CONCEPTUAL DESIGN OF A 25.8 kV, 2.0 kA COMPACT RESISTIVE SFCL FOR POWER SYSTEM INTERCONNECTION

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ABSTRACT

This article presents conceptual design of a 25.8 kV / 2.0 kA resistive superconducting fault current limiter (R-SFCL). The local utility, Korea Electric Power Corporation (KEPCO), has a plan to introduce 154/22.9 kV mini-energy centers (mini-ECs) in urban, a kind of small-scale substations, in 2023, as a pilot project. And the R-SFCLs are expected to install at bus section and bus coupling locations between mini-ECs in order to operate stable loop system on 22.9 kV. The utility demanded the compact R-SFCLs which consist of two cubicle switchboards, each of which is 2,400 mm in width × 2,800 mm in depth × 2,800 mm in height, due to space constraints of the mini-ECs. To meet the requirements, we applied a fast switch (FS) which disconnects the circuit in half cycle after a fault and a modular-type current limiting resistor (CLR) instead of reactor type. The first cubicle switchboard is a superconducting part, which includes high temperature superconducting (HTS) modules and a cryocooling system. And the other is a non-superconducting part, which includes FS, CLR, control units. The HTS module is a combination of multiple bifilar coils wound with HTS tapes supplied by SuNAM. Each bifilar coil has 40 m long HTS tape, which has a critical current value over 700 A at 77 K and a resistance value over 150 mΩ/m at room temperature. The three-phase HTS modules are cooled by subcooled liquid nitrogen in a single cryostat, which has a sidewall cooling structure particularly useful when electrical insulation and compactness are required at the same time. The FS is in series to the HTS module, and it diverts the fault current within half cycle after a fault to the CLR in parallel to the HTS module. The CLR is designed to limit the fault current for maximum 1 second. The FS and the CLR contribute to a system compactness and a competitive price. A Short circuit tests for the single bifilar coil and the CLR showed effective current limitations for prospective fault current.

INTRODUCTION

Distributed energy and independent power plants have been established and interconnected to power system to solve the rising power demands. And interconnection of electrical power grids is growing and becoming a trend in many countries of the world to enhance reliability and flexibility. As a result, faults in power systems cause large short-circuit current [1-2] and the short-circuit levels may exceed the rated fault current breaking capacity of the existing circuit breakers (CBs) [3-4].

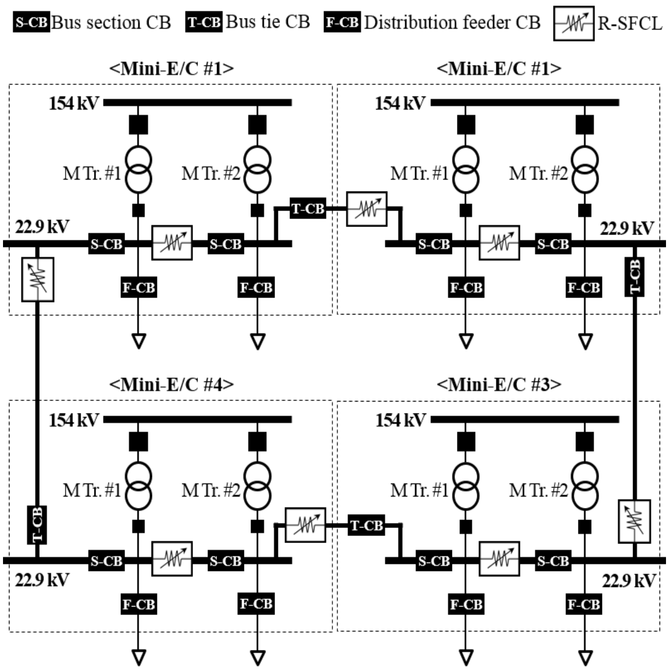

Figure 1. Schematic diagram for loop system operation on 22.9 kV of four mini-ECs with R-SFCL

Table 1. R-SFCL specifications and requirements

Item	Specifications
Ratings	25.8 kV / 2,000 A / 60 Hz
Electrical insulation	AC withstand: 60 kV, 1min
	Lightning Impulse withstand: 150 kV BIL
Installation site	In-house mini substation
Size and location requirements	Two cubicle-switchboards located in the other floor Each cubicle size is W2,400 mm×D2,800 mm×H2,800 mm

