Fault Characteristics of Distributed Solar Generation with Super Conducting Fault Current Limiter

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Abstract
There are no negative or zero sequence currents present in inverter-based distributed energy resources (DERs). A thorough understanding of DER's fault characteristics is essential for fault investigation and relay configuration. While DER models have been extensively studied, there have been few studies examining DER's fault behaviour during real fault occurrences. Dominion Energy's reported fault incidents are examined in this article. To demonstrate that real DER fault responses may vary from prior understandings, fault magnitudes, angles and sequence components are analyzed. Additionally, the conductor's resistance is increased during faults by a Super Conducting fault current limiter (SFCL) linked in series with DER. There is a side-by-by-side comparison with and without the SFCL to highlight the fault characteristics.

Keyword: Distributed Energy Resources, Zero Sequence Currents, Dominion Energy, Super Conducting Fault Current Limiter, Fault Response

Introduction

In the electric power business, distributed energy resources (DER) are a relatively recent phenomenon. The modularity of DERs has led to the concept's rise in popularity. With their modest capacity, they may be seen as more adaptable power sources than centralized energy units. Derived Energy Resources (DERs) are power generating or storage devices that are either directly or indirectly linked to a utility distribution network. Fuel cells, wind power, solar power and a variety of energy storage options are all examples of these energy sources. DERs may be useful resources for the electricity generating and distribution business if hurdles can be eliminated. They have the potential to enhance reliability, electricity quality, and environmental pollution while delaying capital expenditures for transmission and distribution (T&D). However, in order to demonstrate their actual potential, more research is necessary. (Van Ruitenbeek et al., 2014)

The range of values or the ratings of the protective devices, lines may or may not withstand the connection of DG. Connection of DG to the distribution network meets the demand and reliability conditions along with the tendency of introducing fault currents. If the fault current increases more than the fault level design limits of the network then there is chance for the malfunctioning or damage to the equipment and loss of life and property. In order to avoid the above said disasters proper protection study should be carried out before the DG is connected to the distribution network. The conclusions of the protection study sometimes leads to the employment of cost effective and reliable methods in limiting the fault current. The focus on fault current limiters helps in the connection of Distributed Generation to the distribution networks, which eventually results in the enjoyment of advantages of DG through engineering. (Sharma et al., 2014)

Objectives of the Study

The electricity demand is increasing at a very high rate. Introduction of Distributed Energy Sources (DES) is the highest change happening to the distribution network. Following are the objectives of the present study are:

- To understand the DER’s fault characteristics for fault analysis and protective relay setting
- To explore the recorded fault events collected by Dominion Energy
- To update DER with Super Conducting fault current limiter (SFCL)
- To perform comparative analysis with and without SFCL and fault characteristics.

Literature Review

(Paliwal, 2021) Distributed energy resources (DERs), such as wind and solar, may have a significant impact on a system's stability, losses and voltage profile. To put it another way, growing distributed energy resources (DERs) penetration requires an effect assessment, especially if they are stochastic and contain distributed generators (DGs) and a storage system. Analysis of the impact of renewable energy (DER) penetration and location on system losses and voltage profiles is presented here. Given the stochastic nature of RES-based distributed generators, the penetration level has been established. Consideration of intermittent RES-based distributed generators and the dual-nature of storage units is included into the study given here. Probabilistic load flow was employed in this study to account for the inherent uncertainties in RES.

(Nebey et al., 2020) Renewable energy resources were used by the Ethiopian government to meet the country's current energy needs. The examination of solar PV adaptability gives the best sites for solar PV power plant installations. Analytical hierarchy procedures were used to identify and prioritise aspects that influence solar PV site appropriateness. The final suitability map for solar PV was created by multiplying the weighted and classed values. Solar PV generating efficiency decreases and may malfunction as a result of unsuitable site conditions. The site of a solar PV power plant may be optimized by selecting the most appropriate areas. In other words, the goal of this research was to identify the best locations in the South Gondar Zone for installing solar photovoltaic (PV) power generation systems.

