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Fabrication and Tests of the 24 kV class Hybrid Superconducting Fault Current Limiter

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Abstract-- **We fabricated and tested a novel hybrid superconducting fault current limiter (SFCL) of three-phase 24 kV_{rms}/630 A_{rms} rating. In order to apply conventional resistive SFCLs into electric power systems, the urgent issues to be settled are as follows, such as initial installation price of SFCL, operation and maintenance cost due to ac loss of superconductor and the life of cryostat, and high voltage and high current problems. The ac loss and high cost of superconductor and cryostat system are main bottlenecks for real application. Furthermore in order to increase voltage and current ratings of SFCL, a lot of superconductor components should be connected in series and parallel which resulted in extreme high cost. In addition, the method to quench all components at the same instant needs very sophisticated skill and careful operation. Due to these problems, the practical applications of SFCL were pending. Therefore, in order to make practical SFCL, the price of SFCL should be lowered and should meet the demand of utilities. We designed novel hybrid SFCL which combines superconductor and conventional electric equipment including vacuum interrupter, power fuse and current limiting reactor. The main purpose of hybrid SFCL is to drastically reduce total usage of superconductor by adopting current commutation method by use of superconductor and high fast switch. Consequently, it was possible to get the satisfactory test results using this method, and further works for field tests are in the process.**

1. INTRODUCTION

Superconducting fault current limiters are regarded as the suitable solution to prevent the blackout which causes tremendous economical and social losses. And also continuous supply and power quality of electricity can be secured and supported by using these fault current limiters.

Until now, various types of superconducting fault current limiters were developed and the majority of them were adopting principles of resistive and inductive type [1-6]. But both types of superconductors inevitably need long length of superconductors in order to make high voltage and high current system. In other words, the performance, the cost and the reliability of SFCL were totally dependent on the superconductor's characteristics.

Meanwhile, many companies and research institutes had developed small-scale superconducting fault current limiters, but they do not succeed to install these device into electric networks and to develop large-scale fault current limiters. Table 1 shows the summarized major reasons for development of SFCL. Those items mentioned above should be settled to realize and to apply superconducting fault current limiters into electric power system.

LSIS and KEPRI in Korea already developed SFCL based on YBCO and BSCCO materials. But in order to reduce total length of superconductor and to overcome commercialization problems, novel hybrid superconducting fault current limiters were developed at the end of 2006 [7].

In this paper, the working principles and the design of major components including superconductors, fast switch, fuse, and current limiting resistor were shown. And experimental results were specifically introduced. Then, the specifications and the short circuit test results of 24kV/630A three phase system was dealt with. This hybrid superconducting fault current limiter had the biggest capacity up to now, but its price was drastically lowered by introducing hybrid concepts.

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TABLE I
MAJOR REASONS FOR DEVELOPMENT OF SFCL.

Cost	Total cost of superconducting fault current limiters could not meet the demand of the utilities.
Cooperation	The current limiting performance of this system should be arranged and adjusted in accordance with existing protective relay system.
Cryogenic	The long-term reliability of cryogenic systems was not settled yet.
Loss	AC loss of superconductor should be minimized in order to make more compact cryogenic system.
Large scale	Large scale of superconducting fault current limiters for extra high voltage system were not developed due to technical and economical issues.
Coordination	The requirements of electric network such as reclosing, and recovery under load were not be solved.
Legislation	The specification and test methods for superconducting fault current limiters could not available up to now.

2. DEVELOPMENT OF HYBRID FCL

2.1. Concepts

Table 2 shows the brief requirements and our solutions to realize hybrid fault current limiters. The most remarkable point is that superconductor was only used for fault current sensing and current commutation media, not for current reduction tool. And fast switch could be operated by electromagnetic repulsion force generated by fault current itself, not by any external current source.

The operating principle of current commutation method using both superconductor and fast switch were explained in Fig. 1. In normal current flowing state, all currents flow through superconductor and series connected interrupter (Fig. 1 (a)).

