UNIVERSITY OF EDUCATION, WINNEBA

COLLEGE OF TECHNOLOGY EDUCATION – KUMASI

DESIGN OF A SINGLE PHASE GRID CONNECTED PHOTOVOLTAIC (PV) SYSTEM USING MATLAB/ SIMULINK

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Thesis in the Department of **ELECTRICAL/ ELECTRONICS TECHNOLOGY**, Faculty of **TECHNOLOGY**, Submitted to the School of **GRADUATE STUDIES**, University of Education, Winneba in partial fulfilment of the requirement for award of the **MASTER OF TECHNOLOGY EDUCATION** in **ELECTRICAL AND ELECTRONICS TECHNOLOGY.**

JULY, 2016

DECLARATION

STUDENT'S DECLARATION

I, Issaka Salifu declare that this thesis, with the exception of quotations and references contained in the published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or whole, for another degree elsewhere.

SIGNATURE: ....

DATE: ....

SUPERVISOR'S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of Thesis laid down by the University of Education, Winneba.

NAME OF SUPERVISOR: PROFESSOR WILLIE K. OFFOSU

SIGNATURE: ....

DATE: ....

DEDICATION

I dedicate this work to my mother Issaka Adisa and my wife Gbana Bushira for their love, care and prayers throughout the course of my studies.

ACKNOWLEDGEMENT

Thanks be to the Almighty Allah for the gift of life and His grace. I am very grateful to my supervisor, Prof. Willie Ofosu for his cooperation and constructive criticisms during this study.

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Finally, I am very grateful to all my family members, particularly Mr. Issaka Wutirirah Atiku for his support throughout the course of my Education.

I say God richly bless you all.

ABSTRACT

There is much concern about the fossil fuel exhaustion and the environmental problems associated with conventional power generation. PV systems are the most direct way to convert solar radiation into electricity and are based on the PV effect, which was first observed by Henri Becquerel in 1839.

It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically, all PV devices incorporate a PN junction in a semiconductor across which the photo voltage is developed. These devices are also known as solar cells. Light absorption occurs in a semiconductor material. The semiconductor material has to be able to absorb a large part of the solar spectrum. This thesis is primarily focused on grid connected photovoltaic systems with the functionality of harmonic compensation is introduced in this thesis. Increasing interest and investment in renewable energy gave rise to rapid development of high penetration solar energy..

PV systems have the advantage of requiring little or no maintenance as well as being pollution-free but their installation cost is high and, in most applications; they require a power conditioner (DC/DC or DC/AC converter) for load interface.

The simulation developed in this thesis provides a better understanding and significance of PV systems. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analysed based on the I-V curve. As a result, maximum power point techniques have been employed to get the maximum power possible out of the solar cells.

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LIST OF ABBREVIATIONS

PV	photovoltaic
DC	Direct Current
AC	Alternating Current
MPP (T)	Maximum Power Point (Tracking)
P&O	Perturb and Observe
PWM	Pulse Width Modulation
PLL	Phase-Locked Loop
SPWM	Sinusoidal Pulse Width Modulation
TRNSYS	Transient System Simulation (Tool)
PID	Proportional-Integral-Derivative
STC	Standard Test Conditions
MOSFET	Metal–Oxide–Semiconductor Field-Effect Transistor
CCM	Continuous Conduction Modes
TLCI	Thyristor Based Line-Commutated Inverters
IGBT	Insulated Gate Bipolar Transistor
VSI	Voltage Source Inverter
PCU	Power Conditioning Unit

CHAPTER ONE

INTRODUCTION

1.1 Background of study

The world energy consumption and the resulting CO_2 emissions are increasing substantially and this increase puts in danger the ecological stability of the earth, making this an important topic in the society, politically and socially. The energy production has mainly been based on energy sources like oil, gas and coal, which until recently was looked upon as close to inexhaustible. As the world energy consumption is growing at a high rate, the fossil fuel reserve decreases accordingly. Therefore it is important to research into renewable energy sources in order to meet the growing demand.

Also, the study is necessary because Ghana, and the rest of Africa especially, though we have been blessed with a lot of sunlight, is still considered as the dark continent since we cannot generate enough electricity to power our systems and homes. The study aims at exposing the design and implementation of grid-connected PV system which when implemented will go a long way to reduce our energy deficit in a much cleaner and cost-effective way.

