A Study on the Application of a Superconducting Fault Current Limiter for Energy Storage Protection in a Power Distribution System

Won-Sik Moon, Jong-Nam Won, Jae-Sun Huh, and Jae-Chul Kim

***Abstract*—This paper presents the application of a superconducting fault current limiter to energy storage for protection in a power distribution system. An energy storage system is increasingly being used to help renewable energy resources integrate into the grid. It is important to keep an energy storage system interconnected with the grid without interruption and to supply electrical power to the grid. The main objective of this paper is to introduce a superconducting fault current limiter to keep the energy storage system from disconnecting from the grid when ground faults occur. Its effect is analyzed using transient simulation software.**

***Index Terms*—Energy storage, fault current, interconnecting transformer, superconducting fault current limiter.**

I. Introduction

In recent years, more energy storage systems (ESSs) have been interconnected with the power grid in the form of distributed generation units (DGs) owing to growing interest in the environment and energy depletion. An ESS enables energy to be stored when there is an excess of supply and supplies excess energy to loads to compensate for a deficit in supply [1]. ESSs are increasing their impact on the power grid as a solution to stability problems. The one of the main advantages of energy storage is to contribute to the quality of the grid by maintaining the power constant [2]–[4].

Energy storage technologies are essential for modern power systems. Although an ESS does not generate energy, its function appears to be vital for the operation and planning of an electrical power system, particularly for the stability, reliability, and power quality of the power output. In addition, the system defers the costs and upgrades of developing the transmission and distribution capacity for satisfying the growing power demand for peak-shaving purposes. The ESS is installed to enhance the dispatching ability of renewable energy sources and to provide ancillary services such as reactive power support for operations [5]–[7].

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Although an energy storage system adds a number of benefits for power systems, it has a drawback which is concerned with the protection for a single line-to-ground fault current, similar to a DG [8]. There are various types of transformer connections that interface a generator to an existing power system and provide essential isolation [9]. In particular, a grid-side grounded wye-delta winding connection is prevalent for use in interconnecting all central station generation to the utility systems [8]. The energy storage is interfaced with the power system in this connection. The ground fault current trips a ground overcurrent relay on a four wire, multi-grounded neutral distribution systems. In addition, it can disrupt the coordinated power system protection and subsequently disconnect the energy storage from the grid. The presence of energy storage on the distribution feeder introduces new sources of ground fault currents that can change the direction of the fault current and protective relay coordination. The application of super-conducting fault current limiters (SFCLs) to an ESSs for a stable operation of the distribution system has been recognized as one of the promising solutions for fault current problems, because of its fast fault current limiting and automatic characteristics of recovery [10]–[16].

The effect of an SFCL applied to an interconnecting transformer for an ESS is analyzed. A resistive SFCL and distribution system with energy storage has been modeled using the transient simulation software package PSCAD/EMTDC and is described in Section II. Section III describes the effects of fault current limiting not disrupting the protective relay coordination between the distribution system and ESS according to our case studies. Finally, the conclusions are presented in Section IV.

II. Modeling of an SFCL and Distribution Power System With an Energy Storage System

A. Resistive SFCL Model

An SFCL is one of the most promising current limiters to prevent the short-circuit current from increasing in magnitude owing to its rapid current limiting ability. Many models for an SFCL have been developed, such as resistive type, reactive type, transformer type, and hybrid type SFCLs [10], [13]. Among the various types of SFCLs, the resistive type SFCL is preferred because of its simple principle and compact structure of small size [11]–[13]. In this paper, we have modeled a resistive type SFCL using mathematical expressive equations,

TABLE I
SFCL MODELING PARAMETERS

SFCL	$R_n[\Omega]$	T_F	a_1	a_2	b_1	b_2
Value	8	0.01	-20	-50	5	3

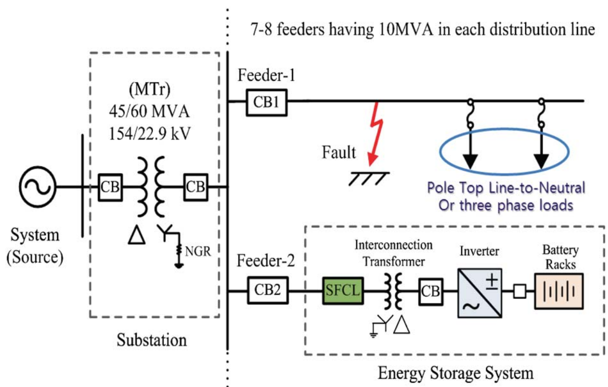

Fig. 1. Power distribution system with an energy storage system.

which were verified by experiments and implemented using PSCAD/EMTDC modeling software [13]–[16].

