Transient Electromagnetic Phenomena during Current Limiting Process in YBCO Thin Film

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Abstract. In order to design a reliable and high-performance fault current limiter, it is necessary to estimate the influences of the inhomogeneous superconducting properties on the current limiting process and S-N transition. This paper describes the measurements of transient electromagnetic phenomena in YBCO thin film using pick-up coils to observe current-sharing process and change of current distribution. At first current distribution in a steady state was measured. And then transient phenomena caused by applying an overcurrent to YBCO thin film covered with a silver layer were measured.

1. Introduction

Superconducting fault current limiters (SFCLs) are highly expected to be developed for electric power networks [1, 2]. Although a resistive-type SFCL using YBCO thin films has been studied in the world as one of the most promising FCL types, further improvement of performance of a single SFCL device is necessary for its practical application [3-5]. Inhomogeneous superconducting properties of YBCO thin films influence current limiting process and S-N transition. For example, S-N transition starts from the area with lower critical current density, and the resultant current concentration may damage YBCO thin film. In order to design a reliable and high-performance fault current limiter, it is necessary to estimate the influences of the inhomogeneous superconducting properties on the current limiting process and S-N transition.

So far we have developed a numerical analysis tool to study electromagnetic phenomena and current limiting characteristics of YBCO thin film [6]. Although current limiting characteristics of YBCO thin film with a locally low critical current density area were investigated by the analysis tool, experimental verification of the results and further numerical analysis are needed for performance improvement of SFCLs. This paper describes the measurements using pick-up coils for observation of transient electromagnetic phenomena in YBCO thin film, such as current sharing and change of current distribution.

2. Experimental setup

YBCO thin film used in the experiments was prepared by a coating pyrolysis process [7]. The specifications of it are shown in table 1. The estimated critical current $I_c$ was 90 A. A silver layer is evaporated on the surface of the superconducting thin film. A voltage tap was attached on the silver layer at the centre of the lateral direction. A schematic drawing of the measurement using pick-up coils is shown in figure 1. Eleven pick-up coils were arranged at even intervals as shown in figure 1. Each pick-up coil had 33 turns of copper wire.

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Table 1. Specifications of YBCO thin film.

| Parameter                             | Value            |
|---------------------------------------|------------------|
| width                                 | 20 mm            |
| length                                | 20 mm            |
| Thickness of YBCO film                | 0.2 μm           |
| Thickness of metal film (Silver)      | 2.0 μm           |
| Thickness of substrate (Sapphire)     | 0.55 mm          |
| Critical current density $J_c$        | 1.9 - 2.6×10⁶ A/cm² |

Figure 1. Schematic drawing of the measurement using pick-up coils.

The relation between the pick-up coil signals $v_1, \cdots, v_{11}$ and the assumed current elements $I_1, \cdots, I_{11}$ shown in figure 1 is given by the following equation.

$$
\begin{pmatrix}
a_{i,1} & a_{i,2} & \cdots & a_{i,11}
\end{pmatrix}
\begin{pmatrix}
dl_1/\ dt \\
dl_2/\ dt \\
\vdots \\
dl_{11}/\ dt
\end{pmatrix}
= 
\begin{pmatrix}
v_1 \\
v_2 \\
\vdots \\
v_{11}
\end{pmatrix}
$$

(1)

where $a_{i,j}$ is the mutual inductance between pick-up coils and current elements. The current distribution was obtained by integrating the pick-up coil signals with respect to $t$ and solving the inverse problem given by the above equation.

3. Results and discussion

This paper aims at evaluation of pick-up coil method for measurement of transient electromagnetic phenomena, such as how the sinusoidal transport current shares itself into the silver layer, how the current distribution changes, etc. The method would be applied to the measurement in the current limiting process in the next study. A sinusoidal transport current $I_t$ was applied to the superconductor.

$$
I_t = I_p \sin 2\pi ft
$$

(2)

where $I_p$ is the amplitude and $f$ is the frequency ($f = 50$Hz). Figure 2 shows time evolution of current density distributions in the period of sinusoidal transport current from 90 to -90 degrees for four kinds of $I_p$. Although a larger current flows in the edge current elements $I_1, I_{11}$ than the other elements for $I_p = 20$ A and 40 A, the current density in $I_1, I_{11}$ relatively decrease with increasing $I_p$. It is presumed from these curves of current distribution that the critical current density $J_c$ near the edge of superconductor was lower. Furthermore, it is likely that $J_c$ in the current elements $I_7, I_8, I_9$ is relatively small because the current distributions for $I_p = 80$ A and 120 A are not symmetry.

The transient phenomena caused by applying an overcurrent ($I_p = 220$ A) to the YBCO film were measured. Figure 3 shows the pick-up coil and the voltage tap signals, the total transport current, and the current in the silver layer. The current flowing in the silver layer was calculated from the resistance of the silver layer and the voltage tap signal. The voltage tap signal begins to rise around $t = 3.0$ ms, when the transport current is about 90 A and begins to flow into the silver layer. In order to investigate such transient phenomena, time evolution of current density distribution and pick-up coil signal distribution in the period from the beginning to the first peak of the transport current are shown in figure 4 and figure 5, respectively.
Figure 2. Time evolution of current density distributions for various transport current.

Figure 3. Pick-up coil and voltage tap signals, total transport current, and current flowing in the silver layer.

Figure 4 indicates that at first the transport current begins to flow more in the edge regions of the superconductor. And then, due to the limitation of current density by $J_c$, the current-carrying area spreads into the inner region with increasing the transport current. The current distribution gradually becomes asymmetry because of inhomogeneous superconducting properties as shown in figure 2. Figure 5 indicates how the current distribution changes. Judging from the voltage tap signal shown in figure 3, the moment at which the transport current begins to flow into the silver layer is between $t = 3.0$ ms and $t = 4.0$ ms. In the period from $t = 3.0$ ms to $t = 4.0$ ms the change of the pick-up coil signals and their distribution are the sharpest as shown in figure 3 and figure 5. Until $t = 3.2$ ms the peak shifts from the outer to inner region in figure 5, which agrees with the result shown in figure 4, where the current is saturated from outside and more concentrated in the middle region of the superconductor. However, at $t = 3.4$ ms the pick-up coil signals in the outer region increase while the middle region decreases. This is the moment at which the current begins to flow into the silver layer. After $t = 4.0$ ms the current in the silver layer equally increases. Thus the moment at which the transport current begins
to flow into the silver layer can be observed more clearly by investigating the change of pick-up coil signals and their distribution.

4. Summary
Electromagnetic phenomena in YBCO thin film were measured using pick-up coils arranged in the lateral direction. Inhomogeneous superconducting properties were roughly estimated by measuring current distribution in a steady state, and it was likely that $J_c$ around the edge regions of the superconductor was relatively small. The transient phenomena caused by applying an overcurrent to the YBCO film covered with a silver layer were also measured. The moment at which transport current began to flow into a silver layer could be observed clearly by investigating the change of pick-up coil signals and their distribution.

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