Quench-induced Dynamic Breakdown Characteristics of HTS Pancake Coil Model for Resistive SFCL

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Abstract. Quench-induced dynamic breakdown (BD) characteristics of LN₂ under transient bubble disturbance at the quench of HTS tapes are crucial to the reliable and rational insulation design of resistive superconducting fault current limiters (RSFCL). We have been investigating the dynamic BD characteristics using a nichrome pancake coil model for RSFCL using bifilar nichrome tapes as a heater. In this paper, we fabricated an HTS pancake coil model for RSFCL using GdBCO tapes and discussed the dynamic BD characteristics as a function of heat flux generated from the actually quenched HTS tapes.

1. Introduction
Resistive superconducting fault current limiters (RSFCL) are expected to protect the electric power grid and have been tested and installed mainly in European countries [1–3]. Under the fault current limiting operation, HTS tapes in RSFCL generate high impedance and heat in LN₂, which can induce transient bubble disturbance and breakdown (BD) in LN₂ under the operating voltage of RSFCL. We call such BD “dynamic BD” peculiar to RSFCL and have been investigating the dynamic BD characteristics with the “intrinsic BD” characteristics without bubbles for the reliable and rational insulation design of RSFCL [4].

Researches on the dynamic BD characteristics of LN₂ are increasing, e.g. under sphere-plane electrode at long gap length [5], turn-to-turn electrode for a pancake coil model for RSFCL [6] and so on. Dynamic BD characteristics in such researches have been obtained by using conventional heater to generate bubbles in LN₂. In order to introduce the actual quench of HTS tapes for RSFCL, in this paper, we fabricated a HTS pancake coil model using a GdBCO tape and investigated the dynamic BD characteristics of the HTS pancake coil model in LN₂ for different heat fluxes and gap lengths.

2. Experimental setup and methods
Figure 1 shows the experimental setup. The cryostat has a FRP capacitor bushing, which is partial discharge (PD) free at 150 kVrms in LN₂. The transient large AC current can be controlled with a thyristor switch and transformers. The GdBCO tape is used for the HTS pancake coil model. Table 1 summarizes the specifications of the GdBCO tape. Figure 2 shows the HTS pancake coil model. The bifilarly wound nichrome tape (4 mm width × 0.3 mm thickness) acts as the high voltage electrode, and the HTS tape acts as the grounded electrode to generate bubbles. Each tape has 3 turns and the gap length g of 2 mm and 6 mm between the adjacent tapes. The HTS and nichrome tapes are supported by FRP spacers and connected to the copper and stainless steel bulk electrodes, respectively. The pancake coil is sandwiched between FRP and PET plates to observe the bubble behavior, and arranged vertically in the cryostat.

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Material

Thickness [μm]
Ag 2
GdBCO 3-4
CeO₂/Y₂O₃ 0.3
Ni/Cu/SUS 2/48/100

Table1. Specifications of GdBCO tape.

Width [mm] 4
Total thickness [mm] 0.18
Critical current \(I_c\) [A] 113-116
n value 23.8-28.8

Figure 1. Experimental setup.

Figure 2. Electrode configuration.
We carried out the following two BD tests for the HTS pancake coil model in LN$_2$ at the temperature of 77 K and the pressure of 0.1 MPa.

2.1. Intrinsic BD test without bubbles
AC high voltage (60 Hz) was applied to the nichrome tape at the increasing rate of 1 kV/ms, until the BD occurs without bubbles. The BD voltage was measured 10 times repeatedly at the same condition. The intrinsic BD voltage $V_{intrinsic}$ with 50% probability was calculated by the Weibull analysis, and converted to the intrinsic BD strength $E_{intrinsic}$ with 50% probability at the tape edges.

2.2. Dynamic BD test with transient bubble disturbance
At the applied voltage $V_a$ below $V_{intrinsic}$, the HTS tape was quenched by the AC current larger than $I_e$ for energizing duration $t_e = 5$–10 cycles (60 Hz) through the thyristor switch and bubbles were induced transiently in the HTS pancake coil model. The generated heat flux was calculated by the product of instantaneous values of voltage and current in the HTS tape.