TABLE II
REQUIREMENT AND SOLUTIONS FOR HYBRID SFCL.

REQUIREMENTS	SOLUTIONS
Minimization of superconductor usage and cryogenic burdens	Superconductors were used for only fault current sensing and commutation of fault currents.
High voltage applications	Fast switch could endure high voltage not a superconductors
Fast switch operation and fault current commutation	Electromagnetic repulsion force was used, and its current source is fault current itself commutated by superconductors
Coordination and reclosing scheme	Coordination and reclosing scheme was considered by commutation method
Cost	1/10 reduction compared to superconduct- ing fault current limiters

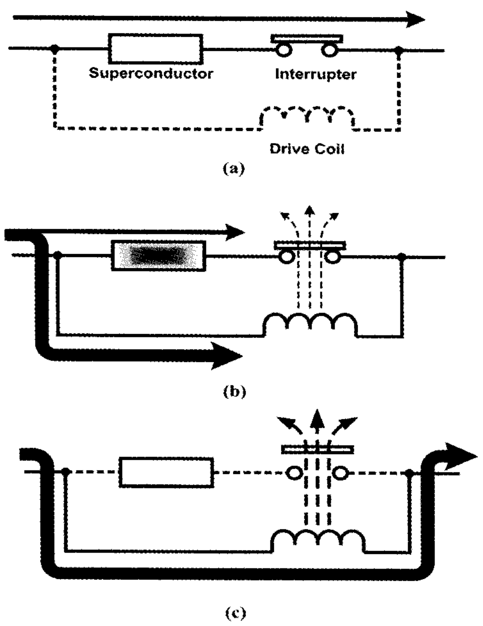


Fig. 1. Fault current commutation using superconductor and fast switch (a) normal operation (b) fault current sensing/commutation (c) opening of main circuit and magnetic field generation by driving coil.

When fault current occurs and flows through superconductor, superconductors were quenched and generated resistance which was enough to commutate the fault current into parallel circuit with driving coil. In proportion to the magnitude of fault current, intense magnetic field was generated by driving coil (Fig. 1 (b)).

Using this magnetic field driving force, the contacts of interrupter were separated with extreme high speed and break minor remained current which flows through interrupter. Finally, when arc existing between the contacts of interrupter was extinguished and total fault currents can flow through parallel circuit (Fig. 1 (c)). The total time of commutation was less than a few mm seconds. Thus, main circuit was remained opened after fault current commutation to the parallel circuit and fault current was controlled using conventional power fuse and installed resistor on the parallel line.

In this system, attracting point is that superconductor was not used for current liming function, but for current sensing and commutation, Owing to this, extremely small amounts of superconductor could be used and no high voltage stress was given to the superconductor. During fault state, major voltage stress was endured by fast switch interrupter. It means that the capacity of hybrid superconducting fault current limiters were mainly dependent on the interrupter ratings of fast switch, not affected by the length of superconductors.

Therefore, compared to resistive or inductive superconducting fault current limiters, superconductor's usage was drastically reduced. According to these advantages, cryogenic burden and AC loss were also reduced. And it was possible to realize more economic and practical superconducting fault current limiters.

2.2. Configuration of Hybrid FCL

The Fast switches energized by electromagnetic repulsion force were introduced and constructed by many researchers [8-9]. But this technology was not widely used and not easily applied to commercial circuit breaker. The reason is that it requires fast fault current sensing relay, and extra current source to operate fast switch. And it also needs extremely fast contact separation before arc generation between the contacts. It was very sophisticated to prevent arc generation and fast fault current commutation. When the arc was generated between switch contacts, it could not be eliminated before current zero point. It means that fast switching was delayed until half cycle of fault currents.

Thus, in order to eliminate arc that was generated between the interrupter, novel fast switch was designed and tested. The main characteristic of this switch is that it has closing contact on the upper side of fast switch interrupter. Due to this closing contact, arc existing between the contacts was eliminated before current zero when the contact of fast switch starts to move upward.

