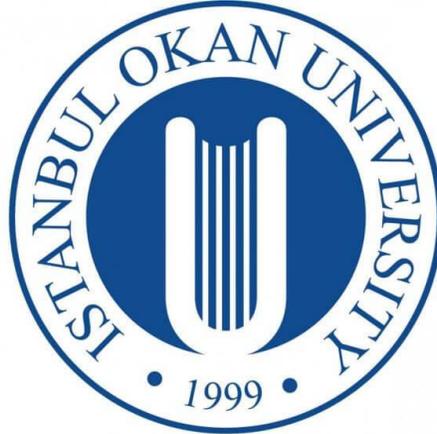FACULTY OF ENGINEERING

POWER ELECTRONICS AND CLEAN ENERGY SYSTEM
DEPARTMENT

A DYNAMIC ON-GRID SOLAR POWER SYSTEM

USING A BI-DIRECTIONAL COUNTER METER

A THESIS PROJECT

Submitted By

MUKTHAR BIDEMI OPELOYERU

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Submitted to the Department of Power Electronics and Clean Energy

OKAN UNIVERSITY

In partial fulfilment of the requirement for the degree of

MASTERS OF ENGINEERING

Approved by

_____

 Prof. Dr. R. Nejat Tuncay

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Nov 2021   Mukthar Bidemi Opeloyeru

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ABSTRACT

A DYNAMIC ON-GRID SOLAR POWER SYSTEM
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Recent advancement in technology has led to a remarkable increase in solar cell efficiency while causing a reduction in the expenses of PV systems and the adoption of a PV system as a reliable source of energy globally. To further reduce the entry barrier of PV systems, most governments have introduced several incentives including a Net-metering tariff which uses a bi-directional meter for grid-connected PV systems. This research work focuses on the design and simulation of a 2kW grid-connected system with an integrated bi-directional metering unit. The system also involved the integration of a bidirectional Vehicle to Grid (V2G) and Grid to Vehicle (G2V) Electric vehicle charging features. The design, modelling, simulation and analysis of the developed system was done using the Simulink interface of the MATLAB suite. The system essentially consisted of a "Perturb and Observe" MPPT system, a phase-locked loop (PLL), an LCL filter and a Mosfet based single phase inverter system. The simulation result obtained from running the model at different levels of irradiance and the response of integrated bidirectional meter indicated a functional system capable of metering energy in both modes.

Keywords: Bi-directional Meter, Grid Connected PV system, LCL filter, PID Controller, MPPT, P&O Algorithm., MATLAB/SIMULINK, Vehicle to Grid (V2G), Grid to Vehicle (G2V)

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CHAPTER ONE

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1.0   INTRODUCTION

The growing environmental concern over the usage of fossil-based energy sources and the relative advancement in science and technology has consequently led to the widespread call for the adoption of renewable energy sources for energy generation.

Renewable energy has been adjudged to be a promising alternative to fossil as they are relatively cleaner and more permanent. The common renewable energy sources are wind, photovoltaic, wave, biomass and tidal as substitute sources to yield electricity (Atiq & Soori, 2017). The global energy report for 2012 indicated that over 16% of the world energy consumption comes from renewable energy sources. While this might be considered a relatively small proportion, Johnson (2013), noted that over half of the new electric power installations in the year 2011 were from renewable energy sources and this was proposed to likely be the trend for the future.

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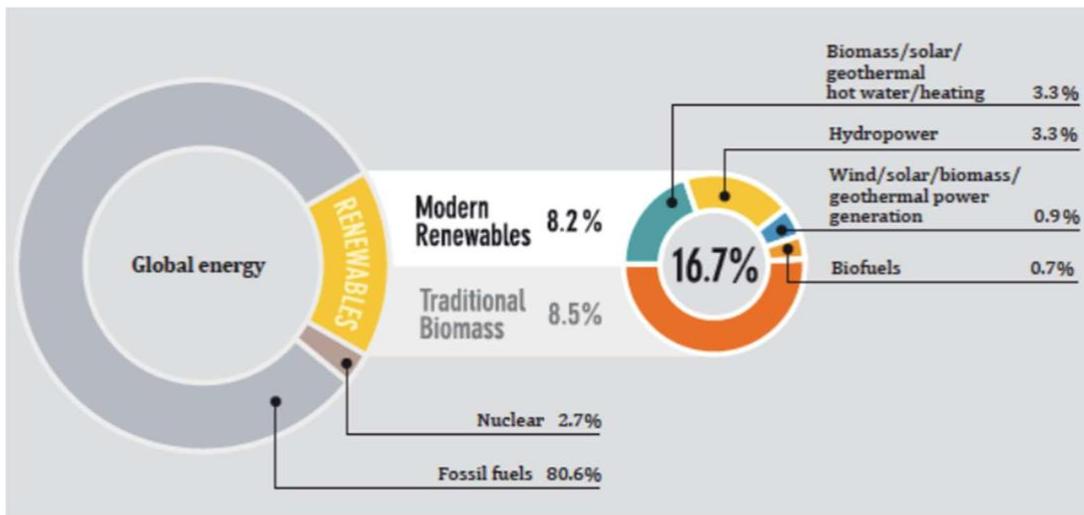
Figure 1.0   Global Energy Consumption 2010

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Although there has been widespread adoption of several renewable energy solutions over the years, solar energy systems have become the utmost significant source of renewable energy. Solar energy is one of the cleanest forms of energy and the process of harnessing the energy from the sun for various purposes is often without the production of any harmful byproduct or waste.

1.1 Harnessing Solar Energy

Nuclear reactions within the sun produce energy that travels to the earth's surface as electromagnetic radiation. The generated electromagnetic radiation is composed of over 50% infrared, with visible and ultraviolent and a myriad of radiation with diverse electromagnetic spectrum accounting for the remainder. As this radiation travels to the earth, a quota of it is dispersed by molecules and dust in the air consequently sending radiation in all directions and a huge proportion of it back into space. The interaction between the generated electromagnetic radiation and the aforementioned elements leads to the reduction of the solar energy instability by about 40% while also altering its structure so that the sunlight which touches the globe's surface consists of 50% evident radiation and 47% infrared.

The advancement in science and technology over the years has led to the development of diverse equipment and technological solutions for harnessing solar energy, the most common ways by which solar energy is harnessed include the following;

1.1.1 Solar Heating and Cooling systems (SHC)

These technologies have been designed to harness the heat from the sun for diverse purposes including space heating, pool heating and cooling for both residential, industrial applications.

Solar cooling systems are essential of two major types: the absorption chiller system and the desiccant variant. The desiccant system essentially leverages the thermodynamics properties of

desiccant materials such as silica gel to absorb moisture from the air to improve thermal comfort. Then spent desiccant is further dried via solar heat and the cycle is repeated afresh.

Absorption chiller systems function similarly to the conventional refrigerating system. Common absorption cooling setups employ solar water heating collectors. The absorption cycle is fundamentally driven by a heated fluid from a suitable solar collector.
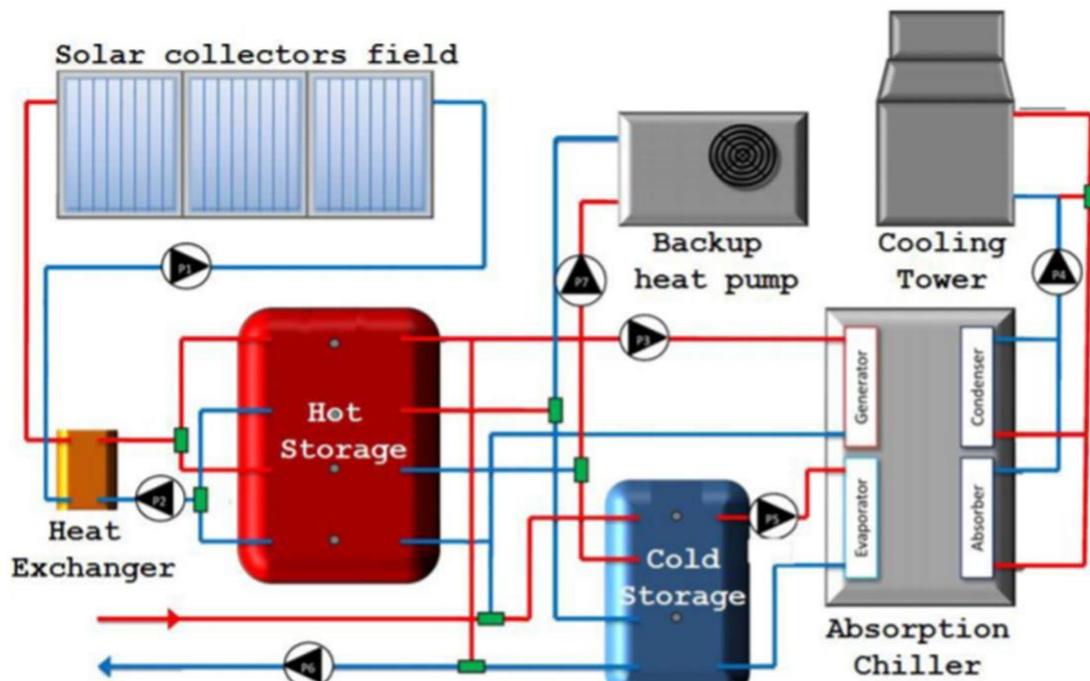
Figure 1.1   Simplified Solar heating and cooling system (Ayadi et al., 2012)

1.1.2   Concentrating Solar Power (CSP)

These systems are designed to focus the energy of the sun on the specialized surface to drive utility-scale, electric turbines that generate electricity. CSP exists in different format arrangements ranging from the parabolic trough, Fresnel reflectors to dish engines. Common CSP uses well-crafted mirrors to concentrate the thermal energy for driving suitable steam turbines and electricity engines. Concentrating solar power systems also enable energy to be stored for electricity generation at peak periods of the day as well as relatively low night time.

1.2   Photovoltaic Systems (PV)

PV systems essentially consist of solar cells arranged into solar arrays, inverters, converters, energy-storing devices and other mechanical and electrical equipment to produce DC and AC power. Although fossil fuel is still high in use for most energy demand, there has been a relatively steady increase in the usage and adoption of solar systems. The development of more efficient solar cells and the comparative decrease in the cost of acquiring and setting up PV systems have greatly increased the rate of adoption of PV systems as a worthy replacement for fossil fuel-based power generation systems (Mohanty et al., 2016).

1.2.1   Solar Cell

This is the fundamental element of photovoltaic systems. Its series combined forms a photovoltaic panel, when these are more arranged in parallel, they are a suitable photovoltaic array. In its basic form, it is a simple diode open to the light. The solar cells are thus prepared from numerous semi-conductor via diverse manufacturing processes. Consequently, the electrical output of solar cells is a function of their intrinsic properties and inward solar energy.

Solar energy is made up of photons at different levels of energy, they get immersed at the p-n junction. The bandgap of semi-conductors is of great importance in its energy generation. The bandgap refers to the lowest amount needed to release a bound electron to its free. In operation, photons consisting of energies lesser than the bandgap of the solar cell are relatively unable to
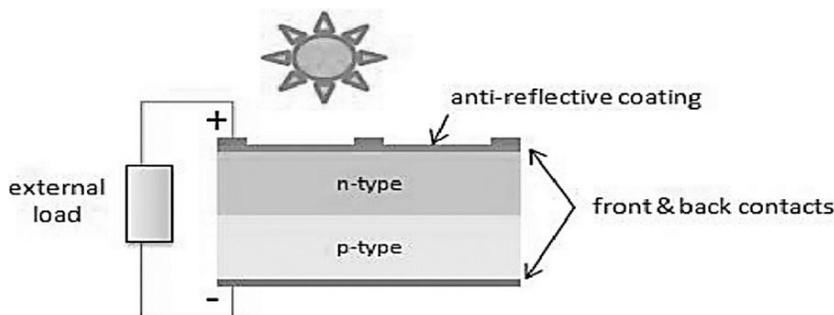
Figure 1.2   Conventional solar cell (Guerra et al., 2018)

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produce an electric current. Although Photons with higher energy generate electricity only those matching to the energy band gap while the remains will degenerate as heat (Rodrigues et al., 2011).

Although diverse use of PV systems has been developed over the years, the following are some of the common applications of PV systems:

I. **Water Pumping:** The ready availability of Sunlight in most parts of the world makes PV systems suitable for deployment in farms and remote settlements having no grid connection. It is not uncommon to find stand-alone solar-powered pumping stations in most villages
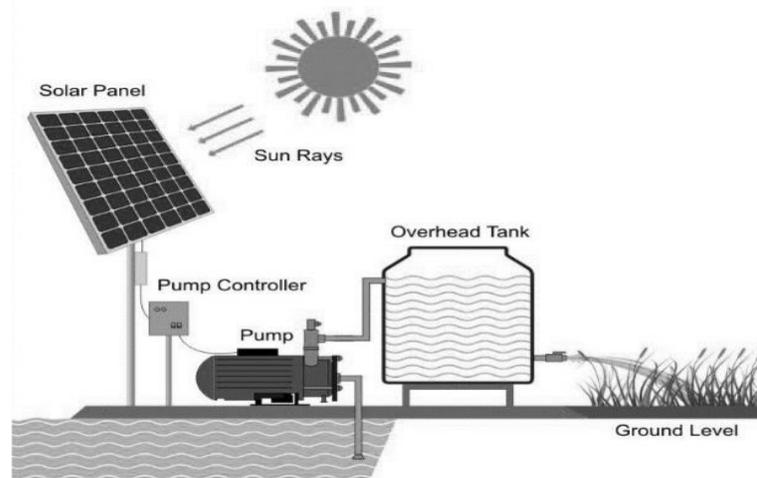
Figure 1.3   PV pumping station (Mohanty et al., 2016)

II. **Lighting and Traffic Signals:** The development of highly efficient energy-saving Light-emitting diodes (LEDs) as well more efficient and highly compact solar panels has in recent times made PV lightning systems very popular. Solar photovoltaic lighting systems are now used for street lights in rural areas
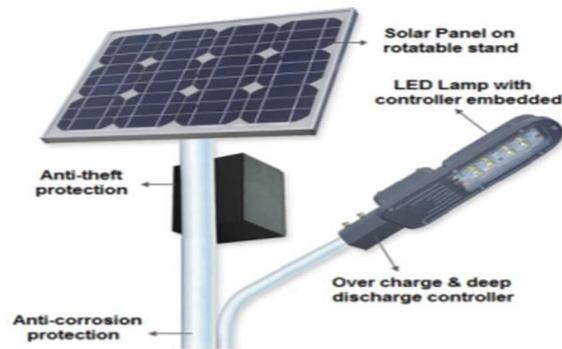
Figure 1.4   Solar powered light (Primiceri & Visconti, 2017)

PV systems exist in different variants. Grid and standalone connected systems are basically the best common configurations (Atiq & Soori, 2017). Standalone PV systems are more suited for remote locations where access to the electric grid is fairly difficult as such, they are independent of the main grid and the resultant energy generated is often stored in batteries.
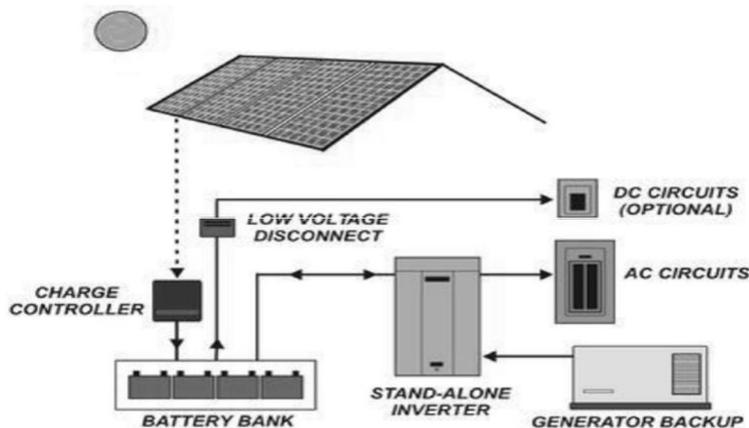
Figure 1.5   Stand-alone PV system (Mohanty et al., 2016)

Grid-connected systems are fairly more advantageous than the stand-alone variant as they are designed to enable a bi-directional transfer of electricity. Energy can be taken or directed to the grid depending on the load request. These can also be installed without battery backup. PV systems without battery backups are often more efficient and consequently produces more power due to

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the reduction of losses. In other to encourage the adoption of Grid-tied PV systems, most governments around the world often tend to have some form of compensation in billing for grid-tied PV systems. This is usually done via a Net energy metering system; an electricity billing mechanism that allows consumers to be billed for the net energy usage over some time thus offsetting the overall cost for running grid-tied systems.

