ASHESI

ASHESI UNIVERSITY

A SMALL PHOTOVOLTAIC INVERTER FOR GRID-CONNECTED OPERATION

CAPSTONE PROJECT

BSc. Electrical and Electronic Engineering

David Katandi Oburu

2020

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A SMALL PHOTOVOLTAIC INVERTER FOR GRID-CONNECTED OPERATION

CAPSTONE PROJECT

Capstone Project submitted to the Department of Engineering, Ashesi University in partial fulfilment of the requirements for the award of Bachelor of Science degree in Electrical and Electronic Engineering.

David Katandi Oburu

2020

DECLARATION

I hereby declare that this capstone is the result of my own original work and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:

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Candidate's Name:

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I hereby declare that preparation and presentation of this capstone were supervised in accordance with the guidelines on supervision of capstone laid down by Ashesi University.

Supervisor's Signature:

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ABSTRACT

Solar energy being one of the most promising renewable resources, plays a very significant role in the energy sector of different economies in the world. However, the photovoltaic (PV) system still faces some challenges such as high costs, low efficiency and the photovoltaic (PV) system's output power intermittent nature as compared to other renewable technologies. This project focuses on three key areas of PV grid-connected inverter control strategies that is the PV Maximum Power Point Tracking (MPPT) using perturb and observe technique, the PV grid-connected Synchronization technique using phase-locked loop (PLL) and PV inverter control using proportionate-integral (PI) technique to control the voltage and the current of the PV grid-connected inverter. The control techniques operate in such a way that during the grid-connected mode, the PV inverter output frequency and the amplitude is controlled by the grid and the inverter operates in a current-controlled mode. The inverter current-controlled mode of operation achieves two requirements that is, the excess energy generated from the PV inverter is transmitted to the grid under no overload condition. During unfavorable weather conditions or overload conditions, both the grid and the PV inverter operate in a voltage-controlled mode in order to maintain a constant frequency and amplitude of the voltage across the load. Simulations in MATLAB/SIMULINK have been used to verify the validity of the proposed system.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

Chapter 1: General Introduction

1.1 Background

The grid-connected photovoltaic systems as the name suggests are the systems that generate power and are connected to the grid. The-connected PV systems are designed to function in parallel with the electricity utility grid [1]. Since the last decade, the PV grid-connected systems have increased significantly globally on account of the abundant nature of solar energy, and the pollution-free photovoltaic process of converting it to electricity and therefore, making the electricity utility grid to shift or tilt towards a situation that is weather reliant [2]. Owing to the quick growth of the grid-connected PV system, the controller mechanism of the system is tackled with enormous challenges of grid reliability and stability [3]. Weather conditions which comprise temperature, irradiation and other meteorological conditions should be considered when designing a grid-connected PV system [3]. Due to the uncontrollable nature of weather conditions, a battery energy storage system is applied to cater for the PV system output power fluctuation when irradiation and temperature changes [4], [5]. Besides, it is very significant to design and control inverter effectively in order to achieve a high-quality output power of the photovoltaic systems [3]. This means that the inverter switch would ideally be designed to ensure that no harmonic current is injected in the grid [3]. Escalating or increasing interest in the photovoltaic systems, calls for growth in research and development (R &D) in other power generating aspects such as Maximum Power Point Tracking (MPPT), power quality, stability and reliability, PV arrays, anti-islanding protection and power electronics [6]

1.2 Problem Definition

The grid-connected PV system installations have been increasing in the recent years on account of improved PV technology [7]. However, there are technological issues or challenges that are still affecting the grid-connected PV operations for example, the power quality and stability issues as well as low and high-frequency parameters to the grid [7]. Central to the successful operation of the grid-connected PV system is the inverter which is also known as a power conditioning unit (PCU). The inverter helps in providing AC power with good power quality that comprises of low total harmonic distortion and high power factor, in addition to the highest possible efficiency of different solar irradiance levels [1]. Besides, inverter requirements consist of operation over a wide voltage and current ranges and regulated output voltage and frequency [1]. In order to minimize or solve these technical challenges, a proper design and management unit is needed. Therefore, this requires an accurate and fast inverter control and synchronization mechanism in the system [7]. Recent research indicates that the phase-locked loop (PLL) based synchronization technique is more reliable and efficient for such applications [8], [9], [10]. This inverter control mechanism will ensure the active and reactive power generated to the grid are controlled which will then result in high quality of injected power and grid synchronization [11].

1.3 Project Objectives

1. To design and simulate a small PV inverter for grid-connected operation systems
2. Using electronic components to design and build a single-phase pure sine wave inverter
3. Designing and building a DC-DC boost converter for the Solar PV array in MATLAB/SIMULINK software
4. Implementing a proportional-integral (PI) control of PV inverter in MATLAB/SIMULINK

1.4 Expected out comes of the Project Work

Successful simulation of single-phase small PV invertor in MATLAB/SIMULINK for grid-connected operations in order to verify the performance of the system. A fully well developed and built single-phase pure sine wave inverter for grid-connected photovoltaic systems in MATLAB/SIMULINK software.

1.5 Motivation of the Project Topic

The ever-increasing energy demand to satisfy the need of energy users. This requires a diversification of the energy supply systems. According to the International Energy Agency (IEA) guide report 2019, global energy demand increased by 2.3% in 2018 and it was the fastest energy demand increase in the last decade [12]. Therefore, this calls for harnessing energy from renewable sources such as the sun. In addition, for a country to be recognized as a developed nation, the per capita energy consumption needs to be considered and this requires a maximum energy generation [13].

Environmental conservation and the need to improve health safety. These days our climate is being threatened by global warming due to the emission of dangerous gases like carbon dioxide in the atmosphere from activities such as the generation of electricity from the combustion of fossil fuels, coal and many more. Therefore, there is a great need to restore the glory of our environment by investing in green energy that is by designing a cost-efficient and reliable solar PV grid-connected inverter with least or no negative impact on environment and ecology.

1.6 Research Methodology Used

1. Review of pertinent literature from journals, books and related topics

2. A thorough consultation with the supervisor and many other resourceful people in different engineering departments of the University
3. Experimental and simulation methodology was also used during the research process

1.7 Facilities used for the research

1. University's science, electronics and mechanical laboratories
2. The university's mechanical workshop
3. Internet, computer and library facilities of the university

1.8 Scope of the Project Work

This project work is limited to the simulation of a small single-phase PV grid-connected inverter, mathematical modeling of Solar PV module, synchronization of the solar PV inverter with the utility grid and implementing the PI inverter control technique in MATLAB/SIMULINK.

1.9 Project Organization

This project is divided into five chapters. Chapter one discusses the overview of the project in general. That is, it defines the problem, states the objectives of the project, project expected outcome, motivation, research methodology and facilities used as well as the scope of the project and the work organization.

Chapter two of this paper focuses on the literature review. This chapter discusses the background, considers the review of the proposed system blocks that is Solar PV array, Battery, Maximum Power Point Tracking (MPPT), DC-DC converter and a filter. This chapter also discusses the survey of related works.

Chapter 3 discusses the design methodology of the small Solar PV inverter for grid-connected operations. The MATLAB/SIMULINK software implementation is also discussed in this chapter.

Chapter four elucidates or discusses in detail the results and discussion of the design. In addition, Chapter five, finally, discusses the conclusions, limitations, lessons learnt and the future work of the project work

Chapter 2: Literature Review

2.1 Background of the Research

Energy is very paramount for the economic, social, and industrial development of a country [13].The PV grid-connected systems always apply the pure sine wave inverters which foster easy synchronization with the wave and the frequency of the grid-connected [14]. The solar PV grid-connected inverter must also have a mechanism to disconnect from the grid in case of the grid breakdown or if the power of sufficient quality in voltage, current or sine wave is not being supplied by the grid [14]. The solar grid-connected PV systems with battery storage help the residential and commercial sites to limit dependence on utility grids [14]. Besides, with the help of PV inverter control in the system, some energy goes straight to the load and some of it is channeled to charge the battery for use in the critical loads such as computer system. A basic PV grid-connected system power generation consists of PV array, Charge controller, DC-DC converters, PV inverter and its control, filter and electricity grid as seen below [15].

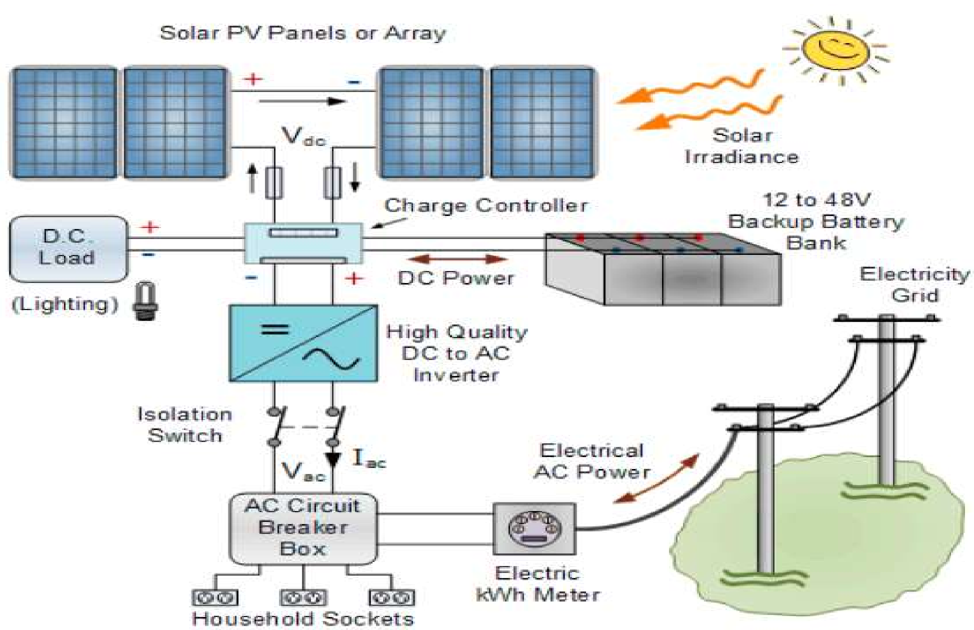

Figure 2.1 A simple Grid-connected PV System

2.1.1 Solar Cell Efficiency and Losses

By definition, a solar cell efficiency refers to the ratio of the output power of the cell or array to sunlight power of the total area of the exposed cell [13]. The maximum capacity of the solar cell is around 47% [13]. Some of the causes of lower efficiency in solar cell include; absorption of some energy by the non-PV cell surface, a reflection of some of energy back to the environment and conversion of some of the energy into heat dissipation [13]. However, there is ongoing research to improve the solar array efficiency.

$$Eff_{solar\ cell} = \frac{Output\ Power}{Total\ area\ of\ the\ solar\ cell\ exposed} \tag{2.1}$$

2.1.2 PV Array Configuration

The PV arrays are typically configured into four different topologies that are AC-cell or AC- module technology, centralized technology, a multi-string technology and single-string technology [16]. In addition, a centralized technology is a conventional one where multiple PV modules are connected in series to form a string of PV modules which are then connected in parallel to form the PV array and feed the inverter [16] as seen in figure 2.2 below.

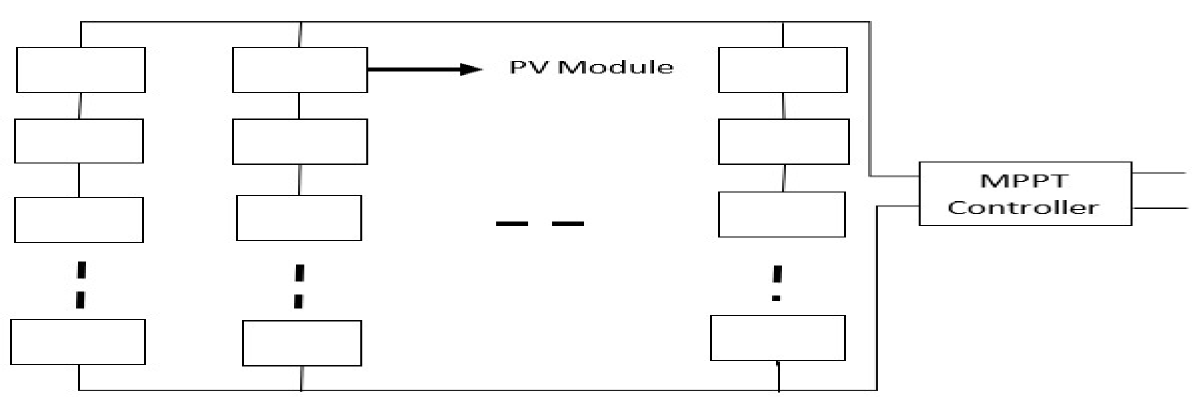

Figure 2.2 Centralized technology PV arrangement

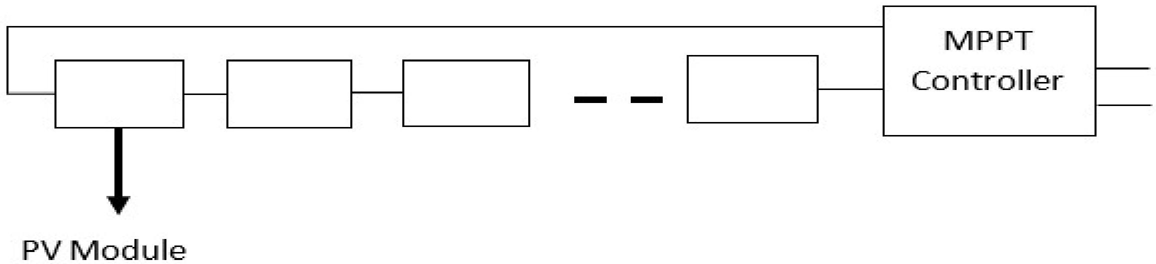

Figure 2.3 Single-string technology PV arrangement

In figure 2.3 above, the PV modules are connected in series to form the PV array

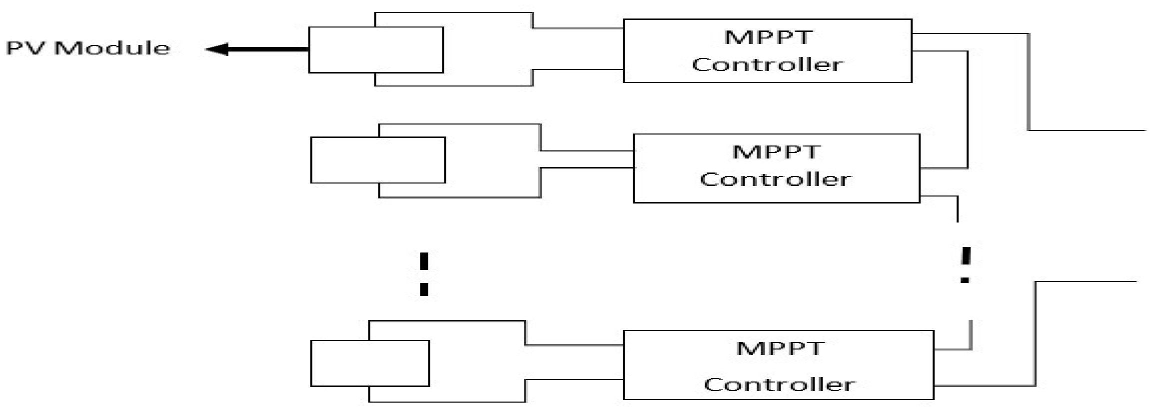

Figure 2.4 Multi-string technology PV arrangement

Figure 2.4 above consists of a PV module that has its own DC-DC converter connected in series and fed to single DC-AC inverter [16].

