# Transition between Stand-Alone and Grid Connected Solar PV Microgrids

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## Abstract

In this study, conversion of Solar Photovoltaic (PV) energy to increase sustainable energy and increase system efficiency is being studied. During the process, both stand-alone mode and grid connected mode microgrid with energy storage system (ESS) have been tested in a simulation environment. Their transition from one mode to another have been discussed for research purpose. Solar photovoltaic PV modules, energy storage devices (Battery), power electronics converters are used to validate the desired results. The study of stand-alone to grid-connected systems will be analyzed and tuned for a stable system performance. During the tuning, the voltage and the frequency are the key driving parameters to be controlled and evaluated. Also, the study of grid connected configurations will be conducted and then both systems will be compiled together using a switching property. The aim is to work on control system for creating the transition in the systems. The study is tested with MATLAB/Simulink platform-based simulations. The major focus will be on the control mechanism of the inverters in both modes, specifically for this study.

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# Table of Contents

## List of Tables



## List of Figures

## List of Abbreviation

| Acronyms | Description |
|---|---|
| PV | Photovoltaics |
| MPPT | Maximum Power Point Tracker |
| EMS | Energy Management System |
| ESS | Energy Storage System |
| DG | Distributed Generation |
| RES | Renewable Energy Sources |
| VSI | Voltage Source Inverter |
| PWM | Pulse-Width Modulation |
| LPF | Low Pass Filter |
| IGBT | Insulated-Gate Bipolar Transistor |
| PI | Proportional Integral |
| FLC | Fuzzy Logic Controller |
| PLL | Phase Locked Loop |
| AI | Artificial Intelligence |
| THD | Total Harmonic Distortion |
| HIL | Hardware-In-The-Loop |
| SOC | State of Charge |
| P&O | Perturb & Observe |

# Chapter 1: Introduction

## 1.1 Introduction

Renewable energy is a very crucial term given in this current growing world as the scarcity of non-renewable energy sources are increasing rapidly. From the usage of domestic appliances to the usage of industrial uses, renewable energy is playing a vast role in this modern era. Usage of non-renewable energy sources is not only getting expensive such as burning hydrocarbons or similar energy sources, but they are also affecting the environment in a massive amount. Apart from the individual use for manufacturing or other household uses, energy sources are most widely used in the sector of power generation. Gas, Oil, or non-renewable energy-based power plants are widely and commonly seen around the globe. With electricity demand growing in a vast majority, the demand for those energy sources is increasing rapidly. This demand and supply growth are making things more costly and alarming for the future. These days, renewable energy sources such as Solar energy, Wind energy, geothermal energy energies, wave energy are being implemented with many modernized technology and plants [50]. Among those, solar energy and wind energy is most widely used and accessible among manufacturers, users, etc. Solar modules and wind energy-based modules are getting cheap in manufacturing hence these are being more accepted in various industries. The power generation industry is focusing mainly on renewable energy-based generation process in order to meet the energy demand for the future. Due to the economic factors of solar and wind modules, microgrids are replacing gradually the traditionally used power grids. Microgrid is a limited group of electricity sources and loads capable of operating in parallel with, or separately from, the main power grid[53].It is a separate energy system which includes generation, storage, demand management, and loads, and usually works when tied to a utility grid but often times, in regions where the absence of grid is present, the microgrids work in islanded or stand-alone modes as well [1], [2].

Among all renewable sources in the field of power generation, solar photovoltaic (PV) power generation is becoming an important component in green energy production. Their scalability feature allows solar PV based microgrids to act as a convenient distributed form of energy to supply power to small communities as well as larger areas of consumers these days. These systems can work autonomously alone as islanded mode or by combining with the main power grid, they can work into grid-tied operation for bi-directional power flow.[51] Depending on the weather, makes PV generation as an irregular power source is which one of its major draw backs. To work with this problem, maximum power point tracking (MPPT) when integrated with a PV system allows us to extract maximum power and thus other forms of storage elements maintains a dynamic behaviour, and hence the entire system meets a room of stability [3], [4].

Electronics components such as AC-DC, DC-AC and DC-DC converters are needed for Solar PV microgrids with energy storage systems to interact with electrical power system. DC-DC converters are mainly used for energy generation side such as for boosting up Solar PV power using maximum power point tracking (MPPT) or controlling bidirectional power flow in battery controller system. On the other hand, AC-DC controllers or Inverters can be used in grid connected system and feed the AC loads by controlling the frequency and the voltage [5]-[7].

Microgrids require crucial control methods to fulfil the stability and dynamic behaviour of power flow throughout the system. A typical microgrid usually accomplishes many tasks such as maintaining power balancing while being connected to main grid and switching autonomously to islanded mode. While those modes are in effect, dynamic balance and steady state power flow throughout the system is very important to balance out the whole system with smooth outputs and parameters. While staying in grid connected mode, things are often easy as the main grid is present to identify and power deficit or pull away any power surplus. While the challenge mainly lies on islanded modes as the entire system relies on Distributed Energy sources and as discussed earlier, energy sources like Solar PV depends vastly on environmental factors hence maintaining stable power flow is a major drawback. Autonomously switching from grid tied to islanded mode of configuration can create several distortions in signals and hence in most cases manual switching is preferred with some minor control changes to work in smooth order. But in this study, we are proposing a system for balanced load, and we are using MATLAB/Simulink for an autonomous switching with minimal loss or distortions using algorithms, for better performance [7]. The motive of this study is to run both systems in simulated environment and discuss the drawbacks, later in the future work both systems will be studied in Real-Time environment and will be examined out if the drawbacks are close enough to their individual states and what can be done to minimize them.

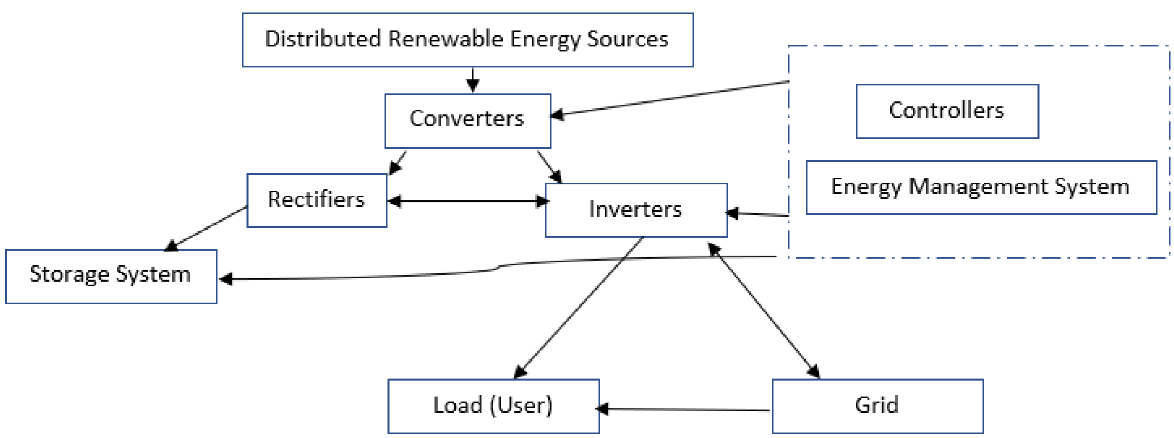



Fig 1.1 Typical Microgrid Arrangement

An overview of microgrid system arrangement is depicted in Figure 1.1. Microgrid operates several tasks such as, incorporate with existing power structures, dynamic control over energy sources, enabling autonomous operations, information systems, and power back to the main grid during power outages [6]. The following features, can be summarized for the microgrid technology [8]:

- Provide power reliability for consumer and owner.
- Enhance the integration of distributed and renewable energy sources.
- Building blocks for a complete smart-grid.
- Clean energy generation and minimizing carbon emission.
- Both consumer and owner can participate in the energy market.

## 1.2 Background Study and Literature Review

### 1.2.1 Focus areas from previous studies

To evaluate relevant works and research done on this field, the classification of building an optimized microgrid needs to be focused on those following topics on which previous works had been contributed:

**Converters:** Renewable energy sources such as the solar energy or wind energy are non-uniform parameters and to regulate them under constant parameters converters are very crucial. DC/DC converters are widely used in regulated switch modes for non-uniform input parameters. In [9] the design of a DC boost converter and the operational modes have been demonstrated. The converter needs components such as inductor, electronic switch, diode, and output capacitor. Solar energy comprises of non-uniform parameters, and throughout the day variation of this parameters may sometimes keep the system idle. A control system is associated with the converter in order to justify where the power is maximum or minimum and for the demand end if the parameters are met. To follow up the construction of a DC/DC power converter, study in [10], discusses the construction of an open loop DC/DC boost converter. The focus here is mainly on continuous conduction mode (CCM) and a state-space averaging method has been used to validate the outcomes in MATLAB-Simulink. Among the power converters such as the boost converter, there are other configurations as well which can often perform well depending on the given situation. In [11], a comparison between buck-converter and a buck-boost converter to validate the outcomes when a solar pv is connected across the converters and perturb & observation algorithm had been implemented to see the better outcome at the converter output end. Both buck and boost converter successfully tracked the maximum power point, but the buck converter showed better outcomes in terms of suppressing the oscillations. Further in [12], a study is discussed for the effect of multiple solar farms connected parallelly with multiple DC converters in order to test the output differences and harmonics affiliated with the system. In order to do so, three solar farms were connected with three boost converters with similar MPPT algorithms into a common DC bus point.

**Solar PV-based Control Systems:** A study in [13], discusses on the various maximum power point tracking methods from a solar pv module which works through the converter. Using MATLAB/Simulink and dSPACE platform, a boost converter is designed and connected to an Agilent Solar Array E4350B simulator to evaluate the analysis. Different methods were used apart from conventional P&O, IC or OCVC methods such as Beta Method, Temperature method, Fixed Duty Cycles, etc. To compare and correlated with this unconventional methods, modified P&O and IC methods have been used by assigning a PID Controller with them. Theoretically it was found that among all these methods, Beta Method was a good solution in terms of high TF compared to others. But the modified versions of P&O, Constant Voltage and IC method were also worth mentioning as they provide good transient behavior with independent sources from manufacturers. Following to this study, works by [14], conducted the comparison of P&O and IC method and found that both of methods are preferrable in terms of tracking maximum power and forwarding to the user end. It was notably observed that P&O method cannot follow faster variations such as temperature change, irradiation, etc. whereas IC method gave a smoother output to variations. In [15], it is suggested to improve the functionality of P&O method in converters for solar based systems. Initially it was verified that the higher the irradiation, higher the power output at the output terminal by single and double diode configurations. A unique P&O algorithm has been used and initially the power is calculated by the product of initial V and I. If at next instance, if the derivative of power with respect to voltage is zero, the algorithm perturbs another value of volage by incrementation and once the derivative is zero, it goes to the old value be negative increment hence, the system sticks to the point where the power is maximum. Hence the efficiency of the P&O method was verified by this process in order to extract maximum solar power from PV modules. Also, the properties of P&O methods have been discussed in the works by [16]-[19], where it is stated that P&O method is easy to implement and reduces the system cost but the only drawback of it is that it fails to react sudden changes in environment as the tendency of this algorithm is to oscillate around the maximum power point. On the other hand, IC method is better as it only moves to next incremental conductance value if there is an increment or hence stays to its last known position hence it quickly defines the maximum power point, but the drawbacks are its complexity to apply.

**Microgrid and Energy management systems:** By combining all the above discussed principles of solar pv based systems, an overall controlled system can be considered as a microgrid with energy management systems (EMS). In the study of [20], a hybrid AC/DC microgrid with the local controls for maximum efficiency is discussed. Co-ordinational control schemes were proposed for all central and local controllers in order to operate in various load situations and in situations where there is deviation in energy resource. Stable ac/dc parameters were secured under different conduction modes and also similar works were seen in [21], where the supply from the grid is rectified and connected with the system with a DC busbar so that when the microgrid sources lacks supply still the demand is met. Control strategy of individual solar pv systems and battery storage enable microgrids have been studied in [22], where distributed energy resources are coordinated with distributed generators to implement both active power and reduce the other disturbance effecting the power signals. Furthermore, in the study, a strategy of PV generators with MPPT and DC converter control has been thoroughly discussed which enhances coordinated control of voltage and stability of frequency. Another feature is that even though inverters are used but the battery storage systems reduce the number of inverters used by connecting together via the DC link.

To develop a running simulated model both works from [23],[24], can be observed simultaneously. In the first work the algorithm used in the control and management system allows the system to pick the best feasible resources form the distributed sources. Real-time control system had been used to operate and validate the hybrid resources in the microgrid experimentally. The lab scaled setup can be implemented into account with large real-life systems which then again discussed or implemented with real life statistics in [24]. The study was based on St. Martin's Island located in Bangladesh where the tourist or individual load demand is met by diesel generators only due to lack of grid facilities. In this study for a standard number of residents, the requirement vs load numerical data has been created. A Solar PV and DFIG based wind energy hybrid microgrid have been simulated in Simulink platform and is designed to meet the highest load demand. Diesel generators backup were involved for emergency situations where wind or sunlight is not favorable. [8],[25],[26], simultaneously discusses the fundamentals of grid tied and islanded mode operations of microgrids. Battery storage system not only suffices the power deficiency at critical times but also reduces the harmonics in addition to smoother signals at user end. Frequency stability and power latency as well as fault situations have been thoroughly discussed in those studies. Variations to the experimental set-ups are usually seen where the microgrid is operated in both modes.

