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

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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.

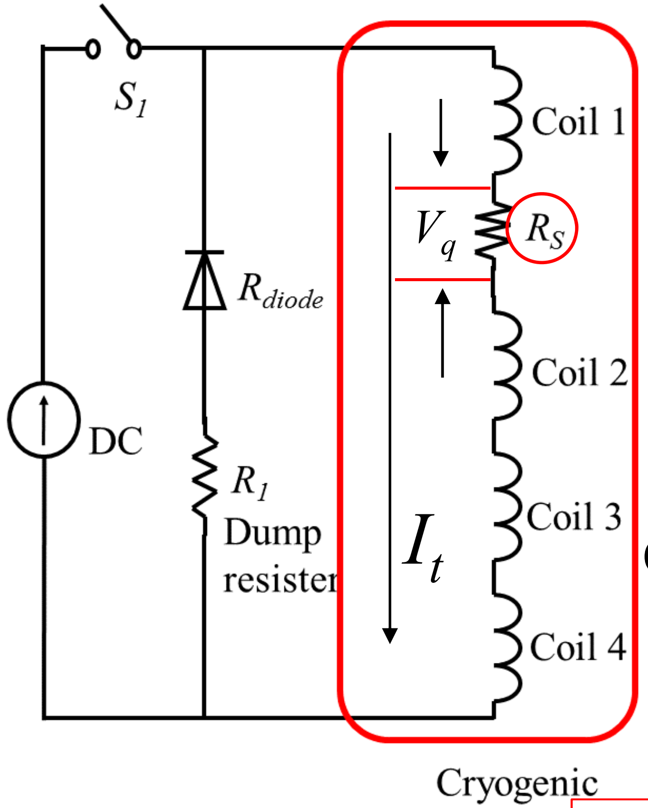
Damage to HTS coil

→ 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



$$I_t = I_0^{(-t/\tau)}$$
$$\tau\ (= L / R_1)$$

L: inductance of the coil

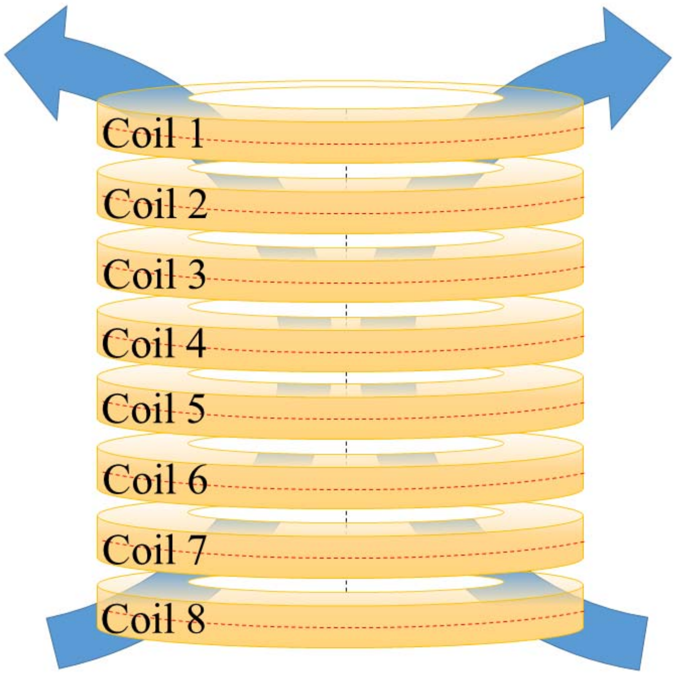
R_L: resistance of the dump resistor

For safe quench protection, values of quench detecting voltage V_q and time decay constant τ should be as small as possible

⇩

Reduction of the value of τ is restricted by a value of L and withstand voltage of the coil

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.

