European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out – Second Edition

Project Acronym: **ERIGrid 2.0**

Project Number: **870620**

Technical Report Lab Access User Project

Smart Microgrid Protection System (SMPS)

Access Duration: 15/06/2022 to 17/07/2022

Funding Instrument:	Research and Innovation Action
Call:	H2020-INFRAIA-2019-1
Call Topic:	INFRAIA-01-2018-2019 Integrating Activities for Advanced Communities
Project Start:	1 April 2020
Project Duration:	54 months
User Group Leader:	Chandan Kumar, (Indian Institute of Technology Guwahati)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 870620.

Report Information

Document Administrative Information	
Project Acronym:	ERIGrid 2.0
Project Number:	870620
Access Project Number:	[134]
Access Project Acronym:	SMPS
Access Project Name:	Smart Microgrid Protection System
User Group Leader:	Chandan Kumar, (Indian Institute of Technology Guwahati)
Document Identifier:	ERIGrid2-Report-Lab-Access-User-Project-SMPS-final
Report Version:	V1.0
Contractual Date:	31/08/2022
Report Submission Date:	dd/mm/yyyy
Lead Author(s):	Chandan Kumar, (Indian Institute of Technology Guwahati)
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Keywords:	system security, power quality, HIL simulation, European Union (EU), H2020, Project, ERIGrid 2.0, GA 870620
Status:	__ draft, _x_ final

Change Log

Date	Version	Author/Editor	Summary of Changes Made
24/08/2022	v1.0	Chandan Kumar	Draft report template

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List of Abbreviations

AFE	Active-front-end
AIT	Austrian Institute of Technology
CSV	Comma-separated value
DG	Distributed generation
LA	Lab access
LVDC	Low-voltage DC
LVAC	Low-voltage AC
MG	Micro-grid
PCC	Point of common-coupling
SC	Short-circuit
SCADA	Supervisory control and data acquisition
SMPS	Smart microgrid protection system
UP	User project

Executive Summary

At the end of the 19th century, AC power systems started to be widely used in the power distribution system by replacing the DC. The main reason behind these changes was that the AC could be more easily transmitted over a long distance and easily transformed into different voltage levels. However, increasing global warming, ageing of current power system infrastructures, increased awareness of limited energy generation resources, higher energy consumption standards, persuaded the scientific community to modernize the conventional power system. In addition to these, advancements in the field of semiconductor and power electronics converter technology also motivates to modernize the distribution system. To manage our future energy demands, a more configurable, flexible, informative energy system is needed. Due to this point of view, microgrids are emerging and becoming more attractive structures with the integration of renewable-based distributed generation (DG) units and energy storage systems (ESSs). In India, still, more than 50 percent of total energy generation comes from coal-based energy resources. Therefore, more penetration of renewable energy is required to reduce the climate change impacts of power generation.

The energy resources such as photovoltaic panels and fuel cells produce DC power and they can be easily connected to a DC distribution system directly or through a DC-DC converter. Using a DC distribution system, it is easier to incorporate more local energy storage and sources. To connect an energy source to a DC system only the voltage has to be controlled, as compared to the AC system where voltage magnitude, frequency, and phase must be matched.

The practical implementation of the LVDC microgrid distribution system is quite challenging. The major challenges are the lack of effective protection solutions that keep the AC-DC systems safe and reliable. DC faults are more difficult to detect and clear; their associated arcs lack zero crossing points and are more dangerous than in AC, and thus require a longer time to be cleared. Additionally, it is challenging to implement protection selectivity due to the comparatively low resistance and inductance in cables. Thus, the protection of an LVDC distribution system differs from the conventional AC distribution system. In addition, LVDC distribution system has more fault situations compared to the conventional distribution system. Therefore, a protection system designed for the conventional system may not protect the LVDC distribution system fully. Researchers have addressed several problems like design of solid state circuit breakers for the interruption of DC faults, converter based fault protection, fault current limiter circuits for protection of converter switches, etc. But still there is a lack of effective protection solutions. Therefore, in depth research is required for the practical implementation of LVDC distribution system.

The researchers have analysed the fault characteristics of asymmetrical faults on the AC side of the converter. They have also analysed the characteristics of the single pole to the ground as well as pole-to-pole faults. But the effects of AC side faults on the DC side has not been discussed much. Similarly, the effect of DC side faults on the AC side converters has very few analysis. Without considering these effects, protection systems may fail to operate appropriately in a hybrid grid system created by meshed DC and AC systems. For exploring these aspects, smart electricity systems and technologies laboratory under center for energy, AIT provided the facility of HIL environments for real-time simulation under Erigrid 2.0 project. By using typhoon HIL 604 setup, the short-circuit behaviours of AC and DC sides of the converters has been explored. Moreover, the effects of short circuit fault on the AC side of the converter to the DC side of the converter has also been explored.

Grid connected converters are simulated under a real-time environment to achieve the following goals:

1. To extract real-time data for different AC and DC faults in the hybrid microgrid.
2. To design better protection system that consider the effect of AC side faults on the DC side of the converter and vice-versa in the hybrid microgrid system.
3. To develop an advanced protection algorithm for fast and selective protection of faults for an LVDC distribution system.

Preliminary findings

1. Faults occurred in AC side of the converter affects the DC side converter's voltage and current. The simulations result show that if an asymmetrical fault occurs in AC side of the converter, negative sequence components will appear in AC side voltages and currents. The negative sequence components will not only change the ac side voltages, but also cause the second harmonics components of voltage and current in DC side.
2. The effect of DC side short circuit faults on the AC side of converter are considered. The simulation results show that DC faults have similar characteristics as symmetrical ac short circuit faults.
3. The DC side faults cannot be detected by AC side protection system unless it is a low impedance fault.

Open threads

1. Test performed to emulate hybrid distribution system does not contain several renewable based distributed generation units, energy storing elements, and different natures of loads due to low processing power of HIL 604.

1 Lab-Access User Project Information

1.1 Overview

USER PROJECT	
User Project Acronym	SMPS
USER Project Title	Smart Microgrid Protection System
ERIGrid Reference	134
ERIGRID2.0 TA Call	4th Call
USER GROUP	
Name (Lead)	Chandan Kumar
Organization, Country	Indian Institute of Technology Guwahati, India
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HOST RESEARCH INFRASTRUCTURE	
Name	AIT Austrian Institute of Technology
Country	Austria
Start and End Dates ('In-person')	14^{th} June to 17^{th} July 2022, 20^{th} to 22^{nd} July, 2022 14^{th} June 2022 to 17^{th} July 2022 (In person- Lakshmi Kant Rao) 16^{th} June 2022 to 17^{th} July 2022 (In person- Somnath Meikap) 20^{th} to 22^{nd} July 2022 (In person- Prof. Chandan Kumar)
Stay and Access days	Lakshmi Kant Rao | Stay Days 34 | Access Days 21 Somnath Meikap | Stay Days 32 | Access Days 20 Chandan Kumar | Stay Days 3 | Access Days 2

1.2 Research Motivation, Objectives, and Scope

1.2.1 Research Motivation

Increasing environmental concerns, depletion in coal reserves, and increasing energy demand of the main grid motivates to increase the penetration of renewable energy generation. To fulfill the increasing demand and peak demand by constructing a new large power plant is not an economical solution. High energy costs together with the limited fund to construct the new large power plant and long-distance transmission line losses are some constraints. In Fig. 1, the present scenario of energy in India is shown. It describes the generation of electric power from different resources over the period of 2016-22 in India. It clearly shows a rise in renewable energy source generation. But, still, it is considerably small in comparison with other energy sources used for power generation. One of the key reasons is lack of infrastructure for renewable distributed generation.

