J Electr Eng Technol Vol. 9, No. 6: 1909-1913, 2014
http://dx.doi.org/10.5370/JEET.2014.9.6.1909

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Analysis on Current Limiting Characteristics According to the Influence of the Magnetic Flux for SFCL with Two Magnetic Paths

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Abstract – In this study, a superconducting fault current limiter (SFCL) having two magnetic paths was proposed, and its current limiting characteristics were analyzed. For the SFCL to effectively perform the current limiting operation, it must be designed considering the magnetic saturation of the E-I core. Further, the influence of the magnetic flux on its peak current limiting characteristics was investigated. In addition, the magnetic flux curves of the SFCL obtained from the fault current limiting experiments were analyzed, and the subtractive polarity winding case was observed to not only further reduce the saturation potential of the core but also perform the peak current limiting functions well when compared with the additive polarity winding case.

Keywords: Peak current limiting, Magnetic flux, Two magnetic paths, E-I core, Superconducting Fault Current Limiter (SFCL).

1. Introduction

The key measures of a creative economy are the creation of many new jobs and increasing industry convergence, for instance, information and communication technology (ICT) fused with preexisting industry.

Currently, environmental concerns as well as energy supply and demand concerns are increasing. Even though government has constructed large scale new power plants and power grids every year to resolve the energy demand for peak power, there has been a reality confronting big trouble due to people's objection. Furthermore, though the electric power demand in the industrial sector has been increasing annually, the power supply is not followed in time as the demand needs.

This increase in power demand and the expansion of the power generating systems have led to an increase in fault current. Numerous studies for reducing the fault current, including those that applied a superconducting fault current limiter (SFCL) have been conducted [1-5]. Among the developed SFCLs, in the magnetic flux-lock type SFCL, the magnetic flux that is generated from the two coils offset each other during normal conditions. However, when a fault occurs, the resistance from the quenching of the high-T_c superconducting (HTSC) element generates the induced voltage through which the fault current is limited. Thus, it has a characteristic of being able to adjust the limit impedance and operational current through which the fault current is limited by adjusting the inductance ratio and the direction of the two coils of the magnetic flux-lock type SFCL [6-8]. On the other hand, the fault current that is greatly increased while the fault occurs may cause saturation of the core because of the increased magnetic flux inside the core, which would reduce the fault current limiting effects of the SFCL. To prevent this, SFCL structures using cores with two magnetic paths or using one core with a third separate coil have been proposed and reported [9-11]. However, to date, there is no reported research on the internal magnetic flux characteristics of the E-I core in a peak current limiting structure having a third coil and an additional HTSC element.

Therefore, this study proposes an SFCL capable of preventing the occurrence of magnetic flux inside the core under normal conditions while preventing saturation in the core owing to the sudden occurrence of magnetic flux and having peak current limiting possibilities. The fault current limiting characteristics of the subtractive polarity winding and additive polarity winding cases and the voltage characteristics of the two HTSC elements have been analyzed through simulation experiments. Furthermore, exciting currents, and current limiting characteristics of each coil were analyzed for different winding directions of the first and second coils. Finally, the Joule heat of the HTSC element and the distribution of the magnetic flux were compared and analyzed for different winding directions. From the magnetic flux distribution analysis of the E-I core during the fault, it was observed that the SFCL with subtractive polarity winding is able to further reduce the saturation potential of the core when compared with the SFCL with additive polarity winding.

2. Theoretical Calculation

The peak current is limited primarily to reduce the fault current burden of the HTSC element by splitting the

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Received: December 4, 2013; Accepted: August 17, 2014

current limiting action when the fault current peak value is very high initially. As shown in Fig. 1, the SFCL having two magnetic paths consists of three coils on the E-I core and two HTSC elements. Its basic principle is that under normal conditions, the magnetic flux generated from two coils (N_1, N_2) that are connected in parallel offset each other. However, when a fault occurs, the resistance from the quench of the HTSC element that is connected in series with the second coil prevents the magnetic flux from being offset, which induces the voltage in each coil and limits the fault current. At the same time, the voltage is induced and the current flows in the third coil because of the magnetic flux, which is not offset, inside the core. Here, the induced magnetic flux in the core is large if the fault current is large in the initial stages, which significantly increases the induced current that flows in the third coil. When the critical current of the second HTSC element that is connected to the third coil exceeds, a resistance is created because of the quench, and the second peak current limiting action is carried out at the initial stages of the fault occurrence.

