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Simulation for current limiting characteristics of the resistive and inductive SFCL with line-to-ground fault

Hyo-sang CHOI, Si-dole HWANG, Sang-joon KIM, Byoung-sung HAN*

Korea Electric Power Research Institute, Daejeon, Korea

** Chonbuk National University, Chonju, Korea*

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Abstract

We investigated the current limiting characteristics of resistive and inductive SFCLs with 100 Ω of impedance for line-to-ground faults in the 154 kV transmission system. The fault simulation at the phase angles 0°, 45°, and 90° showed that the resistive SFCL limits the fault current less than 17 kA without any DC component after one half cycle from the instant of the fault. On the other hand, the inductive SFCL suppresses the current below 14 kA, but with 5 kA of DC component which decreases to zero in 5 cycles. We concluded that the inductive SFCL has higher performance in current limiting effect, but the resistive SFCL was better from the viewpoint of less DC components.

Keywords: Superconducting Fault Current Limiter(SFCL), EMTDC Simulation, Line-to-Ground Fault

I. Introduction

Recently, the increase in power demand causes the rising of fault currents so that they have approached or exceeded the capability of circuit breaker(CB) when the faults occurred in the power grid.[1] So as to solve this problem, we can draw up a plan of either replacing the CB with a new one having a high capability or lowering fault currents until those can be less than the capability of the existing CB. Increasing the capacity of CB has limitations because of the constituents and technical restrictions of CB. So one of the ways of limiting fault currents can be superconducting fault current limiter(SFCL).

We can classify present world-wide researches on SFCL into two kinds. One is resistive SFCL using YBCO thin film, thick film, or bulk, and the other is inductive SFCL, which includes shielded type assuming the form of applied transformer and its hybrid form.[2-5] The resistive SFCL has some merits such as the simple structure and principle and the excellent current limitation and recovery characteristics. On the other hand, it also has some demerits such as a difficulty in enlarging a capacity, generation of much Joule heat, and so on. The research on the resistive SFCL is being researched by Siemens AG group of Germany, and its application to distribution line is being considered.[2] The inductive type is mainly studied on shielded type. While this type is easy to enlarge a capacity and generates relatively little amount of heat, it has fairly large volume because of its structure having core, and also include loss of hysteresis and eddy current loss. The inductive type is being studied to be applied to transmission line by Swiss ABB group.[3]

In this research, therefore, by simulating characteristics of resistive and inductive SFCLs with 154 kV line for line-to-ground fault under the situation in which an available SFCL is not developed yet, we intend to analyze the merits and demerits of each typical SFCL and to use them as data on research and development.

We used transient response analysis program, an

Fax: +82 42 865 5977
e-mail: hschoi@kepri.re.kr

EMTDC(Electromagnetic Transient Direct Current) which is used worldwide as the method of this simulation, and selected parameters with reference to real data in Seoul area. After the investigation of fault current waveform on each phase, we make comparative analyses about fault currents with resistive and inductive SFCLs and about those of transient or steady state.

II. Power system and modeling

The constitution of model system for faults is determined according to reference to real data between arbitrary S1 and S2 substations near Seoul. For a general line-to-ground fault, under the same condition (setting up 100 Ω as the maximum impedance of SFCL), we simulated the faults at the fault angles 0°, 45°, and 90° for the cases that resistive and inductive SFCLs are established, provided that the maximum impedance of SFCL is set up 100 Ω in both resistive and inductive SFCLs, and the time interval of the maximum impedance is set up at 3 msec. This maximum impedance of 100 Ω was determined through many times of simulations in order to meet the value less than the capability of CB. The direction of power flow is from S1 substation to S2. We showed model system for a line-to-ground fault in the fig. 1.

