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Analysis on magnetizing characteristics of current limiting reactor using HTSC module

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Abstract

In this paper, the magnetizing characteristics of the current limiting reactor (CLR) using high-T_C superconducting (HTSC) module were analyzed. Since the saturation of iron core comprising the CLR using HTSC module deteriorates its current limiting operation, the design of the CLR using HTSC module considering the magnetizing characteristics is needed. For the analysis on the magnetizing characteristics, the flux linkage and the magnetizing current of this CLR using HTSC module were derived from its electrical equivalent circuit. Through the analysis on the linkage flux versus the magnetizing current, obtained from the short-circuit tests, the suppressing effect of the iron core's saturation was discussed.

Keywords: current limiting reactor (CLR); saturation of iron core; magnetizing characteristics; magnetizing current

1. INTRODUCTION

As the effective method for reducing fault currents, the various types of the superconducting fault current limiters (SFCLs) have been suggested. Among the suggested SFCLs, the SFCL using magnetically coupled windings, such as the transformer type, has the advantage that can adjust the operating current of the SFCL through the change of the turn ratio between two windings [1-4]. However, the saturation of the iron core comprising the SFCL can make the current limiting operation of the SFCL disturbed.

In this paper, the current limiting reactor (CLR) using high-T_C superconducting (HTSC) module, which consists of one winding and HTSC module with tap changer, was suggested and its magnetizing characteristics during the fault period were analyzed through the short-circuit tests. The CLR using HTSC module has a simple structure than other types of SFCLs. However, like other transformer type SFCL, the saturation of the iron core comprising the CLR using HTSC module is expected to affect the fault current limiting operation [4-5].

To analyze the fault current limiting characteristics of the CLR using HTSC module due to the saturation of the iron core, its electrical equivalent circuit including the magnetizing branch was drawn and the magnetizing current, which is related to the saturation of the iron core, was derived. The tap ratio, among the design parameters of the CLR using HTSC module to affect the saturation of the iron core, was selected. The fault current limiting and the magnetizing characteristics of the CLR using HTSC module were analyzed from the linkage flux and the magnetizing current.

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2. STRUCTURE AND EQUIVALENT CIRCUIT

2.1. Operational Principle

The schematic configuration of the CLR using HTSC module, which consists of one winding with tap, wound on the iron core and HTSC module, was shown in Fig. 1. *k*, representing the tap location on the winding, has a value between 0 and 1. The induced voltage in the HTSC module during its quench generation can be adjusted through the change of the tap location. The operational principle of the CLR using HTSC module is the same as that of the transformer type SFLC as reported in [1-3].

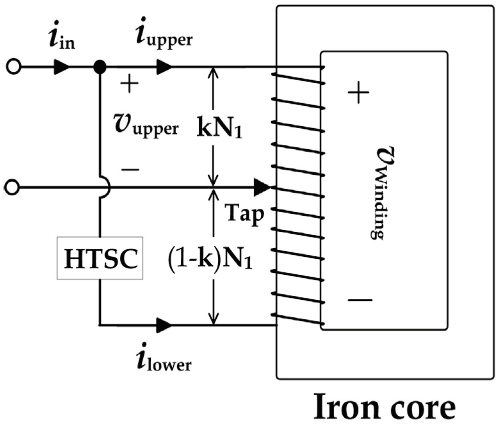

Fig. 1. Configuration of the CLR using HTSC module.

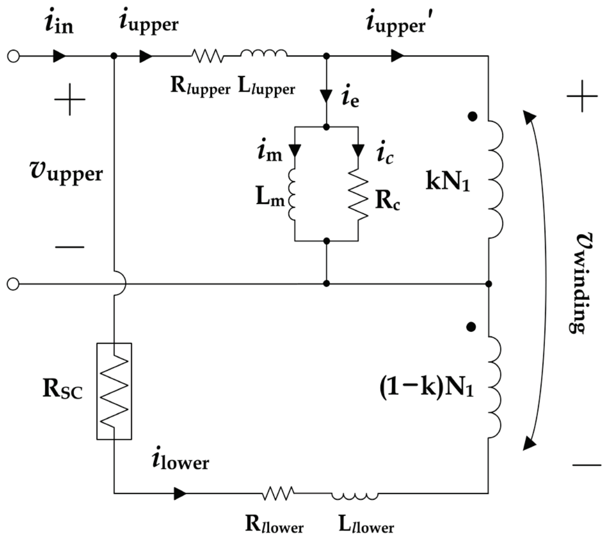

Fig. 2. Equivalent circuit of the CLR using HTSC module.