The dimension of this structure ranges from small housing and viable rooftop structures to bulky scale solar power stations. A small scale grid-tied solar power station consists of a suitable DC/DC converter as well as DC-AC inverter setups.
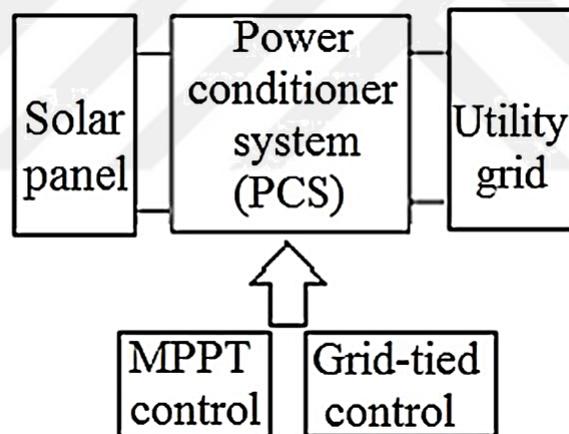
Figure 1.6   Small Scale Grid-Tied PV System (Phap, 2019)

Inverters for grid-connected systems are designed to supply the electricity in a matching condition or state as the main grid. Such power conditioning includes synchronization of frequency to the grid frequency, and islanding protection features. Large scale power solar systems are formed by combining several PV modules combined in series and parallel.
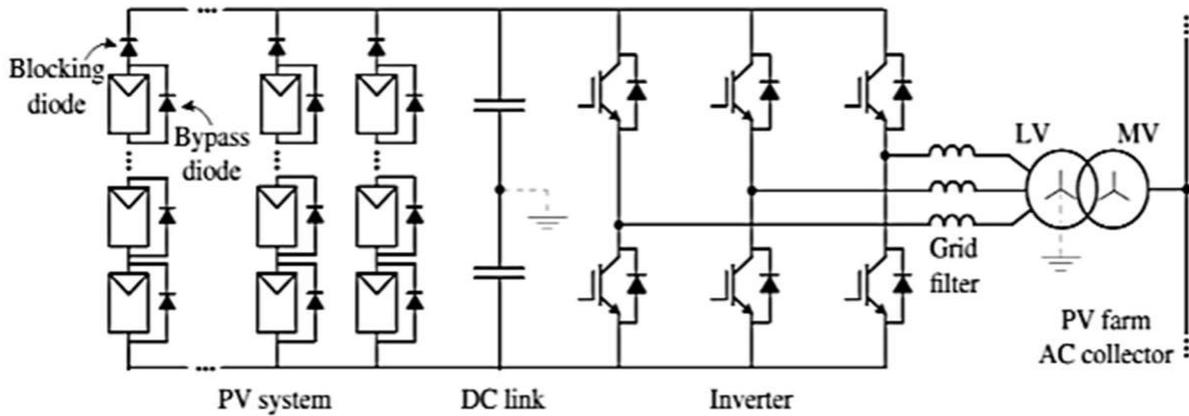
Figure 1.7   Large Scale Grid-Tied PV System (Phap, 2019)

Grid-connected Inverters more often than not are designed to operate with a nearly unity power factor. This consequently will affect the power element of the main grid to be greatly reduced and further result in the distribution grid supplying the reactive power needed via capacitors installed in the primary of the concerned grid. This rather disadvantageous arrangement often causes PV systems because they lose their capacities and resulting in the grid supplying all charges.

1.3   Micro-grids

Microgrids are gradually becoming very popular in most regions of the world. Their ability to provide backups during emergencies as well as allow energy independence makes them highly adaptable for PV systems. The type of grid is an indigenous energy grid using an integrated control ability thus enabling the grid to be decoupled from the old-fashioned grid and function self-sufficiently. Micro-grid operates in two ways, these can be as stand-alone and grid-tied PV systems. In grid-connected mode, the micro-grid either obtains power from the traditional grid or supplies power to the grid to boost the grid thus offering some form of power equalization.

The stand-alone mode essentially involves disconnection from the traditional grid and supplying only connected clients. A micro-grid naturally needs a power balancing system reference of reactive power, rationing dynamic and ensuring collaboration amongst the units to achieve balanced and economic operation.

1.4   Solar Radiation

The measurement of the volume of solar energy established by or unto a specific surface is known to be solar radiation. The term solar irradiance can be expressed in units of kW/m^2. This surface is known as a solar panel where we are dealing with a system powered by PV. The solar radiation is normally quantified in topmost sun hours, these are the corresponding number of hours per day when solar irradiance be around 1 kW/m^2. Note with significance that even though the sun may be beyond the horizon for 14 hours daily, it does only generate energy equal to 6 peak sun hours.

The wavering weather circumstance is also a shortcoming of PV powered systems as this would be saying that the generation of power in a day is not constant. The rather little solar to electrical energy conversion of this type of system is also a major drawback. The productivity of the solar radiation setup ranges from 9% to 17%. MPPT controllers are integrated with PV systems to improve their effectiveness and ensure that maximum power is achieved.

1.5   Maximum Power Point Tracking (MPPT)

Maximum power point tracking enables the PVS to be operated at the topmost power level, thereby permitting the maximum power to be distributed at different irradiance and wavering temperature. A functioning converter of DC to DC transfers the power of the maximum from the PV module and send it to the load by altering the target duty cycle, the load impedance of the source is extensive and coordinated at the point of the topmost power level with the source thus resulting in the transfer the maximum power. Several MPPT control algorithms have been developed, these are the Perturb and observe, open-circuit voltage, incremental conductance, parasitic capacitance, pilot cell, etc. Perturb and Observe method (P&O) is however the most common algorithm. The power of the module changes when a slight perturbation is presented to the system. If there exists

an increase in power when this is done, the perturbation is continued in that route. When the topmost power is reached, power reduces at the next instant and the perturbation reverses after that happens.
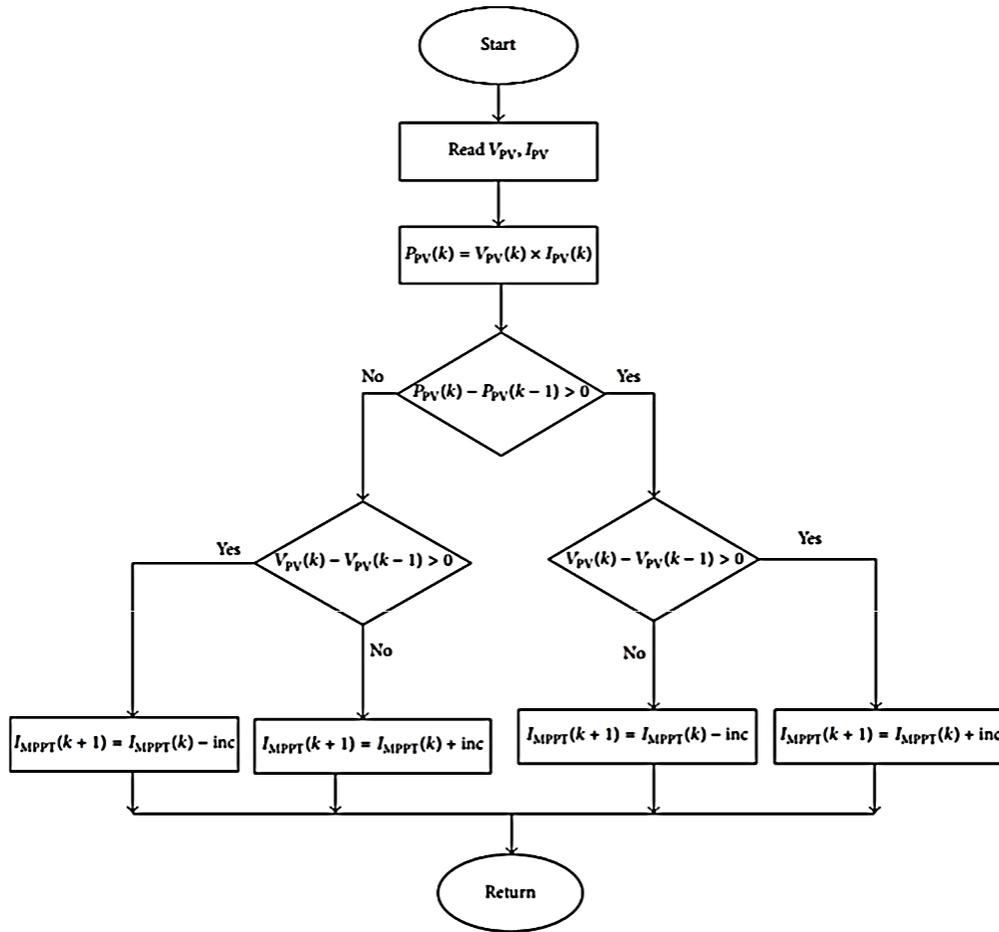
Figure 1.8   Perturb and Observe Algorithm

1.6   Bi-directional Metering

The metering arrangement of a stand-alone PV system is fairly different from grid-connected systems. The concept of net metering has been introduced for grid-connected PV system users in most countries of the world. Net metering offers a relatively cost-effective billing to encourage the adoption of Grid-connected PV systems and features a bi-directional metering arrangement to

allow the user to either supply energy to or from the grid. The user is thus billed for the net energy usage.

This study will give a broad overview of the several ways of harnessing solar energy and explore the concept of solar cells and Photovoltaic (PV) arrays. The modelling of the target PV system will then be considered and suitable performance evaluation will be carried out by analyzing the result obtained from the simulation of the system with Matlab Simulink.

CHAPTER TWO

LITERATURE REVIEW

2.0   Introduction

Existing literature on Photovoltaic solar power systems is reviewed in this chapter. It starts with the review of relevant theoretical frameworks under the study and takes a broad overview of studies done on solar power systems both internationally and locally. The section ends by identifying a research gap and formulating an appropriate conceptual framework for the study.

2.1   Solar Power System

The importance of renewable energy cannot be over-emphasized. Photovoltaic energy has grown at a high rate yearly and is rapidly becoming a vital aspect of energy stability in most areas and power systems (Sreedevi et al., 2017). The global energy profile clearly shows a gradual increase in the global share of renewable energy. In 2010, Renewable energy supplied about 16.7% of the energy consumed globally. This percentage may be seen to be small or irrelevant, Johnson, (2013) duly noted that nearly half of the new electric power capacity installed in the year 2011 was from renewables alone. In 2013, the global renewable energy share has risen to about 19% 2013 and is predicted to increase in a similar trend in the future.
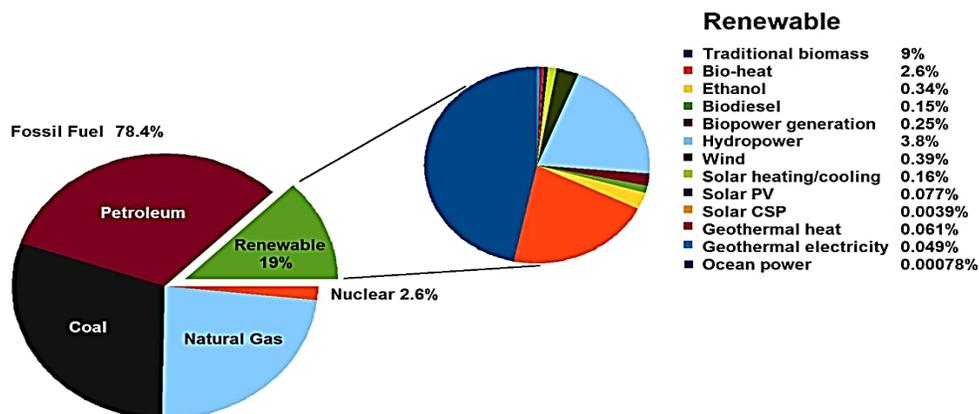
Figure 2.0   (REN21 Renewables 2014 Global Status Report, 2014)

2.2 Photovoltaic Systems

When light strikes a silicon semiconductor, the resulting flow of electrons generates electricity. Solar power is essentially derived from the conversion of sunlight into electricity via suitable devices.

Photovoltaic systems can also be expressed as PV systems and essentially use solar panels to generate solar power. They consist of photovoltaic panels, DC to AC inverter and a tracking system, this system will consist of electrical interconnections, solar panels, and mounting for added modules. "Photovoltaic" is a term coined from the Greek word "Photo" which stands for light and volt, the unit of electromotive force.

2.2.1 Photovoltaic Module

Photovoltaic Modules are made from combining a series of solar cells to form a "laminate" which are then assembled into protective weatherproof enclosures often referred to as solar panels. A solar cell is essentially the elementary component of the PVS. A collection of PV modules connected in series and parallel form PV arrays.

PV arrays often use a DC to AC inverter to produce power that is used for motors, lights and so on. The PV array modules are connected first in series to get the preferred voltage, after which the strings will be connected in parallel to let the system yield further current. A solar array can range from a few watts to megawatts. The measurement of solar panels is usually under standard test conditions (STC) or PVUSA test conditions (PTC) in watts.

2.3 Classification of Solar Power Systems

Three major classes of solar PV systems exist; Grid-connected (Grid- Tied), Grid/hybrid and Off-grid.

2.3.1 Off-grid Solar systems

This kind of solar system is not coupled to the core electricity grid; hence a storage battery is often required for use. Zipp, (2015) noted that these PV systems are well suited for users with geographical limitations or needing a more consistent energy source.