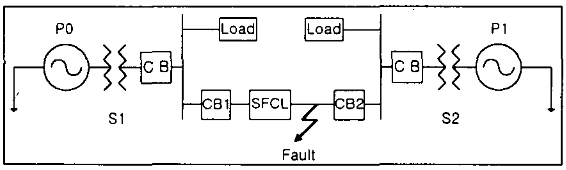

Fig. 1. Model system for a line-to-ground fault

For modeling faults in EMTDC program, necessary constituents are source impedance, line constants, and load. We showed their values and analytical methods in the references in detail.[6]

III. Results and study

We carried out an EMTDC simulation for one circuit system, and we select line constants based on the criterion of ACSR 410 mm^2 which is largely used at 154 kV transmission line. We simulated transient response at fault angle 0° on the C phase between S1 to S2 substations, and got fault current waveform about each phase in the line-to-ground fault. We also showed an incoming current from S2 to S1 substations at fault angle 0°.

In the fig. 2, we showed the fault current waveform that is generated when a single line-to-ground fault (fault angle 0°) occurred at the latter part of CB1 (fig.1) which is about 5.98 km away from S1 substation. If the fault occurs, fault currents on C phase increase up to the maximum of 39 kA, and then stabilize at 23 kA after 5 cycles. Considering that the currents flowing on line at steady state is about 0.45 kA, we can see that, immediately after the fault, the fault currents increased up to the maximum of 87 times as high as currents of steady state and then stabilized at the point of about 53 times. So various protection machines including transformer established on grid can not avoid being damaged to a certain degree during the minimum rated current braking time of a CB (for 3 cycles or so). On the other hand, we can see that, early DC component is generated because of reactance component caused by unbalanced line, and then disappeared after about 5 cycles. For the same fault, the current waveform incoming from the opposite to the direction of power flow from S1 substation to the fault spot, that is, the current waveform at CB2 is showed in the fig. 3. On C phase that the fault occurred, the current waveform increased to the maximum 4.1 kA and then stabilized at 3.2 kA after 5 cycles. We excluded these values from analysis subjects because they didn't particularly influence on capability of CB. And we also simulated the waveform of a single line-to-ground fault at the fault angles 45° and 90°, but fault currents were very little compared to the case of fault angle 0°. So we didn't show those waveforms in the figure.

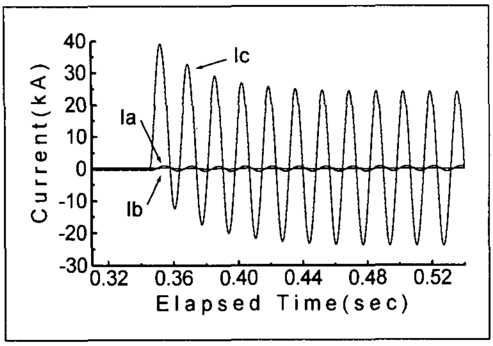

Fig. 2. Fault current waveforms for fault angle 0° at the CB1 (without SFCL)

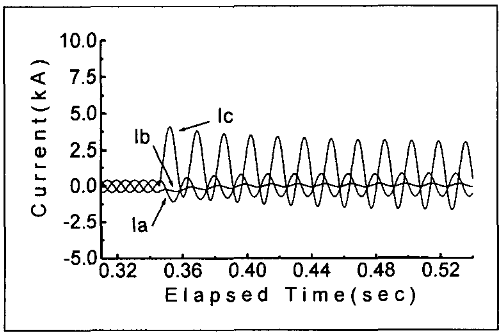

Fig. 3. Incoming current waveforms for fault angle 0° at the CB2 (without SFCL)

3.1 A single line-to-ground fault

In case of applying resistive and inductive SFCLs between CBs when a single line-to-ground fault occurred in power grids we simulated to examine the fault current limit and transient properties at the fault angles 0°, 45°, and 90°.

The fig. 4 shows the result of the simulation after applying the resistive SFCL for a single line-to-ground fault at fault angle 0°. At the fig. 4, the current on C phase where the fault occurred increased up to the maximum of 39 kA(maximum of limiting current) right after the instant of the fault, and then stabilized at 15 kA(stabilized limiting current) within one half cycle. Especially because of the properties of the resistive SFCL, we can hardly see DC components after one half cycle. In other words, DC component caused by unbalanced line at the instant of the fault almost disappeared due to resistance of SFCL when the resistive SFCL is applied.

