Quench initiation and propagation characteristics of HTS wires under liquid nitrogen cooling condition

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Abstract. With the successful commercialization of Bi-2223 powder-in-tube tape and the improving quality & length-scale of YBCO coated tape, HTS magnets for high magnetic field and electric power applications have been developed. Although the operating temperature of HTS magnets must be kept in the designed level, the magnetic energy and mechanical disturbances can cause a thermal run-away. Especially, heat energy generated in the inner HTS winding is apt to accumulate, so a normal region appears in the HTS winding. This paper deals with the quench initiation and propagation characteristics of Bi-2223 wires and YBCO coated conductor, cooled by liquid nitrogen in adiabatic condition. A NiCr heater, mounted onto the surface of the HTS wire was used to provide the artificial heat that initiated quench. The quench characteristics of HTS wires were mainly affected by the material type and the superconductor to matrix ratio.

1. Introduction

Bi-2223 and YBCO High-Tc Superconducting (HTS) materials are widely used in developing HTS power devices such as superconducting fault current limiters (SFCLs), superconducting power cables, superconducting power transformers, and superconducting motors. Especially, with the successful commercialization of Bi-2223 powder-in-tube wire and the improved quality and length-scale of YBCO coated conductor, the demand on the development of the HTS power devices has been increasing strongly [1], [2]. The most important thing considered in the development of HTS power devices is stable superconducting operation without any cryogenic disturbance and quench. The heat inside of superconducting magnet system upsets the thermal equilibrium of the winding and raises the conductor temperature above its critical value [3].

Many experimental data of normal zone propagation (NZP) have been obtained and reported by many research groups and firms. In their experiments, conduction or gas cooling was used to establish adiabatic condition [4]-[6]. By the way, the most common cooling system for superconducting HTS magnets is liquid nitrogen (LN₂) cooling. Although, the inner section of such a superconducting magnet is uncooled (=adiabatic condition), the condition of inner section of LN₂ cooled superconducting magnets is different from that of conduction or gas cooled superconducting magnets. The main purpose of this paper, therefore, was to study a specimen under conditions similar to those in the inner section of a liquid cooled magnet. In this paper, the minimum quench energy (MQE) and the NZP of three types of Bi-2223 HTS wires were studied. A NiCr heater attached to the superconducting wire
was used to apply the external heat energy. One was the High Current Density Wire of AMSC (HC-A), another was the High Strength Wire of AMSC (HS-A) and the third was HTS wire of Innost (HW-I). The NZP of an YBCO coated conductor (CC) was also investigated by injection of heat energy with large transport current.

2. NZP of Bi-2223 wires

2.1. Experiment
Table I shows the specifications of the Bi-2223 wires used. Because the HS-A was reinforced with stainless steel, it has the highest critical tensile stress of 265 MPa. The certified minimum critical current of HC-A and HS-A was 115 A and that of HW-I was 85 A. The fraction of the Ag alloy matrices in the cross-section of HC-A, HS-A, and HW-I were 37.5, 28.45, and 65.4 %, respectively. The specimens were cooled down in a LN\textsubscript{2} bath. The transport current was applied with a magnet power supply (MPS) of Lakeshore and the power of the heater was applied with a DC dual power supply of HP. Each end of HTS wire was soldered on the copper leads and 5 voltage taps each separated 5 cm distance and 1 tap of 25 cm distance were mounted on the HTS wire.

A NiCr heater with 36 was attached between the center voltage taps. As the generated heat in the inner side of the HTS winding hardly transmits to the coolant, the conductor of this area is called “uncooled conductor” [6]. It is similar to the adiabatic condition. To model inner side of the HTS winding, the HTS wire was covered with polyurethane foam.

2.2. Results and discussions
The critical currents of HC-A, HS-A, and HW-I, measured at 77K, were 138 A, 120 A, and 59 A, respectively. There were some variations of critical current in each specimen.

MQE is the energy that is necessary to create the minimum propagation zone (MPZ) in a superconductor. If the appearing normal zone is larger than the MPZ, the normal zone does not recover and propagate. MQE is an important factor in the design of HTS magnets to ensure stable operation [3].

Figure 1 shows the calculated MQE of each specimen. When the transport current was 50% of its critical current, HW-I has the highest MQE. The difference of MQE between the specimens became smaller with increasing transport current. Whenever transport current of HC-A and HS-A increases by 10%, MQE decreases about 4J.

The NZP energies of HC-A are shown in Figure 2. Normal zone appeared in the Tap 3 (heater attached center area) by the externally applied heat energy and it propagated to each end of specimen. HC-A has the lowest NZP energy. When the transport current exceeded 90% of its critical current, NZP of HC-A reached the each end of the wire. The NZP didn’t reach the end of the HTS wire in the other two specimens.