(Kosa et al., 2020) An RL-Indirect SFCL model is presented in the present study. Tape SF 12100 was used to apply the superconducting material (Furukawa Electric Group). The superconducting wire is connected to the grid in the same way as a resistive SFCL when the grid's operating current is high enough. The RL-I-SFCL protection incorporates an additional inductance in case of a grid short circuit. It is connected to the short circuit current via a series of inductances. The superconducting wire's resistance changes instantly, creating an additional impedance in the main circuit. It's a benefit. In order to better understand our SFCL, we measured it and used MATLAB to create a simulation programme.

(Peterson et al., 2019) It was commissioned by the Distributed Generation Interconnection Collaborative (DGIC) since it was determined that there was a need for a comprehensive document detailing concerns, practises, and developing solutions relevant to DER interconnection. In order to comprehend how DER interconnection concerns and techniques may apply to their own circumstances; the paper is aimed for a high-level, strategic-planning audience at utilities. The audience covers a wide variety of utilities and scenarios, including IOUs, municipal utilities (munis), and cooperatives (co-ops) with varying degrees of DER penetration.

(Elatta, 2018) Distributed generation (DG) refers to on-site electrical power generating. Reduce technical losses, improve voltage profile, and enhance power quality with the use of these devices. It saves money by avoiding the need to invest in the transmission and distribution infrastructure if it is properly implemented. Study and analysis of DG advantages from solar renewable energy using the Dumez feeder network of Otovwodo 15MVA, 33/11KV Injection Substation in Nigeria as the case study. Because the study technique entailed collecting essential data from a real Nigerian Power Distribution network, this work has enormous practical value for society and the nation as a whole. Electrical Transient Analyzer Program [ETAP 7.0] software was used to simulate the network..

(NAVIGANT, 2018) Many parts of the United States and the rest of the globe are seeing an increase in the use of distributed energy resources (DER). Many elements, including technological, policy- and customer-driven, have a role. From a financial and environmental standpoint, this is a beneficial development. Because of this, it is possible that customers' adoption of distributed energy resources (DER) might have a negative impact on the overall functioning of the electric grid. Distributed energy management systems (DERMS) have a role in this situation.

(Mahamedi et al., 2018) Distributed energy resources (DER) are the mainstay of micro grids, yet they are unable to provide power at the desired voltage and frequency because of their design. Because of this, inverter-interfaced distributed generators must be used as a conditioning interface between DER and micro grid (IIDG). Fast primary inverter control, on the other hand, might lead to unusual behaviour of IIDGs during fault situations, affecting all relaying components, such as fault detecting and polarization, as well as faulty phase selection, adversely. A micro grid operating in autonomous mode is more susceptible to this problem. This paper analyzes the root causes of such unconventional responses that challenge the traditional protection schemes.

(Ahmadi et al., 2018) Because of their negative influence on the environment, renewable energy sources have a unique chance to develop and improve. Renewable sources like solar power have received the most attention because of their potential for generating electricity. Here, solar energy systems are examined to determine which the most efficient method of generating power is. For example, solar power may be generated directly or indirectly. PV modules are used to convert solar energy into electricity in the direct approach. The indirect technique uses CSP plants like linear Fresnel collectors and parabolic trough collectors to harvest thermal energy. Soar troughs, linear Fresnel collectors, central tower systems, and solar parabolic dishes are all evaluated in this study and their advantages and disadvantages are explored in detail.

(Kabir et al., 2018) One way to meet the rising global need for energy is via the development of new solar power technology. This article discusses both the advantages and disadvantages of solar energy systems. Renewable energy research is also emphasized, along with the positive connections between regulating policy frameworks and their future possibilities, as well as a number of technological challenges. A future roadmap for solar energy research and practice is outlined in order to open up new avenues for study and practice.