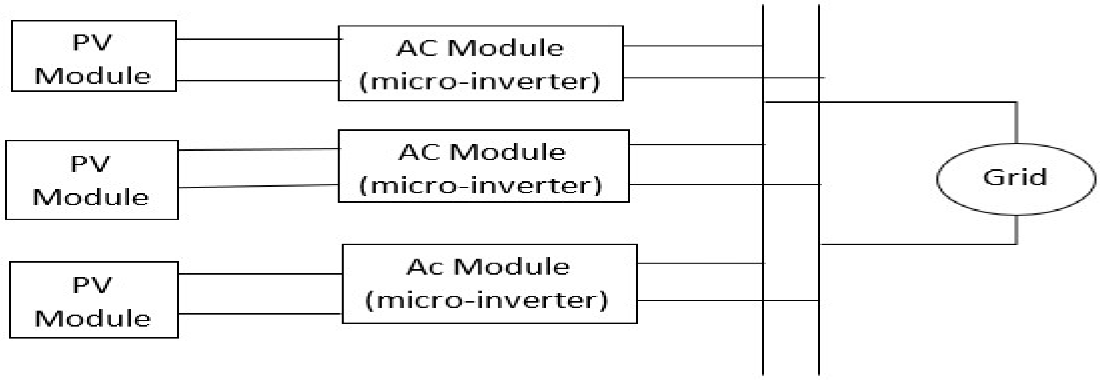

Figure 2.5 AC cell PV arrangement

Figure 2.5 above is a PV configuration which consists of a PV module and an AC module inverter to feed the grid [16]. All the PV configurations have their own pros and cons as seen in the table 2.1 below

Table 2.1 Advantages and disadvantages of each PV configuration

	Advantages	Disadvantages
Centralized Technology	PV array arrangement generates higher voltage and current suitable for large scale systems (>1 MW) Simple and low cost as only one MPPT controller is used	The MPPT controller considers the PV modules arrangement as one whole thus makes the output power smaller
Single-String Technology	PV array arrangement generates higher voltage and low current which is easy to assemble based on power demands	One shaded PV module can cause large power dissipation on the that module as the photocurrent in that module may drop

Multi-String Technology	Each PV module has its own MPPT controller thus maximum power is drawn	Complicated and costly. Shading problem is reduced as only one module is in series
Microinverter technology	The output from this technology can be directly connected to AC system	Has an additional up-front cost

2.1.3 PV Cell Equivalent Circuit

Modeling of the PV module using the data available in the manufacturer's datasheet is necessary in order to analyze the grid connected PV systems. However, the datasheet does not give some of the parameters required for modeling of the PV module [17]. Therefore, in carrying out the modeling of the PV solar cell, the parameter values are estimated from the datasheet to facilitate modeling of the PV cell [17]. See the appendix for the datasheet values.

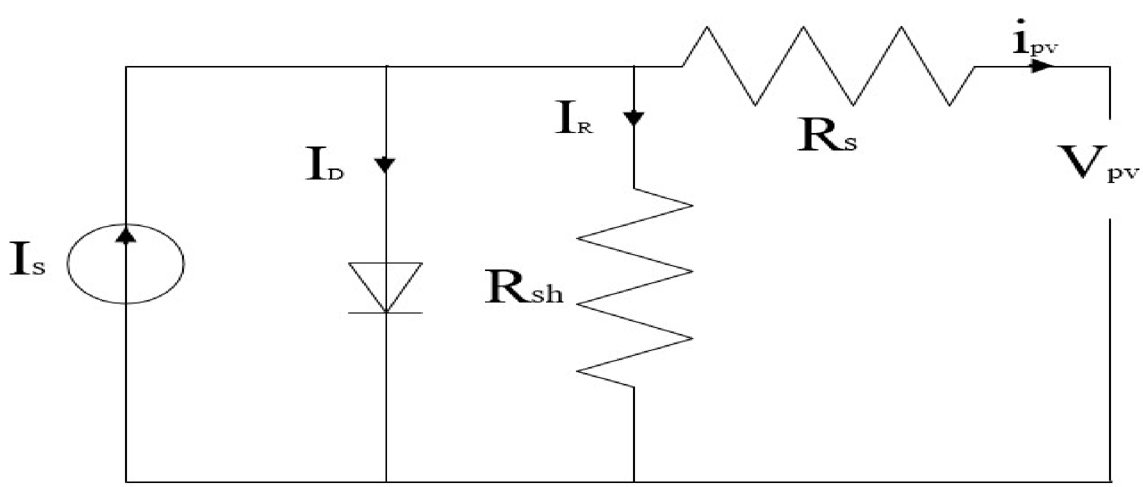

Figure 2.6 Equivalent circuit of a PV module designed using Microsoft Visio

The characteristic equation of a PV module is expressed as seen below [3]

$$I_D = I_0 \left(\exp\left(\frac{q(V_{pv} + R_s i_{pv})}{AkT} \right) - 1 \right) \tag{2.2}$$

Where, I_D is diode current, I_0 is the reverse saturation current, q is the Electron charge, V_{pv} is the output voltage, R_s is the series resistance, i_{pv} is the output current produced by PV battery in amperes (A), A is dimensionless junction material factor, k is Boltzmann's constant, and T Operating temperature of a solar cell (in Kelvin). The constant figures can be seen in the appendix.

Applying Kirchhoff's current law in Figure 2.6, the output current of i_{pv} produced by the PV battery can be expressed as seen below,

$$i_{pv} = I_s - I_0 \left(\exp\left(\frac{q(V_{pv} + R_s i_{pv})}{AkTN_s} \right) - 1 \right) - \frac{V_{pv} + R_s i_{pv}}{R_{sh}} \tag{2.3}$$

Where, I_s is Photocurrent, N_s is the Series number of cells and R_{sh} is the Shunt resistance (Ω)

The luminous or the photocurrent I_s is dependent on the radiation of the solar which can be associated with,

$$I_s = \left(I_{sc} + k_i(T - T_n)\right) \frac{R}{R_n} \tag{2.4}$$

Where, I_{sc} is the short circuit current, k_i Short circuit of the PV cell at 25°C and $100\frac{W}{m^2}$, T_n is the Reference temperature of the PV cell, R is the Solar radiation, R_n is the Nominal solar insolation. The values of some constant parameters have been included in the appendix. The saturation current I_0 changing with the temperature is given as,

$$I_0 = I_{RS}\left(\frac{T}{T_n}\right)^3 \exp\left(\frac{qE_g}{Ak}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right) \tag{2.5}$$

Where, I_{RS} is the Reverse saturation current under the reference temperature and the irradiation, and E_g is the Band-gap energy of the PV solar cell conductor (eV). The output current i_{pv} can also be written as seen below,

$$i_{pv} = N_p I_s - N_p I_D\left(\exp\left(\frac{q(V_{pv}+R_s i_{pv})}{AkTN_s}\right)-1\right) - N_p\frac{V_{pv}+R_s i_{pv}}{N_s R_{sh}} \tag{2.6}$$

Where, N_p is the Parallel number of cells

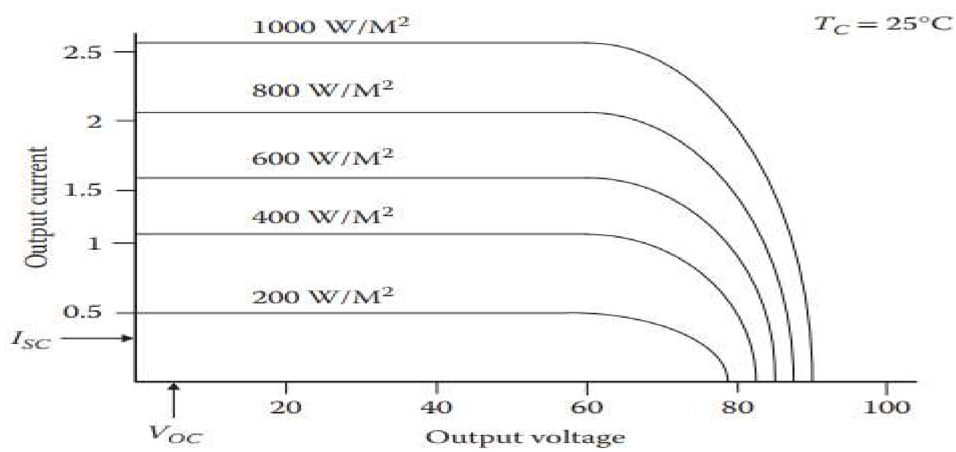

Figure 2.7 I-V characteristics of solar cell 25°C

Figure 2.7 indicates that as the irradiance value increases, both the short circuit current and the open-circuit voltage of the PV cell increases and therefore the power output will also be large [13]. Power in a DC circuit is calculated as the product of voltage and current [13].

$$P\ (\text{watts}) = I\ (\text{amperes}) * V\ (\text{volits}) \tag{2.7}$$

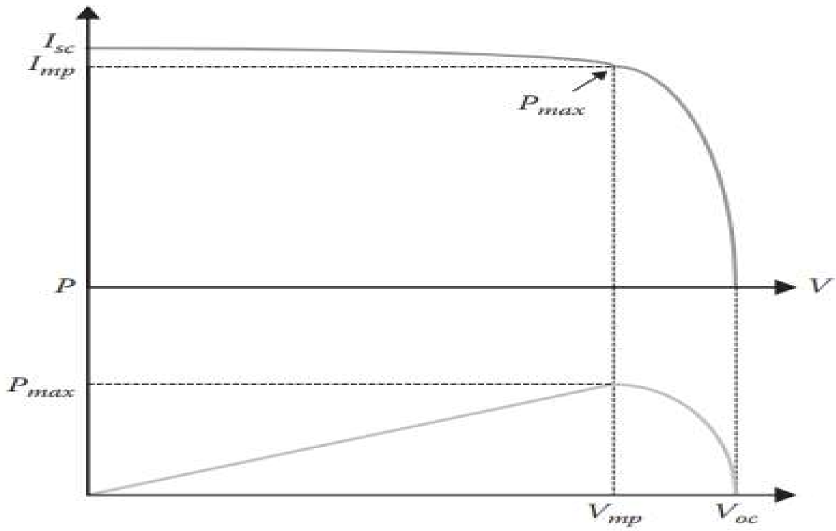

Figure 2.8 PV characteristics of a solar cell

It is also important to note that in V-I characteristics of the solar cell, there is a maximum power point (MPP). Therefore, maximum power P_{max} is

$$P_m = (V_{mp} * I_{mp}) \text{ watts} \quad (2.8)$$

2.2 DC-DC (Boost) Converter

The boost converter also the carries out the function of the Maximum Power Point Tracking (MPPT) by varying the duty ratio [18]. The boost converter can mathematically be modelled using equations 2.9 and 2.10 as expressed below.

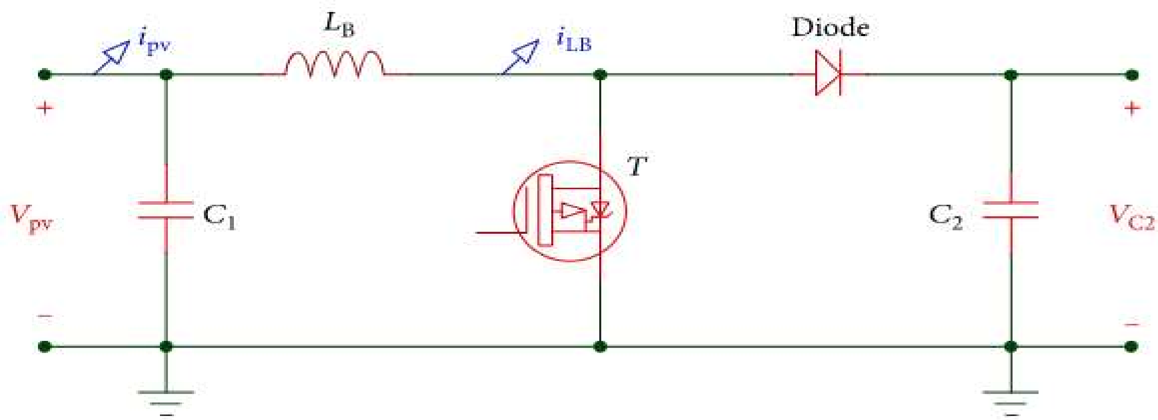

Figure 2.9 Simple schematic diagram of a Boost converter designed using proteus Design Suit

Using Kirchhoff's law in figure 2.9, the dynamic model of the boost converter is expressed as seen below [19].

$$C_1 \frac{dV_{pv}}{dt} = i_{pv} - i_{LB} \tag{2.9}$$

Where i_{pv}, and V_{pv} are the photovoltaic current and voltage generated by the PV array respectively

$$L_B \frac{di_{LB}}{dt} = V_{pv} - (1 - \mu_1)V_{c2} \tag{2.10}$$

Where i_{LB}, and the V_{c2} are inductor current and the boost converter output voltage respectively and μ_1 is a control parameter [19].

2.3 PV Inverter and its classifications

It is important to note that in order to supply energy to the grid, the current of the inverter must lag the grid voltage by a phase angle less than 90° [20]. This is normally achieved when the inverter voltage is ahead from the voltage phase of the grid [20]. A simplified schematic of the inverter power unit is as shown below.

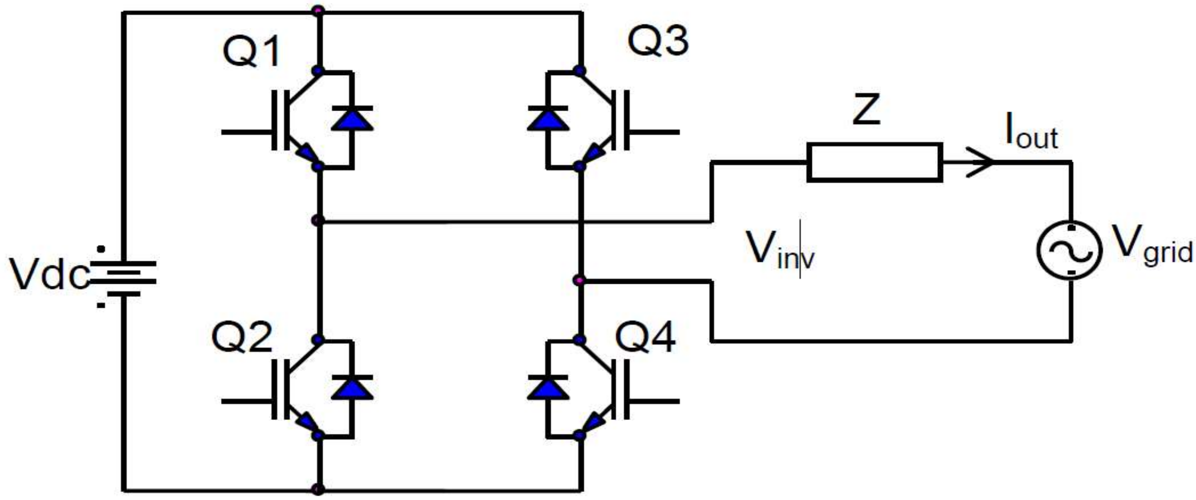

Figure 2.10 A simple schematic diagram of PV grid-connected inverter's power

In a situation of low power, it is always better to consider the active resistance between the inverter and the grid and this is normally determined by the active resistance of the inductive coil, the conductors and by the power bridge's transistors' resistances [20]. In such a case, the output current of the grid is determined by the $\dot{Z}$ impedance and the differences between the inverter and the grid voltages as seen in the equation below [20]

$$\dot{V}_Z = \dot{V}_{inv} - \dot{V}_{grid} \tag{2.11}$$

$$\dot{I}_{out} = \frac{\dot{V}_{inv} - \dot{V}_{grid}}{\dot{Z}} \tag{2.12}$$

Where, $\dot{V}_Z$ represents the $\dot{Z}$ impedance voltage drops, $\dot{V}_{inv}$ represents the root mean square (RMS) value of the first inverter's output voltage harmonic and $\dot{V}_{grid}$ represents the voltage of the grid [20]. Equations 2.11 and 2.12 corresponding to phasor diagrams are as shown below.

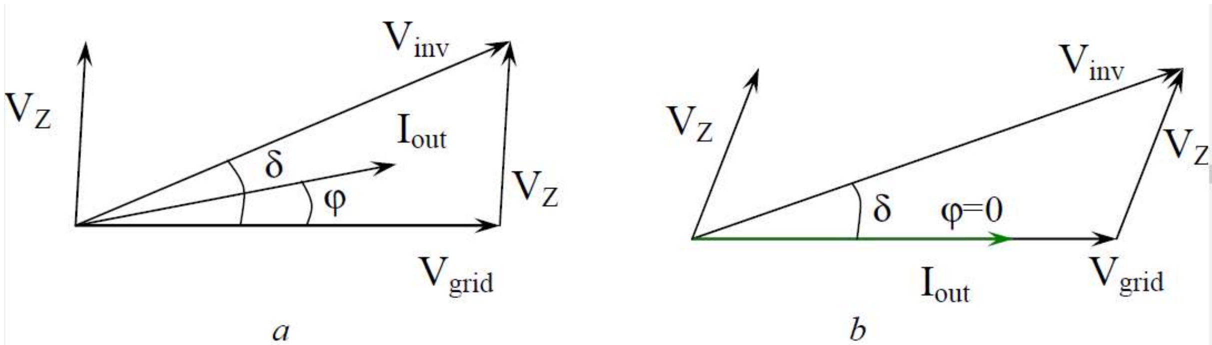

Figure 2.11 The voltages and currents phasor-diagram of the single-phase inverter

In figure 2.11, the phase angle between $\dot{I}_{out}$ and $\dot{V}_Z$ is less than 90° due to the active-inductive character of the $\dot{Z}$ impedance [20]. In a case of real conditions, $\varphi = 0$, the current and voltage of the grid are in phase and this is depicted in figure 2.11b [20]

2.4 Classification of Inverters

The solar PV grid-connected inverters are further grouped into three main categories that is multi-level topology, transformer less topology and structural topology as illustrated in figure 2.7 below [18].