A superconducting fault current limiter (SFCL) has been one of the most promising devices to mitigate the fault current in both the transmission as well as distribution power grid. There have been more than 20 developments and field tests of SFCLs in the world [5]. A dozen manufacturers were involved in development of the SFCLs. LS Industrial Systems (LSIS) was one of them who developed a resistive type SFCL (R-SFCL) [6-8]. In collaboration with KEPCO Research Institute, LSIS successfully developed the R-SFCL having the ratings of 22.9 kV and 630 A. The SFCL was installed at KEPCO's Icheon substation and performed field testing for two years [9, 10].

Recently, a Korea Electric Power Corporation (KEPCO) is going to introduce the "154/22.9 kV Mini-Energy Centers (ECs)" in urban area, a kind of small scale substations in size as well as power capacity. Loop system operation on 22.9 kV of four mini-ECs are planned from 2023 as a pilot project. This power system structure successfully compensates the insufficient power capacity, but results in high fault current which is far exceeding the circuit breaker (CB) interrupting rating. For this reason, the existing protection devices may need to be replaced with higher ratings, if there is no fast, effective, and reliable solution to such huge faults.

To respond to this problem, in collaboration with KEPCO, LSIS launched a project to develop a 25.8 kV / 2.0 kA resistive type superconducting fault current limiter (R-SFCL), which could be more effective, more compact, and probably less expensive than any other SFCL. Multiple R-SFCLs will be installed at bus-section and bus-coupling location between mini-ECs in KEPCO distribution grid on 22.9kV.

This report is focused on the conceptual design of the 25.8 kV / 2.0 kA R-SFCL. The application location of the R-SFCL and the target specifications are listed first, including of utility requirements. And then main components are described; a high temperature superconducting (HTS) module, a cryocooling system (CS), a fast switch (FS), and a current limiting resistor (CLR) focused on the compactness. In addition, the short circuit testing results for the HTS bifilar coil and the CLR are presented.

R-SFCL SPECIFICATIONS

Application location

Figure 1 schematically shows interconnection of four mini-ECs. There are two transformers at one mini-EC. This loop system operation increases not only reliability of power supply but also fault current, which may exceed distribution circuit breaker ratings. For this reason, the utilities open bus tie breakers and bus section breakers to lower fault power. But if a transformer is out-of-service, the resulting imbalance causes loop flows which trip secondary network and dump load. For this reason, the FCLs are applied in series with bus tie breakers and bus section breakers to limit fault current and eliminate possibility of loop flows.

In this scheme, R-SFCLs are to be applied between transformers as well as between the mini-ECs.

Target specifications

The target specifications of the R-SFCL are listed in Table 1 briefly. The R-SFCL has ratings of 25.8 kV / 2.0 kA / 60 Hz, and power frequency withstand voltage and lightning impulse withstand voltage are 60 kV_{rms} for 1 min and 150 kV BIL, respectively. Due to space constraints of the mini-ECs, the R-SFCL is consist of two cubicle-switchboards, each of which is 2,400 mm in width × 2,800 mm in depth × 2,800 mm in height. The cubicles will be installed in a different floor of the substation building, for example upper and lower floor. To meet the requirements mentioned above, the R-SFCL is equipped with a unique FS which has been developed by LSIS. This FS can disconnect the circuit within half cycle after a fault. The FS essentially reduces the quench time of the HTS modules, effectively increasing the allowed voltage of the superconducting tape conductors. And the CLR here will

