Magnetizing Characteristics of Bridge Type SFCL with Simultaneous Quench Using Flux-Coupling

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Background

- Superconducting fault current limiters (SFCLs) are fundamental components of modern electrical systems at both medium and high voltages. Many research efforts have been carried out to reduce fault currents in AC or DC systems.

- Among other SFCLs, bridge type SFCL using reactors do not require quenching and can significantly reduce AC losses. This bridge type SFCL is generally composed of a diode or thyristor and a superconducting coil, and has the disadvantage of being larger than other types of SFCL due to the superconducting coil.

- In addition, this SFCL is expensive and requires controllers and circuit breakers to protect the superconducting coils from accidents. In order to overcome this drawback, DC double reactor type SFCL using switching operation of HTSC device has been proposed and fault current limiting characteristics have been reported.

- However, this DC double reactor type SFCL has not been investigated for the magnetization characteristics and instantaneous power burden characteristics according to the input voltage change at the time of failure.

Background

- In this paper, we proposed a bridge type SFCL with simultaneous quench using flux-coupling as a preliminary step of DC system.
- The fault current limiting operation, voltage waveforms, instantaneous power and magnetic flux, and magnetization of each device are analyzed for this bridge type SFCL.
- When the input AC voltage source was changed, we tried to analyze the range of voltage induced by the magnetizing current, the change of energy consumption, the range of the magnetizing power, and the operating range of the magnetic flux linkage.
- A lab scale prototype was built and failure short-circuit experiment was performed. We tried to verify its usefulness by analyzing fault current limiting operation and magnetization characteristics of bridge type SFCL with simultaneous quench.

Structure and Electrical Equivalent Circuit

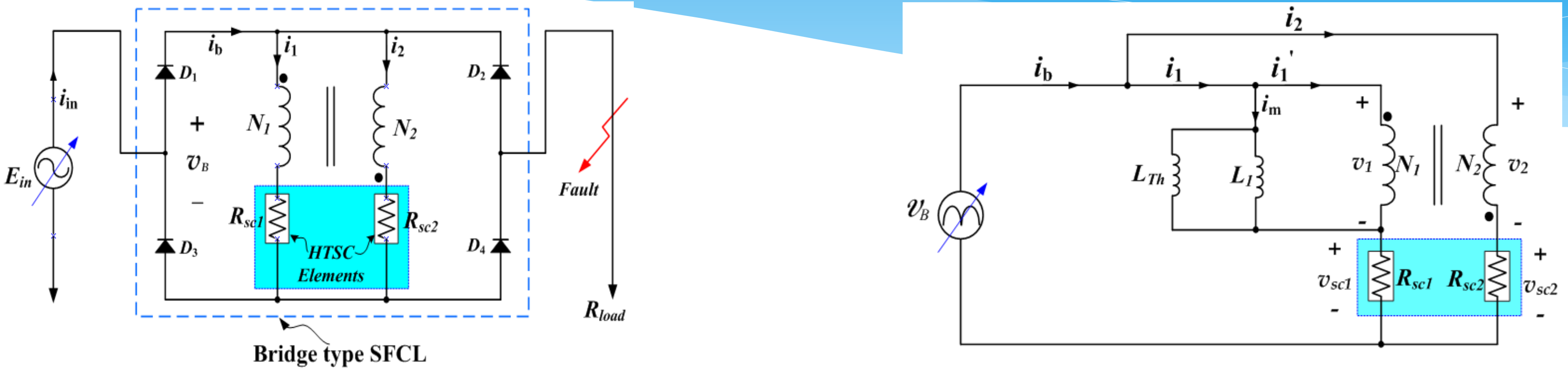

Fig. 1. Schematic configuration and electrical equivalent circuit of bridge type SFCL with simultaneous quench using flux-coupling.