1.2 Problem statement

There is much concern about the fossil fuel exhaustion and the environmental problems associated with conventional power generation. PV systems are the most direct way to convert solar radiation into electricity and are based on the PV effect, which was first observed by Henri Becquerel in 1839.It is quite generally defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system. Practically, all PV devices incorporate a PN junction in a semiconductor across which the photo voltage is developed. These devices are also known as solar cells. Light absorption occurs in a semiconductor material. The semiconductor material has to be able to absorb a large part of the solar spectrum [1].

PV systems have the advantage of requiring little or no maintenance as well as being pollution-free but their installation cost is high [2][3] and, in most applications; they require a power conditioner (DC/DC or DC/AC converter) for load interface. Since PV modules still have relatively low conversion efficiency. The overall system cost can be reduced using high efficiency power conditioners which, in addition, are designed to extract the maximum possible power from the PV module.

The increase in number of PV systems installed worldwide has introduced the need of supervision and control algorithms [4][5][6] as well as design and simulation tools for researchers and engineers involved in these kinds of applications. These tools give a good approach of the PV system design and behaviour in different conditions of work, but when a more detailed simulation is needed to a deep understanding of the different components involved in the whole system, these tools are not powerful enough.

A most significant field of study has been the control of solar PV power. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which can be analysed based on the I-V curve [7]. As a result, maximum power point techniques are usually employed to get the maximum power possible out of the solar cell.

A grid-connected photovoltaic power system will reduce the power bill as it is possible to sell surplus electricity produced to the local electricity supplier. Grid-connected PV systems are comparatively easier to install as they do not require a battery system. Again, grid interconnection of photovoltaic (PV) power generation systems has the advantage of effective utilization of generated power because there are no storage losses involved. A photovoltaic power system is carbon negative over its lifespan, as any energy produced over and above that to build the panel initially offsets the need for burning fossil fuels. Even though the sun doesn't always shine, any installation gives a reasonably predictable average reduction in carbon consumption.

1.3 Aim and objective (s) of the project

The main objective (aim) of this work is to design and implement of grid-connected PV system which when implemented will go a long way to reduce energy deficit in a much cleaner and cost-effective way.

The specific objective is to

- Design a single phase grid-connected PV system containing DC-DC converter, DC-AC inverter and LCL filter.
- Control the PV module by maximum power point tracking
- Design and simulate the above using MATLAB

1.4 Research questions

1. What renewable energy sources are available in today's world?
2. What are the effects of connecting a phototovaltaic system to a single phase?

1.5 Relevance and Delimitation of the study

This research will serves as a source of providing alternatives source of energy aside the convention method of energy production in Ghana. Ghana, and the rest of Africa especially, though blessed with a lot of sunlight, is still considered as the dark continent since it cannot generate enough electricity to power its systems and homes.

This thesis will also serve as source of reference material for students, writers, stakeholders and the general public. The study will only be limited to single phase system.

1.6 Scope and organisation of the study

Chapter one of this project discusses the problem statement, aims and objectives of the project, research questions, significance of the study, the delimitations and the scope and organisation of the project. Chapter two is devoted to the review of the literature. The review has been done in themes covering various aspects of the research topic. Also the third chapter presents formulation and circuit design. Chapter four also deals with the implementation of the project. It looks at all the simulation processes involved. Chapter five focuses on the research results. The chapter also discusses in detail the results. Chapter five is the conclusion and recommendation. The results obtained from the system simulation are explained. Recommendations for future works are given.

CHAPTER TWO

LITERATURE REVIEW

This section presents a review on the existing design of grid-connected PV systems. Design considerations made in the reviewed designs as well as the step by step methodologies are reviewed. The exiting methods of MPPT are also discussed at length.

2.1 Review of Grid-connected PV systems

In [8], a grid-connected PV generation system was designed and simulated in MATLAB as follows:

Firstly, the PV generator is connected to the boost DC-DC converter, the control systems based on the maximum power point tracking (MPPT) with perturb and observe (P&O) algorithm helps PV array to generate the maximum power to the grid with change weather conditions, and then integrated into the AC utility grid by DC/AC inverter control the power active and reactive for achieved unit power factor in connection point.

