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, and Jae-Chul Kim

Abstract—This paper presents the application of a superconducting fault current limiter (SFCL) to energy storage for protection in a distribution power system. Although an energy storage system (ESS) adds a number of benefits for power systems, it has a drawback for ground fault protection. These things are interrelated with a neutral grounding method for an interconnecting transformer used to connect the energy storage and power systems. There are different types of transformer connections used to interconnect with a power grid. In particular, a grid-side grounded wye-delta winding connection is prevalent for interconnect generation to the utility system, as well as for all central-station generation. However, there is a path on the negative side of the fault current created in case of a ground fault in the distribution power lines. The ground fault will generally disrupt the coordinated power system protection and subsequently disconnect the energy storage from the grid. Therefore, an SFCL is applied to the interconnecting transformer of energy storage, and its effect is analyzed using transient simulation software.

Index Terms—Energy storage, interconnecting transformer, fault current, 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]. Rather than using fossil fuels, energy storage such as batteries or ultra-capacitor systems can be used to provide fast frequency regulation, load following, and ramping services when the power system needs to meet the power balance [2].

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 [3].

One of the main shortcomings of an ESS is concerned with the protection for a single line-to-ground fault current, similar to a DG. There are various types of transformer connections that interface a DG to an existing power system and provide essential isolation [4]. Specifically, a grounded wye (utility side)-delta (source side) winding connecting transformer is prevalent for use in interconnecting all central station generation to the utility system. The energy storage is interfaced with the power system in this connection and referred to as a ground source. It disrupts the ground fault relaying coordination on a four wire, multi-grounded neutral distribution system and creates a new zero-sequence current path [5]. 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 superconducting fault current limiters (SFCLs) to a DG and renewable energy for a stable operation of the distribution system has been recognized as one of the many promising solutions for fault current problems, because of its fast fault current limiting and automatic recovery characteristics [6]–[9].

In this study, 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 for preventing the short-circuit current from increasing in

magnitude owing to its rapid current limiting ability [9]. Many models for an SFCL have been developed, such as resistor-type, reactor-type, transformer-type, and hybrid-type SFCLs [9][10]. In this paper, we have modeled a resistor-type SFCL using mathematical expressive equations, which were verified by experiments and implemented using PSCAD/EMTDC modeling software [8]–[10].

The time evolution of the SFCL impedance R_{SFCL} as a function of time t is given by (1), (2), and (3):

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

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

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

where R_n and T_F are the saturated resistance at normal temperature 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 [8]–[10]. The parameter values are listed in Table I.

TABLE I
SFCL MODELING PARAMETERS

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

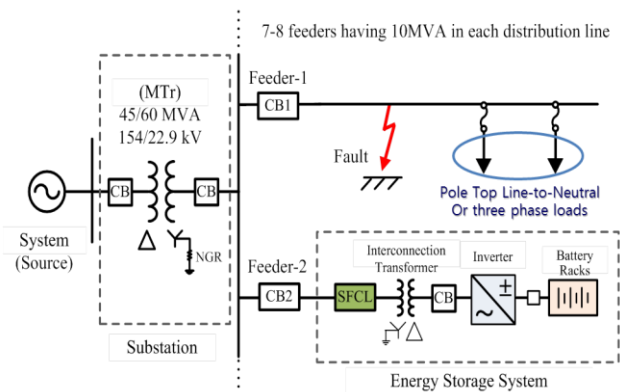### B. Configuration of the Distribution System with an ESS

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

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 [11]. 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 [8][10].

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

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
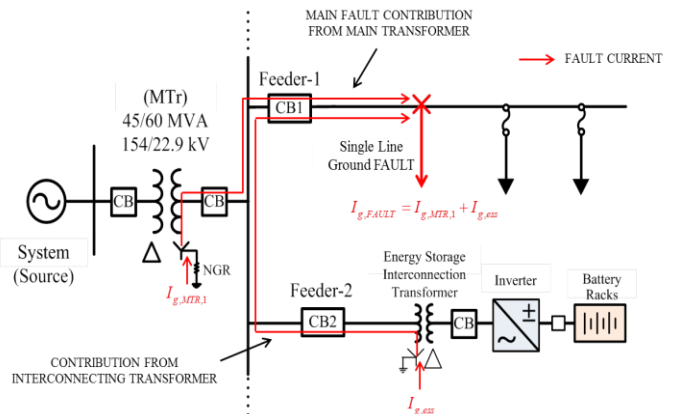

Fig. 2. Effect of a single line-to-ground fault on an ESS interconnecting transformer without an SFCL.

