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# Quench-induced Partial Discharge Characteristics of HTS Cables

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**Abstract**. This paper discusses the partial discharge (PD) characteristics of HTS cables under quench condition, where the thermal stress due to quench would be transiently superposed on the electric field stress under the operating voltage of HTS cables. Such electrical insulation characteristics under thermal/electrical combined stress can be referred to as the "quench-induced PD characteristics" of HTS cables, which should be taken into account for the reliable insulation design of HTS cables. Experimental results using coaxial HTS cable samples revealed that the quench-induced PD could be generated, even under the intrinsic or static PD inception voltage ($PDIV_{sta}$) without the quench. The criteria of the thermal/electrical combined stress level for quench-induced PD inception were quantified for different $LN_2$ pressures and fault durations under sub-cooled condition.

## 1. Introduction

Electrical insulation at cryogenic temperatures has been regarded as a common and crucial problem for the development of superconducting power apparatus [1]. Some field tests of HTS cables with transmission or distribution voltage levels are being carried out in the actual electric power systems [2], though the practical and reliable insulation design has not yet been fully established. Especially, the electrical insulation characteristics of HTS cables should be discussed under quench condition due to fault current larger than the critical current level ($I_c$), where quench-induced thermal stress would be superposed on electric field stress under the operating voltage of HTS cables. Such thermal/electrical combined stress may induce partial discharge (PD) in the electrical insulation layers of HTS cables, leading to the insulation deterioration and final breakdown. Thus, the quench-induced PD characteristics are expected to be elucidated for the enhancement of HTS cable reliability.

From the above background, we have been investigating the quench-induced PD characteristics for a simplified test sample for electrical insulation structure of HTS cables [3]. In this paper, using a sophisticated test sample with coaxial cable configuration, we investigated the quench-induced PD characteristics of HTS cables. Especially, we focused on the criteria of quench-induced PD inception for different $LN_2$ pressures and fault durations.

## 2. Experimental setup and procedure

The test sample used in this paper is shown in figure 1. The test sample has the coaxial cable configuration with the length of 455 mm. Bi2223/Ag tapes and copper tapes as the inner conductor are spirally wound around a copper former, where the copper tapes are used as dummy tapes to control $I_c$ of the test sample before quench. We used 2 test samples with different $I_c$; Sample A with $I_c$=241 A (3 HTS tapes + 8 copper tapes), Sample B with $I_c$=478 A (7 HTS tapes + 4 copper tapes). In each test sample, the electrical insulation layer is composed of 8 layers of polypropylene laminated papers with the thickness of 0.125 mm. The outer conductor consists of meshed copper tapes, where the 60 Hz ac high voltage is to be applied. The inner HTS tapes are grounded and the 60 Hz ac large current is to be injected to induce quench of the test sample.

