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Comparative Analysis on Current Limiting Characteristics of Hybrid Superconducting Fault Current Limiters (SFCLs) with First Half Cycle Limiting and Non-Limiting Operations

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Abstract – The application of large power transformer into a power distribution system was inevitable due to the increase of power demand and distributed generation. However, the decrease of the power transformer's impedance caused the short-circuit current of the power distribution system to be increase thus, the higher short-circuit current exceeded the cut-off ratings of the protective devices such as circuit breaker. To solve these problems, several countermeasures have been proposed to protect the power system effectively from higher fault current and the superconducting fault current limiter (SFCL) has been expected to be the promising countermeasure. In spite of excellent current limiting performances of the SFCL, on the other hand, the efforts to apply the SFCL into power system has been delayed due to both the limited spaces for the SFCL's installation and its long recovery time after the fault removal. In order to solve these problems, a hybrid SFCL, which can perform either first half cycle limiting of first half cycle non-limiting operation, has been developed by corporation of LSIS (LS Industrial System) and KEPCO (Korea Electric Power Corporation).
In this paper, we tried to requirements hybrid SFCL by PSCAD/EMTDC. Simulation results of our analysis of the hybrid SFCL is that its accompanied the characteristics both the limit the fault current and quick recovery caused by the less impact from superconductor.

Keywords: Current limiting characteristics, First half cycle, Hybrid superconducting fault current limiter (SFCL), PSCAD/EMTDC

1. Introduction

The increase of fault current due to large demand has caused the capacity of power machines in power grid to be increased. Among several countermeasures, the superconducting fault current limiter (SFCL) has been noticed as one of the promising ones to solve fault current problem, because of its fast fault current limiting and automatic recovery characteristic. However, in spite of the excellent current limiting performance of the SFCL, the application of the SFCL into a power system has been delayed due to its problems such as an ac loss, a cost, a recovery and a cryostat system. The ac loss and the high cost of the superconducting element and the cryostat system are main bottlenecks for real application. Furthermore, in order to increase the power ratings of the SFCL, a lot of superconducting elements should be connected in series and in parallel, which resulted in extreme high cost. In order to solve these problems, the hybrid SFCL was proposed [1-11].

The developed hybrid SFCL consists of a superconductor element part, a fast-speed switching part and a current limiting part. In the hybrid SFCL, the superconducting element sensed a fault state and the fault current were commutated by the fast-speed switch. The fault current was limited by the CLR which was in parallel connection with the superconducting element. Therefore, presented problems above were solved due to the small burden of superconducting element.

The hybrid type SFCL could perform both the first half cycle limiting operation and the first half cycle non-limiting operation. Between them, the hybrid SFCL with the first half cycle non-limiting operation passed the fault current only for half cycle after the fault occurred and started limiting the fault current after a half-cycle. This operation made it possible to coordinate with conventional relays and to realize optimum current limiting characteristics [12-15].

In this paper, we made an analysis of current limiting characteristics of hybrid SFCL by PSCAD/EMTDC.

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2. Structures and Operating Principles of Hybrid SFCL

Fig. 1 and Fig. 2 show the structure of the hybrid SFCL with the first half cycle limiting and the hybrid SFCL with the first half cycle non-limiting. As shown in Fig. 1 and Fig. 2, the hybrid SFCLs have common operation characteristics. The hybrid SFCLs consist of a superconducting element, a fast-speed switch part which includes two contact switches and a driving coil to operate the interrupters and a current limiting part which was selective between resistance and reactance. The superconducting element was used for fault current sensing and current commutation, not for current limiting. In the fast-speed switch part, the driving coil generated an electromagnetic repulsion force when the fault current was commutated to the path by quenching superconducting element. By electromagnetic repulsion force, the interrupters (SW_a, SW_b) were operated with extremely fast speed at the first current zero point. Most fault current began simultaneously to flow in the current limiting part. Finally, the current limiting part can limit the fault current.