## 1.3 Challenges

Most of the recent works on a microgrid solely focuses on Grid connected mode as this method is getting popular in most of sector and is also easy to rely on the grid for any sort of system loss or support. However, to address any of the modes, firstly to have a stable optimized controller for the converters as well as the inverters is needed. Voltage and Current are the driving parameters for those controllers and here are few typical simulated controllers that have been generated using MATLAB/Simulink platform:

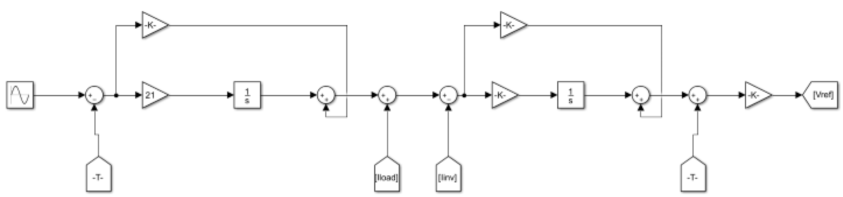



Fig 1.2 Open-Loop Controller

This is an open loop PI (Proportional Integral) controller that generates pulse signals for electronic converters by using a reference carrier signal [27], and these show accurate simulated results with Grid Connected operations but while operating in Off-grid configuration they have very large power loss in the generation side.

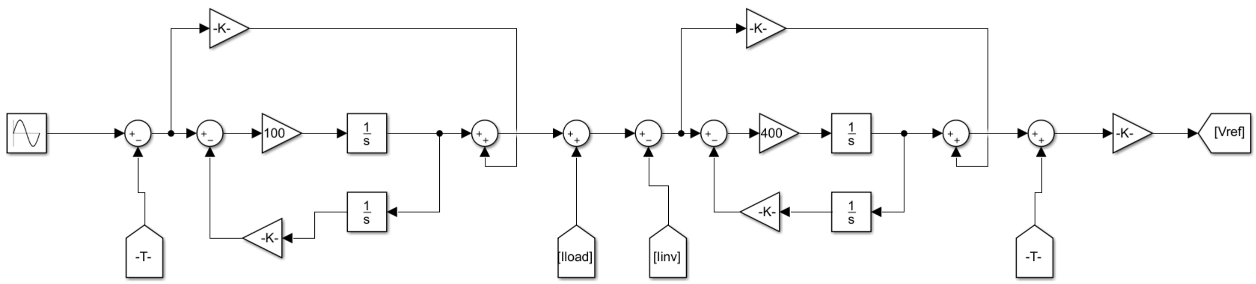



Fig 1.3 Closed Loop Controller

This is a closed loop PI controller, which not only works with a carrier signal but also feedbacks it outputs at small stages and eliminates the error term to move to the next stage to provide desired pulse signals. The efficiency with both configuration of microgrids is 80-90% [21] in numbers but still needs different method of tuning for Islanded modes.

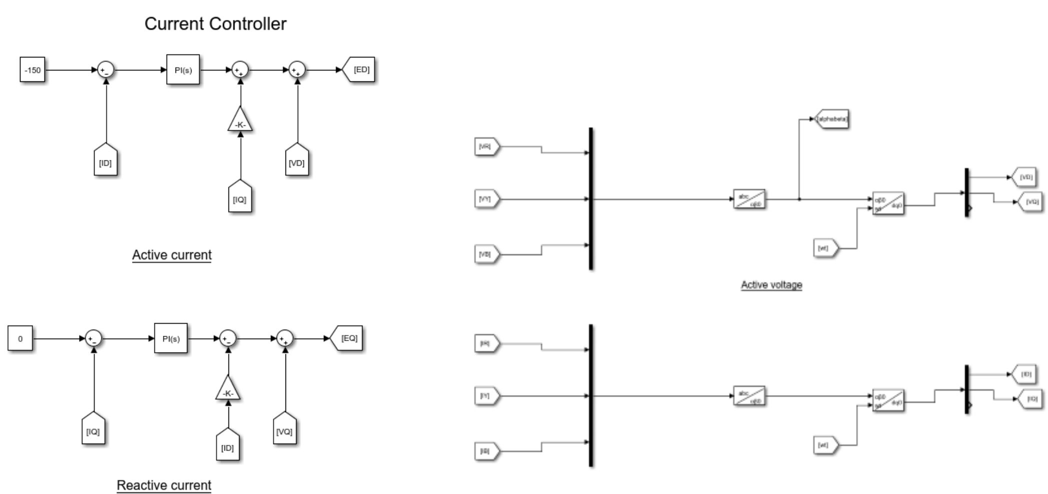



Fig 1.4 Current and Voltage Controllers

Another minor challenge is controlling the reactive and active parameters when switching from Grid connected to Islanded mode is that these parameters fluctuate in Per Unit method [27], hence the stability of the entire system gets distorted, and controllers are needed to address every single stage of transition.

## 1.4 Objectives and Contributions

- **Implementing a Grid-Connected Microgrid:** The system consists of Solar PV module, which is being emulated by a PV profile. The common DC bus consists of converters and Distributed Energy sources which is then fed to inverter. On the other side, main grid is available to feed and deficit power to the consumer.
- **Implementing a Standalone system using separate conversion systems:** with different maximum power point tracking algorithms, the distributed energy systems are connected to the DC bus with converters and later the fed to inverter with new operating topology. This time the grid is removed, and the renewable energy sources are the primary and only source for the load end.
- **For same parameters test both modes and find efficiency:** comparing multiple control system for both modes and reaching an optimal point of operation.
- **Using Different Algorithms for best output:** Algorithms like P&O method, Incremental Conductance method, Open Voltage method to be implemented with each mode and control operation for better stability.
- **Checking for frequency and Phase Deviations using PLL (Phase-Locked Loop controllers):** Building frequency controllers with multiple methods of Tuning, to operate in stand-alone systems.
- **Testing at ideal conditions (assuming maximum irradiances):** Using assumption and predictive profiles for weather and atmospheric conditions, to demonstrate ideal situation both is simulation and Real-Time systems.
- **Developing a switching mechanism for transition:** grid-connected and off-grid systems will be compiled together using switching mechanisms to test the transition of the entire

module in both conditions. It is one of the main contributions from the inverter control mechanisms, made in this study.

## 1.5 Outlines

The thesis work is described in five chapters. The rest of the chapters are organized as follows:

- **Chapter 2** talks about the modeling of the local controller units of the microgrid. Theory and mathematical discussion about controls have been discussed in this chapter
- **Chapter 3** proposes configuration of the microgrid. The operating principle for each mode of the system has been introduced and discussed in detail for better understanding.
- **Chapter 4** describes the simulation set-up and talks about execution of the MATLAB/Simulink platform. The detailed outcomes of the individual mode of the microgrid and also about the outcomes of the transition period is also presented in this section.
- **Chapter 5** tells us about the future scope of the work. And finally, this chapter concludes and summarize the research project.

# Chapter 2: Control of Microgrid

## 2.1 Introduction

Among all the Renewable Energy Sources (RES), Solar PV is the most popular form of distributed generation (DG) due to its availability, response to irradiance and the factor that it is cost efficient in terms of installation. Solar PV panels, storage devices such as batteries are most used DC power sources, and they are mostly configured with power systems in microgrid industries. Even though DC power systems in DC microgrids are more straightforward and commonly used, the complexities arises when AC microgrids are dealt with [49]. AC microgrids require or often Hybrid microgrids require more components in terms of evaluation and maintenance [28],[29]. In this research study, a simulation-based study of behavioural changes from DC to AC microgrids are implemented. A solar PV based microgrid system with a battery storage unit has been designed with the allowance of a simple switching method to change mode of operation from Stand-alone to grid connected mode has ben discussed. The proposed microgrid is depicted in Figure 2.1. The Solar PV is fed through a boost converter and controlled through that component to be transferred to the DC bus. Furthermore, the battery storage unit is controlled by a bi-directional buck-boost converter. The DC side is fed to the inverter side and the output of the inverter is associated with the load and the grid when required through the switches. The necessity of the boost and buck-boost converters is to ensure the output voltage of the converters to be exactly stepped up or down to the DC-link voltage.

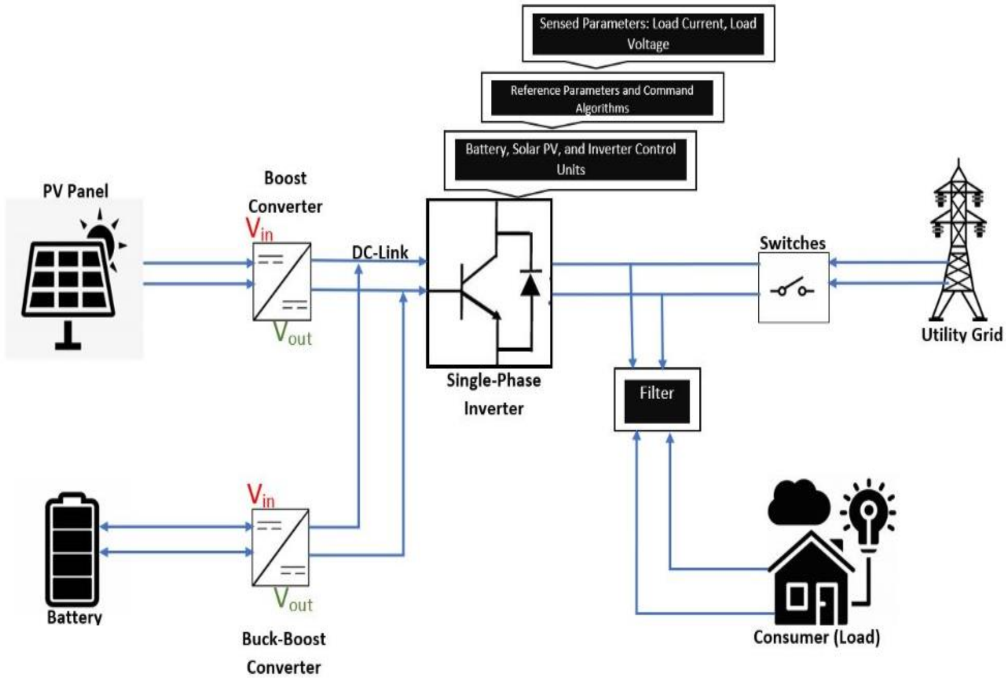



Fig 2.1 Schematic of Solar PV and Battery based Microgrid

The proposed microgrid consists of both Islanded and grid-connected systems where the voltage and frequency of the AC-side is controlled by the grid and the microgrid when detached from the grid. The inverter plays an important role in the system as it converts the DC parameters to AC parameters. The parameters are then fed to the consumer side (the load) and depending on that analysis the control systems are enhanced. In this study, a fixed load is connected the output side and tested in both stand-alone and grid-connected mode. The aforementioned microgrid consists of three major control unit: PV local control; battery storage (BS) local control and inverter control. A de-consolidated control method has been used in between the local control units of the system. Typical trial-error method has been used in the optimization of the proportional integral (PI) controller and the controls of the local units has been discussed in the following sections.

## 2.2. Solar PV Local Control

A solar cell contains layers of semiconductor materials that utilize the photoelectric effect of converting photon energy of the solar radiation into electricity [30], [31]. A typical solar cell can be considered as a non-linear current source [32]. The current-voltage IV curve of the PV array is provided in Figure 2.2, where the relation of the PV current and voltage can be identified easily.

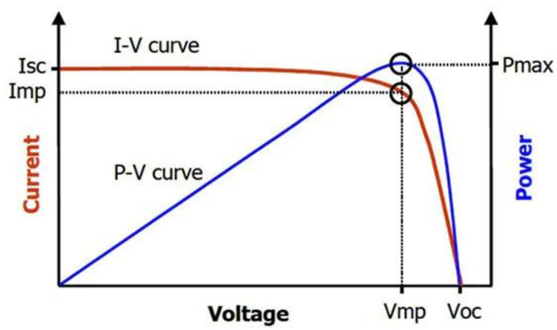



Fig 2.2 IV curve of a PV array [33]

PV units consists of multiple PV arrays and a single PV array can be modelled by using the current-voltage relationship as follows [34]

$$I_{PV} = N_p I_r - N_p I_0 \left[ exp\left( \frac{q(V_{PV} + N_s R_s I_{PV})}{N_s nkT} \right) - 1 \right] - \frac{V_{PV} + \frac{N_s}{N_p} R_s I_{PV}}{\frac{N_s}{N_p} R_p} \tag{2.1}$$

where, $q$ is the electronic charge, k is the Boltzmann constant, n is the ideality factor, $T$ is the cell temperature, $I_r$ is the irradiance current, $I_0$ is the diode saturation current, $R_s$ is the series resistance, $R_p$ is the shunt resistance, $N_s = N_m \times N_c$ ($N_m$ is the number of panels connected in series in the array and $N_c$ is the number of cells connected in series in the panel), $N_p$ is the number of strings in parallel, $I_{PV}$ and $V_{PV}$ are the current and voltage outputs of the PV array, respectively.

The irradiance current, $I_r$, depends on the solar irradiance, $G$, and the cell temperature, $T$, such as

$$I_r = I_{r,STC}\left(\frac{G}{G_{STC}}\right)[+\alpha_T(-T_{STC})] \qquad (2.2)$$

where, $I_{r,\,STC}$ is the irradiance current under STC (Standard Test Conditions), $G_{STC}$ is the irradiance under STC, $\alpha_T$ is the temperature coefficient of the short-circuit current.

And the PV array power, PPV, is given by

$$P_{PV} = I_{PV} \times V_{PV} \qquad (2.3)$$

The DC-DC boost converter is assumed ideal and the voltages are related by the expression

$$V_{dc} = V_{PV}\left(\frac{1}{1-d_1}\right) \qquad (2.4)$$

where, $d_1$ is the duty cycle to operate the IGBT $s_1$.