(Sarikh et al., 2018) Monitoring systems are critical in the solar industry because of the significance of sustainability. However, defect detection is still a manual process in industrial manufacturing. Fault identification in the photovoltaic system is presented in this work based on the varied effects of faults on the I-V curve. Indeed, fault categorization is a critical step in determining the cause of a problem. In addition to uniform dust faults, partial shading faults, short circuit faults, and ageing, the suggested approach covers all of them. Mat Lab Simulink is used to evaluate the suggested method, and experimental measurements of I-V curves in incorrect instances are used to verify it.

Methodology

The SFCL is a device which has the potential to limit fault current magnitude within the first cycle of fault current whereas circuit breaker requires two to three cycles of fault current. The application of SFCL in the power system would not only reduce the stress on the system devices, but also improves the security and reliability of the power system. There are different types of SFCL, which are of different design and of different superconducting material. Figure shows the current with and without SFCL in different operating conditions.

The SFCL first made in 1983, employing low temperature material. The material was NbTi having eminent current carrying capacity but Low Temperature Superconductor (LTS) has one drawback cooling cost were very high. To overcome this drawback High Temperature Superconductors (HTS) are developed. HTS fault current limiter is more satisfactory than LTS fault current limiter because, (Shahrazad, 2014)

(i) More effective thermal stability

(ii) Less Refrigeration cost

(iii) High ordinary specific resistance

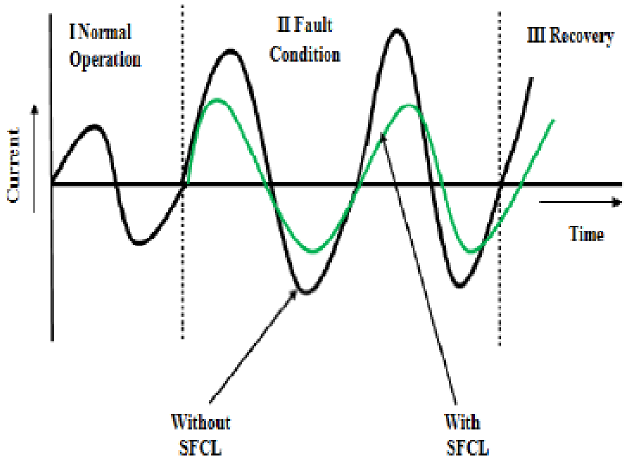

Figure 1: Current during Normal and Faulty Condition with and without SFCL

Operation of the Superconducting Fault Current Limiter can be described by three stages: (Chang & Tao, 2013)

- The superconductor behaviors current under normal operating conditions as at the SFCL; the line sees virtually zero impedance.
- The superconductor unit becomes extremely resistive, causing current to change to the reactor when fault occurs where increase in impedance lowers the fault current.
- A fast-operating switch eliminates superconductor unit from circuit after current transitions to the reactor.

Advantages

- SFCL is applied with the distribution generation
- SFCL reduce the level of short-circuit current during a fault.
- No external controls needed.
- Rapid response.
- SFCLs are invisible in normal operation and do not introduce unwanted side effects.
- SFCLs are economically competitive with expensive conventional solutions.
- Negligible loss during normal system operation.

Disadvantages

- Requires cooling which result in increase in its cost.
- One current disadvantage is that there is energy loss caused by the current leads passing from room temperature to cryogenic temperature that will result in a loss of approximately 40-50 W/kA heat loss per current lead at cold temperature.
- Superconductors tend to the development of thermal in-stabilities (the so called hot spots). In order to protect the materials against these hot spots often a normal conducting bypass is employed.

Applications of SFCLS

- Limit the fault current
- Secure interconnector to the network
- Reduces the voltage sag at distribution system

Results And Discussion

The implementation of the proposed algorithm is done over MATLAB (R2016). The signal processing toolbox helps us to use the functions available in MATLAB Library for various methods like Windows, shifting, scaling etc.