The PV generator used in the proposed system was constructed with four KC200GT solar modules connected in series. This was then interconnected into the grid using power electronics to convert DC to AC power. In order to improve the efficiency of the PV generation system, PV array was controlled to generate the maximum power by a MPPT algorithm, in order to extract the maximum possible power from the PV panels in all the irradiation conditions.

The P&O was operated by constantly measuring the terminal voltage and current of the PV array, then constantly perturbing the voltage by adding a small disturbance, and then observing the changes on the output power to determine the next control signal. If the power increases, the perturbation will continue in the same direction in the following step, otherwise, the perturbation direction will be reversed. The method was found to work well in slow changing environment but has some limitations under rapidly changing atmospheric conditions.

For the first-stage conversion of the PV generation system, boost chopper circuit was used as the boost DC/DC converter. The DC-DC converter raises the low solar voltage to a suitable level corresponding to the optimal PV power. A capacitor was connected between PV array and the boost circuit to reduce high frequency harmonics. The duty cycle of the boost converter was determined by MPPT control system, then constantly perturbing between 0 and 1.

The PV array with boost DC-DC inverter was connected to the ac grid via a DC/AC inverter. The inverter was employed to step down and to modulate the output voltage according to the grid voltage. Finally, the filter was designed to reduce high-order harmonics introduced by the PWM modulation of the DC/AC converter. The control strategy mainly consisted of the DC/AC converter which was designed to supply current into the utility line by regulating the bus voltage to 400V. The control of the power flow to the grid, according to the proposed power systems, is based on the control of active and reactive power.

This paper [9] presented a single phase and three phase eleven-level cascade H-bridge inverter, which uses PLL and MPPT with separate solar panels as DC sources to interact with the power grid. Each inverter bridge was connected to a 200 W solar panel. A Maximum Power Point Tracking (MPPT) algorithm was implemented based on the inverter output power to assure optimal operation of the inverter when connected to the power grid as well as a Phase Locked Loop (PLL) for phase and frequency match. A SPWM approach was presented to deal with the uneven power transferring characteristics of the conventional SPWM modulation technique. This technique proved to be successful due to the irradiance profile and the use of capacitors to smooth the voltage fluctuation. The system was driven at 2 kHz because of speed constrains of the control platform, which required bulk filter components. Grid connection results were shown using the proposed MPPT algorithm. The entire PV system structure and its interaction with the grid through PLL and MPPT algorithms were shown by the simulation results.

In [10], Jiang designs a system which includes a boost converter and a micro controller on a single- chip unit to control the converter directly according to the PV array output power measurements. The paper proposed a single and robust algorithm for MPPT. An extended P&O technique was developed and it was improved with a three-point weight comparison method based on an 8-bit single-chip control unit. The system brought out the following advantages:

- MPP varies with solar insulation and temperature, hence the improvement in the algorithm made the PV operate at its highest efficiency.
- Moreover, the three-point weight point comparison method avoided the oscillation problem in the traditional P&O algorithm.
- This work also developed a low-cost hardware system. The experimental tests verified the tracking efficiency.

A different paper [11] designed the grid tied solar system by omitting the energy storage device like large capacity battery bank. The system block diagram consists of solar PV array, MPPT charge controller, DC to DC converter, High efficient Grid Tie inverter, AC phase synchronizer, Microcontroller, DC power measuring device, CT, PT, ADC (Analogue to Digital converter), Relays and Metering device. The total system is controlled with the help of some sensors and a micro-controller. As a whole a significant reduction in the system costs and efficient system performance can be realized. It had the advantage that:

- By removing the expensive storage device, the system installation cost can be maintained within an acceptable limit. It will not only reduce the internal losses for charging and discharging of battery bank but also at the same time a large amount of cost of the battery will be reduced
- Because is an improved and cost efficient way to synchronize the PV array output with the utility grid by using special control scheme, the grid tied system is more power efficient than a conventional solar system.

The designed system had the following limitations:

- The grid-tied system without storage batteries can't supply power during night or rainy day when sunlight is not sufficient. Again power output from certain renewable energy sources, like wind and solar, can be intermittent.
- Fluctuation in output can negatively affect power grid frequency, voltage, component performance, causing instability in the power generation system and interrupted service to the customers.