Figure 2 shows the experimental setup. The test sample is vertically arranged in the inner vessel of the cryostat and immersed in $LN_2$ at the pressure $P$=0.1-0.2 MPa. Since the outer vessel of the cryostat is filled with $LN_2$ at atmospheric pressure, the test sample can be immersed in sub-cooled $LN_2$ at 77 K. The 60 Hz ac high voltage and large current are simultaneously applied to the test sample in the synthetic test circuit, i.e. with the test sample exposed to the electric field stress, thermal stress due to quench is superposed for the pre-determined duration. When PD is generated in the test sample under the thermal/electrical combined stress, the PD signal can be picked up by a PD detection circuit composed of parallel-connected capacitance and resistance, and recorded with the applied voltage and current signals in the digital oscilloscope. The detection sensitivity of PD signal in this experimental setup is 5 pC. Such a synthetic test is repeated for different applied voltage, current level, $LN_2$ pressure and fault duration.
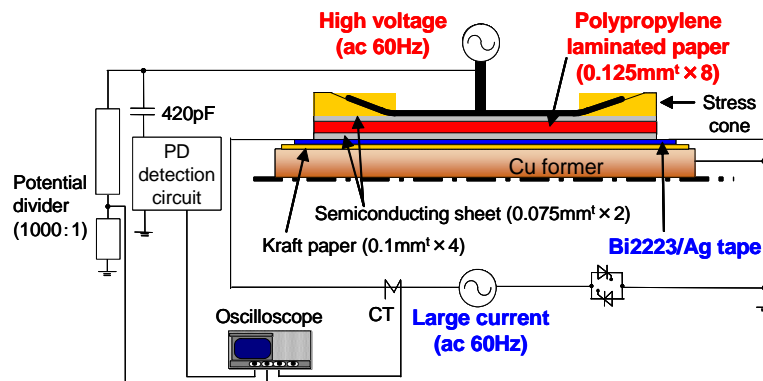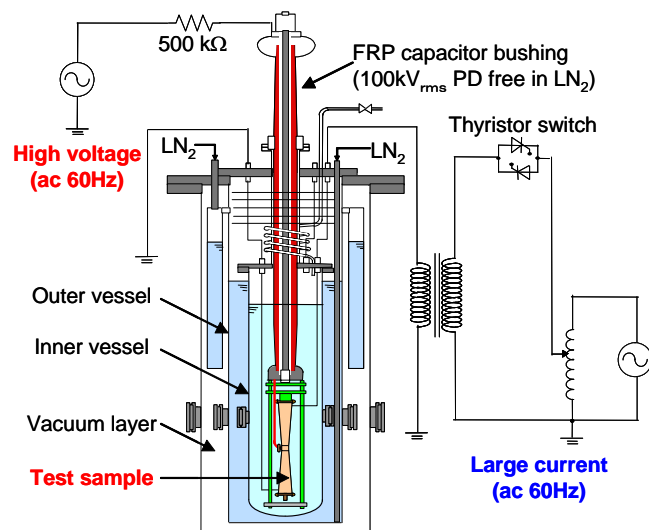


Figure 1  Test sample



Figure 2  Experimental setup

### 3. Experimental results and discussions

#### 3.1. Static PD inception voltage

Prior to the synthetic test by the simultaneous application of high voltage and large current, it is necessary to understand the intrinsic or static PD inception voltage ($PDIV_{sta}$), without the current injection to HTS tapes, by gradually increasing the applied voltage until the PD signal is detected. Figure 3 shows $PDIV_{sta}$ of Samples A and B, respectively, as a function of $LN_2$ pressure $P$. $PDIV_{sta}$ increased by 20-40 % with the increase in $P$ from 0.1 MPa to 0.2 MPa, which is due to the lower generation probability of microscopic bubbles as a trigger of discharge in sub-cooled $LN_2$. The synthetic test for quench-induced PD characteristics was carried out at the applied voltage $V_a$ lower than $PDIV_{sta}$.
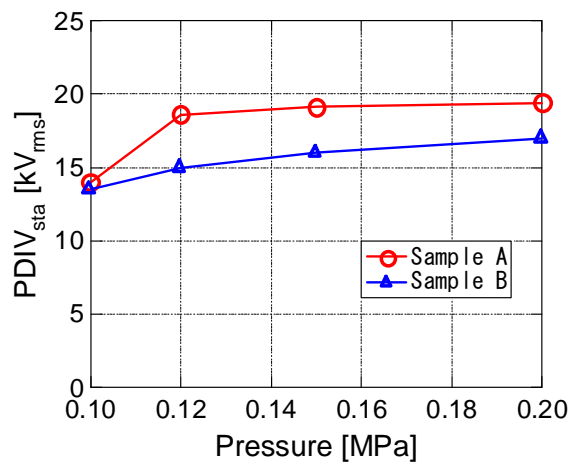


Figure 3  Static PD inception voltage ($PDIV_{sta}$)