The time evolution of the SFCL impedance R_{SFCL} as a function of time t is given by (1)–(3):

$$R_{SFCL}(t)=R_n\left[1-exp\left(-\frac{(t-t_0)}{T_F}\right)\right]^{\frac{1}{2}} \quad t_0\leq t<t_1, \quad (1)$$

$$R_{SFCL}(t)=a_1(t-t_1)+b_1 \quad t_1\leq t<t_2, \quad (2)$$

$$\text{and } R_{SFCL}(t)=a_2(t-t_2)+b_2 \quad t\geq t_2 \quad (3)$$

where R_n and T_F are the convergence resistance and time constant, respectively. t_0, t_1, and t_2 denote the quench-starting time, first starting time of recovery, and second starting time of recovery, respectively. In addition, a_1, a_2, b_1, and b_2 are the coefficients of the first-order linear function denoting the experimental results for the recovery characteristics of an SFCL. The parameter values are listed in Table I.

B. Configuration of the Distribution System With an ESS

A grid-scale ESS consists of a battery bank, control system, power electronics interface for ac-dc power conversion, protective circuitry, and a transformer to convert the ESS output to the transmission or distribution system voltage level [17]. Fig. 1 shows a four-wire multi-grounded power distribution system with an ESS for simulation to analyze the effect of the SFCL application. The nominal voltage of this secondary system is 22.9 kV. There is a substation, 6–9 feeders, single- or three-phase loads, and an ESS interconnecting transformer, as well as protection devices such as a circuit breaker (CB) and relay. There are two circuit breakers to clear the feeder faults through the operation of the relay. CB1 and CB2 are installed on feeder-1 and feeder-2, which is interconnected with the ESS. The rated power of the ESS is assumed to be below 20 MW based on a Korea electric power corporation (KEPCO) guideline for a DG and corresponding generations interconnected with a distribution system [18]. In order to integrate with the ESS, a grounded wye (utility side)-delta (ESS side) connection transformer is used in the analysis and is shown in Fig. 1. The specifications of the power distribution system shown in Fig. 1 are summarized in Table II [13], [15].

TABLE II
SPECIFICATIONS OF THE POWER DISTRIBUTION SYSTEM WITH AN ESS

	Data
Source	154 kV, j1.75%
Main Transformer (MTr)	154/22.9 kV, 60 MVA, j15%, NGR: 5 %
Interconnecting Tr.	22.9/0.44 kV, 20 MVA, j6 %
Line Impedance (ACSR 160 mm^2)	Z_1 = 3.86 + j7.42 %/km Z_0 = 9.87 + j22.6 8 %/km
Feeder Length	Feeder-1: 10 km Feeder-2: 100 m
Fault Location	Feeder-1: 5 km from CB1
System Base	100 MVA, 22.9 kV

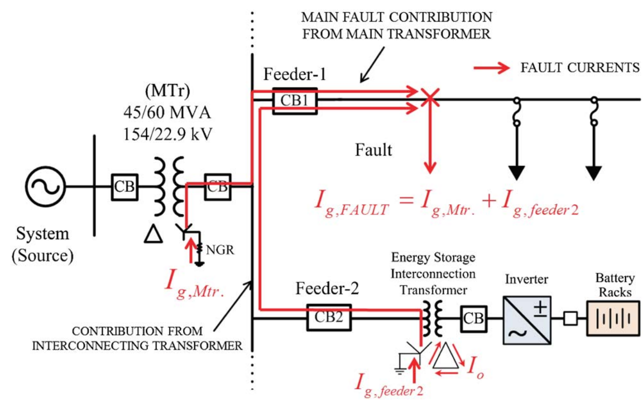

Fig. 2. Effect of a single line-to-ground fault on an ESS interconnecting transformer without an SFCL.

III. CASE STUDY

To evaluate the effect of the SFCL on a single line-to-ground fault in the distribution system with an ESS, simulations were performed with the existence of an SFCL and modeled using PSCAD/EMTDC software.

A. Case 1: Single Line-to-Ground Fault Without an SFCL

The effect of the ESS interconnecting transformer without an SFCL on a single line-to-ground fault is analyzed in case 1. Fig. 2 shows how the ESS interconnection, which is not applied to an SFCL, contributes to a single line-to-ground fault in a distribution system. The red arrows ($I_{\mathrm{g,Mtr.}}$ and $I_{\mathrm{g,feeder2}}$) illustrate the path of the fault currents from the substation and the ESS interconnecting transformer electrical grounds to a fault location. It flows back through the solidly grounded substation transformer and contributes additional current flow to the fault location. The magnitude of fault current depends on the size and impedance of the interconnecting transformer. On the delta side of the interconnecting transformer,

