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Application of SFCL to Protect Battery under Different Faults in a Distributed Generation System

SANJU KONETI¹, ROSAIAH MUDIGONDLA²

¹PG Scholar, Dept of EEE, Arjun College of Technology & Sciences, RangaReddy (Dt), TS, India.

²Assistant Professor & HOD, Dept of EEE, Arjun College of Technology & Sciences, RangaReddy (Dt), TS, India.

Abstract: Distributed Generation (DG) in the form of Renewable Power Generation systems is currently preferred for clean power generation. Energy storage systems (ESSs) are enabling technologies for well-established and new applications such as power peak shaving, electric vehicles, integration of renewable energies, etc. The main objective of this project is to introduce a superconducting fault current limiter to keep the energy storage system from disconnecting from the grid when ground faults occur. The possible advantages of Superconducting Fault Current Limiter (SFCL) as a means to limit the adverse effect of DG on distribution system protection and their effectiveness will be demonstrated. However, the application of the SFCL in the power system affects the protective coordination of the existing protective devices and can deviate their operation time from the original one. Therefore, the study on the protective coordination considering the introduction of the SFCL is necessary prior to its installation is applied for Micro grid application consists of renewable energy sources with PV Source. The simulation results are obtained using MATLAB/SIMULINK software.

Keywords: Superconducting Fault Current Limiter (SFCL), Distributed Generation (DG), Energy storage systems (ESSs).

I. INTRODUCTION

As Conventional sources of energy are rapidly depleting and the cost of energy is rising, photovoltaic energy becomes a promising alternative source. Among its advantages are that it is: 1) abundant; 2) pollution free; 3) distributed throughout the earth; and 4) clean and noise-free source of electricity. 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]. Renewable energy

resources for the 21st century power grid in order to supply electric power which is cleaner, reliable, effervescent and responsive than conventional power systems. Smart grid is based on the principle of decentralization of the power grid network into smaller grids (Microgrid) having distributed generation sources (DG) connected with them, One critical problem due to these integrations is excessive increase in fault current due to the presence of DG within a micro grid [1]. Conventional protection devices installed for protection of excessive fault current in power systems, mostly at the high voltage substation level circuit breakers tripped by over-current protection relay which has a response-time delay resulting in power system to pass initial peaks of fault current [1]. But, SFCL is a novel technology which has the capability to quench fault currents instantly as soon as fault current exceeds SFCL's current limiting threshold level [2].

SFCL achieves this function by losing its superconductivity and generating impedance in the circuit. SFCL does not only suppress the amplitudes of fault currents but also enhance the transient stability of power system [2]. Up to now, there were some research activities discussing the fault current issues of smart grid [4]. But the applicability of SFCLs into micro grids was not found yet. Hence, in order to solve the problem of increasing fault current in power systems having multiple micro grids by using SFCL technology is the main concern of this work. The utilization of SFCL in power system provide them most effective way to limit the fault current and results inconsiderable saving from not having to utilize high capacity circuit breakers. With Superconducting fault current limiters (SFCLs) utilize superconducting materials to limit the current directly or to supply a DC bias current that affects the level of magnetization of a saturable iron core. Being many SFCL design concepts are being evaluated for commercial expectations, improvements in superconducting materials over the last 20 years have driven the technology [3]. Case in point, the discovery of high-temperature superconductivity (HTS) in 1986 drastically improved the potential for economic operation of many superconducting devices.

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 as shown in Fig.1. 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,

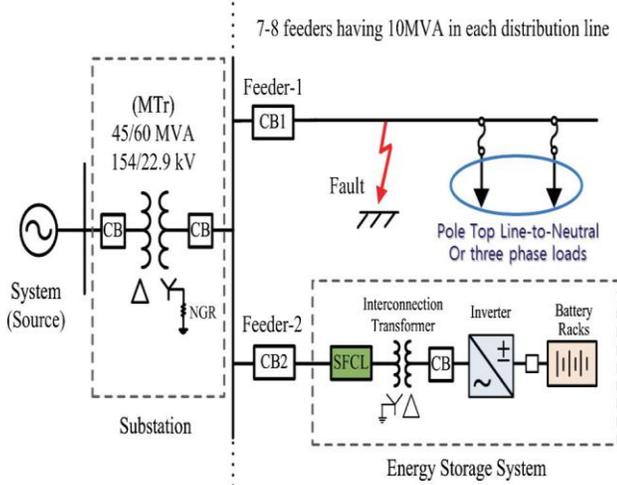


Fig.1. Power distribution system with an energy storage system.

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

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

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

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

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.