#### 3.2. Quench-induced PD phenomena

Figure 4 shows an example of quench-induced PD characteristics for Sample A at $V_a$=10 kV$_{rms}$ ($V_a/PDIV_{sta}$=0.71), $I_{1st}$=1425 A$_{peak}$ ($I_{1st}/I_c$=5.91), $t$=5 cycles, $P$=0.1 MPa, where $I_{1st}$ is the current level at the first peak of the applied ac current, and $t$ is the duration of current flow. PD signal was detected after the current injection, i.e. quench of HTS tapes, with the delay time of about 120 ms. The delay time would correspond to the time from the quench of HTS tapes to the bubble formation in the insulation layers through heat transfer in semiconducting sheets in figure 1.The microscopic bubble would trigger the first PD, and the first PD would induce another bubbles to activate PD generation.
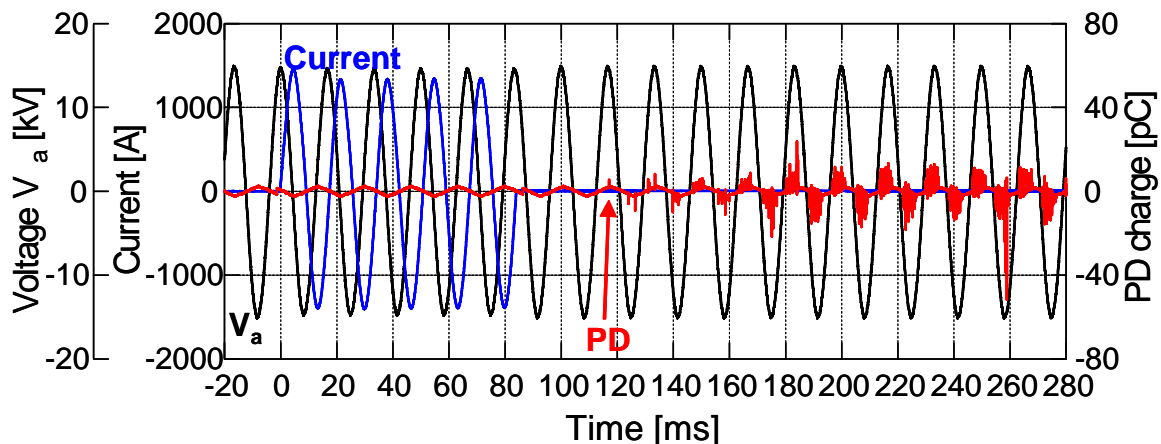


Figure 4  Quench-induced PD characteristics for Sample A
$V_a$=10 kV$_{rms}$ ($V_a/PDIV_{sta}$=0.71), $I_{1st}$=1425 A$_{peak}$ ($I_{1st}/I_c$=5.91), $t$=5 cycles, $P$=0.1 MPa

Such a positive feedback of bubble formation and PD generation could result in the void-type discharge pattern in figure 4 until the bubbles would be disappeared.

### 3.3. Criterion of quench-induced PD inception

The quench-induced PD characteristics for Sample A are summarized in figure 5 for different thermal/electrical combined stress at $t$=5 cycles and $P$=0.1 MPa. This figure tells us that there exists a boundary curve or criterion of quench-induced PD inception. The PD inception strength began to decrease by the thermal stress higher than $I_{1st}/I_c$=3.2, and $V_a/PDIV_{sta}$ decreased into 0.4 at $I_{1st}/I_c$=6. The criterion of quench-induced PD inception for Sample B was almost identical to that for Sample A, when represented by $V_a/PDIV_{sta}$ and $I_{1st}/I_c$ as shown in figure 5. This means that the criterion of quench-induced PD inception can be evaluated by the normalized stresses, even if the test samples have different $I_c$.
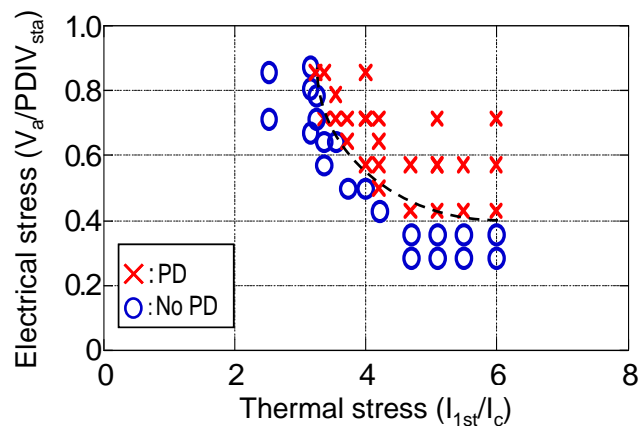