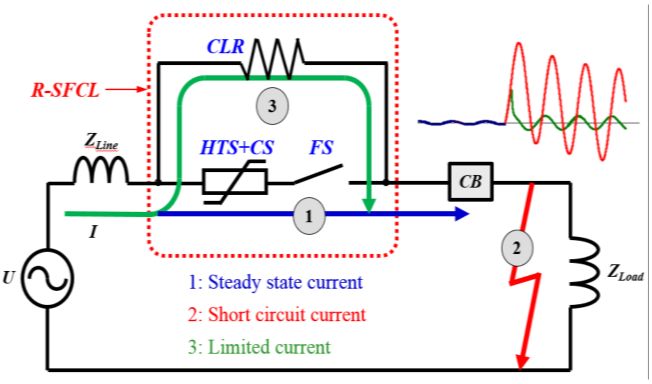

Figure 2. Schematic circuit diagram of the R-SFCL

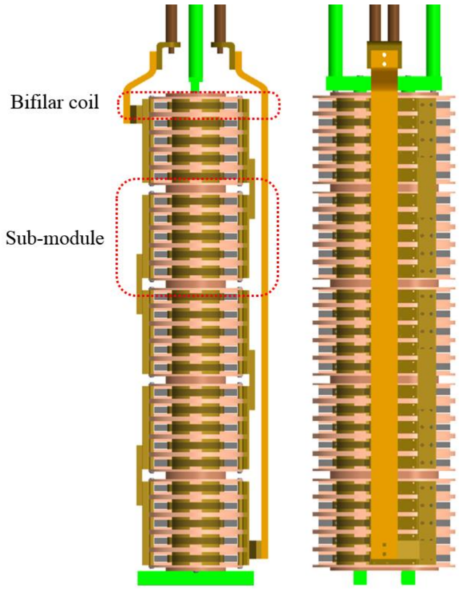

Figure 3. Schematic illustration of single phase HTS module for compact R-SFCL

be made of resister type instead of reactor type for its compact size. The CLR's role is to limit fault current by its impedance. The CLR is of modular type containing multiple unit resistors, so that it can comply the grid requirements to protect coordination in the power system. The R-SFCL is designed by two parts; one for superconducting part of the HTS modules and the cryocooling system, and the other for non-superconducting parts such as the FS, the CLR, the control units.

CONCEPTUAL DESIGN

Schematic diagram

Figure 2 depicts the R-SFCL circuit diagram. Major components are the HTS modules in a cryostat (HTS+CS), the FS, and the CLR. Under the normal conditions, ① in Figure 2, the FS is closed and the load current flows through the HTS modules without any impedance. When huge fault occurs ② in the power system, the fault current transforms the HTS modules from superconducting state into resistive state, and the HTS modules limit and divert the fault current, instantly. Subsequently, the FS opens within half cycle after a fault, so that the fault current is diverted completely to the CLR as ③ in Figure 2. Finally, a circuit breaker in the power grid will open the circuit. When the fault is cleared, the R-SFCL returns to the standby mode, in which the superconductor recovers its superconducting state and the FS is closed well, before the electrical current flows back into the HTS modules and the FS.

Main components design

HTS module

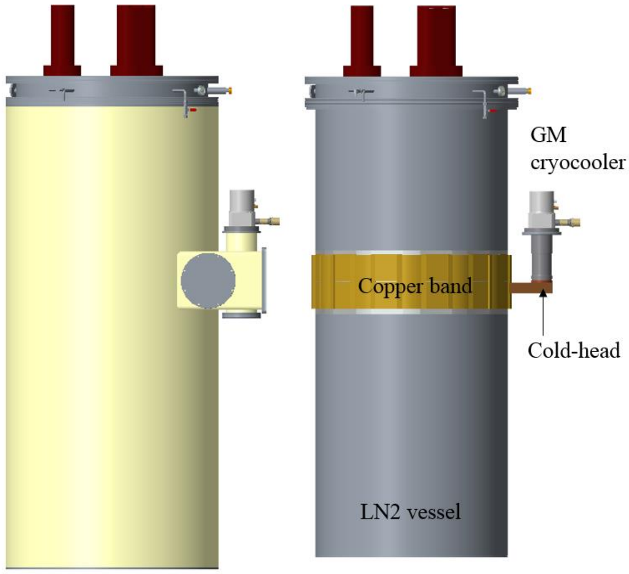

Figure 4. Schematic illustration of the sidewall cooling cryostat for subcooled LN2

Figure 3 shows a schematic design of single-phase HTS module for compact R-SFCL. The single-phase HTS module consists of five sub-modules in series, and each sub-module carries five bifilar coils in parallel. Each bifilar coil is wound with 40 m long second generation (2G) HTS tape supplied by SuNAM. The bifilar coil has an elliptical shape which has a minimum volume under the given bending radius for the HTS tape. This HTS tape has a critical current higher than 700 A at 77 K and a resistance value approximately 150 mΩ/m at room temperature.
Five bifilar coils connected in parallel constitute one sub-module with 3 kV and 2,000 A ratings. Accordingly, a single phase with five sub-modules in series has 15 kV and 2,000 A.