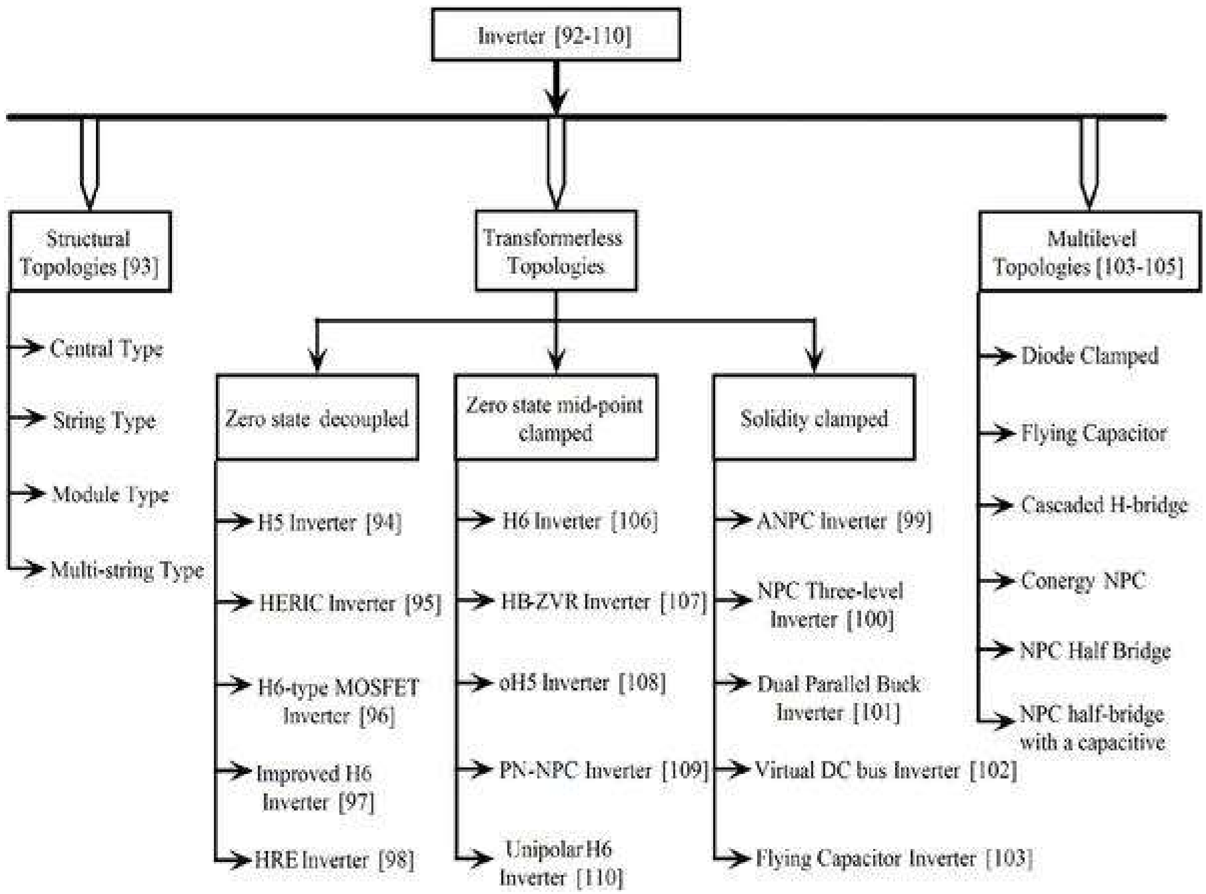

Figure 2.12 Classification of the solar PV grid-connected inverter

Square wave and pure sine wave inverters are also classification of PV grid-connected based on the output voltage [13].

2.5 A Low pass filter

This is applied to cut off the high-frequency components from entering the grid [16]. The frequency component that may enter the grid comes from the Pulse Width Modulation (PWM) switching frequency of the solar PV inverter which is typically in the kilohertz (KHz) range [16]. The low pass filter is of different types such as inductive (L), inductive and capacitive (LC), inductive and resistive (LR), Resistive and capacitive (RC) type as shown in figure 2.13

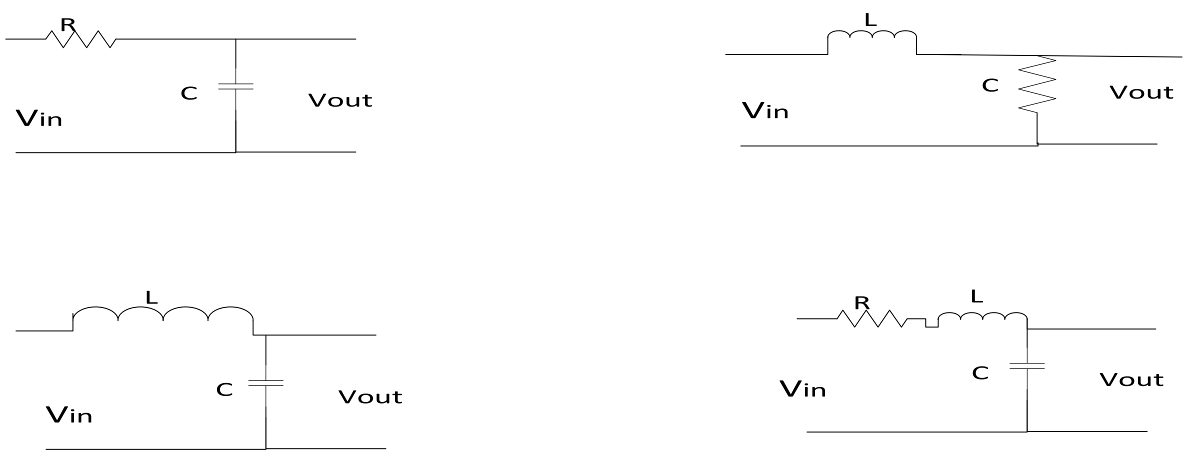

Figure 2.13 Different types of passive low pass filter

The cutoff frequencies for each can be calculated by applying the following formulas;

$$f_c = \frac{1}{2\pi RC} \tag{2.13}$$

Equation 2.13 is for calculating the cutoff frequency for RC low pass filter

$$f_c = \frac{R}{2\pi L} \tag{2.14}$$

Equation 2.14 is for calculating the cutoff frequency for RL low pass filter

$$f_c = \frac{1}{2\pi\sqrt{LC}} \tag{2.15}$$

Equation 2.15 is for calculating the cutoff frequency for LC low pass filter

2.6 Grid Integration Configurations, Synchronization and standards

2.6.1 Grid Integration

The PV inverter grid-connected systems may be of various power sizes and levels [22]. In addition, they are also often designed for specific applications and needs, with a PV inverter Grid-connected system ranging from one PV module to over 100 MW [22]. The generic structure of the PV grid-connected inverter system can be seen in figure 2.1. The PV grid-connected inverter is divided based on a power rating ratio that is small scale, medium scale and large scale [22]. It is also very important to provide the configurations of PV grid-connected inverter system together with advantages and disadvantages of each configuration in order to have clear guidance in choosing the PV grid-connected inverter system type depending upon the requirements [22].

Table 2.2 An overview of PV grid-connected inverter configuration

Comparative index	**Small Scale**	**Medium Scale**	**Large Scale**
Power Range	<350 W	<10 kW	<850 kW
Configuration	AC module	String	Central
Power semiconductor devices (PSD)	MOSFET	MOSFET, IGBT	IGBT
Inverter efficiency	Lowest	High	Highest
Pros	Flexible/modular Highest cost per watt Two-stage in mandatory	Good MPPT efficiency Reduced DC wiring Transformer less (most common)	Simple structure Highest inverter efficiency Reliable
Cons	Higher losses Higher cost per watt Two-stage is mandatory	High component count One string, one inverter	Needs blocking diodes (for array) Not flexible

2.6.2 Grid synchronization

The major challenge facing the inverter and grid integration is the synchronization of the inverter with the grid [22]. The inverter typically, functions or operates like a current source which feeds current in phase with the grid [22]. This therefore, implies that power factor (PF) requires to be maintained near to unity or at unity while a PV inverter system is connected to the grid [22]. In PV grid-connected Inverter system, one of the most important aspect is the synchronization of grid voltage with PV inverter [22]. The key precaution in the synchronization of the PV inverter with the grid is that the total real power of the grid must be equivalent to the sum of the grid voltage and current [22]. This can be expressed mathematically as seen below.

$$\mathrm{P(grid)} = \mathrm{V(grid)} + \mathrm{I(inverter)} \tag{2.16}$$

The injection of current into the grid and the grid integration play a very significant role in the operation of the PV grid-connected inverter system [22]

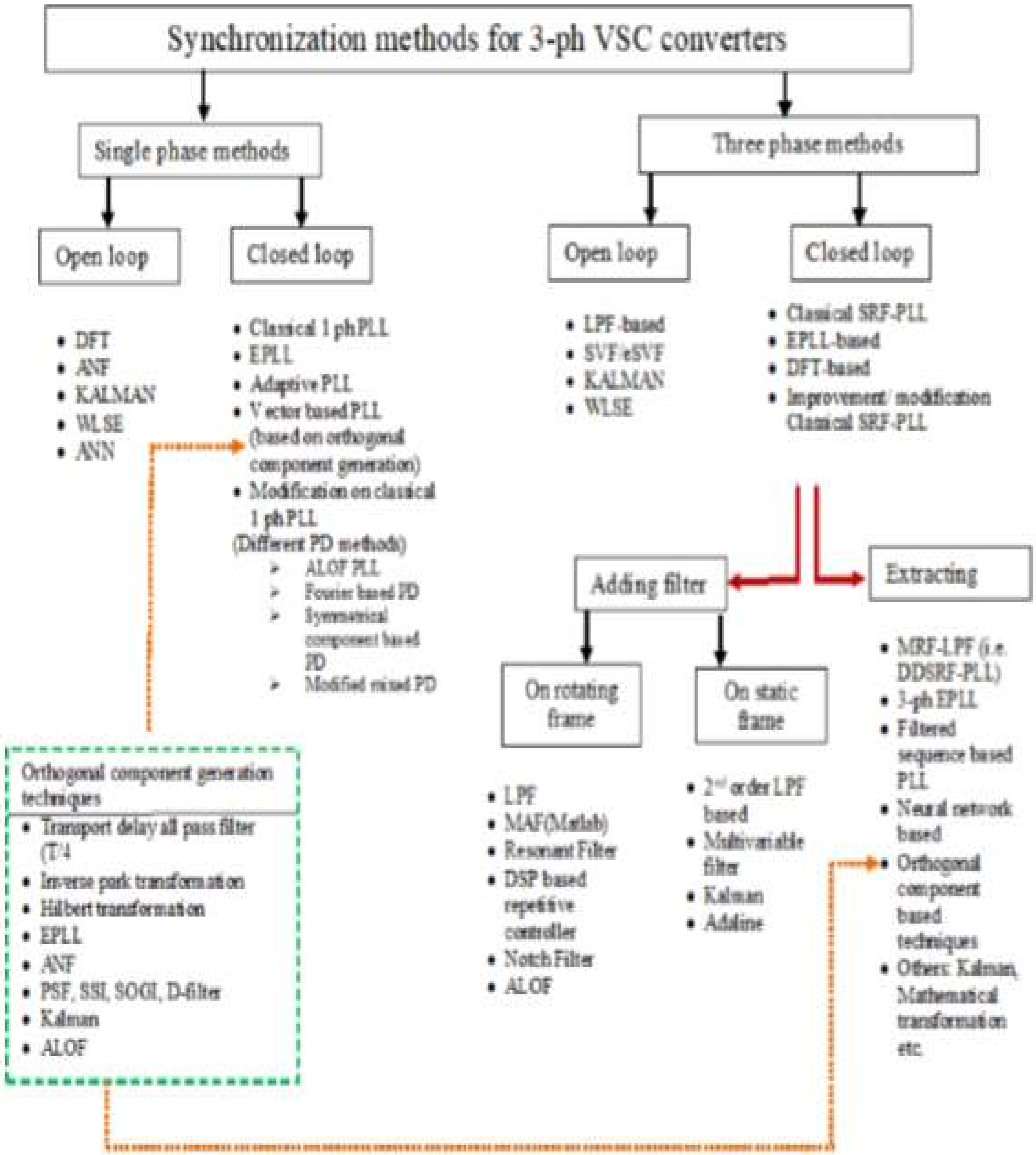

Figure 2.14 PV Grid-connected Inverter System Synchronization Techniques

2.6.3 PV Grid Integration standards

Owing to the increase in the application of PV grid-connected inverter systems, various standards and grid codes (GC) are put in place to ensure efficient and secure transmission of

PV inverter power to the grid [22], [23]. Deutsche Kommission Elektrotechnik (DKE) of Germany, IEA of Switzerland and the Institute of Electrical and Electronic Engineers (IEEE) of USA among others are some of the well-known bodies that develop standards.

Table 2.3 illustrates the summary of International codes for PV applications

Category	Codes	Area of Implication
Grid connected	IEC 61727, IEC 60364-7-712	Installations of buildings.
	IEC 61683, IEC 62093, IEC 62116	Utility interface Measuring efficiency.
	UL 1741, IEC 62446	Interconnected PV inverters, system documentation & commissioning tests Useful in independent power systems
EMI	EN61000	European Union EMC directive for residential, private sectors, light industrial and commercial facilities.
	FCC Part 15	U.S. EMC directive for residential, commercial, light industrial, and industrial facilities
Low voltage ride through (LVRT)	IEC 61727	V< 50% at 0.1s 50% ≤ V < 85% at 2.0 s
Anti-islanding	IEEE 1547/UL 1741IEC 62116	Island detection
	VDE 0126-1-1	Impedance measurement
Monitoring	IEC 61850-7, IEC 60870, IEC 61724,	Transmission grids and systems for power service automation Distributed energy resources and logical nodes Measurement, data exchange, and analysis
Off grid	IEC 62509, IEC 61194, IEC 61702	Battery charge controllers
	IEEE Standard 1526, IEC/PAS 62111	Stand-alone systems
	IEC 62124	Rating of direct-coupled pumping systems Specifications for rural decentralized electrification.
Rural systems	IEC/TS 62257	Medium-scale renewable energy and hybrid systems. Safeguard from electrical hazards. Choice to select generator sets and batteries. Micro power systems and microgrids.

2.7 Related Work on Control Strategies of PV inverter for Grid-connected Operations

The solar PV grid-connected systems require a proper synchronization with the grid and therefore, the control algorithms for solar PV inverter for grid-connected operation is very central to achieve a proper synchronization of the solar PV system and the grid [18]. A considerable number of research works have been done on PV inverter for grid-connected operation, however most of the research works are at the simulation level.

Majid, Rizwan and Kothari [13] presented Synchronous Reference Frame-Based Controller (SRF) for the PV inverter to enable it to only inject the active component of the grid current. This PV inverter controller algorithm helps the PV inverter to maintain the steady-state current error between the desired and the actual grid current to zero at any grid frequency [13]. The phase-locked loop (PLL) generates unit voltage templates (sine and cosine components) and tracks the phase of the input voltage signal [13]. Besides, through this PV inverter controller, the high-frequency harmonic components of the direct quadrature (d-q) currents are filtered out [13].

They further explained that in Synchronous Reference Frame-Based Controller (SRF) control algorithm, the d-q frame is again transformed back to one-phase component and the resulting current is then compared with the source current and any other error is injected to the hysteresis-based pulse width modulation (PWM) signal generator in order to generate the final switching signals which are the pulses for the PV inverter [13]. They used MATLAB/SIMULINK to verify their proposed control mechanism. They concluded that the Synchronous Reference Frame-Based Controller (SRF) control algorithm is quite effective in controlling the PV grid-connected inverter system but its implementation is quite complex. They further defined the terminal voltages of the system as,

$$\nu_\alpha = V_m \cos(\omega t + \phi) \tag{2.17}$$

And the current was defined as,

$$i_\alpha = I_m \cos(\omega t + \theta_n) \tag{2.18}$$

The equation 2.15 gives i_d and i_q which in-phase and reactive components of the grid current as seen below,

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.19}$$

Ajah, Nitin, and Vikas [18] discussed Instantaneous Symmetrical Component (ISC) based control. They stated that this PV inverter control algorithm is basically applied for the correction of power factor and load balancing in the three-phase three-wire or three-phase four-wire system [18]. Furthermore, the authors explained that from the extracted feedback signals of load current with the help of the symmetrical components, all the sequence components are calculated. The main objective of this control algorithm is to remove the zero sequence components so that the load can be realized or achieved [18]. In addition, they also mentioned that the power factor correction can be realized by suppressing the reactive components to zero. The grid reactive and active power are taken care of by the DC link voltage.