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

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. Fig. 2 shows a four-wire multi-

grounded power distribution system with an ESS for simulation to analyze the effect of the SFCL application.

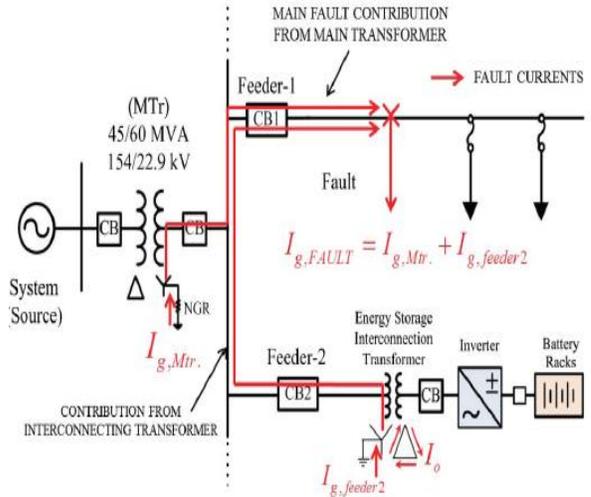


Fig. 2. Effect of a single line-to-ground fault on an ESS interconnecting transformer without an SFCL.

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.

III. DESCRIPTION OF FAULTS

Electrical powers system is growing in size and complexity in all sectors such as generation, transmission, distribution and load systems. Types of faults like short circuit condition in power system network results in severe economic losses and reduces the reliability of the electrical system. Electrical fault is an abnormal condition, caused by equipment failures such as transformers and rotating machines, human errors and environmental conditions. These faults cause interruption to electric flows, equipment damages and even cause death of humans, birds and animals.

A. Types of Faults

Electrical fault is the deviation of voltages and currents from nominal values or states. Under normal operating conditions, power system equipment or lines carry normal voltages and currents which results in a safer operation of the system. But when fault occurs, it causes excessively high currents to flow which causes the damage to equipments and devices. Fault detection and analysis is necessary to select or design suitable switchgear equipments, electromechanical relays, circuit breakers and other protection devices. There are mainly two types of faults in the electrical power system. Those are symmetrical and unsymmetrical faults.

Application of SFCL to Protect Battery under Different Faults in a Distributed Generation System

1. Symmetrical Faults

These are very severe faults and occur infrequently in the power systems as shown in Fig.3. These are also called as balanced faults and are of two types namely line to line to ground (L-L-L-G) and line to line to line (L-L-L).

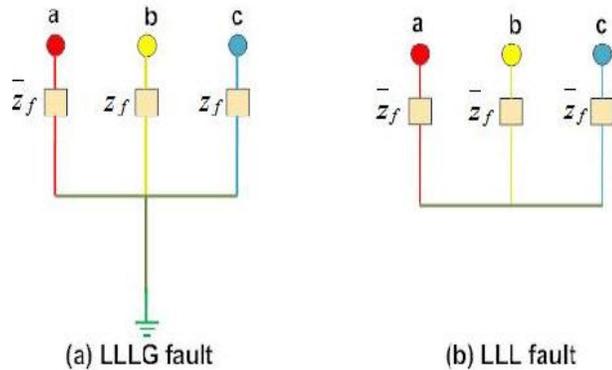


Fig.3. symmetrical faults.

Only 2-5 percent of system faults are symmetrical faults. If these faults occur, system remains balanced but results in severe damage to the electrical power system equipments. Above figure shows two types of three phase symmetrical faults. Analysis of these fault is easy and usually carried by per phase basis. Three phase fault analysis or information is required for selecting set-phase relays, rupturing capacity of the circuit breakers and rating of the protective switchgear.

2. Unsymmetrical Faults

These are very common and less severe than symmetrical faults as shown in Fig.4. There are mainly three types namely line to ground (L-G), line to line (L-L) and double line to ground (LL-G) faults.

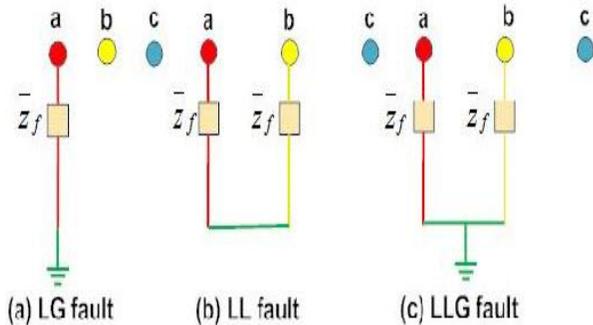


Fig.4. Unsymmetrical faults.