Although straightforward designs are often used to set up off-grid systems, advancements in technology have led to the development of diverse configurations of these systems depending on technical needs and load requirements. Most Stand-alone PV systems often consist of a PV array, charge controllers, battery storage, and a battery-based inverter amongst other things as shown in Figure 2.1 below
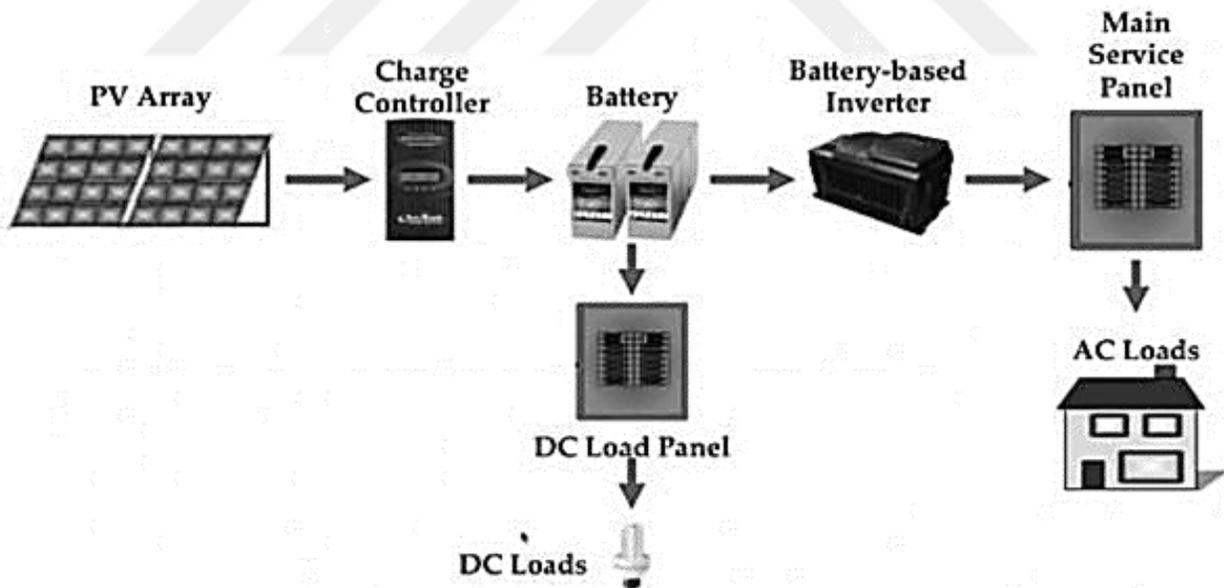
Figure 2.1   Off-Grid PV System (Zipp, 2015)

Stand-alone systems are also often characterized by frequent charging and discharging due to variation in PV outputs (Mohanty et al., 2016). To be easily adoptable, these stand-alone systems should be designed with a consideration on efficiency, reliability and flexibility and cost.

2.3.2 Grid-Hybrid Solar Power systems

These systems are tied to the power grid and also features integrated backup circuitry and backup battery. Hence, they are well suited for sensitive installations and facilities where unscheduled power outbreaks could lead to catastrophic failure in operations. Grid-tied systems that are battery-based generate power through an outage and enable the user to store energy for use in an emergency. These hybrid systems essentially require more components and a backup-sub panel is often needed to isolate and power target devices and equipment (Zipp, 2015).

Figure 2.2: Grid hybrid solar power system

Mohanty et al (2016), in their research on PV systems, noted that the main focus for Grid-hybrid systems is to improve the reliability of the complete system reasonably by the addition of more energy sources.

2.3.3 Grid- Connected Solar Power System

This solar power system essentially makes use of a standard grid-tied inverter. As such, there is no need for a storage battery. Zipp, (2015) noted that the Grid-connected system is impeccabl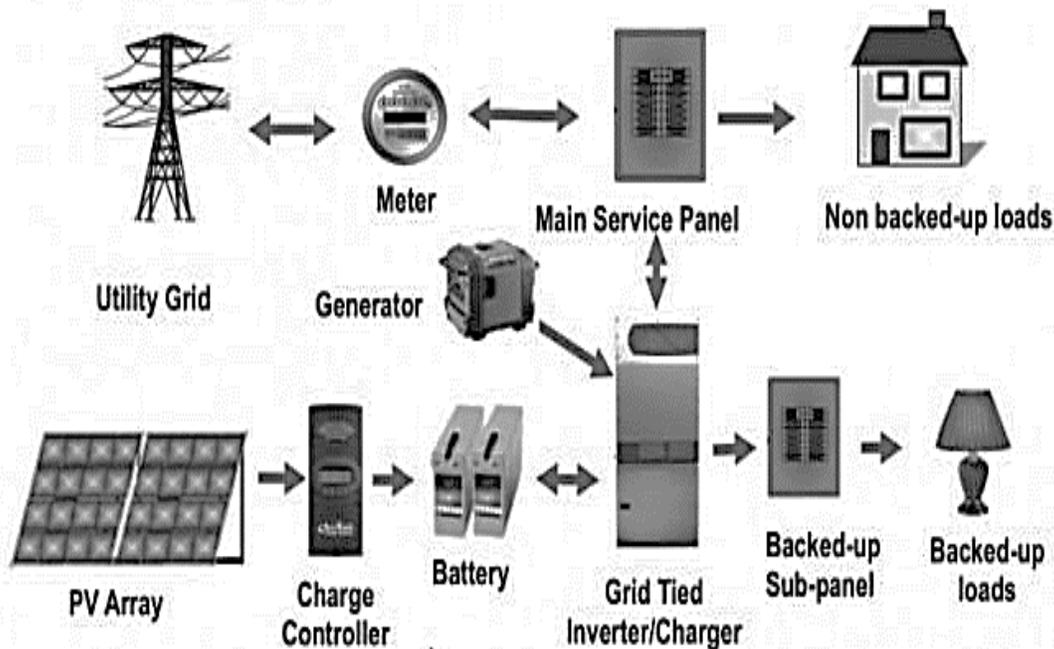e for clients at present who are connected to the electricity grid and are interested to have solar added to their residence.

The idea of introducing photovoltaic power to the electricity grid has received global recognition in the field of renewable energy generation & distribution. Researchers have noted that governments in different countries across the globe have designed different incentives to encourage their citizens to work to adopt these PV systems. The inverters of the grid-connected systems have grown considerably with extraordinary diversity, Effectiveness, size, weight, and dependability. They have all developed significantly with the advancement of innovative and recent inverter configurations, these factors have affected the cost it takes to produce inverters.

Rani & Sharma, (2017) noted that PV systems amount to about 99% of the installed capacity in the world compared to the stand-alone systems that make use of batteries. They require minimum maintenance and are more cost-effective. The power from these systems are directly fed into the grid for transmission, circulation and consumption, as such, there is no need for a storage battery (Sreedevi et al., 2017).

2.4 Specifications of Grid-Connected PV systems

Unlike Direct current systems, several requirements and specifications must be duly followed to safely combine several alternative current sources. To facilitate safe and efficient adoptions of

Grid-connected PV systems, Distribution Network Operators and PV industry experts need to design and constantly review safety and quality specifications. In recent times, several standards have emerged for the interconnectivity of PV systems and utility the International Electro-technical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE) are well adopted in many countries (Rani & Sharma, 2017).

The IEE-1547-2018 provides technical specifications for distributed energy resources and utility electric power systems to test their interconnection and inter-operability. It essentially dictates the general requirements and also specifies the response to abnormal conditions, islanding and as well as installation evaluation, commissioning and a couple of other relevant specifications.

2.5   Challenges with On-Grid Connected PV Systems

Advancements in science and technology over the years have led to a reduction in the cost of PV systems which consequently will result in increased adoption of on-Grid PV systems. While this might be good for the environment, in respect to reduction in the use of fossil-based power sources, there is a resultant increase in the PV penetration rate which can subject the grid to the following problems the grid to a myriad of problems. Sreedevi et al, (2017) in their review of grid-connected systems identified the following problems

I.   Harmonics

Current and voltage are distorted and stray from sinusoidal waveform due to the occurrence of harmonics in electrical systems. The presence of non-linear loads in the inverter circuitry will essentially introduce harmonics into the grid which can negatively impact the quality power, create resonance in the supply system and consequently lead to a decrease in a lifetime, glitch or eternal damage of electrical equipment (Tobnaghi 2016, Sreedevi et al., 2017).

II. Increased Reactive Power

Due to the kilowatt-hour yield system of billing power, PV inverter users often choose to work their systems at harmony power factor. As a result, the Grid is responsible for compensating for the overall reactive power in the system consequently leading to transformers operating at a relatively low power factor.

III. Islanding

Grid-connected systems essentially mean that power could be supply to the grid even though supply from the main station has been interrupted. This is rather unsafe as utility workers are exposed to the dangers of electric shocks and burns during the repair, maintenance and installation process. Islanding could thus increase the incidence of electricity-related accidents and to prevent these strict anti-islanding policies must be enacted for grid-connected PV systems.

2.6   Design and Modeling of Grid-Connected PV systems

In a bid to develop more efficient and easily adopted Grid-Connected PV systems, several scholarly works detailing the trends, design requirements and deployment of these systems in recent times.

Phap (2019), in his study on grid-connected PV systems, states that Grid-Connected PV systems (GCPVS) could either exist as small scale setups or as large scale setups. The researcher identified the essential components of a small GCPVS to be a PV array, a DC/DC converter and a suitable grid-tied DC/AC inverter. An MPPT is often included in most recent DC/DC converters or charge controllers and is essentially used to align the characteristics of the PV module to the maximum power to avoid this power loss. Another essential component in a GCPVS is the Power conditioner system (PCS) which conditions the AC produced from the PV system to match the voltage and phase conditions of the Utility grid.

A consumer's Solar system may produce more or less electricity at any time of the day than is required for the customers home or business. When this system produces electricity that is more than the customer demand, the surplus energy generated goes through the electric meter to the utility grid, and the meter will run backwards to credit the customer account using the Net-metering policy.

2.7   Design and Simulation of PV- Systems

2.7.1 Modeling of PV Module

The basic unit of the solar model is the solar cell and it converts light energy to electrical energy. A solar cell is the essential power conversion unit of PVS. The Solar cell like the diode and other solid-state electronic components is made from silicon. Due to the relatively low electrical output of a unit solar cell (usually around 1W), solar cells are often cascaded to form higher power modules (Ositelu, 2010).

The solar cells are semiconductors with the characteristic thin layer P-N junction. A solar cell in the dark has an I-V characteristic which is similar to the diode. When solar cells are exposed to light such that the bandgap is lesser than the photon energy, a photocurrent is generated whereby it is proportional to the solar radiation (Rodrigues et al., 2011).

Figure 2.3 below shows an ideal solar cell model. G represents solar radiance, I_s is the generated photocurrent, I_d represents diode current, I represents output current and v represents terminal voltage.
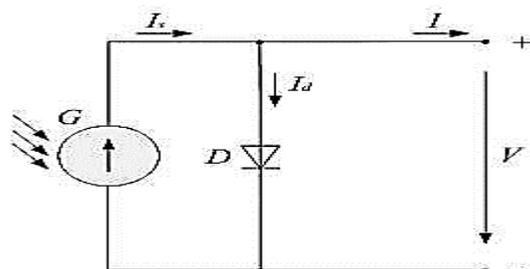

Figure 2.3   Ideal Solar Cell Models

The governing equation that is used for an ideal solar cell is given below

$$I = I_s - I_0 \left[e^{\frac{qV}{mkT}} - 1 \right] \tag{1}$$

Where I_0 represent the reverse bias saturation current of the diode, m represents ideality factor, k represents the constant of Boltzmann and q represents electron charge. T denotes the temperature of the cell.

2.7.2   Grid –Tied Inverter

Conventional utility grids are often AC based systems, whereas PV systems essentially generate DC electricity. Hence, the conversion between AC and DC power is necessary to safely synergize and tie both systems. While power rectifiers are designed to convert AC to DC power. To convert DC to AC Power of required voltage and frequency, a power inverter is been used. A basic inverter system consists of an appropriate transformer as well as switching, and control circuits. The AC waveform is produced by an arrangement of four semiconductor-based switches (two legs). Different types of semiconductor devices such as IGBT, MOSFET or BJT can be used and feedback diodes are often connected in parallel to the switches for inductive loads when the main switch is turned off. Grid-tied inverters are often known as synchronous inverters (Abdar et al., 2012).
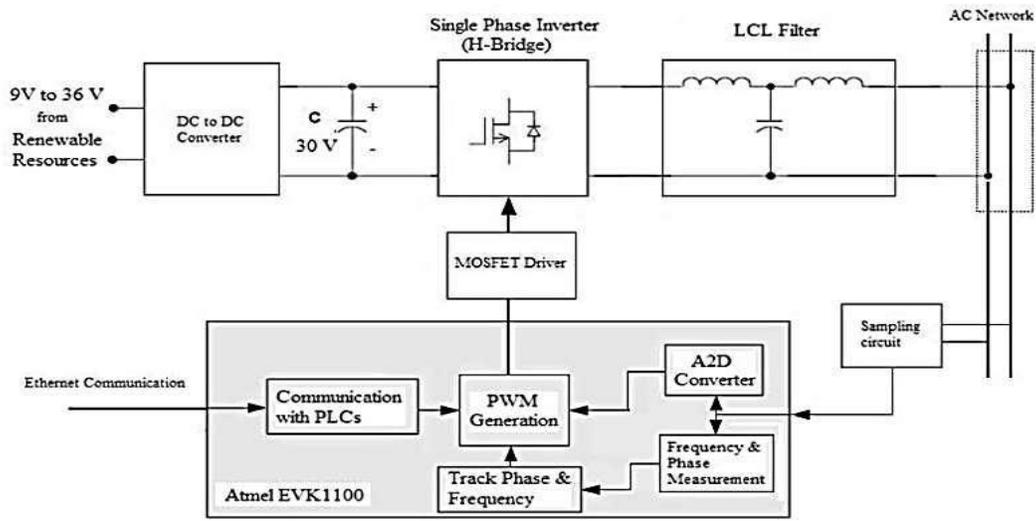
Figure 2.4   block diagram of a synchronous inverter

Several different topologies exist for grid-tied inverters. The self-commutated and line
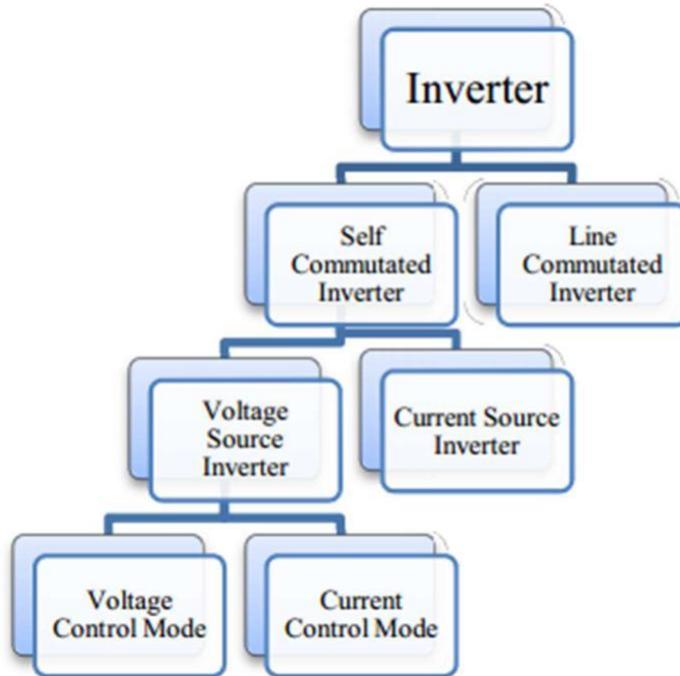
commut

Figure 2.5   Grid Tied Inverter Topologies

The term "Commutation" means the transfer of electric currents from one path to another. The line-commutated topology is designed to allow the power grid to dictate the process. Switching devices such as commutating thyristors are used in this design.

A self-commutated inverter is designed such that the inverter dictates the commutation process. This is the case for circuits including electronic power switches with turn-off capability. Self-commutated inverters are broadly classified into the current-source inverters and voltage-source inverters. The voltage source inverters (VSI) is served from a voltage source and the current source inverter (CSI) is served from a current source. The voltage source inverter inputs is a battery. However, the source voltage from DC can be adjusted to regulate the output voltage of the inverter. The Voltage source inverter dc input voltage stays comparatively constant despite big transient or stable disparities in the input current. When it comes to current source inverters, the input current is relatively constant over an extensive range of dc input voltage variations (Hoft & Hoft, 1986).