Fig. 2 shows the electrical equivalent circuit of the SFCL that has two HTSC elements with two magnetic paths using the duality method [12]. Here, R_{l1}, R_{l2}, and R_{l3} each respectively denote the resistances of each winding whereas L_{l1}, L_{l2}, and L_{l3} denote the leakage inductance of each winding. In addition, N_1, N_2, and N_3 represent the number of turns of each coil. L_1, L_2, and L_3 that are comprised of exiting branches are expressed as magnetization inductances of the E-I core. Here, the areas of the core are expressed as $N_1^2\mu_0\mu_r S_{core}/l_1$ for L_1, $\frac{N_2^2\mu_0\mu_r S_{core}}{l_2}$ for L_2, and $\frac{N_3^2\mu_0\mu_r S_{core}}{l_3}$ for L_3. S_{core} is the area of core. Further, μ_0 is the free space permeability, and μ_r is the relative permeability. From the equivalent circuit in Fig. 2, the exciting current and voltage across the exciting branch can be expressed as Eqs. (1) and (2).

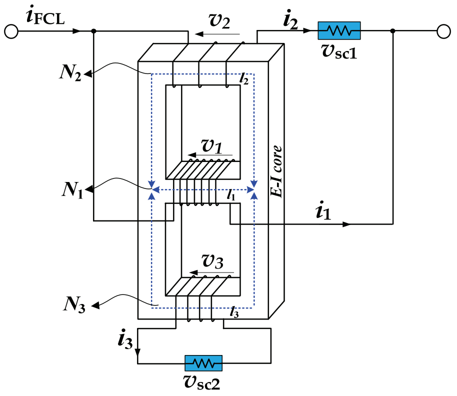

Fig. 1. Magnetic system of flux-lock-type SFCL with two magnetic paths using E-I core.

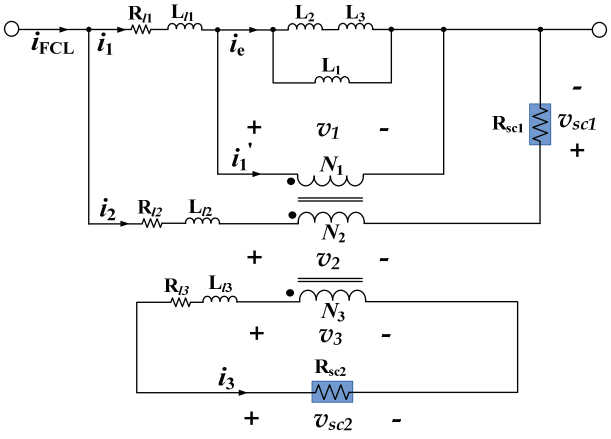

Fig. 2. Equivalent circuit of SFCL with two magnetic paths.

$$i_e = i_1(t) - i_1'(t) \tag{1}$$

$$\frac{d\varphi}{dt} = v_1(t)\_R_{l1} i_1(t)\_L_{l1}\frac{di_1(t)}{dt} \tag{2}$$

In Eq. (1), $i_1'(t)$ is equal to $\frac{N_2}{N_1}i_2(t) + \frac{N_3}{N_1}i_3(t)$. v_1 is the induced voltage in the first coil, and φ is the linkage flux of the E-I core. If each winding is tightly wound and the resistance of each winding is assumed to be small, the leakage inductance (L_{l1}, L_{l2}, and L_{l3}) and the resistance of each winding (R_{l1}, R_{l2}, and R_{l3}) can be neglected. Therefore, the linkage flux of the E-I core can be obtained by integrating the stray voltage in the first winding from t_0 to t.

$$\begin{aligned}\varphi(t) - \varphi(t_0) &= \int_{t_0}^{t} v_1(t)dt \\ &\quad - R_{t1}\int_{t_0}^{t} i_1(t)dt - L_{l1}[i_1(t) - i_1(t_0)] \\ &\cong \int_{t_0}^{t} v_1(t)dt\end{aligned} \tag{3}$$

3. Experimental Results and Discussion

Table 1 shows the design parameters of the SFCL having two magnetic paths. $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film having a critical temperature of 87 K was used as the HTSC element, which was connected to the second and third coils. To protect the thin film device from the heat generated during the quench, a 200-nm-thick Au layer was deposited. The value of the critical electric current was measured to be 27 A. Fig. 3 shows the schematic diagram of the experimental circuit used to simulate the occurrence of a fault, which comprises a 60 Hz AC power supply (E_{in} = 160 V), a line impedance (L_i = 1.82 mH, R_i = 0.097 Ω), a load resistance (R_{Load} = 41.2 Ω), and the SFCL with two magnetic paths using the E-I core. A short circuit was induced for five cycles by turning on the switch SW2 during the fault cycle after inputting switch SW_1; thereafter, the induced voltage and the current that flows in the three coils including the line and the HTSC elements 1 and 2

Table 1. Specifications of SFCL using E-I Core.

