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A Study on the Application Impacts on Korean Power System by Introducing SFCL

Jong-Yul Kim*, Heung-Kwan Choi* 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 154 kV 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 154 kV Superconducting Fault Current Limiter(SFCL) to 154 kV transmission systems is proceeding with implementation slated for after 2010. In this paper, the resistive and inductive SFCLs are applied to reduce the fault current in Korean power system and their technical and economic impacts are evaluated. The results show that the application of SFCL can eliminate the need to upgrade the circuit breaker rating and the economic potential of SFCL is evaluated positively.

Keywords: fault current, circuit breaker, 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 tends 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 return to the superconducting state once fault conditions are removed. 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. In these days, companies world-wide have conducted researches 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 at a research center and university in Korea.

In this paper, resistive and inductive SFCLs are applied to reduce the fault current in Korean power systems and their technical and economic impacts are evaluated.

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 I_{FL}, the superconductor would be designed to have a critical current of $2I_{FL}$ or $3I_{FL}$. 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

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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].

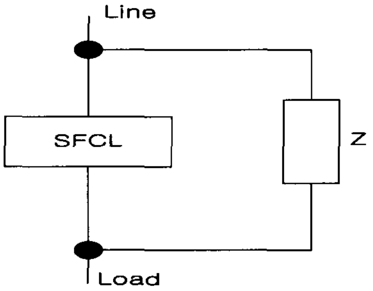

Fig. 1 The resistance type SFCL

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- current and is coupled to an HTS winding, W_{HTS}.

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.

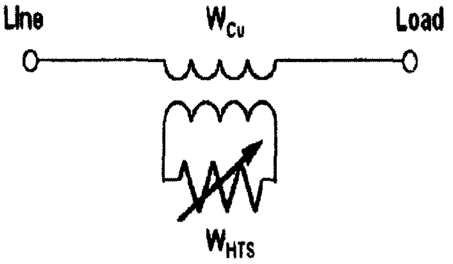

Fig. 2 The inductive type SFCL

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 secondary and the winding loses superconductivity. The resistance in the secondary is reflected into the circuit and limits the fault [4].

3. Prospect of the Fault Current in Korea

3.1 The System Growth and Configuration

The power system's size is now about 8.5 times what it was 20 years ago, having increased from 4,800 MW in 1976 to 40,000 MW in 1996. Although load growth was set back somewhat during 1997 - 1998 because of 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 90,000 MW within 30 years.

The sizes of unit generators are standardized as 1,000 MW for nuclear plants, and 500 MW for coal-fired steam plants. According to generation expansion planning, 800 MW coal-fired steam generators and 1,300 MW 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 6,000 MW at some stations, and 10,000 MW generation stations will appear in the future. Also many combined-cycle gas turbine generators are being installed near load centers, like Seoul and Busan metropolitan areas, to support load variation as well as the system voltage profile.

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

3.2 Fault Current Analysis

We investigated the fault current of 154 kV buses in the Seoul metropolitan area in 2004, 2006, and 2010 by using the PSS/E program and peak data of Korea Electric Power Company (KPCO). The Seoul metropolitan area's fault current problem is an important issue for the stable operation of power systems and the 154 kV 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. 3-5 show the fault current distribution in the peak data of the power systems in 2004, 2006, and 2010. In the

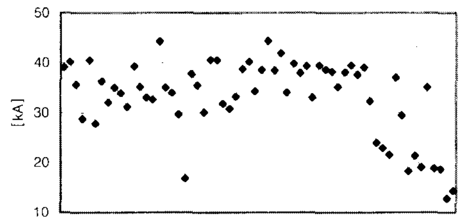

Fig. 3 Fault current in Seoul metropolitan area in 2004

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.3-5, is about 30 – 40 kA in 2004 and increases gradually as time goes by. In 2010, it exceeds 50 kA, the maximum rating of a 154kV circuit breaker. Unless a proper countermeasure is applied, the power system will be damaged by the fault current.