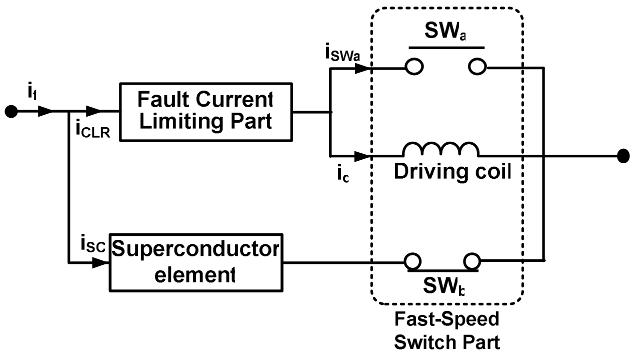

Fig. 1. Structure of hybrid SFCL with the first half cycle limiting operation

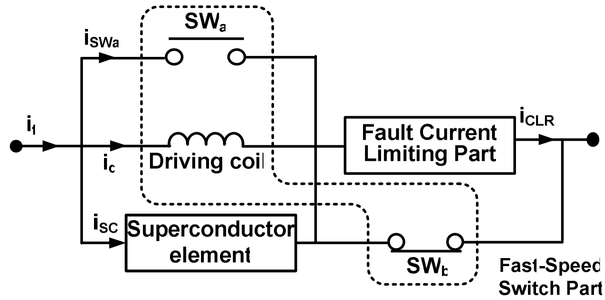

Fig. 2. Structure of hybrid SFCL with the first half cycle non-limiting operation

Between two types of the hybrid SFCL, those were classified by the operation timing to limit the fault current. One of the types limits the fault current with the first half cycle after the fault occurs according to the above basic performance. The other type was to limit the fault current with the first cycle non-limiting operation due to the connection of the end lines between the driving coil and the superconducting element. The cut-off operation takes a primary method from the fault sense to reduce the fault current such as the operation with the first half cycle. However, in the second type, the short wire creates the current path through the SW_b and delays the open timing after a half cycle. This operation is expected to be more advantageous to protective coordination in the simultaneous operation.

The hybrid SFCL was possible due to effect during very short time to minimize the total length of superconducting element in order to reduce material costs and cryogenic burden. In addition, short recovery time of the superconducting element made it possible to coordinate with conventional protection relays.

3. Configuration and Modeling

3.1 Modeling of the hybrid SFCL

As seen in Fig. 2, it consists of the superconducting (SC) element, the current limiting part, and the fast switching part. A resistance of the superconducting element according to time t is given at (1).

$$R(t)=\begin{cases} 0 & (t<t_{fault},\ t>t_{recovery}) \\ R_n\left[1-\exp\left(-\frac{t-t_{fault}}{T_F}\right)\right]^{\frac{1}{2}} & (t_{fault}\le t<t_{fault\_clear}) \\ a(t-t_1)+b & (t_{fault\_clear}\le t\le t_{recovery}) \end{cases} \quad (1)$$

Its basic operation can be divided into three states : the normal time operation, the fault time operation and the recovery time. The current limiting part is to limit the fault current by the CLR when the current path was transferred which had been arranged by the switches in parallel connection with the CLR under a fault condition.

The fast switching part consists of two fast speed switches which were combined with the driving coil as seen Fig. 2. When the fault current flows through the driving coil by the quench of the SC element, it generates the electromagnetic force. Therefore the operation and the arrangement of the fast speed switches were followed at the first current-zero point that the current is flowing into the driving coil.

3.2 Configuration of distribution system

Fig. 3 simply shows the single diagram of the power distribution system, which consists of the generator, the main transformer and circuit breakers (CB) to protect the power system against a fault condition.

In order to decrease the increased fault current and protect the power system, the hybrid SFCL which was selective between two types with the first half cycle non-limiting or limiting as shown Fig. 1 and 2 installed in the line.

In spite of the same limiting effects of the fault current, the internal operation characteristics of each hybrid types depend on the connection of the current paths. Therefore, the application of the hybrid SFCL is required to be analyzed to affect the limit current when a hybrid SFCL is installed in a power system. For the study of the operation characteristics, the parameters to constitute the simulated distribution system are listed in Table 1.