Figure 5  Criterion of quench-induced PD inception (Sample A, $t$=5 cycles, $P$=0.1MPa)

### 3.4. Pressure dependence of quench-induced PD characteristics

The pressure dependence of quench-induced PD characteristics for Sample A is listed in table 1 for different $LN_2$ pressures $P$=0.1 MPa, 0.12 MPa, 0.15 MPa and 0.2 MPa, respectively, at $t$=5 cycles. The quench-induced PD activity such as PD charge and PD duration was suppressed with the increase in $P$ from 0.1 MPa to 0.2 MPa, which is attributed to the suppression of bubble formation and propagation in sub-cooled $LN_2$. Figure 6 shows the criteria of quench-induced PD inception for different $LN_2$ pressures at $t$=5 cycles. With the increase in $LN_2$ pressure, the boundary curve of quench-induced PD inception shifted toward the higher stress region, i.e. the higher PD inception strength is expected against the thermal/electrical combined stresses. However, $V_a/PDIV_{sta}$ would decrease into 0.4-0.5 at $P$=0.1-0.2 MPa, when the thermal stress could reach $I_{1st}/I_c$=6-7.

### 3.5. Fault duration dependence of quench-induced PD characteristics

Taking into account the delay of fault current interruption of HTS cables, the fault duration dependence of quench-induced PD characteristics were investigated. The fault duration was taken as a parameter for $t$=5 cycles (83 ms), 38 cycles (633 ms) and 120 cycles (2 s). As shown in figure 7 for Sample B at $P$=0.1 MPa, the longer the fault duration was, the larger the thermal energy during the fault duration could be accumulated. Figure 8 shows the criteria of quench-induced PD inception for different $LN_2$ pressures at $t$=38 and 120 cycles. Together with figure 6 at $t$=5 cycles, the criteria at the longer fault duration shifted toward the lower stress region, e.g. $I_{1st}/I_c$ where $V_a/PDIV_{sta}$ began to decrease at $P$=0.2 MPa was 5.5 at $t$=5 cycles, 3.3 at $t$=38 cycles and 2.6 at $t$=120 cycles, respectively.

According to the HTS cable projects [2][4], the ratio of prospective fault current and critical current is around 20-30. Thus, experimental results obtained in this paper suggest that PD would be induced in the case of quench of the HTS cables, even if the electric field stress under the operating voltage was lower than the intrinsic PD inception voltage. The quench-induced PD characteristics are expected to be reflected to the reliable insulation design of HTS cables.