Line to ground fault (L-G) is most common fault and 65-70 percent of faults are of this type. It causes the conductor to make contact with earth or ground. 15 to 20 percent of faults are double line to ground and causes the two conductors to make contact with ground. Line to line faults occur when two conductors make contact with each other mainly while swinging of lines due to winds and 5-10 percent of the faults are of this type. These are also called unbalanced faults since their occurrence causes unbalance in the system. Unbalance of the system means that that impedance values are different in each phase

causing unbalance current to flow in the phases. These are more difficult to analyze and are carried by per phase basis similar to three phase balanced faults. Fault currents cause equipment damage due to both thermal and mechanical processes. Goal of fault analysis is to determine the magnitudes of the currents present during the fault. need to determine the maximum current to ensure devices can survive the fault, need to determine the maximum current the circuit breakers (CBs) need to interrupt to correctly size the CBs.

IV. BASICS OF SFCL

Superconducting fault current limiter is a promising technique to limit fault current in power system. Normally non-linear characteristic of superconductor is used in SFCL to limit fault current. In a normal operating condition SFCL has no influence on the system due to the virtually zero resistance below its critical current in superconductors. But when system goes to abnormal condition due to the occurrence of a fault, current exceeds the critical value of superconductors resulting in the SFCL to go resistive state. This capability of SFCL to go off a finite resistive value state from zero resistance can be used to limit fault current. Different types of SFCLs have been developed until now [10-13]. Many models for SFCL have been designed as resistor-type, reactor-type, and transformer-type etc. In this paper a resistive-type SFCL is modeled using simulink. Quench and recovery characteristics are designed on the basis of [14].

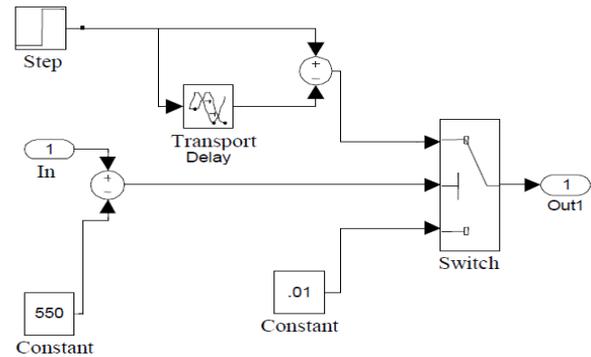


Fig.5. Implementation of resistive SFCL characteristics in simulink.

These parameters are used for implementing resistive SFCL characteristic is shown in Fig. 5. Quenching and recovery time of SFCL are specified using step and transport block respectively. A Switch block is used to give minimum or maximum impedance in output which is determined considering the incoming current. The simulation model of SFCL for a single phase system is shown in Fig. 5. The working principle of the SFCL model developed in Simulink/Sim Power system is described below. Firstly, RMS value of incoming current (passing through current measurement block) is measured by RMS block. Then it compares the current with the specified current in the SFCL Subsystem. SFCL gives minimum resistance, if the incoming current is less than the triggering current level. But if the current is larger than the triggering current, SFCL's impedance rises to maximum state. It ultimately raises the total impedance of the system which results in limiting the

fault current. Finally, the SFCL's resistance will be minimum when the limited fault current is below the triggering value.

IV. SIMULATION RESULTS

Simulation results of this paper is shown in bellow Figs.6 to 25.

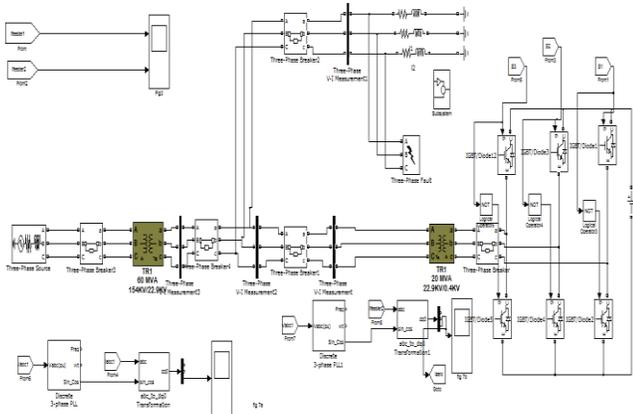


Fig.6. Matlab/simulink model of proposed system without SFCL.