Consequently, after fast switch of main circuit was opened, majority of fault current flow through the fuse or other fast acting switch and then current liming resistor installed on the parallel circuit begins to reduce fault current using its determined resistance. Fig. 2 shows the finalized schematic diagram of our newly developed hybrid superconducting fault current limiters.

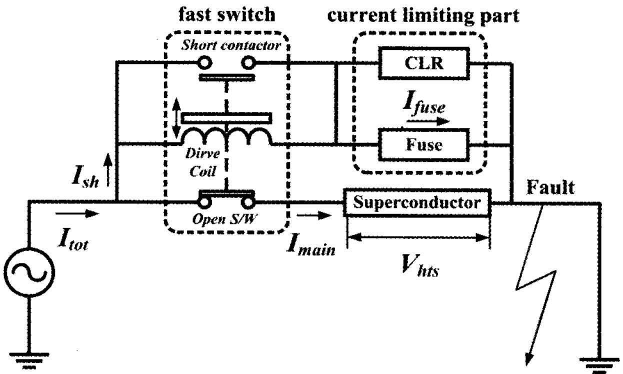


Fig. 2. Configuration of hybrid Superconducting fault current limiters.

3. TEST RESULTS OF HYBRID FCL

3.1. Single phase 14kV/630A short circuit tests

Superconducting trigger module for hybrid SFCL was designed using YBCO this film with 20mm width and 120mm length. Critical current of this film was 160A and 6 parts were connected in parallel to meet the required current level of 630A.The voltage stress of superconductor in this hybrid SFCL is only under 600V. We don't need any series connections of superconductor in order to meet the required current limiting resistance which was essential for resistive superconducting fault current limiters. Fig. 3 and Fig. 4 show the superconducting trigger module for the hybrid SFCL and the composition of components for single phase 14kV hybrid SFCL.

Short circuit tests were done in PT&T in LS industrial systems, which is the official certification institute in Korea.

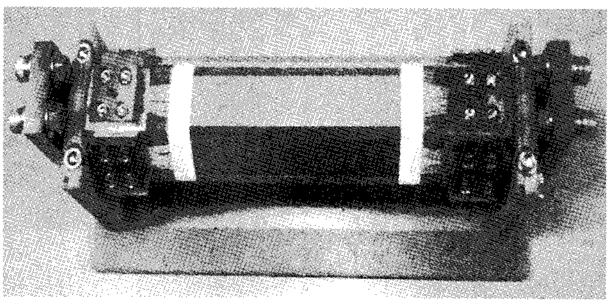


Fig. 3. Superconducting trigger module using YBCO thin films.

Fig. 5 shows the short circuit test results of 14kV hybrid SFCL. Applying voltage is single phase 14kV$_{rms}$, asymmetrical fault current (I_{cal}) is 26 kA$_{rms}$ and the first peak current is 65 kA$_{peak}$. Fault current was soared up to 24.6 kA$_{peak}$ at 2.35 ms after faults. Then fault current (I_{tot}) was limited to 12 kA$_{rms}$, which is the 46% of the original fault current. Voltage stress which was given to current limiting resistor is 11kV$_{rms}$.

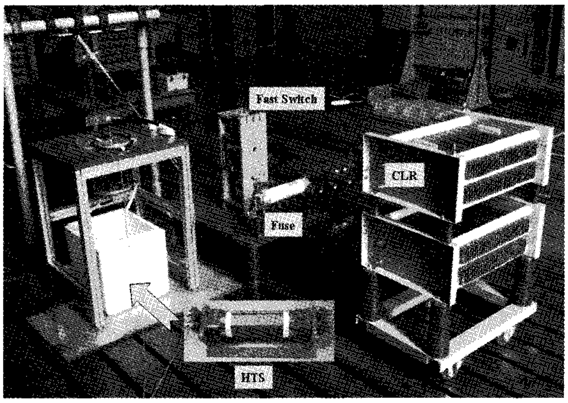


Fig. 4 The experiment setup for single phase 14kV hybrid SFCL.