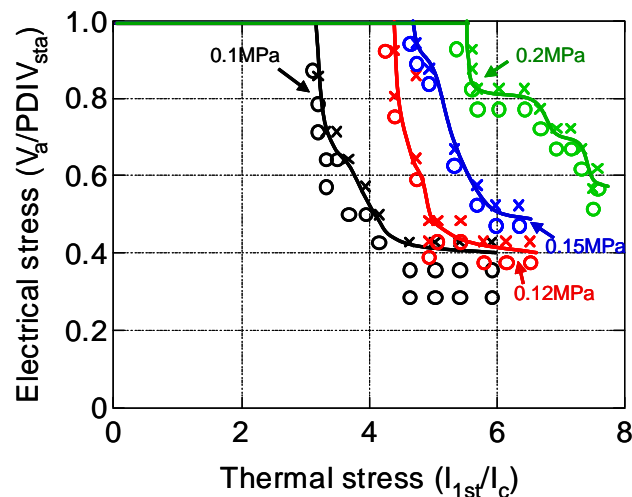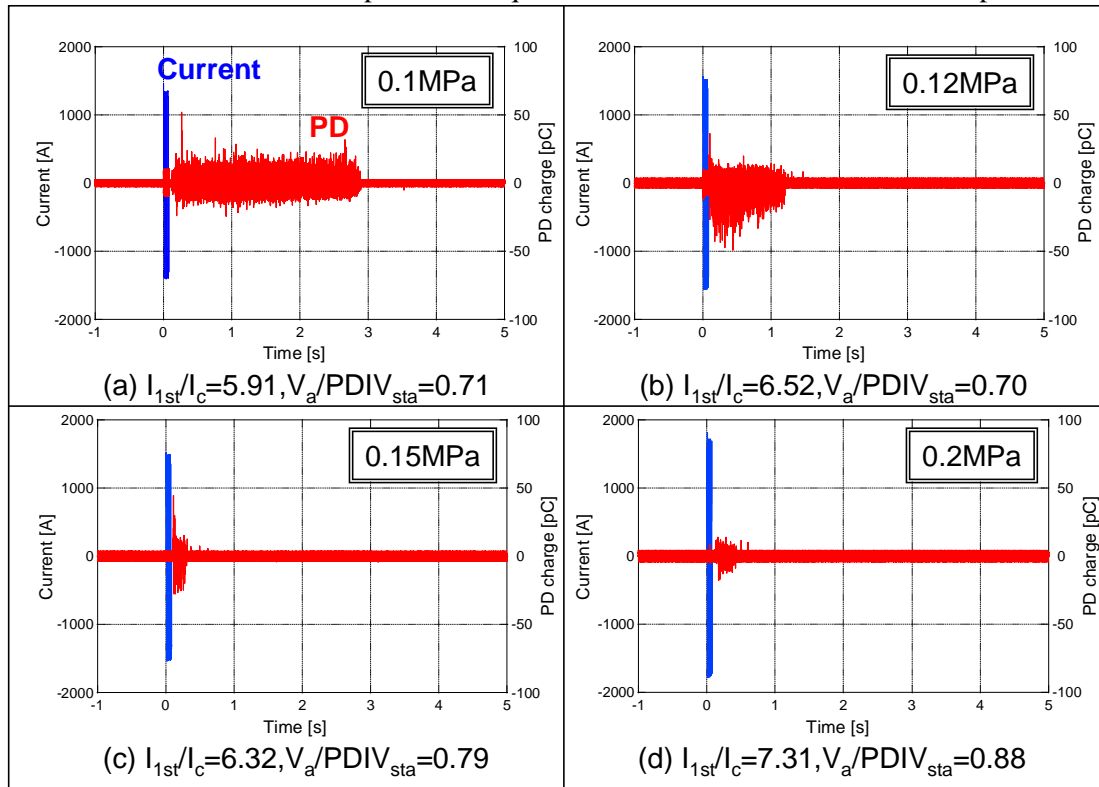Table 1  Pressure dependence of quench-induced PD characteristics for Sample A



(a) $I_{1st}/I_c$=5.91, $V_a$/PDIV$_{sta}$=0.71

(b) $I_{1st}/I_c$=6.52, $V_a$/PDIV$_{sta}$=0.70

(c) $I_{1st}/I_c$=6.32, $V_a$/PDIV$_{sta}$=0.79

(d) $I_{1st}/I_c$=7.31, $V_a$/PDIV$_{sta}$=0.88



Figure 6  Criteria of quench-induced PD inception for different LN$_2$ pressures (Sample A, $t$=5 cycles)

## 4. Conclusions

We investigated the quench-induced PD characteristics of coaxial HTS cable samples under thermal/electrical combined stress. The main results are summarized as follows:

(1) The criterion of quench-induced PD inception can be evaluated by the normalized stresses of $V_a$/PDIV$_{sta}$ and $I_{1st}/I_c$.