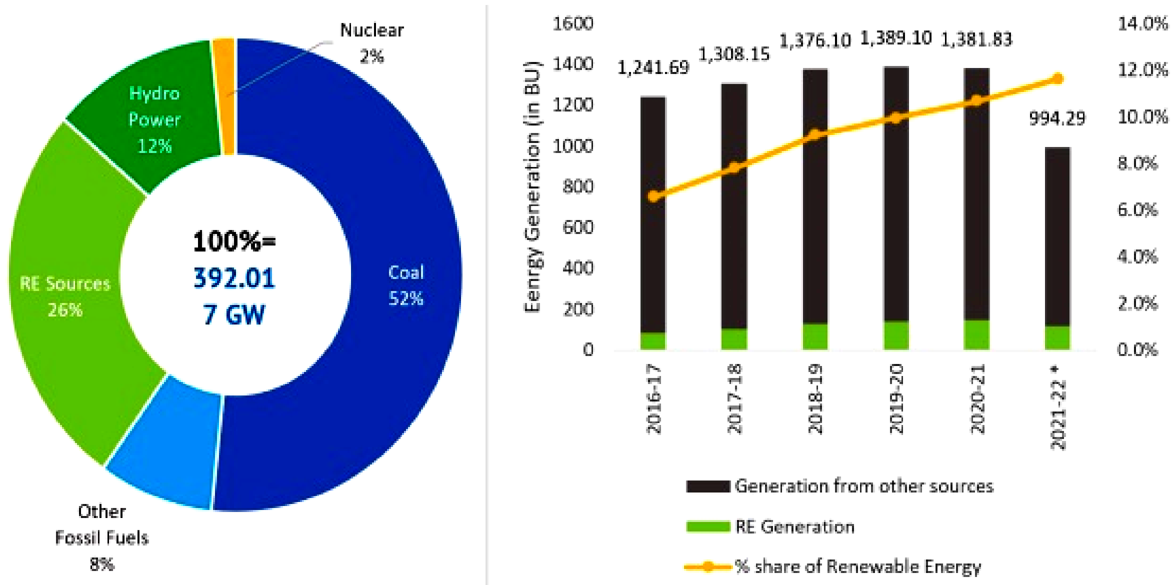

Figure 1: Installed capacity in India (as of 30 November 2021) and energy generation trend.

As most of the renewable energy resources directly produce DC power, their integration in the DC microgrid system is easy with reduced conversion losses and distribution losses. The protection of the DC distribution system is one of the major challenges in the practical application. The DC faults are more difficult to detect and clear due to lack of zero crossing points in the arcs. Additionally, it is challenging to implement protection selectivity due to comparatively low resistance and inductance in cables. Researchers have addressed many problems such as the development of solid-state circuit breakers for the interruption of DC faults, converter based fault protection, fault current limiter circuits for the protection of converter switches, etc.

1.2.2 Scopes and Objectives

The LVDC system is a promising technology. It can be used as an alternative solution to conventional AC distribution systems as it has a high level of cost efficiency and reliability. The use of a DC distribution system makes it easier to incorporate local ESS and DGs. The DGs and ESSs can be used as a backup power supply and grid support for commercial and residential buildings. The DGs and ESSs are arranged together to form an island operation mode. If the distribution zone is disconnected from the grid for any reason, DGs and ESSs operate in island mode to prevent power failure. The practical implementation of LVDC suffers from lack of effective protection solutions.

The main purpose of the lab access is to investigate the different types of faults that can occur at different locations in a hybrid microgrid system. Further, the impacts of fault at a location on the other parts of the microgrid system were investigated during the lab access. These faults are categorized into AC and DC faults. Further AC faults are divided into symmetrical and asymmetrical faults. Each fault has its own sign that helps in the identification of fault location and severity. Real-time data on the faults and their analysis makes the design of the protection system more practical. Thus, the real-time data of the simulated system can be used to design a better protection technique.

1.3 Structure of the Document

This document is organised as follows. Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the realized Lab Access (LA) User Project (UP). Section 3 outlines the performed experiments. Further, Section 4 summarizes the results and conclusions. Finally potential open issues and suggestions for improvements are discussed in Section 5.

2 State-of-the-Art/State-of-Technology

With the advancements in power electronics converters and the rapid increase of DC loads and DC distribution resources, LVDC distribution systems have the potential to be an alternative solution to conventional LVAC distribution systems (Emhemed & Burt, 2014). However, the practical implementation of the LVDC distribution system is challenging. The major challenges are the lack of effective protection solutions, difficult to detect and clear the DC faults, and lack of zero crossing points in the arc associated with the DC distribution system. In addition, the relatively small resistance and inductance in cables make the realisation of protection selectivity difficult. Such issues increase the need for fast and reliable DC protection solutions that reduce the risk and cost of operating such emerging hybrid AC-DC systems (Emhemed, Fong, Fletcher, & Burt, 2017).

At present, researchers have investigated the characteristics of a flexible DC distribution system. For example, reference (Guo et al., 2018) analyses the fault characteristics of asymmetrical fault that occurs on the AC side of the converter. Reference (Dai, Zhang, Chen, & Li, 2018) shows the characteristics of a single pole-to-ground fault on the DC side of the converter and divides the fault process into three subsequent processes: discharging the capacitor, feeding off the grid and stable state. References (Carminati, Ragaini, & Tironi, 2015) further divide the short circuit faults of the DC side converter into a capacitor discharge state, diode natural commutation stage and diode full conduction stage. However, these literature reviews only consider the fault characteristics of the DC side of the converter, without considering the effect of AC side faults. A special analysis of the fault characteristics of the DC side after the AC side fault is required to ensure a normal power supply in the non-faulted area. In (Salomonsson & Sannino, 2007), short-circuit fault characteristics in the radial distribution system are analysed. According to the fault current characteristics of different short-circuit points and different load ratios, a selective protection technique is implemented to realise the selective operation of the circuit breakers to improve the reliability of power supply.

The grid layout of a dc distribution system can be radial, ring or meshed. The structure of the system affects the availability and vulnerability to faults. A radial grid has a lower availability but less vulnerable to faults. However, a meshed grid has a higher availability but more vulnerable to faults (Huan, Guilian, Hongyang, Yi, & Meng, 2018). Researchers analysed that radial topology is preferred to LVDC distribution networks in low power reliability areas. The construction scheme should be chosen according to the distributed power permeability, the cost of DC circuit breakers and the load distribution. The single-terminal ring structure is mainly used for centralised distributed power supply. In this system, converters can be used to isolate the faults, where the voltage recovery is relatively slow after a fault recovery. Two-terminal and multi-terminal structures can be used for the power supply of the DC load concentrated area (Shenai & Shah, 2011). This shows that the network topologies should be designed to be less vulnerable to faults and continue to supply to the healthy part in case of faults occurrence. It should also integrate renewable energy resources and loads easily.

3 Executed Tests and Experiments

3.1 Testing Network

Three types of circuit topologies are considered for creating the simulations carried out under real-time environment. These topologies are:

1. Inverter mode of grid connected converter system.
2. Active front end (AFE) rectifier mode of grid connected converters.
3. Parallel operation of grid connected converters.