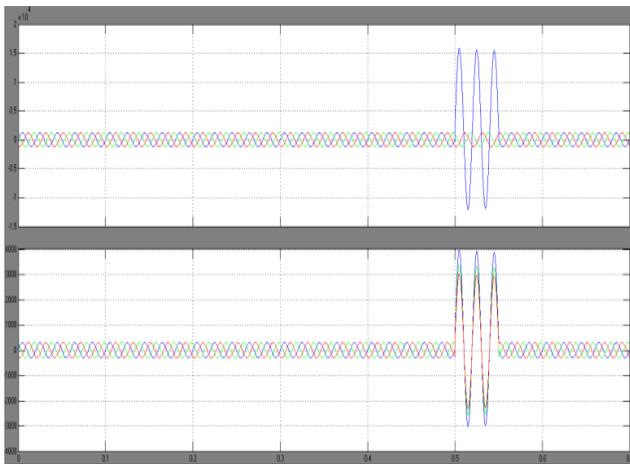


Fig.7. Simulation waveform Feeder currents caused by the single line-to ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

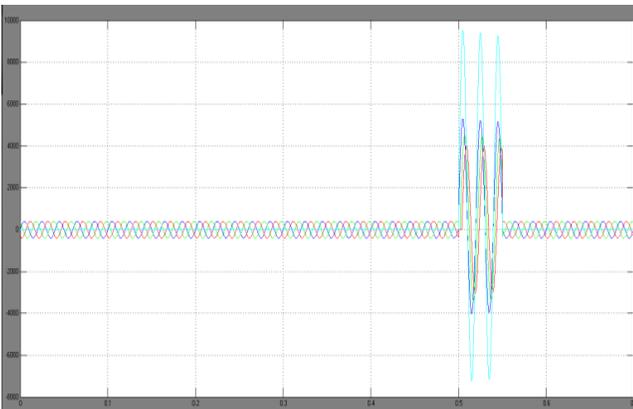


Fig.8. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

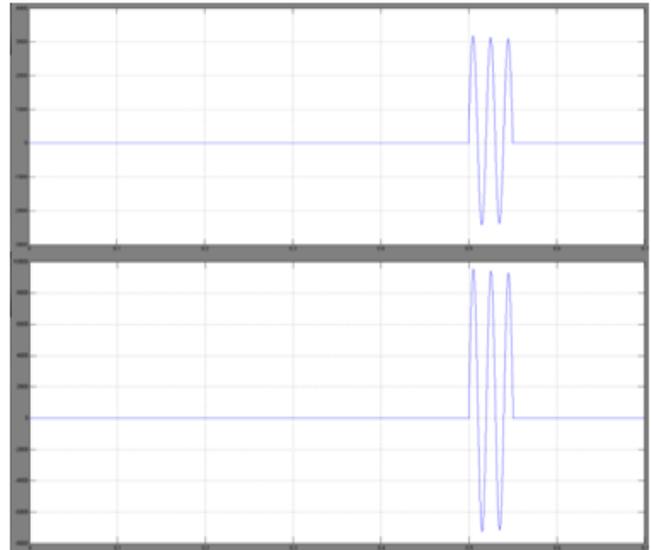


Fig.9. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

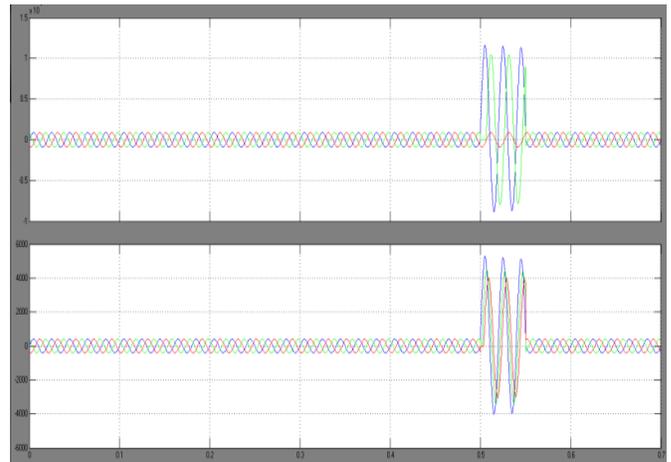


Fig.10. Simulation waveform Feeder currents caused by the double line-to-ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