Simulation parameters

Name	Unit and Value
Supply Voltage	132KV
Power	2500KVA
Step-up down Transformer	132KV/34.5KV
Power rating of step-up transformer	47MVA
Frequency	50Hz
Phase to phase voltage	34.5KV
Active Power	100KW
Reactive Power	50KVAR
Circuit Breaker Resistance	0.01 Ohm
Solar irradiation	1000 W/m^2
Temperature	35 Degree
Duty Cycle	0.5
Capacitor	1000 Micro Farad
Resistance	0.005 Ohm
Inductor	5Mh

Simulation result and discussion

Case I: Simulation of the system without the use of relay

Here the system can be represented as shown in the figure which is the simulation model that is been analysed for faults. From this we can infer the result that the system remains unprotected during the occurrence of fault that leads to large system currents, instant high voltage spikes and also damages the circuit and related equipment.

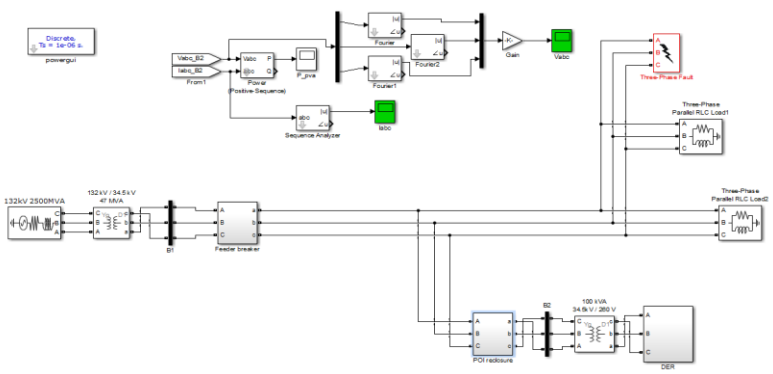

Figure 2: Simulation Model of DER system without relay

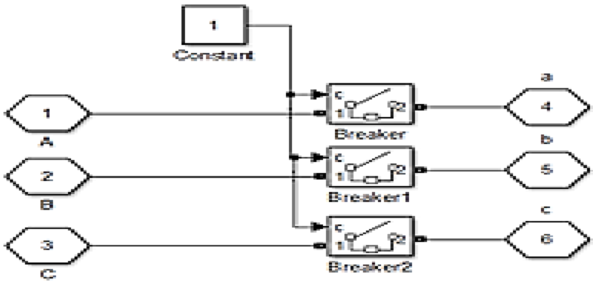

Figure 3: Circuit breaker with no relay protection system

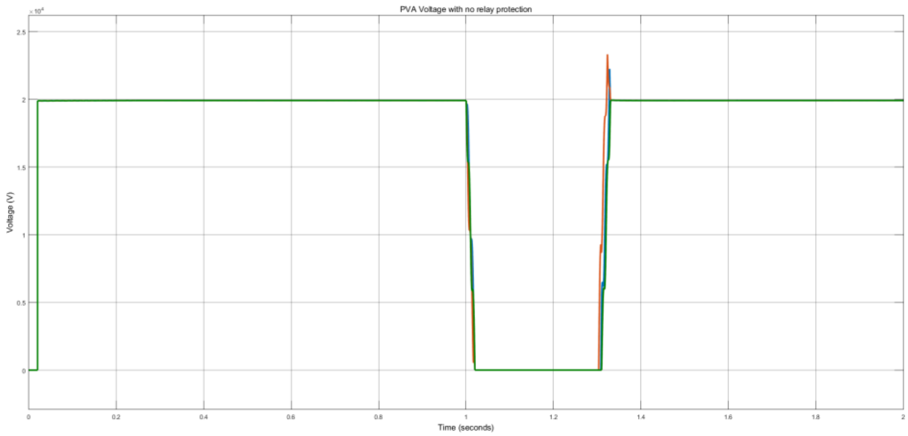

Figure 4: PVA voltages with no relay protection with fault from 1 to 1.3sec

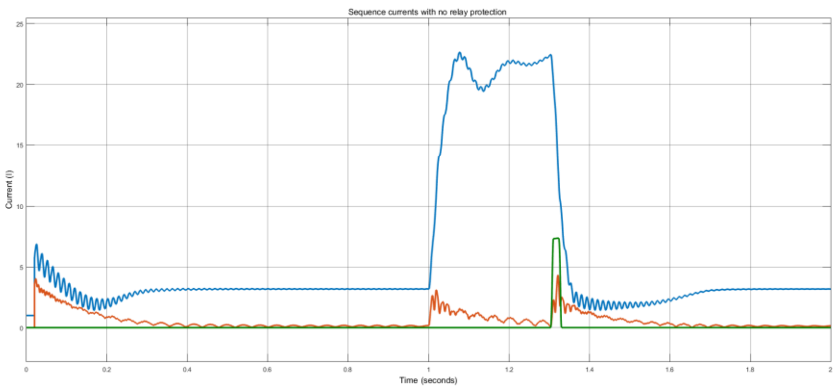

Figure 5: Sequence currents with no relay protection with fault from 1 to 1.3sec

Case II: Simulation model with over current relay

Here we can see in the simulation model that in addition to above mentioned model an over current relay has been included in the circuit. The circuit breaker with over current relay is separately depicted in Fig. On analysis of this circuit we can see that during the occurrence of small transient faults the system may work appropriately but in times of persistent faults where there may be many continuous triggers this over current relay may not work or in other words is not able to handle the situation and thereby leads to high voltage spikes and high valued sequence currents for the time of fault interval and leads to the malfunction or total damage of the system.