⇕

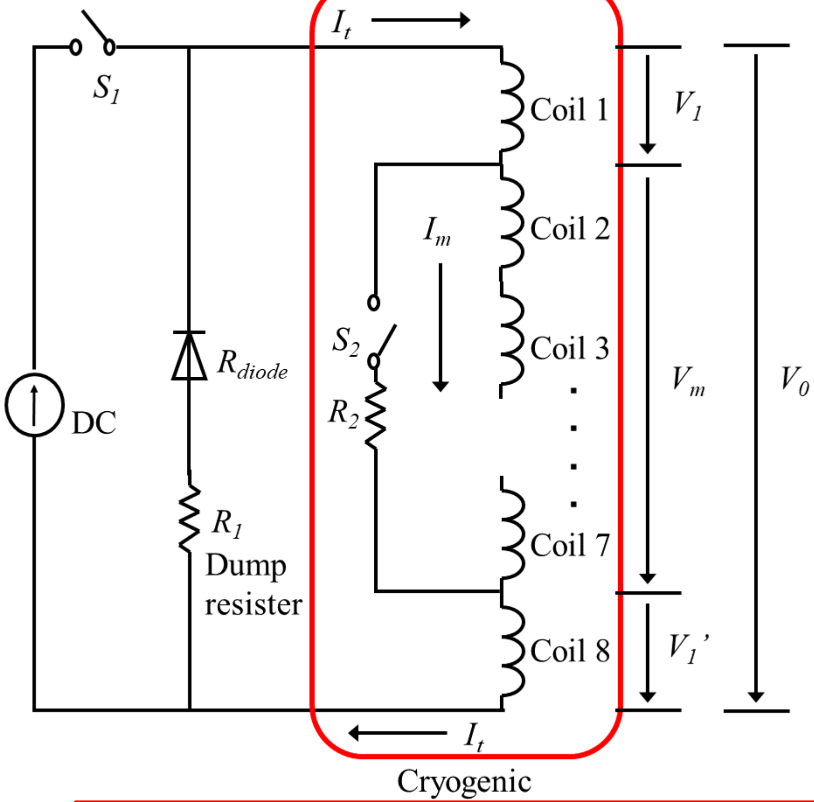
I_c of the wires of Sub-coils 1 and 8 are lower than those of Sub-coils 2 - 7.

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

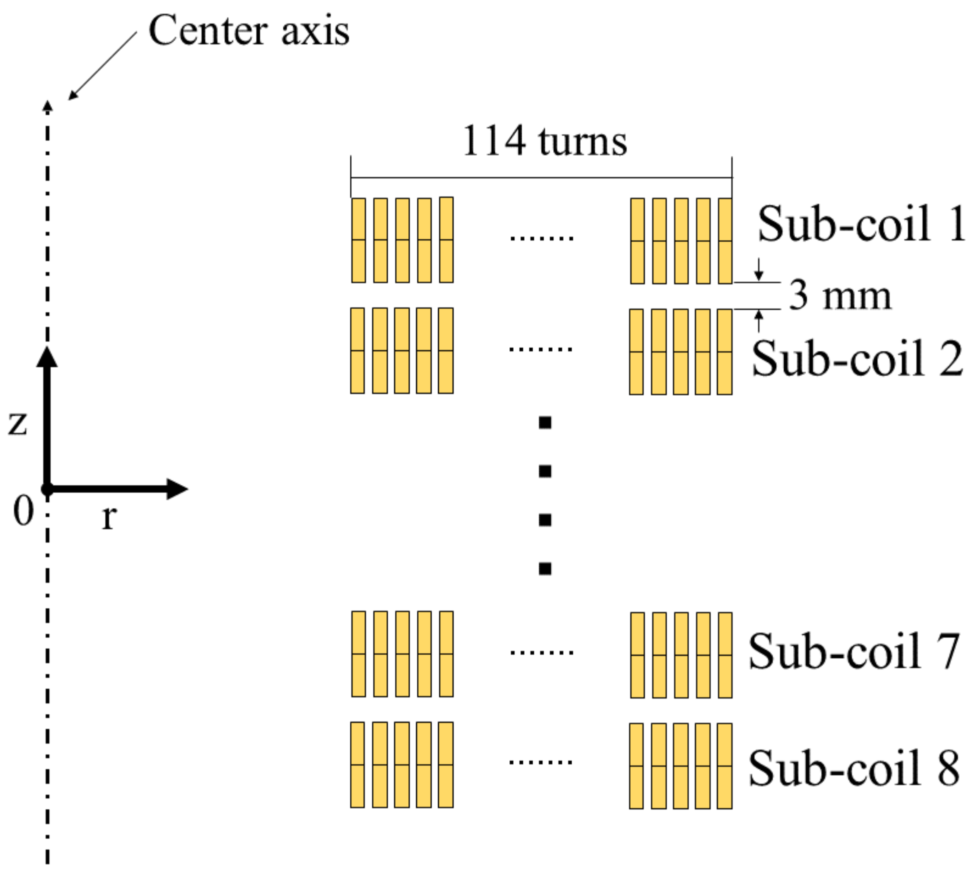
Current in Sub-coils 2–7 I_m increase temporarily due to magnetic coupling between coils