The practical data of all parameters utilized in the system are provided by the center for energy, Austrian institute of technology, Vienna. The network consists of converters, electric grid and loads. Fig. 2 shows a grid connected converter system for inverter and AFE mode of

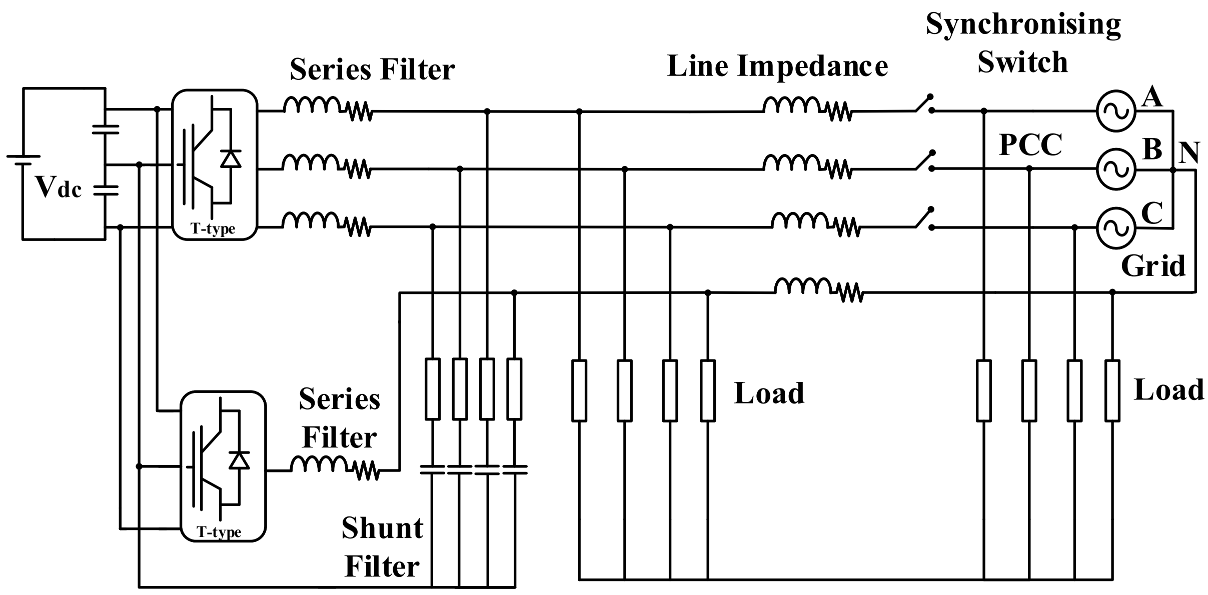

Figure 2: Grid connected converter for both inverter and AFE mode operation.

operation. Fig. 3 shows the parallel operation of grid connected converter system. Both the systems consist of T-type converter, passive filter, local loads, line impedance, a synchronising switch, DC source and electric grid. The synchronizing switch connects the converter when it synchronizes with the grid.

The T-type converter is similar to the three-level neutral-point clamped (NPC) inverter. It provides an additional output voltage level at 0 V, thereby offering improved harmonic performance over a standard two-level inverter. The grid connected converters used in the experiment are taken from typhoon HIL system library. It can be executed in different modes such as open loop, battery operation, PV operation, AFE mode and grid-form. In this experiment battery operation and AFE mode operation are used. The T-type converter has bidirectional power transfer capabilities. Hence, it is commonly used to interconnect AC and DC systems.

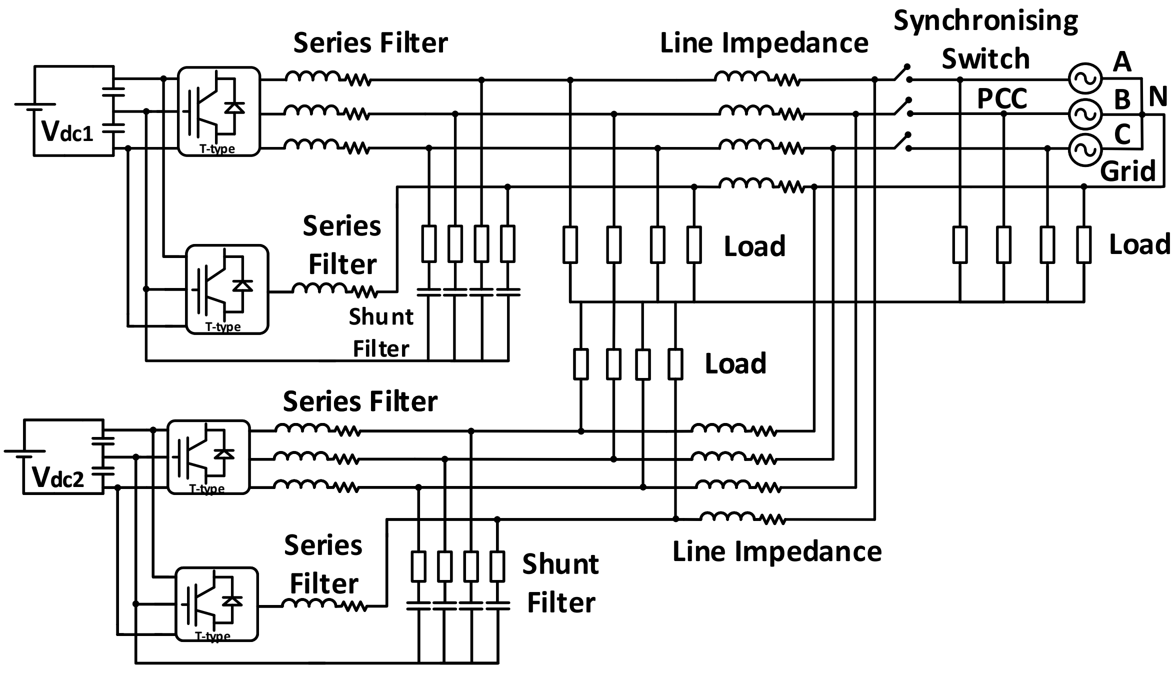

Figure 3: Parallel operation of grid connected converters.

3.1.1 Testing plans on the network

The lab access carried out in June-July 2022 in physical mode focused on developing a protection system by testing the different faults in the distribution system that occurs at distinct locations. The purpose of this test was to get real-time data on different faults that occur on the AC side of the converter as well as on the DC side of the converter. The obtained data can be used to design the protection algorithms. The summary of the testing plans and implementations is shown in Table 1.

The project work started with the interaction of AIT organizing members at smart electricity system and technologies laboratory, AIT. The AIT helped to solve technical issues faced throughout the Lab access. All the relevant data for modelling the real-life system was provided to the lab access user from the center of energy, AIT.

Table 1: Tests performed

Date	Activities
15^{th} June	Introduction between the user group and the AIT host members.
20^{th} June to 24^{th} June	Hands on with Typhoon HIL 604 real-time emulator and their various aspects.
27^{th} June to 1^{st} July	Simulation of parallel operation of grid connected converters, symmetrical and asymmetrical short-circuit faults as well as DC short circuit fault tests.
4^{th} July to 8^{th} July	Simulation of grid connected converters, symmetrical and asymmetrical short-circuit faults as well as DC short circuit fault tests.
11^{th} July to 15^{th} July	Simulation of active front end rectifier connected to grid, symmetrical and asymmetrical short-circuit faults as well as DC short circuit fault tests.

3.2 Test Set-up

The test set-up consists of a DSP based controller module designed for T-type converter system and an HIL setup made of typhoon HIL 604 that emulates real life grid connected system. In the first test setup, a single controller module is used to simulate the grid connected converter system. This converter can operate in inverter and rectifier mode to integrate LVDC and LVAC system. In the next test setup, the HIL system has been used to emulate a parallel converter system that interconnects two LVDC systems with one LVAC system.