Bubbles were generated 10 times repeatedly at the fixed $V_a$, the heat flux $P_{1st}$ at the first peak and gap length $g$ and the generation probability of dynamic BD was obtained. This operation was repeated for different $V_a$ to get the dynamic BD probability at each $V_a$. The dynamic BD voltage $V_{dynamic}$ and strength $E_{dynamic}$ at the tape edges with 50% probability were calculated by the relationship between the dynamic BD probability and $V_a$.

3. Experimental results and discussion
An example of voltage, current and heat flux waveforms of the HTS tape is shown in Figure 3, where $P_{1st} = 33.7$ W/cm$^2$ and the energizing duration $t_e = 5$ cycles. Figure 4 shows some pictures for dynamic BD of the HTS pancake coil at $V_a = 15.6$ kV, $P_{1st} = 48.7$ W/cm$^2$, $t_e = 5$ cycles. The bubble disturbance and BD light emission can be found between turns of the HTS pancake coil.

Figure 5 shows $E_{dynamic}$ as a function of $P_{1st}$ at the first peak between 9.1–48.7 W/cm$^2$ for the HTS pancake coil model together with that for the nichrome pancake coil model [4]. The blue area represents the intrinsic BD strength by its maximum and minimum values. $E_{dynamic}$ was lower than $E_{intrinsic}$ and decreased drastically with the increase in $P_{1st}$ along the similar curve for different gap lengths and energizing durations. This means that $E_{dynamic}$ can be determined by the heat flux at the first peak generated from HTS pancake coil model, where the number and size of bubbles between turns of the pancake coil model would increase with the increase in the heat flux.

It should be noted that $E_{dynamic}$ might have reached the lower limit of around 30 kV$\_peak$/mm, i.e. about 40% of $E_{intrinsic}$ at $P_{1st}$ larger than around 25 W/cm$^2$, which suggests that the gap space between turns of the pancake coil model would have been filled with bubbles. In order to clarify this issue, additional data for different conditions such as $P_{1st}$, $t_e$, $g$ and temperatures and pressures of LN$_2$ should be complemented and discussed in more detail.

4. Conclusion
We fabricated an HTS pancake coil model using GdBCO tapes for RSFCL and investigated the dynamic BD characteristics of the actually quenched HTS tapes. The dynamic BD strength $E_{dynamic}$ was obtained and discussed in terms of the heat flux from the HTS tapes. The main results are summarized as follows:

- $E_{dynamic}$ decreased drastically with the increase in the heat flux for different gap lengths and energizing durations. $E_{dynamic}$ can be determined by the heat flux at the first peak generated from HTS pancake coil.
- $E_{dynamic}$ might have reached the lower limit of around 30 kV$\_peak$/mm, i.e. about 40% of $E_{intrinsic}$ at $P_{1st}$ larger than around 25 W/cm$^2$.

The reliable and rational insulation design of pancake coil for RSFCL based on the dynamic BD characteristic can be expected in consideration of the generated heat flux from the HTS tapes.
**Figure 3.** Voltage, current and heat flux waveform at quench of HTS pancake coil.  
\(P_{1st} = 33.7 \text{ W/cm}^2, \ t_e = 5 \text{ cycles}\)

**Figure 4.** Dynamic BD of HTS pancake coil.  
\(V_a = 15.6 \text{ kV}, \ P_{1st} = 48.7 \text{ W/cm}^2, \ t_e = 5 \text{ cycles}\)
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Figure 5. Relationship between heat flux $P_{stat}$ and dynamic BD strength $E_{dynamic}$. 

| Pancake coil model | Energizing duration $t_e$ [cycle] |
|--------------------|---------------------------------|
|                    | 5     | 10   | 60   |
| Nichrome [4] (g=2mm and 6mm) | -     | -    | ×    |
| HTS (g=6mm)        | -     | -    |      |
| HTS (g=2mm)        | ×     |      |      |

Figure 5. Relationship between heat flux $P_{stat}$ and dynamic BD strength $E_{dynamic}$. 

| Pancake coil model | Energizing duration $t_e$ [cycle] |
|--------------------|---------------------------------|
|                    | 5     | 10   | 60   |
| Nichrome [4] (g=2mm and 6mm) | -     | -    | ×    |
| HTS (g=6mm)        | -     | -    |      |
| HTS (g=2mm)        | ×     |      |      |