⇩

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

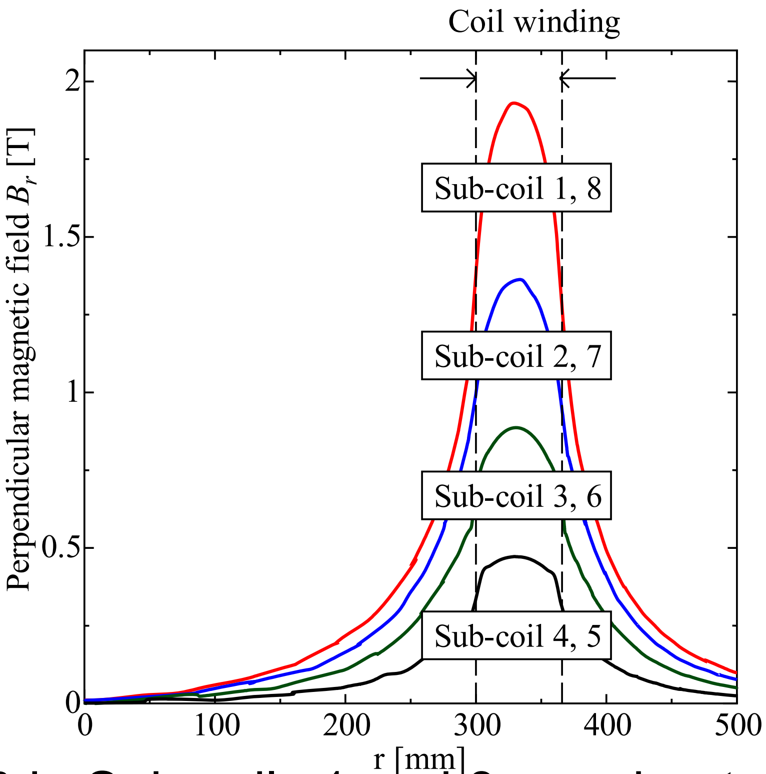


Calculation model

Specification of model coil	
Wire	
Type	Bi / Ag sheathed tape
Width	4.3 [mm]
Thickness	0.23 [mm]
Critical Current	180 [A] (at 77 [K], self field)
Insulation	Kapton Double-wrap of 1.25 [μm]
Element coil	
Type	Single pancake – coil
I. D	600 [mm]
O. D	732 [mm]
Number of turn	228 turn
Composed coil	
Number of element coils	8 coils
Inductances	
-Self inductance	
・Element coil	0.066 [H]
・Composed coil	3.12 [H]
-Mutual inductance	
・Between Coil 1 (or Coil 8) and Coil combined of Coil 2 – 7	0.26 [H]
・Between Coil 1 and Coil 8	0.029 [H]