The test analyses the different types of AC and DC faults in a hybrid microgrid system. A hybrid microgrid means a grid system that consists of LVDC and LVAC buses for power distribution. There are mainly two types of faults, open circuit and short circuit faults. Due to higher severity of short circuit faults, it has been the key focus of experimentation. In an AC system, there are two kinds of short circuit faults: symmetrical short circuit fault and asymmetrical short circuit fault. Symmetrical short circuit fault consists of three-phase short circuit fault and three-phase to ground fault. Asymmetrical short circuit fault consists line to ground short circuit fault, line to line to ground short circuit fault, etc. The most frequent short circuit fault in AC system is line to ground fault, whereas the most severe short circuit fault is from a three-phase to ground fault.

3.2.1 Effect of AC faults in the distribution system

A three-phase or L-L-L fault causes the terminal voltage to fall to a very low value. The voltage and current waveforms during L-L-L fault have a lower degree of harmonics than asymmetrical faults. This can be accredited to the fault's symmetrical nature. When the DC distribution is operating normally, the converter controls the magnitude and phase of AC side voltages to control the active power and reactive power of the system. Due to the constant voltage control function, the voltage of the DC side converter remains constant, and the power changes with the change in load. When asymmetrical faults like line to ground short circuit, line to line short circuit, etc. occur on the AC side of the converter, negative sequence components will appear in AC side voltages and currents. The negative sequence components will not only change the ac side voltages, but also causes the second harmonic component of voltage and current in DC side.

3.2.2 Effect of DC faults in the distribution system

When single pole to ground dc fault occurs, primary fault consequence is the direct discharging of the capacitor on the faulty pole. The voltage of the healthy pole will rise, because of the action of the DC voltage controller. The controller will impose an over-voltage on healthy pole capacitor even if the restriction of the DC pole arrestor is considered. The faulty pole capacitor suffers an overcurrent due to rapid discharging through fault position. The voltage of the faulty pole capacitor will also decrease to a very low level.

When a pole to pole DC short circuit fault occurs, the capacitors are discharged through DC cables, thus a high transient current will flow. It causes rapid decrease of DC voltage and a substantial increase in the AC side current. After the capacitor is completely discharged, the anti-parallel diodes will be forward biased and will allow a high steady state fault currents to be supplied from the AC grid to the fault point. To avoid this, besides blocking the converter, the DC line is needed to be isolated by tripping AC circuit breakers.

3.2.3 Typhoon HIL SCADA

The Typhoon HIL SCADA is used to visualize the results of the setup. The SCADA inputs help to control the switches, such that loads and converters can be activated and deactivated during the simulation. The capture settings of the scope help in visualizing the instantaneous responses of the voltages, currents, and power with the user choices. The real-time simulations were carried out at smart electricity system and technologies laboratory (AIT). The snapshots of the SCADA are captured and these are shown in Figures 4 and 5. Figure 4 shows the SCADA control panel for the hybrid microgrid system. Whereas, Figure 5 shows the SCADA control panel for converter DSP controller module. Figure 4 shows the magnitude and phasor of AC voltage, current of grid as well as converter. It also shows the operational frequency, DC link voltage and current of the converter. Figure 5 shows the expected active power, reactive power, converter DC link voltage, AC output voltage, etc. as per the controller. Table 2 represents different model settings for real-time simulation in HIL 604 environment.

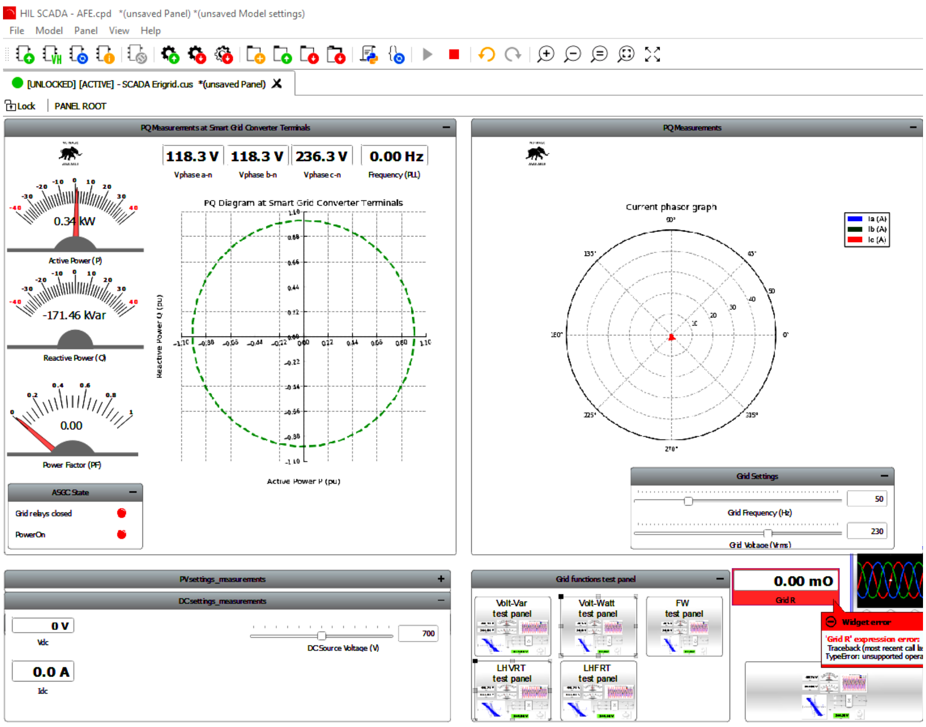

Figure 4: Typhoon HIL SCADA snapshot of AFE mode of operation of grid connected converter when L-L faults occurs.

3.3 Data Management and Processing

The data required for project consists of real converter system design parameters and hybrid distribution system network parameters. All the relevant data for modelling of real system was

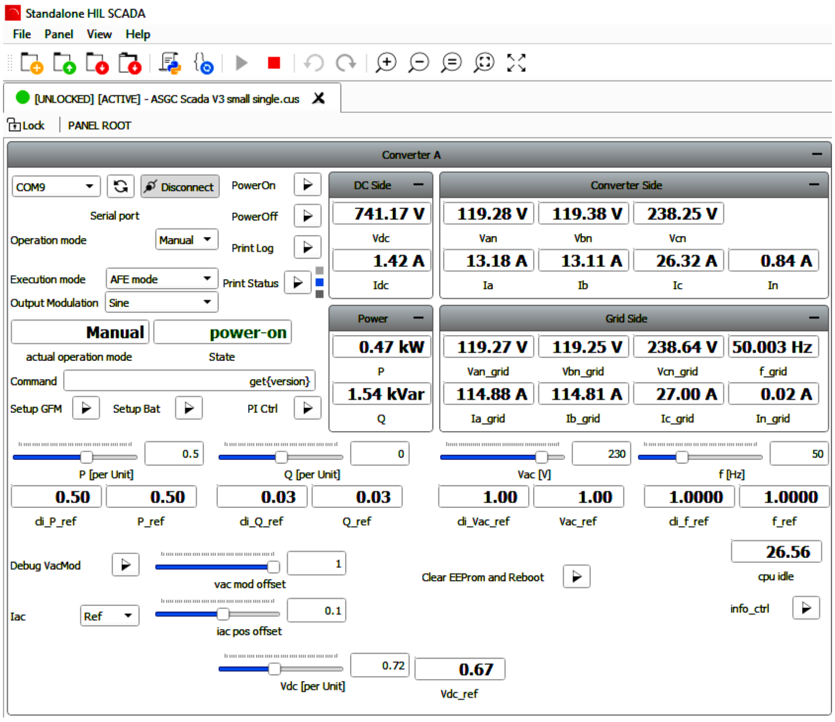

Figure 5: Typhoon HIL SCADA for grid connected converter control for various operation.

provided to the lab access user from center of energy, AIT. The converter system has been modelled as per a real lab setup in smart electricity systems and technologies laboratory, center of energy, AIT. During the HIL simulation, the required data were stored in both images and CSV files format. The stored data contains both normal operation as well as faulty operation of the system. The waveform/results obtained from experiments help us to understand the real life scenario of grid. Whereas, further analysis of data by using MATLAB software helps us to find an alternative approach to detect, and isolate AC and DC short circuit faults. The design of protection system needs both data of healthy as well as faulty operation which is essential for protection algorithm design. Most faults severely harm the physical system therefore, simulated using an HIL configuration. The collected data will be mainly processed for proper modelling of faulty system by using Fourier analysis.

