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Analytical and Experimental Studies on the Hybrid Fault Current Limiter Employing Asymmetric Non-Inductive Coil and Fast Switch

Dong Keun Park, Ki Sung Chang, Seong Eun Yang, Young Jae Kim, Min Cheol Ahn, Yong Soo Yoon, Member, IEEE, Ho Min Kim, Jung-Wook Park, Member, IEEE, and Tae Kuk Ko, Member, IEEE

Abstract—This paper deals with design and operating test of a novel hybrid FCL. The FCL system consists of a coil, a fast switch and a resistor for bypassing the fault current. The switch is driven by novel non-inductive coil suggested in this paper but an extra driving coil is required for fast switch in existing hybrid FCL. We used two kinds of HTS wire for the coil. The impedance of the coil was negligible in normal operation. But different quench characteristics of HTS wires caused asymmetric current distribution which induced effective magnetic flux in the coil during faults. The switch was opened by repulsive force from this magnetic flux in fast response to the fault. Then, all current were flew through the normal conductive bypass resistor connected in parallel to both the coil and the switch. Electromagnetic analysis of the coil based on finite element method was performed. Also, a small-scale asymmetric non-inductive coil was designed, fabricated and tested. The proposed hybrid FCL system showed fast and efficient current limiting characteristic.

Index Terms—Asymmetric coil, fast switch, hybrid SFCL, non-inductive coil, superconducting fault current limiter.

I. INTRODUCTION

FAULT CURRENT limiters (FCLs) have been suggested to solve serious problems from excessive fault current in electric power grids. Many active researches about various types of FCL such as resistive, inductive and hybrid types have been performed. In the recent researches, resistive FCLs using YBCO coated conductor (CC) have been developed and tested [1], [2]. To minimize the impedance of the FCLs, non-inductive winding methods using CC wires were suggested and there was rarely a magnetic flux in the coil during both normal and fault condition [3]. Resistive FCLs, however, have to endure a large fault current for 3–5 cycles until the circuit breaker (CB) cuts it off and the fault current causes high temperature rise in the high temperature superconducting (HTS) wire. FCLs are required to have a fast recovery within 0.5 s for the sake of protection coordination in electric power distribution grids in Korea and it is hard to achieve required recovery time with resistive FCLs. To reduce a recovery time and an amount of HTS wire, there have been some researches about new concept with superconductors and fast switches such as vacuum interrupter (VI), and solid state device [4]. Thus, an additional coil was needed to commutate the fast switch.

In this paper, a novel hybrid type FCL was proposed and its feasibility tests were carried out with finite element method (FEM) analysis. The FCL system consists of an asymmetric non-inductive coil designed to drive the fast switch by its impedance characteristics and a fast switching module. In previous research, we proposed solenoid type non-inductive coil wound with two kinds of HTS wire. The coil generated the magnetic flux in fault condition and it kept non-inductive during normal operation [5]. To make an HTS coil more compact and to have more magnetic flux in fault condition, parallel-pancake type non-inductive coil was developed using two kinds of HTS wire, BSCCO and YBCO wire. The switch connected to the FCL coil in series was designed to be opened by repulsive force from the magnetic flux in the coil as soon as fault occurs.

II. CONCEPT OF THE HYBRID FCL

The proposed hybrid FCL consists of two parts: an asymmetric non-inductive coil using two kinds of HTS wire and a fast switching module including moving parts. The superconducting coil plays roles of current transport and fast switch trigger. The switch separates the superconducting part from the circuit and the fault current flows through the bypass normal conductive limiter. Then, the HTS coil becomes thermally isolated. Benefits from this concept compared with resistive FCLs are as follows:

1) Reduction of an amount of HTS wire
2) Fast recovery
3) Compact system
4) Flexible value of the current limiting impedance

A. Asymmetric Non-Inductive Coil

For this hybrid FCL application, it is important to minimize the impedance in normal operation and maximize magnetic flux generation at fault. Two kinds of HTS wires were used in this research: BSCCO2223/Ag, YBCO CC clad with stainless steel for stabilizer. The parallel pancake type non-inductive coil using...
TABLE I
SPECIFICATION OF THE ASYMMETRIC COIL