Magnetic field of model coil

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

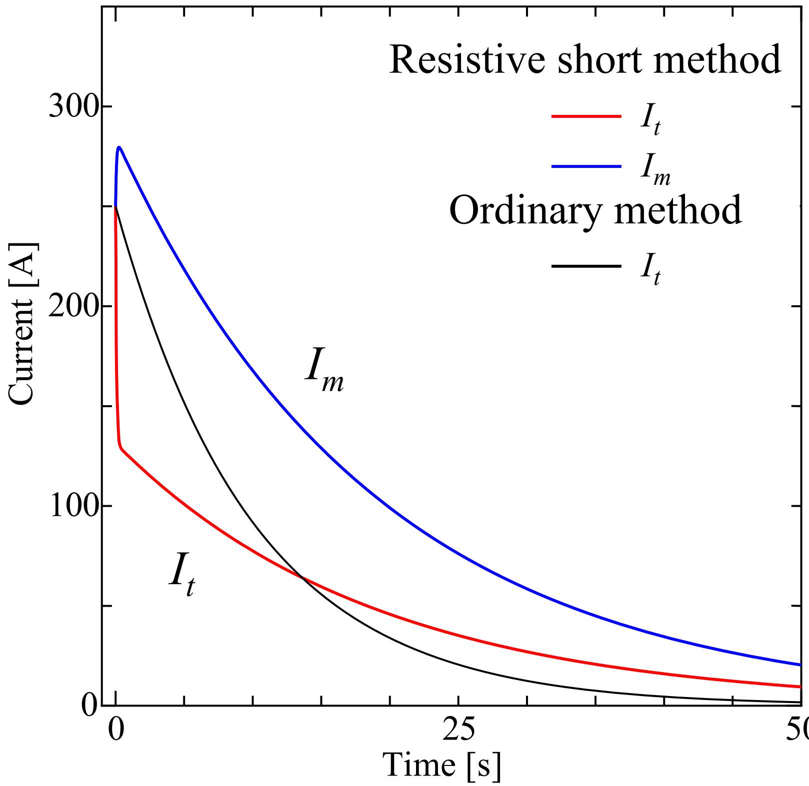


Coil current 250 A

- 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

τ = 10 s, $R_2 = 1.5 R_1$
τ_1 = 0.07 s, τ_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

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

$$\tau_1 < \tau < \tau_2$$

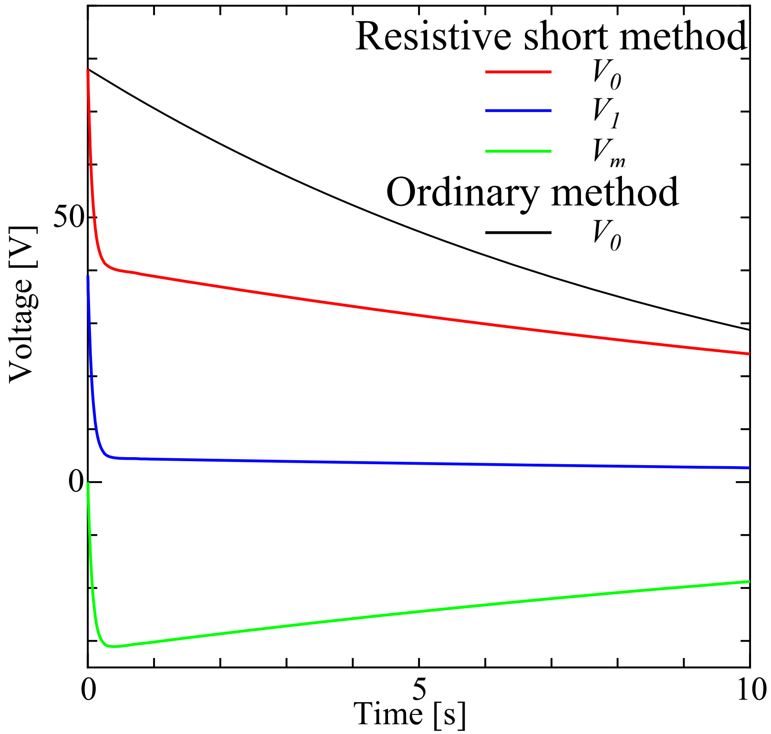
$$\tau_1 = (1+\alpha\beta)\frac{\tau}{2} + \frac{\sqrt{(1+\alpha\beta)^2 {L_{All}}^2 - 4C\alpha}}{2R_1}$$