2.2. Equivalent Circuit

For the analysis of its magnetizing characteristics, the electrical equivalent circuit of the CLR using HTSC module including the magnetization inductance (L_m) and the resistance (R_C) of the iron core loss was shown in Fig. 2.

In Fig. 2, R_{lupper}, R_{llower} and L_{lupper}, L_{llower} represent the resistances and the leakage inductances of the upper and the lower parts of the winding based on tap location, respectively. The magnetizing current (i_m) can be obtained as (1) if the iron core loss is ignored. The linkage flux generated within the iron core (λ_m) can be calculated by integrating the voltage across the upper part of the winding (v_{upper}) assuming that the leakage flux and the resistance of the winding (R_{lupper}, R_{llower}, L_{lupper}, L_{llower}) are lower.

$$i_m = i_{upper} - i_{upper}' = i_{upper} - \frac{1-k}{k} i_{lower} \qquad (1)$$

As seen in (1), the linkage flux and the magnetizing current of the iron core depend on k, which can be adjusted by the tap. With the linkage flux and the magnetizing current, the magnetizing curves of the iron core comprising the CLR using HTSC module can be obtained.

2.3. Experimental Preparation

The design parameters for the CLR using HTSC module are listed in Table I. This CLR using HTSC module consists of an HTSC module, one winding wound on the iron core, and a tap to adjust the tap location. $Y_1Ba_2Cu_3O_{7-x}$ (YBCO) thin film as the HTSC module was used. The schematic circuit system for the short-circuit current, which consists of a 60-Hz ac power supply, a series resistance, a load resistance, and the CLR using HTSC module, is shown in Fig. 3. SW_2 at 0° of the source voltage was closed for five cycles after SW_1 was closed. The voltage and the current of winding and HTSC module were measured with DL850 ScopeCorder device.

TABLE I
DESIGN PARAMETERS FOR THE FABRICATED CLR USING HTSC MODULE.

Iron Core (Silicon Steel)	Value	Unit
Outer Horizontal Length	235	mm
Outer Vertical Length	250	mm
Inner Horizontal Length	137	mm
Inner Vertical Length	155	mm
Thickness	132	mm
Winding with Tap Changer	**Value**	**Unit**
N_1	84	Turns
Tap Location (k)	0.75, 0.60	
HTSC module	**Value**	**Unit**
Fabrication Type	Thin Film	
Critical Temperature	87	K
Critical Current	19	A

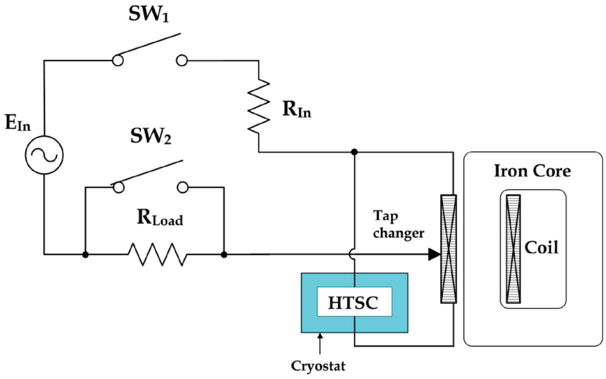

Fig. 3. Schematic circuit system for the short-circuit current.

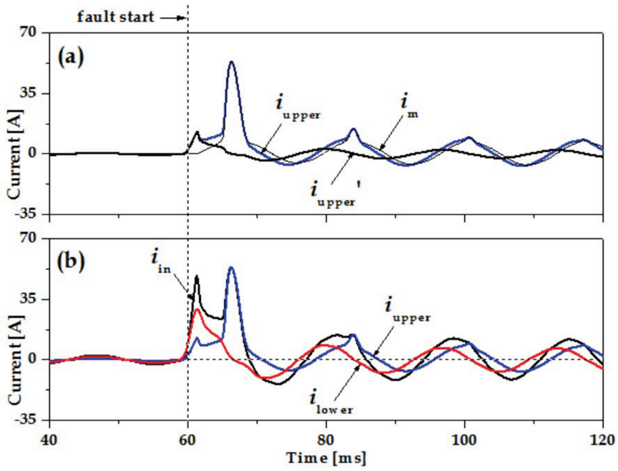

Fig. 4. Current limiting characteristics of the CLR using HTSC module in case that k is 0.75. (a) Current of upper part (i_{upper}), current of lower part viewed from the upper part (i_{upper}') and magnetizing current (i_m). (b) Currents of upper and lower parts (i_{upper}, i_{lower}), current of the CLR (i_{in}).