The fig. 5 shows the waveforms of the case with the inductive SFCL under the same condition as the fig. 4 has. Like the resistive SFCL, fault currents increased to the maximum of 39 kA immediately after the occurrence of the fault, and then decreased to 15 kA within one half cycle, but we can see that fault currents additionally decreased to 12 kA after 5 cycles. The reason of this appearance is thought that most of line impedance and SFCL impedance are such inductance components that DC component is generated at the beginning and lasted for a certain period of time. In the fig. 4 and 5, comparing the resistive type to the inductive type under the same condition, we can see that the inductive SFCL has a higher performance in current limiting effect, but the resistive SFCL is more favorable from the view point of less DC component. In fig. 4 and 5, the reason why the current increased up to 39 kA is that the quench resistance of SFCL was not generated sufficiently within one half cycle yet.

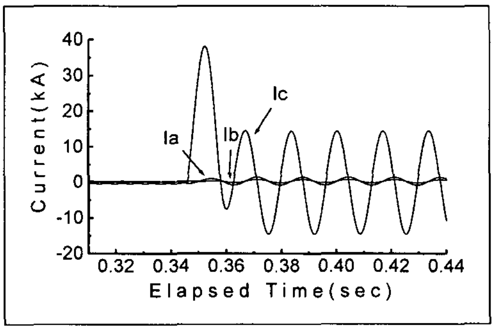

Fig. 4. A single line-to-ground fault with resistive SFCL at fault angle 0°

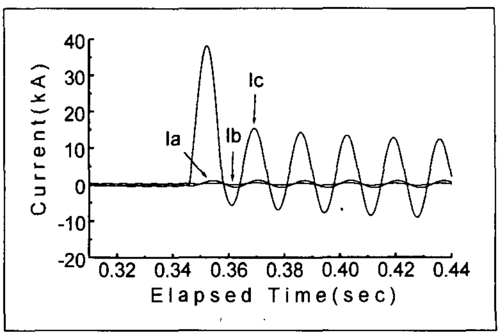

Fig. 5. A single line-to-ground fault with inductive SFCL at fault angle 0°

The fig. 6 shows the fault current limiting effect of a resistive SFCL for a single line-to-ground fault at fault angle 45°. Immediately after the fault occurrence, we can see that the fault current increased to about 27 kA, and then decreased to about 15 kA within one half cycle. On A phase that is not faulted, it hardly changed between before and after the fault.

We showed transient response of the case with an inductive SFCL applied at fault angle 45° in the fig. 7. Like the case of fault angle 0°, the current limiting characteristic increased to the maximum of 27 kA, lessen to 13 kA after one half cycle, and then settled at 12 kA after 5 cycles. DC component at fault angle 45° is comparatively smaller than that of fault angle 0°. That's because in the waveform of the fault instant, an SFCL suppresses the current at the both points of increasing and decreasing of the current so that the increase of fault current after one half cycle is relatively small.

In the fig. 8, we indicated the waveforms which are generated when the resistive SFCL is equipped in front of the fault spot for a single line-to-ground fault at fault angle 90°. Immediately after the instant of the fault, fault currents showed about 11.5 kA, 15 kA within one half cycle, and a stable waveform later on. DC component which is caused by unbalanced line is scarcely showed. The reason why transient currents become small immediately after the fault is considered that the fault occurred at the moment when the current waveforms decreased.

Meanwhile, the fig. 9 shows the waveforms of the case with the inductive SFCL under the same condition as the fig. 8 has. Immediately after the fault, fault current showed about 11.5 kA, and then after one half cycle decreased from 15 kA to 12 kA for the period of about 5 cycles. So to speak, about 3 kA of DC component is generated by inductance of the inductive SFCL. This result is similar to the case of fault angle 0°.

