

A Virtual HIL Approach for the Optimization of Three Phase Grid Connected Converter

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Received 17 September 2022; Accepted 12 February 2023

Abstract

A significant drive is currently underway to integrate an ever-increasing number of distributed energy resources into the power system, termed the "Smart grid." For effective operation of the grid at all levels, it is required to adopt well-advanced software and hardware components. In any instance, the entire process is time consuming and only provides a partial view of the system's behavior under various nominal and fault operating conditions. The Hardware-In-the-Loop (HIL) approach is widely interpreted as a valuable prototype tool for Grid Connected Converter (GCC) development and validation at both the converter and power grid at all levels. The paper is based on the Controller - HIL (C-HIL) approach that demonstrates the Typhoon HIL control center which provides remarkable efforts to test and optimize the GCC control loops. It includes the test and optimization of the converter harmonic performance, optimization of the grid filter, injection of active and reactive power into the grid and analysis of various ride through faults in the system. It also includes the design of the current controller, Total Harmonic Distortion (THD) analysis and comparison of the model with and without implementing the maximum power point optimization technique.

Keywords: HIL, Particle Swarm Optimization, GCC Controller, Typhoon HIL Control Centre

1. Introduction

Photovoltaic (PV) energy offers a high potential for supplying energy with minimal environmental impact because it is clean and pollution-free. Photovoltaic or solar arrays are composed of a large number of solar cells connected in series and parallel. One application for photovoltaic energy is as a peaking power source in a distributed energy system. Sustainable power is progressively viewed as fundamental for meeting future energy needs [1]. PV panels usage has increased compared to the last twenty years in India. According to a survey conducted by International Energy Agency PV Power System Program, India has a total of 44.3 GW solar installed capacity as of August 2021 [2]. The growth of photovoltaic (PV) distributed generation in recent years has been essential in reaching climate and energy policy. This rise is due to both the drop in technological prices and the global support policies that have been implemented [3]. In recent trends, hardware-in-the loop simulation has become a very powerful tool for testing grid connected controllers at all levels [4] with very low time step and sampling frequency by using Typhoon HIL software for the grid validation process [5]. Many real time studies are carried on power grid control functions and its architecture to determine the behavior of grid connected system under transients [6], but PV integrated grid system has many challenges such as power system stability, voltage deviation and power quality [7]. A Hardware-in-the loop simulation is a sophisticated approach which is used to test and develop real-time embedded systems. It is easy to validate, test and optimize the grid level faults using HIL simulation.

The Typhoon HIL field-programmable gate array solver

is a significant type of technology that provides enhanced real-time modelling of power electronics and small-scale power system networks. The virtual HIL environment is shown in Figure 1. It lays a strong groundwork for a wide range of applications from model-based control development through test-driven design and converter C-HIL testing all the way to virtual system integration of modern micro grid analysis and power electronics-enabled power systems [8]. A virtual HIL (V-HIL) approach is an innovative technique to affiliate the users with the Typhoon HIL software toolchain without the usage of a real hardware device.

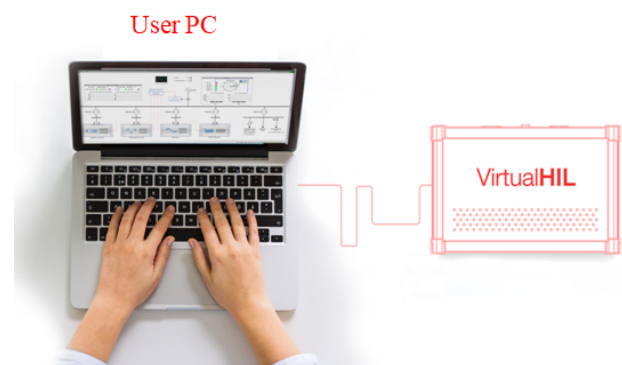


Fig. 1. Virtual Hardware-in-the Loop Environment.