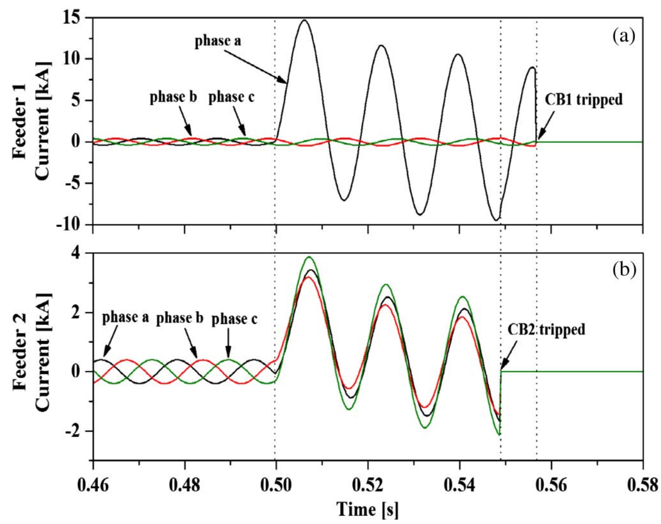

Fig. 3. Feeder currents caused by the single line-to-ground fault in feeder-1 without an SFCL applied to the interconnecting transformer: (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

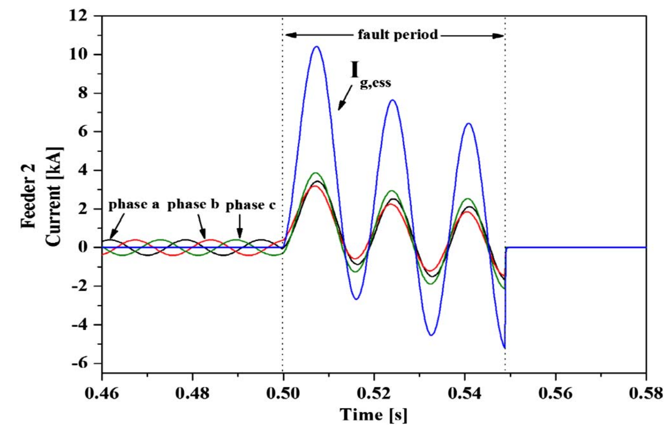

Fig. 4. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

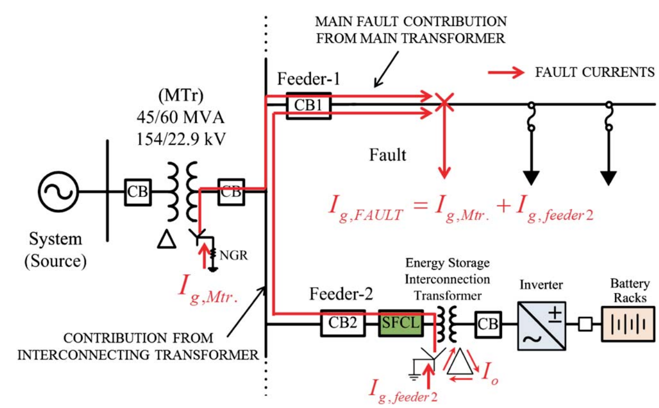

Fig. 5. Effect of a single line-to-ground fault on the ESS interconnecting transformer with an SFCL.

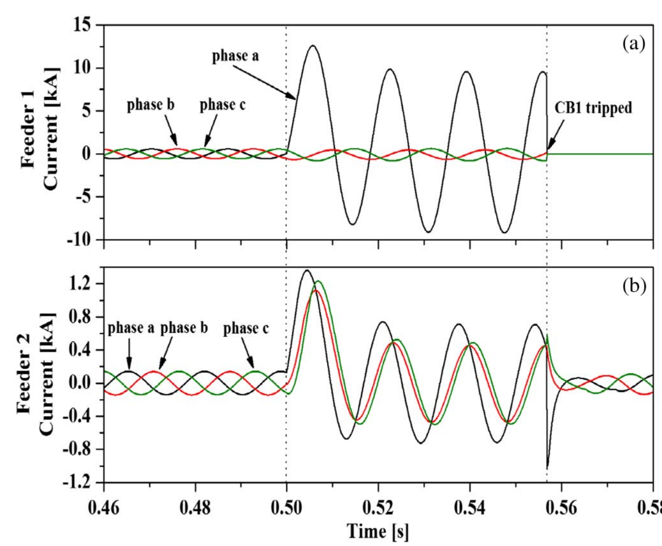

Fig. 6. Feeder currents caused by a single line-to-ground fault on feeder-1 with an SFCL applied to the interconnecting transformer: (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

no zero-sequence currents appear in the lines, though these currents (I_0) circulate in the delta windings to balance the ampere turns in the wye windings [9], [19]. The fault current is primarily designed to flow through the electrical ground of the main transformer and not the electrical ground of the interconnecting transformer. The ESS that is interfaced with the power system creates a new path for a zero-sequence current flowing a fault current or a zero-sequence current.

