Superconductivity and Cryogenics
Vol.11, No.4, (2009), pp.29~32

Bus-tie application scheme of 154 kV class SFCLs in Korean power systems

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Received 13 October 2009; accepted 28 October 2009

Abstract-- **This paper proposes the bus-tie application scheme of 154 kV SFCL (superconducting fault current limiter) in Korean power system. The reduced amount of fault current by SFCL is different by where the SFCL is installed. Therefore the inflow ratio of fault current (IRFC) is suggested to consider the effect of an SFCL's location. The proposed scheme was applied to the Korean Power System of 2010, and fault currents were calculated and analyzed with this coefficient. Simulations show that the location with high IRFC is adequate to install SFCL but more consideration of other things is required to determine the location and capacity of SFCL.**

1. INTRODUCTION

Fault currents in the power systems become higher continuously with the increase and concentration of loads. To solve problems due to the fault currents, in the Korean power systems, several methods have been applied such as separation between areas of different 345 kV buses; bus separation; installation of series reactors; replacement of circuit breakers with those with larger interrupting capacity, etc [1]. However, these measures lower the security and stability of the power systems and require high costs. In addition, they are not the essential solution for the fault current problem.

The high temperature superconducting fault current limiters (SFCLs) has been proposed and studied as the new solution for the fault current problem [2-9]. DAPAS (development of the advanced power system by applied superconductivity technologies) program has been in progress in Korea from 2004. In this program, 22.9 kV class hybrid SFCL was developed and has been prepared to apply to actual power systems by KEPRI (Korea Electric Power Research Institute) and LS Industrial systems. The 154 kV class SFCLs are also planned to be developed and commercialized in 2011 [10, 11]. On the other hand, the application methods of SFCL to power systems have been studied, and it was deduced to be effective that installing SFCL onto 154 kV bus which is the secondary of a 345 kV transformer [12, 13].

In this paper, it is proposed that the application scheme of SFCLs considering the inflow ratio of fault current (IRFC) which represents the combination of lines on a bus. The lines on a bus are grouped by SFCLs and the amount of fault current in each group is different according to the combination of lines. By the analysis of fault currents, the optimal location and capacity of SFCLs are determined and the optimal combination of lines on a bus where an SFCL is installed is also searched. The proposed method was applied to the Korean Power Systems of 2010 when it is planned to apply SFCLs to the actual system in Korea.

2. THE INFLOW RATE OF FAULT CURRENTS

In bus-tie application, an SFCL reduces only a portion of total fault currents in a bus according to lines which they flow through. For example, the fault current IF_1 is reduced by the SFCL in Fig. 1, and IF_2 and IF_3 are not reduced when the fault is occurred at position P_1. Consequently, the effect of the SFCL is different by where it is allocated in a bus.

Generally, the transmission lines connected to a bus are divided to two groups by the bus-tie SFCL. To analyze the effect of an SFCL's allocation in a bus, the inflow ratio of fault current (IRFC), K, is defined as

$$K = \frac{IF_{FCL}}{IF_{total}} = \frac{IF_{FCL}}{\sum_{n} IF_n} \quad (K \leq 0.5) \tag{1}$$

where IFFCL is the amount of total fault currents through an SFCL, IF_{total} is the amount of total fault currents,

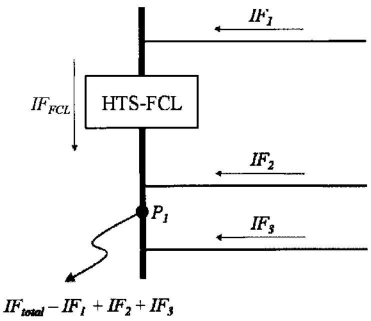

Fig. 1. Bus-tie application of an SFCL and a demonstration of the inflow ratio of fault currents.

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n is the number of total lines connected to the bus, and IF_n is the amount of fault current through the n-th line. In this definition, lines where no fault current flows are ignored and IF_{FCL} is the total fault currents through a group of lines with a smaller amount of fault currents between two groups of transmission lines; hence the value of K is always smaller than 0.5. The combinatorial number of grouping lines, N_k is equation (2). There are accordingly N_k candidates for SFCL location in a bus.

$$N_k = (2^{n-1} - 1), \qquad (2)$$

This consideration is reasonable because the arbitrary combination of lines is possible by setting the circuit breakers in a bus.

3. APPLICATION METHOD OF SFCL

3.1. Assumptions in the Power System to Apply SFCL

In this paper, SFCLs were applied in the Korean Power Systems, and the followings were assumed.