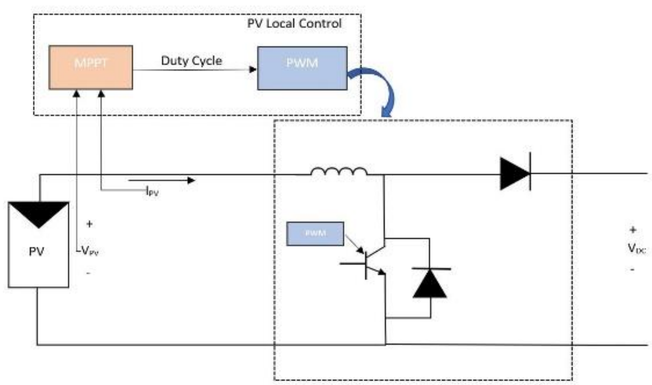



Fig 2.3: Local Control layout of PV

### 2.2.1 Overview of Maximum Power Point (MPPT) tracking method

A typical PV system converts immense and clean solar energy into electricity. As DC is the form of output from a PV system, usually a DC-DC converter is affiliated at the output side of the PV module. A boost DC-DC circuit is implemented using a unidirectional DC-DC converter [35].

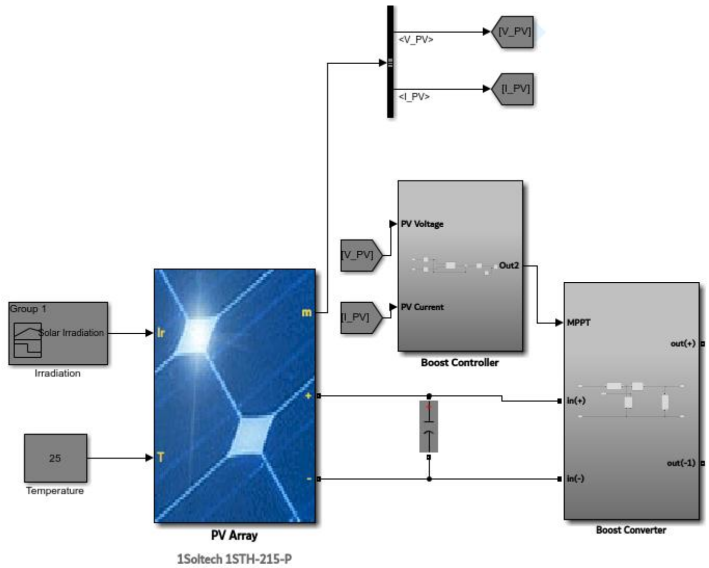
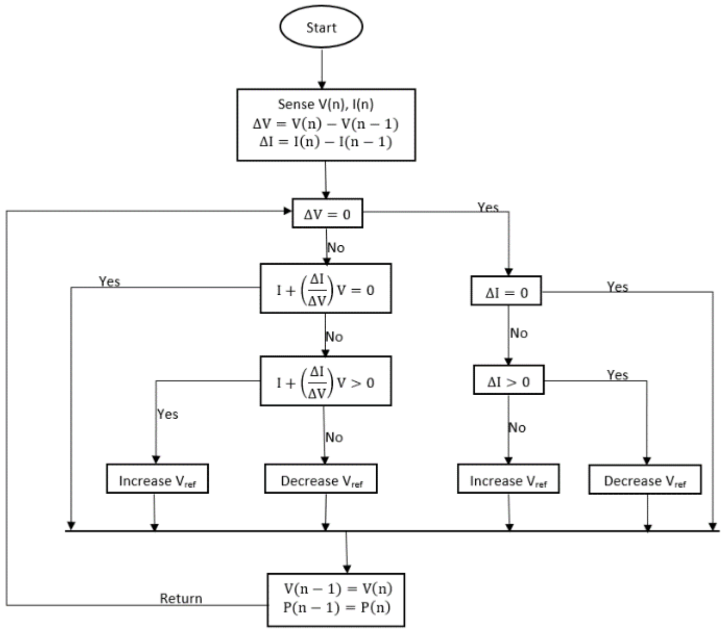
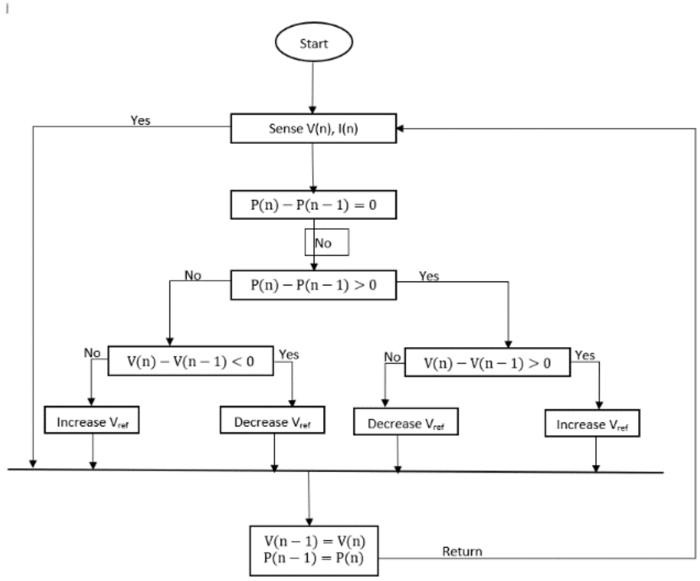



Fig 2.4 Simulink Schematic of PV & DC-DC boost converter control with MPPT

As seen in Fig 2.4, the duty cycle is carried out by the following control structure. Both of the following MPPT algorithms, P&O and Incremental conductance methods have been tested and the results have been somewhere like each other [36]. Therefore, P&O method was selected for final outputs due to ease of its understanding and as it is commonly used in most studies for its effectiveness.




(a)




(b)

Fig 2.5 (a) Perturb and Observe Method (P&O)
(b)Incremental Conductance Method (IC)

The MPPT provides the reference voltage for the PV voltage control loop. In this work, it is assumed that in order to extract the maximum power available from the sunlight the PV array shall be always operating in its maximum potential. For this study, P&O method has been selected for its easiness of understanding and as it is one the most used method. The power tracking algorithm has been used through the MATLAB function block in the software to code the P&O method to send the pulses to the converter. P&O method senses the initial voltage and current, and checks, if there are any changes (increase in units) from either parameter of the current or the voltage side. The algorithm then allows to increase either the value of the voltage or the current until the optimal and maximum point has reached. Hence through this procedure, the system follows the region of power point.

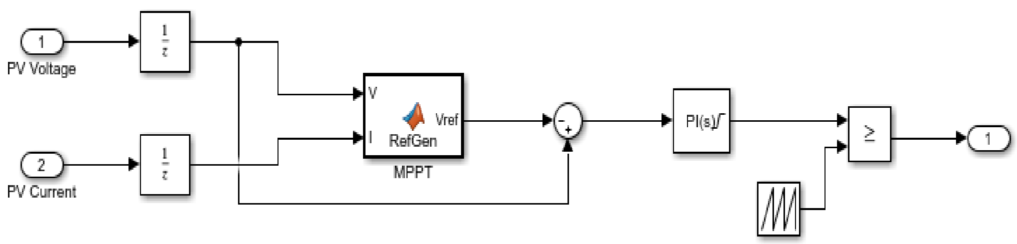



Fig 2.6 MPPT control of the DC-DC boost converter.

## 2.3 Battery local control

Various types of energy storage systems are present such as battery, compressed air, super-capacitor, fuel cell, etc. and each of them have their own advantages and limitation of operations. Among these, a capacitor is an electrical device that stores energy in an electric field between a pair of conductors. Similarly, a supercapacitor works, but it has higher density of energy storage. A fuel cell generates electric current by converting energy from fuel as its source. But most commonly, batteries are used generally for storage of electrical energy through electrochemical reactions inside the unit. There are many different rechargeable batteries among them popular kinds are Nickel-

Cadmium (Ni-Cd), Nickel-metal hydride (Ni-MH), Lead-Acid, and lithium-ion (Li-ion) batteries. Lead-acid batteries are the oldest but still popular rechargeable batteries. Lead and lead dioxide as electrodes and Sulphur acid as electrolyte are used in most lead-acid batteries [32],[37],[38]. They have severe discharge cycle durability and high discharge rates.

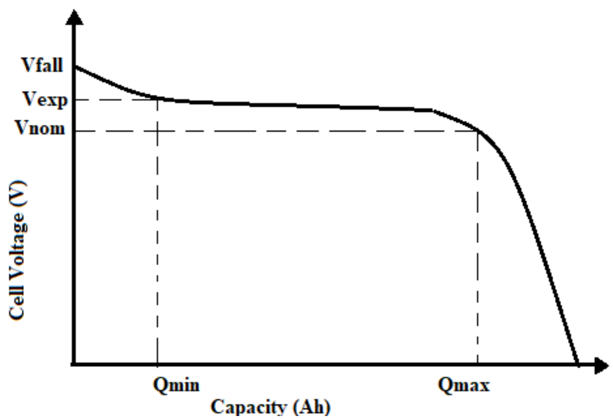



Fig 2.7 Relation between voltage and capacity in a battery storage [32].

In the microgrid, to alleviate and smoothen the fluctuations and interruptions created by the renewable energy sources and also while changing the mode of load, equipping the energy storage system (ESS) is a viable option [39]-[41],[52]. To jointly provide a DC supply, The ESS is usually used to attach the RES to the DC side. The battery (e.g., Li-ion, supercapacitor, lead-acid, etc.) and DC-DC converter (e.g., buck, boost, buck-boost, etc.) are the two main components of the ESS. The relation between voltage and capacity in a battery storage is shown in Figure 2.7, where slight changes in battery cell voltage with change of capacity is observed. Until the minimum capacity, the voltage change is minimum, however, at zero capacity the cell voltage also becomes zero. In Fig 2.8, the aspects of the ESS with a bidirectional DC-DC buck-boost converter are given, where the battery is modeled as a DC power source linked to the low voltage (LV) port.

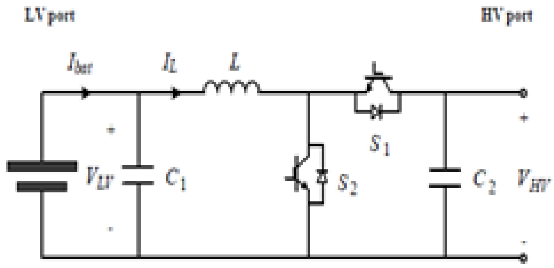



Fig 2.8 Modeling of the ESS.

The output voltage of the battery is given by [32]

$$V_{bat}=V_0-kQ-\int I_{bat}dt+A*exp(-B\int I_{bat}dt)-Ri_{bat} \quad (2.5)$$

where, $V_{bat}$ is the battery voltage, $I_{bat}$ is the battery current, $V_0$ is the constant voltage capacity, $\int I\text{bat}dt$ is the extracted capacity, Q is the maximum battery capacity, k is the polarization constant, dt is the time step in hours, and R is the internal resistance, A is the exponential zone amplitude, *B* is the exponential zone time constant inverse.

The battery power can be expressed as

$$P_{bat}=V_{bat}I_{bat} \quad (2.6)$$

The actual battery capacity is represented by the SOC expressed by

$$SOC(t)=SOC(t\text{-}1) +\int I_{bat}dtQ, \quad (2.7)$$

$$SOC_{min} \leq SOC \leq SOC_{max} \quad (2.8)$$

where, *SOC(t)* is the battery state of charge at time t and *SOC (t −1)* is the previous value of *SOC*. where, $SOC_{min}$ and $SOC_{max}$ are the minimum and the maximum allowable states based on the battery features. The SOC of the battery is a key parameter reflecting the battery performance especially about the remaining capacity of the battery [33]. The SOC is also calculated as

$$SOC(t) = 100\%\left(1 - \frac{\int_0^t I_{d(t)}dt}{Q_0}\right) \quad (2.9)$$

In practice, the battery works in constant current control while in islanded mode it works as constant voltage control driver. Also, it is ideal to set the range of SOC between 10% ~90% to avoid over battery discharge or charge.

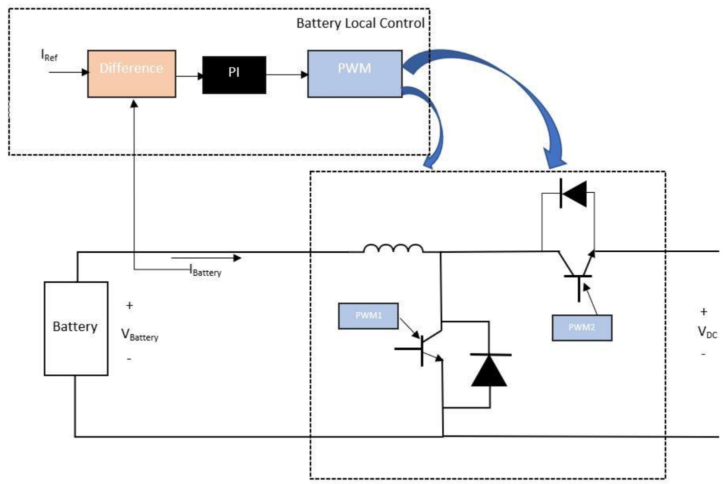



Fig 2.9 Local Control layout of Energy Storage System.

## 2.4 Inverter Local Control (Grid Connected)

To hold uninterrupted DC-link voltage, independent of the direction of power flow, a grid-connected inverter is used in this partial part of the research. After the transition between the modes of the entire system which will be discussed in later chapters, the system transfers to Grid-Connected operation. Due to the availability of the grid, the frequency and voltage are taken from the grid. Although the control is a basic one, still it is globally accepted for its good range of performance.