- This SFCL consists of an iron core, two windings, and two HTSC elements and four diodes. The wiring direction between the primary and secondary windings (N_1, N_2) is an additive polarity winding and is connected in parallel with each other. In addition, the AC power supply voltage (E_{in}) is designed to be variable. HTSC elements (R_{sc1}, R_{sc2}) were fabricated by patterning $Y_1Ba_2Cu_3O_{7-x}$ (YBCO) thin films made by Theva Company, Germany
- In the case of the additive polarity winding between the N_1 and N_2 windings, the magnetizing current (I_m) and the limiting impedance (Z_{SFCL}) of the bridge type SFCL with simultaneous quench using flux-coupling can be expressed by Equations (1) and (2).

$$I_m = I_1 - I_1' = I_1 + \frac{N_2}{N_1} I_2 \quad (1)$$

$$Z_{SFCL} = {}^{1}\Big/\left[-\frac{1}{V_1}\left(\frac{N_2 V_{sc2}}{N_1 R_{sc2}}\right) + \frac{1}{j\omega L_{eq}}\right] + R_{sc1} \quad (2)$$

- As a basic principle of operation, under conditions before failure occurs, the resistance of the HTSC elements becomes zero because no quench occurs. Also, because the current flowing through the windings N_1 and N_2 is DC, these two coils are bypassed and no magnetic flux occurs. Eventually, the impedance of this SFCL becomes zero. However, after a fault has occurred, the transient fault currents exceed the critical currents of the HTSC elements connected in series with the N_1 and N_2 windings, causing resistance in the HTSC elements and quenching them. The DC current flowing through the N_1 and N_2 windings is mixed with the AC ripple component to generate magnetic flux. As a result, the non-inductive coupling breaks, limiting the fault current.

Preparation of Experiment

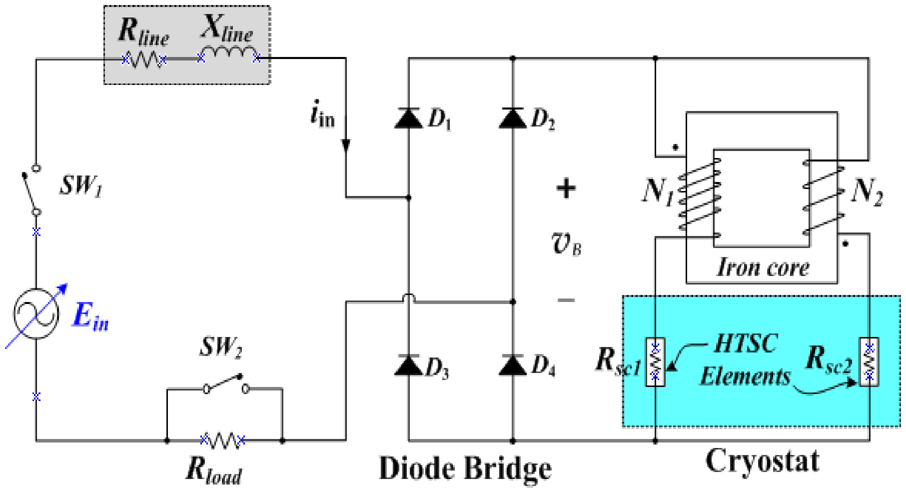

Fig. 2. Schematic diagram for the experimental circuit of bridge type SFCL with simultaneous quench according to the input voltage variation.

Table 1. Specifications of the bridge type SFCL with simultaneous quench using flux-coupling.

Two coils	Value	Unit
Turn Number of First Winding (N_1)	150	Turns
Turn Number of Second Winding (N_2)	150	Turns
Winding connection method	Additive polarity winding	
HTSC Element	Value	Unit
Material	YBCO	Thin Film
Critical Current of HTSC (R_{sc1})	18.15	A
Critical Current of HTSC (R_{sc2})	19.04	A
Total Meander Line Length	420	mm
Line Width	2	mm
Thin Film Thickness	0.3	µm
Gold Layer Thickness	0.2	µm

- Table I shows the design parameters of a bridge type SFCL with simultaneous quench using flux-coupling. The critical currents (I_{c1}, I_{c2}) of HTSC elements 1 and 2 were used by patterning YBCO thin films with 18.15 and 19.04 A, respectively.

- The fault test was performed at 80 V_{rms} and 100 V_{rms} AC input voltage (E_{in}) at 60 Hz and fault angle 0 °. The test equipment consisted of a full-wave bridge for DC, a line reactance of 0.6 Ω (X_{line}), a line resistance of 1 Ω (R_{line}), a load resistance of 50 Ω (R_{load}), two windings on one iron core, two HTSC elements.