Table 2 Estimated cryogenic cooling load for rated current 2,000A

Item		Cooling Load [W]
Current Leads (3pairs)		500
Heat Leak (1 cryostat)	Gas Conduction	10
	Wall Conduction	30
	Radiation	20
HTS Modules (3 phases)	AC Loss	300
	else	100
Total		960

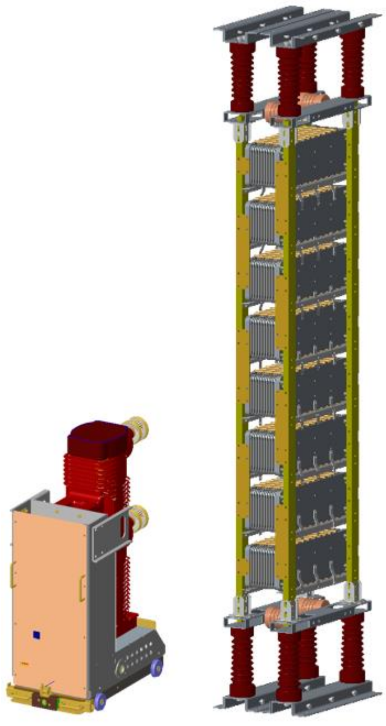

Figure 5. Schematic illustrations of the fast switch (FS) and the current limiting resistor (CLR)

Cryocooling system

In order to design compact cryocooling system, the three-phase HTS modules are cooled by subcooled liquid nitrogen at 77 K in a single cryostat, and continuously refrigerated by multiple GM cryocoolers. Figure 4 illustrates a side cooling structure of the LN_2 cryostat, in which a cylindrical copper band is brazed to the sidewall of the liquid vessel. The copper band collects the distributed heat load and delivers it by conduction to the coldhead of the cryocooler. The sidewall cooling structure is particularly useful when electrical insulation and compactness are required at the same time [11]. A vapor space above liquid nitrogen in the vessel provides a fully open room for high voltage current leads.

The diameter and height of the inner vessel are determined by the size and arrangement of three-phase HTS modules with consideration for electrical insulation. Liquid nitrogen is filled up to the copper band from the bottom of the vessel, thus the liquid volume is approximately 1,200 litter.

The subcooled liquid nitrogen plays roll in supressing bubbles which may deteriorate the breaking voltage of liquid nitrogen, and achieving a spatially uniform temperature by active natural convection of liquid. Thus subcooled state is essential for electrical insulation in high-voltage applications.

Total cooling load for rated current 2,000A is estimated to be 960 W, as shown in Table 2. Heat transmitted through the leads to the cold region is the major source of cooling