Table 2: Different model settings for real-time simulation in HIL 604 environment

Model Settings	Parameters	Values	Comments
Sources	DC link voltage Vs1 and Vs2	750 V DC	
	Grid simulator phase voltages	230 V AC at 50 Hz	
Contactors	Multipole single through contactor		Contactors are modelled with ideal switches that instantaneously change their states upon input signal change.
	Fault switch		Used to create short-circuit (SC) faults.
Switching Blocks	S1, S2, S3 and S4		Active high/ Active low and It depends on control methods. For example, if it is controlled by a model, logic is always active in high.
SCADA Inputs	Grid connected threshold	30 V	
	Neutral	0/1	“0” indicates neutral is not connected and “1” indicates neutral is connected.
	Loads	0/1	“0” indicates load is not connected and “1” indicates load is connected.
	Sg1 and Sg2	0/1	Digital signal is given to logic gates for short-circuit fault. “0” stands for the switch is open i.e. no SC fault and “1” stands for the switch is closed i.e. SC fault is created.

4 Results and Conclusions

4.1 Discussion of Results

This section summarizes the results obtained from the SMPS project during the lab access of smart electricity system and technologies laboratory (AIT). Primarily, focus of the research was on finding the effect of LVAC fault on LVDC and vice versa. So, the converters and AFE rectifiers were chosen due to their wide use in the interconnection of LVDC and LVAC meshed grid systems. The results consist of symmetrical and asymmetrical AC faults along with DC short circuit faults in hybrid grid. The results obtained in this project are further divided into sub-sections for proper explanation.

4.1.1 Inverter mode of grid connected converter system

This section describes the various AC and DC faults occurring in a grid connected converter system. In order to create faults in the system, which is simulated in a Typhoon HIL environment, contractors have been used. The contractors are opened or closed via the master contactor controller in SCADA model shown in Fig. 4.

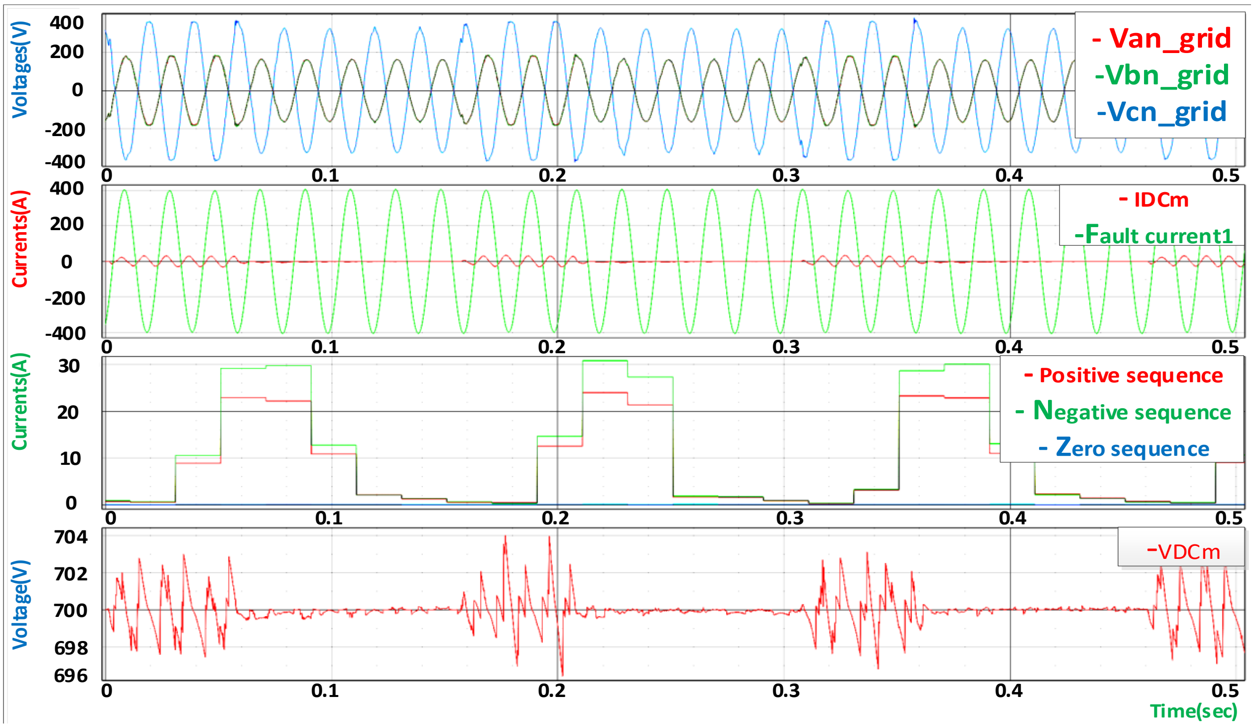

Figure 6: : (a) Grid voltage during L-L fault, (b) fault current in AC side and DC side from converter during fault, (d) sequence current of converter in AC side, (e) DC link voltage variation during fault.

Fig. 6(a) shows the grid voltages during the L-L fault at PCC. It can be seen that the voltages of phase A and B are same and reduced to lower value. In Fig. 6(b), DC current and L-L fault current are shown. Fig. 6(c) shows the sequence components currents of converter, and Fig. 6(d) shows the DC voltage. Fig. 6(b) and (d) shows that there is sustained oscillation in the DC

