub-coils 1-8
$V_1$: Sub-coil 1
$V_m$: Sub-coils 2-7
Magnetic field during quench protection sequence

\[ \tau = 10 \text{ s and } R_2 = 1.5R_1 \]

Peak value of \( B_r \) in Sub-coils 2 and 7 for the proposed method does not exceed peak value of \( B_r \) for the ordinary method.

Possibility of quench starting in one of Sub-coils 2-7 is still lower than that in Sub-coil 1 or 8

By adjusting \( \alpha(= R_1/R_2) \), Quenches of Sub-coil 2-7 can be prevented.
Analytical model

Winding pack of Sub-coil

Defect area (Length $I_d$, $I_c = 90$ A)
Normal area ($I_c = 180$ A)

Heat equilibrium equation

$$C_p \frac{\partial T_i(x,t)}{\partial t} = \frac{\partial}{\partial t} \left( K \frac{\partial T_i(x,t)}{\partial x} \right) + P_i(x,t)$$

- Thermal conductivity [W/mK]
- i Layer joule heat [W/m]
- Heat transfer [W/mK] to both side layer
- Heat transfer [W/mK] to both side layer

Heat capacity [J/mK]

12.5 μm thick Kapton tapes × 2
0.2 mm thick GFRP sheet

Layer with defect

Cooling block B/Ag-sheathed wore wrapped

Analytical model

\[ I_t(t) = I_{sci}(x,t) + I_{Agi}(x,t) \]

\[ V_i(x,t) = I_{Agi}(x,t)R_{Ag}(T_i) \]

\[ V_i(x,t) = V_o \left( \frac{I_{sci}(x,t)}{I_C(B_i,T_{CB})} \right)^{n(B_i,T_i)} \]

\[ P_i(x,t) = V_i(x,t)I_t(t) \]

Coil is safe from damages caused by a quench when the quench detecting voltage is below the safe limit of quench detecting voltage \( V_{qs} \).
Analytical results

Coil current: $I_0 = 250$ A, Defect length $I_d = 4.5$ cm, Detect area $I_c = 90$ A

(a) Ordinary quench protection

- $V_q = 0.068$ [V] ⇒ Thermal runaway (606 [K])
- $V_q = 0.067$ [V] ⇒ Protected

(b) Resistive-short of $\alpha = 1.5$

- $V_q = 0.213$ [V] ⇒ 491 [K]
- $V_q = 0.168$ [V] ⇒ 354 [K]
- $V_q = 0.131$ [V] ⇒ 271 [K]
Simulation results

The safe limit of quench detecting voltage $V_{qs}$ is enlarged by using resistive-short method.

(a) $I_0 = 250\ A$, $\tau = 10\ s$, $\alpha = 1.5$

(b) $I_0 = 250\ A$, $\tau = 30\ s$, $\alpha = 1$
Concluding remarks

• Resistive-short method is proposed to reduce hot spot temperature $T_{HS}$ of coil composed of multiple coils.

• In resistive-short method, current in quenching sub coil is transferred to the other sub coil by shorting the other coil with a resistor.

• The safe limit of detection voltage $V_{qs}$ is increased in the case of resistive-short method comparing with the case of ordinary quench protection method.

• In the case of a short time decay constant $\tau$, thermal run-away can be prevented.

Thank you for your attention