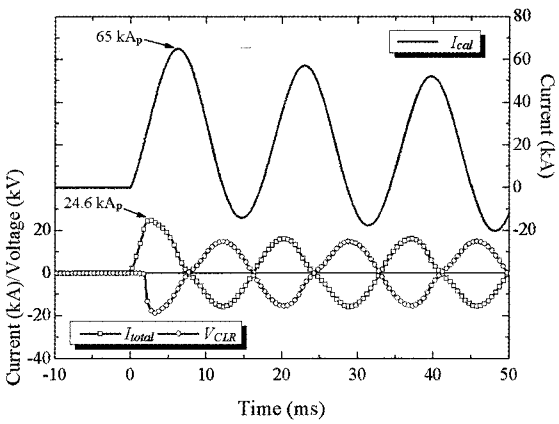


Fig. 5. Voltage and current limiting waveform of 14kV, 26kA hybrid SFCL.

Fig. 6 illustrates the voltage stress given to superconducting YBCO module during fault current reducing operation. I_{main} is the current flowing through the superconductor, and V_{hts} is the voltage stress given to the superconductor. YBCO modules were in quenching state at 1.1ms after fault initiation. Most of the fault current was commutated to the parallel circuit. The peak current of I_{main} which was flowing through the YBCO modules was 1,760 A. And this value was about below 10 % of total fault current. At this moment, voltage which was given to the YBCO modules was 215V. That means superconducting modules didn't need long length in order to endure system voltage applied to hybrid SFCL. Instead, the interrupter of fast switch could in charge of total applied voltage.

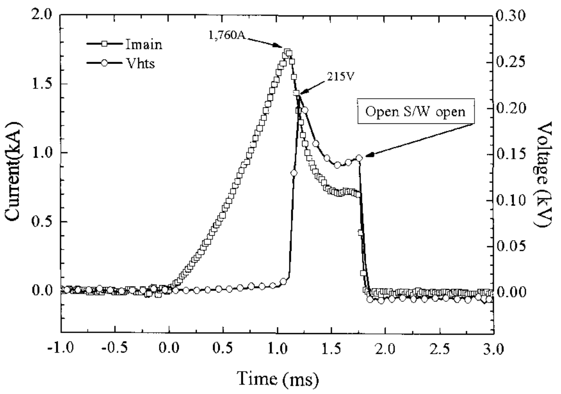


Fig. 6. Voltage and current during quench state of YBCO modules.

Fast switch began to move at 1.1 ms and finished its operation at 1.8 ms after fault occurrence. Then, I_{main} becomes to 0 A, and total fault current flows on the parallel line. Quench duration time of YBCO modules is 0.7 ms. So, the total input energy applied to YBCO modules is also very small compared to conventional resistive SFCL. Therefore, it was possible to realize short recovery time which was needed for reclosing electric networks.

3.2. Development of 3 phase 24kV/630A hybrid SFCL

Thus, in order to eliminate arc that was generated between the interrupter, novel fast switch was designed and tested. The main characteristic of this switch is that it has closing contact on the upper side of fast switch interrupter. Due to this closing contact, arc existing between the contacts was eliminated before current zero when the contact of fast switch starts to move upward.

Fig. 7 shows the picture of 3 phase 24kV/630A hybrid SFCL. The volume of the Hybrid SFCL was 1,000 (W)×2,500(L)×2,000(H)mm, which was possible to enclosed into cubicle switchboard. And the fabrication cost was about 10% of other superconductor based fault current limiters. At present, this newly developed hybrid SFCL has the biggest capacity.

Table 3 shows the major component of 24kV/630A hybrid SFCL which was developed by LSIS and KEPRI in 2006 [7].