- After SW_1 is closed, SW_2 is designed to close at the fault angle 0 ° of the AC power supply and reopen after the fault period.

Experimental Results

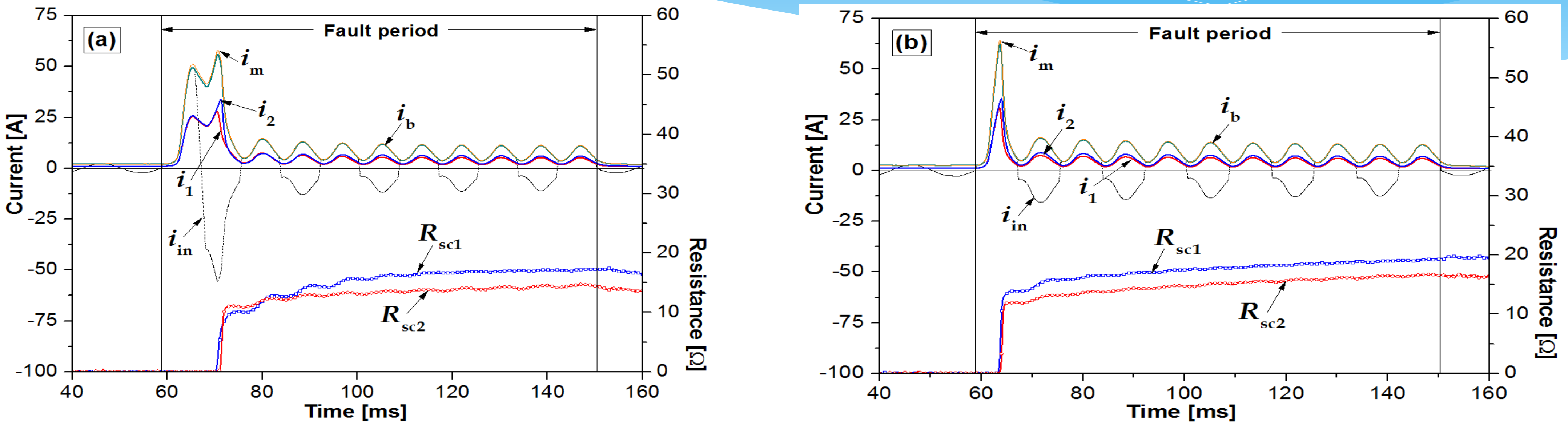

Fig. 3. Fault current limiting operating characteristics of bridge type SFCL using flux-coupling according to the change of input voltage source. (a) E_{in}=80 V_{rms}. (b) E_{in}=100 V_{rms}.

- Figure 3 shows the fault current limiting characteristics of the bridge type SFCL when the input voltage source changes to 80 V_{rms} and 100 V_{rms}, respectively.

- When the input voltage source was 100 V_{rms}, the fault current and the magnetizing current increased much faster after a fault, and the HTSC elements 1 and 2 were quenched at about the same time in half cycle.

- It can be seen that the quench occurs first and the fault current is limited when the input voltage source is 100 V_{rms} rather than 80 V_{rms}.