Fig. 3 shows the feeder currents caused by the single line-to-ground fault in feeder-1 without an SFCL application to the ESS interconnecting transformer. The single line-to-ground fault is simulated at 0.5 s in phase for feeder-1. The fault current trips CB1 as well as CB2, which is tripped by a zero-sequence current fed from the electrical ground of the interconnecting transformer. This means that the ESS is inevitably disconnected from the power system whenever a ground fault occurs. The currents in feeder-2 fed from the ESS increase after a ground fault, as shown Fig. 3(b). This is because the zero-sequence current injected from the electrical ground of the ESS interconnecting transformer is evenly distributed to each phase current in the transformer [9], [19]. Fig. 4 describes the relationship between the zero-sequence current and each phase current.

B. Case 2: Single Line-to-Ground Fault With an SFCL

The effect of the ESS interconnecting transformer with an SFCL on a single line-to-ground fault is analyzed in case 2. In Fig. 5, the red arrows ($I_{\mathrm{g,Mtr.}}$ and $I_{\mathrm{g,feeder2}}$) illustrate the path of the fault current from the substation and the ESS interconnecting transformer ground.

The fault current flowing through feeder-2 and CB2 is reduced by an 8-Ω SFCL applied to the interconnecting transformer and is not enough to trip CB2. Despite a single line-to-ground fault, it is not allowed to disconnect the ESS from the power system, as shown in Fig. 6.

Fig. 7(a) shows the zero-sequence currents flowing into the electrical ground of the main transformer in the substation owing to the single line-to-ground fault, to compare the effect of the presence of an SFCL. When there is an SFCL, the zero-sequence current increases because the SFCL blocks the current trying to pass through the ground of the interconnecting transformer. In addition, Fig. 7(b) shows that the zero-sequence

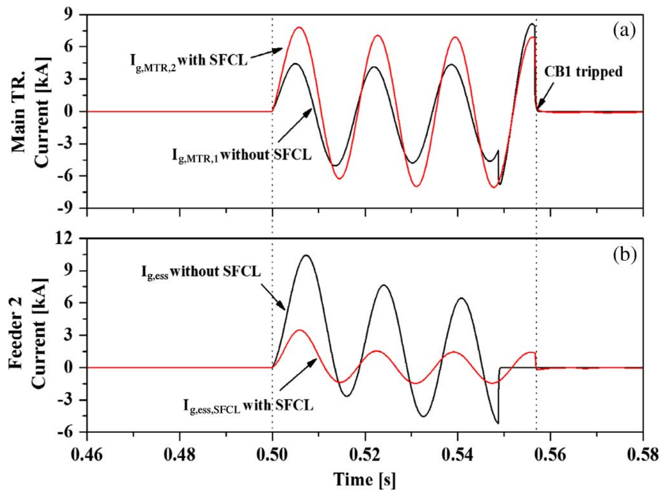

Fig. 7. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

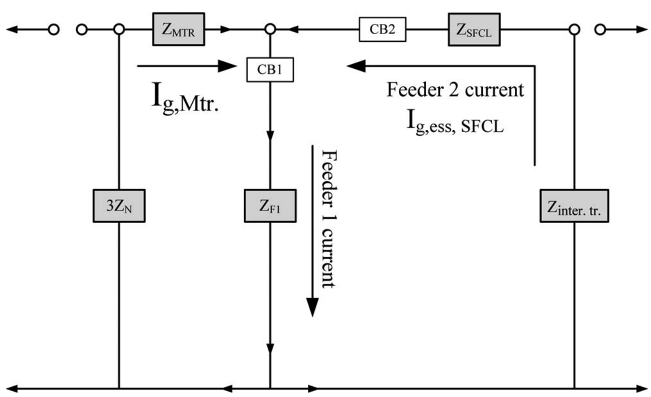

Fig. 8. Zero-sequence component of the equivalent circuit shown in Fig. 5.

current flowing through the ground point of the interconnecting transformer is decreased by the application of the SFCL. In addition, Fig. 8 shows the zero-sequence component of the equivalent circuit shown in Fig. 5.

IV. Conclusion

We have analyzed the effect of the presence of an SFCL on the interconnecting transformer of an ESS. The interconnecting transformer interfaced with an existing power system provides a new zero-sequence current path that is the cause of interruption between the power system and the ESS. The application of the SFCL to the interconnecting transformer solves the problem regarding protective coordination for an ESS. Therefore, an SFCL applied to the interconnecting transformer is used to improve the interconnection for a power system with energy storage by limiting the fault current. Of the two cases, we confirmed that the application of an SFCL to the interconnection transformer is an effective solution for sustainable interconnection.

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