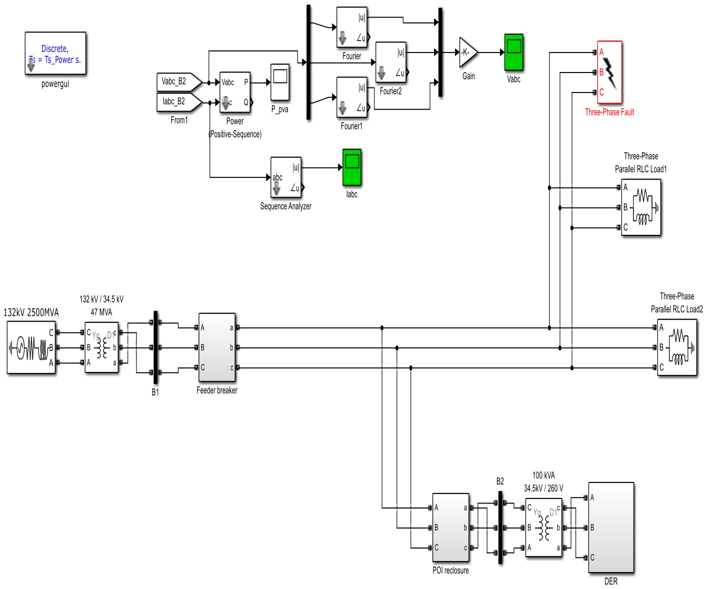

Figure 6: simulation model with over current relay

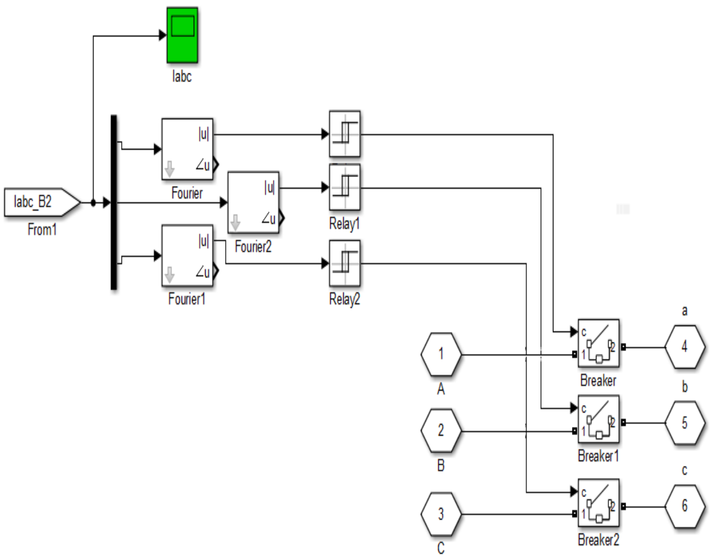

Figure 7: Circuit breaker with over current relay

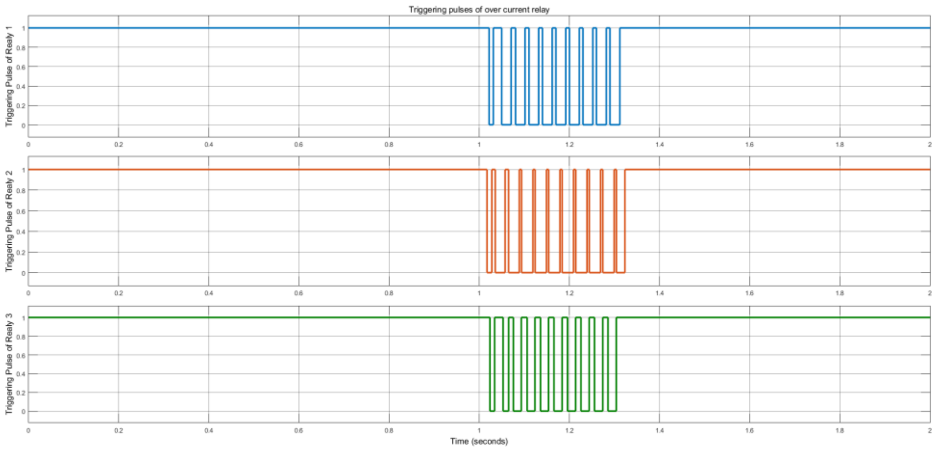

Figure 8: Triggering pulses of over current relay

The number of triggers is very high as the fault is persistent the relay cannot eliminate the fault permanently.

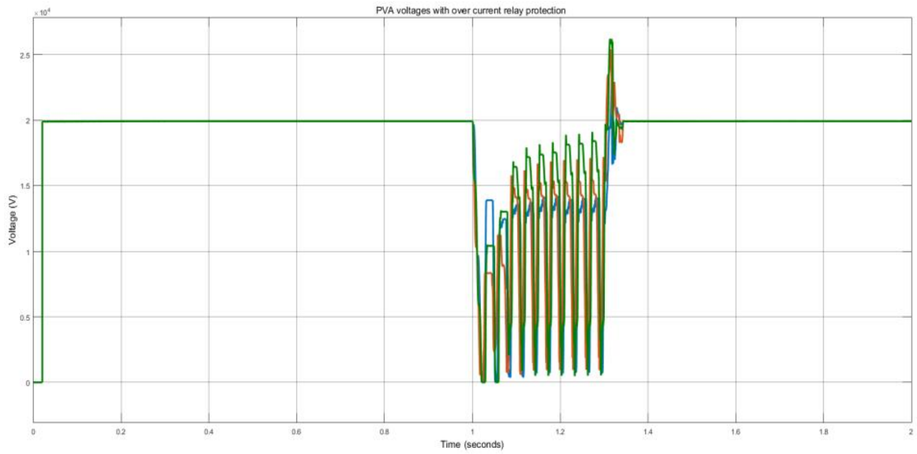

Figure 9: PVA voltages with over current relay protection with fault from 1 to 1.3sec