Experimental Results

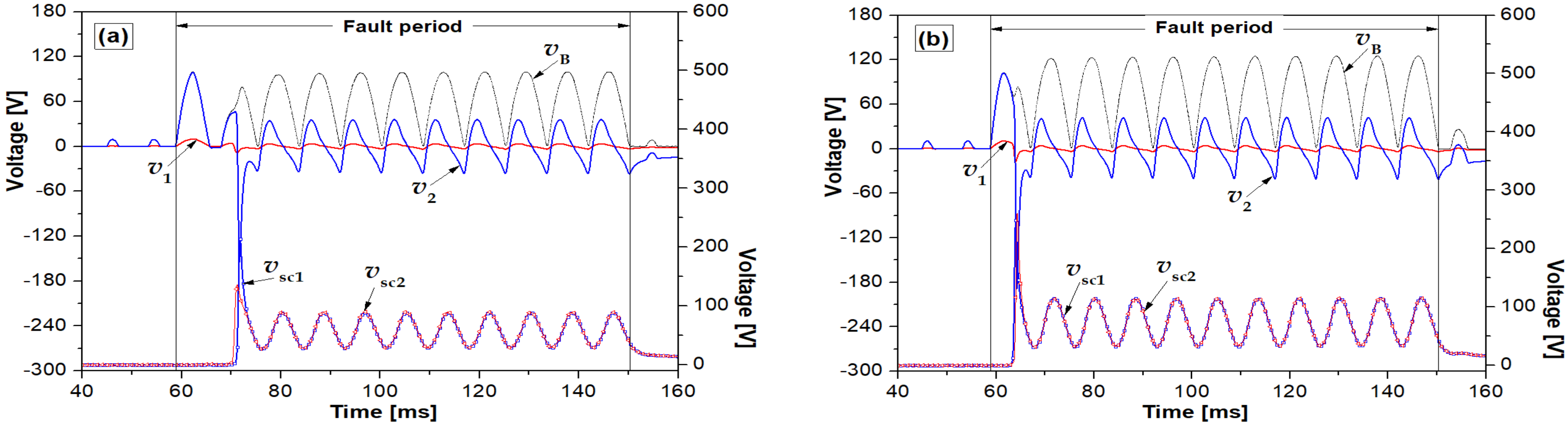

Fig. 4. Voltage waveforms of full bridge circuit, each winding and HTSC elements (V_B, V_1, V_2 and V_{SC1}, V_{SC2}) according to the change of input voltage source. (a) E_{in}=80 V_{rms}. (b) E_{in}=100 V_{rms}.

- Figure 4 shows the voltage waveforms of each winding and HTSC element when the input voltage source changes to 80 V_{rms} and 100 V_{rms}, respectively.
- When the input voltage source was 100 V_{rms}, the voltage waveforms of the HTSC elements, the full-wave bridge voltage waveform of the rectifier stage, and the voltage waveforms of two windings increased.
- However, it can be seen that the voltage across N_2 is minutely generated before the quench occurs due to the leakage current of the winding.

Experimental Results

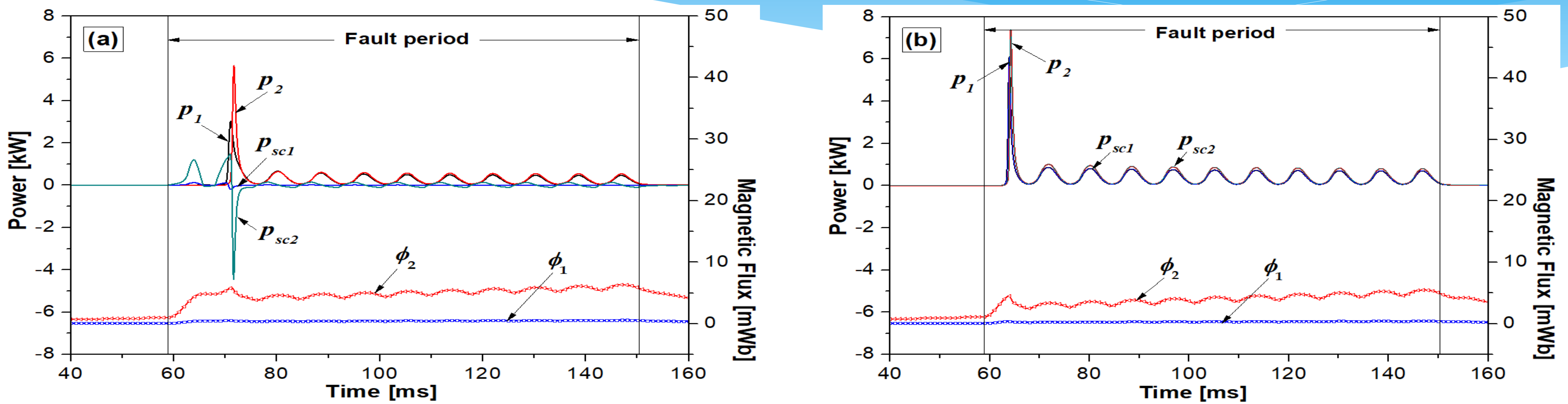

Fig. 5. Instantaneous powers and magnetic flux in each winding of bridge type SFCL using flux-coupling according to the change of input voltage source. (a) E_{in}=80 V_{rms}. (b) E_{in}=100 V_{rms}.