Iron core	Value	Unit
Total mean length ($l_2 + l_3$)	1160	mm
Second leg length (l_1)	310	mm
Cross-sectional area (S_{core})	2790	mm^2
Two coils		
Number of turns of coil 1 (N_1)	45	Turns
Number of turns of coil 2 (N_2)	15	Turns
Number of turns of coil 3 (N_3)	30	Turns
HTSC thin film		
Material	YBCO	
Critical temperature	87	K
Critical current	27	A

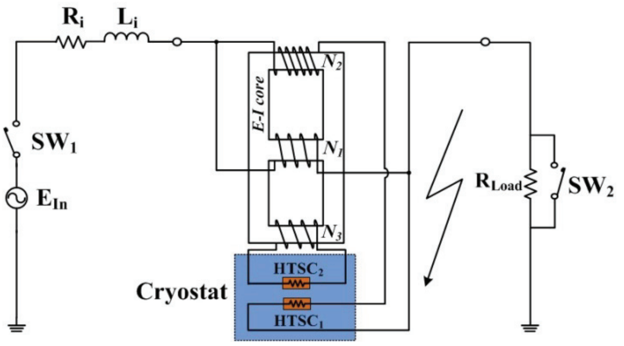

Fig. 3. Experimental circuit of SFCL having two magnetic paths.

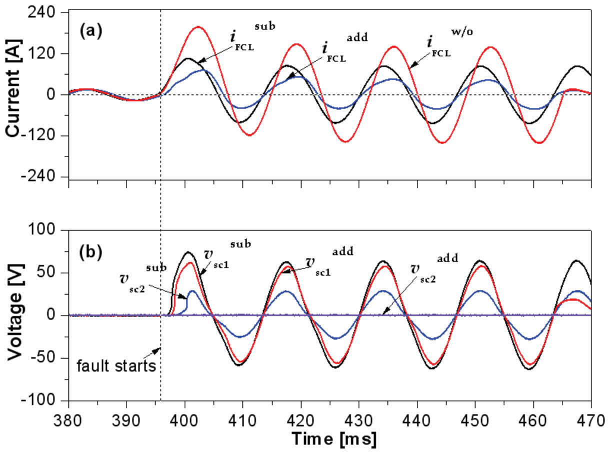

Fig. 4. (a) Limited line currents and (b) voltage curves for each HTSC element of SFCL for different winding directions of the two coils.

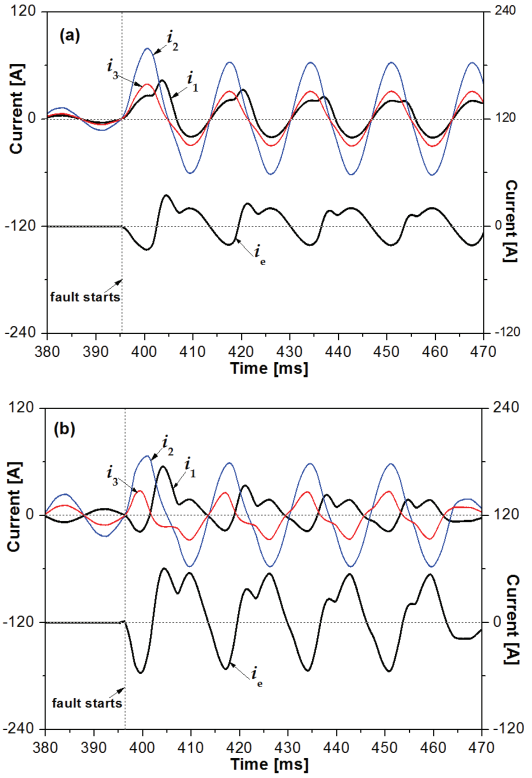

Fig. 5. Current limiting characteristics and exciting current of flux-lock-type SFCL having two magnetic paths for (a) subtractive and (b) additive polarity winding cases when fault occurs at 0°.

were measured and analyzed.

Fig. 4 shows the fault current limiting characteristics of the SFCL with two magnetic paths for different winding directions of the first and second coils before and after the occurrence of the fault as well as the voltage curves of the two HTSC elements. Fig. 4(a) shows the limited line current mode without and with the application of the SFCL based on the winding direction. It can be observed that at the start of the fault, the fault current is limited more effectively in the case of additive polarity winding when compared with that of subtractive polarity winding. As observed in Fig. 4(b), the fault and peak current limiting actions take place because a resistance is generated through the quench of HTSC elements 1 and 2 in the case of subtractive polarity winding.