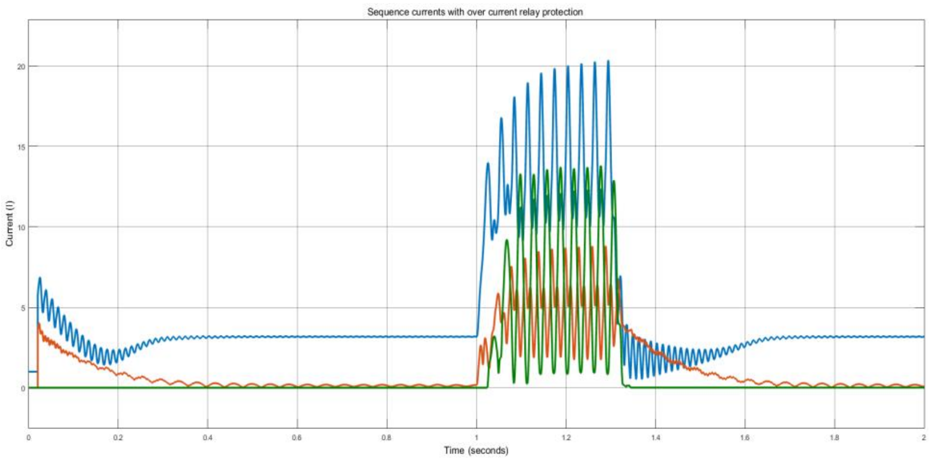

Figure 10: Sequence currents with over current relay protection with fault from 1 to 1.3sec