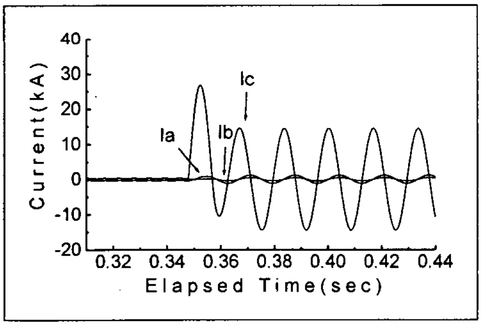

Fig. 6. A single line-to-ground fault with a resistive SFCL at fault angle 45°

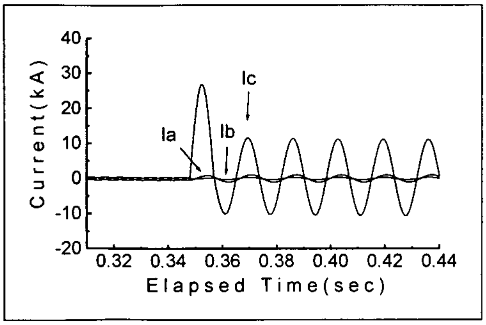

Fig. 7. A single line-to-ground fault with a inductive SFCL at fault angle 45°

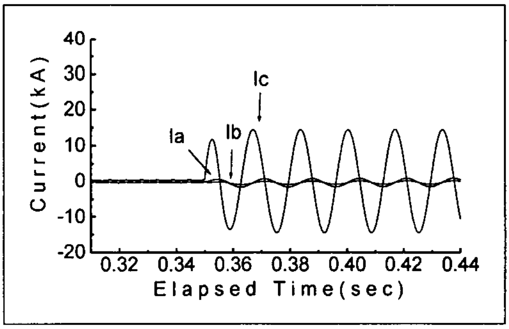

Fig. 8. A single line-to-ground fault with a resistive SFCL at fault angle 90°

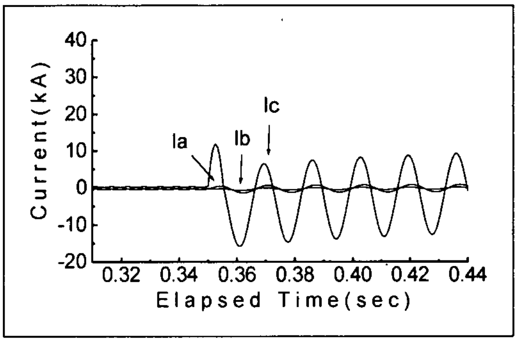

Fig. 9. A single line-to-ground fault with a inductive SFCL at fault angle 90°

3.2 A Double-line-to ground fault

We indicate the waveforms in the fig. 10 which is generated when double line-to-ground fault occurred at the same place where a single line-to-ground fault occurred, and at that time the fault angle was 0°. If the fault occurs, fault currents on B and C phases increase up to maximum 56, 53 kA, and then stabilize at 34 kA after about 5 cycles. Considering the fact that current before the fault occurs is about 0.45 kA, we can see that fault currents increase up to the maximum of 124 times as high as that of normal state and then stabilize at the point of 76 times as high. And like the case of a single line-to-ground fault, in double line-to-ground fault, we can also see that initial DC component is generated on B and C phases due to reactance component, but it disappeared after about 5 cycles. In the fig. 11, we show the waveforms of incoming current flowing in from the opposite side of power flow to the fault spot. After the instant of the fault, the maximum value of 6.7 kA and, after 6 cycles the value of 4.0 kA are showed on B and C phases, but they also can not influence particularly on breaking capability of CB. Waveforms at fault angle 45° and 90° are similar to those of a single line-to-ground fault case.

