Evaluation of the Application Scheme of SFCL in Power Systems

Jong-Yul Kim †, Seung-Ryul Lee* and Jae-Young Yoon*

Abstract - As power systems grow more complex and power demands increase, the fault current tends to gradually increase. In the near future, the fault current will exceed a circuit breaker rating for some substations, which is an especially important issue in the Seoul metropolitan area because of its highly meshed configuration. Currently, the Korean power system is regulated by changing the 154kV system configuration from a loop connection to a radial system, by splitting the bus where load balance can be achieved, and by upgrading the circuit breaker rating. A development project applying a 154kV Superconducting Fault Current Limiter (SFCL) to 154kV transmission systems is proceeding with implementation slated for after 2010. In this paper, SFCL is applied to reduce the fault current in power systems according to two different application schemes and their technical and economic impacts are evaluated. The results indicate that both application schemes can regulate the fault current under the rating of circuit breaker, however, applying SFCL to the bus-tie location is much more appropriate from an economic view point.

Keywords: circuit breaker, fault current, SFCL, technical and economic impacts

1. Introduction

As demands for electric energy have been increasing at a high rate since the 1980s, Korean electric power systems are growing into large complex systems that have high short circuit capacity and line loading constraints over certain trunk transmission lines due to their meshed system configuration. Currently, the transmission network in Korean power systems is protected by 40kA rated circuit breakers for 345kV systems and 31.5kA and 50kA rated circuit breakers for 154kV systems. As the power system becomes more complex and electrical demands increase, the fault current also tends to increase.

Unless an appropriate countermeasure is applied, the fault current will soon exceed the circuit breaker rating for some substations. To solve this problem, several methods are implemented on the power system; changing the system configuration from a loop to a radial system; splitting the bus; and upgrading lower rated equipment to higher rated equipment. Superconductors are utilized for fault current limiter applications because they can transform into a normal state in a few milliseconds, have high resistivity in the normal state, and then return to the superconducting state once fault conditions are removed.

The superconducting fault current limiter (SFCL) reduces the fault current and allows the use of lower rated circuit breakers. Therefore, we can obtain cost-savings by avoiding the need to upgrade lower rated equipment in existing installations. Major companies world-wide have been conducting research on SFCL: ABB (Switzerland), GEC-Alsthom (France), Tokyo Electric (Japan), General Atomics (USA), and Siemens (Germany) [1-3]. A development project for a 154kV class SFCL is proceeding by CAST (Center for Applied Superconductivity Technology) in Korea. In this paper, SFCL is applied to reduce the fault current in power systems according to two different application schemes and their technical and economic impacts are evaluated.

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Received August 16, 2004 ; Accepted October 4, 2004

2. Superconducting Fault Current Limiter

2.1 Resistive type SFCL

The simplest superconducting limiter concept, the series resistive limiter, directly exploits the non-linear resistance of superconductors. For a full-load current of IFL, the superconductor would be designed to have a critical current of 2 * IFL or 3 * IFL. During a fault, the fault current pushes the superconductor into a resistive state and resistance, R, appears in the circuit. The superconductor in its resistive state can also be used as a trigger coil, pushing the bulk of the fault current through a resistor or inductor. The advantage of this configuration, shown in Fig. 1, is that it limits the energy that must be absorbed by the superconductor. The fault-current limiter (FCL) normally is a short across the copper inductive or resistive element, Z.

During a fault, the resistance developed in the limiter shunts the current through Z, which absorbs most of the fault energy.

The trigger coil approach is appropriate for transmission line applications, where tens of megawatt-seconds would be absorbed in a series resistive limiter [4].

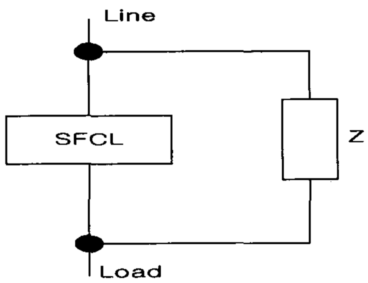

Fig. 1 The resistance type SFCL

2.2 Inductive type SFCL

Another concept uses a resistive limiter on a transformer secondary, with the primary in series in the circuit. This concept, illustrated in Fig. 2, yields a limiter suitable for large currents and is coupled to a HTS winding, WHTS.

During normal operation, zero impedance is reflected to the primary. Resistance developed in the HTS winding during a fault is reflected to the primary and limits the fault.