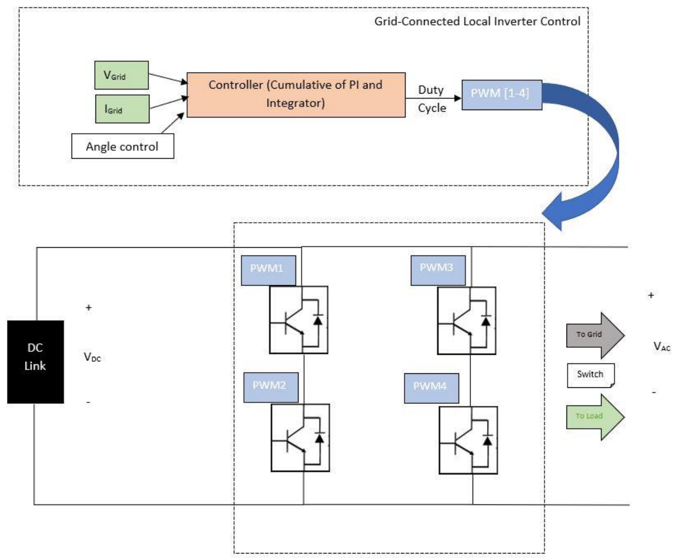



Fig 2.10 Local Control layout of Grid-Connected Inverter.

### 2.4.1 Phase Locked Loop (PLL) Control

Within grid-connected converter control algorithm, it is essential to correctly and precisely determine the grid voltage phase angle (θ) in order to achieve impartial control of active and reactive power flow between the converter input side and the grid. This task is performed by grid synchronization unit [29]. The configuration of grid connected inverter is shown in Figure 2.10. The voltage and frequency are taken from the grid in the control group. So, the voltage and frequency remain the same as the grid, however, only DC-link voltage and current flow is the control method in the inverter control. The feature of the grid management, in addition to the current control configuration, is a key factor which determines the complete control structure quality. Error in the phase angle estimation can lead to the substantial faults in the required converter output voltage, and thus the error is between the reference parameter and injected power (current) into the grid [42]. So, it is mandatory to carefully consider management unit design and test it in various voltage conditions related to the real utility grid.

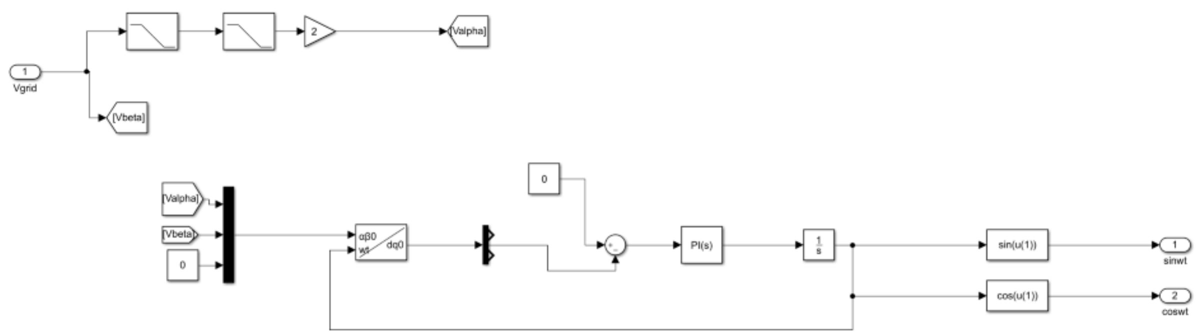



Fig 2.11 Phase Locked Loop (PLL) for Grid-Connected Inverter.

It contains a filter in form of proportional-integral (PI) controller, that determines PLL dynamics. Especially, it is influenced by presence of unbalance and distortion in the grid voltage. Therefore, filter bandwidth is a cooperation between filtering undesirable harmonics that occur in the PLL system due to the measured voltage distortion, and fast response time necessary for tracking voltage during a frequency changes or voltage sags in the grid [43],[44].

Table 2.1 PLL Parameters

| **Parameters** | | **Value** |
|---|---|---|
| PLL**:** | $K_p$ | 10 |
| | $K_i$ | 50000 |

## 2.5 Inverter Local Control (Stand-Alone)

Stand-Alone or Islanded systems are microgrids without any back up energy resources. It means that, the entire system solely depends on the Renewable Energy Sources (RES) associated at the input side and which is the primary source of energy. In this study, a Solar PV based microgrid is proposed. The maximum tests done on the system are based on Islanded system and then the addition of grid connected system is proposed. In the Islanded mode, the components working in the system are the Solar PV panels, the DC-DC boost converter, the Energy Storage system (ESS) and the load. For this research, we are dealing with a single-phase inverter and the load is a fixed 100Ω purely resistive load.

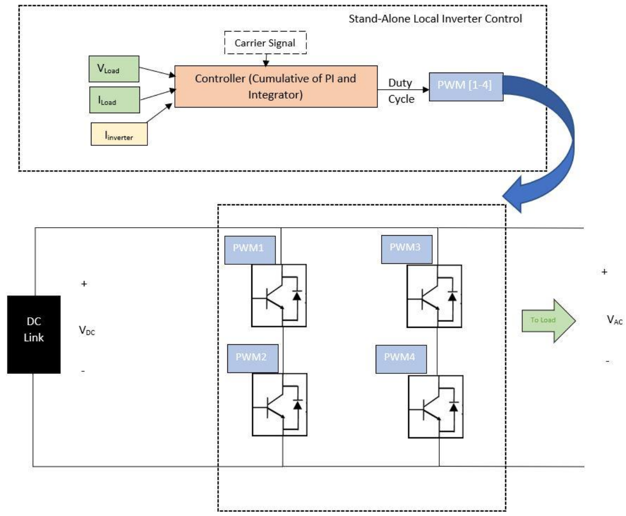



Fig 2.12 Local Control layout of Stand-Alone Inverter.

As discussed earlier, the maximum power at which the boost converter is operating is determined by the P&O method which is the primary maximum power point tracking method here. Hence, in the absences of grid, the changes in solar irradiances play a major role in the system.

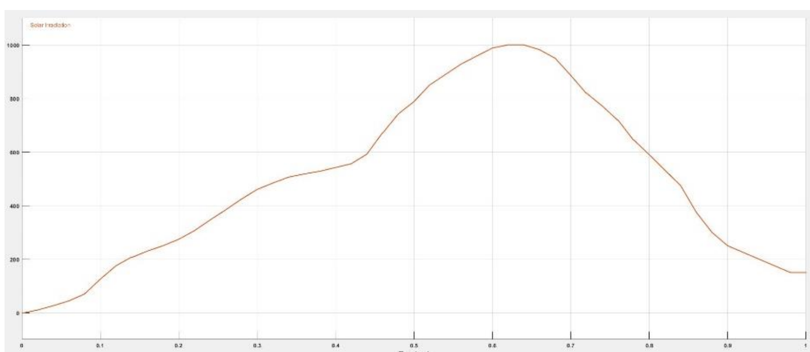


Fig 2.13 Solar Irradiance Profile

The system becomes independent as there is one driving source of energy, as seen in Fig 2.13, and depending on the forecast the consumer demand is met. The DC link is directly fed to inverter via delay capacitor of 470uF in order to response to the sudden changes made by the weather. As for an islanded MG system, its internal power flows need to be balanced, therefore the DC-bus voltage is maintained by the ESS theoretically but practically the results differ. More about those changes and control mechanism of the inverters will be discussed in chapter 3 and 4 with results.

## 2.6 Conclusion

This chapter gives an overall idea of the proposed microgrid and its control units. An overall summary of the control units has been discussed in this chapter and in the following next chapter, the detailed control mechanism of the systems will be discussed with their features.

# Chapter 3: Microgrid Configuration

## 3.1 Introduction

The incorporation of DG and RES along with the battery storage is required for microgrid ideal operation [45], [46]. The focus of any sort of microgrid formation is control management technique, which in this study is the independent control techniques of each parameter. The control management system is very necessary as without an efficient system, a functional microgrid is spare of money and energy.

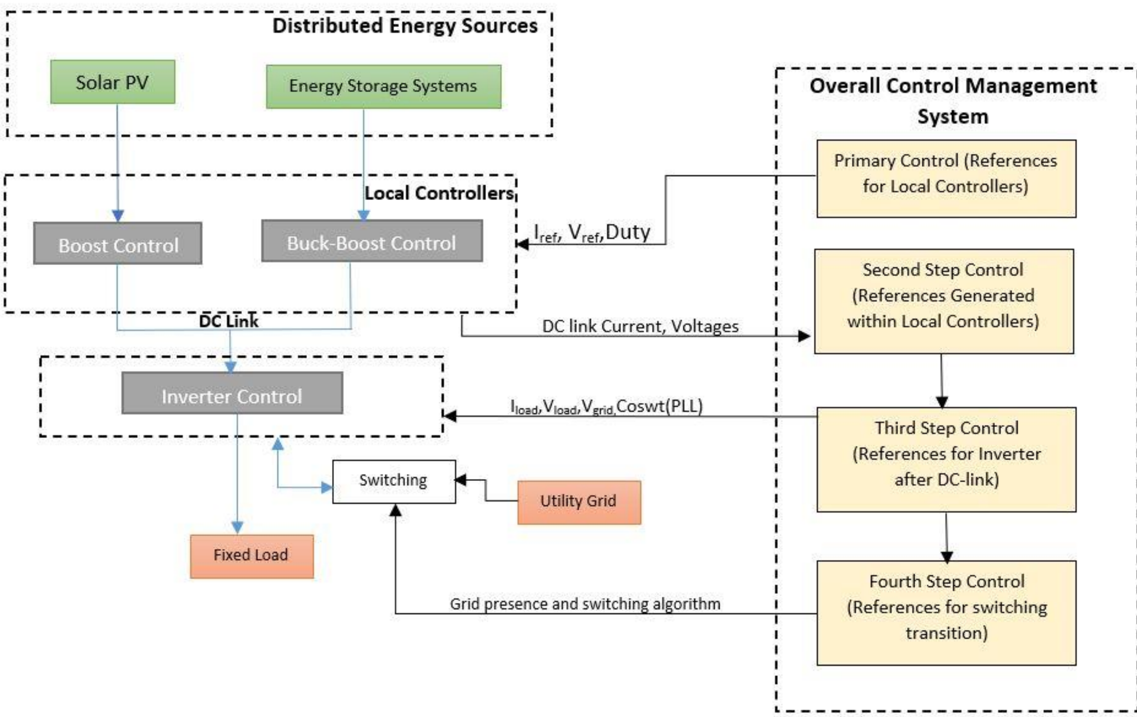



Fig 3.1 Flow diagram of Control Management System

Different constraints arise in different sections, when developing an ideal energy management system. Since renewable energy resources such as solar irradiance, wind speed etc., are variable with any timespan, the system in always unpredictable in behaviour. Hence, the control of each individual parameter on an individual level is priority and then only an ideal scenario can be met.

Researchers have studied different structure and energy management system of microgrids. Most commonly used methods focus either on the generation side energy management or on the load-side. Different studies have been dealt over the years regarding the uncertainty of centralized control management system but even if the simulation studies are always considered as ideal, very few have secured place commercially. This study deals with decentralized method of energy management where the mode deals with more freedom [47], whereas centralized method deals with consumer demand, cost functions etc. The vital function of energy management systems in both approaches is to assure power stability, and power exchange in among generation, load, and grid.

### 3.1.1 Explanation of Control Management System

As seen in the Fig 3.1, the entire microgrid structure can be divided into sections where we see the generation side, the control side of the converters, the grid side, the load side and within them the energy control management system takes place internally and externally. The primary section is defined as user based, as that is the starting point of operating the system according to our needs. Some references come through the user, or some come through the specification sheet of the components. On the other side, when we reach towards the controllers, the initial referential parameters generate more new units of parameters to provide route for the system to move forward. The inverter control after the DC link is important, as that works as a game changer and crucial part for the consumer when there is no presence of the grid. On the other hand, things ease of when the grid jumps into the system, as it acts like a back up but calibration of certain number of factors in order to calibrate with the grid still remains as a challenge. In brief, while connected in islanded mode, the carrier signal defined while designing the controller is the main driving factor, that keeps the system under a given frequency. The controller orders the inverter to follow the carrier signal and hence it converts the signal from the DC link into proper shape. On the other hand, while connected to the grid-connected mode, the driving factor is prioritized by the grid, therefore the effect of the renewable energy sources does not deviate much of the concerning data.

As we move forward in this chapter, we will see the internal control of both Grid-Connected and Stand-Alone mode of microgrids used in this study and their working principles. We will also see the switching mechanisms and their features. In this study, despite there is a presence of ESS, the functionality of it is tested on a basic level. The main focus is given on the control method of inverters in both modes.

## 3.2 Stand-Alone Configuration

In this configuration, the MPPT controller is used at the primary level. The irradiance is tested up to 1000 irradiance as seen in the previous Solar irradiance curve and using the MPPT algorithm we get a maximum output voltage of 376V while being boosted by the boost converter. The temperature is being kept constant and the output of the boost converter is the DC input for our standalone inverter. Hence, the only factor that is variable is the irradiance in this study while the temperature and other factors are kept constant.