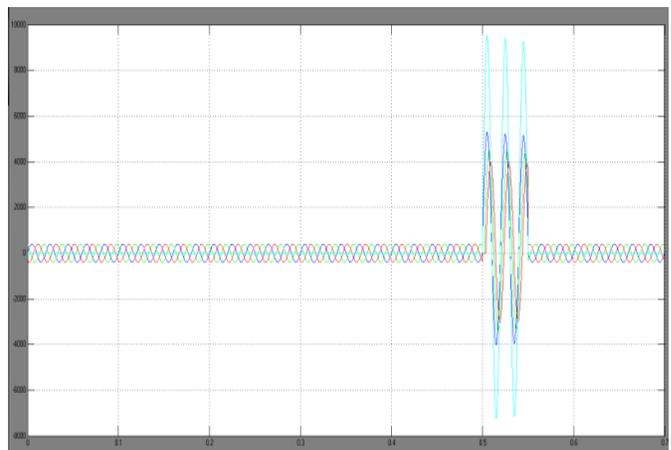


Fig.11 Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

Application of SFCL to Protect Battery under Different Faults in a Distributed Generation System

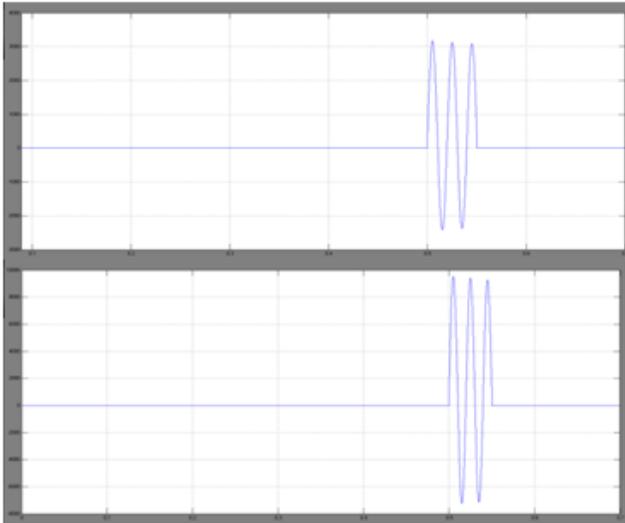


Fig.12. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

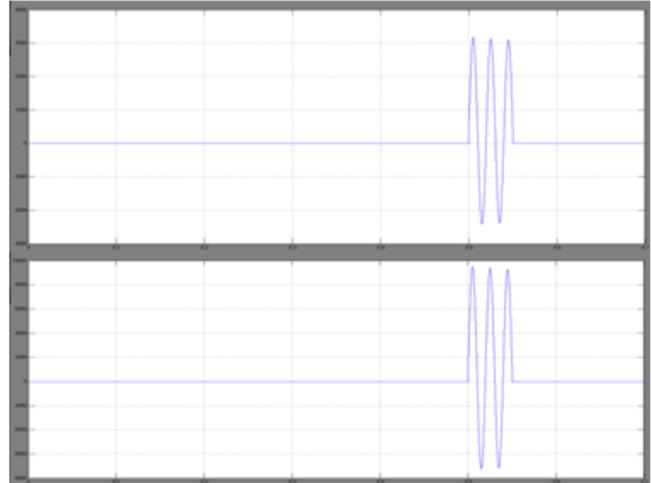


Fig.15. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

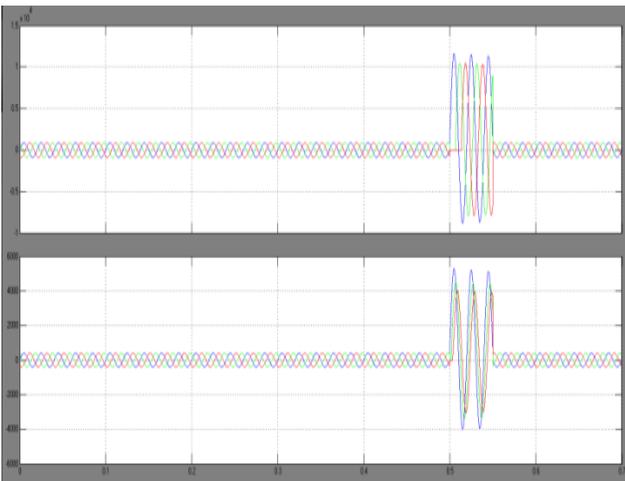


Fig.13. Simulation waveform Feeder currents caused by the three- line-to-ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

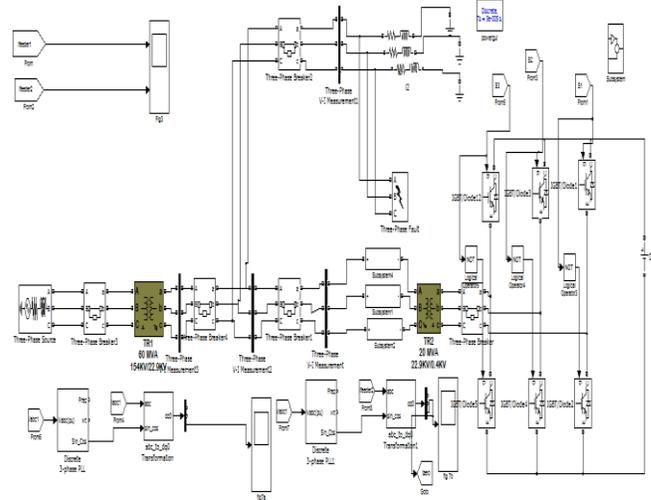


Fig.16. Matlab/simulink model of proposed system with SFCL.

