Fault Current Limitation Coordination of Multiple SFCLs in IEEE 14-Bus Test System

N Hayakawa¹, Y Mori¹ and H Kojima¹

¹Department of Electrical Engineering, Nagoya University, Nagoya 464-8603, Japan
E-mail: nhayakaw@nuee.nagoya-u.ac.jp

Abstract. We have proposed the concept of “fault current limitation coordination” of multiple superconducting fault current limiters (SFCL) to be introduced in a future electric power grid. Using a simplified test system, the transients on fault current and internal phase angle of generators were analyzed by PSCAD/EMTDC and the modeling of resistive SFCL with a variable resistance as a function of both current and temperature at the recovery under load. In this paper, we extended the analyses to the fault current limitation coordination of multiple SFCLs in IEEE 14-bus test system. The effective coordination strategy on the introduction and operation of multiple SFCLs, e.g. introduction lines of SFCLs, operation parameters such as operating current, critical current and prospective fault current of each SFCL, was discussed and optimized for an arbitrary fault location in the test system.

1. Introduction
The fault current is increasing due to the complexity of the power system with the increase in distributed power supply. In the power system, when the fault current exceeds the capacities of installed circuit breakers and protective devices, replacement of the circuit breakers and protective devices is required. However, in practice, replacing the device is very costly. Therefore, it is considered as the effective alternatives to reduce the fault current level by introducing superconducting fault current limiter (SFCL). SFCL has been investigated and developed in the world [1] and extended to extra-high-voltage level [2] and DC network [3]. Furthermore, the SFCL studies have been carried out on the apparatus issues such as recovery characteristics [4][5] and electrical insulation performance [6][7] as well as the system issues such as optimal allocation [8][9] and voltage stability [10][11].

SFCL is usually operated with low loss in the steady state. On the other hand, SFCL generates high impedance and suppresses fault current at the time of fault occurrence. In addition, introducing SFCL has the effect of improving transient stability. When introducing SFCL into power systems, it is necessary to consider both fault current limitation and transient stability.

From the above background, we have proposed “fault current limitation coordination” between the SFCL and the power system behind the SFCL [12]. Figure 1 shows the conceptual diagram of fault current limitation coordination. Fault current limitation coordination means the mutual relationship between prospective fault current (I_pro) of a transmission line in a grid, quench current (I_quench) of protected equipment such as HTS cables, limited current (I_lim) after fault and limitation, critical current (I_c) of SFCL, and operating current (I_op) before fault. The correlation of these currents affects the optimal design of SFCL and the reliability of the power system.
In addition, the effect of SFCL depends on the location and the number of SFCLs in the power system. When we introduce multiple SFCLs, it is essential to consider where and how many SFCLs are installed. In this paper, we examined fault current limitation coordination of multiple SFCLs in the IEEE14-bus test system.

2. Models and simulation methods

2.1. Model of SFCL

In the simulation, we used the model of resistive SFCL. SFCL was modeled by the simplest form of a variable resistance as a function of both current $I$ and temperature $T$. Figure 2 shows the $E$-$I$-$T$ characteristics of a HTS tape in Table 1 as our experimental database [13], where $E$ is the electric field strength along the HTS tape length. Each SFCL is designed to have the length depending on the operating current of the transmission line at the introduction point. The details on the SFCL modeling can be referred to our previous paper [12].

| Table 1. Specifications of HTS tape |
|------------------------------------|
| HTS layer                          | YBCO (2μm) |
| Stabilizer                         | Ag (2μm)   |
| Buffer layer                       | Alumina/YSZ/IBAD MgO/MgO/LMO |
| Substrate                          | Hastelloy (100μm) |
| Total thickness                    | 0.1mm      |
| Width                              | 12mm       |
| $I_c@77K$                          | 220A (0.3μV/cm) |
| $n$ value@$I_c$                    | 36.5       |

Figure 1. Conceptual diagram of fault current limitation coordination [12].

Figure 2. $E$-$I$-$T$ characteristics of HTS tape (experimental database) [13].
2.2. Model of power system
Figure 3 shows the model of power system in this paper. The model system simulates an electric power grid of 220/132 kV transmission system with 5 generators, 14 buses, 3 transformers, 20 lines and the total load of 259 MW [14]. SFCLs are illustrated by the red boxes. Three-phase ground fault is assumed to occur for 5 cycles (60Hz) at each of 9 buses (bus4, bus5, bus7, bus9, bus10, bus11, bus12, bus13, bus14) without generator, because SFCLs are expected to be introduced in transmission lines in this study. We calculated the fault current limitation by SFCLs and the internal phase angle oscillation of generators as the transient stability by PSCAD/EMTDC.

2.3. Simulation methods
The ratio of $I_c$ to $I_{op}$ was set at $I_c / I_{op} = 2$ [p.u.] as the operating parameters of SFCL. The lower the $I_c$ is, the earlier the current limitation starts, then a large resistance occurs. In other words, the lower the $I_c$ is, the better the current limitation effect is. However, due to the risk of malfunction of SFCL during normal operation, $I_c$ cannot be lowered too much. The above ratio can be regarded as the maximum of current limitation effect with the margin to prevent malfunction.

