Operational Characteristics of a Flux-Lock Type SFCL Integrated with Voltage-Controlled Voltage Source Inverter

Su-Won Lee*, Sung-Hun Lim†, Sung-Hun Ko and Seong -Ryong Lee*****

Abstract – In this paper, a flux-lock type superconducting fault current limiter (SFCL) integrated with a voltage-controlled voltage source inverter (VC-VSI) is proposed. The suggested equipment, which consists of a flux-lock type SFCL and a VCVSI, can perform the fault current limiting operation from the occurrence of a short-circuit. In addition, it can compensate the reactive power that the non-linear load requires and also perform the uninterruptible power supply (UPS) as well as the load voltage stabilization by controlling the amplitude and the phase of the inverter's output voltage. The specification for a test model was determined and its various functions such as the fault current limiting and the power conditioning operations were presented and analyzed via computer simulation. Through the analytical results based on the computer simulation, the validity of the analysis was confirmed and its multi-operation was discussed.

Keywords: Flux-lock type superconducting fault current limiter, Load voltage stabilization, Power conditioning operation, Uninterruptible power supply, Voltage-controlled voltage source inverter

1. Introduction

Superconducting fault current limiters (SFCLs) have been noticed as one of the most promising power machines because of their advantageous characteristics such as self-fault current sensing, self-recovery, and fast fault current limiting operations. These characteristics are expected to be unique countermeasures to solve the drawbacks that the conventionally developed FCLs, e.g., power fuse and solid state FCLs based on power electronic technology, have not overcome [1-3]. Among the various types of SFCLs, the flux-lock type has been reported to increase the current limiting capacity of the SFCL by adjusting the inductance ratio and the winding direction of two coils and by also being able to combine with the power compensator through its third coil [4,5].

The voltage source inverters (VSIs), which have the parallel connection between the source and the non-linear load, have been widely used to perform the power quality improving operation: power conditioning, load voltage stabilization and uninterruptible power supply (UPS) [6,7]. However, the topologies to protect the VSIs from a short circuit effectively, together with the functions for the power quality improvement, have not been vastly developed. Most of the research performed to protect the VSIs from short-circuit have been focused on the circuit breaker or series reactor, not the multi-functional equipment using VSIs [8,9].

In this paper, we propose the flux-lock type SFCL integrated with the VSI operated with the voltage control (VC) algorithm. The suggested equipment can compensate the reactive power that the non-linear load requires by controlling the amplitude and the phase of the VSI's output voltage for the source voltage and thus perform the power conditioning operation, the demand side management (DSM), and the UPS as well as the load voltage stabilization. In addition, it can limit the fault current in case that short-circuit happens by the operation of the flux-lock type SFCL. Through the analysis for the various operations based on computer simulation, the validity of the suggested equipment was confirmed and its operational characteristics were discussed.

2. Structure and Operational Principle of Flux-lock Type SFCL Integrated with VC-VSI

2.1 Structure of Flux-Lock Type SFCL Integrated with VC-VSI

The schematic diagram of the flux-lock type SFCL integrated with the VC-VSI is shown in Fig. 1. This constitution is composed of a flux-lock type SFCL and a VC-VSI. The flux-lock type SFCL consists of two parallel coils

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wound on an iron core with a high-T_C superconducting (HTSC) element and a third coil wound on the same iron core, which is isolated from the other two coils. The major function of the flux-lock type SFCL is to limit the fault current [4,5]. The VC-VSI, which is connected to the third coil of the flux-lock type SFCL through an ac/dc converter such as a bridge diode, is composed of a decoupling inductor (L_M) for voltage control of VSI, an LC filter (Lr, Cr), a bi-directional inverter, and a dc capacitor (C_{DC}).

The transformer, if the higher output voltage of the VC-VSI compared to the battery voltage (E_B) is required, can be added to the VC-VSI as seen in Fig. 1. The bi-directional VSIs can be classified into VC-VSIs and current-controlled (CC) VSIs depending on whether their control target is the output voltage or the output current of the VSIs [10,11]. In this paper, the VC-VSI with the benefit of load voltage support was selected. By controlling the voltage, the suggested integrated equipment can execute the following several operations for the improvement of the power quality including the fault current limiting operation, power conditioning, load voltage stabilization, DSM, and UPS.