2.8   Net- Metering

The billing mechanism that is used in crediting the owners of the solar energy system for their surplus electricity added to the grid is what we call net metering. It allows customers to counterbalance their electricity use with self-produced electricity from PV systems. The design of Net metering units allows them to spin bidirectional. The meter twirls forward when a customer is making use of power from the utility grid and vice versa. The figure below shows the block model of a functional net metering system.
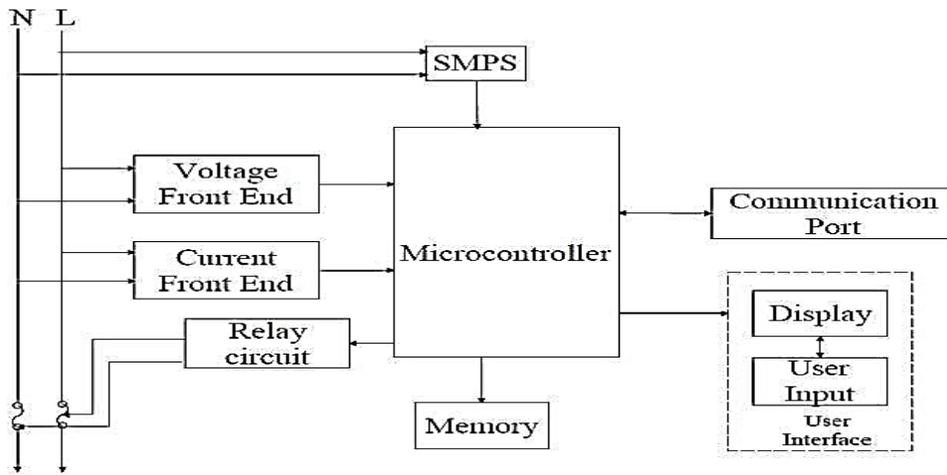
Figure 2.6   Net Metering block diagram

2.9   Modeling of MPPT Algorithm

The Maximum Power Point Tracker enables the module to be used at the topmost power level so that the maximum power can be supplied under changing temperature and irradiance situations.

This is often attained by altering the duty cycle between the load impedance and duty cycle by the source to the level of topmost power with the source. Several MPPT algorithms have been developed over the years to enhance the efficiency of Photovoltaic systems. Raut & Bhattrai, (2013) in their research "Performance Analysis of Grid Connected Solar PV System Using Matlab/Simulink" employed   the Perturb and Observe (P&O) algorithm in bid to obtain the maximum power under varying irradiation. The "perturb and observe" method essentially involve providing some level of perturbation

2.10   Research Gap in Grid-Connected PV System

Several researchers have designed different variants of grid-connected PV systems in recent times. Atiq & Soori, (2017) designed and simulated a Grid-tied PV system comprising of an MPPT controller, a boost converter, and LC filter amongst other functional parts. The design was simulated with the Simulink Environment of the Matlab IDE and was tested with a 2.75kW three-phase load as shown in the block diagram in Figure 2.7
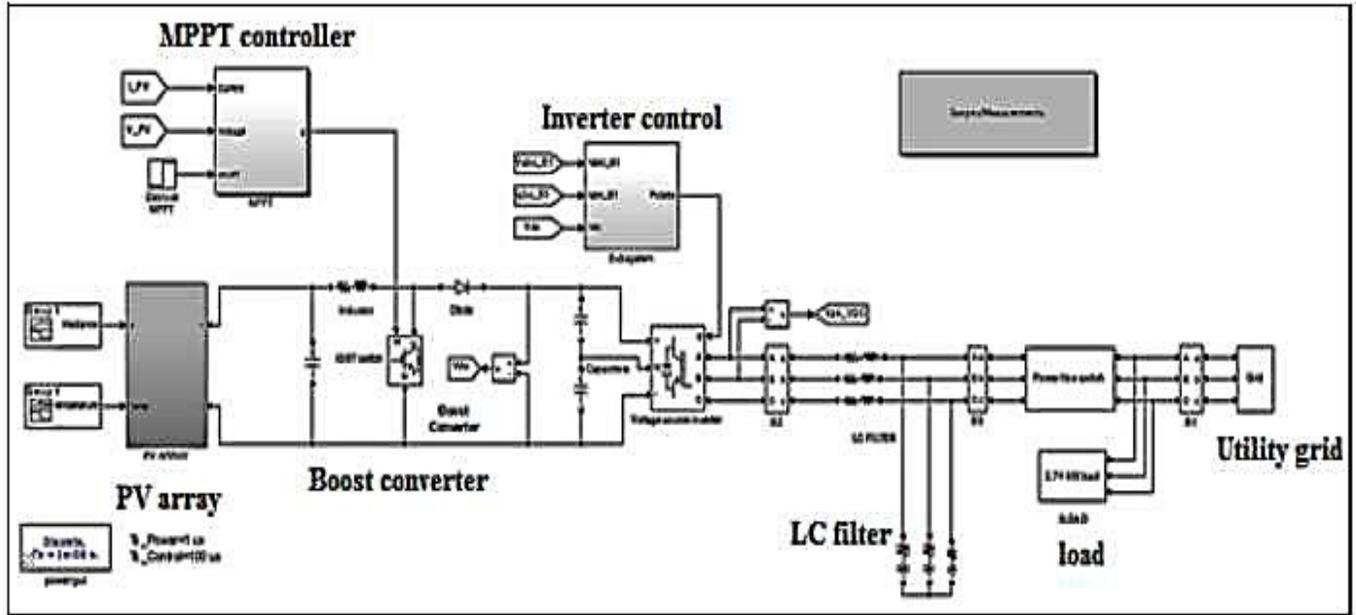
Figure 2.7   Grid-Tied PV System, Atiq & Soori, (2017)

Dolas et al., (2020) designed and analyzed a Grid-tied PV system to study the behaviour and performance of this aforementioned PV system. The Researcher duly noted the presence of harmonics in the three-phase voltage and current waveform relative to the supplied form the mains which were 120 degrees apart and having the same magnitude.

Although several functional Grid Tied PV systems are existing in recent times, the proposed design in this research work will include in its architecture a functional bi-directional meter. The design will be developed and simulated with the Simulink interface of Matlab Suite.

CHAPTER THREE

METHODOLOGY

3.0   Introduction

This chapter gives an outline of the research methods that were followed in the study. It provides a broad overview of the grid-connected photovoltaic system, the design parameters as well as the Perturb and observe the maximum power point tracking algorithm.

3.1   System Description

The designed model essentially consists of a PV array and a connection to a single-phase inverter. Maximum Power Point Tracking (MPPT) is implemented in the boost converter via Simulink using the 'Perturb & Observe' technique. The block overview of the model is given in Figure 3.0 below
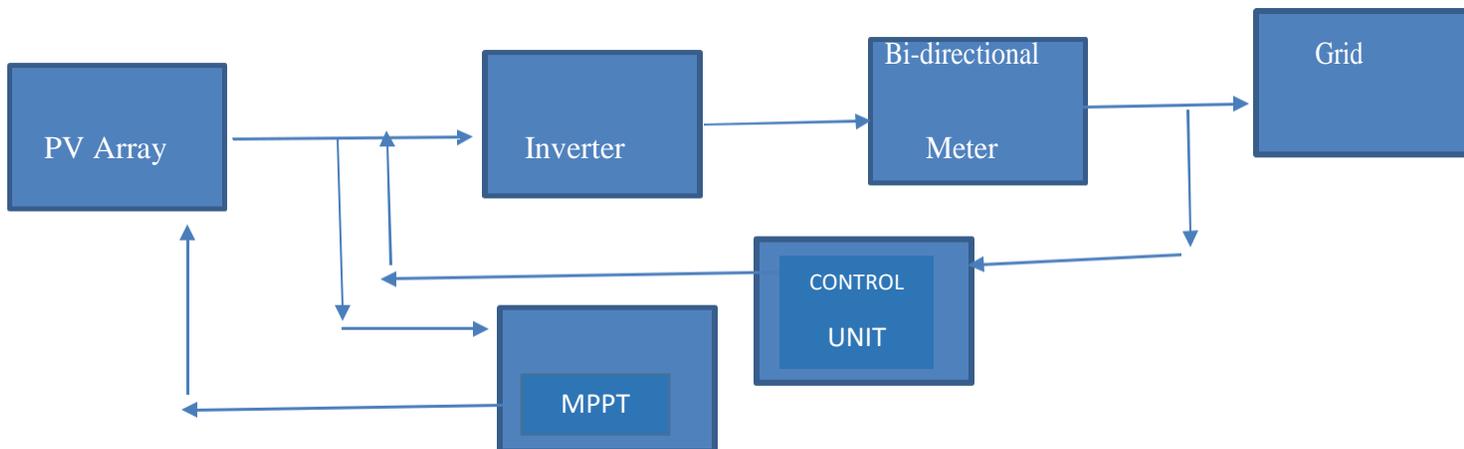

Figure 3.0   Block Diagram of designed system

3.1.1   Open Circuit Voltage (VOC)

Open circuit voltage refers to peak voltage available when no current is been drawn from the cells.

3.1.2   Switching Frequency

In a pulse width modulation process, the switching frequency refers to the frequency at which the DC voltage is switch between both logic levels. Frequency in switching a converter or an inverter is the rate at which the switching device is turned on and off. Usual frequencies vary from some kilohertz (kHz) to some megahertz (MHz) (20 kHz-2MHz).

Generally, an increased switching frequency allows for a reduction in other components such as inductors, resistors etc. and consequently allows for a more compact housing.

Basic parameters for the models are shown below

1	Open Circuit Voltage	493.5V
2	Switching Frequency of Inverter	10kHz
3	Grid Voltage	230V
4	Grid frequency	50Hz

3.2   Modelling of the PV System

The designed system essentially consists of the following parts

1. The PV array

2. Maximum power point tracking

3. The phase lock loop PLL

4. A single-phase inverter

3.2.1 PV Array

Solar PV system basically captures sunlight and converts it to electricity. The output of the solar cell is dependent on two major factors, the ambient temperature and irradiation. The change in the output power of a Photovoltaic system due to a change in the cloud is often a major technical drawback. Fluctuation in voltage and the light flickering is amongst the most common challenges faced due to cloud transients. The irradiation and the temperature in this research are duly modelled via the constant block of the Simulink interface.
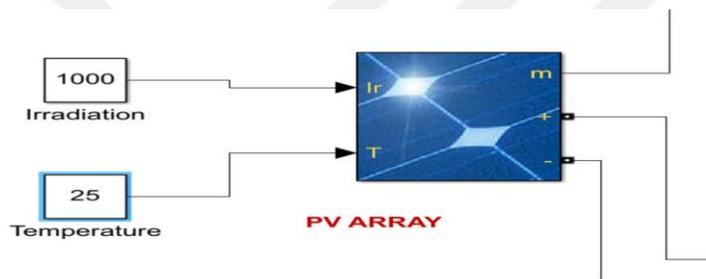

Figure 3.1   Irradiation and Temperature Block

A change in any of the aforementioned factor either positively increases or decreases the output of the solar cell. The PV array consists of 1parallel string. Each string has 11 Zytech ZT190S Engineering Technology modules connected in series.
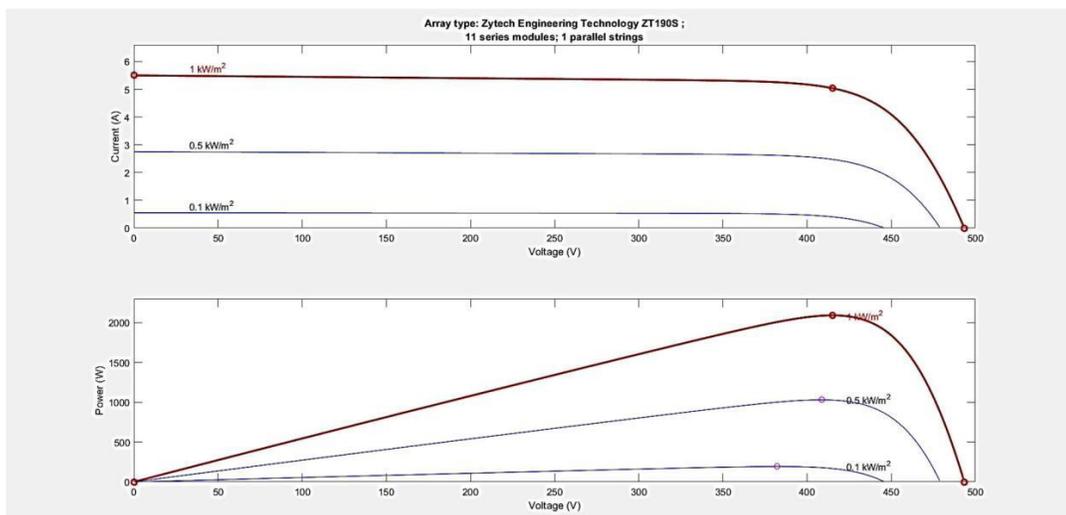

Figure 3.2   Irradiation and Temperature simulation

3.2.2   LCL Filter

When power conversion devices are switched, the main factor-causing problems to sensitive equipment or the connected loads, especially for applications above several kilowatts, where the price of filters and total harmonics distortion (THD) is also an important consideration in the systems design phase. The inductance of the input or output circuits of the power conversion
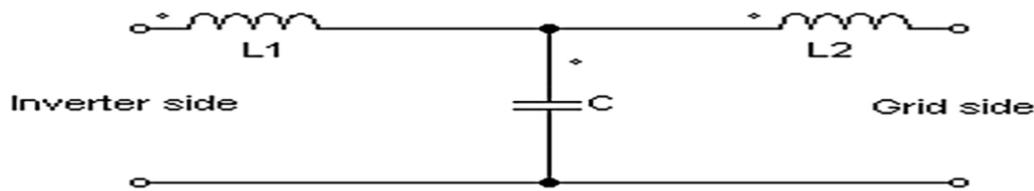

Figure 3.3   LCL Filter

devices have conventionally been used to reduce these harmonics. However, as the capacity of the systems has been increasing, high values of inductances are needed, so that realizing practical filters has been becoming even more difficult due to the price rises and the poor dynamic responses. An L filter or LCL filter is usually placed between the inverter and the grid to attenuate the switching frequency harmonics produced by the grid-connected inverter (Kahlane et al., 2014).

3.2.3   Inverter Capacitor Specification

The capacitor used is essentially designed based on the reactive power immersed at the rated conditions. The reactive power represented as "Q" is often limited to 5% of rated power.

$$Q = \frac{V^2}{(0.5 * 2\pi f C)}$$

$$Q = \frac{V^2}{(0.5 * 2\pi fC)} = 5\% \ of \ S$$

$$C = \frac{0.05 \times 2000}{(230^2 \times 2 \times \pi \times 50)} = 6.01uF$$

3.2.4 Inverter Inductor Specification

Inverter side inductor L1 is selected based on the maximum permissible current ripple.