Bouzidi, Bendaas, Barkat and Mansour [24] presented sliding mode control of three-level Neutral Point Clamped (NPC) inverter-based grid-connected photovoltaic system. Using this PV inverter control mechanism, the three-level NPC inverter is compelled to supply just active power to the grid while regulating its self-sustaining DC bus voltages using three sliding mode controllers [24]. The authors further explained that applying this control mechanism involves the three-level Neutral Point Clamped (NPC) inverter to be connected to the PV panel through a DC-DC converter. They as well used MATLAB/SIMULINK to verify the validity of their proposed PV inverter control mechanism [24]. However, the authors failed to show the limitations of their PV Inverter control mechanism although they presented very detailed research work.

Khan, Saleem, Ahmad and Ayaz [25] addressed a hybrid phase-locked loop (PLL) technique to synchronize a PV system with single-phase grid. They further explained that to determine synchronization, the PV system is based on a reference system which is controlled by a PIC16F877 microcontroller which has an inbuilt pulse width modulation technique to trigger the inverter in order to achieve efficient synchronization with the grid [25]. They further used the optocoupler and digital phase lock loop to detect the real-time zero-crossing detection and to control the phase angle and frequency of the PV grid-connected inverter system respectively. They simulated the proposed PV inverter control mechanism in Proteus Design Suite simulator. The authors concluded that the harmonics due to disturbances were reduced and the effective result of PV grid-connected synchronization was achieved.

Hossain, Hassan, Monowar, and Rafiqul [26] designed and implemented and a half-bridge inverter which consists of two dc voltages that is able to process real power bidirectionally as well as two active switches. Besides, the proposed half-bridge inverter performs the function of the elimination of harmonics to improve power quality [26]. According to the research paper [26], the DC bus filter does the suppression of DC-link voltage fluctuations and it also filters out the AC components on the DC side for the Maximum power point tracking (MPPT), while the utility grid and the half-bridge inverter are being interfaced by the output filter [26]. The research paper [26] also proposed two Atmel89C51 microcontrollers to control the operations of the proposed half-bridge inverter with the grid. One of the two Atmel89C51 microcontrollers was programmed to generate MOSFET operating signals and the other programmed to match with the inverter voltage level, wave form and controlled various operational features of the inverter [26]. The authors concluded that the half-bridge inverter showed that it was capable of synchronization and satisfactory performance for PV grid-connected operations [26].

Juntao, Yunkai and Hua [27] reported a disturbance observer-based fuzzy sliding mode control (DOBFSMC) strategy for a PV grid-connected single-phase inverter. Under this PV grid-connected inverter control mechanism, a disturbance observer is designed purposefully to estimate uncertainties of the system in real-time [27]. The sliding mode controller was designed with the help of the disturbance output information to control the inverter output voltage [27]. Furthermore, the upper bound of the observation error between the actual disturbance and its observation value is approximated using a fuzzy system in order to improve the performance of the control system [27]. The authors used MATLAB/SIMULINK to simulate the system to verify the effectiveness of the proposed PV inverter control method. The authors concluded that the inverter had strong robustness since the disturbance can adequately be compensated [27].

Yaoqin and Rong [28] proposed voltage source Grid-connected PV inverters based on MPPT and Droop control. The research paper [28] focuses on achieving both the MPPT and seamless transfer by dynamically adjusting the droop curves. On account of difficulty to control DC voltage during grid connecting and hence affecting the stability of the system and the MPPT efficiency, the research paper [28] proposed a control method which includes an active power inner loop and a DC voltage outer loop. Simulation in MATLAB/SIMULINK was carried to validate the proposed control strategy and the results indicated that both the MPPT operation mode and the seamless transfer between the standalone-alone mode and grid-connected mode were realized [28].

This paper, therefore, proposes PI control strategy of the PV inverter for the grid-connected operation, MPPT control for PV maximum power extraction and implementation of phase lock loop synchronization technique with a filter in the single-phase pure sine wave inverter for grid-connected operation. The filter has been included to cut off the higher frequencies coming from the pure sine wave inverter output signal and also to determine the first harmonics of the current supplied to the grid in order to ensure power improvement [29]. The phase-locked loop controller is to ensure that the phase, voltage and the frequency of the electricity grid and the pure sine wave PV grid-connected inverter are matching for the synchronization to take place. MATLAB/SIMULINK was used to verify the validity of the proposed small PV inverter control for grid-connected operations.

Chapter 3: Design Methodology

3.1 Requirement Specifications

It is important to note that every technology under study requires a certain metric to concisely, precisely and accurately gauge its achievements regarding design, development and implementation of the technology. For this project, the system and the user specifications have been treated as the major foundational requirement specifications for the single-phase PV grid-connected inverter.

3.2 The System Requirement

3.2.1 The PV Grid-Connected System Requirement

There are two major tasks involved in the PV grid-connected inverter system which include but not limited to the following [30], [31]

1. The solar panels in the system should be operated at maximum power point (MPP)
2. The current from the PV inverter injected to the grid should be sinusoidal which all must comply with some specific standards as seen in Tables 3.1, 3.2, 3.3, and 3.4
3. The phase sequence between the PV power system and the grid power must be compatible that is they should match. For example, the phases are 120° apart in three-phase systems
4. The frequency of the grid and the PV inverter system should match for example in Ghana the grid frequency is 50 Hz. Therefore, the PV inverter system should also operate at a stable 50Hz frequency with little tolerance in order to facilitate the synchronization process.
5. The PV inverter output voltage and that of the utility grid should be compatible that is the output voltages of the grid and the PV inverter should match.

3.2.2 Grid Requirement

There also specific standards that are regulated by the utility in each country that PV grid-connected system must comply with. The standards include, IEEE 1547.1-2005, VDE0126-1-1, EN 50106, and IEC61727 and these standards deal with issues such as reconnection and synchronization, islanding operation detection (non-islanding or islanding), system grounding, frequency and voltage for regular operation, leakage current, individual harmonic current and injected DC current levels and total harmonic distortion (THD) [30].

Table 3.1 IEEE 1547 Requirements for Grid-connection

Nominal power	30 kW
Harmonic currents	(2-10) 4.0% (11-16) 2.0% (17-22) 1.5% (23-34) 0.6% (> 35) 0.3% Total Harmonic Distortions (THD) 5%
DC current injection	< 0.5% of rated output current
Abnormal voltage	V < 50% or V > 137% 6 cycles
Disconnection	50% < V < 88% or 110% < V < 137% 120 cycles
Abnormal frequency	f < rated-0.7 Hz 6 cycles
Disconnection	f > rated+0.5 Hz 6 cycles

In table 3.1, the DC current injection has been limited to 0.5% of the rated output current in order to neglect generally the saturation of distribution transformer. However, it very difficult to maintain this value precisely with the exciting circuit inside the inverter [30].

Table 3.2 IEC Standard Description of the Maximum DC current injection

Standard	IEC61727	VDE0126-1-1	IEEE1547
DC current injection	< 1% of rated output current	<1A	< 0.5% of rated output current

Table 3.2 deals with the voltage characteristics of electrical energy in the public distribution system. Besides, it also deals with requirements of the main voltages and their permitted deviation ranges at the point of common coupling (PCC) in medium and low voltage distribution system under normal operating conditions [30]

Table 3.3 EN standard Requirements for Grid-connection

Parameters	Characteristics of the supply voltage	
	Low voltage	Medium voltage
Power efficiency	± 1% (49.5-50.5Hz) for 99.5% of week -6% / +4% (47-52 Hz) for 100% of week	± 1% (49.5-50.5Hz) for 99.5% of week -6% / +4% (47-52 Hz) for 100% of week

Voltage magnitude variations	$\pm$ 10% for 95% of week	$\pm$ 10% for 95% of week
Rapid voltage changes	5% Normal 10% infrequently	4% Normal 6% infrequently
Supply voltage dips	P_{It} ≤1 for 95% of week	P_{It} ≤1 for 95% of week

In table 3.3, the medium and low voltages are defined as the phase-phase nominal distribution system under normal operating condition [30].

Table 3.4 Leakage current value and their corresponding disconnection times listed in VDE-0126-1-1

Leakage current value (mA)	**Disconnection time (s)**
30	0.3
60	0.15
100	0.04

The German VDE-0126-1-1 standard deals specifically with transformer less PV inverter concerning leakage or fault current levels. Besides, 0.3 is the disconnection time of the inverter from the grid when the root mean square (RMS) value of the leakage current is greater than 30mA.

3.2.3 PV inverter characteristics Requirement

1. PV inverter should operate over a wide range of currents and voltages [1]
2. It should also regulate the frequency and output voltage [1]
3. The PV inverter should also be able to provide AC power with good power quality [1].

3.3 Proposed Single-Phase PV Grid-connected Inverter

The single-phase PV Grid-connected inverter consists of PV array, DC-DC converter boost converter with MPPT, Charger controller, Battery for Energy storage, inverter and its PI control system. The Low Pass LC filter has been included in the system in order to cutoff and block high-frequency components from entering the grid as shown in figure 3.1 below

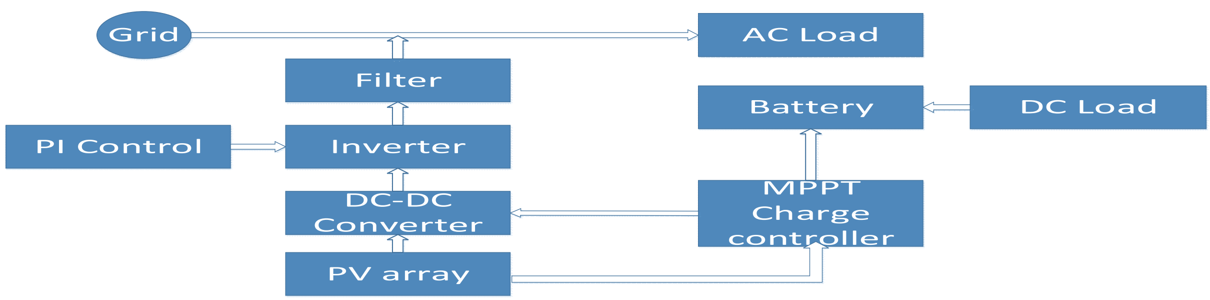

Figure 3.1 A block diagram for a proposed PV Inverter for Grid-connected Operation

From figure 3.1 above, the MPPT control algorithm depends on the voltage and the input currents of the PV array. In order to facilitate for active regulation of power transfer, the DC-DC bidirectional converter and the inverter are incorporated in the system [2]

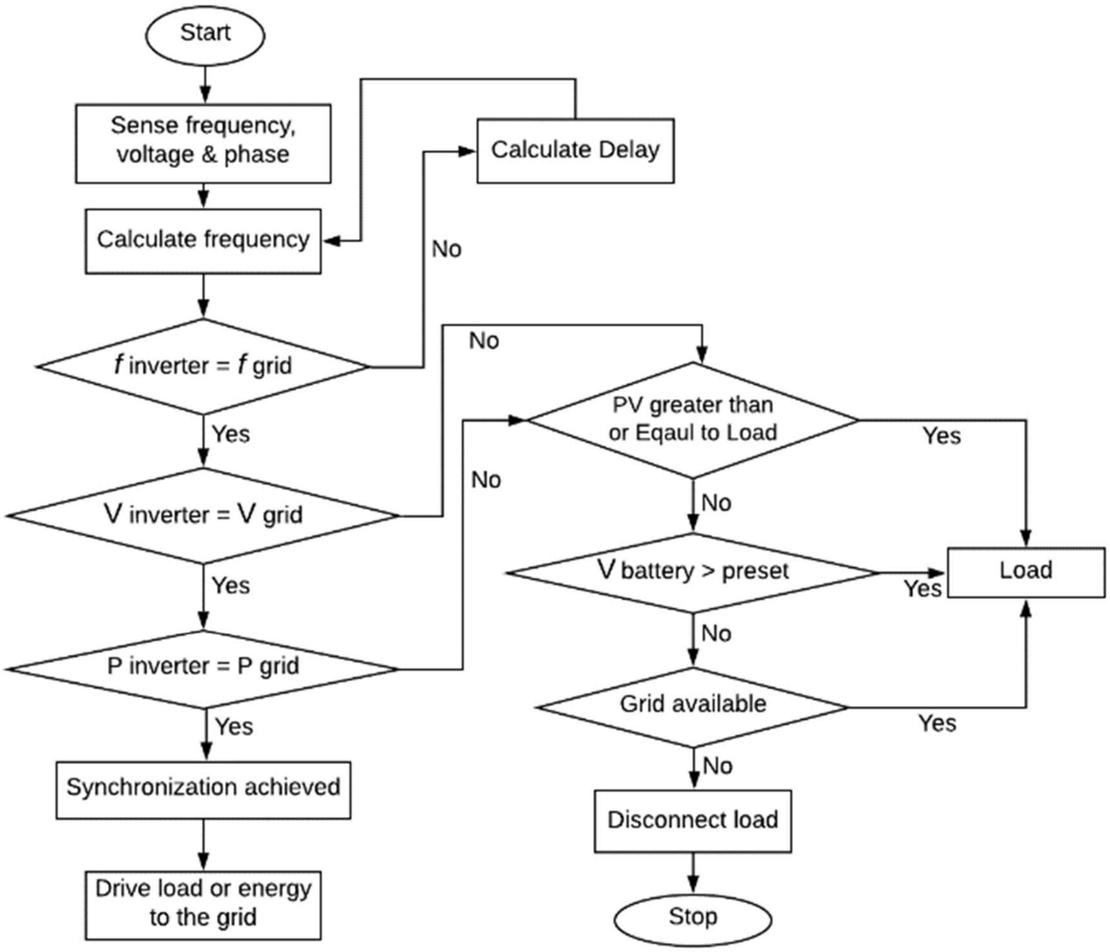

Figure 3.2 Flowchart of control of a proposed PV Inverter for Grid-connected Operation

3.3.1 Design Components

It is very paramount to have a proper working design of each component in figure 3.1 in order to satisfy the different aspects the system requirement

3.3.1.1 Solar PV Modules

The solar PV modules are very central in a photovoltaic system. The solar modules are normally made by connecting solar cells in series strings [13]. The number of solar cells which are used in the formation of the solar PV modules depend on the rating of its voltage and current [13]. Strings of modules are parallelly connected to form an array [32]. In order to make a complete PV system, solar PV modules are required together with other parts such as support structures, the balance of system (BOS), storage and conversion devices [13].