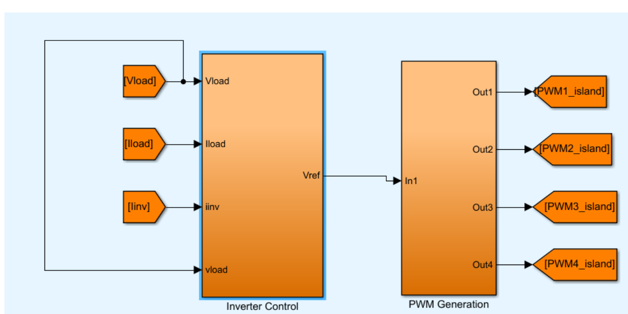



Fig 3.2 MATLAB Schematic of Stand-Alone Inverter Control

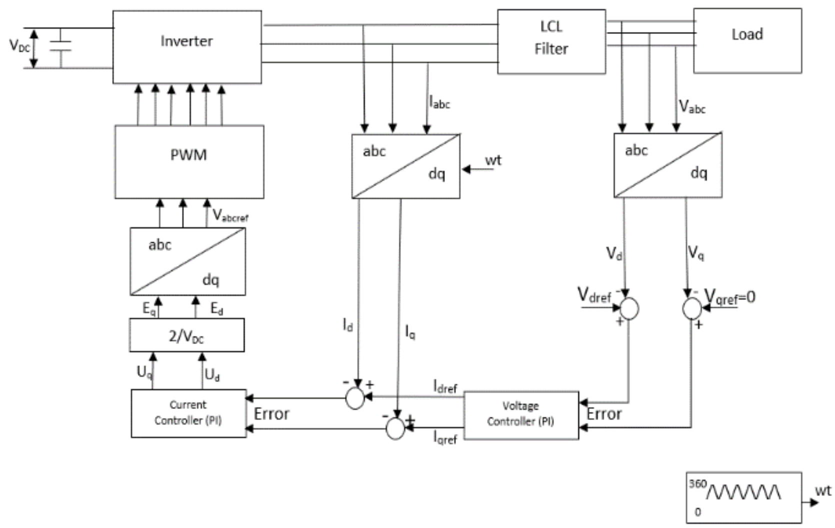



Fig 3.3 Flow Diagram of a Stand-Alone Inverter Control

As seen in Fig 3.3, firstly, from the load side, line to line voltages $V_{abc}$ are sensed. Then using an abc-dq transformation block the voltages are converted in dq parameters. The amount of d-axis voltage is set according to our own need to perform the desired control mechanism of voltages and the q-axis reference voltage is set to zero. Then the d-q voltages are compared with reference voltages to detect the error. The error is then fed to a Voltage or PI controller through which, the parameters for the reference currents are detected. Then we sense the line-to-line currents and transform similarly into dq parameters. Then these d-q currents are compared with our reference currents which then again gives another error and similarly it is fed to a current controller [48]. Then using reverse transformation, we again get $V_{abcref}$ which are used to generate the pulse width modulation (PWM) signals for each insulated gate bipolar transistor (IGBT) in the inverter. This controller is designed to work in a balanced load configuration.

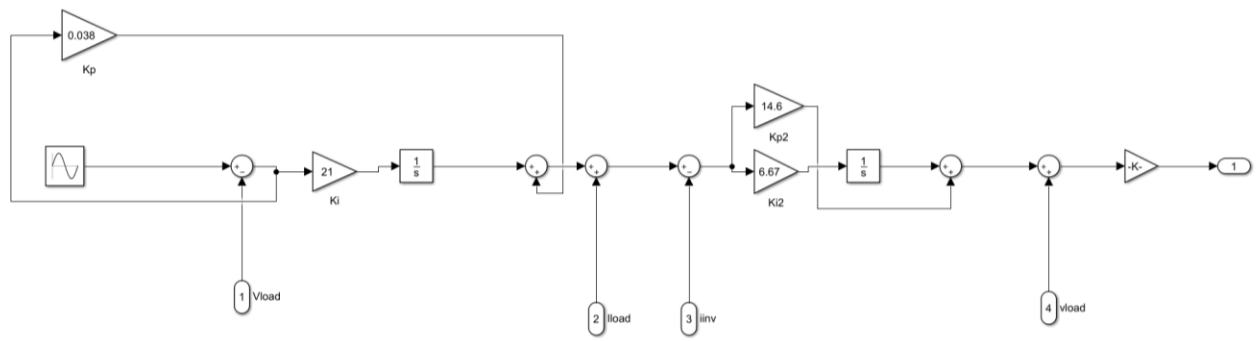



Fig 3.4 Detailed inner diagram of Stand-Alone Inverter Control

### 3.2.1 Frequency Control

As depicted in Fig 3.4, in the stand-alone mode, everything is dependent on the RES units. The error between the load voltage and a carrier signal, that we want our inverter output signal to resemble is calculated and integrated through a PI controller. As an obvious factor, due to the sole dependency on renewable energy sources as primary energy source, the deviation of parameters will affect the system. To maintain the course to meet the consumer demand and to operate the designated loads, we need to reach the frequency as per required. Hence, the carrier signal is sinusoidal wave with a frequency of 50Hz that is being sent as a comparative factor for our system in order to match the desired output signal from the end of the inverter. Therefore, in chapter 4, we will see the results are maintaining similar course of frequencies, despite distortions or other factors. The $K_p$ and $K_i$ values are based on trial-error method and have been tested until better stability had been reached. Then, using the load current and the inverter current and passing through the same procedure we then get an internal reference for how our load voltage is supposed to be in ideal case and compare with actual load voltage and pass as duty for our inverted control signals. This method was described in the beginning of this chapter where the internal references are generated based on the controller functions and that way the control or energy management system works independently.

## 3.3 Grid-Connected Configuration

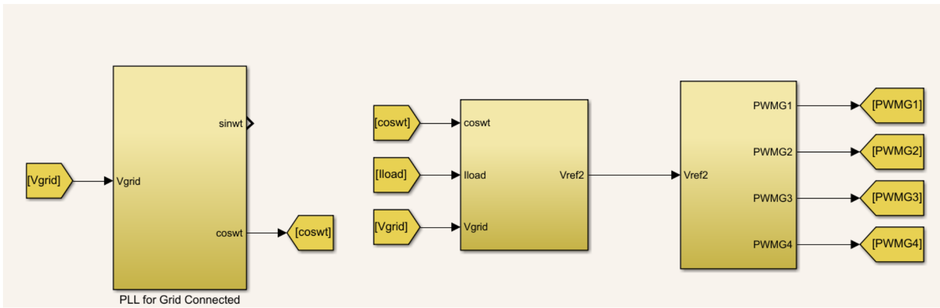



Fig 3.5 MATLAB Schematic of Grid-Connected Inverter Control

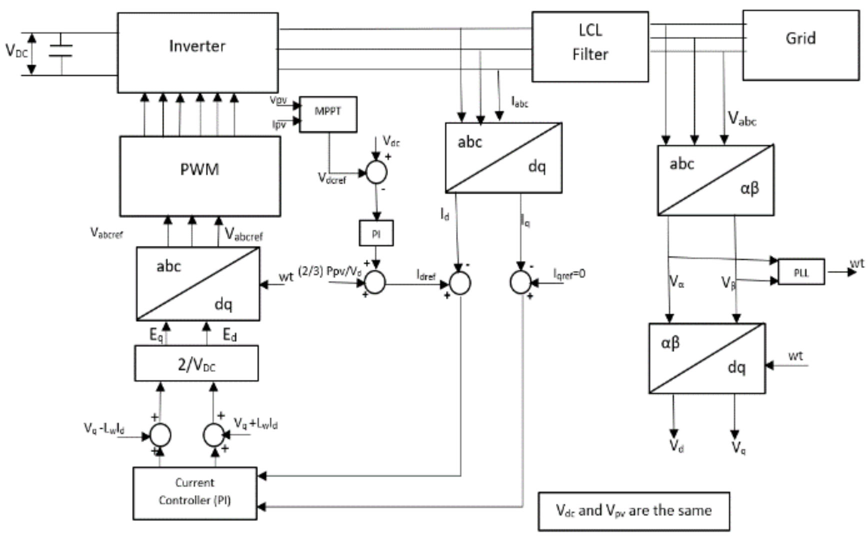



Fig 3.6 Flow Diagram of a Grid-Connected Inverter Control

The structure of the controller is almost same as the standalone mode but there are few modifications in this section for better performance in the presence of grid. It has been observed that in the standalone system the MPPT generates PWM signal for the boost controller but here the MPPT is used to generate the reference voltage for the DC bus voltage controller. Another difference is that a feed forward term is provided to the output of the DC bus voltage controller.

The control of this configuration is depicted in Fig 3.5 and Fig 3.6. Also as previously described, Phase Locked Loop (PLL) has been seen in order to move alone the desired grid parameters.

While testing both modes of microgrids, the inverter side parameters and filter designs are set by

$$f_{res} = \frac{F_{sw}}{10} \tag{3.1}$$

where $f_{res}$ is the resonant frequency and $f_{sw}$ is the switching frequency of our system.

Using the typical power relation,the base parameters of the inverter are determined as follows

$$C = \frac{0.05*s}{(v^2*2*pi*f)} \tag{3.2}$$

$$L = \frac{1}{w_{sw}*\frac{I_g(sw)}{V_i(sw)}(1-\frac{w_{sw}^2}{w_{res}^2})} \tag{3.3}$$

$$L_{max} = \frac{0.2\times V_{grid}}{2\times\pi\times 50\times I} \tag{3.4}$$

where $C$ is the filter capacitance is the filter inductance and $L_{max}$ is the maximum amount of inductance with respect to the grid voltage and all these parameters are used on the load end for islanded mode or when the grid is present, the use for a filter capacitance is not very essential.

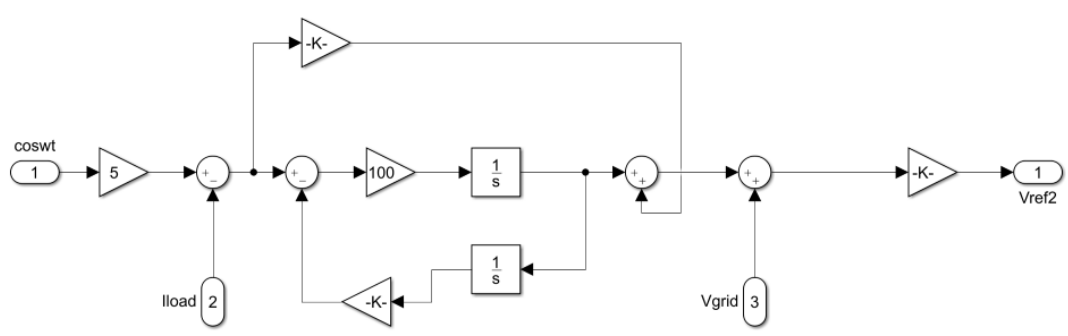



Fig 3.7 Detailed inner diagram of Grid-Connected Inverter Control

The output of the PLL controller is the angle of the active current which is meant to be kept in phase with he input signals while alpha-beta signals are converted to d-q parameters. Then, using this angle from the PLL controller, we generate the cos*wt*, which is the active current reference signal for our inverter control. Then using a feedback, closed PI controller and integrator, we go backwards internally to generate a reference voltage which is believed to be matched with the grid voltage. Then feeding the actual grid voltage and finding the error between the actual and theoretical grid voltage differences, a reference voltage $V_{ref2}$ generates which is basically the duty for the PWM generation of the inverter. And thus, almost the similar principle of the stand-alone inverter control has been followed with inner references which the user has no control of.

## 3.4 Switching Configuration

The switching mechanism is based on a conditional algorithm that seamlessly makes the transition from the grid connected to the islanded mode of the microgrid as shown in Fig.3.8.

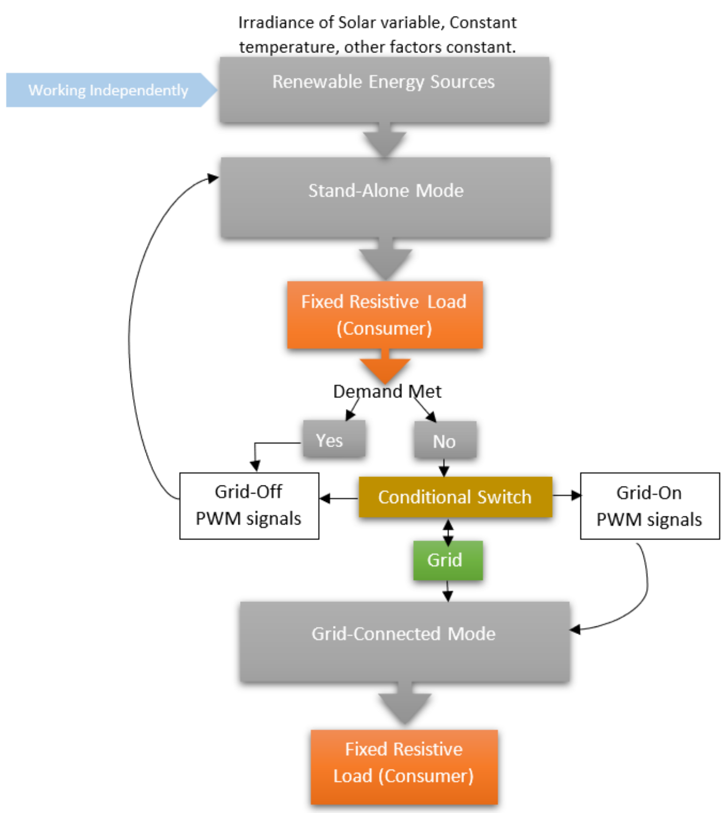



Fig 3.8: User defined conditional algorithm flow chart.

As seen in Fig 3.8, the algorithm works on the factor if the consumer demand is met which is also solely depending on the weather forecast to meet the required specifications of the Solar PV panel. On a bad weather day, it is obvious that the demand cannot be met solely by the renewable energy source, hence on that instance, a manual override is needed to switch on the presence of the Grid in order to fulfil the lack of energy demand. Two sets of 4-PWM signals are made from individual inverter control method as seen earlier. The manual override is only to monitor the grid condition and allow the entire system to shift from stand-alone mode to grid-connected mode. The decision of sending the required sets of PWM signals are made at the switch and sent to the inverter accordingly which reduces the cost of additional components as one inverter is working in both modes depending on the pulses.