3. RESULTS AND DISCUSSIONS

Figs. 4 and 5 show the current limiting characteristics of the CLR using HTSC module in case that k is 0.75. The magnetizing current (i_m), as shown in Fig. 4(a) can be

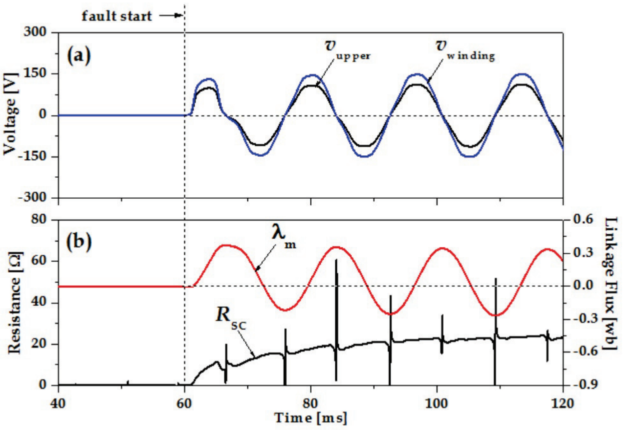

Fig. 5. Current limiting characteristics of the CLR using HTSC module in case that k is 0.75. (a) Voltage of upper part of winding (v_{upper}) and voltage of winding ($v_{winding}$). (b) Linkage flux (λ_m) and resistance of HTSC module (R_{SC}).

derived from the current at the upper part (i_{upper}) and the converted current into the upper part from the lower part of the winding (i_{upper}') using Eq. (1). The directions of the currents flowing across the upper part and the lower part of the winding (i_{upper}, i_{lower}), as compared in Fig. 4(b), have the same direction before the fault occurs.

The magnetizing current (i_m) sharply increases directly after the fault occurs and makes larger distortions in the voltage waveforms (v_{upper}, $v_{winding}$) as seen in Fig. 5(a).

In spite of the resistance generated in the HTSC module (R_{SC}) as observed in Fig. 5(b), the sharply increased magnetizing current at the initial fault time causes the second peak in the current of the upper part of the winding (i_{upper}) as seen in Fig. 4(b) and, makes the fault current limiting operation of the CLR using HTSC module deteriorated.

The voltages across the winding and the upper part ($v_{winding}$, v_{upper}) as displayed in Fig. 5(a) are generated proportionally to the number of the winding's turns after

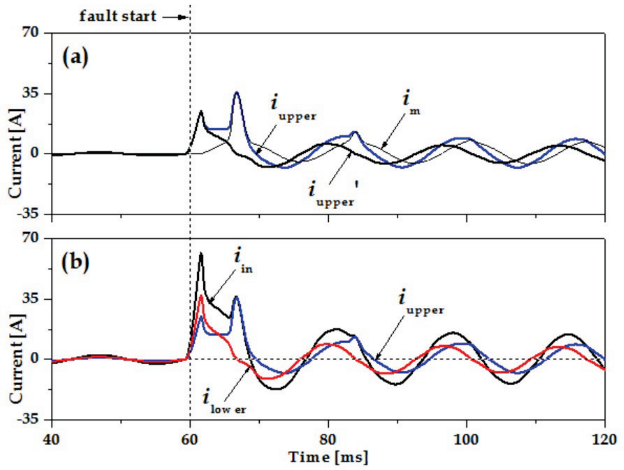

Fig. 6. Current limiting characteristics of the CLR using HTSC module in case that k is 0.60. (a) Current of upper part (i_{upper}), current of lower part viewed from the upper part (i_{upper}') and magnetizing current (i_m). (b) Currents of upper and lower parts (i_{upper}, i_{lower}), current of the CLR (i_{in}).

the fault occurs. The linkage flux (λ_m) in Fig. 5(b), calculated from the voltage across the upper part of the winding, increases up from almost zero immediately after the fault starts and decreases gradually.

To investigate the magnetizing characteristics of the CLR using HTSC module during the fault period, the tap location was changed from 0.75 to 0.60. The current

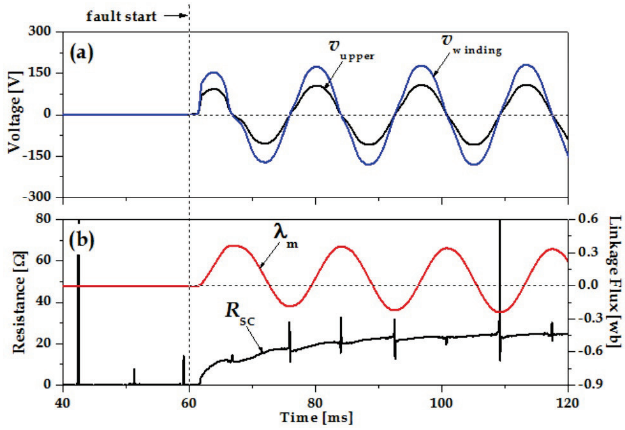

Fig. 7. Current limiting characteristics of the CLR using HTSC module in case that k is 0.60. (a) Voltage of upper part of winding (v_{upper}) and voltage of winding ($v_{winding}$). (b) Linkage flux (λ_m) and resistance of HTSC module (R_{SC}).