2.2 Grid-Connected PV-Design considerations

In the first part of this section, a review of the design considerations and methodologies of grid-connected PV systems is presented.

2.2.1 General Considerations

According to [10] grid-connected PV designs can be made to either include transformers or not based on the overall configuration. Line frequency transformer configurations have the drawback of low voltage levels and increased harmonics compared to the transformerless counterpart. The transformerless design allows the use of DC-DC converters to boost output voltage to rated value. This makes these unique power electronics topologies suitable for flexible ac transmission systems (FACTS) and custom power applications [11]

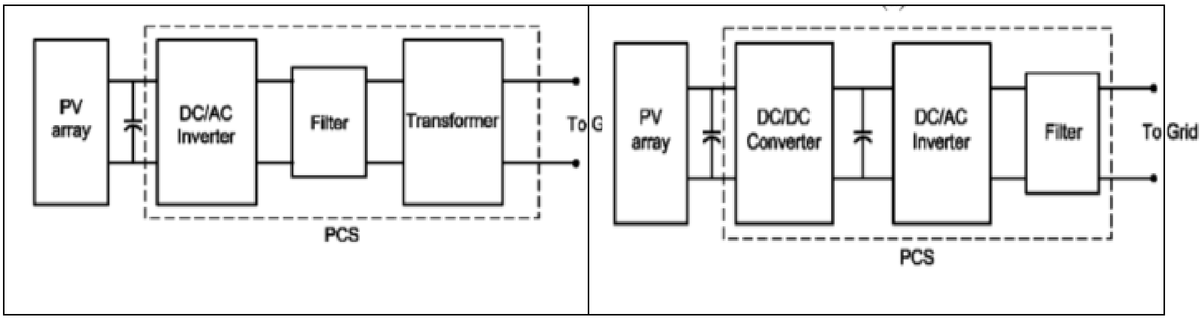

Figure 2. 1: Line frequency transformer and transformerless PV configurations

2.2.2 Inverter Considerations

Design of the PV system depends to a great extent on the type and configuration of the inverter to be used. Different forms of DC-AC inverters exist and are used differently according the system requirements. The power of the inverter must be selected according to the way it will be used. The sum of the power of all loads must not exceed the rated power of the inverter. The maximum power of the inverter must be able to cover the starting currents of the loads.

In [12], a unipolar based voltage source PWM (pulse width modulation) dc to ac inverter was used so that the shape of the output is square PWM wave. As a result, passing this type of signal in a low pass filter gave a pure sine wave which matched to the grid.

Paper [9], in an attempt to achieve multilevel inverter, used an inverter design with four-switch combination. By connecting the DC source to the AC output by different combinations of the four switches, Q11, Q12, Q13, and Q14, three different voltage output levels can be generated for each DC source, $+V_{dc}$, 0, and $-V_{dc}$. A cascaded inverter with N input sources will provide (2N+1) levels to synthesize the AC output waveform. The DC source in the inverter comes from the PV arrays, and the switching signals come from the multicarrier sinusoidal pulse width modulation (SPWM) controller.

In [13], the PV inverter sizing analysis of a grid-connected PV system has been studied using TRNSYS simulation. The sizing analysis was based on three parameters: the annual inverter output per rated PV output, the annual inverter output per specific cost of the system and annual inverter output per annualised specific cost of the system. For a high efficiency inverter, the system performance was affected only by 2% when the sizing ratio varied by 42% from the optimum value. The study revealed that the optimum PV/inverter sizing ratio depends on PV/inverter cost ratio. When inverter cost increases relative to PV cost, optimum system performance was achieved for sizing ratio greater than 1, i.e., inverter rated capacity lower than PV rated capacity. The impact of sizing ratio on the PV system performance is more significant for a low efficiency PV inverter system than a high efficiency PV inverter system.

This paper [14] describes a novel concept of an inverter for grid connected photovoltaic arrays. It is shown that the use of a three level voltage source inverter without transformer is a reasonable solution for the input to grid in the lower power range (< 5kW). To maximize the system efficiency the inverter must be optimized in design and control. For a 2.5kW photovoltaic power system a single phase voltage source inverter is developed which requires only a minimum number of components.

Most commercial inverters for photovoltaic applications include a transformer and several sections of power conversion. To reduce the degree of complexity the paper proposed to omit the transformer and to use only one section of power conversion thereby decreasing system losses, size and costs.