1) The status of the Korean Power System where SFCLs are applied is based on the estimated data of 2010 because it is planned to apply SFCL to actual power systems in Korea in 2010.
2) There are two ways in application of SFCL: line application and bus-tie application. SFCL is applied as bus-tie application in this research because, between those two ways, the bus-tie application is known to be more appropriate from the technical and economic point of view in 154 kV transmission systems by previous researches [12, 13].

3.2. Application Scheme of SFCLs

The objective of installation SFCL is to decrease fault currents below the allowable range with the small costs of SFCL. In this paper, the optimal location and capacity of SFCL were found as followings.

First, all bus fault currents were calculated using PSS/E and it was found that which buses had fault currents more than the allowable range. And then the areas which included those buses were distinguished and reduced to the equivalent system using E-Tran. With this reduced system, the fault currents were analyzed using PSCAD/EMTDC and the adequate location and capacity of SFCL was determined. In simulations, SFCL was simulated by the EMTDC model which was constructed in [14]. Fig. 2 shows the procedure for the application scheme of SFCLs.

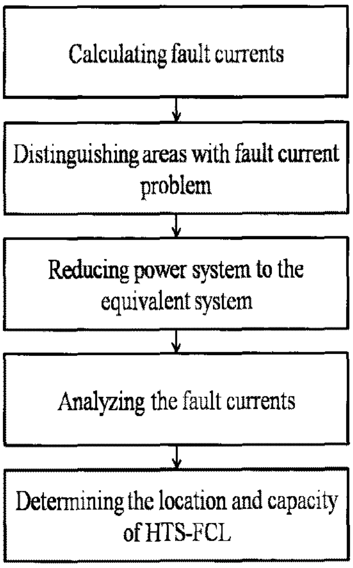

Fig. 2. Flowchart of the procedure for the application scheme of SFCL.

4. SIMULATION RESULTS

4.1. Selection of Buses to Apply SFCL

SFCLs were applied at 154kV buses in the Korean Power System to demonstrate the proposed method in this paper. First, using PSS/E, the fault currents were calculated on 3-phase bus faults at all 154 kV buses in the Korean Power System with peak load data. The rated interrupting capacity of circuit breakers at 154 kV power systems is 50 kA in Korea, so all cases with a fault current of more than 50 kA were investigated. The results are summarized in Table I.

In investigating the fault currents, most of buses having fault current problem were concentrated within the same area. Therefore, among these buses, SungDong1 and MiGuem1/MiGuem1S were selected to apply SFCLs in this paper. In actual system, *MiGuem1* and *MiGuem1S* are, without SFCLs, operated separated from each other when the amount of fault current exceeds the interrupting capacity of circuit breakers. However, as dealt with in this paper, these two buses can be operated without separation by an SFCL. Figure 3 is the one-line diagram of the power system around the *SungDong1* (Bus 4) and *MiGuem1/ MiGuem1S* (Bus 14/14S), and bus 14 and 14S were regarded as one bus.

4.2. Reduction of the Objective Power Grid

The fault currents were calculated by PSCAD/EMTDC after replacement of the objective power grid with the reduced model of that. The power grid around the substations corresponding to the selected two buses was reduced using E-Tran. The power grid connected to selected buses by more than three lines was reduced and transmission lines were modeled as pi-model.

4.3. Application of SFCLs

Table II shows the amounts and ratios to the total amounts of fault current flowing into Bus 14 through each route. There are 6 routes of fault currents flowing into Bus

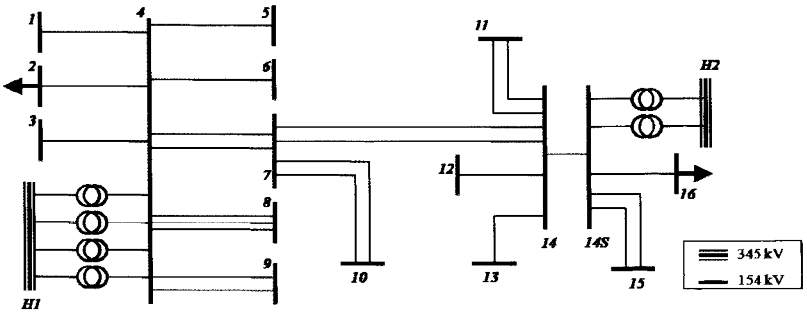

Fig. 3. One-line diagram of the studied system. Bus 4 and Bus 14 represent SungDong1 and MiGuem1, respectively.

TABLE I
BUSES WITH FAULT CURRENT MORE THAN 50KA ON A BUS FAULT.