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<tr>
<th>Winding part</th>
<th>Upper (CCW)</th>
<th>Lower (CW)</th>
</tr>
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<tbody>
<tr>
<td>Name</td>
<td>Bi-2223</td>
<td>344S</td>
</tr>
<tr>
<td>HTS</td>
<td>BSCCO2223</td>
<td>YBCO123</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>4.28</td>
<td>4.3</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>150</td>
<td>310</td>
</tr>
<tr>
<td>Length (m)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Critical current (A)</td>
<td>133</td>
<td>116</td>
</tr>
<tr>
<td>Index n value</td>
<td>16</td>
<td>37.2</td>
</tr>
<tr>
<td>Inner Diameter (mm)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Inductance (μH)</td>
<td>9</td>
<td>10.5</td>
</tr>
<tr>
<td>Total inductance (μH)</td>
<td></td>
<td>3</td>
</tr>
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Fig. 1. The photograph of the asymmetric non-inductive coil.

different types of HTS wire was proposed and designated as asymmetric non-inductive coil. It has two adjacent windings which have common copper terminal inside. The upper winding wound counterclockwise (CCW) and the lower wound clockwise (CW). In normal operation, two HTS wires were both superconducting states and the magnetic flux from each winding was countervailed. The different quench characteristics of two wires such as generated resistance and index n values caused unequal current distribution which induced the different amount of magnetic fluxes from each winding. Therefore, the magnetic flux was generated in the coil. Table I presents the specification of the asymmetric coil. Index n values from 10 to 100 μV/√Hz were 19.2 in Bi-2223 and 34.8 in 344S. More detailed comparison between two HTS wires was described in [5]. A large portion of fault current might flow through Bi-2223 winding when the fault occurs. The magnetic field generated from the unequally distributed fault currents induced eddy-currents in the lower AP of moving parts. Since the eddy currents create their own fields in the opposite direction of the field from the coil, the AP ring is repelled from the asymmetric coil. The force pushes moving parts upwards and then, the switch is opened. The Bi-2223 wire was used as the upper winding of the asymmetric coil which was placed just under the AP ring for good electromagnetic coupling, an important design parameter for drive efficiency. Fig. 2(b) shows a photograph of the hybrid FCL for feasibility test. Operating feasibility of the fast switch driven by the asymmetric coil could be confirmed by this module.

B. Operating Principles of the Fast Switch

To separate the superconducting coil from fault current flowing circuit within a cycle, a fast switch must be needed. In this research, a prototype fast switch was proposed and fabricated in order to verify operating feasibility of suggested hybrid FCL. Fig. 2(a) shows a schematic of the hybrid FCL module employing fast switch. The fast switch module consists of three rings of aluminum plate (AP) and a guide bar. Two mechanically connected AP rings were used as moving part and the upper AP was one of the switching contacts, designated as moving contact. An asymmetric non-inductive coil was used as a drive coil at fault occurrence. The lower AP of moving parts was set up just above the coil and insulated from the coil. One of the terminals in the coil was connected to the moving contact of the switch.

Relatively very high current flows through the Bi-2223 winding when the fault occurs. The magnetic field generated from the unequally distributed fault currents induced eddy-currents in the lower AP of moving parts. Since the eddy currents create their own fields in the opposite direction of the field from the coil, the AP ring is repelled from the asymmetric coil. The force pushes moving parts upwards and then, the switch is opened. The Bi-2223 wire was used as the upper winding of the asymmetric coil which was placed just under the AP ring for good electromagnetic coupling, an important design parameter for drive efficiency. Fig. 2(b) shows a photograph of the hybrid FCL for feasibility test. Operating feasibility of the fast switch driven by the asymmetric coil could be confirmed by this module.

III. FEM ANALYSIS OF THE ASYMMETRIC COIL

In this paper, simulation of the magnetic flux density distribution in the hybrid FCL in normal and fault conditions was conducted by using three-dimensional (3-D) magnetic quasi-statics model. Fig. 3 shows the simulation result in normal operation with mesh view. Current through each winding was set to 50 A.
The calculated inductance is 1.63 $\mu$H and there is an error compared with the measured value of 3 $\mu$H.

