A Feasibility Study of Smart High-Temperature Superconducting Cable to Improve Stability of KEPCO System

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Abstract. The Korean power system is a very tightly coupled island system. The installed capacity is about 100 GW and the load demand is gradually increasing. Especially in metropolitan areas where the load is concentrated, the system fault current often exceeds the breaker capacity due to the strong connection. The system operator limits the fault current by bus split operations considering the breaker capacity but this reduces system stability. Therefore, various efforts have been made using a fault current limiter to overcome these problems. A smart superconducting (SC) cable is a type of SC power transmission cable. It has not only standard structure of the existing SC power cable but also a fault current limiter. The cable has a SC characteristic in a normal state, while when a fault occurs, it can limit a fault current through generating impedance that adjusts electrical and thermal properties of SC cable and material and cross-sectional area of SC cable. In this paper, a technique is proposed to reduce system fault current while improving the system stability using a smart high-temperature SC cable. In addition, the appropriate cable capacity and locations are selected to improve the reliability of the Korean power systems using the smart SC cables. The proposed locations and capacities will be applied to the smart SC cable development project that started in May last year.

1. Introduction

Due to the constant load increase, the power system is gradually operating at its stability limit. In addition, due to the development of related technologies, additional new power facilities are being installed. Especially, high temperature superconductivity (HTS) has been discovered in 1986 and drastically applied to power system facilities as an application field of the system. As an example of power system application devices, Superconducting fault current limiter (SFCL) has been developed, and a 22.9kV hybrid SFCL has been operated in Ichon substation near Seoul. The applications that are being considered are superconducting (SC) substations, energy storage systems, and superconducting (SC) cables, which can have advantages when connecting offshore wind power systems [1-5].

The Korean power system has independent systematic characteristics, which are not linked to other systems. In particular, 40% of the total load is concentrated in Seoul area. Therefore, it has a structure to supply electric power to the metropolitan area through transmission lines from the power stations in
non-metropolitan area, which are constructed with lower cost than ones in urban areas. However, the power grid is tightly connected to the power supply in the dense metropolitan area. In the strongly connected power system, there is a problem that a fault current is very high when the system fault occurs. Thus, system operators have introduced various schemes into the system to limit the fault current. Typically, the bus separation and the line opening operation, the current limit reactor installation, and the system separation using BTB (Back-to-Back) HVDC (High Voltage Direct Current) have been used. Since each method has advantages and disadvantages, a smart SC cable is introduced to improve it.

Recently, there have been many attempts to apply SC cable applications to the grid [6, 7]. The SC cables have a great advantage in the operation because they have zero resistance in DC when maintaining superconductivity, however they have the disadvantage of requiring an additional cooling equipment to maintain the superconductivity. Therefore, in this paper, we will explain the merits of the SC cable with the FCL (Fault Current Limit) function that can be applied to the power system. In addition, the smart SC cable with FCL function was applied to the KEPCO system and the applicability was examined.

2. Korean power system in the metropolitan area

In the Korean power system, there is a problem that the fault current increases sharply due to the concentration of the load in the metropolitan area and the increase of the connecting lines. The system operator operates the system separately to prevent the increase of the fault current. The operation of system separation has an effect on the reduction of the fault current, but has an adverse effect on the stability of the system.

![Figure 1. Korean power system configuration in metropolitan area.](image-url)

The fig. 1 shows the current method of operation in the Korean metropolitan area. The metropolitan area has a loop network composed of 345kV systems. From the 345kV substation, the loads are connected by radial using 154kV networks. At this time, in order to prevent increase of fault current among the 154kV networks, each 154kV network is separately operated by the opening operation. In other words, the one 154kV network connected to the only one 345kV network. Therefore, if a fault occurs in a 345kV substation, which is a power supply line, the loads connected to the 154kV network supported by the 345kV substation cannot be supplied power because there is no bypass line due to opening operation. The blackout area in fig. 1 could be explained as an example for the disadvantage of the opening operation.

The fig. 2 shows the situation of the power grid system, when the fault occurs at Yeongseko substation (345kV). By the open operation between Shingil and Bongcheon substation, after the fault, Shingil and Yeongseko system is separated from the main system. The fault progression process is as follows. First, the insulation of the busbar breaker is broken. The system failure occurs. The protection relay in the
busbar breaker is activated. All lines connected to the busbar are opened. Approximately 300,000 households of seven 154kV substations supplied from Yeongseo Substation are shut down.

3. A model for smart superconducting cable
A model of the smart SC cable proposed in this paper is shown in Fig. 3. The smart SC cable with resistive type is shown in (a) and the inductive type is shown in (b). In the figures, R1 is a radius of inner nitrogen layer for cooling the superconductor. “R2-R1” is a former layer. The outer of R2 is a conducting layer using HTS tape. From the outer of the conducting layer to R3 is the insulation layer using PPLP (Polypropylene Laminated Paper). There is the external nitrogen in the shielding layer. The inductive type cable is additionally covered with a high permeability material around the resistive type cable. The material layer is generating a high current inductance when a fault current is detected. The proposed smart SC cables are testing in order to verify their characteristic.