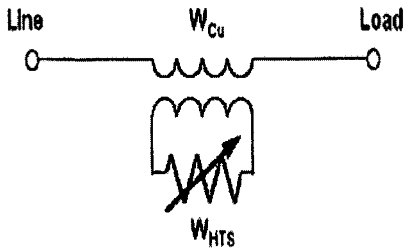

Fig. 2 The inductive type SFCL

The inductive limiter can be modeled as a transformer. The impedance of this limiter in the steady state is nearly zero, since the zero impedance of the secondary (HTS) winding is reflected to the primary. In the event of a fault, the large current in the circuit induces a large current into the secondary and the winding loses superconductivity. The resistance in the secondary is reflected into the circuit and limits the fault [4].

3. Application Scheme of SFCL in Power Systems

There are two major ways to apply the SFCL in power systems, one is installing the SFCL in the transmission line and the other is in bus-tie location. In the first application scheme the SFCL is installed in the transmission line or secondary side of the transformer in series as shown in Fig. 3. In this way, the SFCL can be expected to limit the fault current effectively.

However, many SFCLs are needed to reduce the fault current, because if a certain transmission line consists of 4 circuits, the four SFCLs are required to be installed in each circuit. In this regard, it has some demerit from an economic vantage point. In the second application scheme the SFCL is applied in the bus-tie location. This method uses only one SFCL as shown in Fig. 4, which gives greater economic benefit than applying the SFCL in the transmission line. The SFCL installed at the bus-tie location has almost zero impedance in a superconducting state, which provides the same power system configuration before splitting the bus.

Once the fault is occurred, the state of SFCL is transformed from a superconducting state into a quenching state, which can provide the same effect as splitting the bus. That is, the SFCL can supply many technical advantages such as reliability of the power supply and power system stability. Otherwise, in the conventional fault current reduction method of splitting the bus, these technical aspects are lowered.

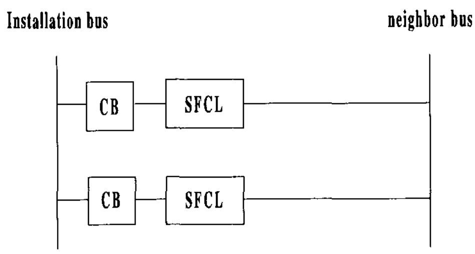

Fig. 3 SFCL in transmission line

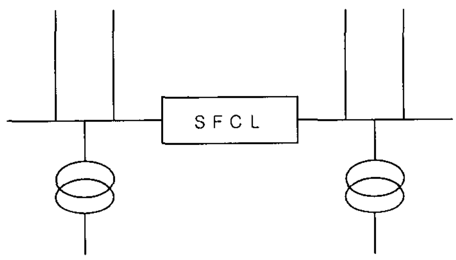

Fig. 4 SFCL in Bus-Tie

4. Fault Current Problem in the Korean Power System

4.1 System Growth and Configuration

The power system's size is now about 8.5 times what it was 20 years ago, having increased from 4,800MW in

1976 to 40,000MW in 1996. Although load growth was set back somewhat during 1997-1998 because of the financial crisis, the increase in demand for electricity during 1999-2002 shows that the Korean economy is rapidly recovering from the crisis and the system size is forecasted to reach 90,000MW within 30 years. The sizes of unit generators are standardized as 1,000MW for nuclear plants, and 500MW for coal-fired steam plants. According to generation expansion planning, 800MW coal-fired steam generators and 1,300MW nuclear generators will be added to the system in 2003 and 2008, respectively. With the increase of unit generator size and the number of generators installed at a station, the installed generation capacity becomes larger than 6,000MW at some stations, and 10,000MW generation stations will appear in the future.

Moreover, many combined-cycle gas turbine generators are being installed near load centers, like in the Seoul and Busan metropolitan areas, to support load variation as well as system voltage profile. The transmission system has also been reinforced to supply electricity for the growing load demand.

The transmission system consists of 154kV, 345kV, and 765kV systems. The 765kV system was launched in 2002 and additional transmission systems are under construction to efficiently transfer more than 6,000MW of electric power from large generation complexes to the load center of the Seoul metropolitan area.

