# Comparative Study of Current Limiting Characteristics for Hybrid Type and Flux-Lock Type SFCLs

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In this paper, we compared the current limiting characteristics of both the hybrid type and the flux-lock type superconducting fault current limiters (SFCLs), which have a magnetic coupling structure between a primary winding and several secondary windings. The limiting impedances of two SFCLs were derived from each equivalent circuit considering the design parameters of SFCL such as the self-inductance of secondary winding and the resistance of high-$T_C$ superconducting (HTSC) element. Through the comparison for the limiting impedances of two SFCLs considering the dependence of the HTSC element's resistance on the applying voltage into the SFCL, the hybrid type SFCL was confirmed to have larger limiting impedance with smaller resistance of HTSC element than the flux-lock type SFCL. It was expected from the analysis that the hybrid type SFCL was more advantageous than the flux-lock type SFCL from the viewpoint of the fault current limiting level.

*Keywords* : Current limiting characteristics, Hybrid type SFCL, Flux-lock type SFCL, Limiting impedance

## 1. INTRODUCTION

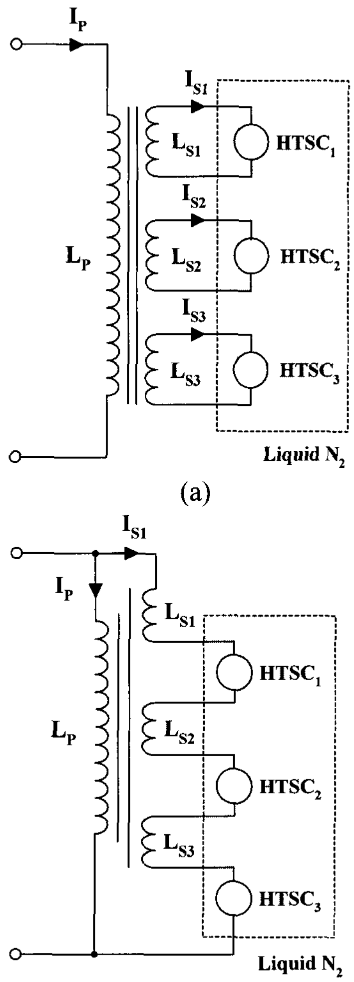
For the application of superconducting fault current limiters (SFCLs) into power system, voltage and current ratings of SFCLs have been required to increase. Especially, in order to increase the voltage ratings, superconducting elements comprising SFCL should be connected in series. However, slight difference in critical current between high-$T_C$ superconducting (HTSC) elements makes power burden among HTSC elements unequal, which has been a drawback to increase the voltage ratings of SFCL[1-3].

The hybrid type and the flux-lock type SFCLs are suggested to be advantageous structure to solve the imbalanced power burden due to different critical currents among HTSC elements, which is expected to be profitable to increase the voltage ratings of SFCL compared to other type SFCL. The common operational characteristic of these two models, which induces the balanced power burden among HTSC current limiting elements, is that the fault current can be limited by the flux linkage between the primary winding and several secondary windings through one iron core[4,5].

In this paper, we derived the limiting impedances of two SFCLs from each equivalent circuit considering the design parameters of SFCL such as the self-inductance of secondary winding and the resistance of HTSC element. From the comparison for two SFCLs, the limiting impedance of the hybrid type SFCL reached the higher value than that of the flux-lock type SFCL as the applying voltage into the SFCL increased. Therefore, the fault current limiting level in case of the hybrid type SFCL appeared lower than that of the flux-lock type SFCL. We could confirm that the hybrid type SFCL was more advantageous than the flux-lock type SFCL from the viewpoint of the fault current limiting level and the power burden of HTSC elements.

