Fault Current Limiting Characteristics of a Small-Scale Bridge Type SFCL with Single HTSC Element Using Flux-Coupling

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Background

- Superconducting fault current limiters (SFCLs) are the best alternative to limit fault currents at the medium and high voltage levels that are fundamental components of modern power systems.

- SFCL can be classified into four types according to structure and principle of operation: resistance type, rectifier type, self-shielding type, and saturated core type.

- Among these SFCLs, rectifier type (bridge type) SFCLs do not require quench generation and can significantly reduce AC losses.

- Bridge type SFCL has recently proposed a thyristor or IGBT switch instead of a diode, and a DC resistance type with the addition of a superconducting coil that can be quenched in a diode bridge has also been proposed.

Background

- However, this type of SFCL has the disadvantage of being larger than other types of SFCL due to the superconducting coil.
- This SFCL is also expensive and requires controllers and circuit breakers to protect the superconducting coils from accidents.
- To overcome these drawbacks, we proposed a bridge type SFCL with a single high-temperature superconducting (HTSC) element using flux-coupling that can be used as a preliminary step of a DC system.
- The fault current limiting operation due to the quench of a single HTSC element, the voltage characteristics of each element, the magnetic flux and instantaneous power of the two windings, and the energy consumption were compared.

Structure and Electrical Equivalent Circuit

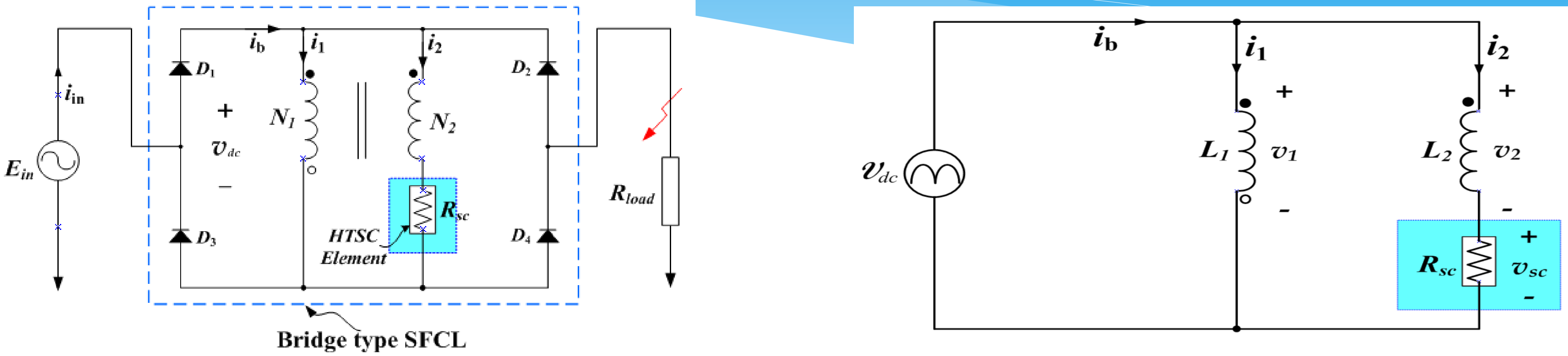

Fig. 1. Schematic configuration and electrical equivalent circuit of bridge type SFCL with a single HTSC element using flux-coupling.

- The SFCL consists of four diodes connected in the form of full-wave bridges for operation at DC, two coils wound around one iron core, and HTSC element connected to only one coil in series. The winding direction between the primary and secondary windings (N_1, N_2) can be changed to either subtractive polarity winding or additive polarity winding. The HTSC element was $Y_1Ba_2Cu_3O_{7-x}$ (YBCO) thin films deposited with a 200 nm thick layer of platinum and used a product of Theva, Germany.

- In the case of a subtractive polarity winding and an additive polarity winding from the equivalent circuit of Fig. 1, the fault current limiting operating current (I_{op}) can be represented by equations (1) and (2), respectively.

$$I_{op-sub} = \frac{L_2+\sqrt{L_1L_2}}{L_1+\sqrt{L_1L_2}} \times I_c \qquad (1)$$

$$I_{op-add} = \frac{L_2-\sqrt{L_1L_2}}{L_1-\sqrt{L_1L_2}} \times I_c \qquad (2)$$

- The basic operation principle is that the resistance of the HTSC element becomes zero because no quenching occurs under conditions prior to the failure. In addition, since the current flowing through the N_1 and N_2 windings is DC, these two coils are bypassed so that no magnetic flux occurs. Of course, even if AC ripple occurs due to the loss of the diode, the magnetic fluxes cancel each other out and become zero. However, after a fault has occurred, the transient fault current exceeds the critical current of the HTSC element in series with the N_2 winding, and the HTSC element has a resistance that causes a quench. The DC current flowing through the N_1 and N_2 windings causes a mixture of AC ripple component to generate magnetic flux. As a result, non-inductive coupling breaks and limits the fault current.