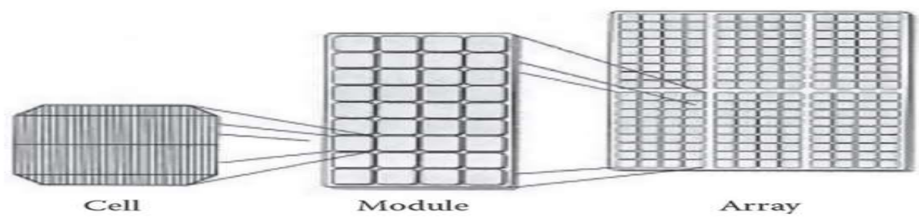

Figure 3.3 Solar PV cell, module, and array formation

It is important to note the DC Power from the PV system is dependent on some factors such as PV peak power at standard test condition (STC), solar radiation, and cell temperature [33]. This can be represented using a simple model as seen below.

$$P_{PVout} = P_{PVpeak} * \left(\frac{G}{G_{ref}}\right) * \left[1 + K_T\left(T_C - T_{ref}\right)\right] \tag{3.1}$$

Where; P_{PVout} is the PV array output power, P_{PVpeak} is the PV array power at standard test condition (STC), G represents solar radiation in W/m^2, G_{ref} is solar radiation at STC and it amounts to 1000 W/m^2, K_T represents the temperature coefficient of monocrystalline and polycrystalline-silicon cells which is equivalent to $K_T = -3.7 * 10^{-3}(1/°C)$, T_{ref} = 25°C which is the reference temperature. T_C is the cell temperature which is calculated by the empirical equation below [33], [34].

$$T_C = T_{amb} + (0.0256 * G) \tag{3.2}$$

Where, T_{amb} represents the ambient temperature

3.3.1.2 DC-DC Boost Converter

The DC voltage variation from PV array causes the input of the boost converter to vary while the output is controlled to follow a constant desired voltage [16]. The Boost converter is to increase the low input voltage coming from the PV array to a standard DC bus voltage value that is to a DC voltage value of 400 V [16]. The MPPT algorithm modulates the duty cycle of DC-DC power converter in order to achieve the instantaneous maximum power of the PV source [16]

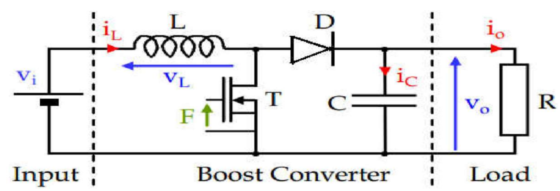

Figure 3.4 Boost converter and its schematic

It is important to note that under ideal conditions, input and output voltage of the DC-DC boost can be related mathematically as seen below.

$$V_i = V_0 * (1 - D) \tag{3.3}$$

Where V_i and V_0 are input and output voltages respectively and D is a duty cycle [16]

In a situation where the value of the duty cycle (D) is known, the minimum values of inductance and capacitance can easily be found by using the given equations below.

$$L_{min} = \frac{(1 - D)^2 D.R}{2f} \tag{3.4}$$

$$C_{min} = \frac{D.V_0}{V_r R.f} \quad (3.5)$$

Where V_r, R and f are ripple voltage, resistance and switching frequency respectively [16]. Below is the table showing the parameters used in modeling and simulating DC-DC Boost Converter [16]

Table 3.5 DC-DC Boost parameters used in Simulation

Parameter	Value
Pulse width	92.5%
Period	4*10^-5 s
Inductance	7.63e-4 H
Capacitance	35e-4 F

3.3.1.3 Grid-Connected PV inverter

The inverter is very helpful in converting DC power from the PV array to AC power for different uses [18]. The solar PV grid-connected inverter fosters the synchronization of the PV system with the grid (magnitude and frequency) [35]. The PV grid-connected inverter through its control strategies also helps in the control and optimization of the flow of energy during the system operation periods [35]. The solar PV inverter main features are extraction of maximum power from the PV array and converting it into a suitable pure sine wave voltage [13].

3.3.1.4 Inverter Control

The inverter controller plays a very important role in the grid-connected operation. The synchronization of the grid and the solar PV is possible due to proper inverter control strategies [36]. For a solar PV grid-connected operation, the PV inverter is supposed to have a mechanism that enables it to disconnect from the grid in case of any abnormal grid conditions in terms of frequency and voltage at the point of common coupling [36]. The control also helps the PV inverter to meet the requirements for grid-connection that is the phase and the voltage magnitude of the inverter and the utility grid must be the same [37].

To achieve the inverter control strategy for single-phase grid-connected PV system, this paper considered the following controllers;

1. Maximum Power Point Trucking controller with DC-DC Boost Converter
2. Grid synchronization controller using phase-locked loop (PLL)
3. The PV inverter controller using the Proportionate-Integral (PI) controller

3.3.1.5 The PV Inverter control using Proportionate-Integral (PI)

Below is the proposed schematic diagram of the PV grid-connected inverter using the PI controller

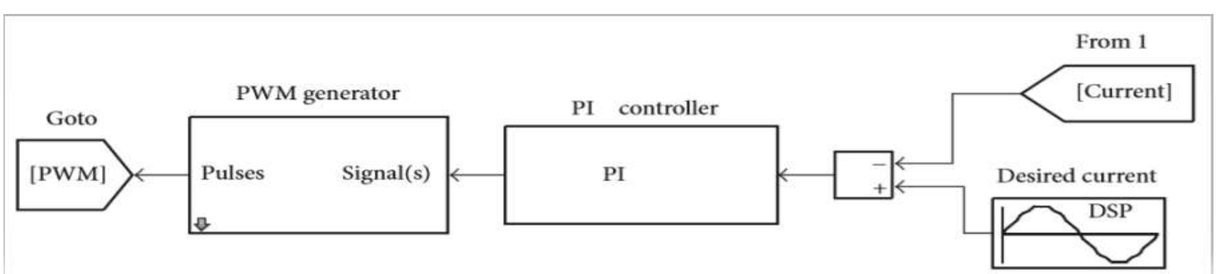

Figure 3.5 MATLAB SIMULINK Schematic Diagram of a PV inverter PI control

Figure 3.6 above is to be integrated with the entire PV Grid-connected inverter system shown in figure 3.1 and it will be done under section 3.4 (design implementation). The optimal or good enough PV inverter controller is the one that is not only able to aid the PV inverter to attenuate the harmonic components but also be able to safely and efficiently operate the inverter in both grid-connected mode and a stand-alone mode in case of power outages [38]

3.3.1.6 Battery

The battery act as an energy management system in a solar PV grid-connected operation [2]. Rechargeable batteries are electrochemical devices that convert electrical energy to chemical energy during discharging [2]. Rechargeable batteries have gone through evolution from lead-acid battery to lithium-ion batteries. Lithium-ion battery due to its higher power density, higher terminal voltage and higher energy density has gained wide applications in as far as energy management is concerned [2]. The batteries are often designed as a voltage source that is dependent on the actual state of charge (SOC) [2]. However, there are also other types of batteries used in PV system such as Alkaline batteries like Nickel-cadmium [32]

3.3.1.7 Maximum Power Point Tracking (MPPT) Charge Controller

This is necessary for utilizing the whole of the power produced by the solar PV module by dictating the voltage of the battery charging state [39]. The MPPT is also necessary for extracting maximum power under varying temperature conditions and irradiations [39]. The charge controller maintains the current and the voltage at an optimized level and it also prevents overcharging of the batteries [39]. The most frequently used MPPT algorithm is Perturb and observe (P & O) technique on account of its simplicity in implementation [35]. The Perturb and observe method uses duty cycle (D) as a control parameter and it obligates the derivatives of $^{dP}/_{dD}$ to be zero, and this case (P) is the power output of the PV array [35]

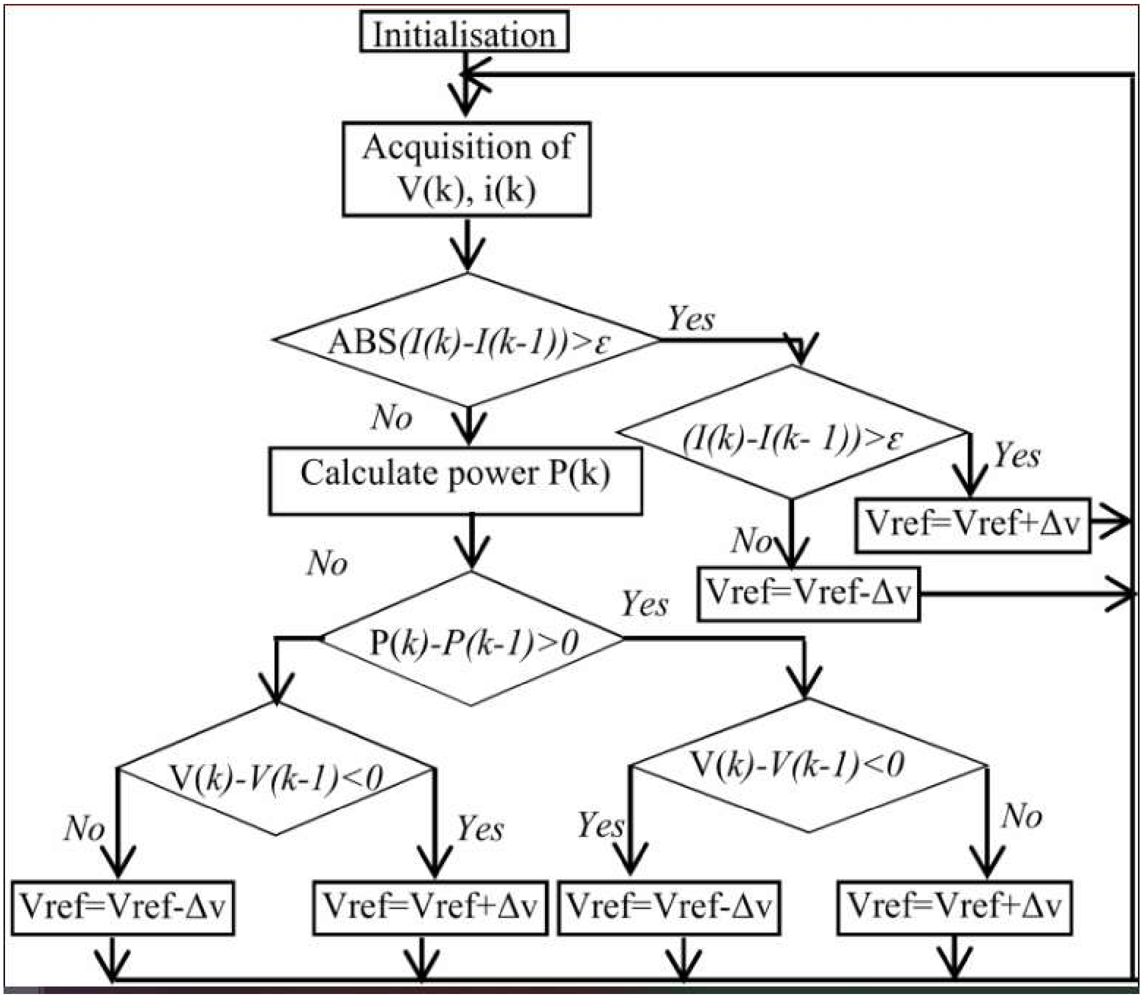

Figure 3.6 The Perturb and Observe method flowchart for MPPT charge controller

From figure 3.8 the current is also perturbed and when $dP/_{dV}$ is positive, the power maximum occurs at a voltage higher than optimum voltage and when it is negative, the power maximum occurs at a voltage lower than the optimum voltage [35]. Besides, the desired voltage is obtained when $dP/_{dV}$ approaches zero.

3.4 Methodology (Design Implementation)

Given the capabilities of the MATLAB/SIMULINK, some of the components of the figure 3.1 such as PV array, DC-DC converter, Maximum Power Point Tracking (MPPT), filter, the Inverter and its PI control, Grid and Battery was modelled using the standard researched values in order to verify their validity and practicability of the system. Under this section, the main concern is the realization of the proposed PV inverter for grid connected operations. In addition, this section focuses on integrating all the relevant auxiliary components of the proposed PV grid-connector inverter system as seen in figure 3.1.

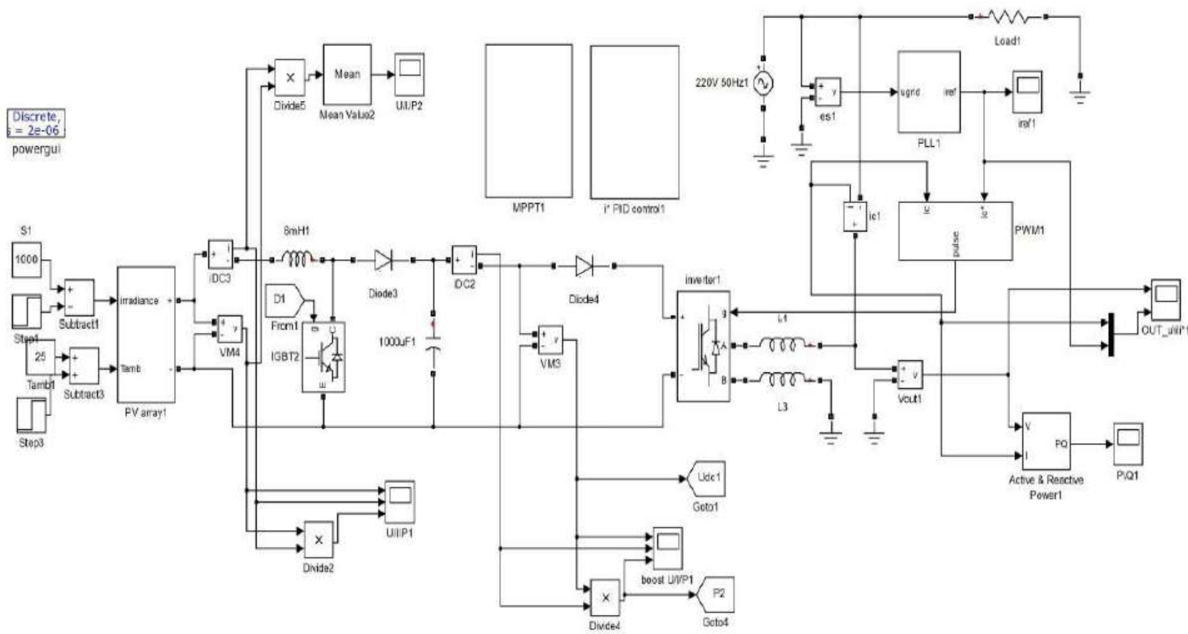

Figure 3.7 MATLAB/SIMULINK simulation schematic Diagram of the PV grid-connected Inverter

3.4.1 Mathematical Modeling of PV Array

The PV array modeling was carried out on MATLAB/SIMULINK using the datasheet values at Standard Test Conditions (STC) and some estimated values and different parameters used in the equations 2.1, 2.2, 2.3, 2.4 and 2.5. The datasheet values and the estimated values are presented in Table 5.1 in the appendix. This mathematical modeling was done in order to validate the I-V and the P-V characteristics of the PV array.

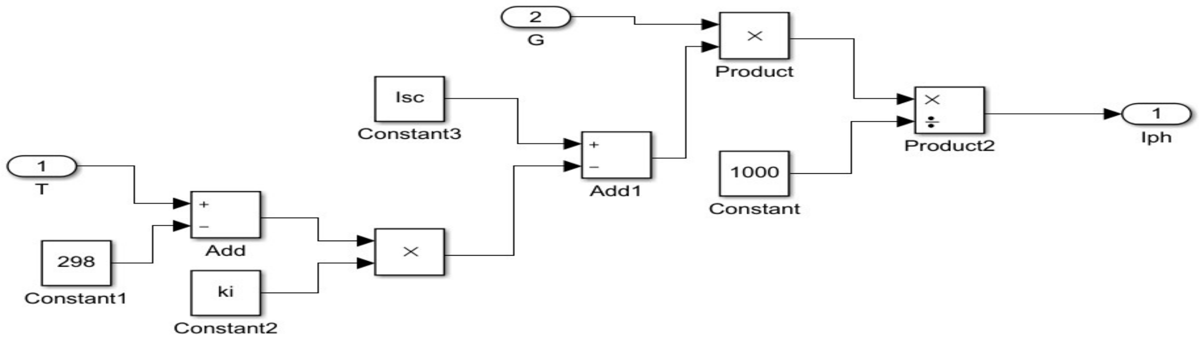

Figure 3.8 MATLAB/SIMULINK simulation of the photocurrent I_s (equation 2.3)

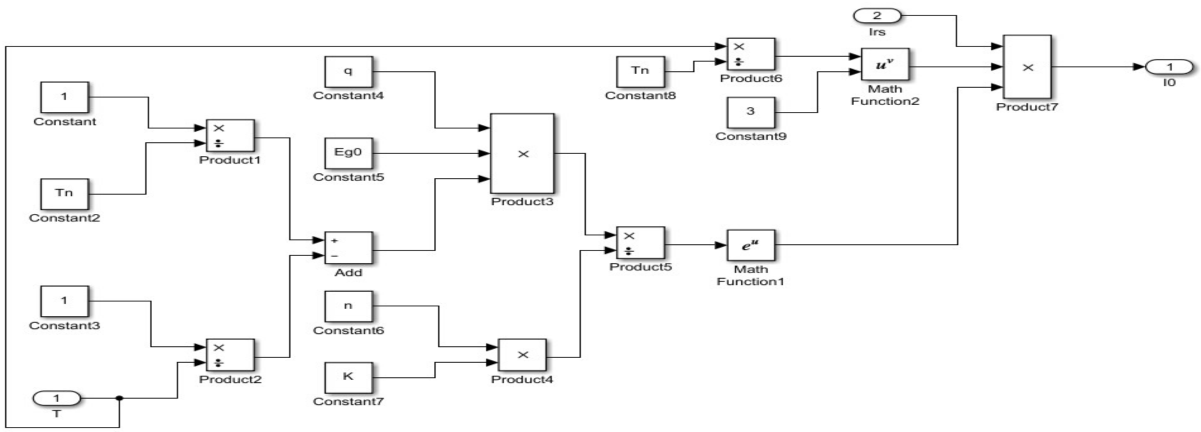

Figure 3.9 MATLAB/SIMULINK simulation of Saturation current I_0 (equation 2.4)