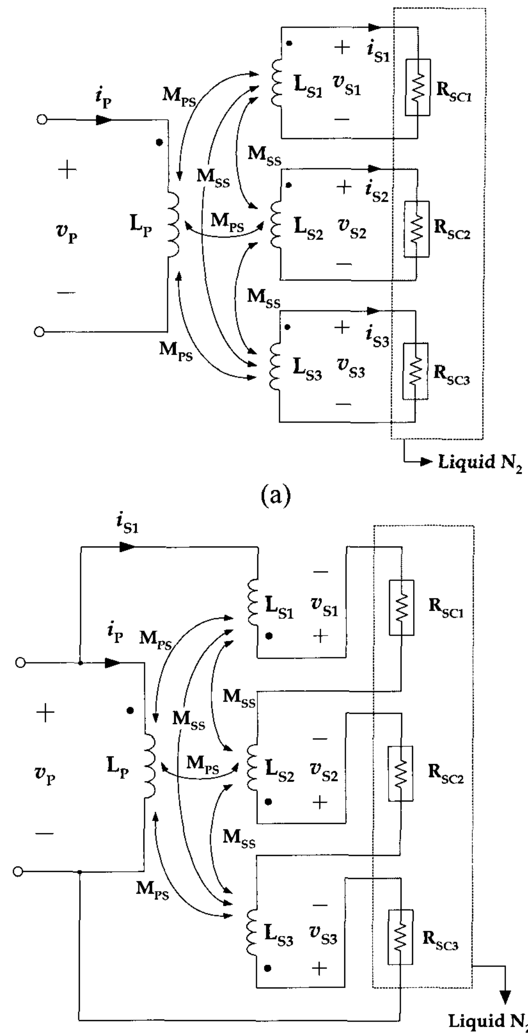
## 2. STRUCTURE OF HYBRID AND FLUX-LOCK TYPE SFCLS

Figure 1 shows the schematic diagrams of the hybrid type and the flux-lock type SFCLs, each of which consists of a primary winding, three secondary windings and three HTSC elements. The basic operational principle of each SFCL was referred to references[4,5]. The flux linkage between the primary winding and the secondary windings can alleviate the imbalanced power burden among HTSC elements directly after a fault happens and thus, the balanced power burden among HTSC elements can be achieved. The equivalent circuits for both the hybrid type and the flux-lock type SFCLs are shown in Fig. 2.



(b)

Fig. 1. Schematic diagrams of the hybrid type and the flux-lock type SFCLs.
(a) Hybrid type SFCL. (b) Flux-lock type SFCL.



(b)

Fig. 2. Equivalent circuits.
(a) Hybrid type SFCL. (b) Flux-lock type SFCL.

Assuming that the coupling coefficients between two windings are 1 and that the resistances of HTSC elements ($R_{S1}, R_{S2}, R_{S3}$) and the self inductances of the secondary windings ($L_{S1}, L_{S2}, L_{S3}$) are equal to $R_S$ and $L_S$, the limiting impedances of both the hybrid type and the flux-lock type SFCLs from each equivalent circuit can be derived as the equations (1) and (2), respectively.

$$Z_{limit}^{h} = \frac{3w^2 M_{PS}^2 - w^2 L_P (L_{S1} + 2M_{SS}) + jwL_P R_S^{h}}{R_S^{h} + jw(L_{S1} + 2M_{SS})} \quad (1)$$

$$Z_{limit}^{fl} = \frac{jwL_P 3R_S^{fl} - w^2 L_P (3L_{SS} + 6M_{SS}) + 9w^2 M_{PS}^2}{3R_S^{fl} + jw(L_P + 3L_{SS} + 6M_{PS} + 6M_{SS})} \quad (2)$$

Where $M_{PS}$ and $M_{SS}$ are the mutual inductances between the primary winding and the secondary winding and the mutual inductance between the secondary windings, respectively and w is angular frequency. Superscripts of h and fl in equations (1) and (2) mean the first characters of hybrid and flux-lock words to distinguish the hybrid type SFCL from the flux-lock type SFCL.

The resistances of HTSC elements comprising both the hybrid type and the flux-lock type SFCLs can be drawn as the equations (3) and (4), respectively.

$$R_S^{h} = \left[\frac{L_S}{L_P}\right]^2 \frac{V_P}{I_S} \quad (3)$$

$$R_S^{fl} = \left(\frac{1}{3} + \left[\frac{L_S}{L_P}\right]^2\right) \frac{V_P}{I_S} \quad (4)$$

Where $I_S$ is the current passing each HTSC element. $L_P$ and $L_S$ represent the self-inductances of both the