- Figure 5 shows the magnetic flux of each winding and instantaneous power burden of each device as the input voltage source changes to 80 V_{rms} and 100 V_{rms}, respectively, during the fault period.
- As the input voltage source was increased, the magnetic flux (ϕ_1) of the primary winding hardly changed, but the magnetic flux (ϕ_2) of the secondary winding decreased significantly.
- On the other hand, it can be observed that the instantaneous power consumed by the primary and secondary windings and the HTSC elements 1 and 2 are much larger when the input voltage source is increased immediately after the failure.

Experimental Results

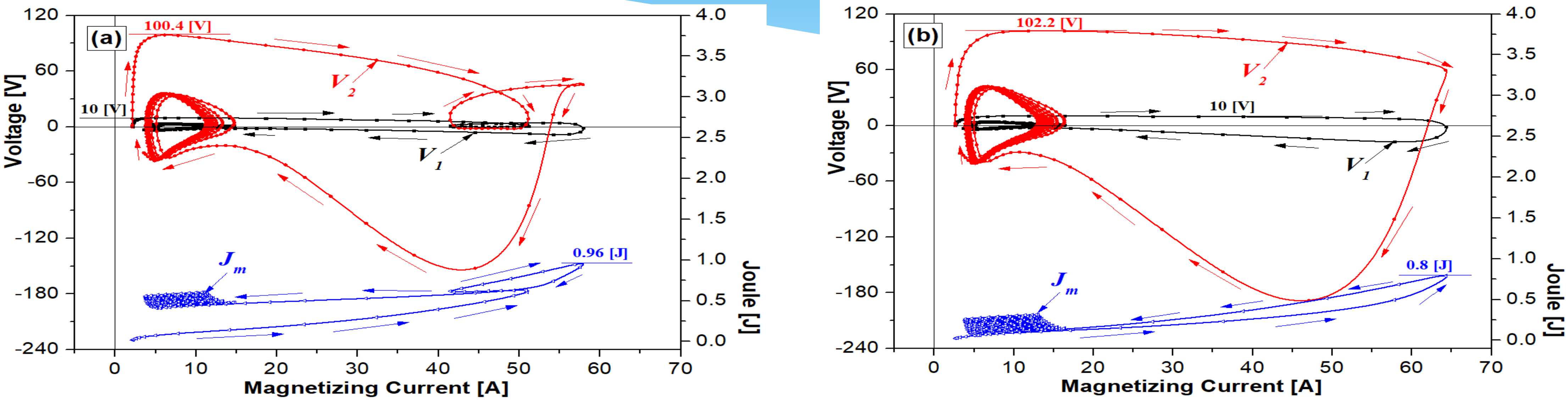

Fig. 6. Variation of induced voltage and consumed energy of each winding due to magnetizing current (i_m) during fault period in the bridge type SFCL using flux-coupling according to the change of input voltage source. (a) E_{in}=80 V_{rms}. (b) E_{in}=100 V_{rms}.

- Fig. 6 shows the characteristics of the energy dissipated by the magnetizing force and the range of fluctuation in the voltage induced in each winding for the magnetizing current during the fault cycle when the input voltage source changes to 80 V_{rms} and 100 V_{rms}, respectively.
- When the input voltage source increases during the fault cycle, the range of voltage induced in the primary winding is large, but the range of voltage induced in the secondary winding appears small and converges to nearly zero.
- In addition, it can be seen that during the fault period, the magnetizing force energy increases with the increase and decrease of the magnetizing current and then decreases to converge to the magnetizing current 10 A point.
- It can be observed that as the input voltage source increases, the range of increase and decrease of magnetizing current is wide, but energy consumption is low.