On the other hand, in the case of additive polarity winding, only the fault current limiting action takes place because only the HTSC element 1 (R_{sc1}) is quenched immediately after the fault occurs. Further, the voltage of the HTSC element 2 is not induced because the current that flows in the third winding does not exceed the critical current value of the HTSC element 2 (R_{sc2}).

Fig. 5 shows a comparison of the current limiting characteristics and exciting current mode of the SFCL with two magnetic paths that use the E-I core when the fault occurs at 0° for the subtractive and additive polarity winding cases. The exciting current can be determined by using Eq. (1). As seen in Fig. 5(a), in the subtractive polarity winding case, the current mode of the first coil is limiting the fault current as the exciting current is increasing without significant distortion. However, in the case of additive polarity winding, as shown in Fig. 5(b), the fault current limiting is less because the current that flows in the first, second, and third coils is greatly distorted. Even if the fault current is limited through the quench occurrence of the first HTSC element, the exciting current increases greatly because the saturation of the E-I core causes the

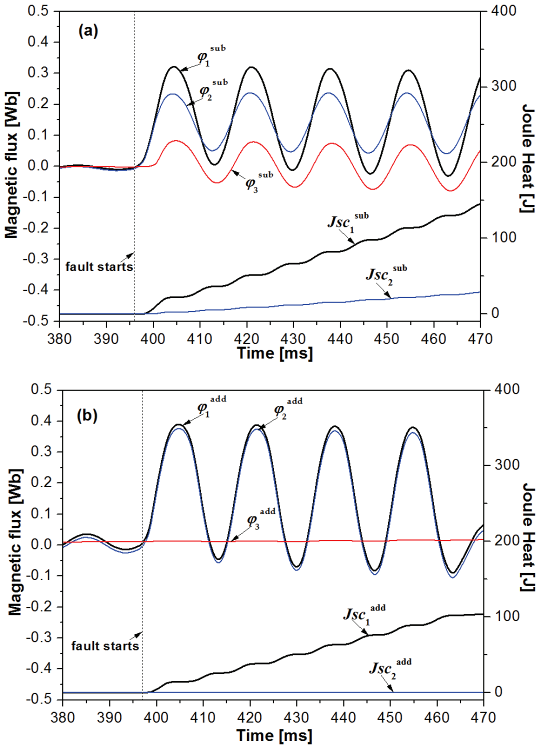

Fig. 6. (a) Magnetic flux of SFCL and Joule heat curve of each HTSC element for the subtractive polarity winding; (b) Magnetic flux of SFCL and Joule heat curve of each HTSC element for the additive polarity winding.

second peak current of the first coil. Therefore, the saturation of the iron core must be taken into consideration for different winding directions between the two coils when designing the SFCL having two magnetic paths using the E-I core.

Fig. 6 shows the magnetic flux distribution of the SFCL having two magnetic paths and the Joule heat characteristics of each HTSC element with respect to the winding direction of the first and second coils when the fault occurs. Here, the magnetic flux of the three legs of the E-I core was calculated from the induced voltage of Eq. (3). In the subtractive polarity winding case, the Joule heat was significantly higher for HTSC element 1 when compared with HTSC element 2 and showed a gradual increase. It can be observed that the magnetic flux generated from the central and left legs of the E-I core flows to the right leg in case of the subtractive polarity winding during the fault. However, in the case of additive polarity winding, the magnetic flux generated from the central and left legs flows to the right leg very minimally. Additionally, most of the magnetic flux travels through the paths of the left and right legs. Therefore, the Joule heat is generated in only the first HTSC element. Therefore, the maximum value of the magnetic flux inter-linkage increases slightly more in the case of additive polarity winding when compared with that of the subtractive polarity winding, signifying that there is greater possibility of saturation in the iron core in the additive polarity winding case.

4. Conclusion

A peak current limiting structure in which the first and second coils are connected in parallel using one E-I core and an additional second HTSC element is used in the third coil is proposed in this study. The internal magnetic flux characteristics of the E-I core before and after the occurrence of the fault as well as the fault current limiting effects were analyzed through short-circuit simulation. Although the fault current limiting effects were slightly superior in the case of additive polarity winding, when compared with the subtractive polarity winding case, the fault current limiting action was observed to be present in only one HTSC element thus increasing the burden of the HTSC element and preventing the peak current limiting function. Furthermore, from the magnetic flux distribution, the maximum value of the magnetic flux inter-linkage and the value of the magnetization current were observed to be small in the subtractive polarity winding case, thus confirming that the saturation potential in the iron core can be reduced.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) (No. 2010-0028509) and by the Basic Science Research Program through the NRF funded by the Ministry of Education (2013R1A1A2004916).

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