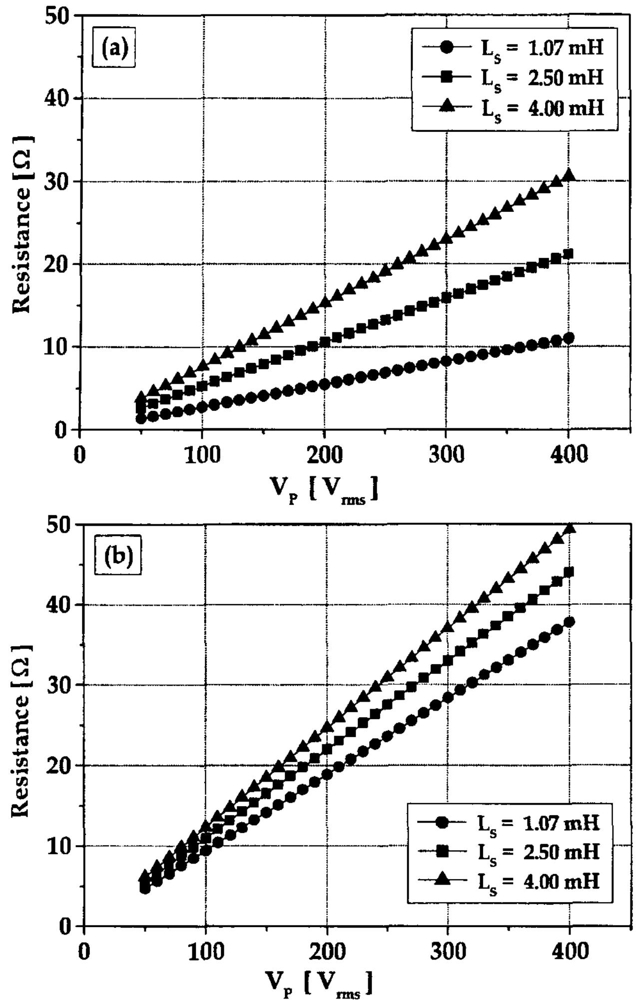



Fig. 3. Variance of resistance in HTSC element comprising each SFCL dependent on both the primary winding's voltage and the self-inductance of the secondary winding. (a) Hybrid type SFCL. (b) Flux-lock type SFCL.

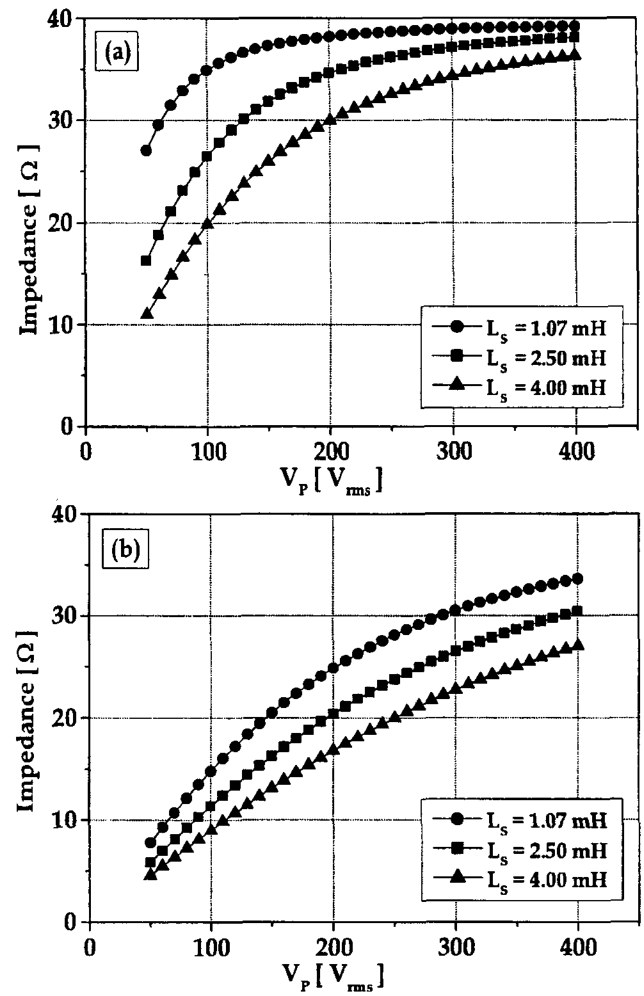



Fig. 4. Limiting impedances of two SFCLs dependent on both the primary winding's voltage and the self-inductance of the secondary winding.
(a) Hybrid type SFCL. (b) Flux-lock type SFCL.

primary winding and each secondary winding. In case of the hybrid type SFCL, the currents passing HTSC elements are assumed to be the same as $I_S$. The limiting impedances of two SFCLs can be compared by inserting the equations (3) and (4) into the equations (1) and (2), respectively.

## 3. RESULTS AND DISCUSSION

Figure 3(a) and Fig. 3(b) show the variance of resistance in each HTSC element comprising the hybrid type and the flux-lock type SFCLs dependent on both the primary winding's voltage ($V_P$) and the self-inductance of the secondary winding ($L_S$) for the given current passing through HTSC element ($I_S = 4.2$ A) and the self-inductance of the primary winding ($L_P = 87.5$ mH).