![Figure 1. MQE of Bi-2223 wires.](image1)
![Figure 2. NZP Energy of HC-A.](image2)

Table 1. NZPV of each specimen
Table I shows NZPV of each specimen. Although whole NZP was not observed in HW-I, the NZPV was similar to the velocity of HC-A. In HS-A the mechanical property of Bi-2223 wire is reinforced by stainless steel tapes soldered on each side of the wire. HC-A and HW-I were the non-reinforced Bi-2223 wires. In HC-A and HW-I, fraction of the Ag matrix in the each conductor cross section was 37.5% and 65.4%, respectively. NZP is the result of the increased temperature in superconductor by the propagation of the applied heat energy. While heat flows to superconducting core and Ag matrix in HC-A and HW-I, when normal zone appeared, heat also flows to the added stainless tapes in HS-A. This is why NZP energy of HS-A was larger than HC-A. Although HW-I consists of superconducting filaments and Ag matrix, it has the highest NZP energy. The normal zone of HW-I just propagated to the adjacent Tap 4. But NZPV of HW-I is faster than any other specimen because of the higher superconductor to Ag alloy ratio. When normal zone appeared in HW-I, generated heat energy flowed along the Ag matrix. As the length of specimen was too short to prevent the propagation of heat energy from center point to end side (cooler), the heat energy in deposited HW-I was removed by the coolant.

The NZP energy obtained in the present work was very high because of the short length of specimen and the slow NZPV properties of HTS materials. High NZPV means that the appeared normal zone in the HTS winding can be eliminated easily. In other words, to make the HTS magnet highly stable, HTS wire should have a high NZPV. Based on the results of this paper, it is expected that the normal zone appearing in the inner side of the HTS magnet wound with Bi-2223 wire makes the operation of HTS winding unstable. Therefore, the superconducting system with Bi-2223 wire materials should be carefully designed not to make normal zone appear inside of the system. Especially, when a cooling system is designed, the speedy and smooth transmission of the heat between the coolant and superconducting materials should be considered.

3. NZP of YBCO coated conductor

It was verified, based on the NZP test of Bi-2223 wires, that NZP is influenced by thermal property and superconductor to matrix ratio and NZPV of HTS wires is very much lower than that of LTS wire. Then, it is very difficult to design stable HTS magnets in considering that they have very high NZPE and very low NZPV. Another way to provide the stable operation of HTS magnets is a design based on cryogenic stability. CC is a newly developed excellent HTS wire, which overcomes the weaknesses of Bi-2223 wire. It may be used in high magnetic field applications having high energy density, such as magnetic levitation vehicle (MAGLEV), magnetic resonance imaging (MRI), synchronous motor, etc. The maximum enduring input power of CC was examined in LN2 bath with 10 cm long AMSC’s CC having critical current of 203 A @ self field and pulse current of 300, 400, 500, 600, 1,000, 1,200, 1,250 A. The sequence of pulse current was like that; 162.4 A (0.8% of $I_c$) → pulse current with 100 ms → 162.4 A (0.8% of $I_c$).

There was some time delay in the recovering to superconducting state when the transport current exceeded 400A (2$I_c$). Figure 3 shows the result with transport current of 600 A. The specimen was burned-out by a pulse current of 1250 A. Figure 4 shows the burned-out specimen. The calculated input energy density was 30 J/cm$^2$. 

| $I/I_c$ | NZPV: velocity of first NZP (Tap 3 • Tap 4) (cm/s) |
|--------|---------------------------------|
|        | HC-A   | HS-A   | HW-I   |
| 0.5    | 0.89   |        |        |
| 0.6    | 0.92   |        | 0.75   |
| 0.7    | 0.91   | 0.36   | 0.76   |
| 0.8    | 1.02   | 0.35   | 0.88   |
| 0.9    | 1.13   | 0.34   | 1.15   |
| 0.95   | 1.21   | 0.54   | 1.51   |
4. Summary

By means of applied heat energy, the normal zone propagation characteristics of the HTS wires were studied in this work. When the transport current was 50% of its critical current, HW-I has the highest MQE. When the transport current is increased, the difference of MQE between the three specimens became smaller. When the transport currents of HS-A and HC-A increase by every 10%, MQE decreases about 4J. When the transport current exceeded 90% of its critical current, NZP of HC-A reached the each end of the wire. NZP didn’t reach the end of the HTS wire in the other two specimens.

There was some time delay in the recovering to superconducting state when the transport current exceeded about two times of its critical current. The CC specimen was burned-out by the input energy density of 30 J/cm$^2$.

It was verified that NZP is influenced by thermal property and superconductor to matrix ratio. It is very difficult to design stable HTS magnets because of very high NZPE and very low NZPV. Another way to achieve the stable operation of HTS magnets is a design based on cryogenic stability.

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