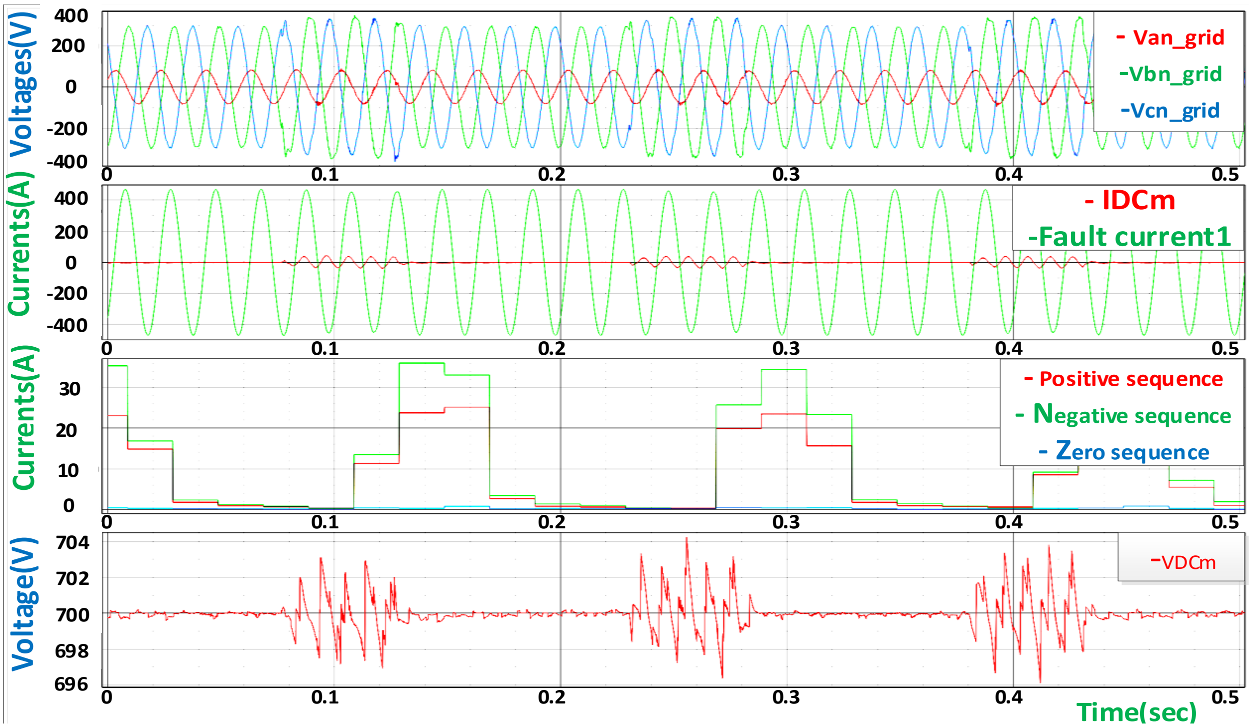

Figure 7: (a) Grid voltage during L-N fault, (b) fault current in AC side and DC side from converter during fault, (d) sequence current of converter in AC side, (e) DC link voltage variation during fault.

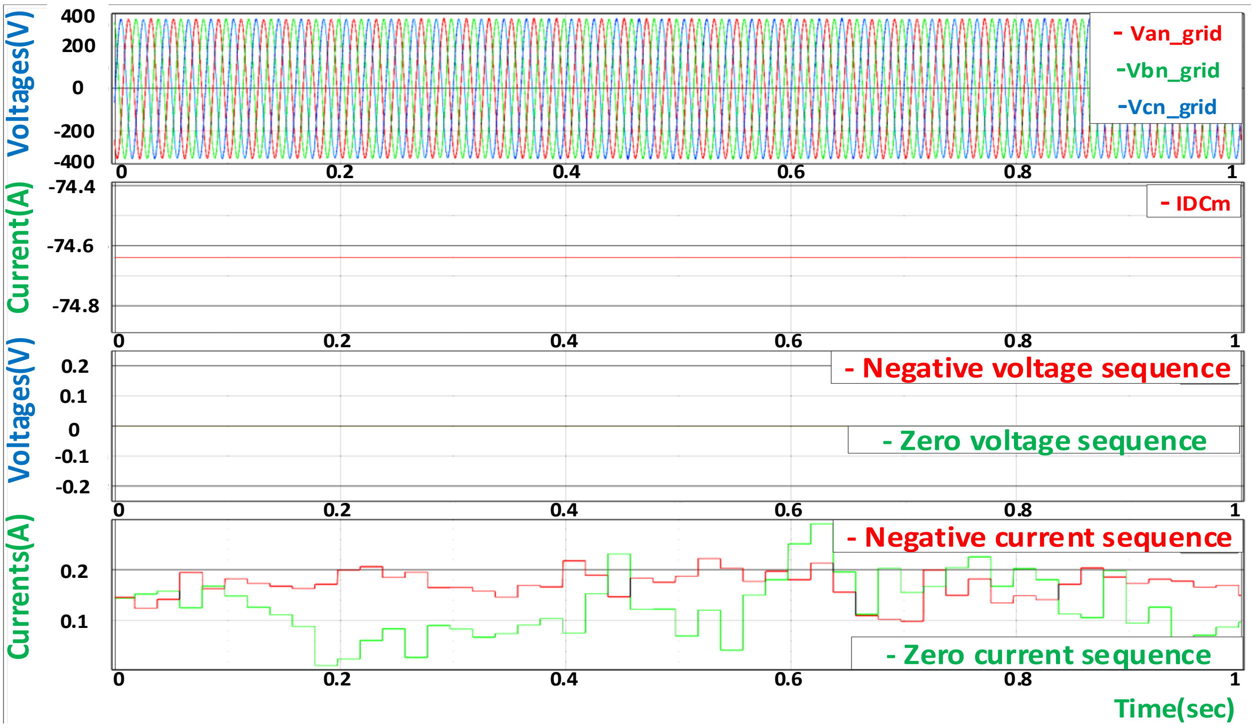

Figure 8: Grid voltage during DC side capacitor short circuit fault, (b) fault current in DC side from converter during fault, (d) sequence components of grid voltage in AC side, (e) sequence components in the grid current during fault.

side current and voltage during L-L fault. The reason behind the oscillation in dc side is due to unbalance current flowing in AC side. This oscillation may affect the performance of DGs and

DC loads connected to DC bus.

Fig. 7(a) shows the grid voltages during the L-N fault at PCC. It can be seen that phase A voltage is reduced. In Fig. 7(b), DC current and L-N fault current are shown. Fig. 7(c) shows the sequence components currents of converter, and Fig. 7(d) shows the DC link voltage. Fig. 7(b) and (d) shows that the nature of DC side current and voltage is similar to L-L fault case.

From the above results it can be concluded that the L-G and L-L faults cannot be distinguish by nature of DC side voltage and current waveforms. The presence of sustained oscillation in DC side voltage and current can be considered as occurrence of asymmetrical faults (L-G, L-L) in AC side. Although, AC side faults can be identified by conventional approaches. Alternative protection system can be implemented by using the DC parameters i.e. DC current and DC link voltage of the converter. This approach can be implemented when a large number of DGs are present in the hybrid microgrid, where the fault detection issues are very common. Since the sensor for the DC side is cheaper with better resolution. DC current or voltage-based fault protection systems can be cheaper and faster.

Fig. 8(a) shows the grid voltages during a DC-Link capacitor short circuit fault. In Fig. 8(b), DC fault current is shown. Fig. 8(c) shows the sequence components of grid voltage. Fig. 8(d) shows sequence components of grid current. Fig. 8(c) and (d) shows no significant rise in sequence components in grid voltage and current. This shows that the DC-link capacitor short circuit fault act as a symmetrical AC fault by nature and can be detected by AC side.

When the fault occurs, DC link capacitor discharges through the DC cables, thus resulting into a large DC current. Simultaneously rapid decrease in DC voltage and a substantial increase in the AC side current is observed. Switches of the converter have to be blocked immediately to protect from high fault current. Due to high AC fault current, AC circuit breaker attempts to isolate the AC side from DC side. However, DC current still circulates through freewheeling diodes, AC filter capacitors and line inductance by forming a loop. This results in continued circulation of fault current even after the AC circuit breaker have opened. Hence the detection of DC faults in AC side as a symmetrical fault can be used to open both AC side and DC side circuit breaker to isolate the AC and DC side system. This technique can protect the converter such that switches does not damage from overcurrent.

4.1.2 Active front end rectifier mode grid-connected converter system

In AFE mode, the converter acts as a rectifier to supply power from LVAC to LVDC system. It is required during the non-generation period of DG sources or the peak load period in the LVDC grid. The effect of unsymmetrical faults has been analysed in the AFE mode operation.

Fig. 9(a) shows the grid voltages during AFE rectifier mode operation. In Fig. 9(b), DC current of the converter is shown. Fig. 9(c) shows the sequence components of AC side current. Fig. 9(d) shows the DC link voltage during normal AFE mode operation. Fig. 10(a) shows the grid voltages during the L-L fault at PCC. It can be seen that the voltages of phase A and B are the same and reduced to a lower value. In Fig. 10(b), DC side current is shown. Fig. 10(c) shows the sequence components currents of the converter. Fig. 10(d) shows the DC link voltage during L-L fault. Fig. 10(b) and (d) shows that there is sustained oscillation in the DC side current and voltage during L-L fault. Fig 10(b) shows that the DC current of the converter has zero crossing point which can be used to disconnect the DC source easily using LVAC circuit breaker system.