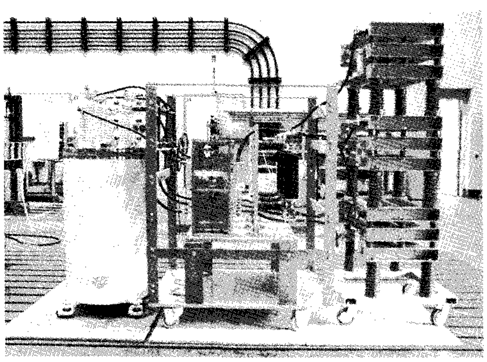
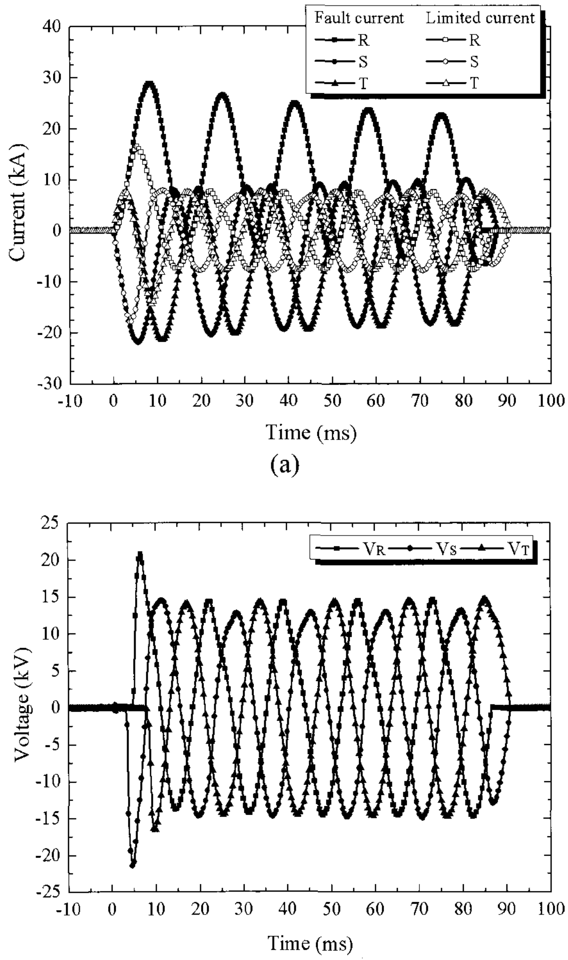


Fig. 7. 3 phase 24kV/630A hybrid SFCL.

TABLE III
SPECIFICATION OF THE 3PHASE 24KVHYBRID SFCL.

Superconductor	YBCO Ic = 160A Number of parallel = 6
cryostat	OD : 520mm ID : 420 mm Height : 1300mm
cryo-cooler	Cooling power : 300W
Total loss	135 W
Fast switch	Open S/W : -7.2kV/630A vacuum interrupter Short contactor - open contactor
Current limiting part	Fuse & Resistive type Fuse : 14kV/160G CLR : 1 Ω

In Fig. 8, test result of 3 phase short circuit test was shown. It was confirmed that the hybrid SFCL has excellent current limiting performance. This hybrid SFCL will be tested and verified at KEPCO (Korea Electric Power Corporation) field test next year.



(a)

(b)

Fig. 8. 24kV, 10kA$_{rms}$ 3 phase fault test results of hybrid SFCL (a) currents (b)V$_{CLR}$.

4. CONCLUSION

We presented fabrication and test results a novel hybrid superconducting fault current limiter of single phase $14kV_{rms}$ and three-phase 24 kV_{rms}/630 A_{rms}. The single phase 14kV hybrid SFCL successfully suppressed the fault current up to $25kA_{rms}$ below $12kA_{rms}$. Test result of three phase 22.9kV hybrid SFCL shows excellent current limiting performance. In order to realize more practical and economical superconducting fault current limiters, we develop hybrid fault current limiters which have several merits such as low cost, high performance, coordination with conventional systems. The main purpose of hybrid SFCL is to drastically reduce total usage of superconductor by adopting current commutation method by use of superconductor and high fast switch. Consequently, we were succeeding in developing world unique hybrid fault current limiters and it was possible to get the satisfactory test results using this device. And further works for practical applications are in the process.

ACKNOWLEGMENT

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