The current ripple is limited to 20% of the rated current

$$L_1 = \frac{V_{DC}}{4 \times F_{sw} \times \Delta I_{pp\max}}$$

$$L_1 = \frac{V_{DC}}{4 \times 10000 \times 8.69 \times 1.414 \times 0.2} = 4.06mH$$

The total inductance in the LCL is selected based on the maximum voltage drop across

the inductor which is limited to 10% of the rated voltage. Thus

$$V_{L_1+L_2} = I \times X_{L_1+L_2} = I \times 2\pi f (L_1 + L_2)$$

$$I \times 2\pi f (L_1 + L_2) = 10\% \ of \ V$$

$$L_1 + L_2 = \frac{10\% \ of \ V}{S/V) \times 2\pi f}$$

$$L_1 + L_2 = \frac{0.1 \times 230^2}{2000 \times 2 \times \pi \times 50} = 8.41mH$$

$$L_2 = 8.41mH - 4.06mH = 4.35mH$$

3.3   Modeling the Maximum Power Point Tracking

The I-V characteristics of the photovoltaic module are dependent on the load as such the power obtained from the module differs at a different operating point. The maximum power point tracking ensures that the maximum power is obtained from the load at every condition. MPPT works by controlling the duty cycle or the operating voltage of a photovoltaic system to ensure maximum power at all times. Although a myriad of MPPT algorithms have been developed over the years, the most common algorithms are given below:

I.   **Perturb and Observe (P&O):** The most commonly used algorithm is the "perturb and observe" algorithm. The algorithm involves perturbation of the duty cycle or operating voltage based on a comparison of the generated power. This algorithm ensures maximum power point.
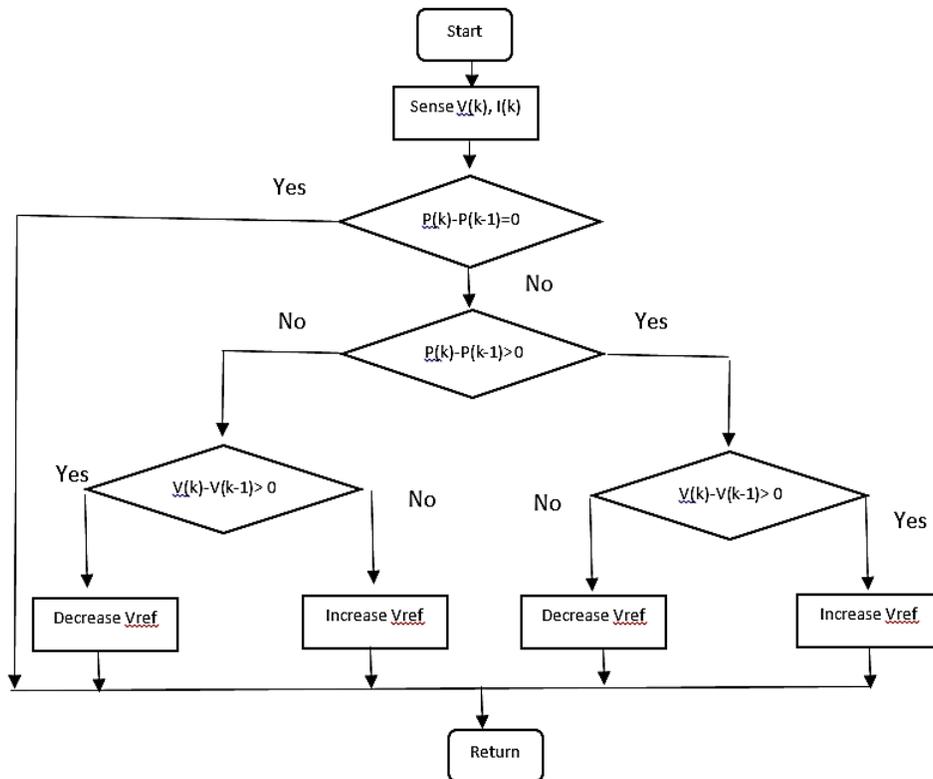

Figure 3.4   The Perturb and Observe Algorithm

II.   **Incremental Conductance**

This algorithm is slightly more complex and robust. The central idea is that the incremental conductance is compared to the instantaneous conductance, and the duty cycle is adjusted accordingly.
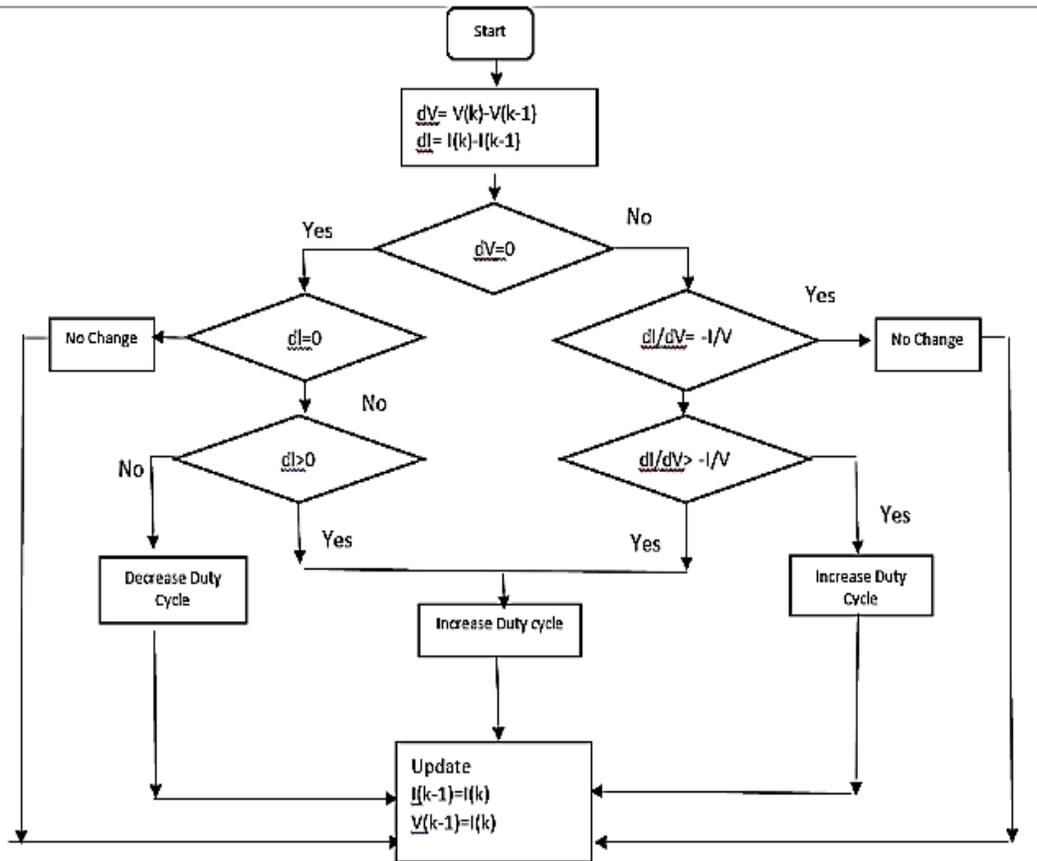

Figure 3.5   Incremental Conductance Algorithm

This algorithm is different from the first two and is based on the principle that the maximum power point voltage is always a constant fraction of the open-circuit voltage.

3.4   Inverter

Inverters do convert DC to AC, which can either be single-phase or multi-phase. Several topologies exist for both the single-phase and multi-phase inverters. An inverter is made up of switches that are turned in such a way that the upper and lower switches are never on at the same time to avoid short-circuiting the DC source (Khatib & Elmenreich, 2016).
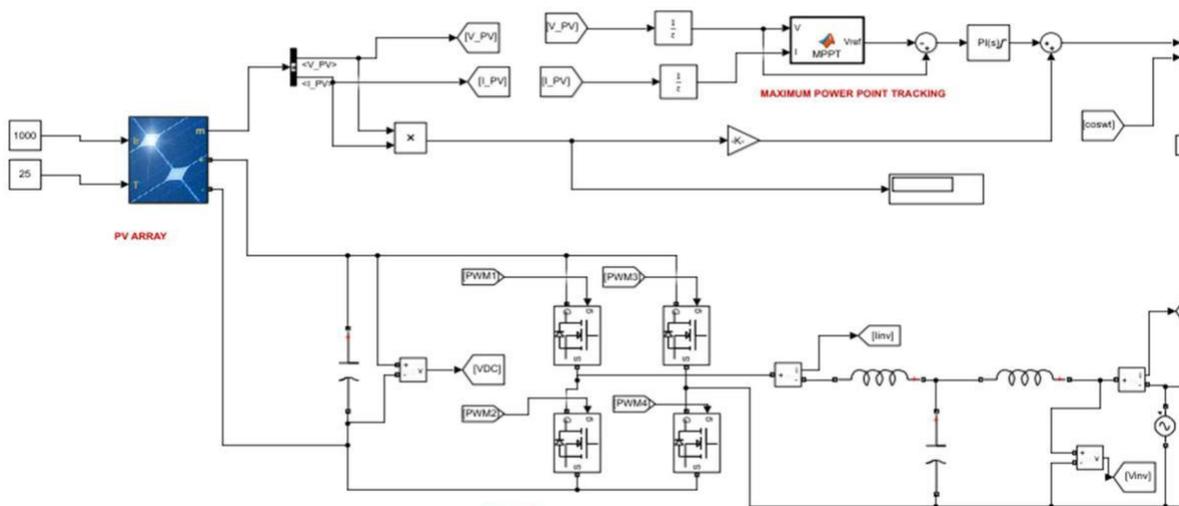

Figure 3.6   Inverter Schematic

3.5   Phase Locked Loop (PLL)

A mismatch in the frequency of the grid and inverter could result in diverse conditions which could lead to the damage of electronic devices. Since the frequency of the grid often changes with variation in loading, it is of great importance that a suitable phase lock loop is integrated into the system.
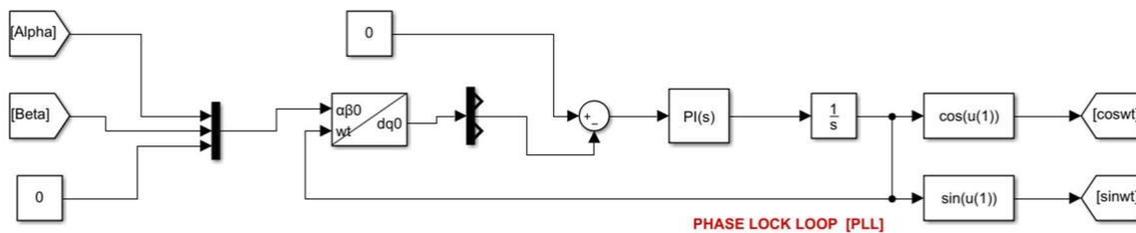

Figure 3.7   Phase-Locked Loop

The Phase lock Loop essentially adjusts a voltage or current-driven oscillator to produce an output signal with a synchronized phase as the input signal.

3.6   Bi-directional Metering

The bidirectional meter essentially consists of a bi-directional counter which increments its value if the load requirement is more than the inverter output (sourcing from the grid) and decrements when the load requirement is less than the available inverter output. The bi-directional counter thus gives a net reading over some time. The bi-directional counter model consists of the input block, a bi-directional counter subsystem as seen in figure 3.8
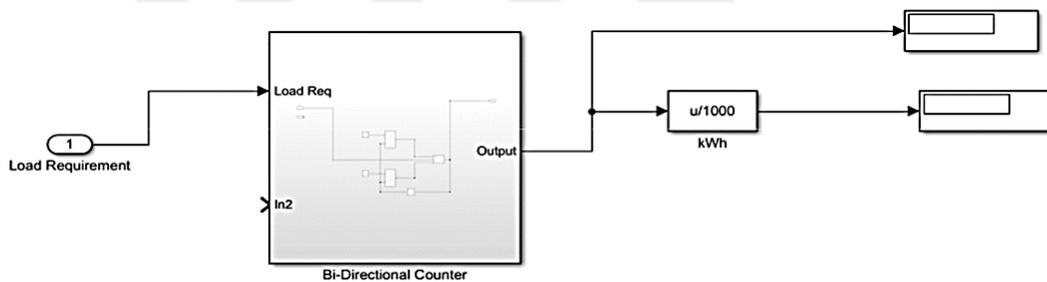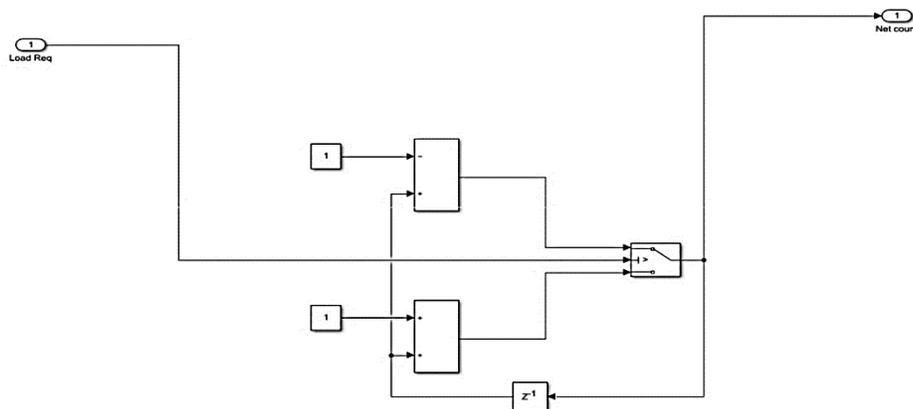

Figure 3.8   Bi-directional Metering

The counter subsystem is made of a series of summation, delay and the switch-block to effectively achieve a negative or positive counter as dictated by the program logic.

3.7 OVERVIEW OF EV VEHICLE CHARGING SYSTEM

The electric vehicle charging system was modelled using the Simulink platform. The model bi-directional charging module is consist of the following

    i.   The storage battery

   ii.   The Buck Converter Unit

  iii.   The DC/AC converter module

  iv.   The control circuitry

3.7.1 Storage Battery

Electric vehicle capacities are often measured in kilowatt hour (kWh). Due to their specific energy requirements, most electric vehicles are made from Lithium –ion due to their relatively high energy per unit mass. The high power-to-weight ratio, efficiency and temperature performance also marks them   quite suitable for EV application. The specifications for the selected battery is given below

Battery Type	Lithium Ion
Capacity	200Ah
Initial SOC	80%
Nominal Voltage	250V

The integrated bi-directional electric vehicle charging system consist of the following essential components
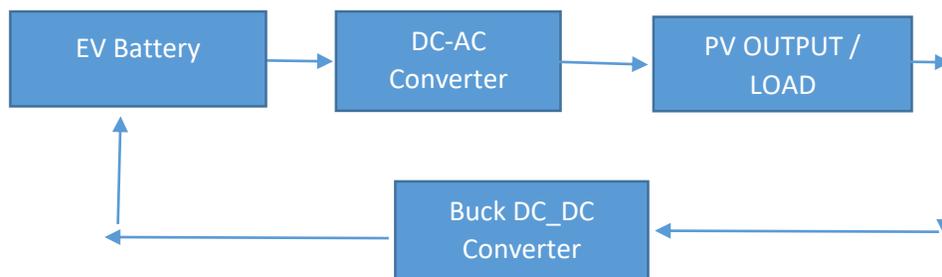

Figure 3.9   Block diagram of EV Supply and charging system
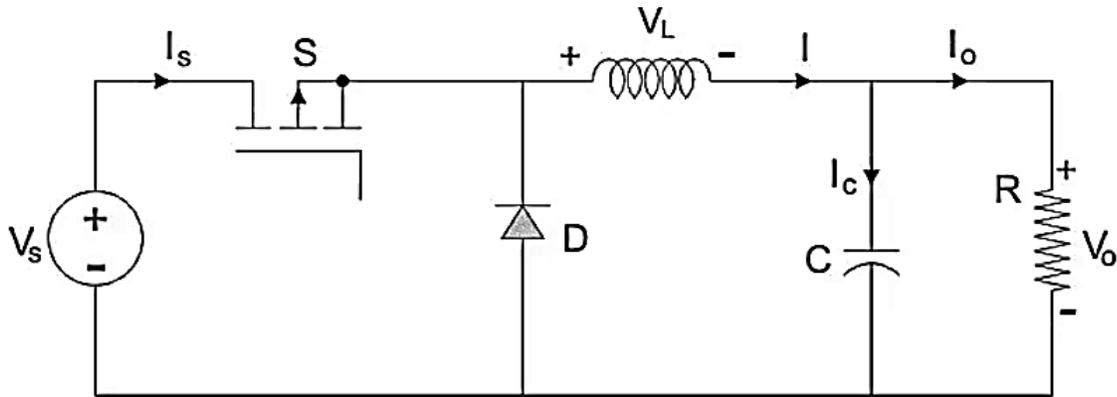
DC-DC Buck Converter