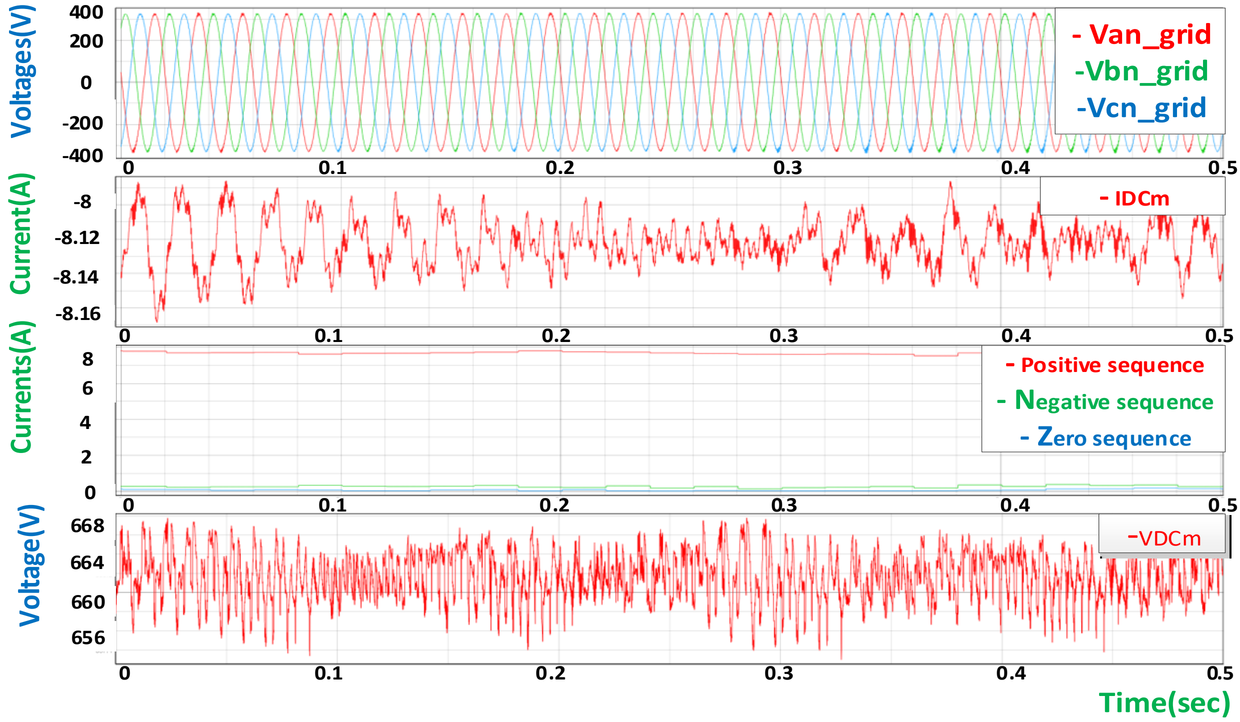

Figure 9: (a) Grid voltage, (b) current in DC side, (d) sequence components of grid current in AC side, (e) DC link voltage of converter in AFE mode operation.

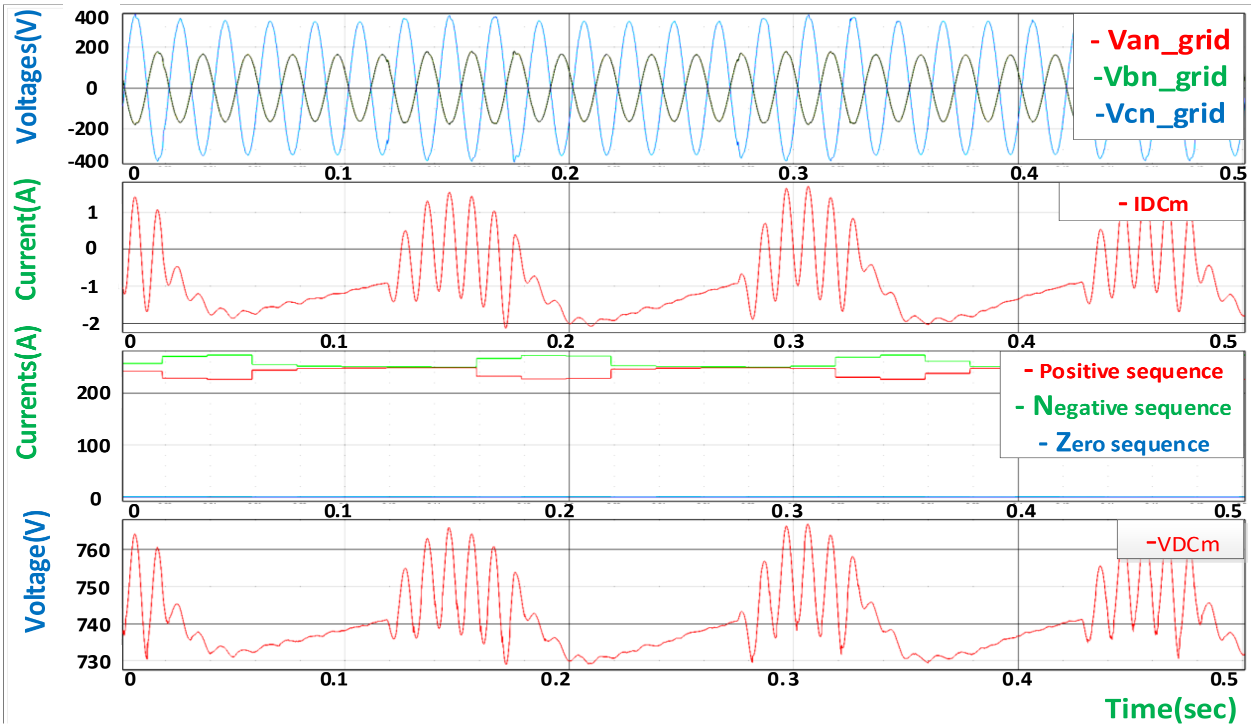

Figure 10: (a) Grid voltage during L-L fault, (b) current in DC side during fault, (d) sequence components of grid current in AC side, (e) DC link voltage of converter in AFE mode operation.

Fig. 11(a) shows the grid voltages during the L-L fault at PCC and fault current flowing between phase A and B. In Fig. 11(b), DC side current is shown. Fig. 11(c) shows the sequence components current of converter. Fig. 11(d) shows the DC link voltage during L-L fault after