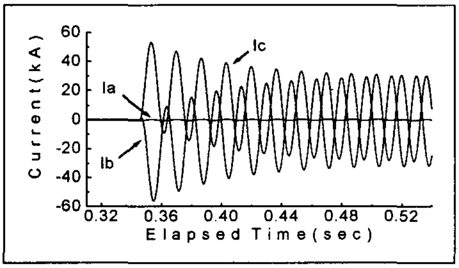

Fig. 10. fault current waveforms for fault angle 0°

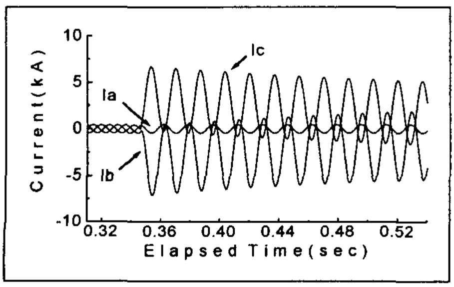

Fig. 11. Incoming current waveforms for fault angle 0°

When double line-to-ground fault occurred in power system, in case of applying the resistive and inductive SFCLs in front of CB, we simulated fault current limitation and transient properties at the fault angles 0°, 45°, and 90° respectively.

Fig. 12 shows the result of simulation for double line-to-ground fault with the resistive SFCL applied at fault angle 0° on the C phase. Investigating of C phase where the fault occurs, we can see that fault currents increased up to the maximum of 44 kA(maximum of limiting current) immediately after the fault, and then settled at 15 kA(stabilized limiting current) within one half cycle. Especially DC component is hardly showed after one half cycle due to resistance that the resistive SFCL has after quench.

Fig. 13 shows the waveforms of the case with the inductive SFCL installed under the same condition of fig. 12. Similar to the case with the resistive SFCL, the fault current on C phase increases up to 44 kA, and decreases to about 18 kA within one half cycle, but showed an additional decrease to about 14 kA during the period of about 5 cycles. The reason of this appearance is considered that most of impedances which are generated on line of power system and on the inductive SFCL after quench are such inductance components that DC component is generated initially and lasts for a certain period of time. At fig. 12 and fig. 13, when we compare the resistive SFCL to inductive SFCL under the same condition, we can see that the inductive SFCL is more advantageous in current limiting effect, while the resistive SFCL is better from the viewpoint of less DC components.

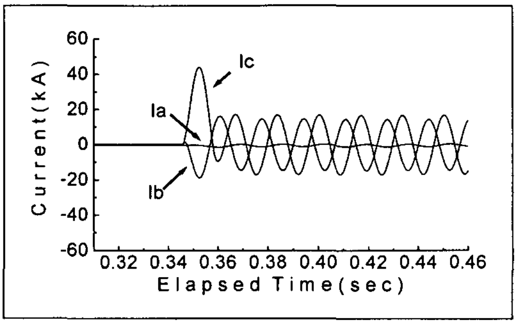

Fig. 12. Double line-to-ground fault with resistive SFCL at fault angle 0°

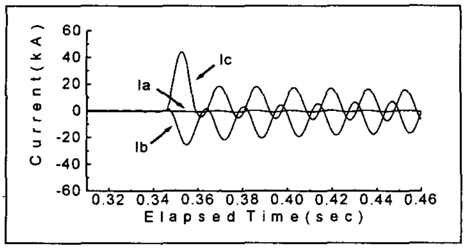

Fig. 13. Double line-to-ground fault with inductive SFCL at fault angle 0°

When the resistive SFCL is applied in the power system for double line-to-ground fault at fault angle 45°, its fault current limiting effect is showed in fig. 14. We can see that fault current on B phase increases up to about 51 kA immediately after the fault and then decreases to about 17 kA within one half cycle. Also, DC component is hardly generated after one half cycle. That is, DC component that is caused by unbalanced line and reactance almost disappears due to resistance of SFCL when the resistive SFCL is applied. In the case of A phase, there is less change between before and after the fault.

The fig. 15 shows transient response that occurred when the inductive SFCL is applied in the same condition. On B phase current limiting characteristic increases to the maximum of 51 kA and passes through the value of 19 kA after one half cycle, and then settles at 14 kA after about 5 cycles. This result is similar to the case of fault angle 0°. Compared with the case of fault angle 0°, initial transient current increases a little bit higher, but it shows almost similar aspects from the view point of DC component. The reason why initial transient current is a little bit higher than the case of fault angle 0° is considered that the fault occurred at the moment the current increases.