The conditional algorithm is developed mostly on the grid side portion. A switching mechanism is used to disconnect or connect the grid from the microgrid which can allow to operate in stand-alone mode when necessary. In this study, a switch has been used at the grid side with a state mode, called as the grid status. When the switch is on, the inverting signals are computed by the grid mode inverter control, which generated four sets of PWM signals. On the other side, when the grid status if zero, the switching block executed four sets of different PWM signals from stand-alone or islanded mode of inverter control. It is depicted in Fig 3.9

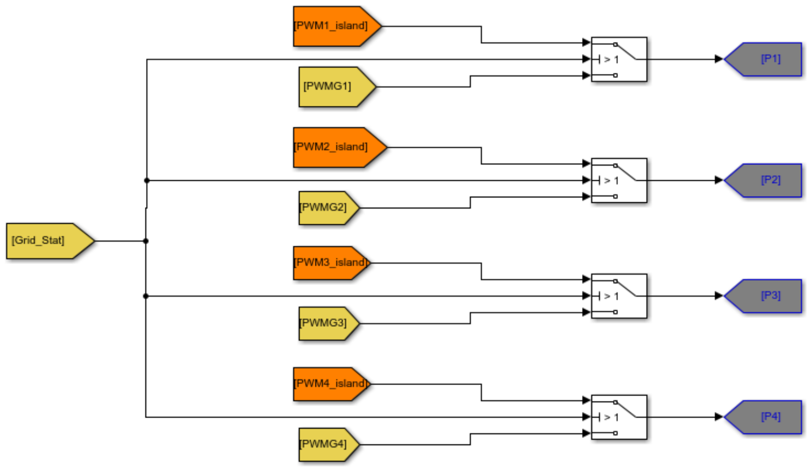



Fig 3.9: MATLAB/Simulink based switching mechanism.

## 3.5 Conclusion

In this chapter, the discussion of the detailed control mechanism of grid-connected and stand-alone inverters have been thoroughly discussed. The functioning of control management system has been established where we see, how the inner parametric values effect on each other. Finally, the switching mechanism or functionality has been highlighted through which a single inverter works in two modes of operation. In the next chapter, the outcomes of the overall systems and the drawbacks of the entire system have been discussed in detail.

# Chapter 4: Simulations and Results

## 4.1 Simulation Set-up

The entire test-bench has been built in MATLAB/Simulink platform and tested accordingly. Simulink is a very interactive platform in order to execute the ideal mechanism of electrical systems. Its library is rich with electrical power components, proportional controllers as well as direct power converters. The simulation bed has enough capability to solve complex mathematical execution and calculations without the user of worrying about the integral calculations. It also allows to detect the bugs and errors specifically and experiment from minor systems to large power grid scale systems in form of block diagrams. The use of algorithms can be implemented in form of C-programming as main language of code or flow diagrams inside of the editor panel of Simulink. Real-time simulators can also be integrated with Simulink in order to test hardware platforms to actually gain the experimental results.

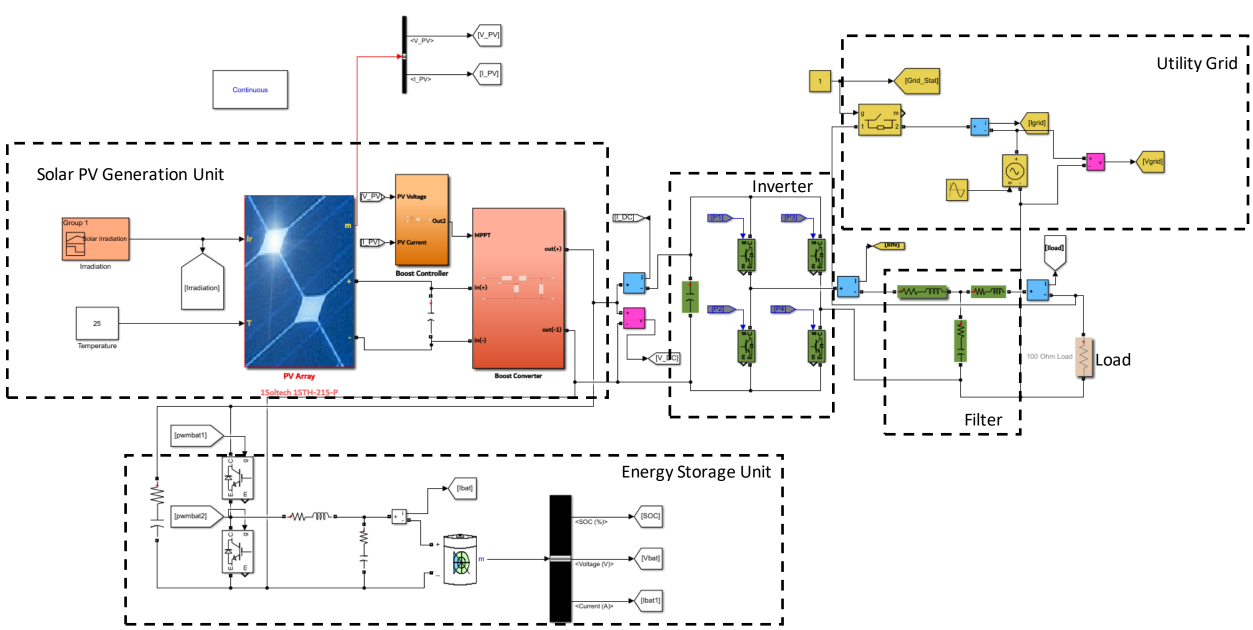



Fig 4.1 Solar PV and ESS based microgrid in Stand-alone and Grid connected mode in Simulink.

According to the Fig 4.1, the following list of components have been used as seen in the Table 4.1.

Table 4.1 List of Components

| **Component Name** | **Model/Rating** |
|---|---|
| PV Array | 1Soltech 1STH-215-P |
| Boost Converter | Inductor-100mH, Capactor-470uF, IGBT (Internal resistance-1mOhm, Snubber resistance-1x10$^5$Ω, Snubber capacitance-inf) |
| Lead-Acid Battery | Nominal voltage (V)- 320, Rated capacity (Ah)-150, Initial state-of-charge (%)-50, Battery response time (s)-1. |
| Buck-Boost Converter | Capacitance (F)- [1000e-6, 20e-6], Inductance (H)- 13e-3, Resistance (Ω)-1e-4, IGBT (Internal resistance- 1m Ω, Snubber resistance-1x10$^5$ Ω, Snubber capacitance-inf) |
| Single-Phase Inverter | Capacitance (F)- 470uF, IGBT (Internal resistance- 1m Ω, Snubber resistance-1x10$^5$Ω, Snubber capacitance-inf) |
| Filter (RL) | Resistance (Ω)- [0.001, 0.0042, 0.001], Inductance (H)- [ 4.06e-3, 4.35e-3], Capacitance (F)- 6.01e-6. |
| Resistive Load | 100Ω |

In order to execute the simulation platform, few steps are necessary in order to perform a secured execution. First the correct compiling method is necessary to select from the solver method section of Simulink. After selecting the solver method, it is necessary to build the system and check if there are any errors and initially the grid status is selected zero. So that allows the system to work in islanded mode, and when checking the deficiency of energy, the grid status is changed to 1 which brings the introduction of the grid and hence the entire case is studied.

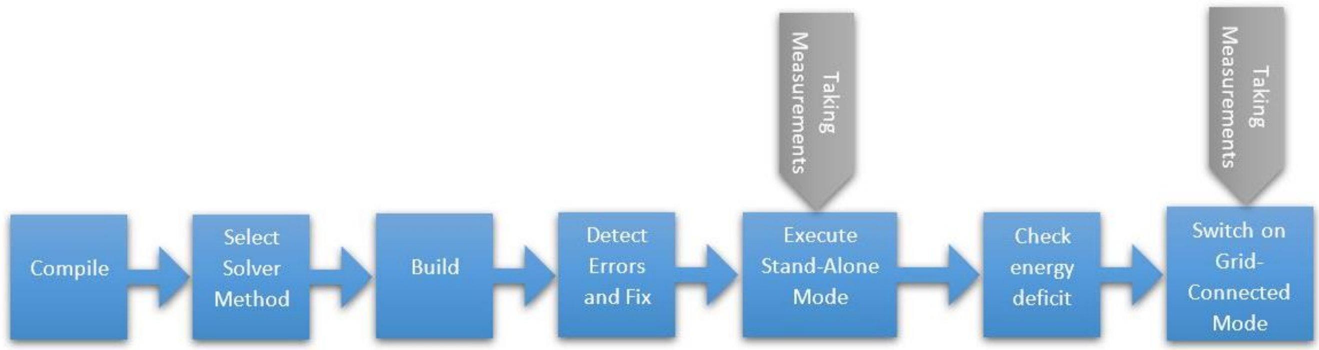



Fig 4.2 Flow Diagram of Execution.

## 4.2. Test of Standalone parameters (solar inverter)

At the first instance, the development of Solar inverter was carried out in order to see the performance of the inverter, as it plays a crucial part of the entire system. The irradiance of the Solar PV model has been manually changed and the performance of the controller for the inverter has been checked to verify the functionality.

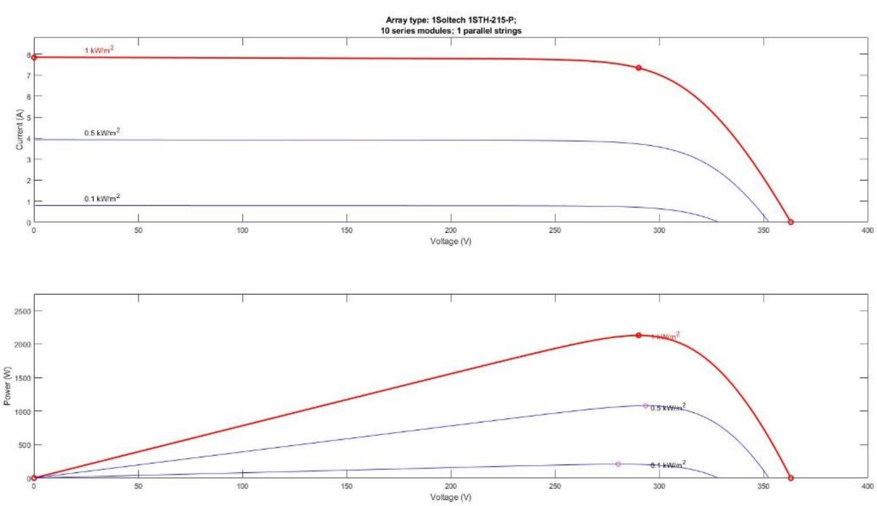
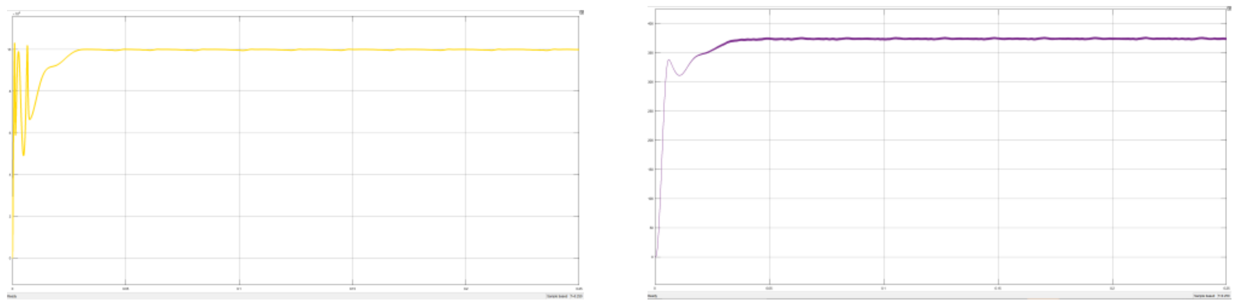



Fig 4.3 Solar PV array irradiance and power curve (1Soltech 1STH-215-P)

As seen in Fig 4.3, the specificized curves at different irradiances for the current, voltage as well as the power can be seen. In order to execute the entire system, based on this ideal curve, the outcome of the inverter had been tested hence, we can see the performance of the solar inverter in the following section.

At Stand-Alone inverter control reference value=250V.



(a) (b)

Fig 4.4 (a) Ppv, Irradiance=1000, Temp=25 (b) Vdc=376.

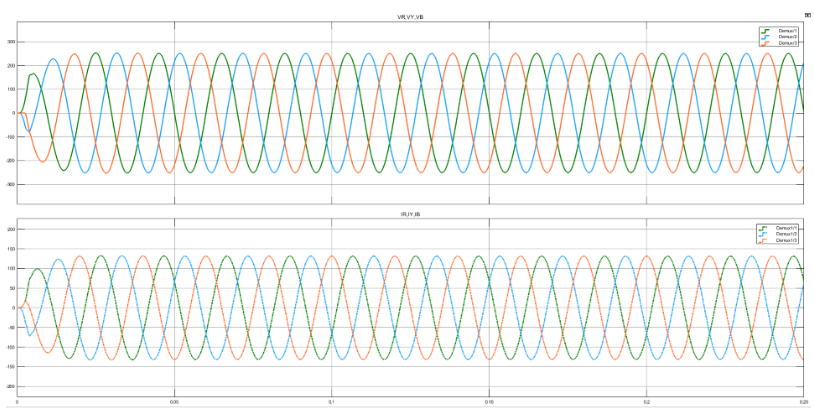
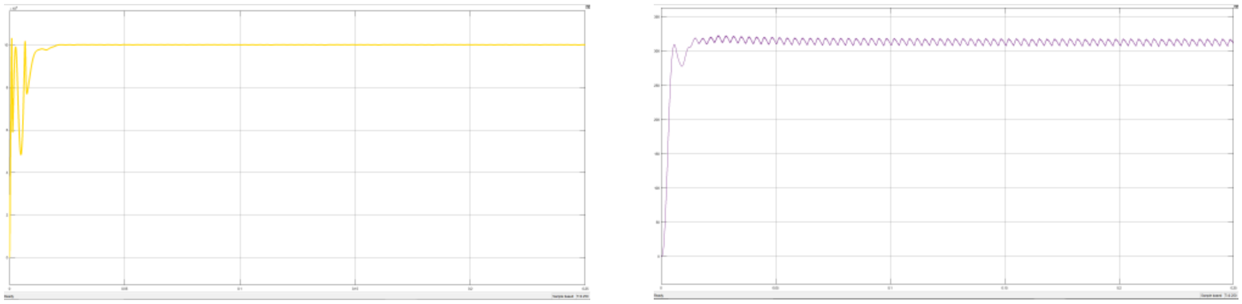


Fig 4.5 Voltage and Current output of the inverter.