In the introduction of SFCL, it is effective to arrange SFCLs in the vicinity of the fault point. However, in practice, various fault points must be assumed. Figure 4 shows a flowchart of SFCL introduction, where the SFCLs are principally arranged in the transmission lines with large expected values of $I_{pro} / I_{op}$, comprehensively taking the transient stability improvement in consideration. The introduction goal is to minimize the number of SFCLs with keeping both the effective fault current limitation and transient stability of the power system. 8 SFCLs in Figure 3 are obtained based on the flowchart in Figure 4 as the result of simulation and discussion in the next section.

Figure 3. IEEE-14 bus test system [14].
3. Simulation results and discussion

As an example, Figure 5 shows the current waveform of line 6-11 for the fault point at bus14 in Figure 3. The fault current is limited from $I_{pro}/I_{op} = 9.2$ without 8 SFCLs to $I_{pro}/I_{op} = 3.2$ with 8 SFCLs. Figure 6 shows the internal phase angle waveform of G5. The internal phase angle oscillation is reduced from $\Delta \delta = 6.0$ deg without 8 SFCLs to $\Delta \delta = 3.1$ deg with 8 SFCLs, where $\Delta \delta$ is the difference in internal phase angle before and after the fault.

![Figure 4. Flowchart of SFCL introduction.](image1)

![Figure 5. Current waveform of line 6-11.](image2)

![Figure 6. Internal phase angle waveform of G5.](image3)
Figure 7 shows the expected value of fault current $I_{pro}/I_{op}$ [p.u.] in 20 lines with and without 8 SFCLs in Figure 3. We calculated $I_{pro}$ (total $20 \times 9 = 180$ patterns) for each line and each fault point and converted it to the ratio $I_{pro}/I_{op}$ as the impact of fault in each line. The expected values of $I_{pro}/I_{op}$ in most lines were effectively reduced by 8 SFCLs in Figure 3. However, $I_{pro}/I_{op}$ in line 6-13 with 8 SFCLs was larger than that without 8 SFCLs. SFCL has not been introduced in line 6-13, because line 6-13 was located in a big loop (6-12-13-14-9-10-11-6) and had a low $I_{pro}/I_{op}$ owing to a large $I_{op}$. When 8 SFCLs are introduced in Figure 3, the fault current made a detour to line 6-13.

Figure 8 shows the expected value of internal phase angle oscillation $\Delta\delta$ of 5 generators with and without 8 SFCLs in Figure 3. The expected values of $\Delta\delta$ in all generators were effectively reduced by 8 SFCLs in Figure 3. We have confirmed that the expected values of $I_{pro}/I_{op}$ and $\Delta\delta$ with 8 SFCLs in Figure 3 are equivalent to those with SFCLs in all 20 lines. The smaller number of SFCLs in Figure 3 resulted in the less effective SFCL introduction mainly in $\Delta\delta$, i.e. transient stability. Thus, in order to optimize the SFCL introduction pattern, both the fault current limitation and transient stability should be coordinated.
4. Conclusion
This paper described the fault current limitation coordination of multiple SFCLs in IEEE14-bus test system. Simulation results suggested the SFCL introduction strategy based on the expected values for fault current limitation and transient stability. It should be noted that the optimal SFCL introduction pattern depends on the size and configuration of the power system, but it would be obtained in terms of fault current limitation coordination.

Acknowledgment
This work was supported in part by JSPS KAKENHI Grant Number JP17H03215.

References
[1] Noe M, Hayakawa N, et al. 2015 CIGRE WG D1.38 Technical Brochure 644
[2] Moyzykh M, Sotnikov D, Gorbunova D, Myshlakov S and Samoilenkov S 2017 European Conference on Applied Superconductivity (EUCAS) 1LO1-02
[3] Escamez G, Vialle A, Bruzek C, Grosse V, Bauer M and Tixador P 2018 IEEE Transactions on Applied Superconductivity 28 2805998
[4] Tamashima M, Takaya S, Shirai Y, Shiotsu M, Honda G and Isojima S 2017 IEEE Trans. on Appl. Supercond. 27 5601805
[5] Yuki K, Ito S, Hashizume H, 2020 10th ACASC / 2nd Asian-ICMC / CSSJ Joint Conference 8P-60
[6] Chassagnoux R, Lesaint O, Bonifaci N, Gallot-Lavallée O, Flury S, Palenzuela J L, Legendre P, Escamez G, Creusot C and Girodet A 2018 Applied Superconductivity Conference (ASC) 2MPo1D-04
[7] Hayakawa N, Mimbu M, Kojima H, Isojima S, Kuwata M 2019 IEEE Trans. on Appl. Supercond. 29 5603106
[8] Kong S, Jo H, Wi Y and Joo S K 2016 IEEE Trans. on Appl. Supercond. 26 2547882
[9] Alaraifi S, Moursi M S and Zeineldin H H 2013 IEEE Trans. on Power Systems 28 pp 4701-4711
[10] Morandi A 2013 IEEE Trans. on Appl. Supercond. 23 5604608
[11] Yehia D M and Mansour D A 2018 IEEE Trans. on Appl. Supercond. 28 5603006
[12] Hayakawa N, Maeno Y and Kojima H 2018 IEEE Trans. on Appl. Supercond. 28 5602304
[13] Kojima H, Osawa T and Hayakawa N 2015 IEEE Trans. on Appl. Supercond. 25 5401904
[14] Demetriou P, Asprou M, Tortos J Q and Kyriakides E 2017 IEEE System Journal 11 pp 2108-2117