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

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

τ = 10 s and $R_2 = 1.5R_1$

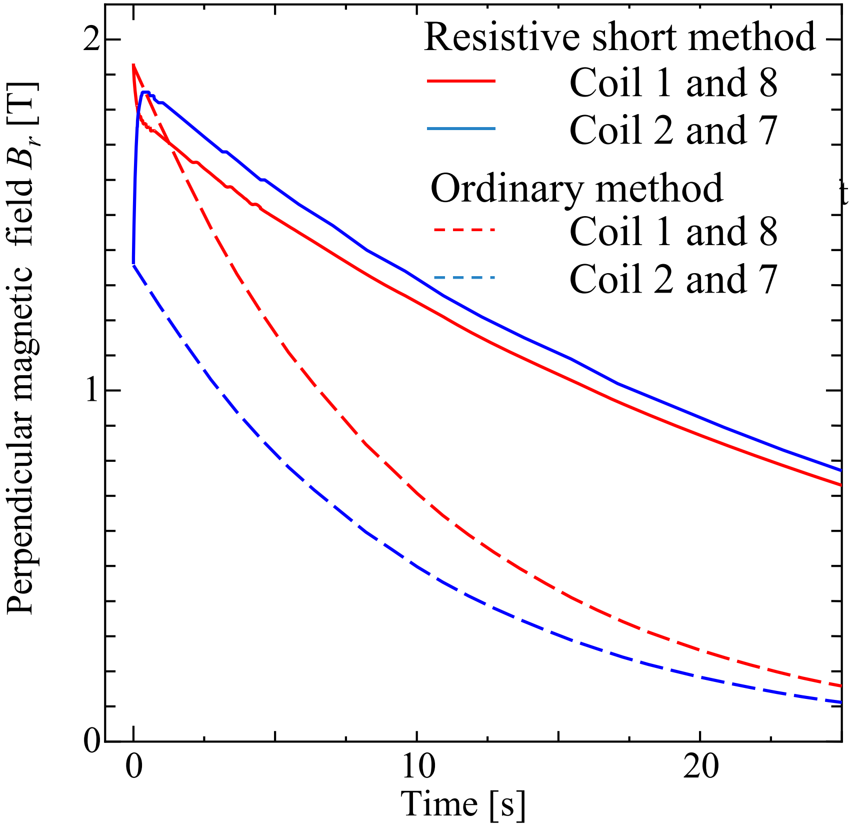


V_0: Sub-coils 1-8
V_1: Sub-coil 1
V_m: Sub-coils 2-7

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

Magnetic field during quench protection sequence

τ = 10 s and $R_2 = 1.5R_1$



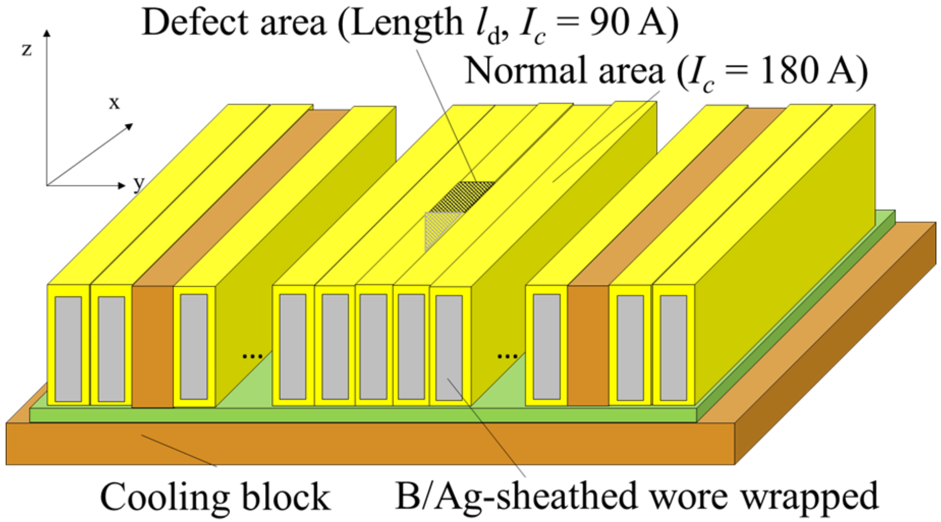
Peak value of B_r in Sub-coils *2 and 7* for the proposed method does not exceeds peak value of B_r for the ordinary method.