At Stand-Alone inverter control reference value=350V.



(a) (b)

Fig 4.6 (a) Ppv, Irradiance=1000, Temp=25 (b) Vdc=311.7.

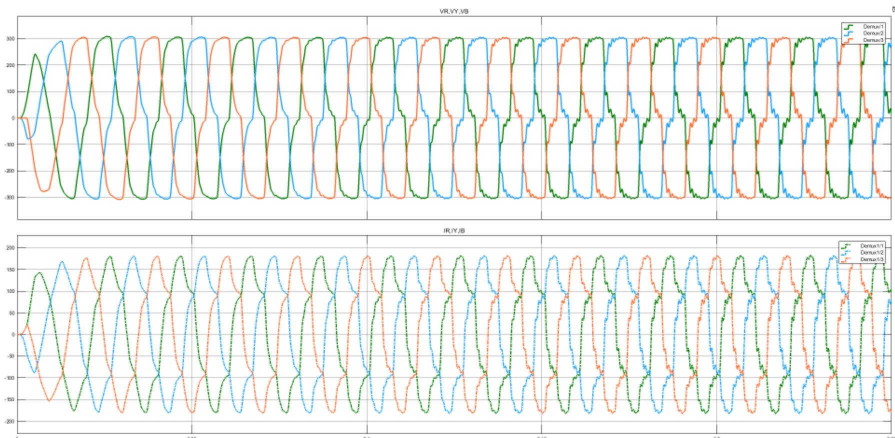


Fig 4.7 Voltage and Current output of the inverter.
(Voltage is shown to follow the $V_d$ref=350 of Controller)

The controller of the solar inverter in stand-alone mode seems to give the desired output, as we begin from setting the voltage from 250V as reference. But as we keep the irradiance and temperature constant from the solar input end, and increase the reference voltage of our controller, as we can see the third figure of the inverter, even though the controller is still following the track but there are some distortions in our signal. Now as the converter approaches the maximum power point; the distortions seem to increase and that is one of the challenges so far. The controller has come to limitations of operating point and needs adjustments and regulative boundaries. Even though the controllers both in this section and the next section at first is tested on three-phase inverter, but in this study, we are dealing with single phase parameters in the microgrid.

Table 4.2 Parameters for Stand-Alone Inverter Controller

| Parameters | | Value |
|---|---|---|
| Voltage Controller: | $K_p$ | 0.038 |
| | $K_i$ | 21 |
| | Carrier Wave | Amplitude: 300, Frequency: 314.14 rad/s |
| Current Controller: | $K_p$ | 14.6 |
| | $K_i$ | 6.67 |

## 4.3 Test of Grid-Connected parameters (solar inverter)

In this section, the test for the Grid-Connected inverter has been implemented. Even though the grid is present to overlap the need of frequency and voltage control, but an additional phase locked loop (PLL) as discussed earlier is needed to follow the phase and be aligned with the grid parameters. As depicted from Fig 4.8-4.10, it is seen that based on the irradiation, the reference voltage for the voltage controller is giving the desired output accordingly. The changes can be seen at the 3-phase current magnitude which is obvious as we are using the MPPT algorithm to get the maximum power which is driver by voltage hence current is variable in this process. As MPPT is directly applied to the solar pv, adding a boost converter is also to be studied for better results.

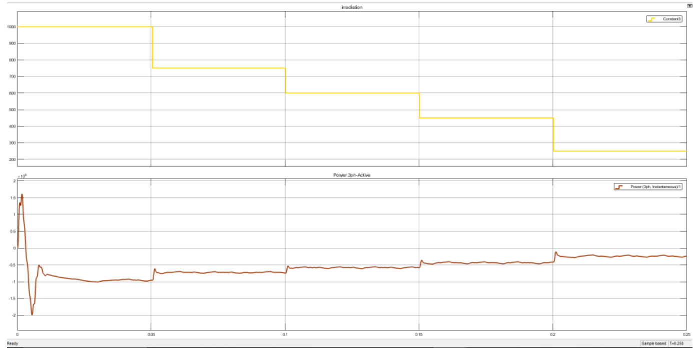



Fig 4.8 Irradiation (1000,750,600,450,250) and 3-phase Inverter power

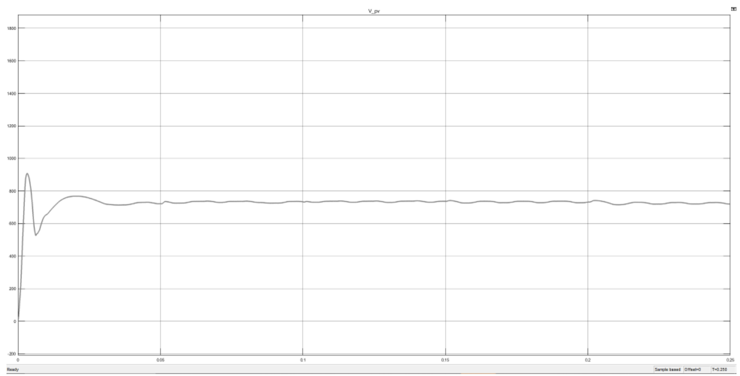



Fig 4.9 Solar PV voltage at different irradiations}

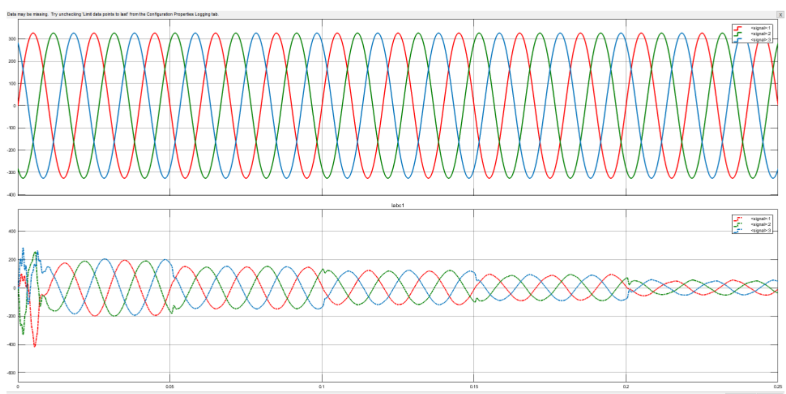



Fig 4.10 3-phase voltage and current at irradiations (1000,750,600,450,250)

## 4.4 Test of entire microgrid system with switching

In the Stand-Alone mode configuration, a purely resistive load of 100Ω has been tested at the load end with the grid status of the switching module being kept at zero (to keep the grid disconnected).

### 4.4.1 Simulation Results: Scenario-1 [Standalone Situation]

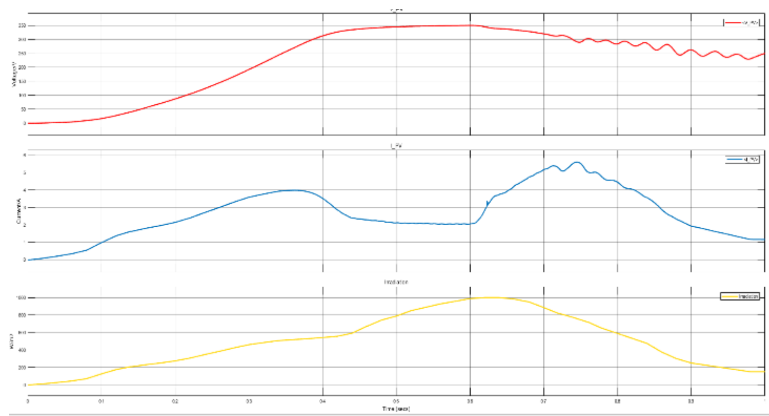


Fig 4.11 PV voltage, PV current and solar irradiation for Stand-alone configuration.

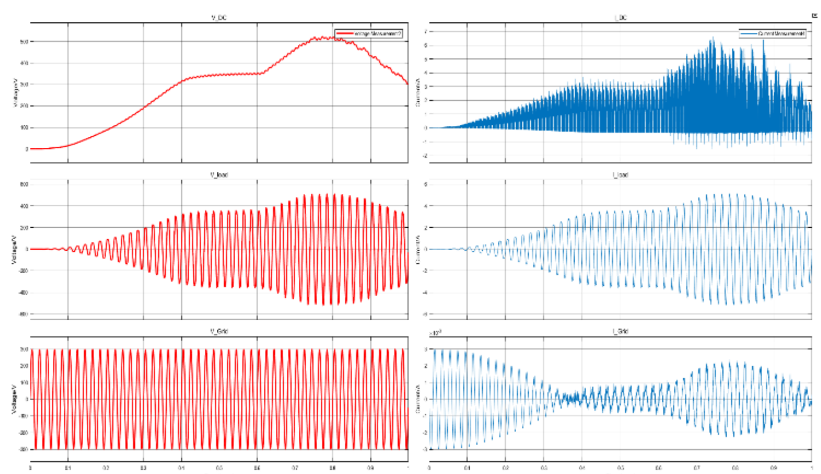


Fig 4.12 Voltages (DC, load, grid) and currents (DC, load, grid) for stand-alone configuration.

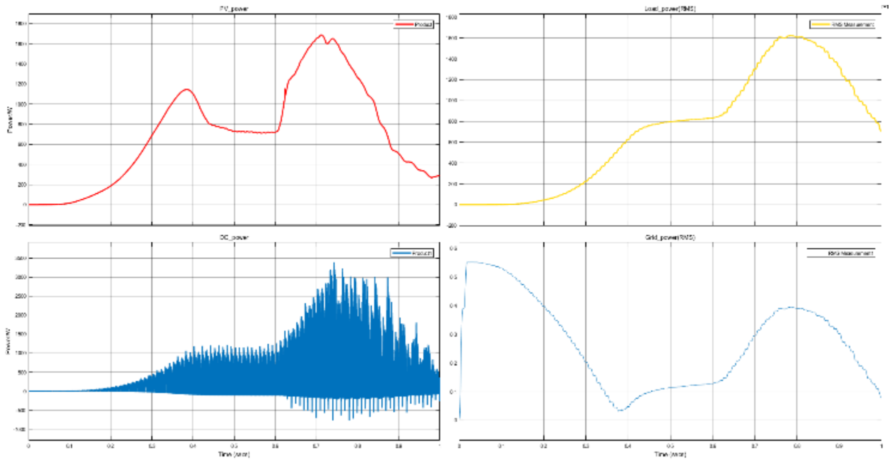


Fig 4.13 Power (PV, DC, load, grid) for Stand-alone configuration.

**Analysis:**

As seen from the Fig 4.11., based on the solar irradation profile, the Solar PV array maitans a good course of voltage with smooth transitions. It is seen to reach the maximum power point that is being controlled by the MPPT-Boost converter.When there is a downfall of the irradation curve due to climate or environmental forecast,there is we see there is a voltage drop but as the drop of irradation is sudden, the solar pv voltage drop is not as smooth as when it was rising towards the best results. On Fig.4.12, the analysis of the voltages and currents can be seen.Firstly, the Vdc is boosted and follows the pattern of the Solar PV voltage hence similarity between the figures can be seen except the numeric values are boosted. The current is also seen to follow an adequate manner and with respect to that,we can analyze the load current and voltage with respect to the DC-link. We can the change of the Load voltage and current is solely dependent on the flow of the Solar PV as it is the primary source of energy.On the third portion we can see the presence of Grid voltage and current but they have no effect on the Load voltage as,the at this mode the grid status is set to zero,meaning that the even though the grid is present but it is not actualy present in the main system.

Finally when we have a look at Fig 4.13., the trend of power curves from the system can be observed and understood. The PV power is independent as discussed on the prior sections due to it being the only primary form of energy generation input source,depending on it the rest of the parameters are changed. It is obvious the DC power will be not smooth due to the availability of the the converters from both the PV boost controller and Buck-Boost converter of the ESS. Hence we see a little distortion of signal but when we analyze the load power,the it is seen to follow a smooth pattern with respect to the energy source hence we can deduce that the inverter is doing its task. Like mentioned earlier, the grid is not connected to the system hence the power is very negligible.

### 4.4.2 Simulation Results: Scenario-2 [Grid-Connected Mode]

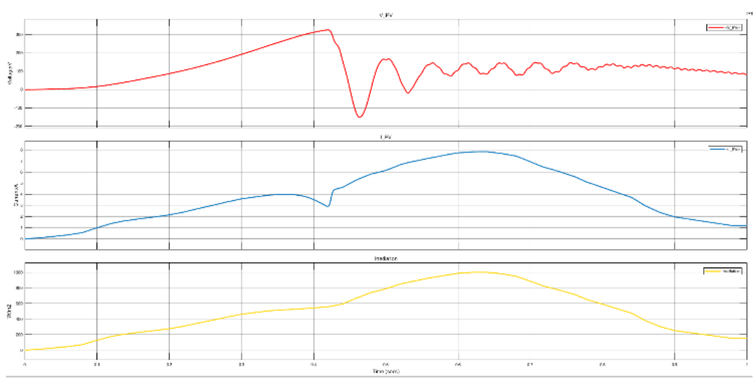


Fig 4.14 PV voltage, PV current and solar irradiation for Stand-alone configuration (Transition to grid-connected configuration at 0.4s).