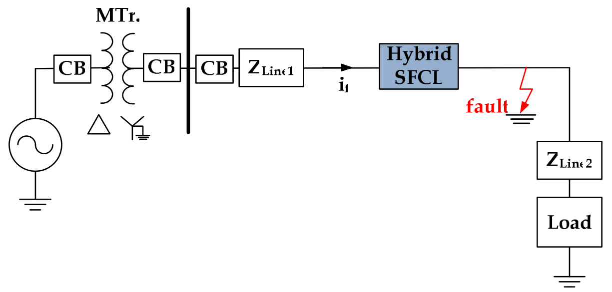

Fig. 3. Schematic configuration of circuit for characteristics tests of the hybrid SFCL.

Table 1. Specifications of modeling circuit

Source	Value	Unit
Zero sequence impedance [%] Positive sequence impedance [%]	1∠80 1.778∠80	
Transformer	Value	Unit
Capacity Voltage of primary side Voltage of secondary side	45 154 22.9	MV kV kV
Impedance	Value	Unit
Line1 (3,000m) Z_0 Line2 (2,000m) Z_1	3.48 + j7.44 10.8 + j23.6	% %
Load	Value	Unit
Load	10	MVA
CLR	Value	Unit
Resistance	2	Ω

4. Results of Hybrid SFCL Modeling

Fig. 4 shows the operation characteristics of hybrid SFCL with the first half cycle limiting operation. Where i_f is the total current in case that the hybrid SFCL was applied, $i_f^{w/o}$ is the total current without the hybrid SFCL, i_{SC} is the flowing current through SC element, i_{SWa} is the flowing current through SW_a, i_d is the flowing current through driving coil, i_{CLR} is the flowing current through CLR, R_{SC} is the resistance of SC element, SW_a and SW_b were both operation signals of switches.

At the normal condition, the current and resistance of the SC element show load current and zero ohm in Fig. 4. The fault occurs at 0.1 s. After the fault, the operations of the hybrid SFCL were divided into four sections. The first section from 0.1s to ①, sensing period of a fault through the fault current and most current pass on the SC element. The second section from ① to ②, the fault current was increased more than critical current of the SC element. The SC element generates a resistance and the fault current was split in two paths through the SC element and the driving coil which generates an electromagnetic force by its resistance. Because of no operation of the switches, all current of the driving coil flows on the CLR.

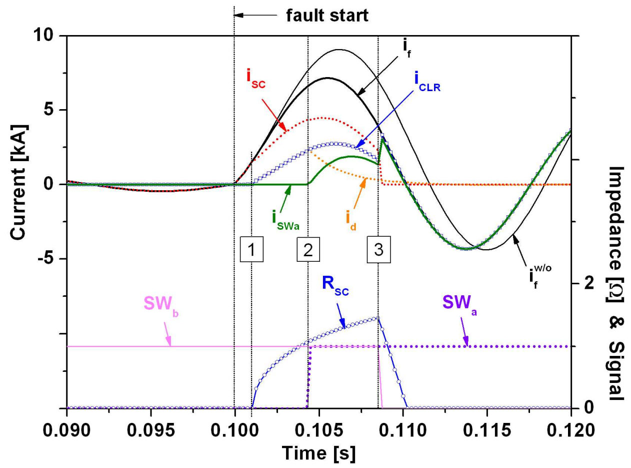

Fig. 4. Operation characteristics of hybrid SFCL with the first half cycle limiting operation