Bus name	Fault current (kA)	Area
SungDong1	53.4	1
WangSipRi	52.7	1
MaJang	52.4	1
MiGuem1	51.7	1
MiGuem1S	51.7	1
HwiGyoung	50.7	1
SinSiHeung21	50.2	3
SinSungNam1	52.1	3
DMigeum1	50.8	1
DSinSungNam1	52.1	3

TABLE II
FAULT CURRENTS INTO BUS 14 WITHOUT SFCL.

Total fault current (kA)	Flowing line	Fault current (kA)	Ratio (%)
51.7	15 – 14	4.4	8.5
	H2 – 14	20.8	40.2
	7 – 14	18.5	35.8
	12 – 14	1.8	3.5
	13 – 14	2.5	4.8
	11 – 14	3.7	7.2

TABLE III
FAULT CURRENT ON FAULTS AT BUS 14 WITH SFCL
: WITH 5 Ω OF QUENCHING RESISTANCE.

(Case) Combination	K	Fault current (kA)			Decrease rate (%)
		X	Y	Average	
(A) 7,11,H2 / 12,13,15	0.168	50.6	35.2	42.9	17.0
(B) 7 / 11,12,13,15,H2	0.358	47.9	41.2	44.6	13.8
(C) 7,12,13,15 / 11,H2	0.474	38.7	36.2	37.5	27.6
(D) 7,13,15 / 11,12,H2	0.491	39.4	39.0	39.2	24.1

TABLE IV
BUS FAULT CURRENT AT NEIGHBOR BUSES WITH SFCL AT BUS 14
: WITH 5 Ω OF QUENCHING RESISTANCE.

Bus	Fault current (kA)		
	Without SFCL	Case C	Case D
4	54.7	46.7	48.7
7	50.7	41.3	42.4
16	50.8	38.7	39.4

TABLE V
FAULT CURRENT ON FAULTS AT BUS 14 WITH SFCL
: WITH 10 Ω OF QUENCHING RESISTANCE.

(Case) Combination	K	Fault current (kA)			Decrease rate (%)
		X	Y	Average	
(A) 7,11,H2 / 12,13,15	0.168	50.6	34.7	42.7	17.5
(B) 7 / 11,12,13,15,H2	0.358	47.8	40.9	44.4	14.2
(C) 7,12,13,15 / 11,H2	0.474	36.3	33.7	35.0	32.3
(D) 7,13,15 / 11,12,H2	0.491	38.0	37.6	37.8	26.9

TABLE VI
BUS FAULT CURRENT AT NEIGHBOR BUSES WITH SFCL AT BUS 14
: WITH 10 Ω OF QUENCHING RESISTANCE.

Bus	Fault current (kA)		
	Without SFCL	Case C	Case D
4	54.7	44.9	47.7
7	50.7	39.1	41.1
16	50.8	36.3	38.0

14, and, therefore, 31 combinatorial cases of grouping cases by (2). For each case, IRFC and fault currents were calculated using PSCAD/EMTDC with various values of a quenching resistance of SFCL.

Table III shows the amount of fault current for the 4 selected combinations. Case A and B represent the typical cases with low and middle IRFC respectively, and Case C and D were selected to show the results with high IRFC. There are 2 groups of bus faults by where the fault position is located in. The fault currents X and Y in Table III represent the amount of total fault current for each group of faults, and the average value of X and Y was compared in simulations.

In Case A where the IRFC is 0.168, though SFCL reduced fault currents much more for some cases, the average value of the reduced fault currents is lower than other cases. The fault current was even not reduced to within the allowable range on some faults.

In Cases C and D, to the contrary, the average amounts of the reduced fault current were large. Generally speaking, the closer to 0.5 IRFC was in simulations, the larger the amount of the reduced current was. However, the reduced amount of fault current was not exactly proportional to IRFC, as shown in Cases C and D; the reduced amount of fault current was larger in Case C although IRFC was larger in Case D. It is supposed that the amount of fault current is also influenced by the 345 kV bus where the line is connected.

To more practical results, the bus fault currents at neighbor substations were investigated. Table IV shows the amounts of fault currents at each neighbor bus on the bus fault. In both cases C and D, the bus fault currents at neighbor buses were below the allowable range. The reduced amounts of fault currents were smaller in Case C than in Case D analogously with the bus fault currents at Bus 14. Tables V and VI show the results where the quenching resistance was 10 Ω. With the larger quenching resistance, the fault currents reduced more and the tendency of the reduced amounts of fault currents was similar to that with the smaller quenching resistance.

From these results, the location and the capacity of SFCL were determined. The adequate location was Bus 14 with the combination of Case C. The amount of the quenching resistance of SFCL influenced the fault current, but the reduction of fault currents became saturated as the quenching resistance became higher. Therefore, SFCL was installed at Bus 14 with the combination of Case C (between {7, 12, 13, 15} and {11, H2}) and the quenching resistance of SFCL was determined to 5 Ω, considering economical efficiency.