4.2 Results of the Fault Current Analysis

We investigated the fault current of 154kV buses in the Seoul metropolitan area in 2004, 2006, and 2010 by using the PSS/E program and peak data of the Korea Electric Power Company (KEPCO). The Seoul metropolitan area's fault current problem is an important issue for the stable operation of power systems and the 154kV network in the Seoul metropolitan area is very complex. The result shows that the fault current tends to exceed the circuit breaker rating at some substations and this tendency will continue until an appropriate countermeasure is developed. Figs. 5-7 present the fault current distribution in the peak data of the

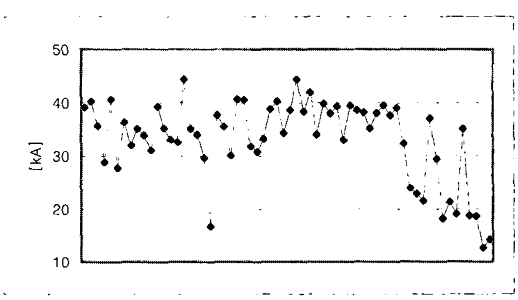

Fig. 5 Fault current in Seoul metropolitan area in 2004

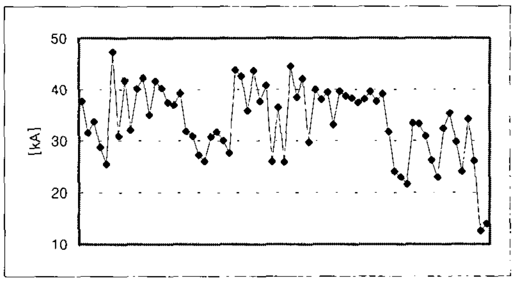

Fig. 6 Fault current in Seoul metropolitan area in 2006

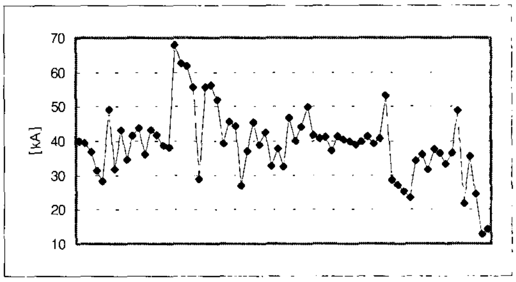

Fig. 7 Fault current in Seoul metropolitan area in 2010

power systems in 2004, 2006, and 2010. In the figures, the horizontal axis represents the bus in the Seoul metropolitan area and the vertical axis represents the fault current of the bus. The fault current, shown in Figs. 5-7, is about 30kA to 40kA in 2004 and increases gradually as time goes by. In 2010, it exceeds 50kA, the maximum rating of a 154kV circuit breaker. Unless a proper countermeasure is applied, the power system will be damaged by the fault current.

5. Technical Effect of the SFCL

5.1 Test Case

We have studied many cases, but in this paper, we introduce the southern Seoul metropolitan area case. Because the southern Seoul metropolitan area has very high load density, the possibility of the fault current to exceed the circuit breaker rating is higher than any other region in Korea. We used peak data of KEPCO in 2010 and the three-phase fault was considered. Assuming that the rating of the 154kV circuit breaker is 50kA, the fault currents of 8 buses exceed the rating of a circuit breaker. In these 8 buses, bus 2510 is selected as a test power system because this bus had the greatest large fault current exceeding 60kA in 2000 among the 8 buses and each case study showed similar results. Fig 8 indicates the configuration of bus 2510 and neighboring buses. The bold lines in Fig. 8 indicate 345kV lines and buses, the thin lines indicate 154kV lines and buses. The fault current of bus 2510, enclosed by dotted lines exceeds their circuit breaker rating of 50kA.

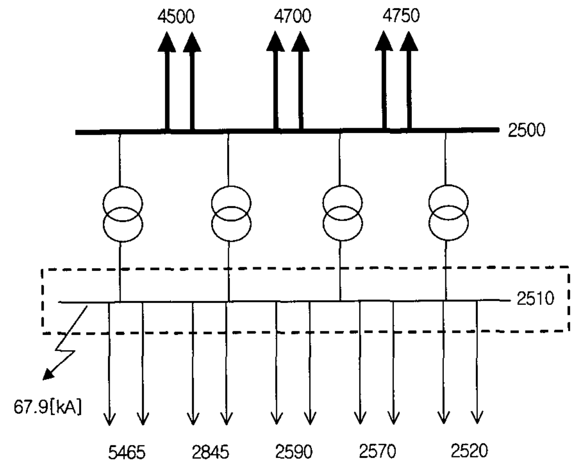

Fig. 8 Diagram of the test area

5.2 Application of the SFCL

5.2.1 Installation of SFCL in Transmission Lines

In order to solve the fault current problem by using the SFCL, its most effective installing location must be predetermined.