Figure 3.10   Basic Buck Converter

Buck converters often referred to as choppers essentially produces a lower voltage than the input voltage. The device is controlled by Pulse Width Modulation (PWM) applied to the gate of the solid state device and essentially reduces the voltage from the PV to a relatively smaller voltage thus increasing charging current and reducing charging voltage fluctuations resulting from fluctuations in irradiation level of the PV array. The developed buck converter system is shown in Figure 3.11   below.
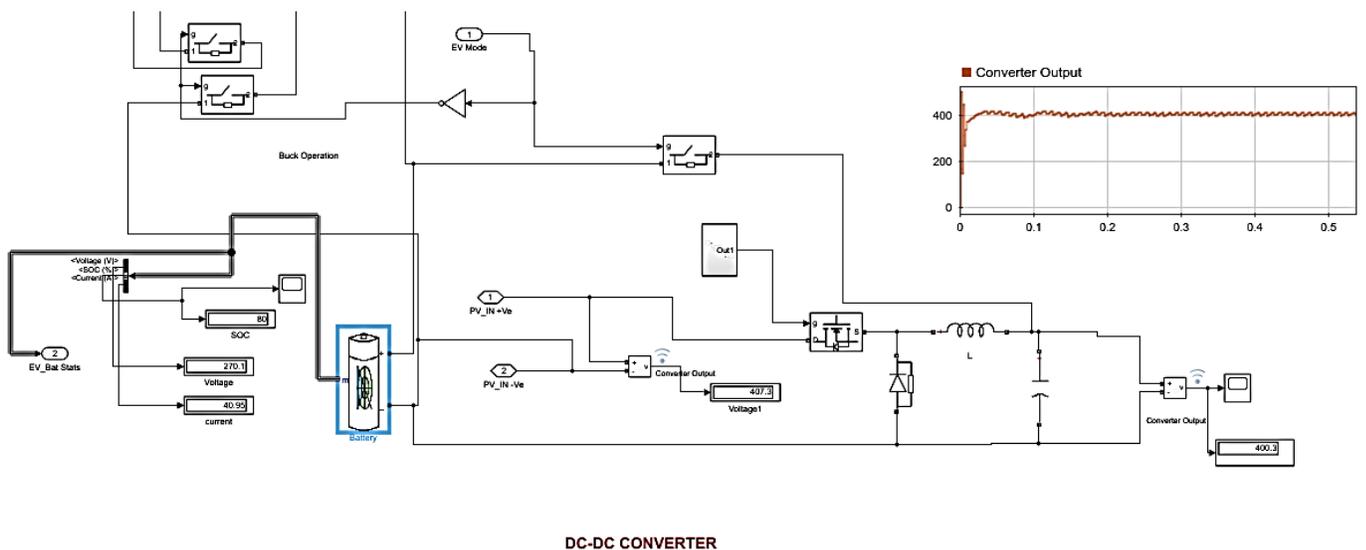

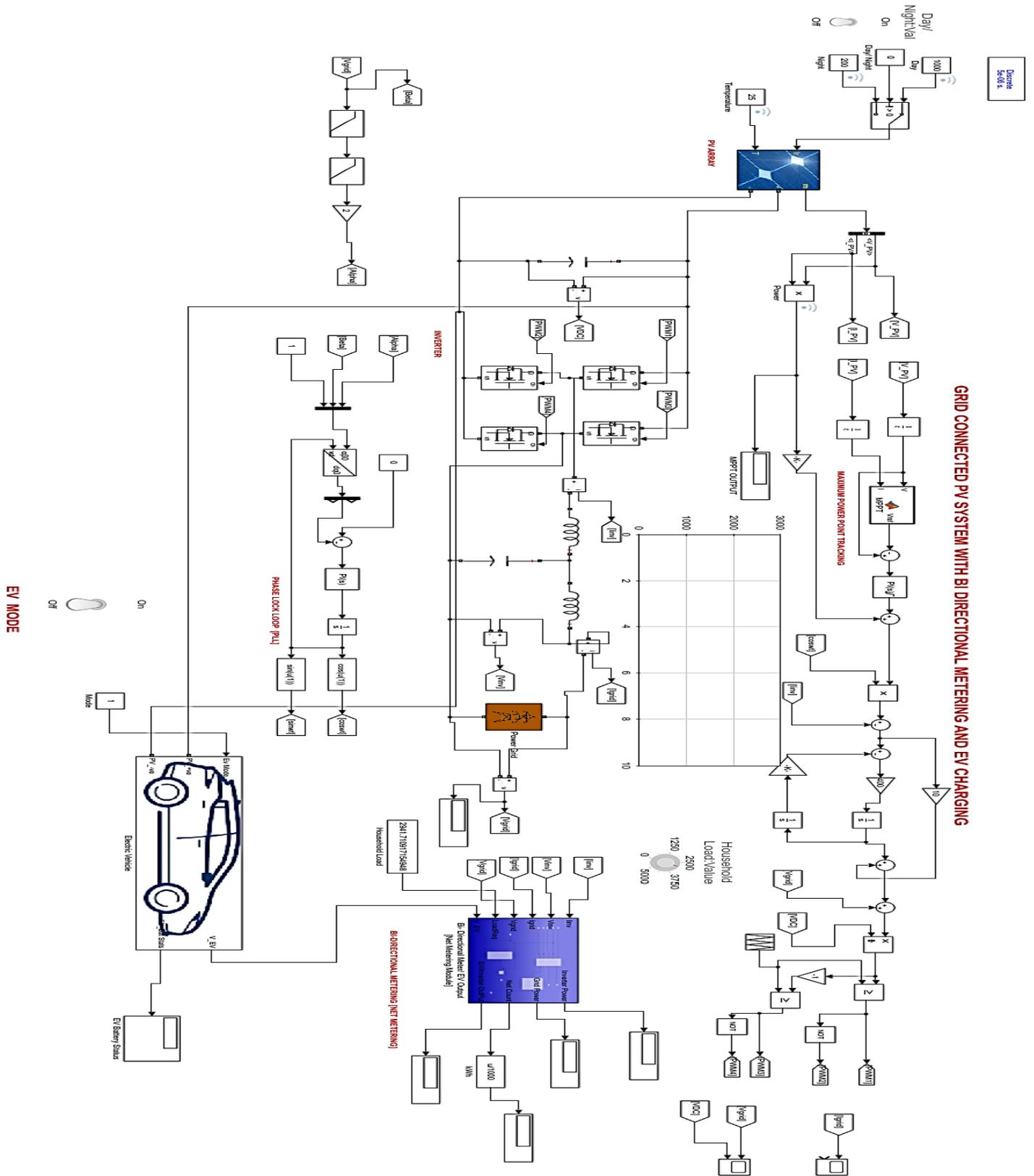Figure 3.11   Developed Buck Converter

Figure 3.12   Simulink Model of Grid Connected PV System with Bi-directional EV Supply and Net Metering

CHAPTER FOUR

RESULT AND PERFORMANCE EVALUATION

4.0 Introduction

This chapter covers the performance evaluation of the result obtained from simulating the proposed system via the Simulink interface of the Matlab Suite. An analysis of the performance of vital parameters such as power at maximum power point on the IV curve, bi-directional usage measurement was duly carried.

4.1 Model Description

A single-phase grid-connected photovoltaic system was thus designed and simulated using the Simulink module of the Matlab Suite. The PV system essentially consists of a PV array, a DC-AC inverter, MPPT unit, the PLL unit, a bi-directional metering unit and Electric Vehicle charging Unit. The system was tested at 1000W/m2 and 800W/m2 irradiation levels to evaluate the performance and output of the overall system.

4.2 Performance Evaluation of the MPPT

A functional maximum power point tracking essentially extracts the maximum obtainable power from PV modules by making them operate at the most efficient voltage (Maximum Power Point). The developed system uses the "Perturb and Observe" algorithm and its performance was evaluated by comparing the expected output at the target irradiance level and temperature with the obtained values during simulation.

4.2.1 Evaluation at 1000 W/m^2 irradiance and 25°C

The characteristic I-V plot for 1000 W/m^2 and a temperature of 25°C for the selected PV configuration is given in Figure 4.1
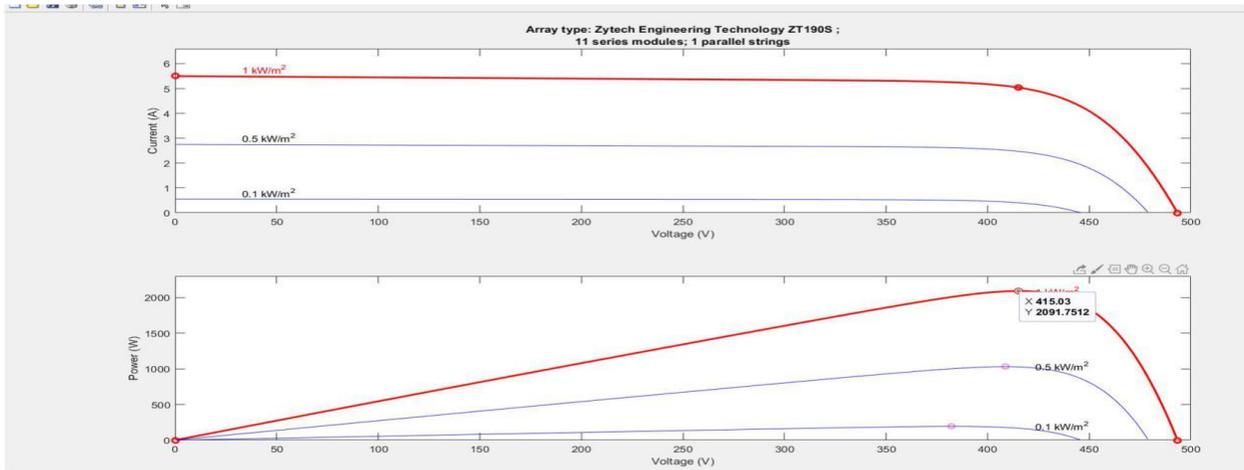
Figure 4.1   Standard MPPT point at 1000W/m and 25°c

The I-V Plot of the selected PV array shows a value of 2091.7512W as the peak point obtainable at 1000W/m^2 irradiation and 25°C temperature.
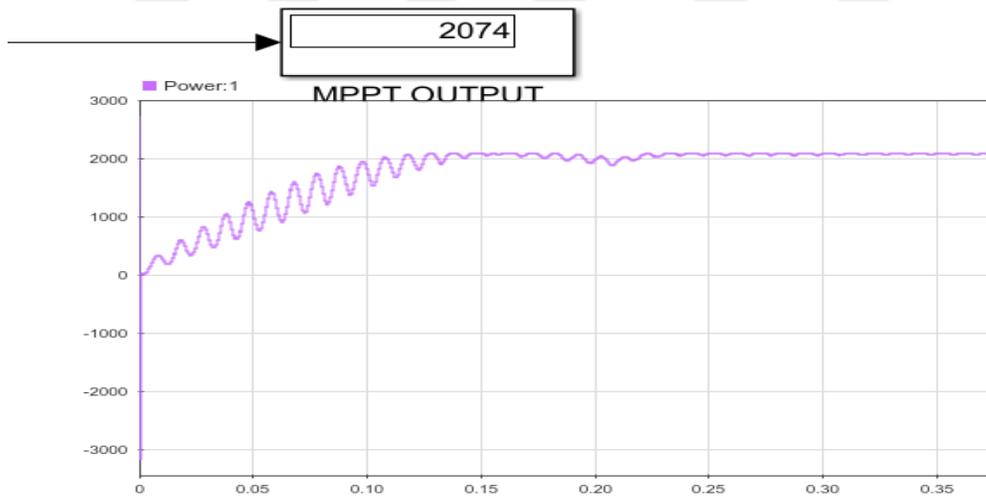

Figure 4.2   Simulation MPPT point at 1000W/m and 25°c

Figure 4.2 clearly shows a steady rise in the value of the power till the peak point was obtained at an average reading of 2090W as compared to 2091.7512W thus indicating a fully functional MPPT system.

4.2.2 Evaluation at 800 W/m² irradiance and 25°C

The performance evaluation of the MPPT unit was repeated at an irradiance value of 800W/m²
and a plot of the standard performance was compared to the performance generated by the
simulation model as seen in Figures 4.3 and 4.4 which clearly shows a relatively effective MPPT
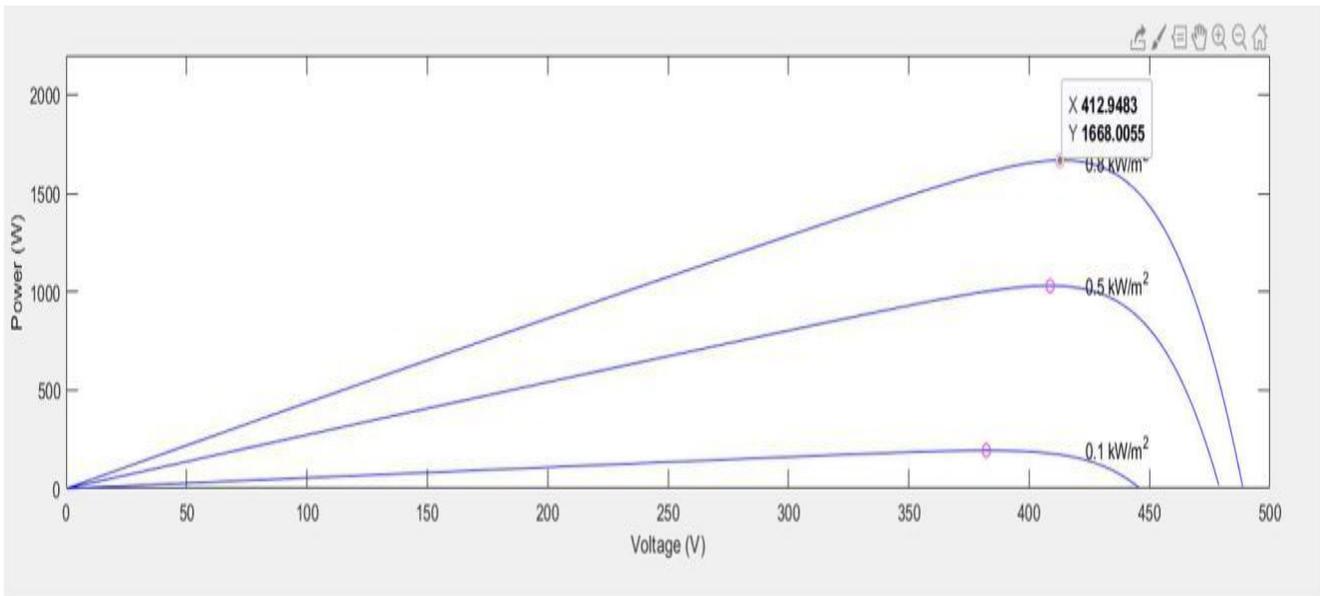algorithm.