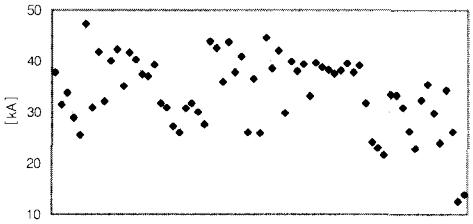

Fig. 4 Fault current in Seoul metropolitan area in 2006

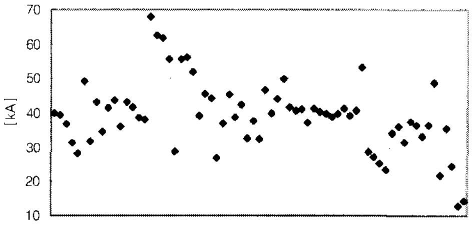

Fig. 5 Fault current in Seoul metropolitan area in 2010

4. Technical Impact of SFCL in Power Systems

4.1 Test Power System

In many cases, we have studied the technical impact of SFCL in Korean power systems. But in this paper, we introduce the southern Seoul metropolitan area case.

Because the southern Seoul metropolitan area has a very high load density, the possibility that the fault current exceeds the circuit breaker rating is higher than any other areas in Korea. In this analysis, we used KEPCO peak data for 2010 and the three-phase fault was considered.

Table 1 The results of fault current analysis

Bus	Fault current [kA]
2510	67.9
2520	62.5
2525	61.7
2530	55.6
2540	55.6
2570	56.1
2580	52.0
2845	53.2

Assuming a 50 kA rating of the 154kV circuit breaker, the fault currents of eight buses exceed the rating of the circuit breaker as shown in Table 1.

4.2 Procedure for Applying SFCL to Power Systems

We proposed a procedure for applying SFCL to power systems to resolve the fault current problem as shown in Fig. 6. First, investigate the contribution of the fault current and select a candidate location at each bus where the fault current exceeds the circuit breaker rating. The selected candidate locations are evaluated for the application effect.

Finally, according to the application effect, determine the most effective location to limit the fault current. Until the fault current problem is resolved, install the additional SFCL at next effective location.

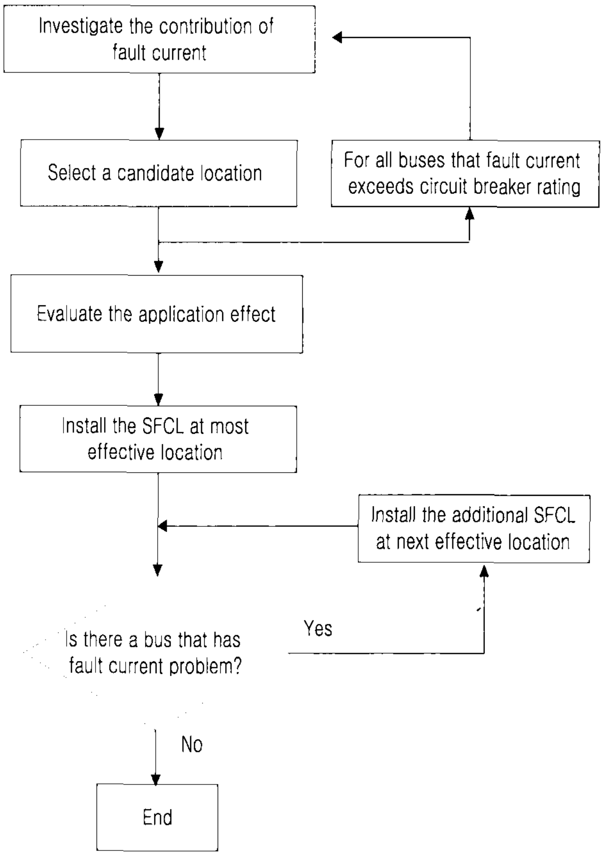

Fig. 6 Procedure of applying SFCL in power systems

4.2.1 Contribution of Fault Current

The contribution of the fault current is investigated at all buses where the fault current exceeds the circuit breaker rating as shown in Table 2.