(2) With the increase in LN$_2$ pressure, the criteria of quench-induced PD inception shifted toward the higher stress region. $V_a$/PDIV$_{sta}$ would decrease into 0.4-0.5 at $P$=0.1-0.2 MPa, when the thermal stress could reach $I_{1st}/I_c$=6-7.

(3) The criteria at the longer fault duration shifted toward the lower stress region. $I_{1st}/I_c$ where $V_a/PDIV_{sta}$ began to decrease at $P$=0.2 MPa was 5.5 at $t$=5 cycles, 3.3 at $t$=38 cycles and 2.6 at $t$=120 cycles, respectively.
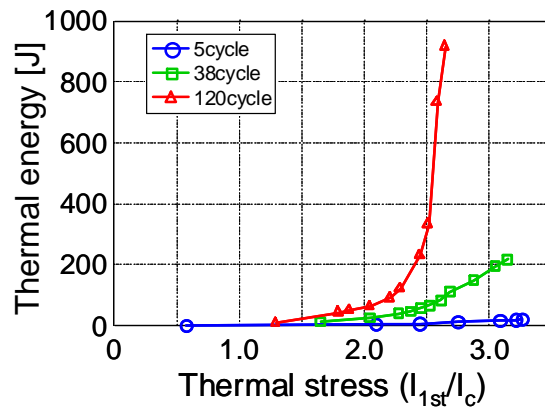


Figure 7  Thermal energy accumulated during fault duration (Sample B, $P$=0.1 MPa)
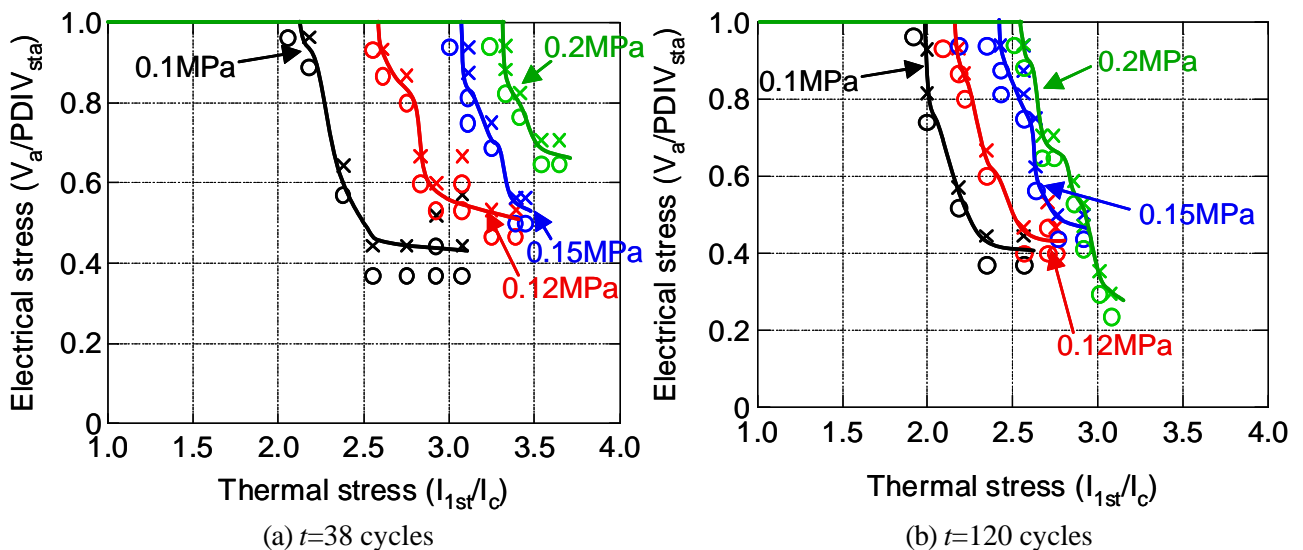


(a) $t$=38 cycles

(b) $t$=120 cycles

Figure 8  Criteria of quench-induced PD inception for different LN$_2$ pressures (Sample B, $t$=38 and 120 cycles)

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