To estimate the repulsive force between the coil and the AP, transient analysis during first quarter-cycle during a fault was conducted. The induced current in AP could be calculated from a quasi-static vector potential equation, defined by (1).

$$\sigma \frac{\partial \vec{A}}{\partial t} + \frac{1}{\mu} \nabla \times (\nabla \times \vec{A}) = \vec{j}_e$$

(1)

where $\sigma$ is the conductivity, $\mu$ the permeability, and $\vec{j}_e$ the external current density. Fig. 4(a) shows a FEM result of azimuthally directed eddy current density and streamline of magnetic flux density in a cross section of the AP. Equation (2) gives the Lorentz force, repulsive force, on the AP and the simulation result of force distribution is shown in Fig. 4(b).

$$\vec{F} = \vec{j} \times \vec{B}$$

(2)

We calculated the force by volumetric integration in the AP with time-increasing. The repulsive force was exceeded the weight of the moving APs in the fast switch, 1.5 N, after about 0.85 ms from a fault occurrence.

IV. EXPERIMENTAL RESULTS

A. Experimental Setup

To investigate operating characteristic of proposed hybrid FCL, short circuit tests were carried out and the circuitry drawing for the tests is shown in Fig. 5. Previous to tests of whole hybrid system, preceding short circuit tests of the asymmetric coil excluding fast switching module were performed to know the impedance characteristic of the coil. The fast switch including two AP contacts was placed above the liquid nitrogen and the lower AP of the moving parts and the coil was placed in LN$_2$. The upper AP of the moving parts was electrically connected to the asymmetric coil in series. A normal conducting (N/C) resistor was connected in parallel to the FCL module to limit the current after fast switch was opened and its value was 0.15 $\Omega$. Short circuit tests were carried out under the existence of N/C resistor. To measure the current in each winding, shunt resistors, which didn’t affect the coil’s impedance characteristic, were connected. All faults were set 0.1 s (6 cycles in 60 Hz) and fired at 0 degree.

B. Characteristic Tests of the Asymmetric Coil

Fig. 6 shows the current and voltage waveforms in the asymmetric coil at applied voltage of 20 V$_{rms}$. A hatched region in Fig. 6 clearly shows that the coil voltage and line current are not in phase caused by inductive component generated in the coil. The fault current flowing through 344S was limited by faster and higher generated resistance due to higher index n value and higher resistivity of matrix respectively compared with Bi-2223. Thus, the fault current was distributed unequally during the fault
of 0.1 s due to their resistance difference, while almost same current flew through each winding in normal operation.

C. Fault Current Limiting Tests of Hybrid FCL

Short circuit tests of the hybrid FCL module with and without the N/C resistor were performed at applied voltage of 20 $V_{\text{rms}}$. Current and voltage waveform in the coil are shown in Fig. 7. The moment of sharply dropping in the current and voltage waveform was shown in the first swing during fault and we could analyze that it took 3 ms to open the fast switch by the magnetic flux in the coil. Since the arc was generated between separated AP contacts and it was disappeared at first zero crossing, the fault current through the asymmetric coil was cut off after a cycle. Then, paralleled HTS windings turned to be a closed circuit with inductance. The opposite directed remaining current in each winding was descended with gentle slope and disappeared within 2 cycles. Dotted line shows that the N/C resistor limits the fault current after one cycle from the fault occurrence. Fig. 8 shows the current and voltage waveform in the asymmetric coil during whole fault cycles of 0.1 s. We calculated energy dissipation of the coils with and without fast switch by using integration of the product between current and voltage resulting in 25.5 and 966.3 J, respectively. The fast switch could reduce heat generation in the coil. Thus, fast recovery would be possible.

V. CONCLUSION

Novel concept hybrid FCL was proposed and tested. The fast switching driven by the asymmetric HTS coil was achieved within 3 ms and it could reduce the heat generation in the HTS coil during fault. Existing hybrid FCLs with fast switch have an auxiliary driving coil but the proposed one does not need it.

For the practical use of this hybrid FCL, further investigation for improving both the asymmetric coil and fast switch such as longer HTS wire use for the coil wound with epoxy impregnation, a commercial fast switch connection such as VI should be carried out in the future. We confirmed the feasibility of proposed hybrid FCL in this paper.

REFERENCES