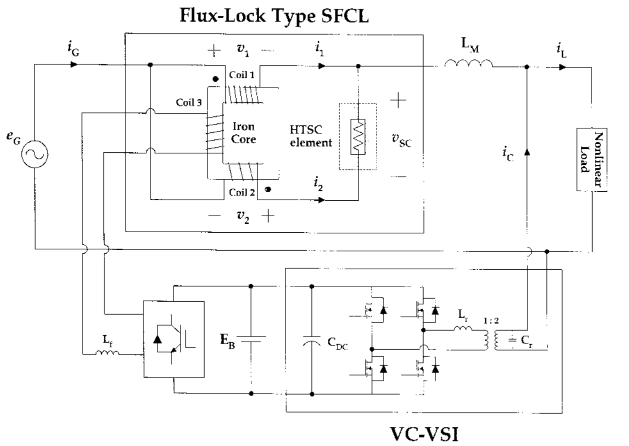

Fig. 1. Schematic diagram of the flux-lock type SFCL integrated with the VC-VSI

2.2 Operational Principle of Flux-Lock Type SFCL Integrated with VC-VSI

The operation of the flux-lock type SFCL integrated with VC-VSI can be largely divided into the fault current limiting operation and the power quality improving operations such as power conditioning, load voltage stabilization, DSM and UPS.

In case that the suggested equipment performs the fault current limiting operation, the flux-lock type SFCL of this equipment plays a leading role. The basic principle of the flux-lock type SFCL is the same as in the previous report [4,5]. Fig. 2 indicates the equivalent circuit in case that this equipment performs fault current limiting operation. L_1, L_2, and L_3 represent the self-inductance of each coil, respectively. M_{12}, M_{23}, and M_{13} represent the mutual inductance between two coils, respectively. When short-circuit happens and the resistance of HTSC element (R_{SC}) is generated, the voltages of coil 1, coil 2, and the coil 3 are induced and thus, the fault current can be limited. In addition, the amplitude of the fault current can be adjusted by changing the self-inductance of coil 3 using a tap changer or by controlling the current of coil 3 using a power conversion circuit such as an ac-dc converter [12,13]. Together with the adjustment of the fault current, the suggested equipment during a fault period has a function that the battery can be charged by the induced voltage in coil 3 through the bridge diode as seen in Fig. 2.

During normal operation, this equipment performs the power quality improving operation. As the control algorithm for the performance of the power quality improvement operation using the VSI, the voltage control algorithm, which is more profitable compared to the current control one from the point of view of the load voltage support, is used [10,11].

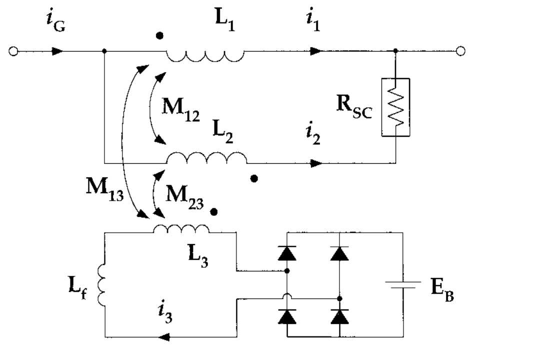

Fig. 2. Equivalent circuit in case of the fault current limiting operation

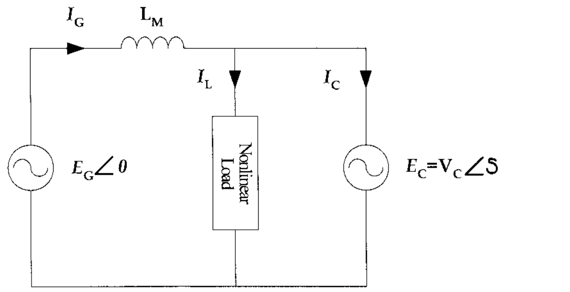

Fig. 3. Simplified equivalent circuit diagram in case of the power quality improving operation