As observed in Fig. 3, the resistance of HTSC element can be observed to increase in proportion to the primary winding's voltage and the self-inductance of the secondary winding in both cases of the hybrid type and the flux-lock type SFCLs. The resistance of HTSC element in the flux-lock type SFCL was observed to be higher than that of HTSC element in the hybrid type SFCL and thus, the power loss of each HTSC element in case of the hybrid type SFCL is expected to be decreased compared to the flux-lock type SFCL.

Figure 4 shows the limiting impedances of two SFCLs dependent on both the primary winding's voltage and the self-inductance of the secondary winding. The resistance value of HTSC element in each SFCL, which is expressed as a function of the applying voltage into SFCL and the self-inductance of the secondary winding as shown in equations (3) and (4), was reflected into the SFCL's limiting impedance of the equations (1) and (2).

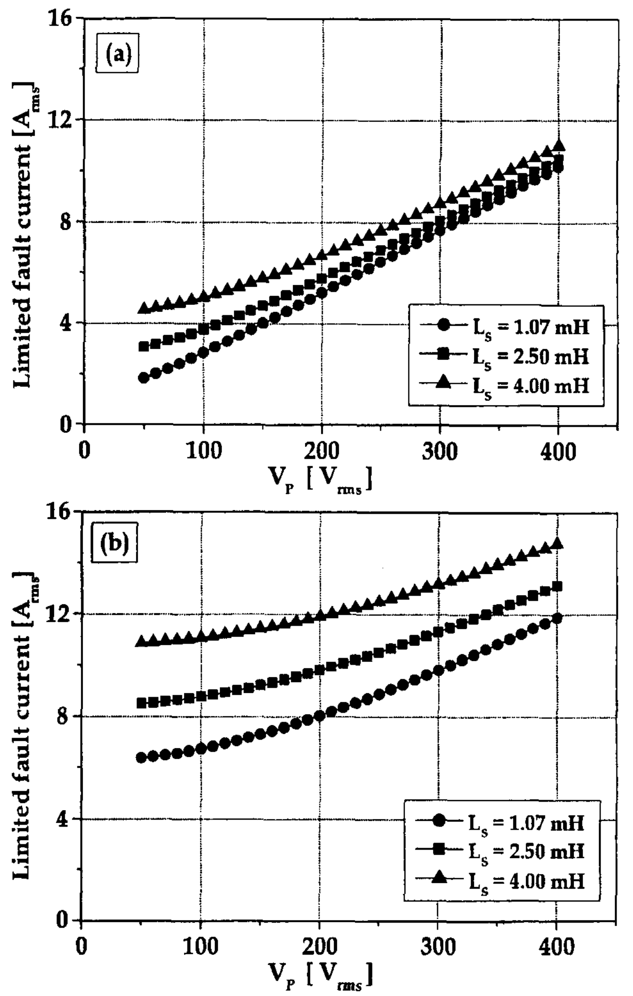



Fig. 5. Fault current limiting level of two SFCLs dependent on both the primary winding's voltage and the self-inductance of the secondary winding. (a) Hybrid type SFCL. (b) Flux-lock type SFCL.

It was observed from Fig. 4 that the limiting impedance of each SFCL decreased as the self-inductance of each secondary winding increased at the fixed primary winding's voltage and that the variance in the limiting impedance due to the self-inductance of the secondary winding lessened more as the primary winding's voltage increased in case of the hybrid type SFCL. In comparison of the limiting impedance for two SFCLs, the limiting impedance of the hybrid type SFCL was higher than that of the flux-lock type SFCL, which means that the hybrid type SFCL was more effective compared the flux-lock type SFCL from the viewpoint of the fault current limiting operation.

Figure 5 displays the dependence of each SFCL's limited fault current on both the primary winding's voltage and the self-inductance of the secondary winding. From Fig. 5, the fault current limiting level in case of the hybrid type SFCL was confirmed to be lower compared to the flux-lock type SFCL, which was expected from Fig. 4.

## 4. CONCLUSION

We derived the limiting impedances of two SFCLs from each equivalent circuit considering the variance of the resistance in HTSC element, which was expressed as a function of the voltage of the primary winding and the self-inductance of the secondary winding of SFCL.

We obtained through the comparison for the limiting impedances of two SFCLs that the hybrid type SFCL had larger limiting impedance with smaller resistance of HTSC element than that of the flux-lock type SFCL. In addition, we confirmed from the fault current limiting level point of view that the current limiting operation of the hybrid type SFCL was more advantageous than that of the flux-lock type SFCL.

In the further work, we will investigate the hysteresis characteristic of the iron core for two SFCLs and the dependence of the hysteresis characteristic on the self-inductance of the secondary winding of two SFCLs.

## ACKNOWLEDGMENT

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