Measurement of relation between current applying time and trigger current level of Y123 thin film for sinusoidal current

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Abstract. The voltage - current characteristics of Y123 thin film have been measured by use of sinusoidal currents of various frequencies and amplitudes. As a result, relation between the operational current at which the Y123 thin film changes its state from superconductive to normal conductive and frequency of the current has been obtained. The relation between operational current and frequency is discussed by considering the heat generation and transfer. It is shown that the heat transfer to the coolant is an important factor that determines operational current of a certain frequency.

1. Introduction
Superconducting fault current limiters (SFCLs) are able to reduce the fault currents to an acceptable value. This feature enables to reduce capacity of the circuit breakers and difficulty of power system designing. Moreover, SFCLs are expected to improve the stability of power systems. For these reasons, various types of SFCLs have been proposed and studied[1].

To introduce SFCLs to the power grid, FCL should operate for fault in the protective section, but should not do for switching surge generated substation out of the section. The surge current is large but momentary.

The previous experiment points out that the operating current of HTSFCL is larger for higher frequency of the current. This property is good for SFCL. This paper describes some consideration on the relation between operational current and frequency.

2. Measurement of operational current of Y123 thin film
Table 1 shows the specification of Y123 thin film used in the experiment.

Figure 1 shows the structure of the thin film. Y123 thin film is on sapphire substrate, and covered by layer of gold. Voltage across Y123 thin film is measured through electrodes.

Figure 2 shows the circuit configuration for measurements. The thin film is connected to a current source. In all experiments, a protective resistor is used to protect from burn out by heat generation after S/N transition.
Table 1. Specification of thin film

|                  |       |
|------------------|-------|
| Width [mm]       | 10    |
| Length [mm]      | 100   |
| Thickness [µm]   | 0.30  |
| Ic [A/]          | 60    |
| Thickness of protection layer [µm] | 150  |
| Thickness of sapphire substrate [mm] | 1    |

The operational current for applying a half cycle of AC current are measured. The result for wave front time, which is defined as time from start to peak value of the wave, and it is defined as \( \frac{1}{f} \) where \( f \) is the frequency of current, is shown Figure 3. Previous experiments pointed out that once resistance of the thin film exceeds 10mΩ at 10A, it remains normal conductive state even if the current becomes small and this is the condition whether the S/N transition occurs or not \(^2\). Measurements were carried out by use of impulse current also obtain operational current of high frequency. The operational current level becomes larger for shorter wave front time, that for higher frequency.

Figure 1. Structure of Y123 thin film

Figure 2. Circuit configuration

3. Discussion

Figure 4 shows the relation between cycles and current when the different frequency sinusoidal current flow through the thin film for a half cycle. The values of the current peak when the thin film becomes a normal state are different from each frequency. The current through thin film decrease after operation, because the current is shared by the protection resister and the thin film.

Note that S/N transition does not occur at the peak of current, but at a little time after the peak. It means that the peak value of current doesn’t affect operation of thin film directly.

The state changes of thin film from superconductive to normal seems to be caused by rise of temperature by generated heat. Relation between operational current and wave front time is discussed with influence of generated heat \(^3\).

The resistance of thin film and heat flux from thin film to coolant depend on temperature of
thin film, however, to consider simply, it is assumed that they are constant values in following analyses.

Heat accumulated in thin film until operation $Q$ is

$$ Q = \int_{T_0}^{T_1} (RI^2 - qS) dt $$

(1)

$R'$ is resistance of thin film, and $I'$ is current through thin film, defined as $I = I_0 \sin(2\pi ft)$. $I_0'$ is peak of current though thin film, $f'$ is frequency of current, $t'$ is time, $q'$ is heat flux, and $S'$ is surface area of thin film. So, $RI^2$ signifies heat generated by current, and $qS$ signifies heat flow to coolant. $T_0'$ means time beginning to generate heat. $T_1'$ means operating time. $Q$, $T_0$, $T_1$ is assumed to be constant values. These constant values are estimated as follows.