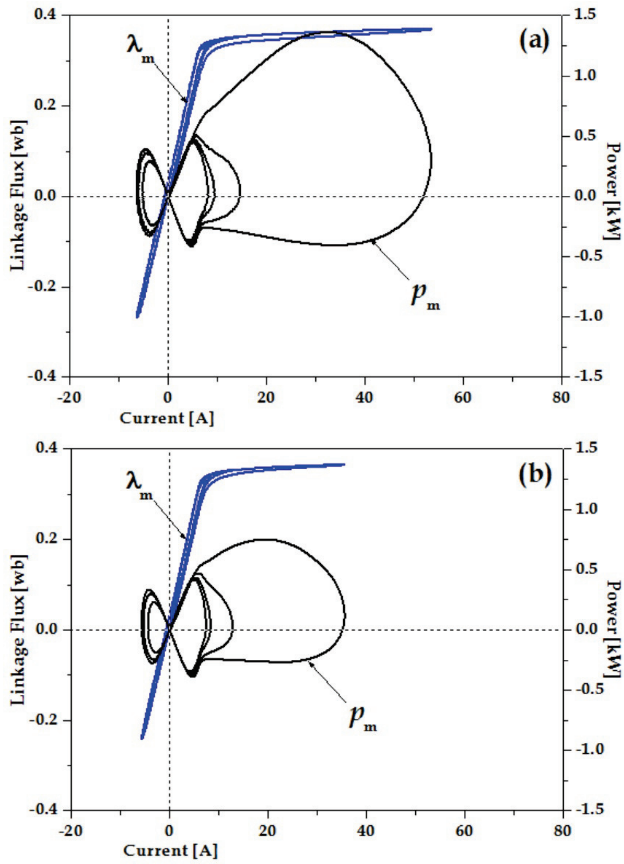

Fig. 8. Variation of flux linkage's operational range (λ_m) and magnetizing power (p_m) dependent on magnetization current (i_m) during the fault period in the CLR using HTSC module. (a) In case that k is 0.75. (b) In case that k is 0.60.

limiting characteristics of the CLR using HTSC module in case that k is 0.60 are displayed in Fig. 6 and Fig. 7.

The induced voltage in the upper part of the winding (v_{upper}) as seen Fig. 7, which is related with the induced voltage in the magnetizing branch in its electrical equivalent circuit of Fig. 2, decreases little more than in case that k is 0.75. On the other hand, the amplitudes of the generated resistances in the HTSC module as compared between Figs. 5(b) and 7(b) are a little different. The decreased induced voltage of the upper part of the winding (v_{upper}), in case that k is 0.60, lowers the magnetizing current (i_m) and the second peak in the current of the upper part of the winding (i_{upper}), which is expected to contribute to the suppression of the iron core's saturation.

From above analysis, the decreased induced voltage (v_{upper}) in the upper part of the winding during the fault period suppresses the iron core's saturation of the CLR using HTSC module, which makes the current limiting characteristics of the CLR using HTSC module improved.

For two k values of 0.75 and 0.6, the flux linkage and he magnetizing power of the CLR using HTSC module during the fault period are displayed in Fig. 8. Unlike the analysis in Fig. 4 to Fig. 7, the different flux linkage's operational ranges (λ_m) can be observed together with the magnetizing power from Fig. 8. In case that k is 0.6, the flux linkage curve recovered into the linear region after about one cycle with more small magnetizing power area (p_m) compared to the case that k is 0.75.

4. CONCLUSIONS

The current limiting and magnetizing characteristics of the CLR using HTSC module considering its tap ratio, which could adjust the induced voltage in the upper part of the winding, were investigated through the short-circuit tests. For the analysis on the dependence of the magnetizing characteristics of the CLR using HTSC module, the flux linkage and the magnetizing current were derived from its electrical equivalent circuit with the nonlinear magnetizing branch. For the CLR using HTSC module designed with the lower induced voltage in the upper part of the winding (k = 0.6), the saturation of the iron core comprising CLR using HTSC module was a little more suppressed, especially directly after the fault occurrence, than the case designed with more induced voltage in the upper part of the winding (k = 0.75).

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