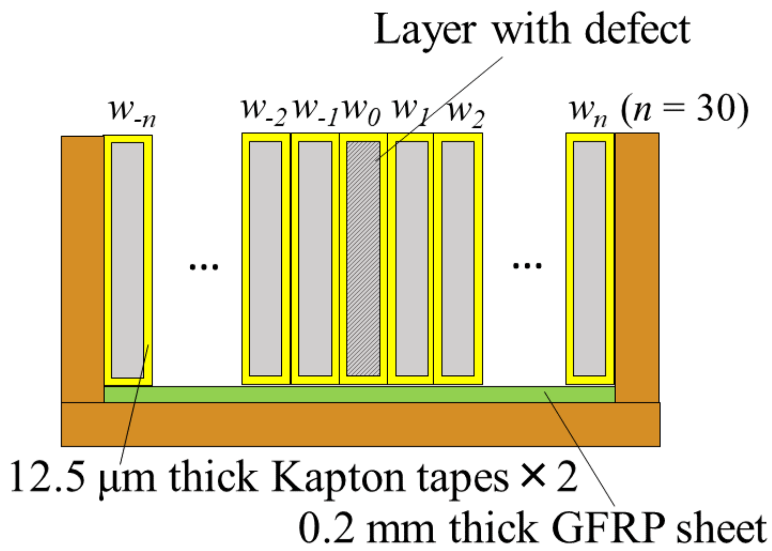
Possibility of quench starting in one of Sub-coils 2-7 is still lower than that in Sub-coil 1 or 8

By adjusting α(= R_1/R_2),
Quenches of Sub-coil 2-7 can be prevented

Analytical model

Winding pack of Sub-coil





Heat equilibrium equation

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

$$- h_l (2T_i - T_{i-1} - T_{i+1}) - h_b (T_i(x,t) - T_{CB})$$

- C_p: Heat capacity [J/mK]
- K: Thermal conductivity [W/mK]
- P_i: i Layer joule heat[W/m]
- h_l: Heat transfer [W/mK] to both side layer
- h_b: Heat transfer [W/mK] Between Coil and cooling block

h_l, h_b : T. Ariyama, et al., IEEE Trans. Appl. Supercond., vol. 27, no. 4, Art. no. 8800106, April 2017.