Case III: Simulation Model with Super conducting fault current limiter at DER

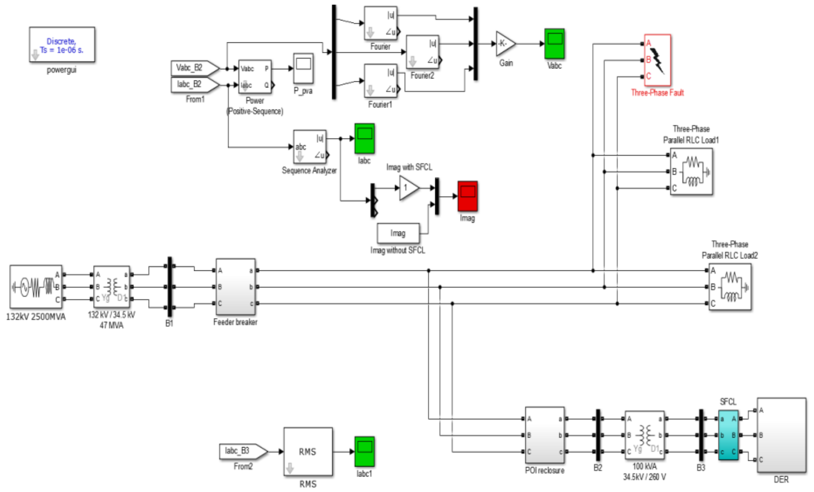

Figure 11: proposed simulation system with SFCL at DER

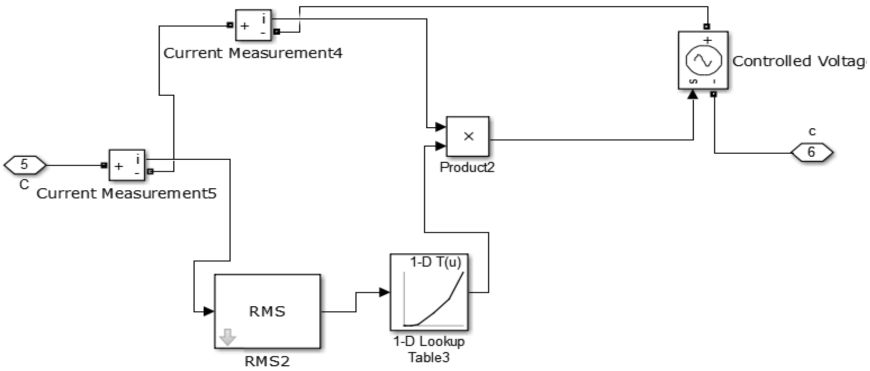

Figure 12: SFCL modelling

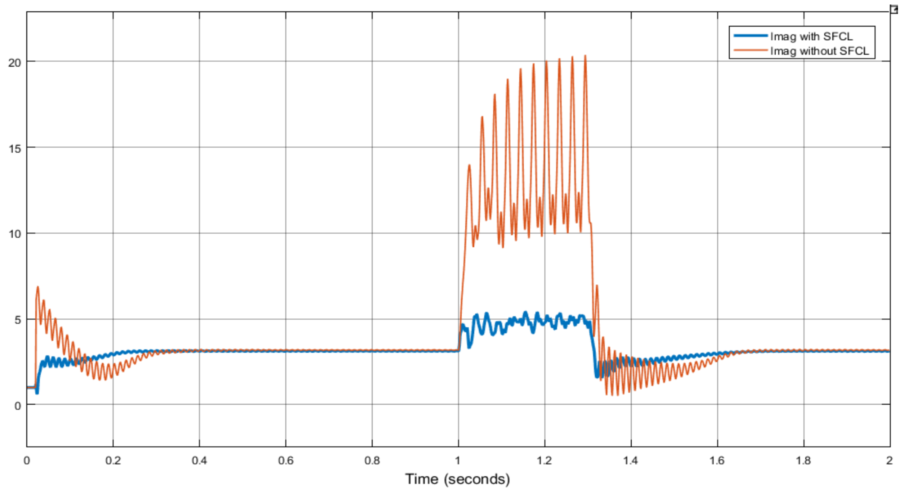

Figure 13: Fault current comparison without and with SFCL

In the above figure it can be seen that the fault current is completely suppressed during the fault timing on the transmission line. The fault current is suppressed with increase in the resistance of SFCL during the fault which can be seen below

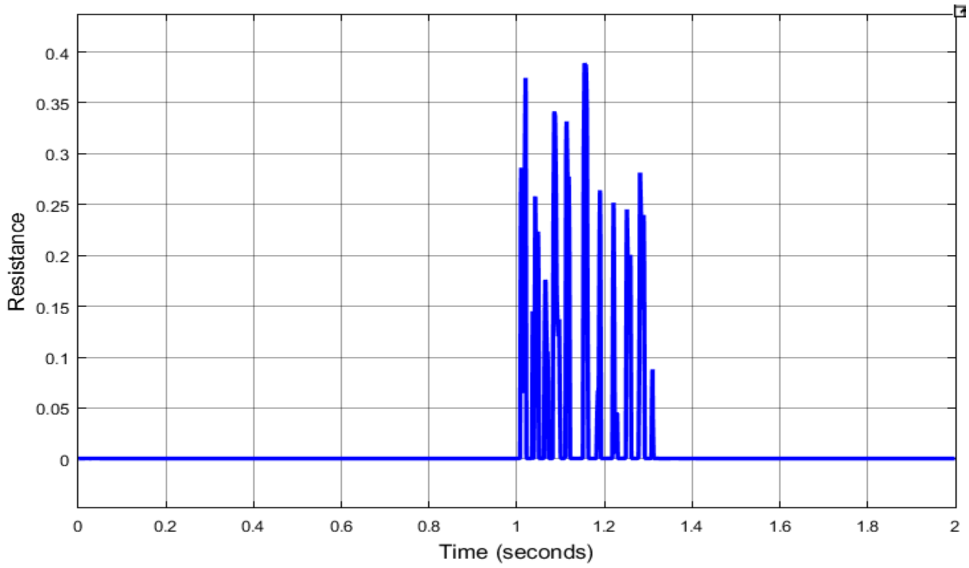

Figure 14: Resistance of the line during normal and fault conditions

Conclusion

This paper explores the fault characteristics of inverter-based solar DERs with SFCL connected in series through multiple recorded fault events. Both transient and steady-state fault responses are analysed. High phase and negative sequence fault currents are noticed during transient periods. The fault current magnitude is affected by fault severity and pre-fault output conditions. During steady state, it is discovered that fault currents are consistently less than rated output current. Both negative and zero sequence currents are negligible. Power factor is regulated during faults, resulting in tight phasor alignment between positive sequence voltage and current. The active power output is proportionally curtailed to positive sequence voltage magnitude. The findings in this paper affect fault analysis and relay setting that involve distributed solar generation. The fault current reduction can be seen when the system is connected with SFCL during the fault timing.

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