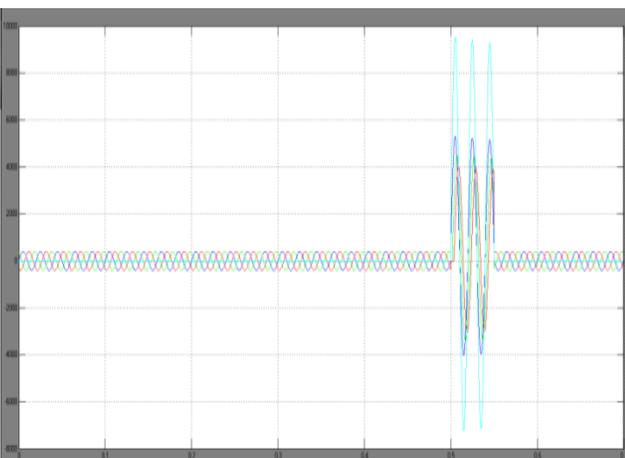


Fig.14. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

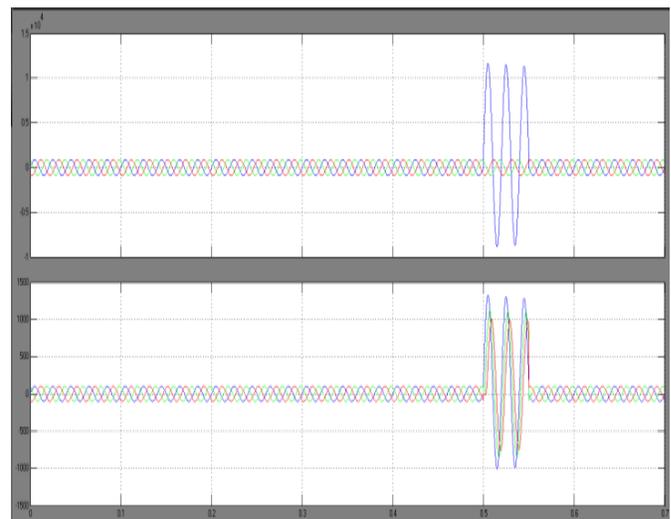


Fig.17. Simulation waveform Feeder currents caused by the single line-to-ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