Table 2 Contribution of fault current

Bus	Neighbor bus	Contribution of Fault current [kA]
2510	2500	32.9
	2520	14.9
	2570	6.2
	2590	0.0
	2845	9.1
	5465	4.8
2520	2510	27.3
	2525	23.9
	2530	11.3
2525	1965	24.5
	2520	37.2
2530	2520	30.7
	2540	24.9
2540	2530	24.4
	2570	26.4
	2580	4.8
2570	2510	34.1
	2540	18.6
	2580	3.4
2580	2540	25.5
	2570	26.5
2845	2510	42.6
	2725	7.2
	4580	3.4

4.2.2 Select a Candidate Location

Though the SFCL is installed at the same bus, the fault current reduction effect is different according to the location's relation to the neighbor bus. The maximum fault current reduction effect could be obtained by installing the SFCL at a position connected to the neighbor bus with the largest fault current contribution. By using the fault current contribution, we select a candidate location that has the largest fault current contribution at each bus where the fault current exceeds the circuit breaker rating. In the case of bus 2510, the fault current from neighbor bus 2500 is larger than from other neighbor buses. Therefore, the candidate location of bus 2510 is position ①, as shown in Fig. 7. After all, we select a total of eight candidate locations as shown in Table 3.

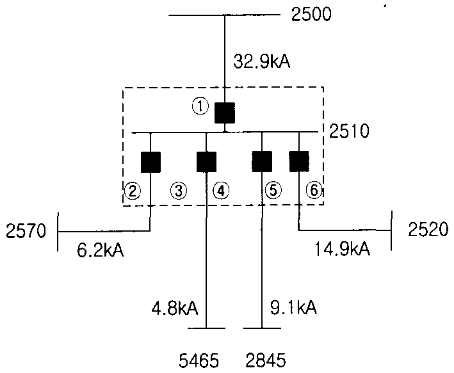

Fig. 7 Select a candidate location at bus 2510

Table 3 Candidate locations

Installation bus	Neighbor bus
2510	2500
2520	2510
2525	2520
2530	2520
2540	2530
2570	2510
2580	2570
2845	2510

4.2.3 Evaluate the Fault Current Reduction Effect

The Resistive type SFCL and the inductive type SFCL are installed in the trunk transmission line to evaluate the fault current reduction effect as shown in Fig. 8. The impedance of the SFCL after quenching is assumed to be 0.05 [p.u] (based on 100[MVA]).

In case the SFCL is installed at bus 2525, the fault currents of seven of eight buses are reduced below 50 kA as shown in Table 4. Therefore, bus 2525 can be considered the most effective location among candidate locations.

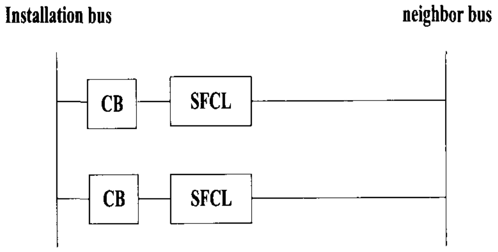

Fig. 8 Installation of SFCL in transmission line

Table 4 Application effect of candidate location

Installation bus	Neighbor bus	Resistive type SFCL	Inductive type SFCL
2510	2500	5	5
2520	2510	0	0
2525	2520	7	7
2530	2520	4	4
2540	2530	4	4
2570	2510	4	4
2580	2570	1	1
2845	2510	1	1

4.3 Results of Case Study

According to the proposed procedure shown in Fig. 6, the SFCLs are installed at bus 2525 and bus 2510 (see Table 5).

The resistive type SFCL and the inductive type SFCL are considered and Table 6 shows the results of the case study.

Table 5 Installation of SFCL

Installation bus	Neighbor bus	Circuit Number
2525	2520	2
2510	2500	4

Table 6 Results of case study

Bus	Without SFCL [kA]	Resistance type SFCL [kA]	Inductive type SFCL [kA]
2510	67.9	43.5	39.6
2520	62.5	39.8	36.4
2525	61.7	31.7	35.3
2530	55.6	37.9	34.3
2540	55.6	38.2	34.5
2570	56.1	38.5	34.8
2580	52.0	36.6	33.1
2845	53.2	39.8	35.9

As seen in Table 6, the SFCLs at bus 2525 and bus 2510 reduce to 50 kA the fault current of eight buses that have the fault current problem. Therefore, the application of SFCL can prevent the need to upgrade the substation breakers.