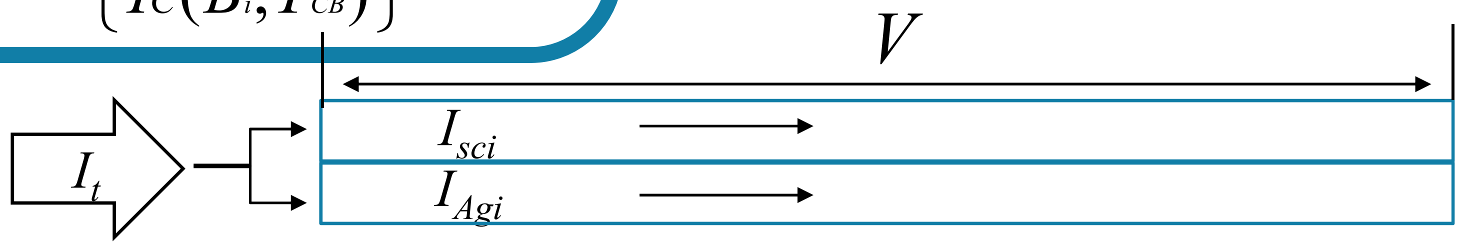
Analytical model

$$I_t(t) = I_{sci}(x,t) + I_{Agi}(x,t)$$

$$V_i(x,t) = I_{Agi}(x,t) R_{Ag}(T_i)$$

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

$$P_i(x,t) = V_i(x,t) I_t(t)$$

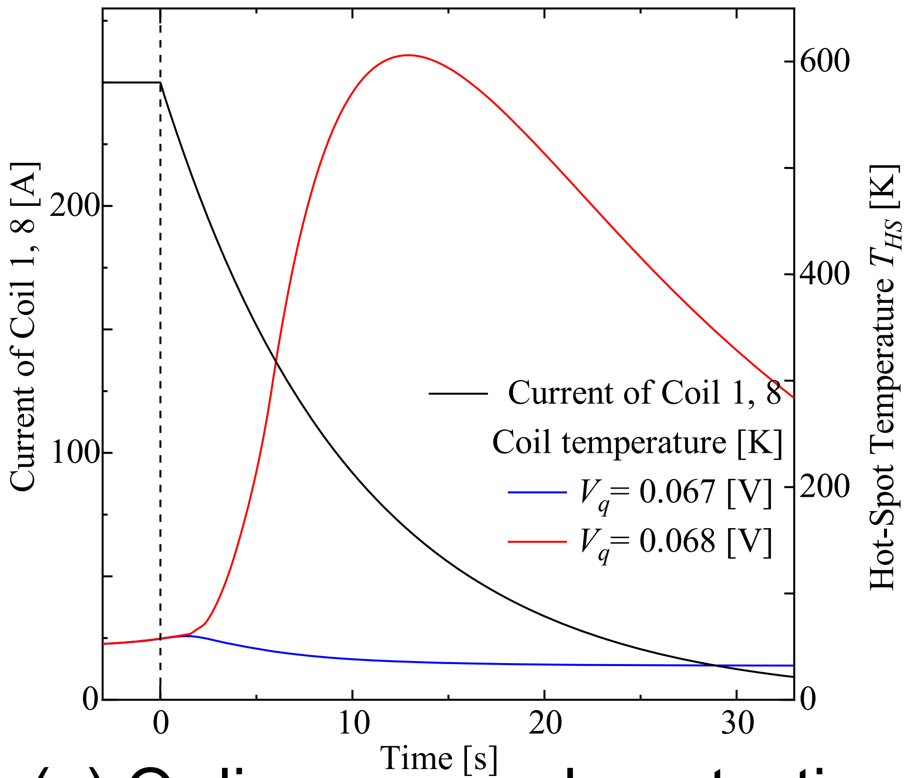


Current sharing model (n value model)

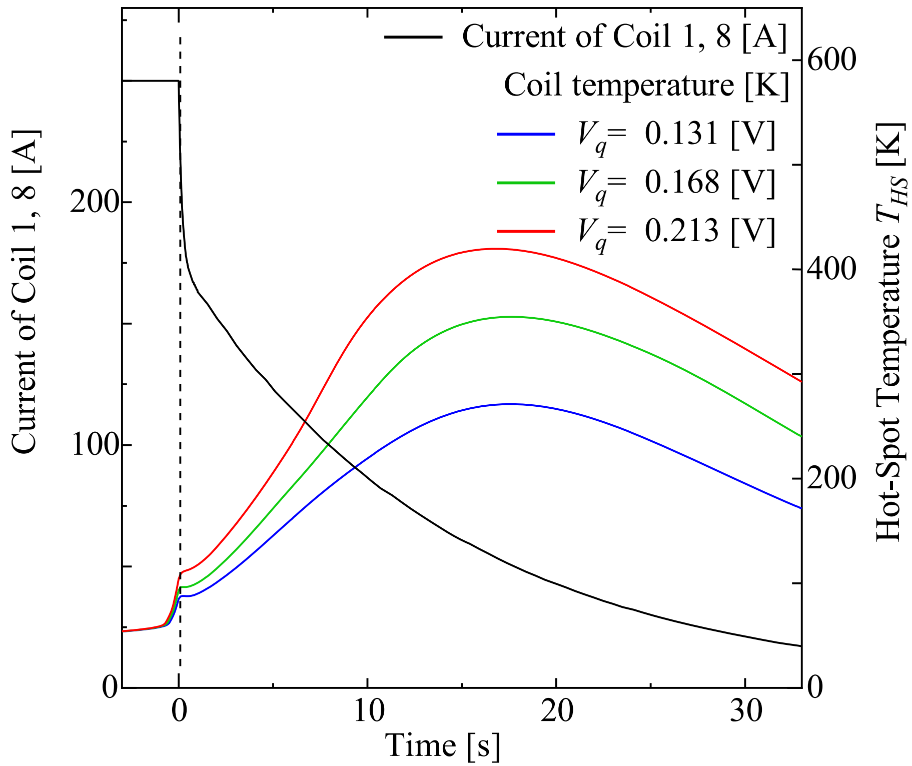
Coil is safe from damages caused by a quench when the quench detecting voltage is below the safe limit of quench detecting voltage V_{qs}