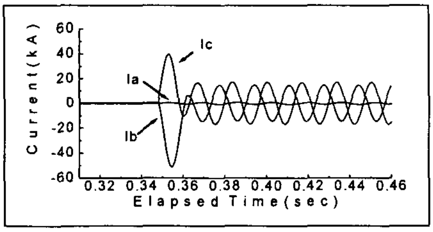

Fig. 14. Double line-to-ground fault with resistive SFCL at fault angle 45°

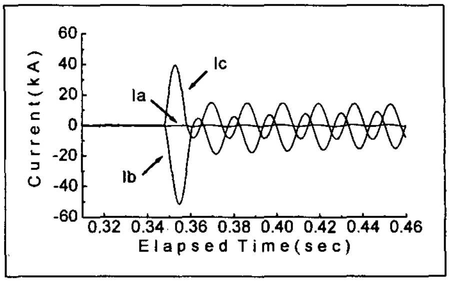

Fig. 15. Double line-to-ground fault with inductive SFCL at fault angle 45°

In the case of double line-to-ground fault at fault angle 90°, the waveforms of the time when the resistive SFCL is established in front of the fault spot are shown in fig. 16. On B phase, fault current shows the value of 37 kA immediately after the fault, then decreases to 17 kA within one half cycle, and shows a stable waveform later on. DC components are scarcely showed, and the reason why the fault current immediately after the instant of the fault is small is thought that the fault occurred at the moment when current waveform decreased.

In the meantime, the fig. 17 shows the waveforms of the time when the inductive SFCL is applied under the same condition as the fig. 16 was. Immediately after the fault, we can see about fault current of 37 kA, then 15 kA after one half cycle, and then it decreased to 12 kA for the period of about 5 cycles. In other words, about 3 kA of DC component is generated because of unbalanced line and inductance of the inductive SFCL. This is the similar result to the case of fault angle 0°.

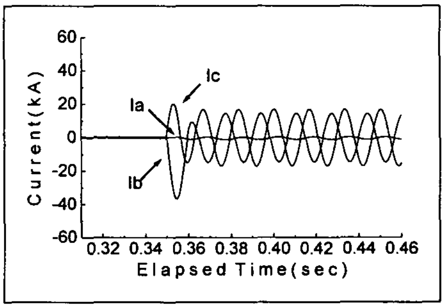

Fig. 16. Double line-to-ground fault with resistive SFCL at fault angle 90°

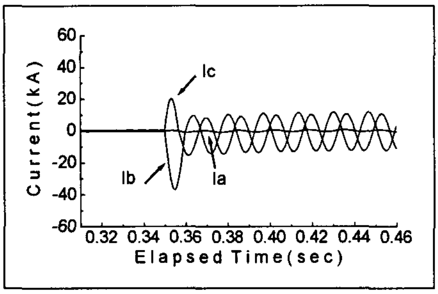

Fig. 17. Double line-to-ground fault with inductive SFCL at fault angle 90°

IV. Summary

For the line-to-ground fault which frequently occurred of all faults in power system, referring to the real data between arbitrary S1 and S2 substations, we simulated the fault current by using EMTDC program, and investigated the current limiting effect by each fault angle to which resistive and inductive SFCLs applied.