5. CONCLUSIONS

This paper proposed the bus-tie application scheme of SFCL. The amount of fault current flowing through SFCL is different by where SFCL is located, which was investigated with the inflow ratio of fault current (IRFC). After finding the buses with the fault current problem, bus fault currents were calculated with the reduced power system model. Simulation results were analyzed by IRFC, and then the location and capacity of SFCL was determined.

The proposed algorithm was applied to the Korean Power System of 2010. The simulation results show that the location with high IRFC is adequate to install SFCL but more consideration of the configuration of grids is required to determine the location and capacity of SFCL.

ACKNOWLEDGMENT

This research was supported by a grant from Center for Applied Superconductivity Technology of the 21st Century Frontier R&D Program funded by the Ministry of Education, Science and Technology, Republic of Korea.

REFERENCES

[1] *The 4th Basic Plan for Long-Term Electricity Supply and Demand (2008~2022)*, Ministry of Knowledge Economy, Korea, Dec. 2008.

[2] H. Kameda and H. Taniguchi, "Setting method of specific parameters of a superconducting fault current limiter considering the operation of power system protection-resistance-type and rectifier-type SFCLs in overhead transmission systems," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 1355-1360, June 1999.

[3] M. Noe and B. R. Oswald, "Technical and economical benefits of superconducting fault current limiters in power systems," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, part I, pp. 1347-1350, June 1999.

[4] M. Sjostrom, and D. Politano, "Technical and economical impacts on a power system by introducing an HTS FCL," *IEEE Trans. Appl. Supercond.*, vol 11, no. 1, part II, pp. 2042-2045, March 2001.

[5] M. Tsuda, Y. Mitani, K. Tsuji, and K. Kakihana, "Application of resistor based superconducting fault current limiter to enhancement of power system transient stability," *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, part II, pp. 2122-2125, March 2001.

[6] K. Hongesombut, Y. Mitani, and K. Tsuji, "Optimal location assignment and design of superconducting fault current limiters applied to loop power systems," *IEEE Trans. Appl. Supercond.*, vol. 13, no. 2, part II, pp. 1828-1831, June 2003.

[7] M. Steurer, M. Noe, and F. Breuer, "Fault current limiters - R&D status of two selected projects and emerging utility integration issues," in *Proc. 2004 IEEE Power Engineering Society General Meeting*, vol. 2, pp. 1423-1425, June 2004.

[8] E. Leung, B. Burley, N. Chitwood, H. Gurol, G. Miyata, D. Morris, L. Ngyuen, N. O'Hea, D. Paganini, S. Pidcoe, P. Haldar, M. Gardner, D. Peterson, H. Beonig, J. Cooley, Y. Coulter, W. Hults, C. Mielke, E. Roth, J. Smith, S. Ahmed, A. Rodriguez, A. Langhorn, M. Gruszczynski, and J. Hoehn, "Design and development of a 15 kV, 20 kA HTS fault current limiter," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 832-835, March 2000.

[9] W. V. Hassenzahl, D. W. Hazelton, B. K. Johnson, P. Komarek, M. Noe, and C. T. Reis, "Electric power applications of superconductivity," in *Proc. IEEE*, vol. 92, no. 10, pp. 1655-1674, Oct. 2004.

[10] J.-Y. Kim, H.-K. Choi, and J.-Y. Yoon, "A study on the application impacts on Korean Power System by introducing SFCL," *KIEE Intern. Trans. Power Engineering*, vol. 3-A, no. 1, pp. 1-6, 2003.

[11] J.-Y. Kim, S.-R. Lee, and J.-Y. Yoon, "Evaluation of the application scheme of SFCL in power systems," *KIEE Intern. Trans. Power Engineering*, vol. 4-A, no. 4, pp. 221-226, Dec. 2004.

[12] S.-R. Lee, J.-Y. Kim, H.-K. Choi, and J.-Y. Yoon, "Feasibility study on the application of 154kV SFCL in Korean Power System," KIEE Trans., vol. 53, no. 12, pp. 661-669, 2004.

[13] Korea Electrotechnology Research Institute, *Modeling and protection of superconducting devices*, Ministry of Education, Science and Technology, July 2004.

[14] J.-Y. Yoon, J.-Y. Kim, and S.-R. Lee, "Resistive SFCL EMTDC modeling by using probabilistic design methodology," *KIEE Intern. Trans. Power Engineering*, vol. 4-A, no. 2, pp. 69-72, 2004.