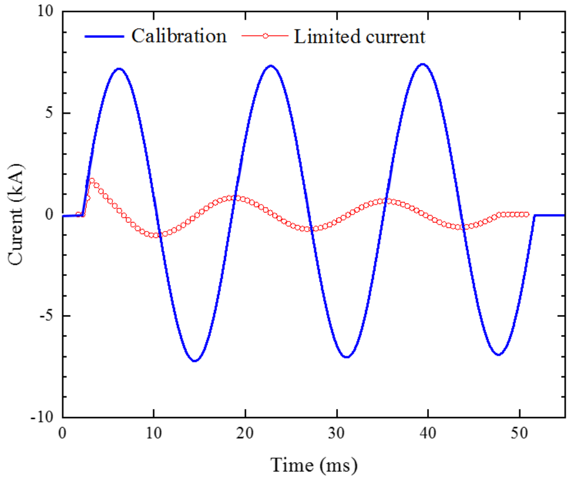

Figure 6. Short circuit tests for a bifilar coil

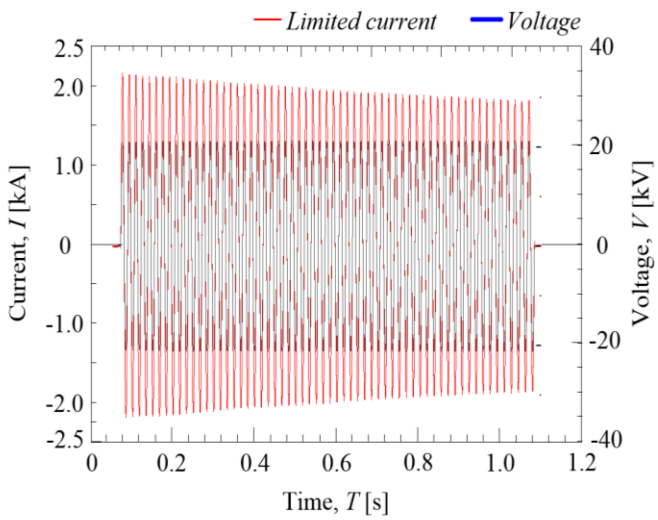

Figure 7. Short circuit tests for a current limiting resistor with 10 Ω

load, the length-to-area ratio of conductor should be optimized such that the total load has a minimum. Cooling load by the current leads has been analysed in reference [12] and it was approximately 500 W for three phases and 2,000A_{rms} rating. The AC loss of the three-phase HTS modules is estimated to be 300W for 2,000A_{rms} rating, which is based on the measured value for single bifilar coil for 400A_{rms}.

Fast switch and Current limiting resistor

Figure 5 shows the schematic illustrations of the FS and the CLR. The FS are composed of a vacuum interrupter (VI), a driving coil, and a permanent magnetic actuator (PMA). The VI plays roll in commutating fault current by its opening and closing operation. The driving coil and PMA are designed to drive the VI. The driving coil is to open the VI quickly by electromagnetic repulsion force. Once the VI opens, the fault currents divert to parallel circuit, CLR. The PMA is to close VI after the fault is

cleared completely in the power system.
The CLR is modular type resistors whose unit value is 1 Ω and the resistance is determined by analysis by power grid on which the R-SFCL will be installed. The limiting time of the CLR was designed to be maximum 1 second.

SHORT CIRCUIT TEST

HTS module

Figure 6 demonstrates the current limitation capability of the HTS module. It shows effective current limiting capability for both asymmetric and symmetric faults. The first peak current does not exceed 2.0 kA at any moment under the fault currents of 5 kA_{rms}. In order to investigate the reliability of current limitation, fault currents were repeatedly applied up to 75 times. The single bifilar coil proved reliable current limitation without performance degradation at all.

Current limiting resistor

Figure 7 shows that the fault current was limited from 65.0 kA_{peak}, which is the peak value of the maximum test current of 25 kA_{rms} for an asymmetric fault, to 2.15 kA_{peak}. As time goes by, the limited current is declined by 18.7% since the CLR resistance increases due to temperature rise.

SUMMARY

The conceptual design of the 25.8 KV, 2.0 KA R-SFCL for power system interconnection of four mini-ECs has been performed according to the utility's requirements especially in compact size. For compact design, the FS and the CLR are applied to the system, and the amount of HTS tape and cooling load are reduced. The single HTS module is composed of five sub-modules in series, and each sub-module is five bifilar coils stacked in parallel. Each bifilar coil carries 40 m long HTS tape. The critical current at 77 K and the resistance at room temperature of the HTS tape have over than 700 A and 150mΩ/m, respectively. The three-phase HTS modules are cooled by subcooled liquid nitrogen at 77 K in a cryostat, and continuously refrigerated by multiple GM cryocoolers which are vertically mounted on a side of the liquid vessel. Total cooling load for three phases is about 960 W, the current lead cooling load with 500 W is analysed and the AC loss with 300W is estimated based on the measured value for a single bifilar coil. The FS is in series to the HTS module, and it disconnects the circuit in one cycle after a fault and divert the current to the CLR, minimizing the heat generation by the HTS module. The CLR is in parallel with the HTS module, and it limits the fault current for maximum 1 second.

Acknowledgments

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