Analytical results

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



(a) Ordinary quench protection

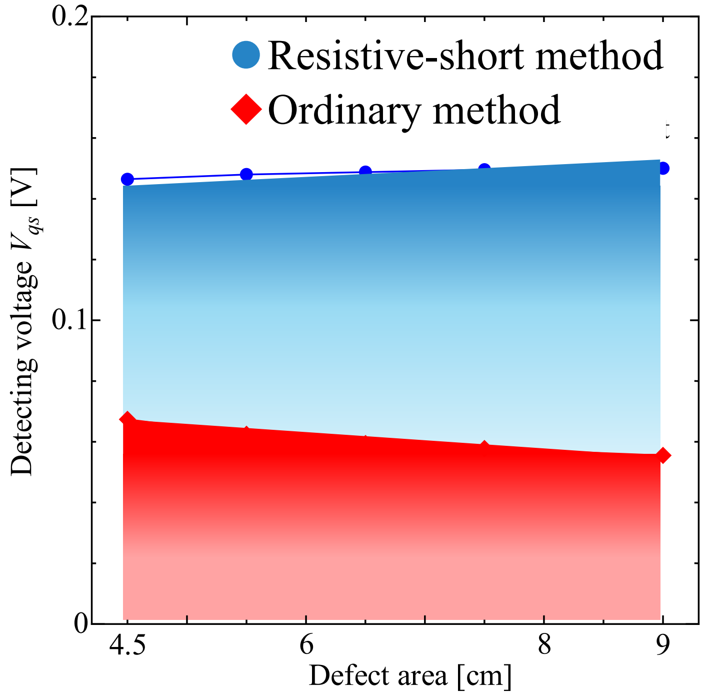


(b) Resistive-short of α = 1.5

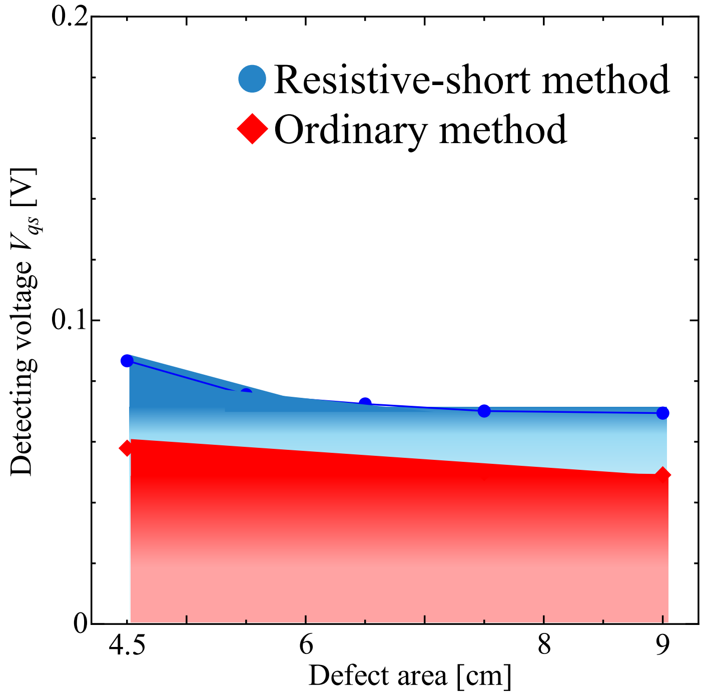
V_q = 0.068 [V] ⇒ Thermal run-away(606 [K])
V_q = 0.067 [V] ⇒ Protected

V_q = 0.213 [V] ⇒ 491 [K]
V_q = 0.168 [V] ⇒ 354 [K]
V_q = 0.131 [V] ⇒ 271 [K]

Simulation results



(a) I_0=250 A, τ=10 s, α = 1.5



(b) I_0=250 A, τ=30 s, α = 1

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

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 τ, thermal run-away can be prevented.

Thank you for your attention