Fig. 3 shows the simplified equivalent circuit diagram in case that the suggested equipment performs the power quality improvement operation with the VC algorithm. The decoupling inductor (L_M) is the essential component for applying the VC algorithm into this VSI. From Fig. 3, the source current (I_G), and the complex powers of the source (S_G) and the VSI (S_C) corresponding to the fundamental occurrence induces the voltages across coils 1, 2, and 3 and limits the fault current, which is the same operation as reported in reference [12,13]. After a fault occurs, the current of coil 3 starts to flow and charges the battery, which is connected with coil 3 through the bridge diode. However, the coil 3's waveform is rather distorted because of the non-linear property of the bridge diode for its current and voltage and, the distortion in the current waveform of coil 3 influences the current and the voltage waveforms of the other two coils as seen in Figs. 7 and 8. During a fault period, the operations for the improvement of the power quality can be ceased by generating the switching signals with zero into the PWM generator block.

Through the above analysis, the various operations of the proposed equipment for the improvement of power quality including the fault current limiting operation were confirmed. It is expected that the suggested equipment can contribute to the expansion of the function as the equipment for the improvement of the power quality as well as the fault current limiter.

4. Conclusions

We have proposed the flux-lock type SFCL integrated with the VC-VSI. The suggested equipment, which consists of a flux-lock type SFCL and a VC-VSI, could perform not only the operations for the improvement of the power quality but also the fault current limiting operation. The validity of the suggested equipment was confirmed through the analysis based on computer simulation. The operations for the improvement of the power quality in the proposed equipment were achieved by controlling the amplitude and the phase of the VSI's output voltage for the source voltage. The fault current in case that short-circuit happens could be limited as well by the operation of the flux-lock type SFCL, which was connected with the VC-VSI through coil 3. During its fault current limiting operation, the battery, which was needed for the operations of the DSM and the UPS, could be charged through the ac-dc circuit such as the diode bridge by the induced voltage in coil 3.

The research to solve the distortion of the current waveform in coil 3 during a fault period will be proceeded in consideration for the ac-dc circuit in the future.

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in Fig. 4, the VC-VSI supplies the reactive power for the non-linear load before the source fails at 0.25 s. Therefore, the non-linear load can be supplied with the active power from the source only. However, in case that the source failure occurs at 0.25 s, the VC-VSI supplies all the reactive power and the active power that the non-linear load needs as seen in Fig. 5.

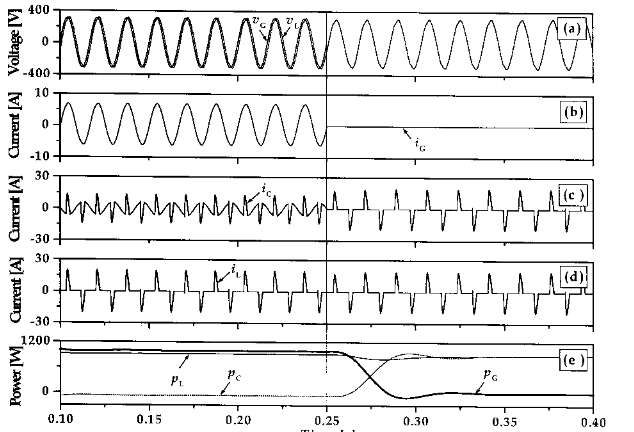

Fig. 5. UPS operation of the flux-lock type SFCL integrated with VC-VSI. (a) Source and load voltages. (b) Source current. (c) VC-VSI current. (d) Load current. (e) Active powers of source, VC-VSI and load

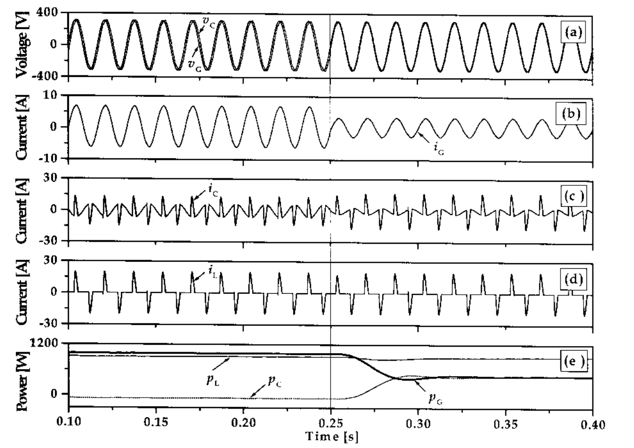

Fig. 6. DSM operation of the flux-lock type SFCL integrated with VC-VSI in case that the active power that the available RES supplies for the non-linear load increases from 0% to 50%. (a) Source and load voltages. (b) Source current. (c) VC-VSI current. (d) Load current. (e) Active powers of source, VC-VSI, and load