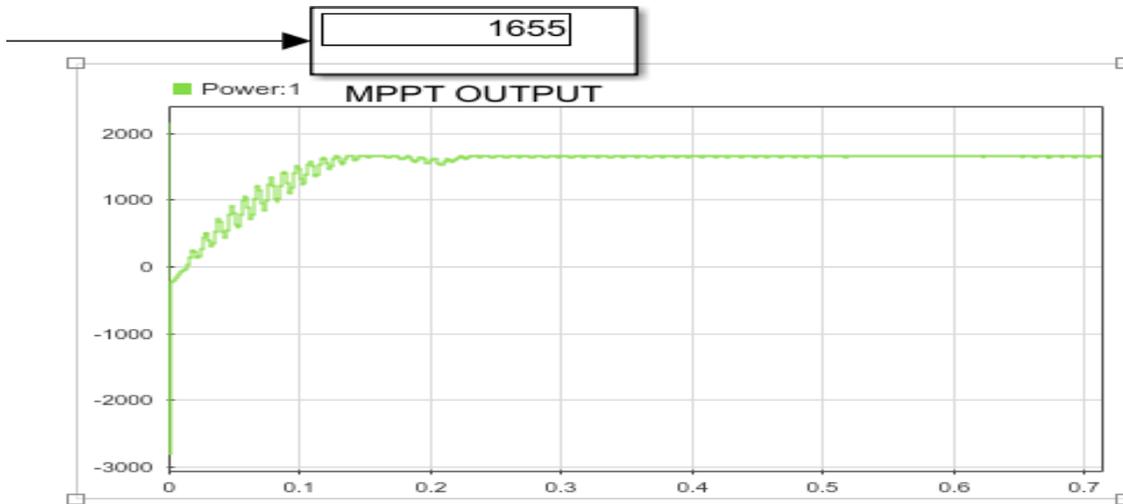Figure 4.3   Standard MPPT point at 800W/m² and 25°C

Figure 4.4 Simulation. MPPT point at 800W/m^2 and 25°C

4.3   Current and Voltage Output

The current profile of both the grid and the PV system is seen in the figure below.

Figure 4.5   Inverter current and Grid current profile

4.4   Metering Unit

The metering unit essentially implements a net-metering arrangement such that a PV system user can either send electricity to the grid or source from the grid as the need arises. This simulation result shows that the meter was able to generate a net reading by counting in both directions depending on the ratio of the load requirement and the grid supply.
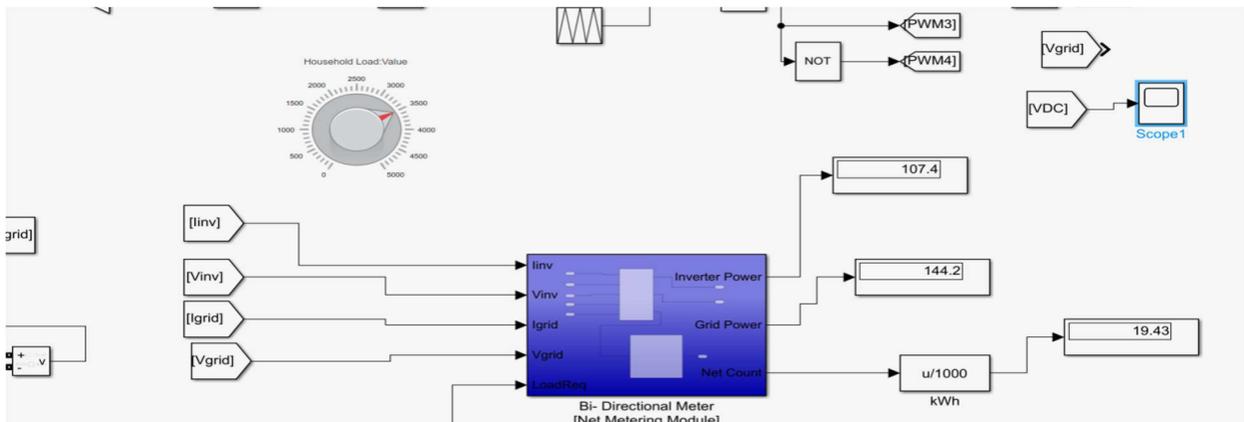

Figure 4.6   Bi-directional Net Meter

4.5   Varying Irradiance

The response of the inverter was thus testing for varying conditions of irradiance via a repeating sequence block as seen in Figure below
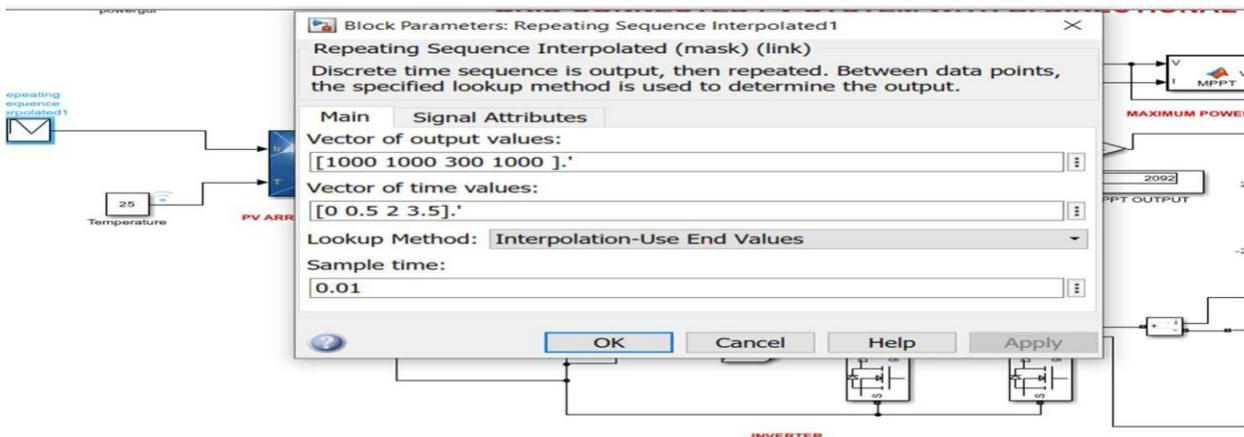

Figure 4.7   Repeating sequence for different levels of irradiance (W/m^2)

A variation in the level of irradiance consequently affects the peak voltage generated as clearly seen in the MPPT output over the given period.

The inverter response to the varying level of irradiance from 1000W/m^2 to 300W/m^2 is also seen in the figure in the current profile.
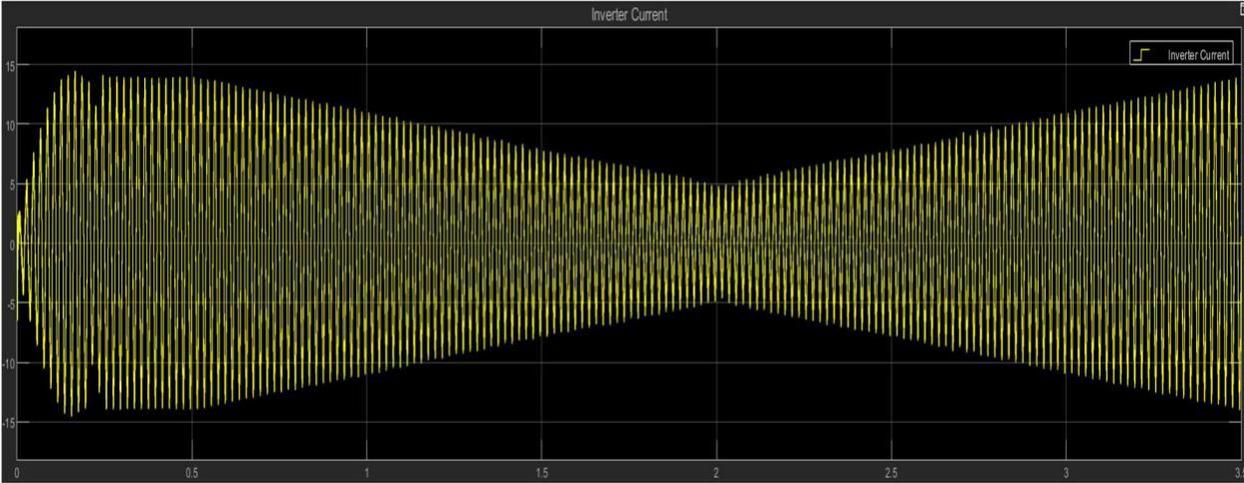

Figure 4.8   Inverter Current Profile for different levels of Irradiance

4.6   Charging and discharging of Electric vehicle battery

The system is designed to supply power to the electric vehicle in the night as simulated by low irradiation. The EV-PV system V2H functionality can be toggled on or off by the dashboard toggle switch on the Simulink model.

The performance of the integrated Electric Vehicle Charging functionality was tested both charging and discharging mode as seen in figure 4.9.1 and figure 4.92 respectively

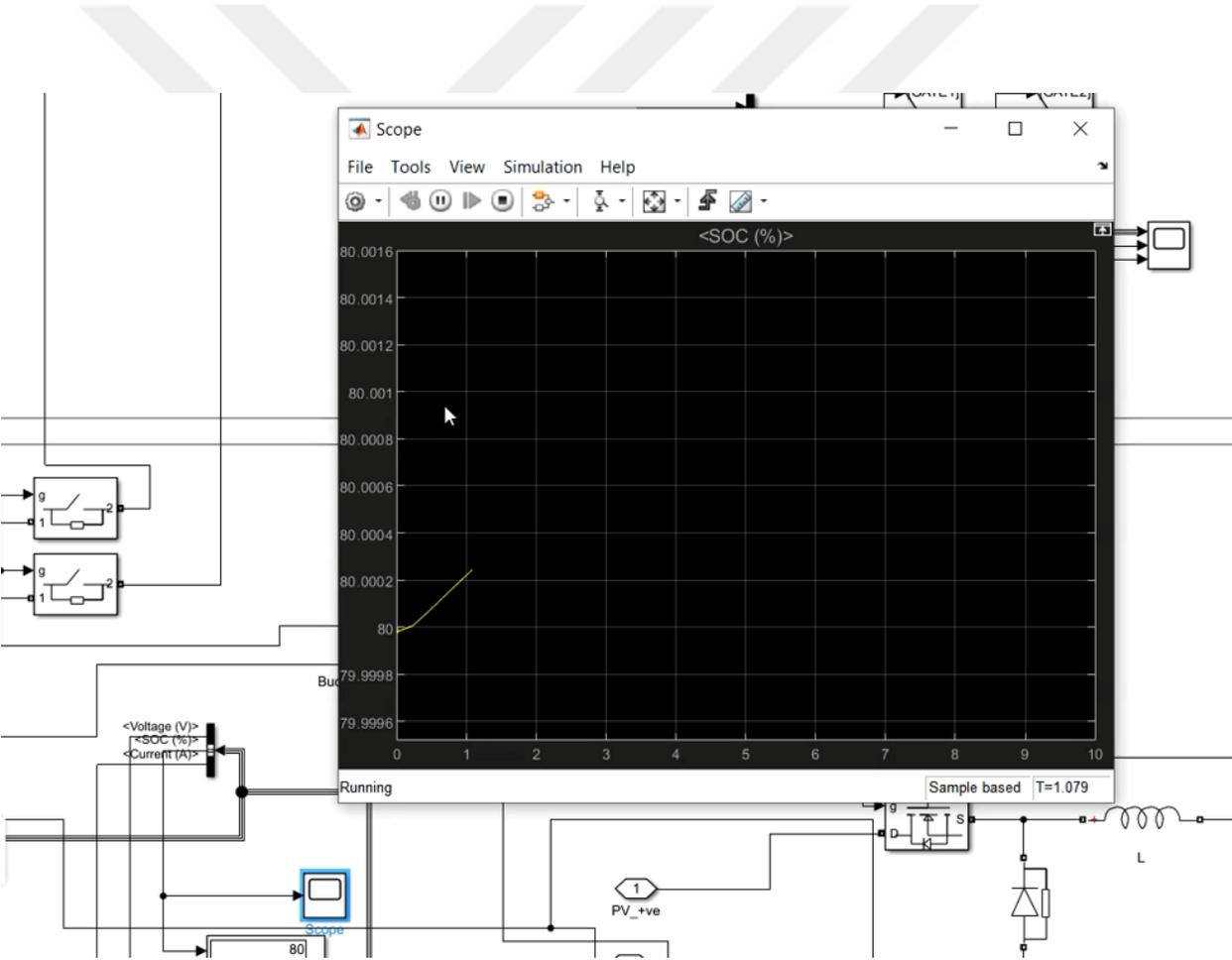Figure 4.9 Charging of Electric Vehicle Battery at 80% SOC

Figure 4.10 Discharging of Electric Vehicle Battery at 80% SOC

4.7 PV OUTPUT VOLTAGE AND CURRENT

The output of the PV array showed an unfiltered DC output with a voltage of 420V DC and a current of 13A.
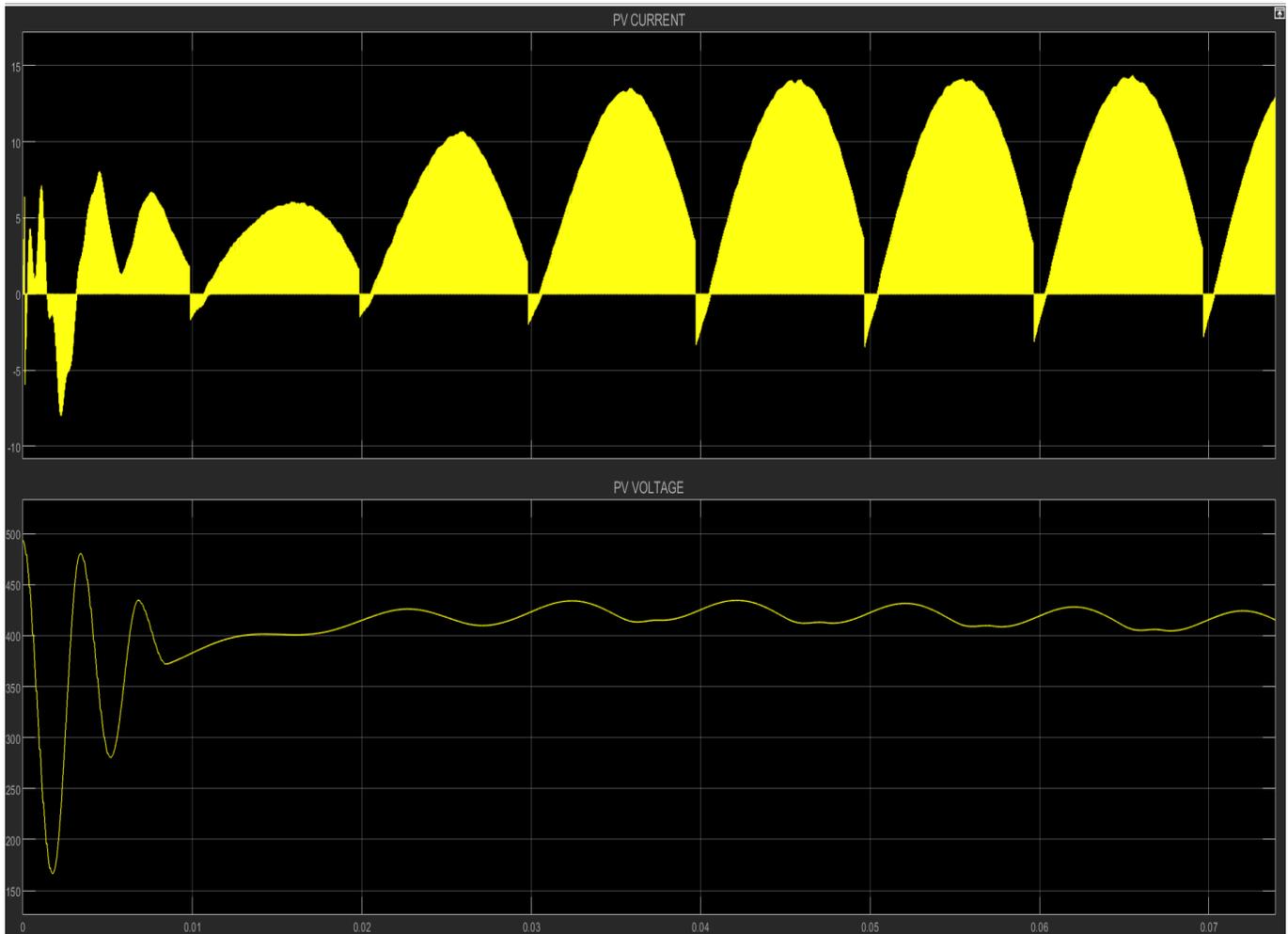