Preparation of Experiment

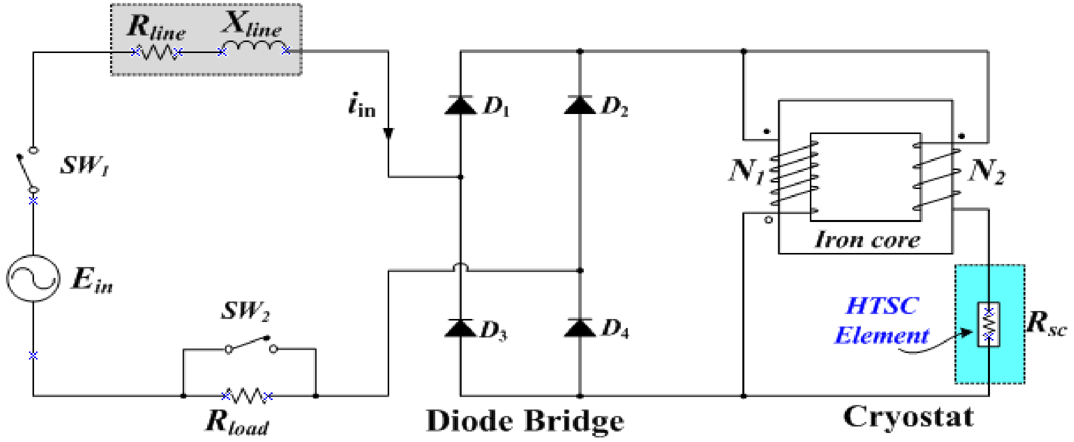

Fig. 2. Short-circuit test of bridge type SFCL with a single HTSC element using flux-coupling.

Table 1. Specifications of the bridge type SFCL with a single HTSC element using flux-coupling.

Windings (Turn Number, Self-Inductance)	Value	Unit
Primary Winding (N_1, L_1)	45, 20.293	Turns, mH
Secondary Winding (N_2, L_2)	15, 1.295	Turns, mH
HTSC Element (R_{sc})	**Value**	**Unit**
Material	YBCO	Thin Film
Critical Current (I_c) of HTSC element	18.15	A
Total Meander Line Length	420	mm
Line Width	2	mm
Thin Film Thickness	0.3	µm
Gold Layer Thickness	0.2	µm

- Figure 2 shows the schematic diagram of the experimental device for analyzing the fault current limiting operation characteristics, voltage waveforms, instantaneous power and magnetic flux change of a bridge type SFCL with a single HTSC element.

- A fault short-circuit experiments were performed at 40 V_{rms} AC input voltage (E_{in}) at 60 Hz and a fault angle of 0 °.

- The test equipment consists of a bridge circuit to obtain full-wave rectification, a line reactance (X_{line}) of 0.6 Ω, a line resistance of 1 Ω (R_{line}), a load resistance of 50 Ω (R_{load}), two windings on an iron core, and one HTSC element.

- This short-circuit tester is designed to supply AC power (E_{in}) by short-circuit SW_2 after SW_1 is closed and open the SW_1 and SW_2 after the fault cycle to cut off the power supply.

- The design parameters of a bridge type SFCL with a single HTSC element using flux-coupling are shown in Table I.