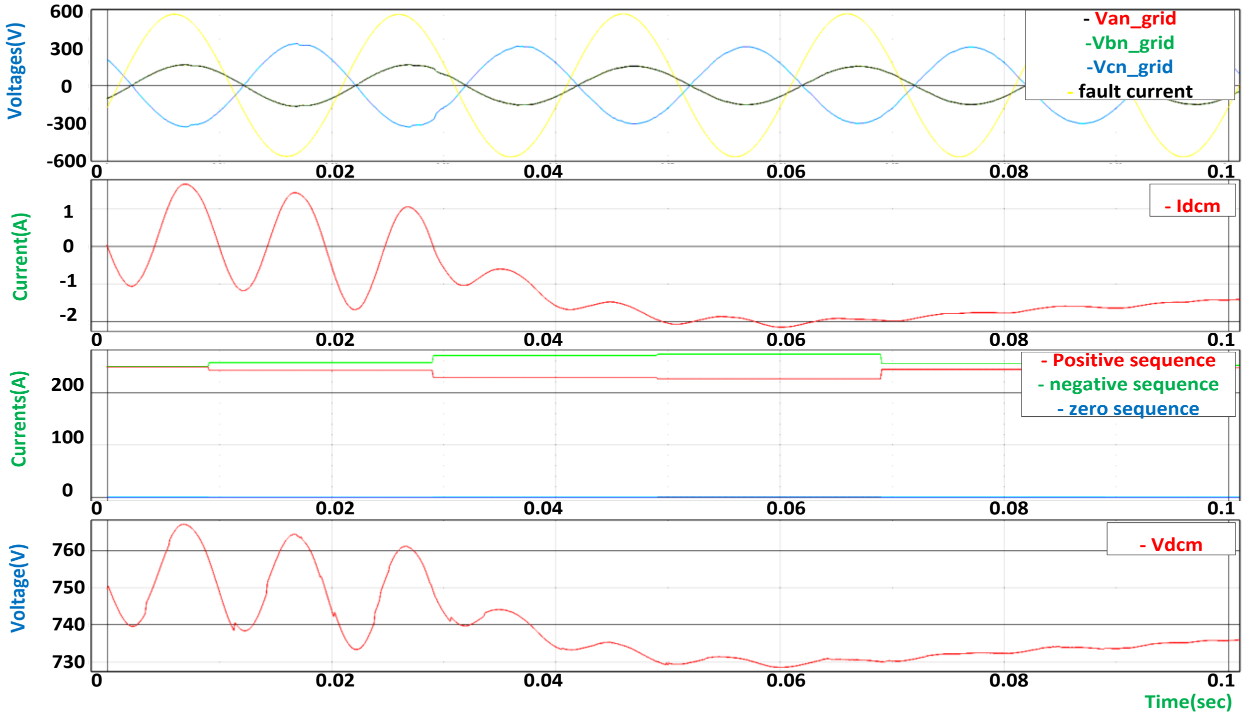

Figure 11: (a) Grid voltage during L-L fault after LVDC disconnection, (b) fault current in DC side during fault, (d) sequence components of grid current in AC side, (e) DC link voltage of converter in ALE mode operation during AC fault with LVDC grid disconnection.

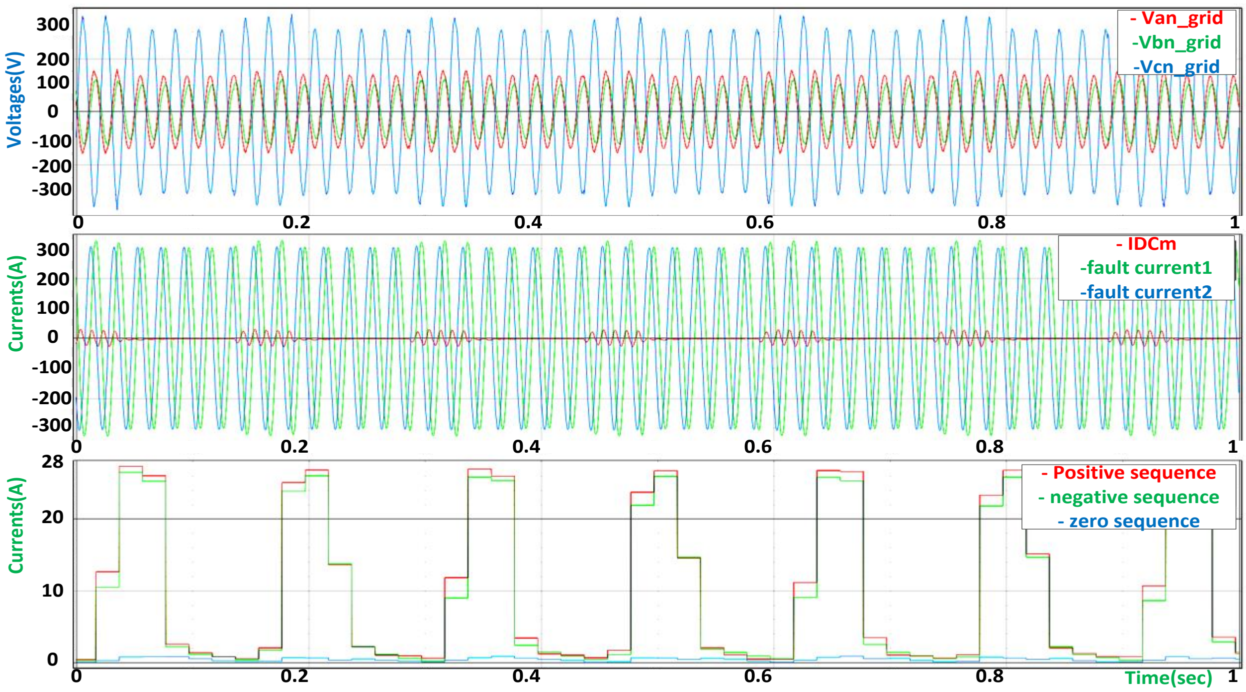

Figure 12: (a) Grid Voltage during L-L-N fault, (b) fault current at AC side and DC side of the converter, (c) sequence current for AC side current component in converter.

disconnection of DC supply in AFE mode operation.

Fig. 11(b) and (d) shows that the DC link voltage of converter is becoming constant and the DC link current is settling towards zero. This experiment shows that if DC source or LVDC grid is disconnected faster than converter, then the current flowing through converter will reduce significantly. This can help in reducing the effect of L-L fault on converter system.

4.1.3 Parallel grid connected converter system

Fig. 12(a) shows the grid voltages during the L-L-N fault at PCC. In Fig. 12(b), DC current and L-L-N fault current are shown. Fig. 6(c) shows the sequence components currents of the converter. Fig. 12 shows similar results as shown in Fig. 6. So, It can be concluded that even if there is more number of converter or LVDC system interconnection, the characteristics of the dc side current and voltage of the converter remains the same.

4.2 Conclusions

Different potential faults and their characteristics have been studied in order to put a hybrid low voltage distribution system into practice. The primary focus was to analyses the different AC and DC faults. This work also considered the effect of AC side faults on DC side of the converter and vice-versa. The key conclusions of the work are summarized as follows:

1. The unsymmetrical AC faults can be easily distinguished by the LVDC side via the DC side current and voltage waveforms. This will allow the LVDC system to easily utilize circuit-breakers to remove connections to the faulty LVAC side. It also provides an alternative process to detect unsymmetrical faults.
2. During a DC side fault, the AC side of the converter detects the fault as a symmetrical fault. This fault cannot be detected easily unless it is a low impedance fault.
3. AFE rectifier mode operation results show the effect of unsymmetrical AC faults on the DC side of the converter. It also shows the reduction in DC fault current when the DC source is disconnected via circuit breakers from the converter. The reduction in fault current makes the disconnection of the converter from LVAC grid.

5 Open Issues and Suggestions for Improvements

The Typhoon HIL 604 processor was used in the SMPS project's implementation. Table 3 shows the difficulties that were faced and remain unsolved.

Table 3: Status of the real-time simulations SMPS

Issue	Status	Comments
Designing of entire LVDC and LVAC grid system in Typhoon HIL	Unresolved	The entire LVDC and LVAC network cannot be formed due to element limitations in Typhoon HIL. Each Typhoon HIL 604 can be used for two controller systems and thus can be used to design two converters.
Utilization of DC-DC Converters in the creation of LVDC grid system	Unresolved	The controller systems available were of converter systems; thus, protection schemes on DC-DC converters could not be explored.

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 870620.