The core of the VHIL is Typhoon HIL Control Centre which is based on the Model based system Engineering (MBSE) tool chain that can design, analyze, verify and validate the system development phase. The Typhoon Hardware-in-the loop simulators are built with patented MARTHA (Multi core architecture for real time hybrid

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doi:10.25103/jestr.161.17

applications) technology which is highly versatile and has low very low latency, predictable time execution rate and it has a fast response to the simulations of power systems and power electronics on Real time operating systems (RTOS) [9]. Many applications such as developing motor driver circuits, testing the transmission lines, Internet protocols and marine power systems are perfectly validated in this software with acts as a barrier to outperforming all the technologies present in this field. The modelling and compiling process in this software are explained.

The model building in Typhoon HIL software and its algorithm is depicted in Figure.2. This procedure is used for optimal testing and validation. After computer modelling, simulation is done to know any errors while operating [10]. There are two main stages in Typhoon HIL software they are Schematic editor and SCADA panel. The simulation part is executed and code generation takes place in the schematic editor and the .tse file is generated after which it is loaded into the SCADA panel to visualize the results.

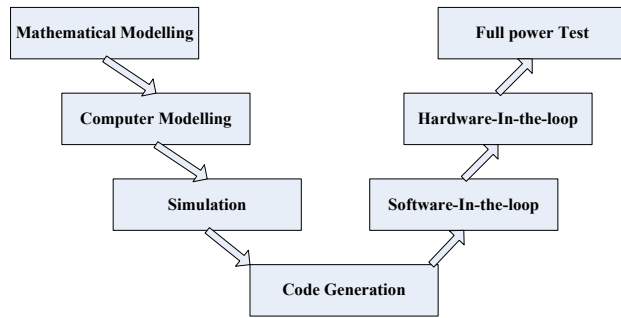


Fig. 2. Steps Followed in Testing a Model in the HIL toolchain.

A few existing technologies such as MATLAB/Simulink and OPAL-RT supports hardware-in-the loop simulation but the Typhoon HIL technology is far better due to its ultra-low latency and very low time step as mentioned in Table 1.

Table 1. Comparison Typhoon HIL & other platforms.

| Properties | Typhoon HIL | Other Simulation Platforms |
|---------------------------------|------------------------|----------------------------------|
| Software & hardware integration | Vertical Integration | Third party software integration |
| Processor type | FPGA based | CPU based |
| Solver | Component based solver | Application based solver |
| Code generation | Automatic generation | Generated by VHDL |
| Time step | Down to 500ns | 10+ μ s |

2. Proposed model

This paper deals with the Virtual Hardware-in-the Loop (VHIL) simulation with Particle Swarm Optimization (PSO) of three phase grid connected controller which is executed in FPGA based Typhoon HIL. The virtual emulation is a mimic of real time simulation with the User PC as the main controller. Here the study and modelling of optimized GCC are tested with PSO algorithm under new technology software with and without implementing the algorithm. Figure 3 depicts the block diagram model.

The output of the PV array is connected to the boost

converter with MPPT control of the PSO algorithm which gives the best voltage from the swarm iteration and fed to the boost converter to boost the voltage. An inverter converts DC to AC with harmonics, so grid filters are adopted to remove the disturbances.

2.1. Photovoltaic Source

The PV block is connected as a voltage source to the system and it can be implemented in the SCADA part with a desired PV panel. The output of the PV panel is connected to MPPT control which is called an Advanced C function block in the Typhoon HIL software where PSO code is dumped into it to achieve the optimization in the proposed model. The parameters which are attained from the PV source are fed to an advanced C function block where the product of voltage and current occurs to obtain maximum power. The best voltage at the MPP from the optimization is fed to boost the converter to get maximum efficiency from the panel.

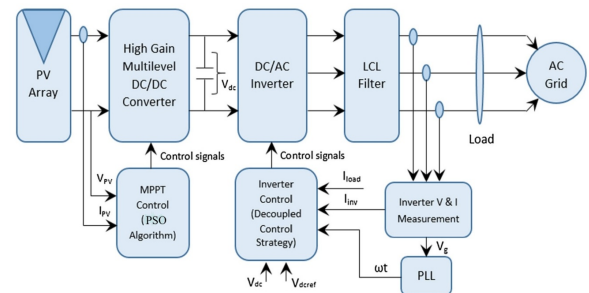


Fig. 3. Block Diagram of PSO Optimized Grid Controller.