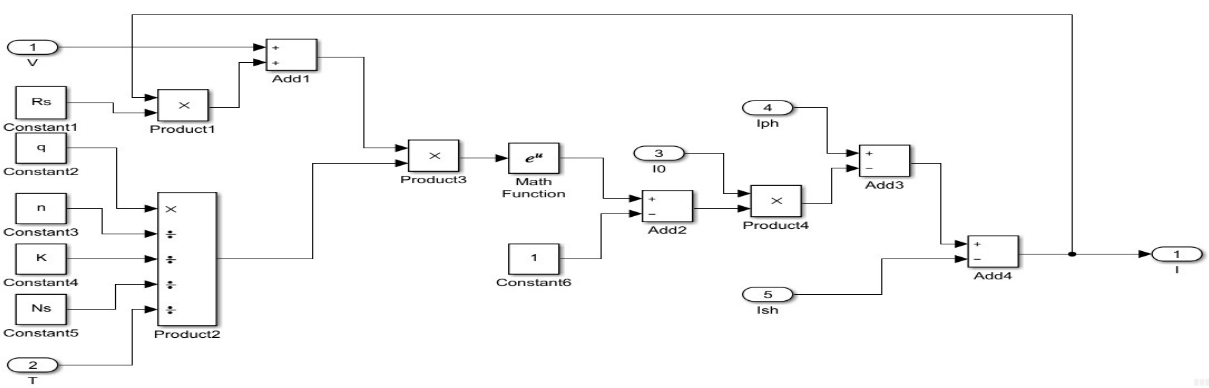

Figure 3.10 MATLAB/SIMULINK simulation of the output current i_{pv} (equation 2.5)

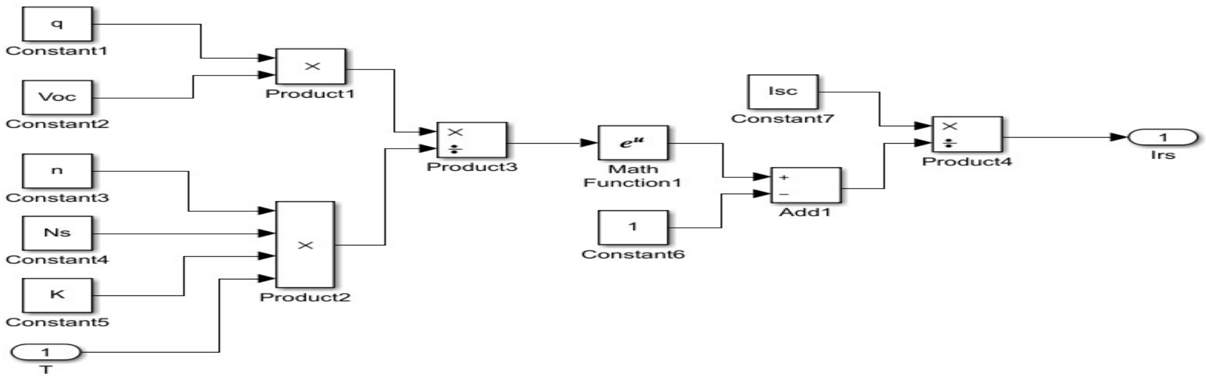

Figure 3.11 MATLAB/SIMULINK simulation reverse saturation current I_D (equation 2.2)

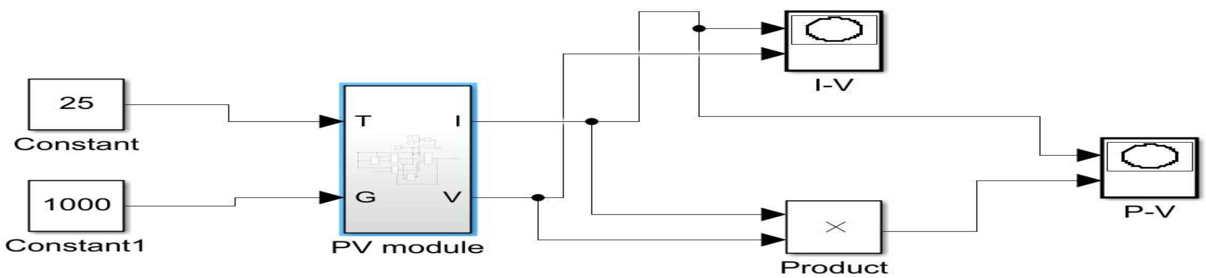

Figure 3.12 MATLAB/SIMULINK simulation of the overall schematic for the PV module

Table 3.6 Solar cell Parameters used in the Simulation

Parameters	**Value**
Open circuit voltage V_{oc}	21.7 V
Short-circuit current I_{sc}	3.35 A
Maximum power point voltage	17.4 V
Maximum power point current	3.05A
Serial Number	36
Parallel Number	1
Reference Temperature	25℃

Reference light intensity	$1000\,\frac{W}{m^2}$

3.4.2 Simulation of the PV Maximum Power Point Tracking (MPPT) Controller with DC-DC Converter

As stated earlier under section 3.2.1 (The PV grid-connected system Requirement) that in order to make the synchronization between the PV inverter and the grid, the solar panels in the system should operate at maximum power point (MPP) such that the whole power produced by the solar PV module is utilized [39]. The MPPT has been implemented in the DC-DC boost converter using the perturb and observe technique as seen in figure 3.15. Therefore, with the help of the perturb and observe approach of Maximum Power Point Tracking of a solar panel, the algorithm modulates the duty cycle of the DC-DC power converter in order to achieve the instantaneous maximum power of the PV source [16], as already stated in section 3.3.1.2 (DC-DC Boost Converter). Below is the MATLAB/SIMULINK simulation diagram of the PV MPPT and DC-DC boost convert to test the effectiveness of the MPPT algorithm

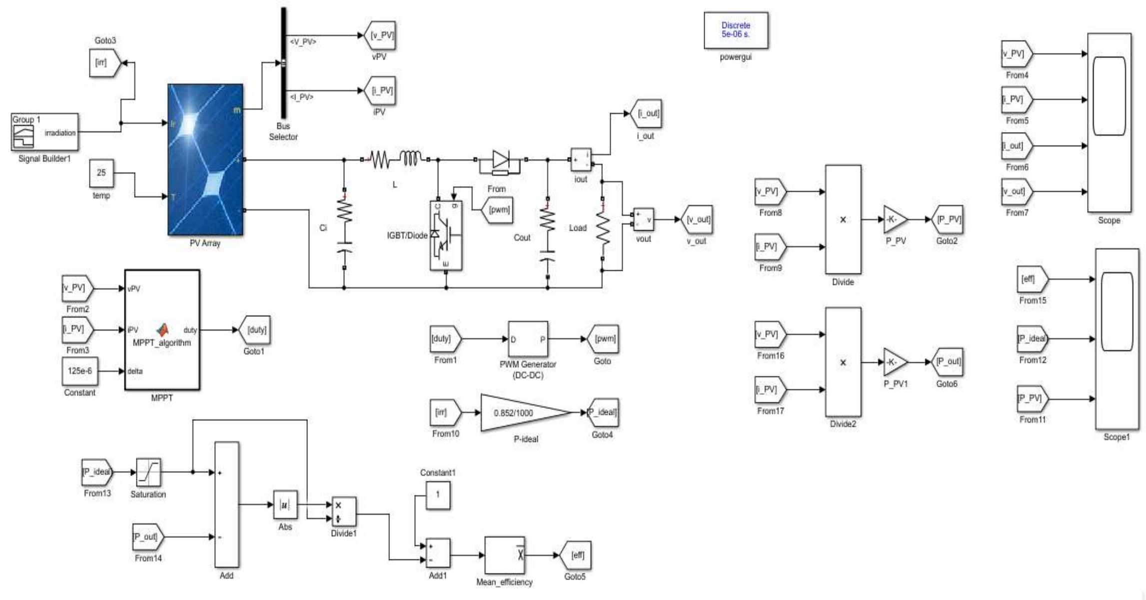

Figure 3.13 MATLAB/SIMULINK PV MPPT and DC-DC Boost Converter simulation diagram

3.4.3 Grid Synchronization Controller

As mentioned earlier in section 3.2.1 that for PV inverter and the grid to be synchronized, both the grid and the PV inverter should have the same phase angle, frequency and amplitude [17]. This is made possible using a single-phase locked loop (PLL). This single-phase locked loop is a feedback control which adjusts the phase of a locally generated PV signal to match the phase of an input signal automatically and therefore provides a unity power operation [17]. The objective of the PLL synchronization technique is to integrate the PV inverter output current with the grid voltage [17]. This was simulated in MATLAB/SIMULINK as seen in figure 3.16 as shown below.

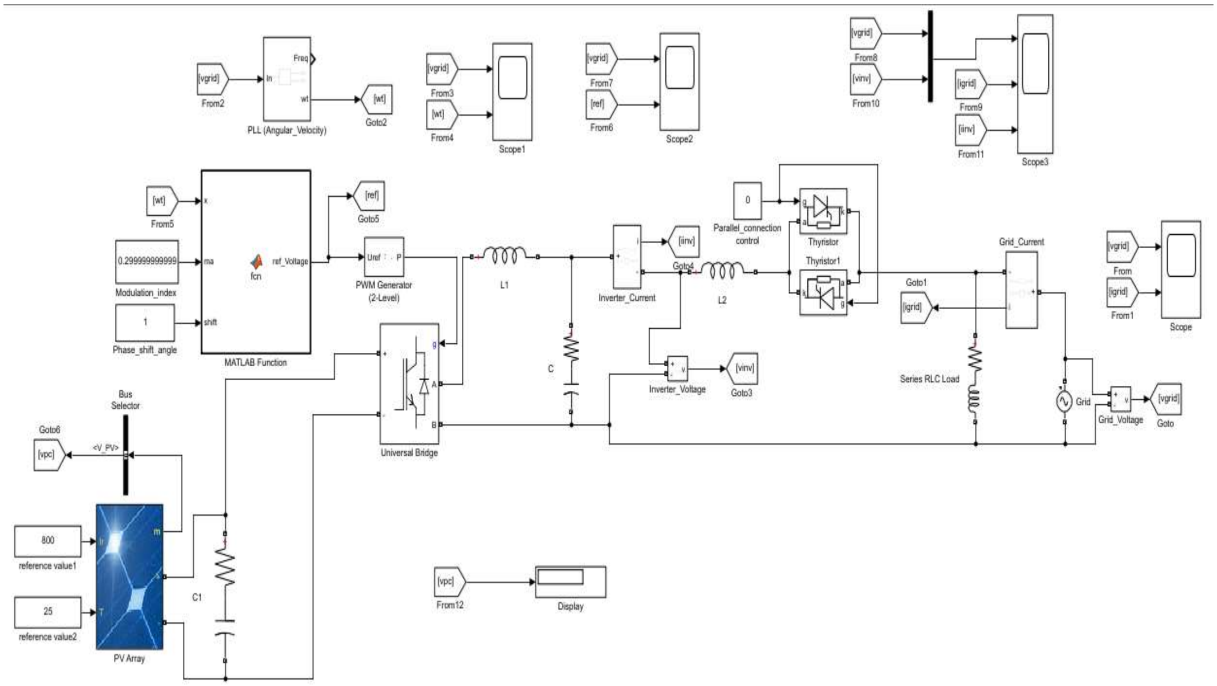

Figure 3.14 Grid Synchronization Controller Simulation

It is vital to note that the single-phase locked loop (PLL) as an electronic circuit with a current or voltage-driven oscillator, it continuously adjusts the inverter signal to match the phase and frequency of the utility system [31]. The PLL normally generates an error signal when the output waveform of the inverter is not in phase with that of the mains supply [31]. The error signal generated is used by the inverter to synchronize its output waveform with that of the grid [31]. The time needed for the synchronization is dependent on the PI block parameters [17]. The error in the PI controller of the PLL is as seen below

$$e = V_g sin\theta_g \cos\theta - V_g Cos\theta_g \sin\theta = V_g \sin(\theta_g - \theta) \qquad (3.6)$$

Where; e is the error signal generated, θ_g and θ are grid and PLL phase angles respectively

3.4.4 The PI Inverter Control Simulation

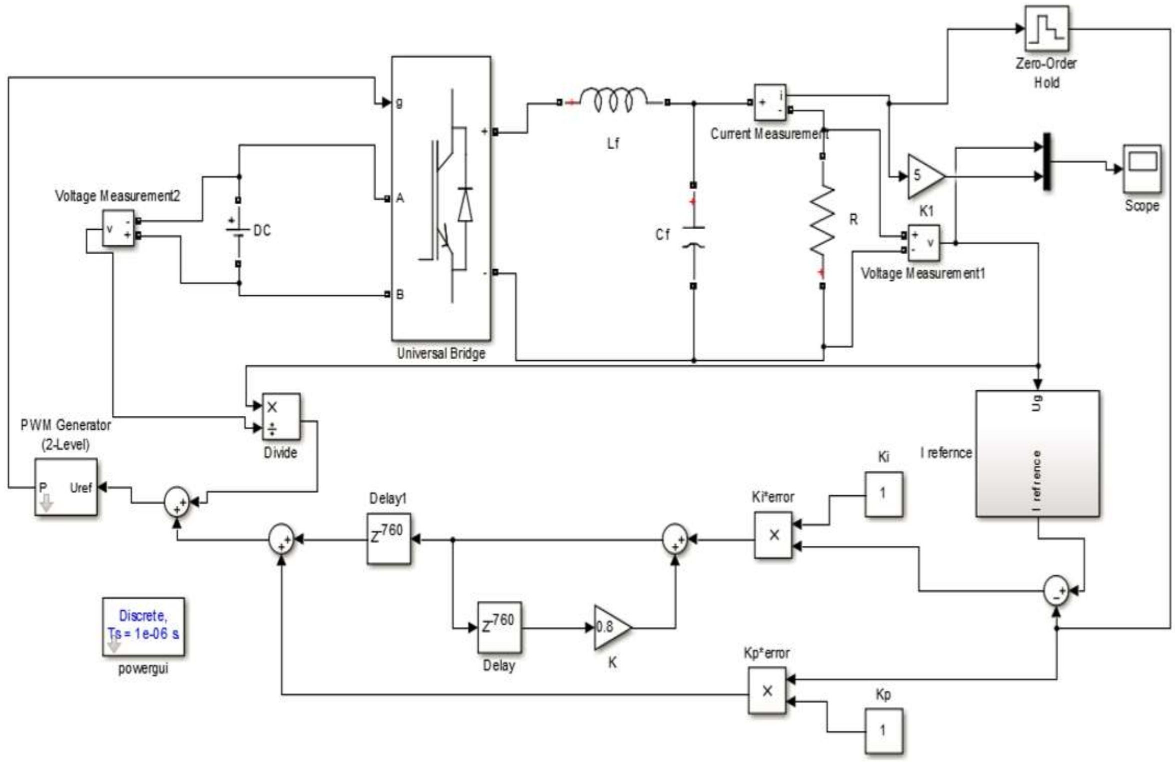

Figure 3.15 PI control of PV grid-connected inverter Control Simulation in MATLAB/SIMULINK

The behavior of the PI controller system of the PV grid-connected inverter as seen in figure 3.17 can be analyzed as seen below in terms of the controllers output signal [17]

$$u(t) = K_p e(t) + K_I \int_{t_0}^{t} e(t)\, dt \qquad (3.7)$$

Where; proportional and integral constants are K_p and K_I respectively, the time and the initial time are t and t_0 respectively, and the $e(t)$ is the error control that in this case is used as the input signal of the PI controller [17]

Chapter 4: Results and Discussions

4.1 Introduction

The results for this project are basically simulated results from MATLAB/SIMULINK. This includes the results from the mathematical modeling of PV array, and the PV inverter grid control that is the Maximum power point tracking (MPPT) controller with a DC-DC Boost converter, Grid Synchronization controller and the PV Inverter controller using the proportionate-Integral (PI) controller).