5. Economical Impact of SFCL in Power Systems

5.1 Cost of upgrading Circuit Breakers

In the case study, the fault currents of eight buses exceed the circuit breaker rating. The typical conventional solution is the replacement of substation circuit breakers at an estimated cost of about $8,000,000.

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. Table 7 summarizes the number of substation circuit breakers and the estimated upgrading cost.

Table 7 Cost of upgrading circuit breakers

Bus	No. of CBs	Estimated Price of CB	Upgrading Cost
2510	16	$125,000	$2,000,000
2520	8	$125,000	$1,000,000
2525	6	$125,000	$750,000
2530	6	$125,000	$750,000
2540	8	$125,000	$1,000,000
2570	8	$125,000	$1,000,000
2580	6	$125,000	$750,000
2845	6	$125,000	$750,000
Total	64	-	$8,000,000

In this calculation, the upgrading cost is based only on circuit breakers. However, other electrical equipment, including DS, may need to be replaced in some buses. Thus, the total cost for upgrading electrical equipment is expected to be more than $8,000,000.

5.2 The Prospect of SFCL Price

At this point, forecasting the cost of SFCL is very difficult. The cost of the HTS wire and the refrigeration system in SFCL are keys to commercial success. In this paper, we not only review the present HTS wire cost and refrigeration system cost, but also project these costs for the future [5].

5.2.1 HTS Wire

The cost of HTS wire is generally described by a figure-of-merit measured in dollars per killoamp-meter ($/kA-m), which is dependent on two parameters: first, the maximum amount of current the HTS wire will conduct; and second, the manufacturing cost per meter of wire. Both parameters are expected to improve as a result of advances in manufacturing techniques. Fig. 9 shows the prospective cost of HTS wire ($/kA-m) from 2025 to 2025. In this figure, the asymptotic value is about $20/kA-m.

5.2.2 Refrigeration System

The impact of refrigeration on the future competitiveness of SFCL is critical. The 1999 benchmark cost of a medium-sized refrigeration unit was about $60,000/kW at 77 K. The manufacturers assert that the cost of refrigeration will decrease as demand increases and more units are produced. Therefore, the cost will drop to less than $20,000/kW.

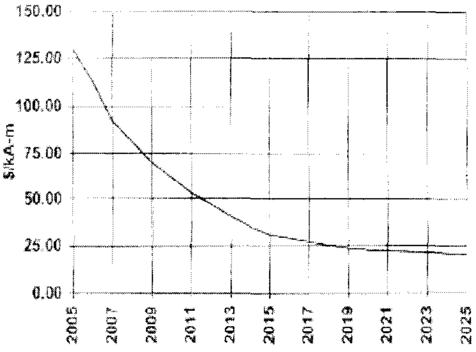

Fig. 9 The prospect of HTS wire cost

We prospected the cost of the HTS wire and the refrigeration system. Though the cost of SFCL is currently somewhat higher than of the cost of replacing circuit breakers, future advances in manufacturing techniques will lead to an enormous economic benefit from applying SFCL.

6. Conclusion

A development project applying 154 kV Superconducting Fault Current Limiter (SFCL) to 154 kV transmission systems is proceeding with implementation slated for after 2010. In this paper, the technical and economic impacts of applying SFCL in the Korean power system are carried out in relation to this project. The effects of applying SFCL as a potential countermeasure to reduce fault currents in the Seoul metropolitan area were evaluated positively. In the case study, a SFCL is installed at two different buses, the most effective locations to reduce the fault current. By applying the SFCL, the fault current is reduced below circuit breaker rating, preventing the need to replace the circuit breakers and any other equipment and thus yielding a cost-saving of, more than $8,000,000.

As the cost of HTS wire and refrigeration drops, the economical potential of SFCL is evaluated positively.

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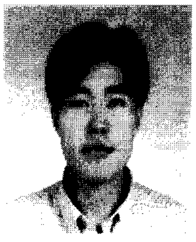

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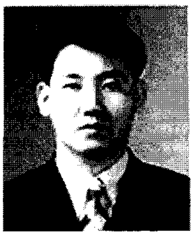

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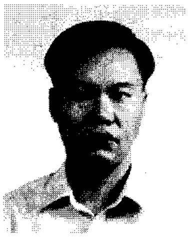

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