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 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. 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.
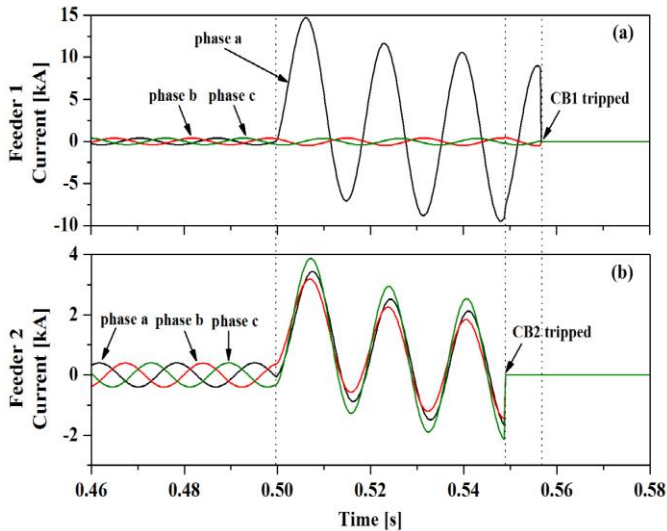

Fig. 3. Feeder currents caused by the single line-to-ground fault in feeder-1 without an SFCL applied to the interconnecting transformer: (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.
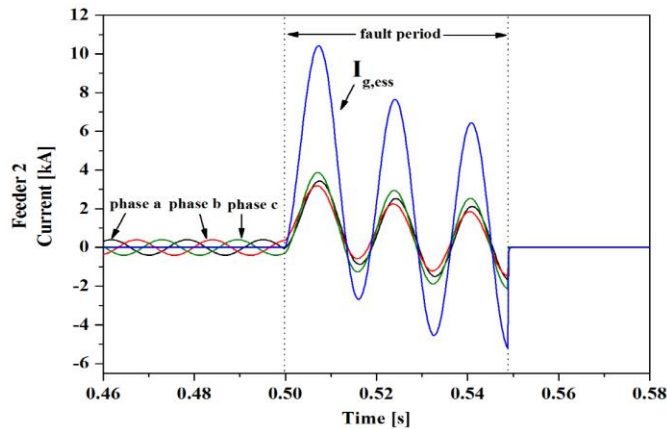

Fig. 4. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

Fig. 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 [5]. 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 illustrate the path of the fault current from the substation and the ESS interconnecting transformer ground.
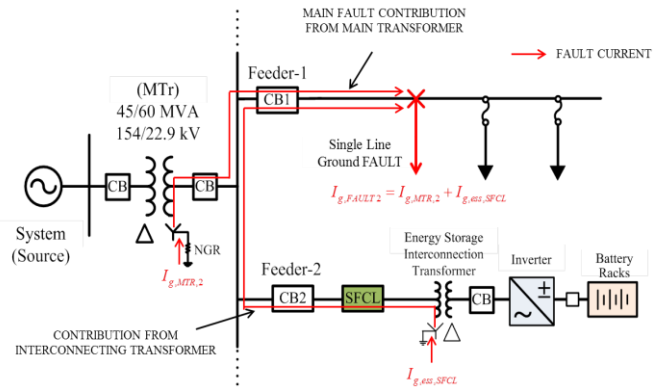

Fig. 5. Effect of a single line-to-ground fault on the ESS interconnecting transformer with an SFCL.

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. In contrast, the fault current flowing through feeder-1 increases in response to the decrease in the fault current in feeder-2, as shown in Fig. 6.
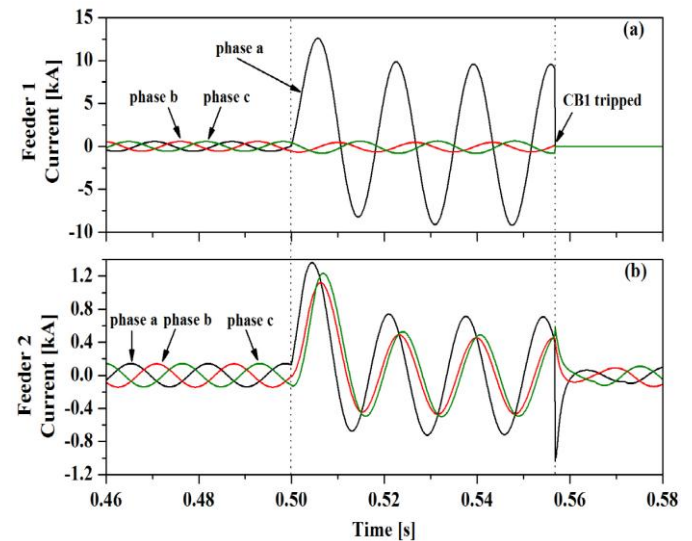

Fig. 6. Feeder currents caused by a single line-to-ground fault on feeder-1 with an SFCL applied to the interconnecting transformer: (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

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 the zero-sequence currents flowing through the ground point of the interconnecting transformer.
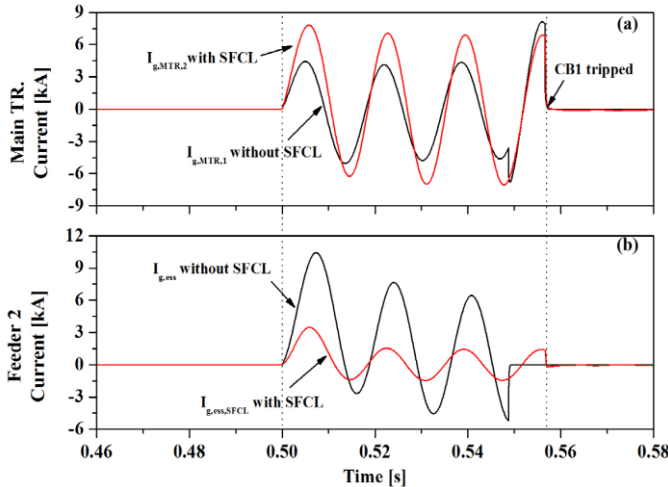

Fig. 7. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

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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