4.2 Mathematical Simulation Result of the PV array

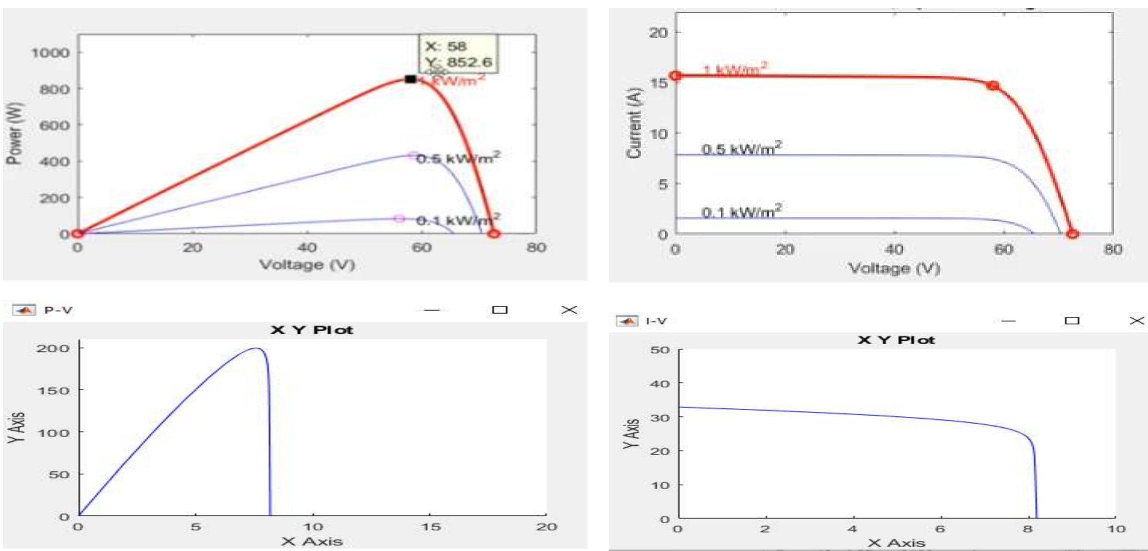

Figure 4.1 MATLAB/SIMULINK Simulation Results of the Power Vs. Voltage and current Vs. Voltage as indicated on the graphs.

It is important to note that the increase in temperature above 25℃ results in a decrease in power output as shown in the P-V voltage graph and this was due to a decrease in photovoltaic voltage as a result of rising temperature as observed in figure 4.1.

4.3 Maximum Power Point Control (MPPT) Simulation Results

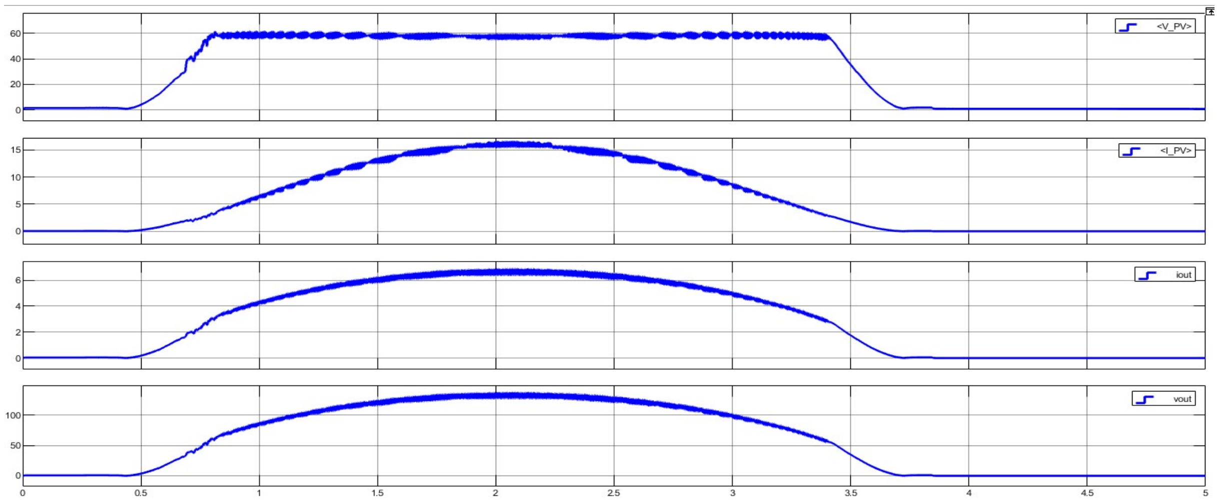

Figure 4.2 MATLAB/SIMULINK Simulation results for the PV Voltage, the PV current, the PV inverter output current, and the PV inverter output voltage respectively during MPPT control of the PV Grid-connected Inverter system.

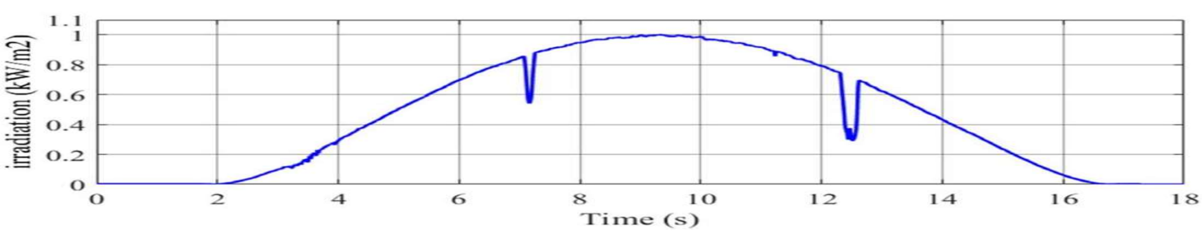

Figure 4.3 MATLAB/SIMULINK simulation results of the PV Irradiation curve using Perturb and Observe the technique of MPPT control.

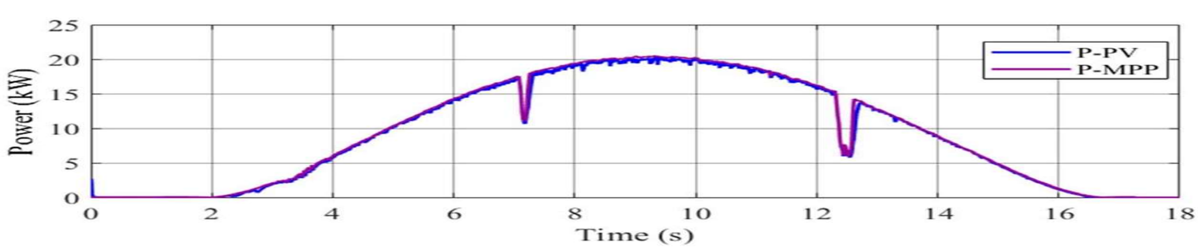

Figure 4.4 MATLAB/SIMULINK simulation result of the PV output power using of Perturb and Observe the technique of MPPT control

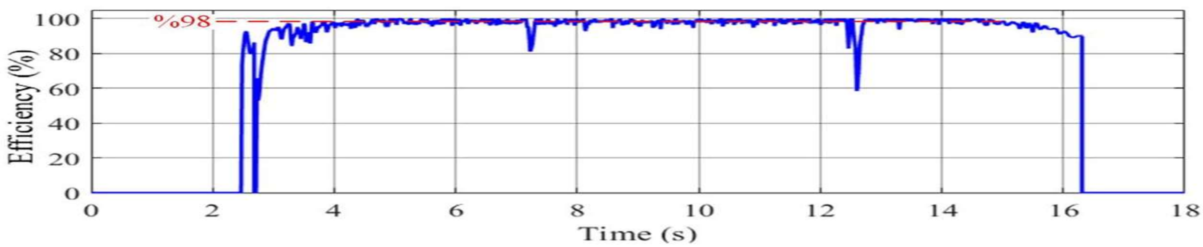

Figure 4.5 MATLAB/SIMULINK simulation result of the MPPT Efficiency using Perturb and Observe the technique of MPPT control

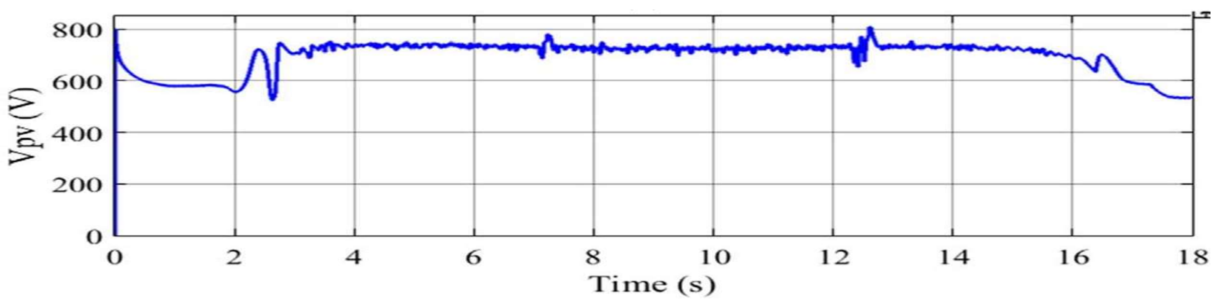

Figure 4.6 MATLAB/SIMULINK simulation result of the PV output voltage using Perturb and Observe the technique of MPPT control

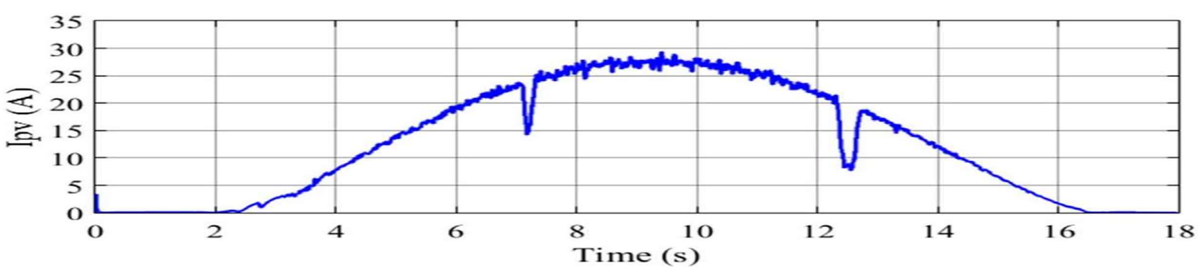

Figure 4.7 MATLAB/SIMULINK simulation of the PV output current using Perturb and Observe the technique of MPPT control

Figure 4.3 represents the PV irradiation curve under different temperature or cloud conditions of the day. Figures 4.4 and 4.5 also represent power results from the PV array using the observe and perturb method of Maximum Power point tracking (MPPT). In addition, from figure 4.5, the Maximum Power Point Tracking algorithm (Perturb and Observe), is tacking the Maximum Power Point (MPP) with an efficiency of 98%. Furthermore, from figure 4.5, it is very important to note that efficiency is less than 100% due to the effects of different weather conditions [32]

Figures 4.6 and 4.7 represent the PV array voltages and currents respectively. From figure 4.7, it is observed that the current as the PV current increases towards 28A, the voltage of the PV remains constant approximately. This is due to the nature of the Observe and Perturb technique of Maximum Power Point Tracking and the results communicate much about the performance control of the Observe and perturb algorithm [32].

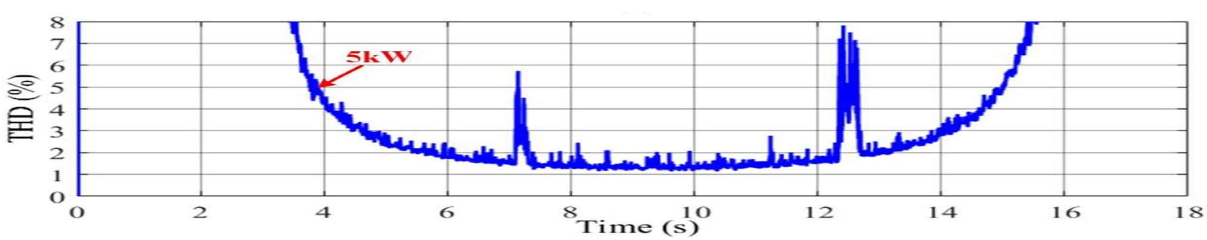

Figure 4.8 MATLAB/SIMULINK simulation result of the Total Harmonic Distortion of the PV Grid-connected Inverter

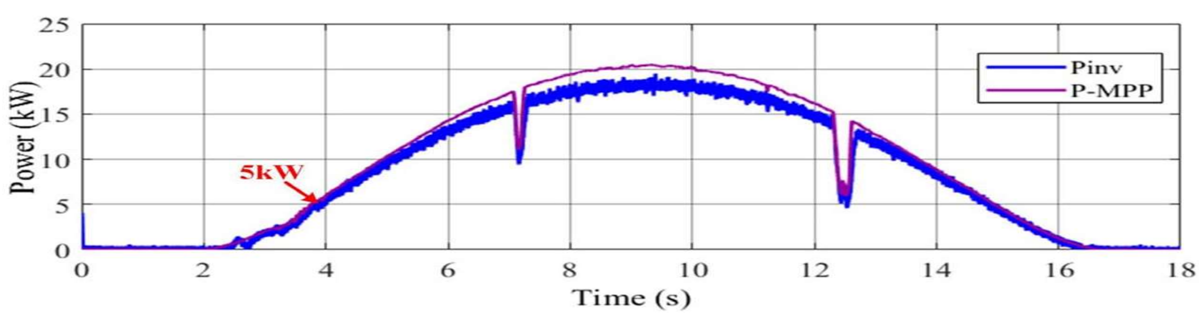

Figure 4.9 MATLAB/SIMULINK simulation result of the Inverter output power

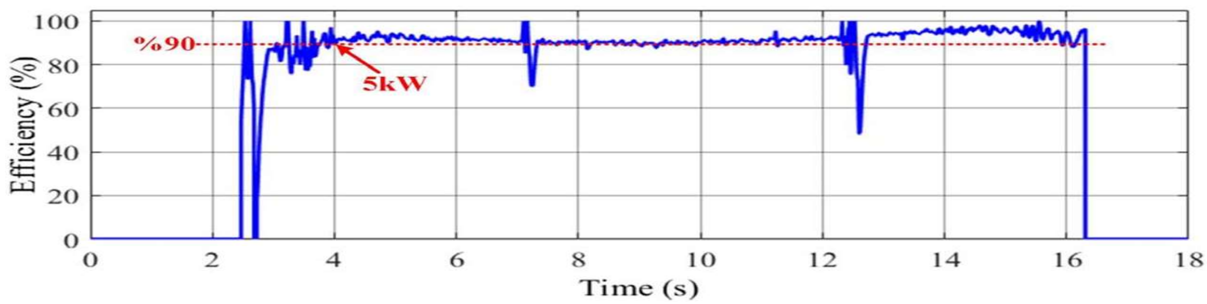

Figure 4.10 MATLAB/SIMULINK simulation result of the overall efficiency of the PV Grid-connected Inverter using perturb and Observe Technique of MPPT

It is also very paramount to note that apart from the performance test of the Observe and Perturb algorithm of Maximum Power Point Tracking of the PV array, the PV Grid-connected inverter in regards to harmonic distortions, power and efficiency was also examined as seen in figures 4.8, 4.9 and 4.10 respectively. Besides, in figure 4.8, it is observed that that the total harmonic distortions (THD) are lower than 5% for the power values bigger than 5kW. The total harmonic distortions (THD) are in this case lower than the specified standard limit as seen in Table 3.1 [30]. The achieved result, therefore, meets the PV Inverter and the Grid synchronization standards and therefore the PV grid-connected requirement was met.

Besides, the inverter output power which is transferred to the grid and the ideal Maximum Power Point curves have as well been compared to examine the proposed PV grid-connected inverter system's overall efficiency as seen in figure 4.9. In addition, figure 4.9 further illustrates the output power losses between PV inverter and the maximum power curve. The increase in power losses around the nominal power was also evident in figure 4.9 and this is due to the inductance of the low pass filter placed between the PV inverter and the grid as seen in figures 3.1 [16]. From figure 4.10, is observed that for power values bigger than 5 kW, the system's minimum frequency is approximately 90% even though the power losses increased.

From figures 4.5 and 4.10, the efficiency of the inverter can be calculated as approximately 92 %.