Though SFCL is installed at the same bus, the fault current reduction effect is different according to the location's relation to the neighboring bus. Usually the maximum fault current reduction effect could be obtained by installing the SFCL at a location connected to the neighboring bus with the biggest fault current contribution [5]. In this case study, there are six candidate locations for installing the SFCL as shown in Fig. 9.

To select the most effective installing location, at first, the fault current contribution flowing into bus 2510 through each connected transmission line and transformer is evaluated by fault analysis.

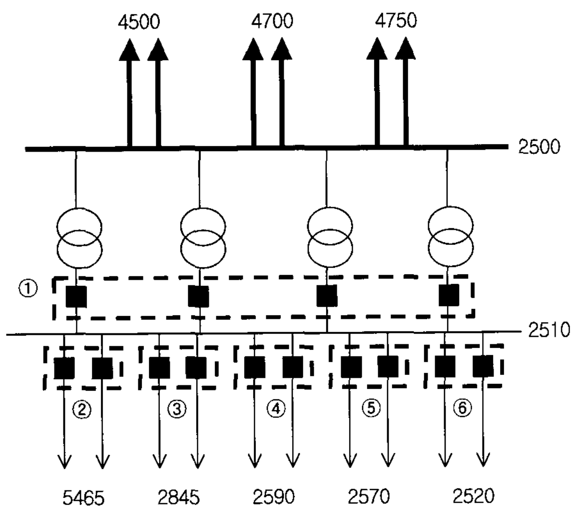

Fig. 9 Candidate locations of installing the SFCL at bus 2510

As shown in Table 1, fault current from bus 2500 is the most significant, having the magnitude of 32.9kA, which means location ① is the most effective installing location to solve the fault current problem at bus 2510. According to this result, the four resistive SFCLs with the impedance of 0.1p.u (about 23.7Ω based on 100[MVA]) after quenching are installed at location ①

Table 1 Fault current contribution

Faulted Bus	Connected Bus	Fault Current [kA]
2510	2500	32.9
	2520	14.9
	2570	6.2
	2590	0.0
	2845	9.1
	5465	4.8

5.2.2 Installation of SFCL in Bus-Tie

Bus 2510 is split into two buses, bus 2510 and 2511, and then a resistive SFCL is applied at bus-tie location between bus 2510 and 2511 to reduce the fault current as shown in Fig. 10.

The impedance of SFCL after quenching is also 0.1pu (about 23.7Ω based on 100[MVA]).

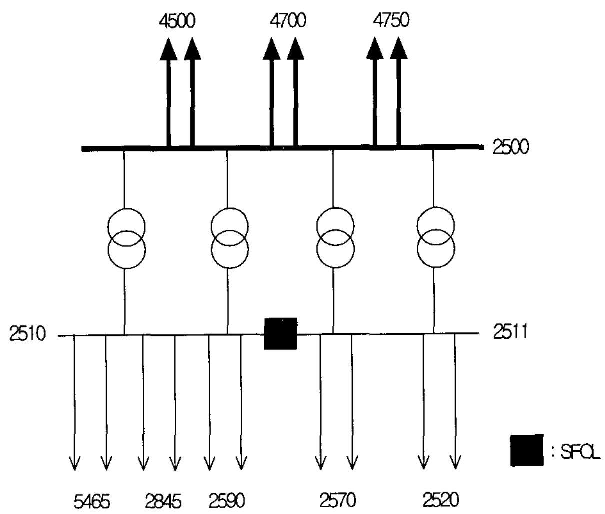

Fig. 10 Application of SFCL in Bus-Tie Location

The SFCL installed at bus-tie location has almost zero impedance in normal state, which gives the same power system configuration prior to splitting bus 2510. If the fault is occurred at bus 2510 and 2511, the SFCL gets to have immense impedance due to quenching of the super-conductor, which can provide the same effect as splitting of bus 2510. In case that the three phase fault is occurred at bus 2510, the fault current I_{SFCL} flowing into bus 2510 from bus 2511 is reduced by the SFCL with the impedance of 0.1pu and the fault current of bus 2510 is also limited.