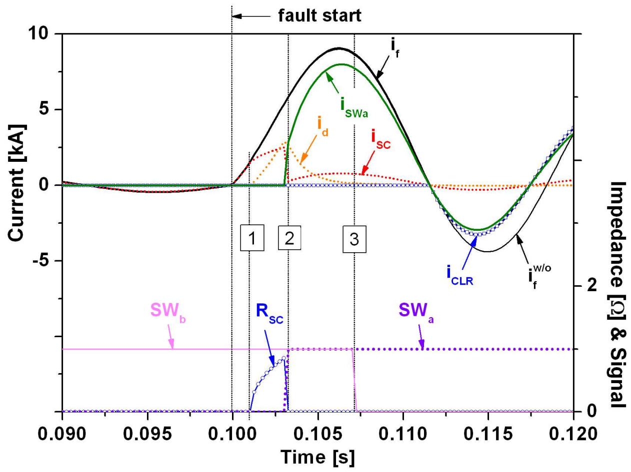

Fig. 5. Operation characteristics of hybrid SFCL with the first half cycle non-limiting operation

The third section from ② to ③, the SW_a was operated at ② point by the electromagnetic force on the driving coil. With the change of the current paths, the current in the driving coil was decreased and transferred toward SW_a. The last section, after ③ point, the last component, SW_b of the hybrid SFCL was operated. The currents on the SC element and driving coil do not flow because the SW_b cuts off the line which includes the SC element with series connection. In addition, the SC element recovers from the effect of the quench.

Finally, the fault current flows through the CLR and the fault current was limited by hybrid SFCL with the first half cycle which was confirmed to contrast with the $i_f^{w/o}$ in spite of the different phase because of the X/R ratio of the fault condition.

Fig. 5 shows the operation characteristics of hybrid SFCL with the first half cycle non-limiting operation. The performances which were fault start, quench condition, SW_a operation and SW_b operation were similar to the first half cycle limiting operation SFCL.

However, in the second and third sections, the both currents on the driving coil and SW_a were higher than previous type because the current not flow through the fault current limiting part. Therefore, the operation times of the switches were fast and the fault current was not limited during the first half cycle after a fault happens.

After all operation, the SW_b was operated with extremely fast speed at the first current zero point. At the first current zero point, all fault current began to flow in the CLR which is to limit fault current after a half cycle.

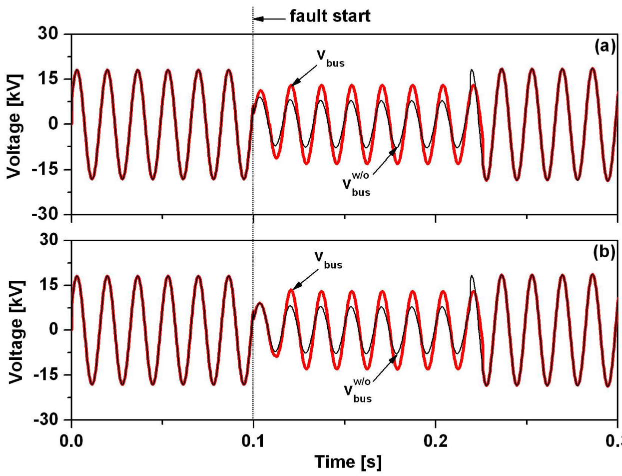

Fig. 6. Bus-voltage waveforms according to applications of the hybrid SFCL: (a) With the first half cycle limiting operation; (b) With the first half cycle non-limiting operation

Fig. 6 shows the bus-voltage waveforms according to the application of the hybrid SFCL. In cases, when we applied the hybrid SFCL with the first half cycle limiting operation or with the first half cycle non-limiting operation to a feeder-out going point, the bus-voltage drop compensation effects were confirmed in Fig. 6(a) and (b) respectively. When the hybrid SFCL was applied where the feeder-out going point, it contributes to a bus voltage stability to supply the power demand.

5. Conclusion

In this paper, we confirmed the current limiting characteristics of hybrid SFCL with the first half cycle limiting operation and with the first half cycle non-limiting operation by PSCAD/EMTDC. Through the analysis of modeling, hybrid SFCL operation was confirmed. When we applied hybrid SFCL with the first half cycle non-limiting operation, it could pass a half-cycle fault current without any limitation, and start limiting the fault current after a half-cycle. When we applied hybrid SFCL with the first half cycle limiting operation, in the other hand, it was limits immediately the fault current.

As a result of the difference of the half cycle operation, the application into the power system was considered the operation type to protect power system with protective coordination.

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