![Figure 2. Yeongseo area blackout.](image)

![Figure 3. Smart superconducting cable with fault current limiter function.](image)
4. Smart superconducting cable with fault current limit function
The smart SC cable proposed in this paper has the functions to supply the power while maintaining the superconductivity in the normal operation, to detect the fault current in short-circuit accident, and to limit the fault current by generating the high current resistance and inductance in high speed. Fig. 4 assumes that the smart SC cable is applied to the Shingil and Bongcheon substation. The Shingil-Bongcheon lines is open because of fault current problem before applying for the smart SC cable. However, in the case of an open operation, it plays a role of damaging the stability when a system failure occurs. In this paper, we propose the smart SC cable reducing the fault current. Due to the limited fault current, the Shingil-Bongcheon line will be connected. Finally, the Yeongseo area grid will be stable though the fault occurs at Yeongseo 345kV substation. In the simulation, we assumed that the resistance and inductance of the SC cables are 1 Ω / km ~ 2 Ω / km.

![Smart Superconducting Cable Diagram](https://doi.org/10.1088/1742-6596/1293/1/012068)

**Figure 4.** Smart superconducting cable with fault current limiter function.

5. Simulation results
In this paper, the feasibility of the smart SC cable with a FCL function is examined in the Korean power system in 2029, which has peak loads. The conventional line between Shingil and Bongcheon is replaced with the smart SC cable. The results of the fault current calculation are summarized in Table 1. In this paper, ASCC (Automatic Sequencing fault Current Calculation) method is used for the fault current calculation. The method is normally used in power system operators in the world. In the base-case of the conventional line connection, there are 25 buses that exceed the fault current limit. In the case of the open operation of the line, there is no bus that exceeds the fault current limit. In the case of installing a current-limiting reactor (assuming 2 Ω / km), the fault current exceeds the reference value (50kA) at four buses. In the case of applying the smart SC cable, the number of fault current exceeding buses that exceed the fault current limit is 4 to 11. Because the resistance of smart SC cable is 1 Ω / km to 2 Ω / km. This is the same result as the value of the fault current limit using the inductance. Although the smart SC cable cannot completely limit the fault current compared to the line opening, the effect of lowering the fault current is confirmed.

Fig. 4 shows the voltage on the bus when the fault occurs. The simulation scenario is as follows:
- 0.0s: start the simulation
- 0.5s: three phase fault at Yeongseo 345kV S/S
- 0.6s: the fault clear and the transformer between Yeongseo 345kV and 154kV S/S is open
- 5.0s: end the simulation

In the case that the line is completely opened, the voltage of the bus is reduced to 0 after contingency. Finally, the power failure occur on the bus. On the other hand, when the conventional line is connected and operated, it can be seen that the voltage rises to the voltage range in steady state after the contingency. However, in the case of the smart SC cable connections, the fault may not be removed because some buses exceed the fault current limit. On the other hand, the smart SC cable can be confirmed that the bus runs within the allowed voltage range after a contingency in Korea even though the bus voltage is on the lower bound of the range as shown in Fig 4. Therefore, it can be seen that the use of smart SC cable helps to improve the stability because by limiting the fault current in the event of fault and additionally
enabling operation by connecting the line. However, when the fault current cannot be completely removed and the bus voltage is slightly lower after the contingency due to the resistance and the inductance of the smart SC cable, it is considered that the part needs to be improved.

Table 1. Fault current calculation results by measures for fault current limit

| Measures                  | # of buses (50kA above) | Remarks                                                                 |
|---------------------------|-------------------------|-------------------------------------------------------------------------|
| BaseCase (Line Connecting)| 25                      | Yeong-Seo and Shinyangjae system (Maximum-65kA, Shinyangjae 154kV)       |
| Line Opening              | 0                       | No bus exceeding 50kV                                                   |
| Fault Current Limiter     | 4                       | Shinyangjae, Yangji, Yeoksam, Kyodae                                   |
|                           |                         | [2Ω/km] Shinyangjae, Yangji, Yeoksam, Kyodae                            |
| Smart Superconducting     | 11                      | Yeongseo1, Shinyangjae, Yangji, Yeoksam, Sadang, Boncheon, Kyodae, Seocho, Nonil, Shinsa, Gwacheon |
| Cable [1Ω/km]             |                         |                                                                         |
| Smart Superconducting     | 4                       | Shinyangjae, Yangji, Yeoksam, Kyodae                                   |
| Cable [2Ω/km]             |                         |                                                                         |

Figure 5. Shingil substation voltages

6. Conclusion
Currently, a smart SC cable with fault current limiting function is being developed in Korea. The smart SC cable was applied to the Korean power system with very robust connectivity and the feasibility study was conducted. In the metropolitan area, there are many parts that are separated and operated due to the
fault current problem. If the smart SC cable is used for separated operation lines, the fault current is limited and the system stability can be improved. However, the smart SC cables have disadvantages in installation costs, and efforts to overcome them are necessary. In addition, it is possible to limit the fault current, but since there is an overload in some connected systems, the smart SC cable can be introduced considering the different system configuration in actual operation. In addition, we will review other power system application areas.

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