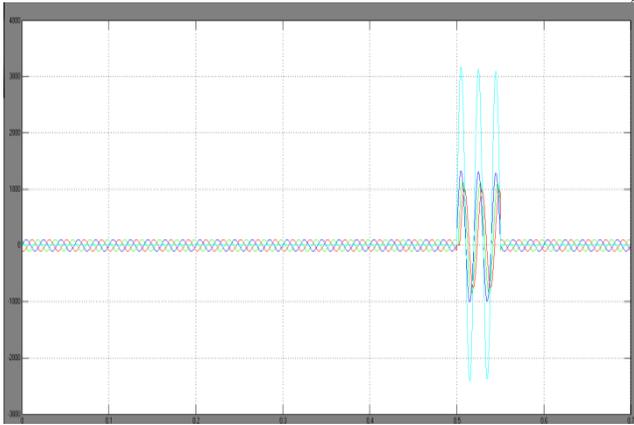


Fig.18. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

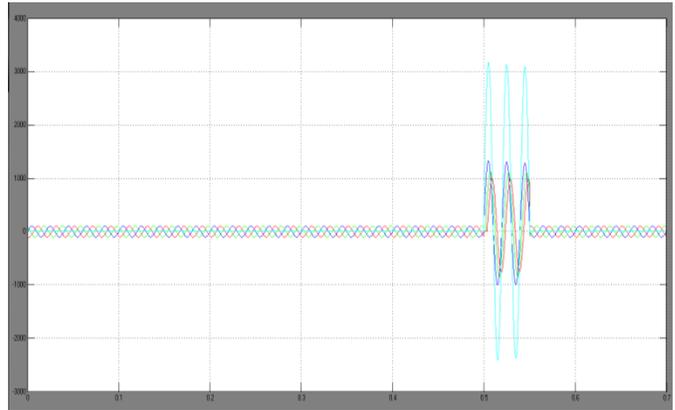


Fig.21. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

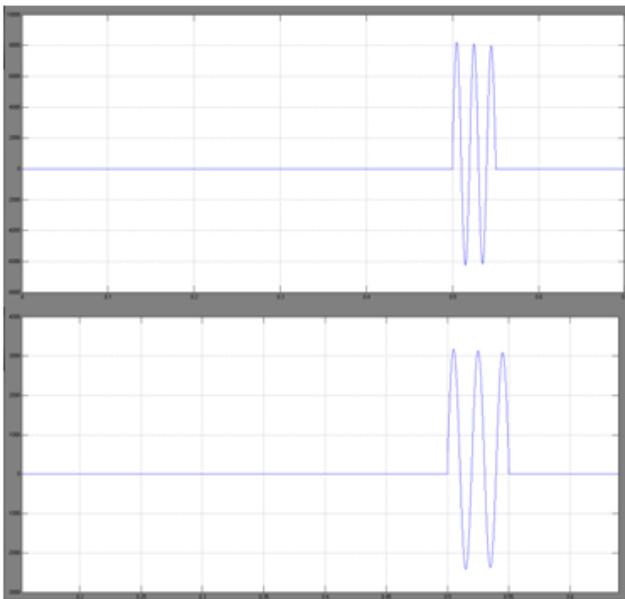


Fig 19. Zero-sequence currents due to a single line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

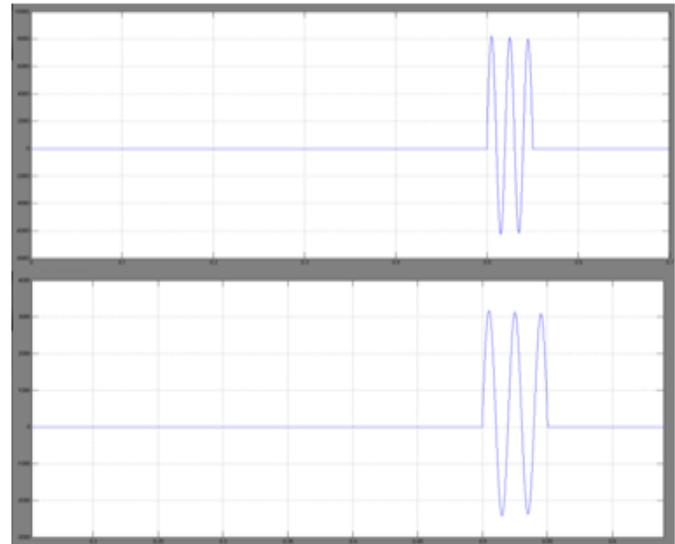


Fig.22 Zero-sequence currents due to a double line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

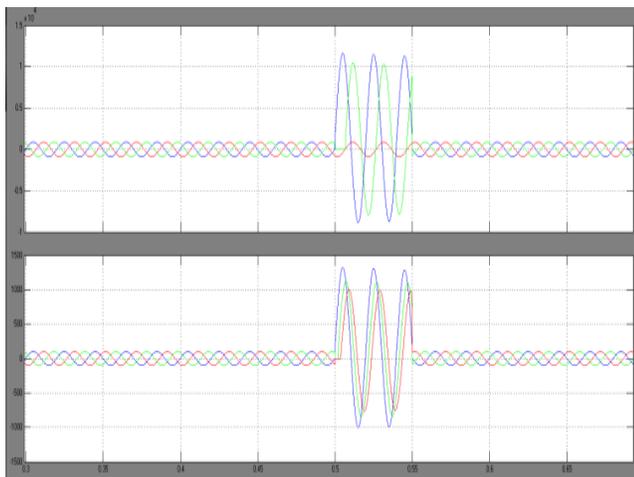


Fig.20. Simulation waveform Feeder currents caused by the double line-to-ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2.