Experimental Results

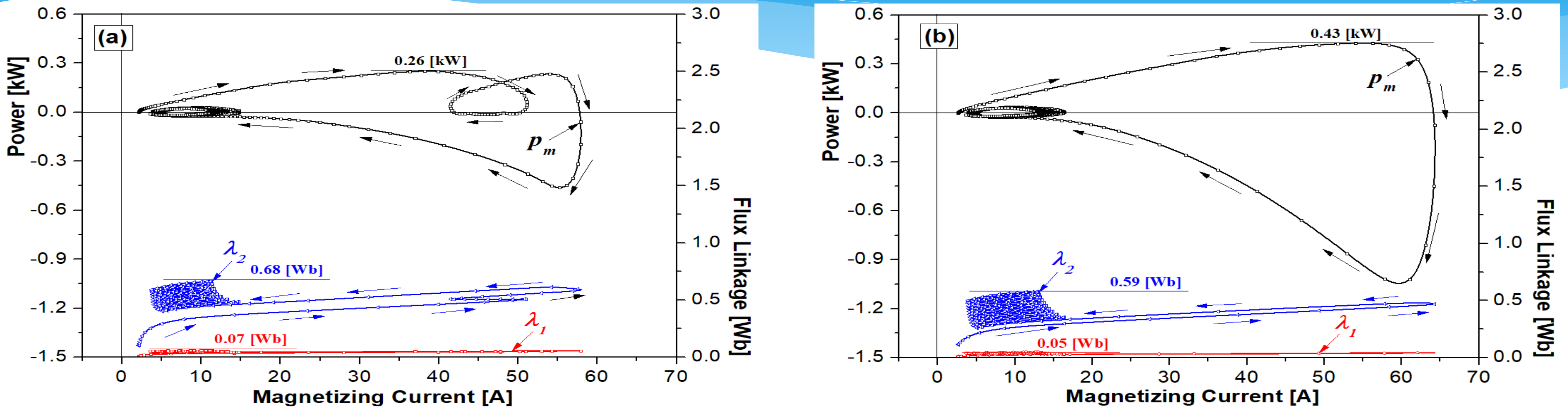

Fig. 7. Variation of magnetizing force (p_m) area and flux linkage's (λ) operational range dependent on the magnetizing current (i_m) during fault period in the bridge type SFCL using flux-coupling according to the change of input voltage source. (a) E_{in}=80 V_{rms}. (b) E_{in}=100 V_{rms}.

- Figure 7 shows the operating range of the magnetizing force (p_m) and the magnetic flux linkage (λ) according to the magnetizing current during the fault period when the input voltage source changes to 80 V_{rms} and 100 V_{rms}, respectively.
- As the input voltage source increases, the maximum magnetizing force is 0.17 kW higher, and it can be seen that the change of the magnetizing force area according to the magnetizing current is much larger.
- As the magnetizing current increases and decreases, the operating range of the flux linkages 1 and 2 gradually increases and then decreases again, showing that the magnetization current converges at about 10A.
- When the input voltage source increases, the maximum flux linkages 1 and 2 are smaller than 0.02 and 0.09 Wb, respectively, but the operating range of the flux linkages 1 and 2 is slightly larger.

Conclusion

- In this paper, we compared and analyzed the energy consumption change, magnetizing force area change, and flux linkage operating range due to magnetizing current when the input voltage source is changed to 80 V_{rms} and 100 V_{rms}, respectively.
- Immediately after the fault, the fault current and magnetizing current increased even more rapidly, and it was observed that HTSC elements 1 and 2 were simultaneously quenched in half cycle.
- When the input voltage source was increased from 80 V_{rms} to 100 V_{rms}, it was confirmed that the quench occurred at 100 V_{rms} first to limit the fault current.
- The magnetic flux (ϕ_1) of the primary winding was almost unchanged as the input voltage source increased, but the magnetic flux (ϕ_2) of the secondary winding was significantly reduced.
- On the other hand, it can be observed that the instantaneous power consumed by the primary and secondary windings and the HTSC elements 1 and 2 are much larger when the input voltage source is increased immediately after the fault.
- When the input voltage source was increased during the fault period, the increase and decrease range of the magnetizing current was wide when the range of the voltage induced in the primary winding increased, but the energy consumption was small.
- When the input voltage source was increased, the maximum magnetizing force was 0.17 kW higher, and it was confirmed that the change of the magnetizing force area by the magnetizing current was much larger.
- In addition, the maximum flux linkages 1 and 2 were smaller than 0.02 and 0.09 Wb, respectively, but the operating ranges of the flux linkages 1 and 2 were slightly larger.