As another operation related with the improvement of the power quality, the DSM operation can be performed in the flux-lock type SFCL integrated with the VC-VSI. The waveforms for its DSM operation are shown in Fig. 6 in case that the available RES capacity to supply the active power demanded by the non-linear load increases from 0% to 50%. From Fig. 6, the load voltage can be observed to maintain the nominal value by the operation of the VC-VSI while the VC-VSI begins to support 50% of the load demand. As seen in Fig. 6(b), on the other hand, the source current is reduced to 50% of the original value during the 50% supply from the VC-VSI based on RES. The relationship between the active power demanded from the load and the active one supplied by both the source and the VC-VSI is confirmed from Fig. 6 (e).

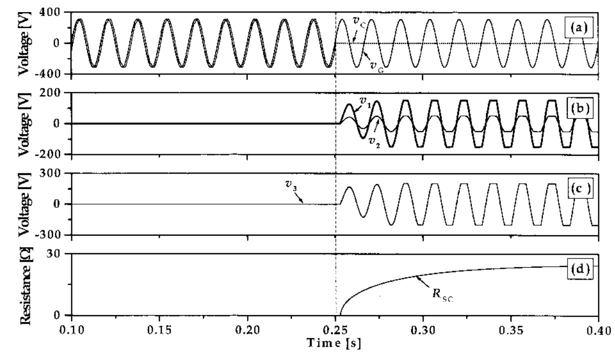

Fig. 7. Voltage waveforms and resistance curve of HTSC element in case of the fault current limiting operation of the flux-lock type SFCL integrated with VC-VSI. (a) Source and VC-VSI voltages. (b) Voltages of coils 1 and 2. (c) Voltage of coil 3. (d) Resistance curve of HTSC element

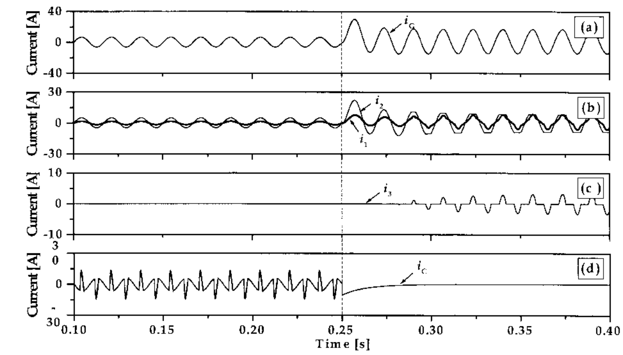

Fig. 8. Current waveforms in case of the fault current limiting operation of the flux-lock type SFCL integrated with VC-VSI. (a) Source current. (b) Currents of coils 1 and 2. (c) Current of coil 3. (d) Current of VC-VSI

With the several operations for the improvement of the power quality, the flux-lock type SFCL integrated with the VC-VSI can perform the fault current limiting operation. Figs. 7 and 8 give the simulated voltage and current waveforms in case of the fault current limiting operation of the flux-lock type SFCL integrated with the VC-VSI. The resistance curve of HTSC element was reflected on this simulation circuit with the expressive equation for its resistance curve [5,14]. As seen in Fig. 7, the resistance generation of HTSC element due to the fault current occurrence induces the voltages across coils 1, 2, and 3 and limits the fault current, which is the same operation as reported in reference [12,13]. After a fault occurs, the current of coil 3 starts to flow and charges the battery, which is connected with coil 3 through the bridge diode. However, the coil 3's waveform is rather distorted because of the non-linear property of the bridge diode for its current and voltage and, the distortion in the current waveform of coil 3 influences the current and the voltage waveforms of the other two coils as seen in Figs. 7 and 8. During a fault period, the operations for the improvement of the power quality can be ceased by generating the switching signals with zero into the PWM generator block.

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The research to solve the distortion of the current waveform in coil 3 during a fault period will be proceeded in consideration for the ac-dc circuit in the future.

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