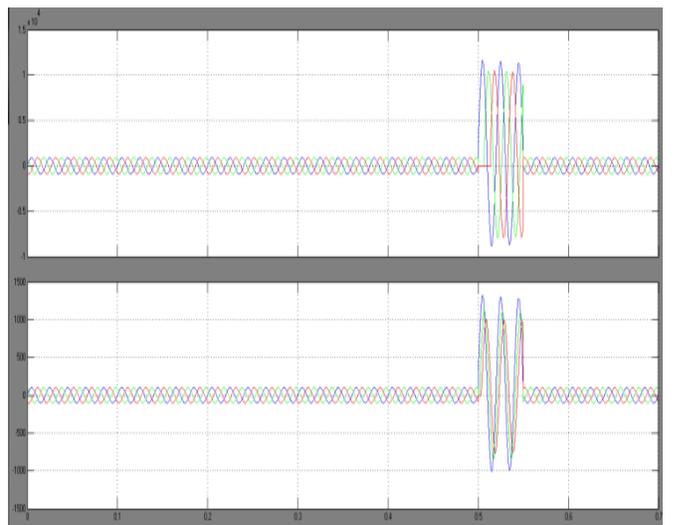


Fig.23. Simulation waveform Feeder currents caused by the three-line-to-ground fault (a) feeder-1 currents at CB1 and (b) feeder-2 currents at CB2 with SFCL.

Application of SFCL to Protect Battery under Different Faults in a Distributed Generation System

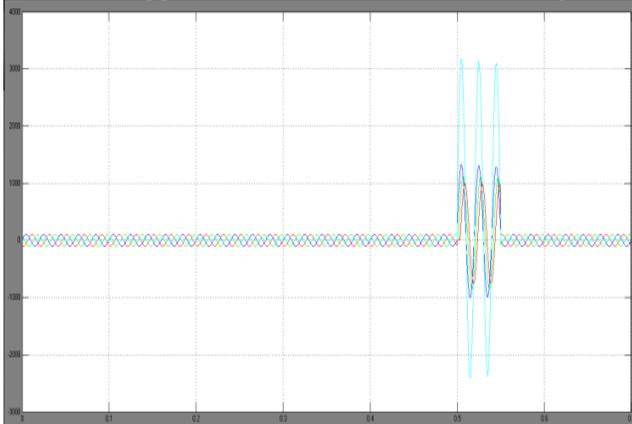


Fig.24. Phase currents in feeder-2 and the zero-sequence current to the electrical ground of the ESS interconnecting transformer.

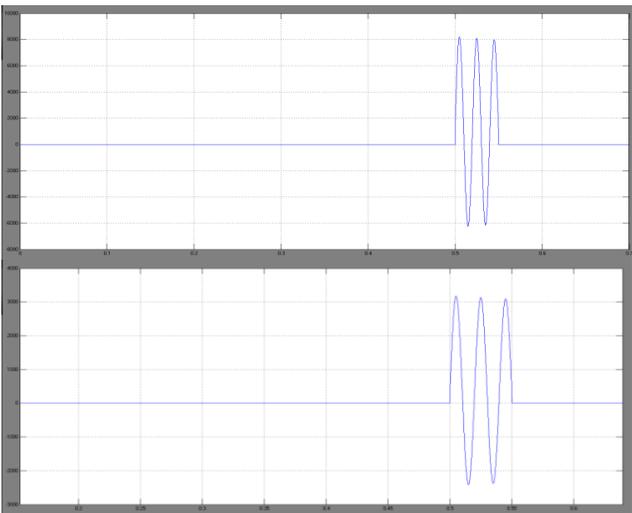


Fig.25. Zero-sequence currents due to a triple line-to-ground fault for (a) the main transformer and (b) the interconnecting transformer.

V. CONCLUSION

Due to the growing concern with energy shortage and network stability, the concepts of distributed generation (DG), microgrid systems become progressively more popular; especially with the decreasing costs of various clean renewable energy sources (RES). These DG systems would be connected to the utility grid under normal operating conditions, but also have the additional capability to sustain a local system by sourcing power directly from the renewable energy sources and energy storage devices if necessary to make grid transmission level black- and brownouts seem transparent to the local system loads. 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 FCL to the interconnecting transformer solves the problem regarding protective coordination for an ESS. Therefore, an FCL 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 FCL to the interconnection transformer is an effective solution for sustainable interconnection.

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Author’s Profile:



Sanju Koneti, Mtech Student Scholar, Arjun College of Tech & Sciences, Batasingaram, R.R Dist, JNTUH, Btech-Chilukur Balaji Institute of Technology & Sciences, Azziz Nagar, R.R District, JNTUH, Email id:ksanju307@gmail.com.



Rosaiah Mudigondla, HOD, Asst. Prof. Acts, B.Tech-Arjun College of Tech & Sciences, Batasingaram, R.R Dist, JNTUH-2010. M.Tech-Ayaan College of Engg & Technology-2014, Moinabad ,R.R Dist ,JNTUH, Email.id-rosaiah0228@gmail.com.