2.2. PSO based MPPT Algorithm

The MPPT algorithm explains the PSO approach to solve the MPPT controller problem in a PV system. PSO is a computer method for problem solving that involves iteratively improving a possible solution in terms of a quality metric. This method begins with a collection of periodically produced possible solutions called particles. These particles will search for the best optimal solution around the space. The next location is determined by the best known position of each particle, as well as the best known position of all other particles combined known as a swarm.

This approach outperforms all others, including the Perturb and Observe the incremental conductance method, and the constant voltage method [13]. To find the best position of the particle and velocity below equations are used.

$$x_i^{j+1} = x_i^j + v_i^{j+1} \quad (1)$$

$$v_i^{j+1} = wv_i^j + a1k1\{P_{besti} - x_i^j\} + a2k2\{G_{besti} - x_i^j\} \quad (2)$$

The representations of all the terms are expanded here, where w is the weight of inertia constant, the coefficients of acceleration are a_1 and a_2 while the random values are k_1 and k_2 which ranges from 0 to 1. The best position of a particle is P_{best} and the best position of a swarm will be G_{best} . To initiate the PSO algorithm firstly the position (x) variables in (1) and (2) are used as current references ($I_{dc, ref}$), while the velocity (v) variables are used as correction terms for the current references. The PSO algorithm goal is to increase the converter's input power. The particle position and velocity are iteratively updated using the following equations:

$$\phi_i^{j+1} = w\phi_i^j + a1k1\{I_{Pbest}^j - I_{dc,i}^j\} + a2k2\{I_{Gbest}^j - I_{dc,i}^j\} \quad (3)$$

$$I_{dc,i}^{j+1} = \varphi_i^{j+1} + I_{dc,i}^j \quad (4)$$

Here $I_{dc,i}^j$ is the reference current for input, $I_{dc,i}^{j+1}$ is modified current reference for input. According to the flow chart presented in Figure 4, the PSO algorithm delivers initial values of dc current reference to the converter controller and senses the produced power to begin the optimization process. The algorithm then changes the dc current reference and transmits the new currents to the converter which is based on equation (3) and (4). Until the convergence requirement described in equation (5) is satisfied, the process of creating new references and calculating related power continues to iterate to choose the best swarm value.

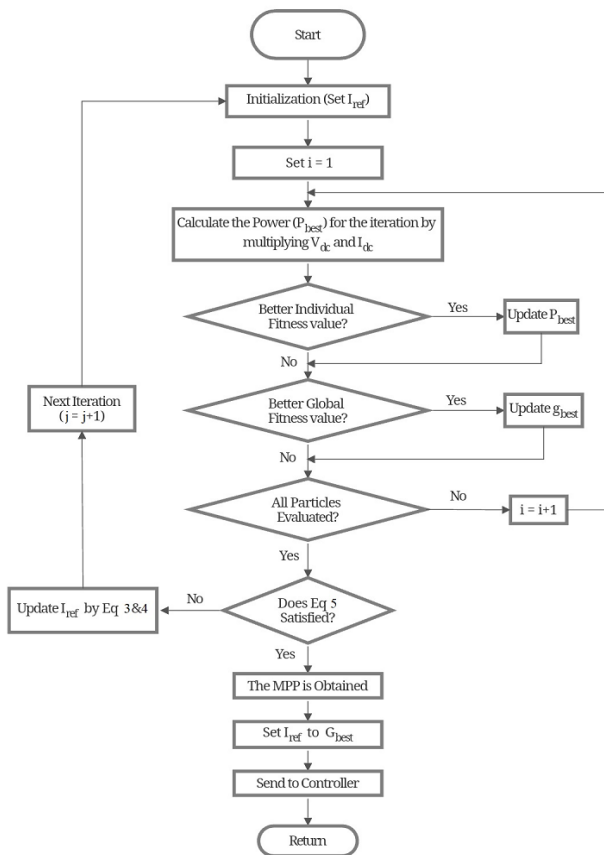


Fig. 4. Flow Chart of Proposed PSO Algorithm.

3. HIL Schematic Modelling of Circuit

The proposed model is designed on the Typhoon HIL control centre using the schematic editor panel in the software tool. It consists of four main tools after opening the software they are Schematic Editor, HIL SCADA, Typhoon Test IDE and Test Suite. Firstly the model needs to be drafted using schematic editor where all the required blocks are easily available on the library.