4.4 PV Inverter Grid-connected Synchronization Simulation Results

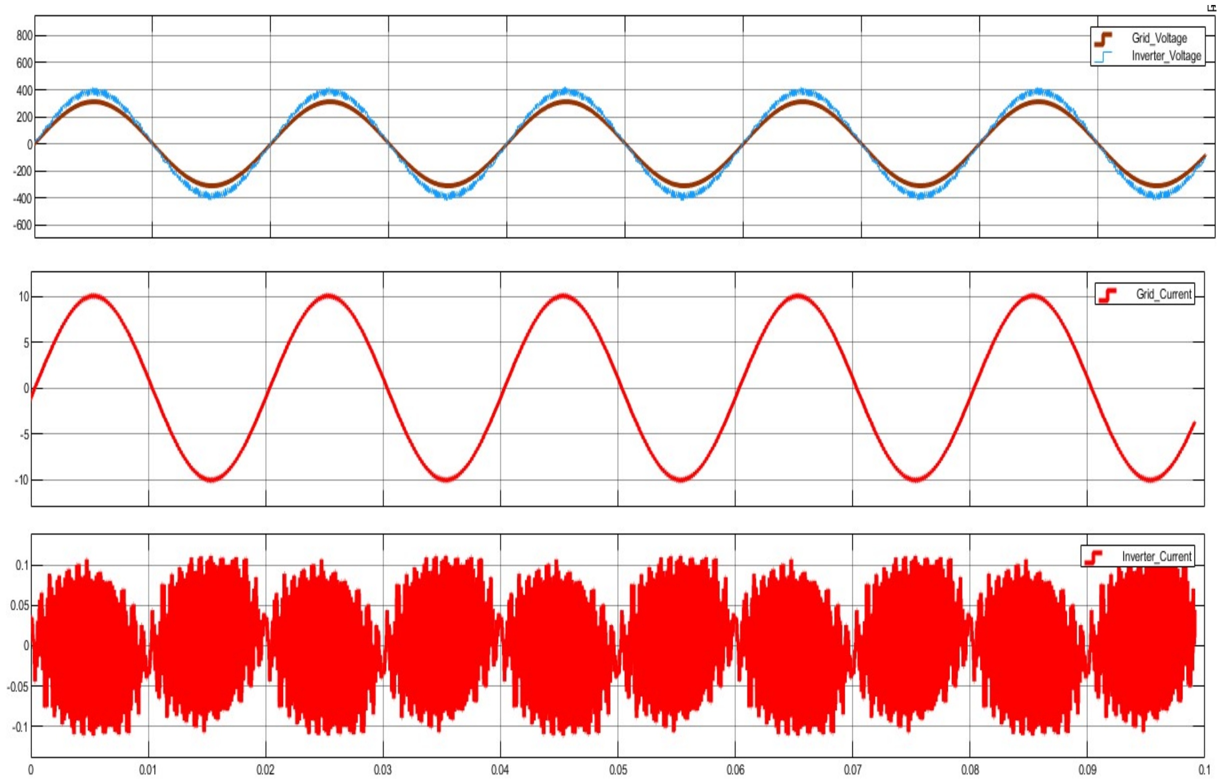

Figure 4.11 MATLAB/SIMULINK Simulation result of the PV Grid-connected Inverter before Synchronization using a single-phase locked loop (PLL) technique

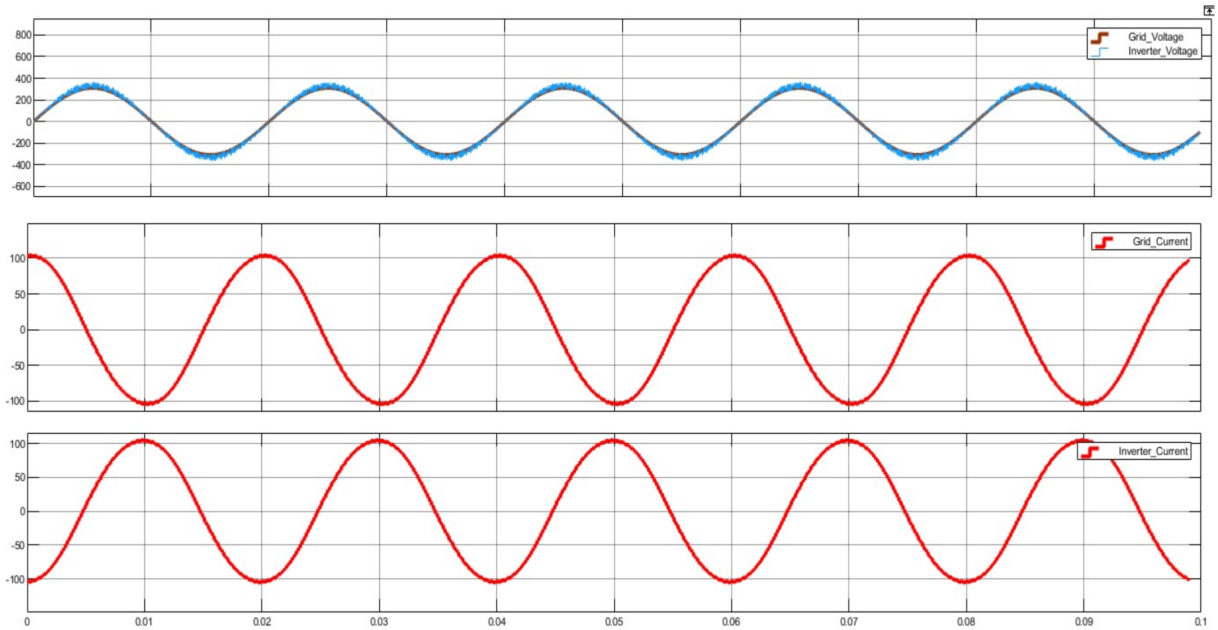

Figure 4.12 MATLAB/SIMULINK Simulation result of the PV Grid-connected Inverter after Synchronization using a single-phase locked loop (PLL)

From figure 4.11 and figure 4.12, before and after the synchronization between the PV inverter and the grid, both the output PV inverter voltage and the grid voltage seem to be matching though not perfectly to the standard when the modulation index was set to 0.4 in the MATLAB function of figure 3.16 and this is due to some harmonic distortions from the proposed PV inverter system components. Besides, the PV inverter output voltage is injected into the grid is sinusoidal and this meets the requirement mentioned earlier under section 3.2.1 of this paper.

4.5 PI Grid-connected Inverter Control Simulation Results

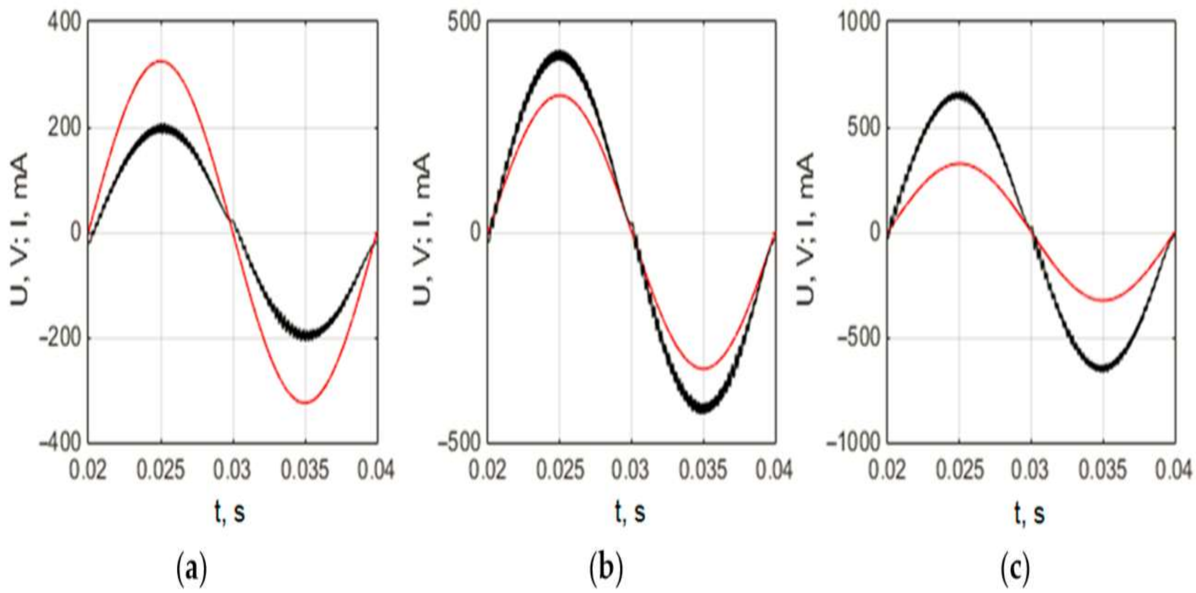

Figure 4.13 MATLAB/SIMULINK Simulation result of the PV Inverter output current and grid voltage using the PI controller at different load Power that is (a) 32 W; (b) 62 W and (c) 97 W

The black and the red curves in figure 4.13 represent the PV inverter output current and electric grid voltage respectively. In addition, the PI parameters in figure 3.17 were adjusted while paying attention to the inverter output current minimal total harmonic distortion (THD). During the adjustment of the parameters of the PI controller K_p, K_I were obtained as 10, 15 respectively. Furthermore, from figure 4.13, a distortion less electric grid voltage was obtained. The PV inverter output current with 200 mA, 400 mA, and 600 mA amplitude and corresponding 32 W, 62 W, and 97 W power injected in the grid were analyzed as seen in figure 4.13.

Moreover, from figure 4.13, the output current of the PV inverter is close to the pure sine wave which is a PV Grid-connected inverter synchronization requirement. It is also important to note that from figure 4.13, the high-frequency ripples of PV inverter output current as seen in figure 4.11 has been reduced by the PI controller that was proposed. The total harmonic distortion was observed to be 4.4%, 3.4% and 3.3% at 32 W, 62 W and 97 W load power respectively and these harmonic distortions (THD) values meet the standard as seen in Table 3.1 [30]. In addition, the main aim of tuning the proposed PI controller of the PV grid-connected inverter; was to obtain K_I and K_p for which the total harmonic distortion (THD) of the output current of the PV inverter is minimal. Moreover, it was estimated and observed that the PI controller proportionate K_P, is a determining factor of the frequency ripples' amplitude- meaning that as K_P value decreases the frequency ripples also decreases. However, it is also important to note that when a very low K_P value is introduced, the shape and the phase shift of the PV inverter output worsens. Therefore, it is very critical to obtain a good range of K_P values to ensure proper control of the PV grid-connected inverter. Singh and Joshi [41] further describe different techniques of tuning the PID controller.

Chapter 5: Future Work, Limitations, Lessons Learnt and Conclusion

5.1 Future Works

1. Modelling and building of a PV-battery-grid energy management system control in order to; regulate or minimize the difference between the electricity consumption and the PV array production, maximize the PV energy usage within the house and finally improve on the battery life by decreasing the excessive charge-discharge cycles [42]
2. Implementing the physical model for the perturb and observe method using microcontrollers and testing it on a real-life PV array.
3. Implementing the physical model of battery management algorithm which will provide power management between all the sources that are PV, grid, and battery storage.
4. Designing and implementing at a simulation level, the bidirectional kWh energy meter to be used in measuring the power consumed from the grid while supplying the load or charging the battery block when needed. The bidirectional kWh energy should also be able to measure the power injected into the grid from the PV System and ensuring that the parameters used tally with the data from the electricity regulation
5. Improving the system by further reducing the harmonic distortions during the PV inverter synchronization by applying algorithms such as the SOGI PLL to achieve a fewer harmonic oscillation during transient and steady-state conditions.
6. Implementing the islanding mode of PV grid-connected inverter in MATLAB/SIMULINK

5.2 Limitations of the Research

1. The parameters used in modeling and simulating the proposed PV-grid inverter were not the parameters from say the Electricity Company of Ghana (ECG) but rather

assumed parameters from the research papers. This was mainly due to difficulty in acquiring the real-time grid data from any of the electricity companies in Ghana

5.3 Lessons Learnt

1. There are different techniques of PV inverter control that is MPPT control, PV inverter synchronization control and PV inverter control. However, it is always important to strike a balance between cost, reliability, effectiveness, complexity and the efficiency of the different techniques to ensure the affordability of the device and its smooth running.

5.4 Conclusion

In this paper, three control strategies of the PV grid-connected inverter that is Maximum Power Point (MPPT) control using perturb and observe technique, PV grid-connected inverter synchronization using single-phase phase-locked loop (PLL) technique and Proportionate-Integral (PI) controller has been proposed. The results indicate that the perturb and observe the technique of Maximum power point tracking of PV solar offered effective tracking under varying irradiation that is the MPPT control efficiency obtained was 98%, the PV inverter efficiency obtained was 92% and the overall system efficiency for both perturb and observe MPPT technique and PV inverter was roughly 90%. The proposed PI controller was able to further reduce the steady-state error while tracking down the high-frequency signals as well as reducing the total harmonic distortions (THD) of the PV inverter current output. It was also noticed that during PV inverter synchronization with the grid using the PLL technique, the power injected into the electric grid by the PV inverter is dependent on the amount of power extracted from PV solar and the efficient processing of that power by the PV inverter. It is also important to note that the operational characteristics of PV array and electric grid regulations and standards on the design of PV grid-connected inverters were considered in this paper.

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Appendix

Table 0.1 Datasheet values at Standard test conditions (STC) and some estimated Values and of different parameters used in the equations

Parameter	Description	Value	Parameter	Description	Value
I_s	Photocurrent		k_i	Short circuit of the PV cell at 25℃ and $100\,\frac{W}{m^2}$	
R_{sh}	Shunt resistance (Ω)	415.405	T_n	Reference temperature of PV cell	$300°K$
q	Electron charge (C)	$1.6 * 10^{19}$	E_g	Band-gap energy of the PV solar cell conductor (eV)	1.1
R_s	Series resistance (Ω)	0.221	I_{Rs}	Reverse saturation current under the reference temperature and the irradiation	

I_0	Reverse saturation current		N_s	Series number of cells	54
k	Boltzmann's constant	$1.38 * 10^{-23}$	N_p	Parallel number of cells	1
i_{pv}	Output current produced by the PV battery (A)		A	Dimensionless junction material factor	
I_{sc}	Short circuit current (A)	8.21	I_D	Diode current	
R	Solar radiation	800	R_n	Nominal solar insolation	1000
T	Operating temperature of a solar cell (in Kelvin)	$301°K$	v_{pv}	Output voltage	
V_{oc}	Open circuit voltage (V)	32.9	P_{max}	Rated power (W)	200.143
V_{mp}	Voltage at maximum point (V)	26.3	I_{mp}	Current at maximum point (A)	5.58

U	Grid voltage	380V	f	Grid frequency	50Hz
T_s	Sampling time	$20\mu F$	C_f	Filter capacitance	$5\mu F$

MATLAB for Code Maximum Power Point Tracking (MPPT)

```
function duty = MPPT_algorithm (vPV, iPV,delta)
% I simply used the MPPT algorithm in the MATLAB examples and modified it a
% bit
duty_init=0.1;
% Min and Max values are used to limit the duty between 0 and 0.85
duty_min=0;
duty_max=0.85;
persistent vold pold duty_old;
% persistent variable type can be used to store the data
% We need the old data by obtaining the difference between old and new
% value
if isempty (vold)
   vold=0;
   pold=0;
   duty_old=duty_init;
end
p=vPV*iPV; % This is the power
dv=vPV-vold; % difference between old and new voltage
dp=p-pold; % difference between old and new power
% The algorithm below does the dp/dv=0
% If the derivative equal zero, duty cycle will not change
% If old and new power not equal and PV voltage is bigger than 30% the duty
% duty will work
if dp~=0 && vPV>30
   if dp<0
      if dv<0
         duty=duty_old-delta;
      else
         duty=duty_old+delta;
      end
   else
      if dv<0
         duty=duty_old+delta;
      else
         duty=duty_old-delta;
      end
   end
```

```
else
   duty=duty_old;
end
% The code below allows the duty to operate between min and max values
if duty>=duty_max
   duty=duty_max;
elseif duty<duty_min
   duty=duty_min;
end
% Stored data
duty_old=duty;
vold=vPV;
pold=p;
```

PV inverter and Grid Synchronization MATLAB Code

```
function ref_Voltage = fcn(x,ma,shift)
% Code generation
shift_k=shift*pi/180; % Converting from degrees to rad/s
ref_Voltage=(ma*(sin((x)+shift_k)));
% where; x is Angular velocity (rad/s)
% ma is Modulation index
% shift is phase degree (degree)
```

PV inverter Filter and DC-DC Boost Converter parameter calculation in MATLAB

```
clear all
clc
% Inverter filter calculation
Tss=2.5e-6; % This is sampling time
P=10e3; %Rated active power
U=380; % Inverter phase-to-phase voltage
f=50; % frequency
fsw=5e3; % Switching frequency
Cfmax=(0.05*P)/(2*pi*f*U^2); % 11uF
Lf=(0.1*U^2)/(2*pi*f*P); % 4.6 mH
RLf= Lf*100; % resistance of inductor
Ts=1e-06; % This is the sampling time for inverter
f=50; % System frequency
Vbase=380; % Grid voltage
fs=99*f; % Switching frequency
Ts_Power=1/(fs*100); % Sampling time
P=50e3; % Inverter power
% This equation is taken from MATLAB samples
% The filter inductance pearameters/filter coil parameters
Pbase=Vbase^2/P; % The phase calculation
```

```
RL=1.5e-3*Pbase;
L=0.15*Pbase/(2*pi*f);
% The filter capactor parameters
Qc=0.1*P;
Pc= Qc/50;
D=53.125;
Vin_min=25;
fs=20000;
L=1.559e-4;
C=2.767e-4;
R=9.6;
Ts=1e-6;
```