Experimental Results

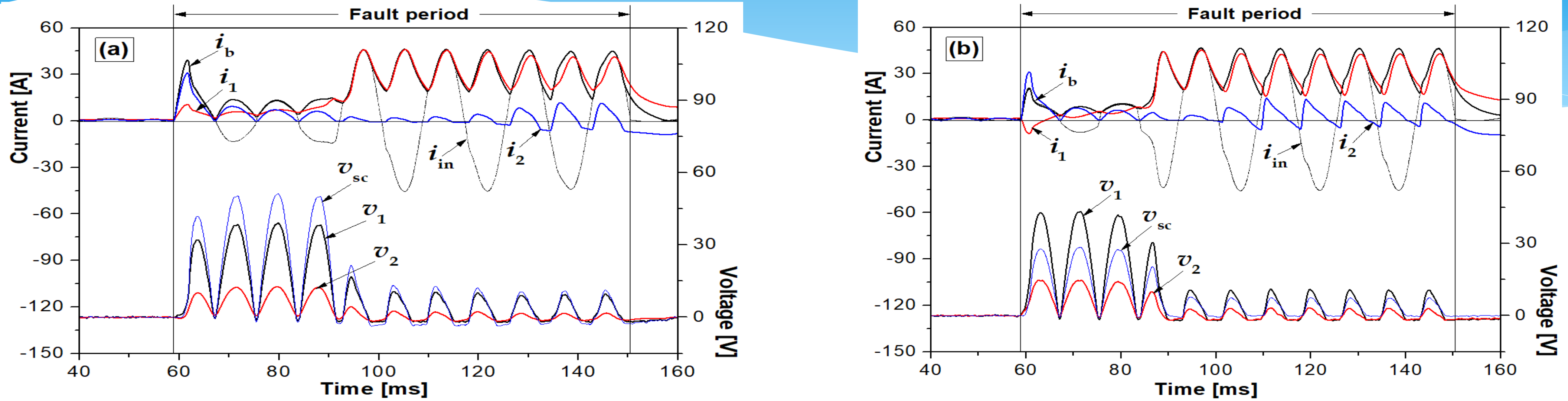

Fig. 3. Fault current limiting characteristics and voltage waveforms of bridge type SFCL with a single HTSC element using flux-coupling according to the connection direction between N_1 and N_2. (a) In the case of the subtractive polarity winding. (b) In the case of the additive polarity winding.

- Figure 3 shows the fault current limiting characteristics and voltage waveforms of a bridge type SFCL with a single HTSC element using flux-coupling when the two windings are connected to the subtractive polarity winding and the additive polarity winding at the input voltage source of 40 V_{rms} and the fault angle of 0 °.

- The line current (i_{in}) gradually increased immediately after the fault, but it was observed that the fault current suddenly increased before the quench occurred in the HTSC element. This phenomenon is due to the saturation of the iron core, and the fault current increases rapidly, causing quenching of the HTSC element. This shows that the fault current is limited.

- It can be seen that the voltage generated due to the quench of the HTSC element is smaller in the case of the additive polarity winding than that of the subtractive polarity winding. In addition, it can be seen that the current flowing through the secondary winding (N_2) is larger in the case of the additive polarity winding than that of the subtractive polarity winding from 3.5 cycles.

Experimental Results

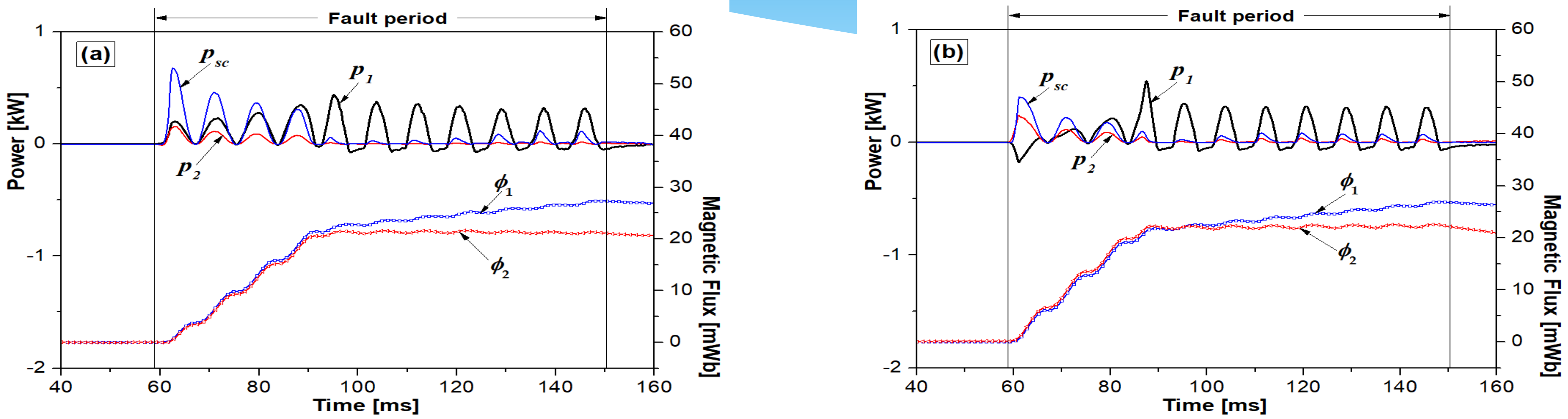

Fig. 4. Instantaneous powers and magnetic flux in each winding of bridge type SFCL with a single HTSC element using flux-coupling according to the connection direction between N_1 and N_2. (a) In the case of the subtractive polarity winding. (b) In the case of the additive polarity winding.

- Figure 4 shows the instantaneous power burden characteristics of the devices and the magnetic fluxes (ϕ_1,ϕ_2) of the two windings in a bridge type SFCL with a single HTSC element using flux-coupling when the two windings are connected to the subtractive polarity winding and the additive polarity winding during the fault period.