To test this circuit virtually VHIL is selected and the whole model needs to be saved as .tse file with a specific path. Set all the parameters to the designed value of the model and run the model to check for any errors. Then compilation process can be executed to generate the C code. The real time simulation can be performed using the Typhoon HIL 402 device can be depicted in the Figure 5. It has a user PC and a real time HIL device with configuration 1, which acts as a

controller interface between the system and the device.



Fig. 5. The real time simulation setup with Typhoon HIL 402 device.

The values of all the parameters which are used in the simulation of proposed model are tabulated in Table 2. These are called in schematic editor before compiling the model to make ease of running the model without any error logs. If any computational errors model will not load into SCADA panel.

Table 2. Simulation parameters.

| Parameter | Value |
|--------------------------------------|----------------------|
| Time step (Ts) | 200μs |
| Resistance (R) | 0.1Ω |
| Inductance (L) | 1mH |
| Capacitance (C) | 2mF |
| Filter capacitance (C _f) | 1μF |
| Irradiance | 1000W/m ² |
| Temp | 25° C |
| Vdc Link | 800v |
| V _{grid} | 400v |

As seen in the Figure 6, the circuit is made up of blue and black segmentation. The plant or electrical part of the model is represented by using black color, while the controller part or signal processing part is represented by the blue color.

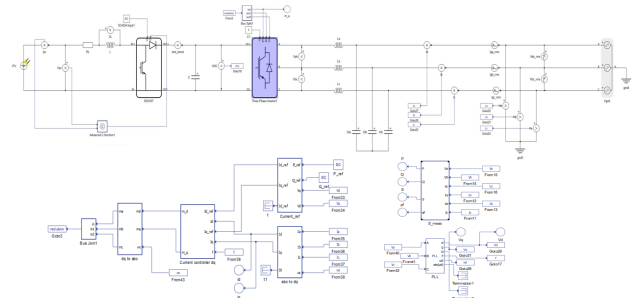


Fig. 6. Schematic Circuit Diagram of Proposed Model in HIL.

3.1. Modelling of Boost Converter

The HIL modelling of boost converter is explained as shown in the Figure 7 with its properties and assumed values assigned in this model. It's a DC-DC converter with a lower input voltage than its output. This converter boosts the output voltage and it is widely used in solar applications to increase the voltage level of solar electricity.

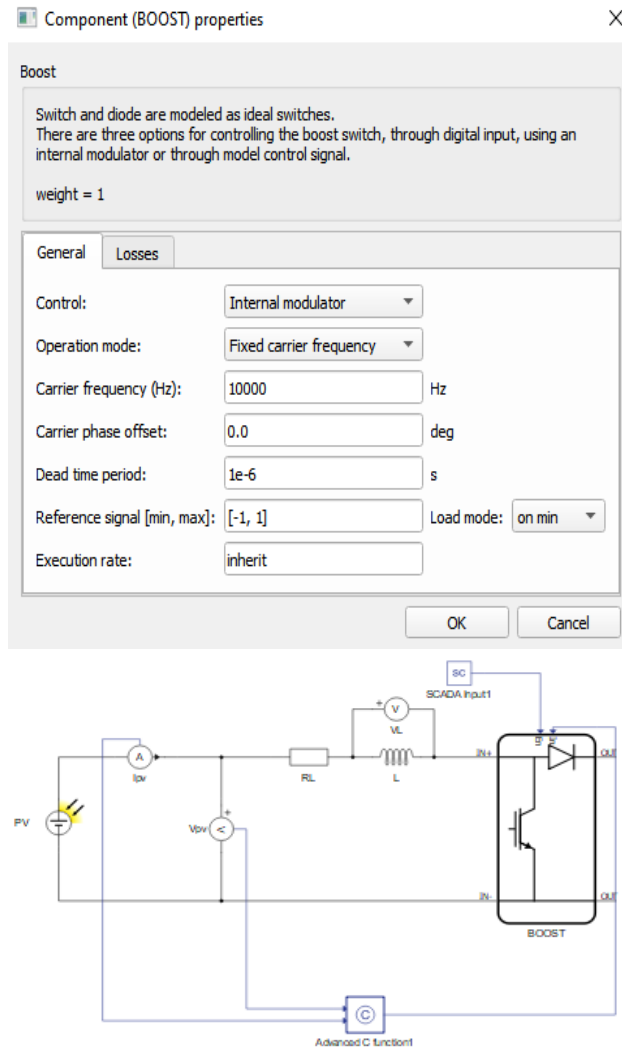


Fig. 7. HIL Modelling of Boost Converter.