When the fault occurred at the point of 60 % of the distance from S1 to S2 substation s, in a single line-to-ground fault, the fault current of S1 side is about 39 kA at fault angle 0°, which is about 87 times as high as a steady current. In addition, fault current after 5 cycles is about 23 kA, which is 53 times as high as that of steady state. When resistive and inductive SFCLs are applied in front of CB, we investigated the current limiting effect by each fault angle. At fault angle 0°, the case of applying resistive SFCL showed maximum of limiting current of 39 kA immediately after the fault occurred and stabilized final limiting current of 15 kA. And DC component hardly occurred at transient state. The case of inductive SFCL showed 39 kA immediately after the fault occurred as maximum of limiting current, and final 12 kA as stabilized limiting current. At this time DC component is 3 kA. In the cases of fault angle 45° and 90° with the resistive SFCL, the currents of 27 kA and 11.5 kA are showed immediately after the fault occurred respectively, these values settled at 15 kA steadily within one half cycle and DC component is scarcely generated at this time. In the same cases with the inductive SFCL applied, the currents of 27 kA and 11.5 kA are showed immediately after the fault occurred respectively, they are settled at maximum of limiting current of 12 kA and DC component is 1 kA and 3 kA at respective cases.

When a double line-to-ground fault occurred, the fault current is the maximum of 56 kA at the fault angle 0°, which is about 124 times as high as the steady current. Even the value after 5 cycles shows 34 kA which is 76 times as high as that of steady state. When resistive and inductive SFCLs were established on power grid, we investigated the current limiting effect at each fault angle. The case of applying the resistive SFCL showed 44 kA as maximum of limiting current immediately after the fault occurred and 15 kA as stabilized limiting current at fault angle 0°. At this time DC component in the transient state hardly occurred. The case of applying the inductive SFCL showed the maximum value of 44 kA immediately after the fault occurred and stabilized limiting current of 14 kA. At this time DC component is about 4 kA. In the cases of fault angles 45° and 90°, the resistive SFCL showed the currents of 51 kA and 37 kA immediately after the fault occurred in respective cases. These values are stabilized at 17 kA and then maintain the stable state. DC component is hardly showed then. The inductive SFCL showed the values 51 kA and 37 kA immediately after the fault occurred in each case. They settled at maximum of limiting current of 14 kA and 12 kA, and DC component is 5 kA and 3 kA in respective cases.

Synthesizing a single and a double line-to-ground faults, we can see that a double line-to-ground fault only has larger magnitude of fault current and DC component of the inductive SFCL than a single line-to-ground fault regarding the application of SFCL. Under the same condition (setting up 100 Ω as the last impedance for SFCL), the inductive SFCL was advantageous in current limiting effect, and the resistive SFCL was better from the view point of DC component generation initially. Even though the impedance is same, the reason why the inductive SFCL is favorable in current limiting effect is considered that the difference of phase angle is relatively smaller than the resistive SFCL in the process that the impedances of power grid and SFCL are summed up.

Like the above, we investigated current limiting properties and the transient state of inductive and resistive SFCLs through EMTDC analysis about line-to-ground faults in the 154 kV transmission system. We will carry out the simulation for current limiting properties according to quench time in future.

Acknowledgments

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References

[1] Joon-Hwan KIM, Kang-wan LEE, "Fault current increasing and solving methods in the power system", Electrical Journal, Vol. 5, pp. 24-31, 1998.

[2] Nell E. Reimann, *et al.*, "Simulation of the Transient Response of a High-Tc Superconduc-ting Current Limiter Inserted in an Electrical Distribution System", IEEE Trans. on App. Supercon., Vol. 7, No. 2, pp. 836-839, June 1997.

[3] L. S. Fleischman and Y. A. Bashkirov, "Design Considerations for An Inductive High Tc Superconducting Fault Current Limiter", IEEE Trans. on Applied Superconductivity, Vol. 3, pp. 570-573, 1993.

[4] W. Paul, *et al.*, "Fault Current Limiters Based on High Temperature Superconductors", Inst. Phys. Conf. Ser. No. 148, pp. 73-78, July 1995.

[5] J. R. Cave, *et al.*, "Test Results for Laboratory Scale Inductive High Tc Superconducting Fault Current Limiters", IEEE Trans. on Mag., Vol. 30, No. 4, pp. 1895-1898, July 1994.

[6] Hyo-sang CHOI, Si-dole HWANG, Ok- bae HYUN, "Simulation of a resistive supercon-ducting fault current limiter for line faults in the power grid", KIASC, Vol 1, No. 1, pp. 28-32, 1999.