- The magnetic fluxes of the primary and secondary windings were similar in magnitude regardless of the wiring direction between the two coils. On the other hand, it can be observed that the instantaneous power consumed in the HTSC element is much larger in the case of the subtractive polarity winding than that of the additive polarity winding immediately after the failure.

- Also, it can be seen that the instantaneous power consumed in the secondary winding is higher in the case of the additive polarity winding than that of the subtractive polarity winding immediately after the failure.

Experimental Results

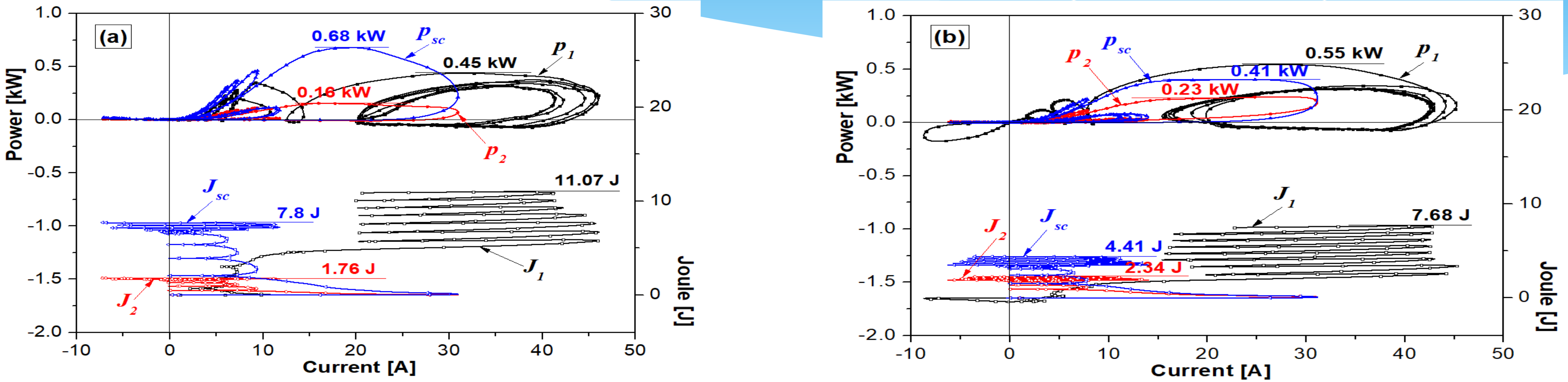

Fig. 5. Current vs. power consumption and energy consumption characteristics of each device according to the connection direction between N_1 and N_2 during the fault cycle. (a) In the case of the subtractive polarity winding. (b) In the case of the additive polarity winding.

- Figure 5 shows the power consumption and energy consumption of the HTSC element with respect to current of a bridge type SFCL with a single HTSC element when the primary and secondary windings are connected as the subtractive polarity winding and the additive polarity winding during the fault period.

- When a fault occurs, the maximum power consumption of the HTSC element is 0.27 kW higher in the case of the subtractive polarity winding than that of the additive polarity winding, but the maximum power consumption of the primary and secondary windings is 0.1 and 0.07 kW less, respectively.

- During the fault cycle, the maximum energy consumption of the HTSC element is found to be 3.39 J higher in the case of the subtractive polarity winding than that of the additive polarity winding. It can be observed that the maximum energy consumed in the primary winding is as high as 3.39 J, while the maximum energy consumed in the secondary winding is as low as 0.58 J.

Conclusion

- In this paper, the fault current limiting characteristics, instantaneous power, and energy consumption of a bridge type SFCL with a single HTSC element were compared according to the wiring direction between the two coils during the fault period.
- Since the HTSC element operates under nearly DC conditions, the fault current rapidly increased due to saturation of the iron core immediately after the fault occurred. However, it can be seen that the fault current is limited by the quenching of the HTSC element.
- It can be seen that the quench voltage of the HTSC element is much larger in the case of the subtractive polarity winding than that of the additive polarity winding.
- Instantaneous power dissipated in the single HTSC element is much larger in the case of the subtractive polarity winding than that of the additive polarity winding immediately after the fault.
- However, it could be confirmed that the instantaneous power consumed in the secondary winding was larger in the case of the additive polarity winding.
- In addition, the maximum energy consumed by the HTSC element during the fault period was higher in the case of the subtractive polarity winding than that of the additive polarity winding.
- At this time, the maximum energy consumed in the primary winding was higher in the case of the subtractive polarity winding, but the maximum energy consumed in the secondary winding was less.
- In conclusion, it was confirmed that the power consumption and energy consumption of the HTSC element was lower in the case of the additive polarity winding than that of the subtractive polarity winding, and the fault current limiting characteristics was excellent.