From the PSO algorithm, the best voltage at maximum power point (V_{MPP}) using swarm iteration is fed to this boost converter. To remove the input harmonics RL filter is used. The carrier frequency is set to 10 KHz with the internal modulator control. It means it enables the PWM control to the converter with two configuration settings named as enable and input where enable acts as a switch and input acts as a reference signal to the internal PWM modulator [14].

3.2. Modelling of Three Phase Two Level Inverter

The inverter block's features are depicted in Figure 8, and it is controlled by an internal modulator. The inverter is used to control magnitude and frequency of the alternating current output voltage [15]. It is also controlled in internal modulator mode. There are different control modes for three phase inverter which are based on the digital inputs. It converts the DC signal into Alternating current with some disturbances at the output which can be removed by using grid filters.

3.3. Modelling of Three Phase PLL in HIL Schematic editor

The Three Phase PLL (Phase-Locked Loop) component in Schematic Editor may be seen in Figure 9, which delivers output signals whose phase is proportional to the phase of an input three phase signal. The synchronous frame three phase PLL is employed to generate the signal of synchronization to the inverter. PLL has some challenges such as voltage

imbalance, harmonic distortion and phase angle alignment which can be carefully modeled to reduce the disturbance in the system and also to improve the power quality of network [16].

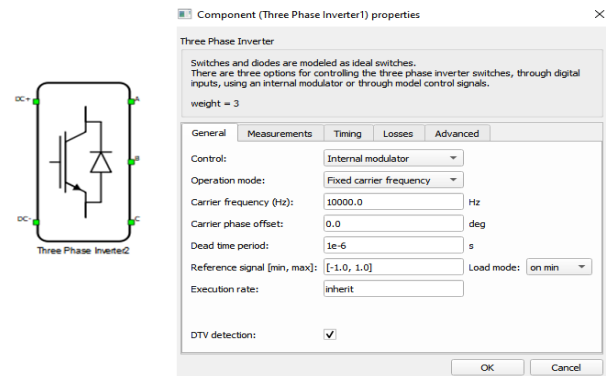


Fig. 8. Modelling of Three Phase Inverter in HIL.

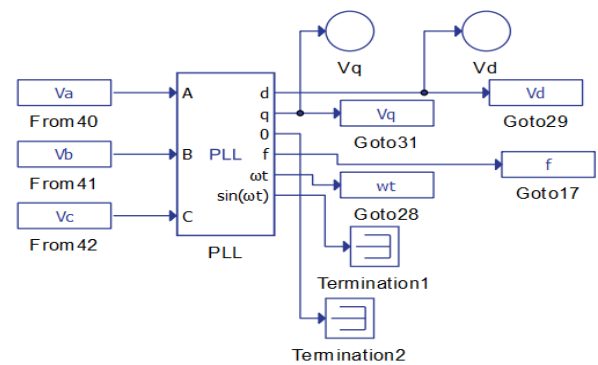


Fig. 9. HIL Modelling of Three Phase PLL.

3.4. Designing Current Controller in HIL

For HIL modelling of proposed current controller is shown in Figure 3, in this current controller, three functions are mandate which are current reference block, abc-dq and dq to abc transformations. By the use of this controller only grid synchronization is achieved by injecting the active (P) and reactive power (Q) into the system along with voltages of dq frame to produce the current reference signals (I_{d_ref} & I_{q_ref}) which acts as input to current controller. The currents are converted into dq frame reference with the use of abc-dq block which acts as input to current controller [17]. Then with these set of inputs it produces a reference angle for synchronizing with the grid but this has to be converted into dq to abc variables so that block is implemented finally which is connected to Inverter modulator [18].