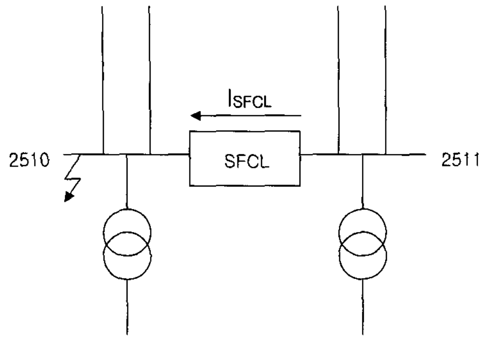

Fig. 11 Fault current reduction effect of SFCL

5.3 Results of applying SFCL

To evaluate the application effects of the SFCL by different applying locations, the SFCL is installed at both the transmission line and bus-tie of bus 2510. Table 2 shows the application effects of the SFCL by applying location, respectively. As can be seen in Table 3, both SFCLs installed at transmission line and bus-tie can reduce the fault current of bus 2510 (bus 2511 in case of bus-tie) under their circuit breaker rating of 50kA. The four SFCLs are installed in case of transmission line application; otherwise, only one SFCL is used in bus-tie application with almost the identical fault current reduction effect.

Table 2 Application effects of SFCL

Bus	Without SFCL	SFCL in Transmission line	SFCL in Bus-Tie
	Fault Current[kA]	Fault Current[kA]	Fault Current[kA]
2510	67.9	44.2	40.7
2511	-	-	47.5

6. Economic Effect of SFCL

6.1 Cost of upgrading Circuit Breakers

In the case study, the fault currents of bus 2510 exceed the circuit breaker rating. The typical conventional solution is the replacement of substation circuit breakers; however this solution not only costs a lot of money, but also can result in lowering reliability of the power supply. Therefore, by applying the SFCL, the fault current is reduced below the circuit breaker rating, eliminating the need to upgrade the substation circuit breakers and saving electric utilities this cost.

In this case study, the total cost of upgrading the circuit breaker is calculated taking into account the circuit breaker and other electrical equipment, which is assumed to be about 40% percent of the total price of the circuit breakers in need to change. In this paper, the price of a 63kA rated circuit breaker for 154kV is estimated at $312,500, based on the price of conventional 50kA rated circuit breakers for 154kV systems and 63kA rated circuit breakers for 345kV systems.

The number of circuit breakers required to be upgraded is 17 in total and the overall price of the circuit breakers is about $5,300,000. Therefore, the complete cost of upgrading the circuit breakers is expected to be $7,400,000.

6.2 Economic Feasibility of SFCL

In this paper, based on the above upgrading cost of circuit breakers, we can evaluate economic feasibility of the SFCL. In this case study, if the SFCL is installed in the transmission lines, a total of four SFCLs are needed to limit the fault current.

However, if the SFCL is applied to bus-tie, only one SFCL is required. Therefore, the price of the SFCL in transmission line application must be below a quarter of the total cost of upgrading the circuit breakers. It costs about $1,850,000, otherwise, the price of the SFCL in bus-tie application is economically feasible if it is under $7,400,000. As a result, we can say that applying the SFCL in bus-tie application is more feasible than in transmission lines from an economic stand.

7. Conclusion

A development project applying 154 kV Superconducting Fault Current Limiters (SFCLs) to 154 kV transmission systems is proceeding with implementation slated for after 2010. In this paper, the technical and economic impacts of applying the SFCL in the Korean power system are carried out in relation to this project. In particular, the fault current reduction effect of the SFCL by application schemes is evaluated respectively. In the case study, two application schemes can show positive technical effect. However, in an economic aspect, applying the SFCL to the bus-tie location is more feasible than to the transmission line. Therefore, we can say that the bus-tie location is the more appropriate location to reduce the fault current, taking into account the technical and economic aspects.

Acknowledgements

The authors would like to express their gratitude with special thanks to the Center for Applied Superconductivity Technology in Korea for their financial support and cooperation.

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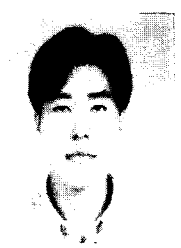

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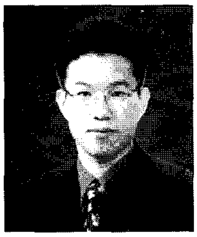

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