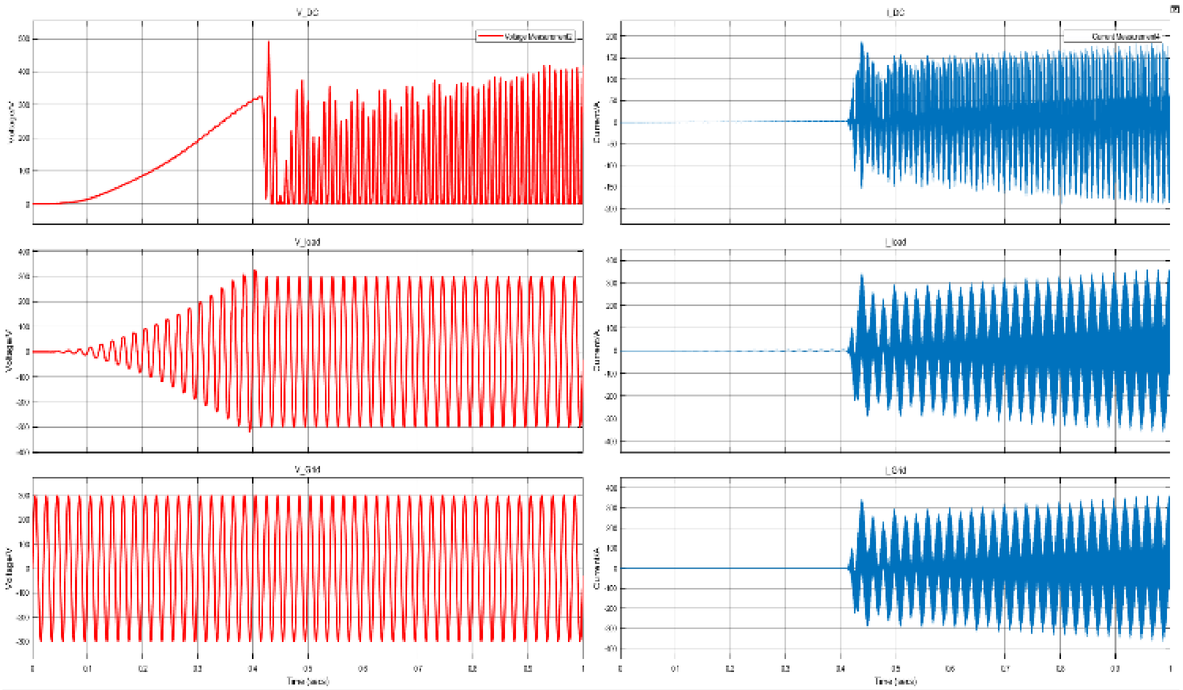



Fig 4.15 Voltages (DC, Load, Grid) and Currents (DC, Load, Grid) (Transition to grid-connected configuration at 0.4s)

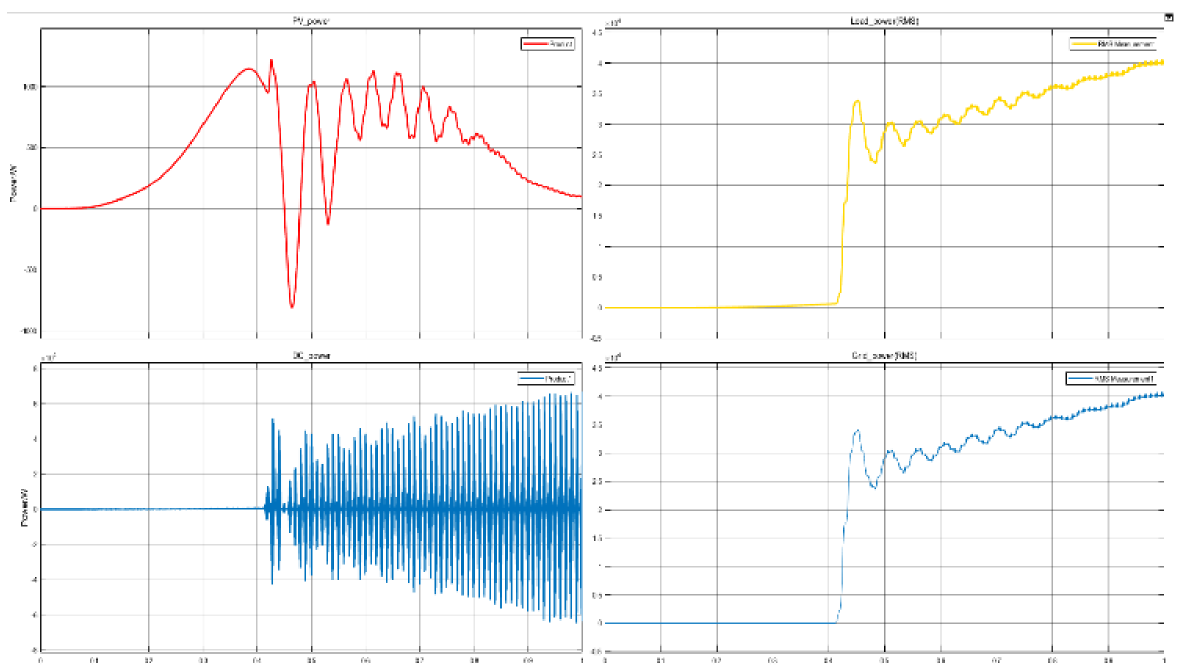



Fig 4.16 Power (PV, DC, load, grid) (Transition to grid-connected configuration at 0.4s)

**Analysis:**

As seen in Fig 4.14, even though the PV current has no major effect in it's wave form,but when we look at the wave form of the PV voltage at 0.4s, the PV voltage does not seem to behave the trend of the solar irrdaition. The reason behind that is,at 0.4s the grid status of the utility grid is turned 1, meaning that the grid is being attached and introduced to the system**.**The inverter,flows bidirectionally,hence the grid interferes with the primary signal and creates distortion as our main aim was to feed the load with the help of the grid due to umavability of Solar PV energy.This is a just a predcited case to study the behaviour for the rest of the system.The following effect can further be seen in the Fig 4.15,wehere the load current and voltage turns out to flow constatnly as soon as the grid is turned on,hence it stabilizes the system.Finally,when we look at Fig 4.16, we see the power of the load is following the power of the grid as the grid itself is the major factor that is overcoming all the defiency created from the distributed energy sources.The switching does create a little anomalous behavior but stabilizes as the execution period passes throughout the whole simulation time and does get better when the grid is being introduced.

### 4.4.3 Analysis of energy storage system

As cited earlier, this study is mainly focusing on the control method and results of the inverter in both stand-alone and grid-connected modes.The energy storage system is a basic addition of the battery and the work in order to turn it into an effiecient system can be done in the future. For this study, the control mechanism of the battery or the energy storage system has been discussed in previous section.Using a PI controller,the vallue of refference current is positive while charging and negative while discharging the battery. As seen in Fig 4.17, initally the current of the battery is followed ideally.When the controller current refference is set to postive value the battery is being charged and when the value is negatyive it is being discharged.

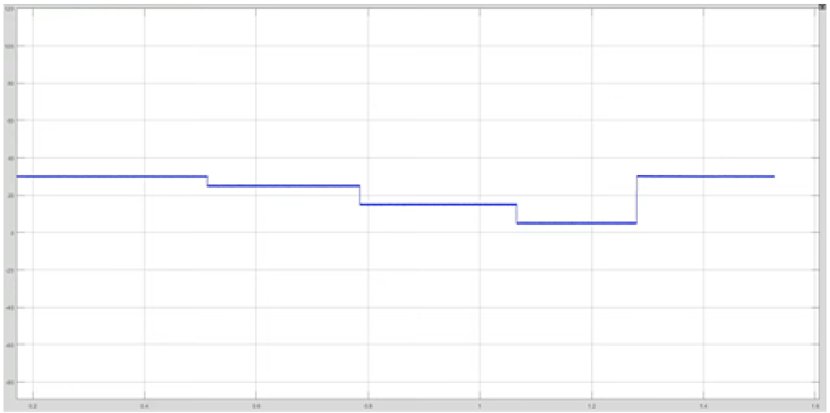


Fig 4.17 Battery Current from the Ideal ESS

As we look in Fig 4.18 and Fig 4.19, we can see the performance of the ESS in stand-alone mode.

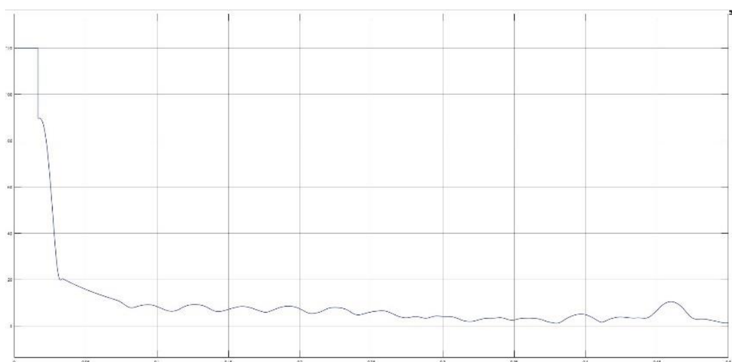


Fig 4.18 Battery Current from the Actual ESS

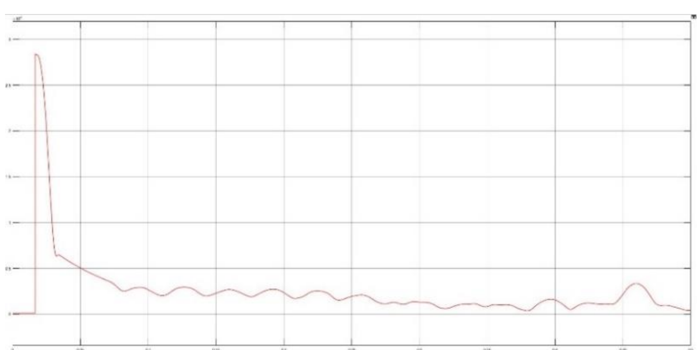


Fig 4.19 Battery Power from the Actual ESS

The refference value is controlled manually, meaning here for charging phase the battery current refference is set to 1A but if we look closely,in Fig 4.18, the current is fluctuating around the given current refference but is not constant due to the weakness of the control mechanism. Even though we are trying to work with the active current,but there are reactive currents from the system moving back and forth in the ESS as we are using a bidrectional converter. Even at the 50% of execution time, when the current reference is set to negative parameters,to discharge it is seen that the solar PV via the DC link is still effecting the current waves and power.Hence,the discharging is not succesfful as it should be ideally. Further works on the control of DC link can be useful to make this ESS system in a better shape. Eventhough in islanded mode the energy storage system is supposed to control the DC link but in practive it creates anamalous behaviour with further challenges.

## 4.5 Conclusion

In this chapter the discussion of the simulation of the systems have been divided into smaller portion and tested. The whole testbed was designed in MATLAB/Simulink and with the use of the rich library from Simulink, the tests have been carried out. The main concepts were tested between Stand-Alone mode and Grid connected mode and in between their transitions. It was seen that the transition creates distortions at certain levels but eventually the system stabilizes with the help of grid when it is introduced in the system.

# Chapter 5: Conclusion and Future Scope

## 5.1 Conclusion

A solar PV microgrid has been implemented in MATLAB/Simulink environment. It can be operating in stand-alone and grid-connected modes. Control systems and a switching mechanism have been developed to operate the PV microgrid in both modes. The tests have been done for fixed load, but the controllers can be improvised to operate under unbalanced loads. The research has been done to see the trends of behaviour when we try to switch from a running islanded system to a grid-connected system. The focus was set on the control methods of the inverters in both sets of operation. Several approaches have been tested gradually from individual converters to comprised version of the microgrid. Even though in theory, ideally the switching should be working seamlessly but even in simulation bed the results were uncertain at certain levels with distortions. Firstly, when connected in islanded mode, the sole operator or supplier of energy was the solar PV panel and hence depending on it several factors were affected. An unstable form of irradiations was fed but it was seen that the voltages from the inverter were following as it should be but the distortions arose mainly in the current waveforms. The reason could be the fixed resistive load as well as the effect of the ESS that was also controlling factor for the DC link but as discussed earlier, the ESS was not able to operate properly. Hence not only in the stand-alone mode but also when the system was introduced with the utility grid, the bi-directional flow of the currents through the grid to the DC link and vice-versa was affecting majorly. An effective DC link control can stabilize the aforementioned distortions and hence it can be worked better in future.

## 5.2 Future Scope

The present research work can be extended further. The opportunities for future work can include the following changes:

- Instead of using basic PI controller with Trial-and-Error method, for an instant, artificial neural networks (ANN) or fuzzy based controller can be used. MATLAB has a rich library and toolkit for ANN implementation hence it could be a good approach for parametric optimization.
- The Energy Storage System (ESS) needs major work as it is a crucial factor for controlling the DC link in islanded operation. The ESS controller can be focused with optimized control method in order to stabilize the factors of current in the entire system which was a major drawback in this study.
- The DC link control can be another driving factor to be studied as regulating some parameters at the DC link can enhance the performance of the inverter without facing distortions.
- The system can be tested in Real-Time platforms such as OPAL-RT or Typhoon HIL for better understanding of the efficiency of the system.
- The system can be reconfigured easily for hybrid (wind, solar and fuel-cell) system or with any other distributed energy sources.

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