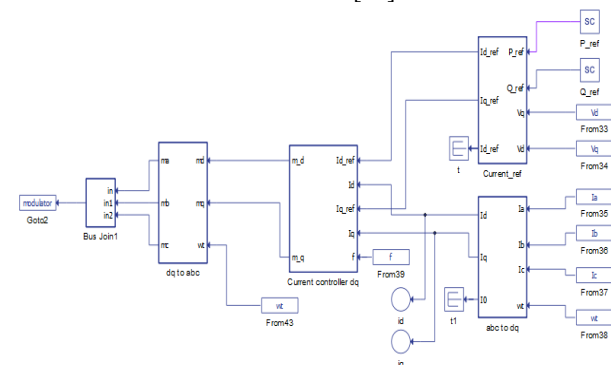


Fig. 10. HIL Modelling of Current Controller.

4. Modelling of Circuit

After the successful drafting of whole circuit in Schematic editor of the HIL software, compile the model and load the model in VHIL, then we can see the SCADA panel where results can be represented based on the application draft all the required widgets which shows the results.

4.1. Case 1: Grid Connected converter with PSO in HIL SCADA

The proposed model is shown in Figure 11 which is run by implementing the selected optimization method using an Advanced C function Block and a boost converter to boost the output of PV panel in order to supply to the grid efficiently. Here the energy source such as Photovoltaic source is used to develop this grid model and test it under virtual Hardware-in-Loop (HIL) using the Typhoon HIL software centre and hence this paper is justified and named under it. In this mode PSO code is inserted into the block which is already tested in Matlab. The Phase voltages and the currents with PSO in pure sine wave mode can be seen in Figure 12 which is captured from the scope widget. Sliding method is used to inject the active and reactive power reference signals which can initialize the PLL and current controller to get the angle of reference required for synchronization. Let us observe the ride through faults in the model and its analysis using HIL.

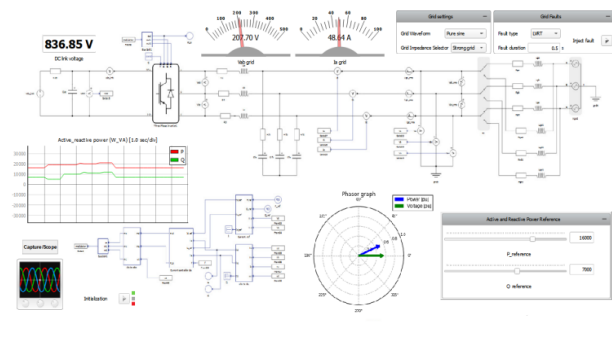


Fig. 11. Proposed Model with PSO algorithm.

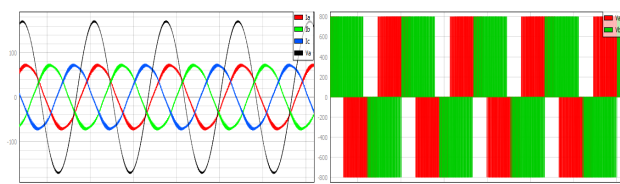


Fig. 12. Phase voltages and currents with PSO in pure sine wave mode.

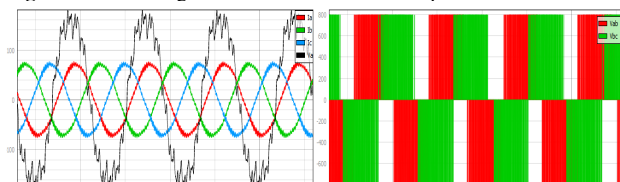


Fig. 13. Phase voltages and currents with Harmonics.

In this mode after running the model it takes few seconds to initialize the widgets then we can observe the DC link voltage as 826.22V and V_{ab} grid is 207.60V and I_a grid is 48.64A. The voltage is introduced with third and fifth harmonics which is depicted in Figure 13. It is observed that the voltage waveform has uneven peaky structure which indicates the harmonics.

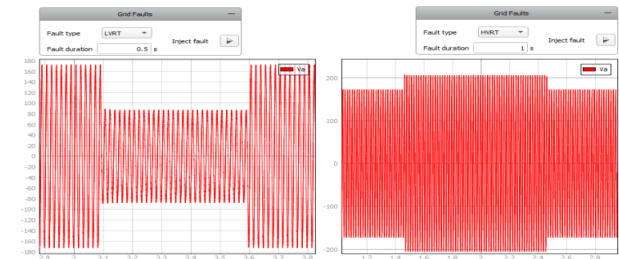


Fig. 14. LVRT & HVRT Fault Analysis.