Figure 5 shows the relation between cycles and total generated heat before S/N transition occurs Heat at 0 cycle can be regarded as $Q$, and it is estimated to be 0.18J.

Figure 6 shows current-voltage characteristics for 50Hz and 2Hz sinusoidal current. Voltage is generated at about 75A for both 50Hz and 2Hz current. This property is independent of current frequency. Therefore, $T_0$ is defined as

$$ T_0 = \frac{1}{2\pi f} \sin^{-1} \left( \frac{75}{I_0} \right) $$

(2)

Operational cycle for a half cycle sinusoidal current is independent of frequency as shown in Figure 4. The time to operate is estimated 0.3 cycle from Figure 4. So, $T_1$ is assumed to be $\frac{0.3}{f}$ in this analyses.

Relation between wave front time and current peak is obtained by equation Equation (1) and estimated $Q$, $T_0$ and $T_1$. It is expressed as

$$ \frac{Q}{T_w} = \frac{RI_0^2}{2\pi} \left[ 1.2\pi + \sin \left\{ 2\sin^{-1} \left( \frac{75}{I_0} \right) \right\} - \sin(1.2\pi) 
- 2\sin^{-1} \left( \frac{75}{I_0} \right) \right] - 4qS \left\{ 0.3 - \frac{1}{2\pi} \sin^{-1} \left( \frac{75}{I_0} \right) \right\} $$

(3)

$T_w'$ is a wave front time. Other constant values are assumed as

$$ R = 5 \times 10^{-3} \Omega \quad S = 1.0 \times 10^{-3}[m^2] \quad q = 2.5 \times 10^4 \text{ [W/m}^2\text{]} $$
$R$ is estimated from an average resistance of the thin film until S/N transition occurs. $S$ is estimated as an area of gold because thermal conductivity of gold layer is much higher than that of sapphire substrate. $q$ is estimated from the average heat transfer from a metal surface to liquid N\textsubscript{2} under normal atmospheric pressure and the temperature difference between liquid N\textsubscript{2} and the metal surface is 7 K.

Figure 7 shows the operational current calculated from equation Equation (3) (○), and measured one (□) for various wave front time currents. The calculated values are close to the measured ones for longer wave front time than 20ms. However, there is much difference between the calculated values and the measured ones for short wave front time.

When wave front time is short, heat does not transfer to liquid N\textsubscript{2} or sapphire substrate so much. $Q$ must be smaller value in such cases. If the generated heat does not transfered from thin film to other layers, $Q$ is calculated with thermal capacity of Y123 is $8.4 \times 10^5$[J/m\textsuperscript{3}K], rise in temperature is 15[K], and volume of thin film is $3 \times 10^{-10}$ [m\textsuperscript{3}]. As a result, $Q$ is $3.78 \times 10^{-3}$[J]. Calculated values by use of $Q = 3.78 \times 10^{-3}$[J] is shown in Figure 7 as ●, and they are closed to measured ones under short wave front time.

The time for normal area expanse into whole thin film can be calculated by solving the heat equation\textsuperscript{[3]}. Figure 8 shows the estimated time for operational current. The time for expanse becomes smaller for larger current.

![Figure 7. Comparison between calculated values and experimental results](image)

![Figure 8. Estimated time for normal area expanse into whole thin film for operational current](image)

From these results, it is shown that the wave front time is an important factor that determines the operational current.

4. Conclusion
The operational currents of a Y123 thin film have been measured by use of various frequency sinusoidal current. It is shown that the operational current becomes larger for shorter wave front time. The relation between wave front time and operational current has been discussed with influence of generated heat. It is shown that this relation is affected by the properties and geometry of super conductor. The discussion of obtained Y123 thin film properties will be useful to consider which one is the best geometry for SFCL.

References
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