Figure 4.11 Unfiltered DC output from PV array

The design was further tested at the two modes Day and Night; having irradiation of $1000w/m^2$ and $200w/m^2$ respectively and the MPPT point were captured from the scope as shown in Figure 4.12
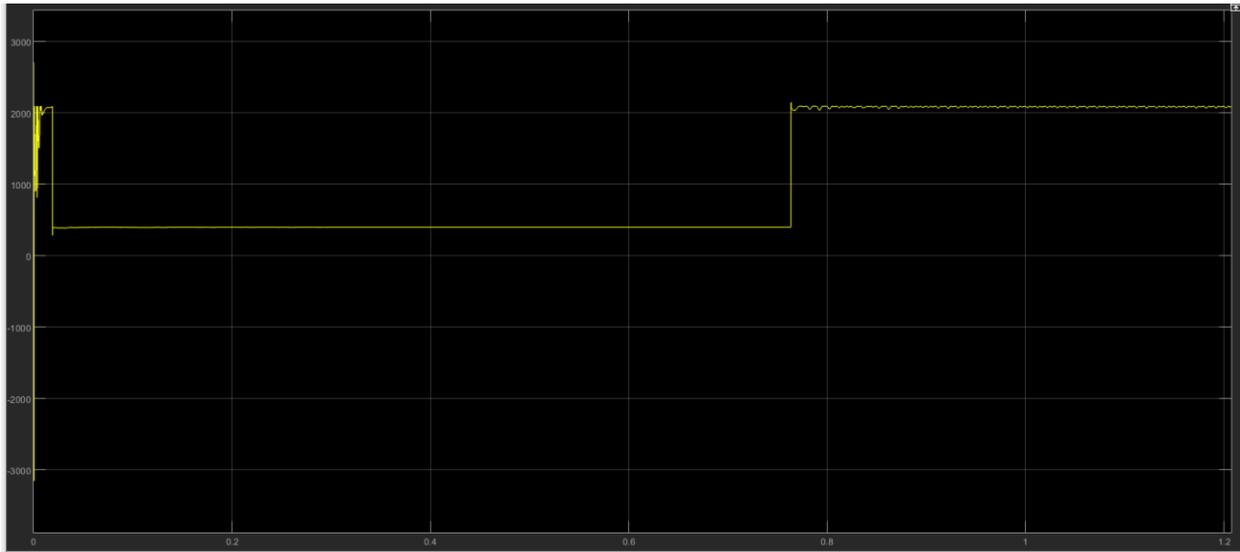
Figure 4.12 MPPT Plot Night and Day Mode

4.8   Inverter Voltage and Current

The output voltage and current of the inverter 320V and 13A respectively as shown in Figure 4.13
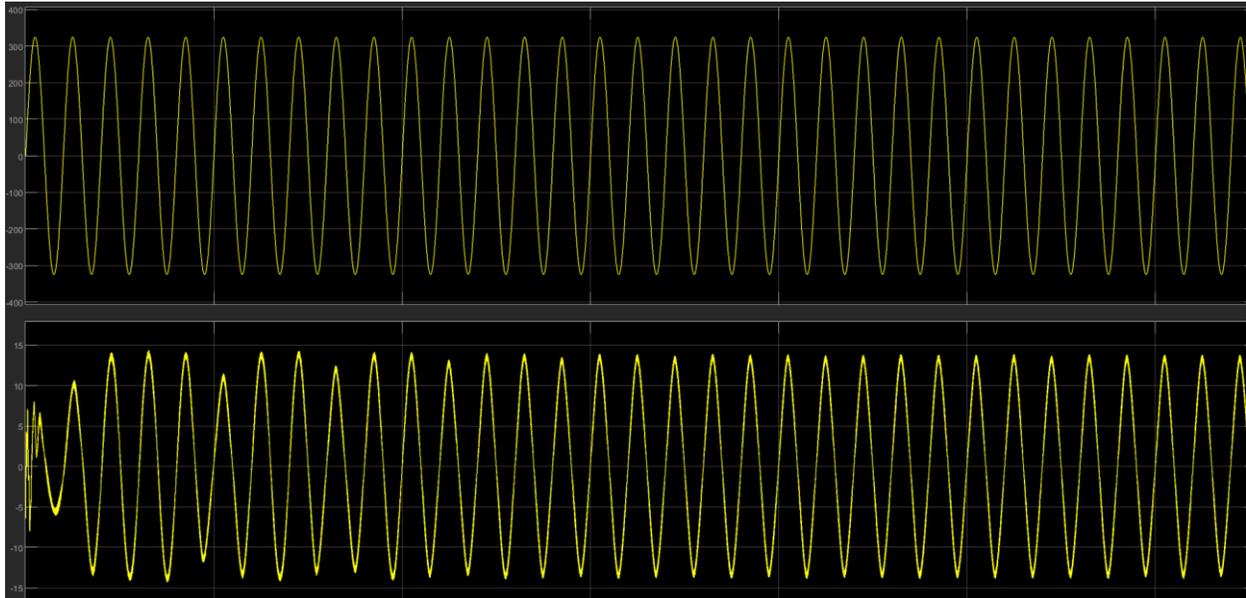

Figure 4.13 Output voltage and current of the inverter 320V and 13A

4.9   Electric Vehicle current and Voltage overview at Charging and Discharging

The simulated current and voltage profile of the designed Electric Vehicle.
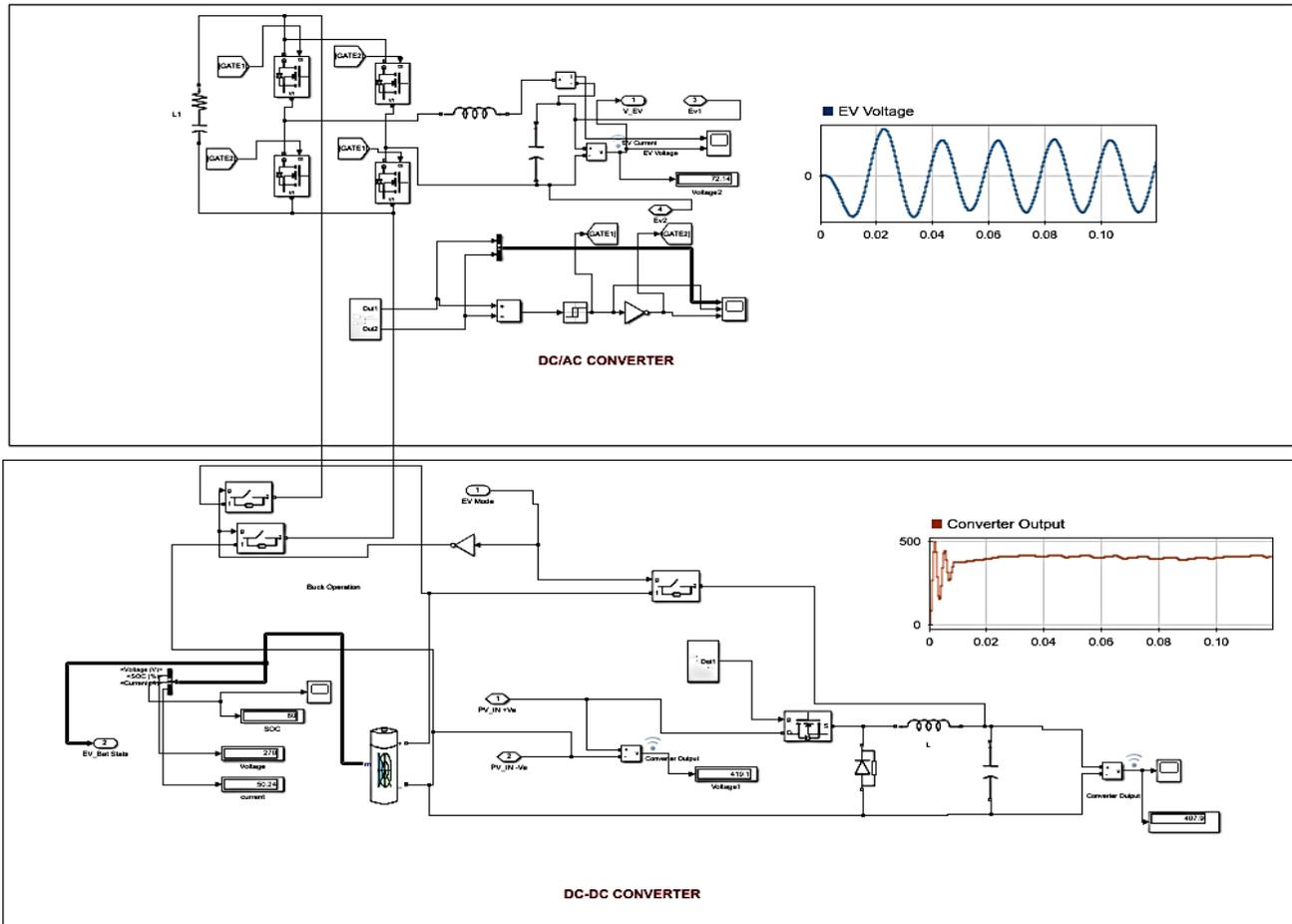

figure 4.14: Electric vehicle V2H/H2V

CHAPTER FIVE

5.0   Conclusion

This research work has presented the design and simulation of a grid-connected photovoltaic system with a bi-directional net meter.

The study involves the implementation of a "Perturb and Observe" MPPT system, a phase lock loop (PLL), a Mosfet based single-phase inverter and a bi-directional metering unit. The result obtained from the simulation showed that the PV array operated at maximum power point irrespective of variations of solar irradiance. Simulation at 1000W/m^2 and 800W/m^2 at 25°C resulted in peak readings of 2091.8W and 1665W respectively.

The I-V characteristics of the designed on-Grid inverter showed a synchronized Grid-Inverter output as controlled by the integrated phase lock loop unit. The designed counter-based bi-directional metering effectively supplied power from the grid when the simulated household load requirement was above the power generated by the inverter and vice-versa thus resulting in an overall smart system with Net Metering and billing capability.

The design and simulation were carried out via the Simulink platform of the Matlab software and the result obtained showed the designed system was functional and able to meet research objectives.

Further research can be done in the integration of suitable anti-islanding features and multi-stage inverter systems.

REFERENCES

[1]   Atiq, J., & Soori, P. K. Modelling of a grid-connected solar PV system using MATLAB/. International Journal of Simulation: Systems, Science and Technology, 17(41), 45.1-45.7. https://doi.org/10.5013/IJSSST.a.17.41.45

[2]   Abdar, H. M., Chakraverty, A., Moore, D. H., Murray, J. M., & Loparo, K. A, Design and implementation of a specific grid-tie inverter for an agent-based microgrid.   2012 IEEE   Energytech, Energytech 2012, (2012). https://doi.org/10.1109/EnergyTech.2012.6304676

[3]   Dolas, N. A., Sharma, R. B., & Sindekar, P. A. S. (2020). Solar PV grid-connected system analysis. May, 7360–7364.

[4]   Hoft, R. G., & Hoft, R. G,   Self-Commutated Thyristor Inverters. Semiconductor Power Electronics, 239–268. https://doi.org/10.1007/978-94-011-7015-4_11 ((1986).

[5]   Johnson, B. A. (2013). Modelling and Analysis of a Pv Grid-Tied Smart Inverter'S Support Functions. Master's Thesis, May.

[6]   Karthikeyan, V., Rajasekar, S., Das, V., & Pi, K. (2017). Grid-Connected and Off-Grid Solar   Photovoltaic System Grid-Connected and Off-Grid Solar Photovoltaic System (Issue   May 2018). https://doi.org/10.1007/978-3-319-50197-0

[7]   Ibrahim, K. A., Gyuk, P. M., & Aliyu, S. (2019). THE EFFECT OF SOLAR IRRADIATION ON SOLAR CELLS. 14(1), 20–22.

[8]   Maharaja, K., Pradeep Balaji, P., Sangeetha, S., & Elakkiya, M.   Development of bidirectional net meter in grid connected solar PV system for   domestic

consumers. International Conference on Energy Efficient   Technologies for

Sustainability, ICEETS 2016, April, 46–49

https://doi.org/10.1109/ICEETS.2016.7582897 (2016).

[9]   Kahlane, A. E. W. H., Hassaine, L., & Kherchi, M, LCL filter design for   photovoltaic

grid connected systems. Third International Seminar on New and   Renewable Energies,

8(2), 227–232. (2014)

[10]   Khatib, T., & Elmenreich, W. (2016). Modeling of Photovoltaic Systems Using

MATLAB ®   Modeling of Photovoltaic Systems Using MATLAB ®

https://doi.org/10.1002/9781119118138

[11]   Mohanty, P., Sharma, K. R., Gujar, M., Kolhe, M., & Azmi, A. N., PV system design

for off-grid applications. In Green Energy and Technology (Vol. 196, Issue September).

https://doi.org/10.1007/978-3-319-14663-8_3, (2016).

[12   Ositelu, O, "Design and Simulation of a Distributed PV System for

Pennsylvania   State University," Analysis, pp. 1–72, 2010.ed PV System for

Pennsylvania State   University. Analysis, 1–72, (2010).

[13]   Phap, V. M,   "Study on Grid Connected Photovoltaic System Using PSIM"

Program.   8(10), 706–710. (2019).

[14]   Rani, A., & Sharma, G, A Review on Grid-Connected PV System. International

Journal of Trend in Scientific Research and Development, Volume-1(Issue-4), 558–563.

https://doi.org/10.31142/ijtsrd2195 (2017).

[15]   Raut, D. B., & Bhattrai, & A. (2013). Performance Analysis of Grid Connected Solar PV System Using Matlab. Simulink Rentech Symposium Compendium, 3(September), 48.

[16]   REN21 Renewables 2014 Global Status Report. (2014). Total world energy consumption   by source 2013.

[17]   Rodrigues, E. M. G., Melício, R., Mendes, V. M. F., & Catalão, J. P. S. (2011). Simulation of a solar cell considering single-diode equivalent circuit model. Renewable Energy and Power Quality Journal, 1(9), 369–373. https://doi.org/10.24084/repqj09.339

[18]   Sreedevi, J., Ashwin, N., & Naini Raju, M. (2017). A study on grid connected PV system. 2016 National Power Systems Conference, NPSC 2016, 0–5. https://doi.org/10.1109/NPSC.2016.7858870

[19]   Zipp, K. (2015). What are some common types of solar PV and storage installations? Solar Power World. https://www.solarpowerworldonline.com/2015/10/what-are-some-common-types-of-solar-pv-and-storage-installations/