In the Figure 14, the response of the V_a under Low voltage Ride Through (LVRT) fault which is injected for 0.5s can be observed to left side, it is observed that during the faulty condition the voltage has dipped to 50% of original value to compensate the loss of energy under low demand while supplying. The HVRT fault is injected for 1second is to observe the response of the system. This fault describes the voltage rise in the grid than the nominal voltage.

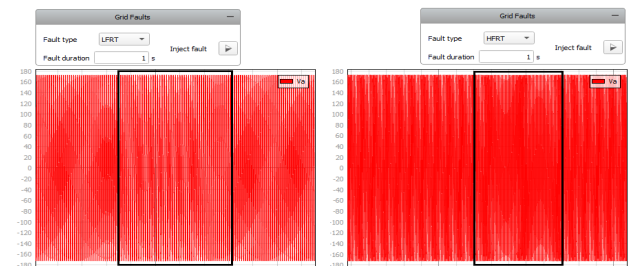


Fig. 15. LFRT & HFRT Fault Analysis.

The LFRT fault is injected for 1s as depicted in the Figure 15, and it is observed that the waveforms are lighter which are distorted due to low frequency than specified limit by the utility grid. HFRT phenomena are observed to right side of figure and the waveforms are compressed due to increase in frequency than original frequency of the grid.

4.2. Case 2: Grid Connected converter without PSO in HIL

In this case, the proposed model is shown in Figure 16 which is executed without implementing any optimization algorithm to compare the use of adopting proposed methodology. The V_{dc} link voltage is set to 800V while simulating the circuit and after running the model if the value is approximately nearer to the initial value then synchronization takes place. Here the active and the reactive power injected as 16kW and 7kvar respectively and varied accordingly to tabulate the readings seen in Table 2. A comparative result has been provided in Table 3 with the simulation time step of 20 seconds. It can be observed that the MPPT with PSO has better performance compared to without PSO technique.

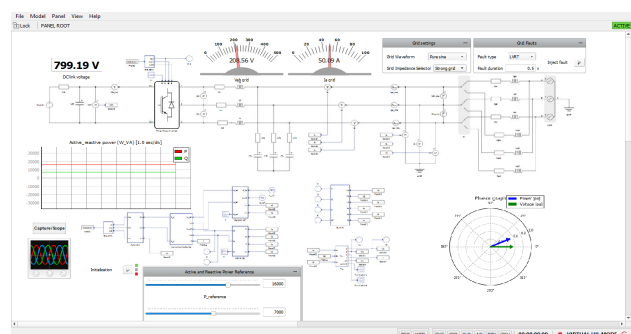


Fig. 16. Proposed Model without PSO algorithm.

Table 3. Comparison of proposed model with & without Optimization.

| P_ref | Q_ref | Without PSO | | | With PSO | | |
|-------|-------|----------------------|----------------------|---------------------|----------------------|----------------------|---------------------|
| | | V _{dc} link | V _{ab} grid | I _a grid | V _{dc} link | V _{ab} grid | I _a grid |
| 16000 | 7000 | 798.77 | 208.56 | 50.09 | 836.81 | 207.70 | 48.64 |
| 19000 | 5000 | 798.56 | 208.69 | 56.35 | 824.52 | 207.70 | 54.70 |
| 19000 | 10000 | 799.06 | 208.71 | 60.18 | 823.67 | 207.70 | 59.79 |
| 20000 | 11000 | 798.06 | 209.20 | 63.46 | 819.94 | 207.70 | 63.44 |
| 21000 | 12000 | 798.96 | 209.25 | 67.04 | 814.95 | 207.70 | 67.23 |

5. Conclusion

This paper is mainly intended to present the use of real time simulation platform Typhoon HIL control center for testing the model. The main idea behind the Typhoon HIL was highlighted by extending the voltage at the maximum power point to 836.81v using PSO algorithm than compared to non-optimizing technique. Grid fault analysis is performed by using VHIL emulation with very low time step using

Typhoon HIL control Centre. This simulator enabled hardware controllers have been made to test and develop the complex Microgrid Testbed models.

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