2.3 MPP Control Methods

This section reviews the existing control methods that are employed to extract the maximum power output from PV systems under various operating conditions. Maximum power output of the PV array changes when solar irradiation, temperature, and/or load levels vary. Control is therefore, needed for the PV generator to always keep track of the maximum power point [16]. A number of techniques have been put forward which are accepted and widely used today, for maximum power point control.

2.3.1 Perturb and Observe MPPT Algorithm

The issue of MPPT has been addressed in different ways in the literature but, especially for low-cost implementations, the perturb and observe (P&O) maximum power point tracking algorithm is the most commonly used method due to its ease of implementation. The P&O MPPT algorithm is mostly used, due to its ease of implementation. It is based on the following criterion: if the operating voltage of the PV array is perturbed in a given direction and if the power drawn from the PV array increases, this means that the operating point has moved toward the MPP and, therefore, the operating voltage must be further perturbed in the same direction. Otherwise, if the power drawn from the PV array decreases, the operating point has moved away from the MPP and, therefore, the direction of the operating voltage perturbation must be reversed.

The P&O algorithm does not require previous knowledge of the PV generator characteristics or the measurement of solar intensity and cell temperature and is easy to implement with analogue and digital circuits [17]. The algorithm perturbs the operating point of the PV generator by increasing or decreasing a control parameter by a small amount (step size) and measures the PV array output power before and after the perturbation. If the power increases, the algorithm continues to perturb the system in the same direction; otherwise the system is perturbed in the opposite direction. The number of perturbations made by the MPPT algorithm per second is known as the perturbation frequency or the MPPT frequency (f_{MPPT}).

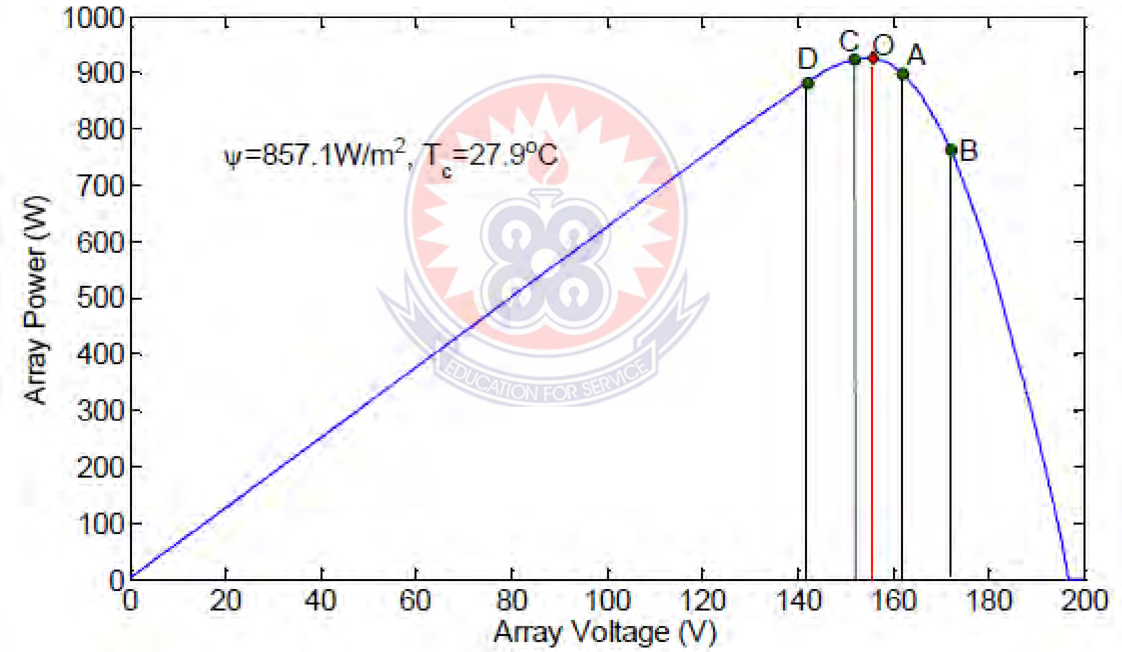

Figure 2. 2: P&O algorithm with reference voltage perturbation

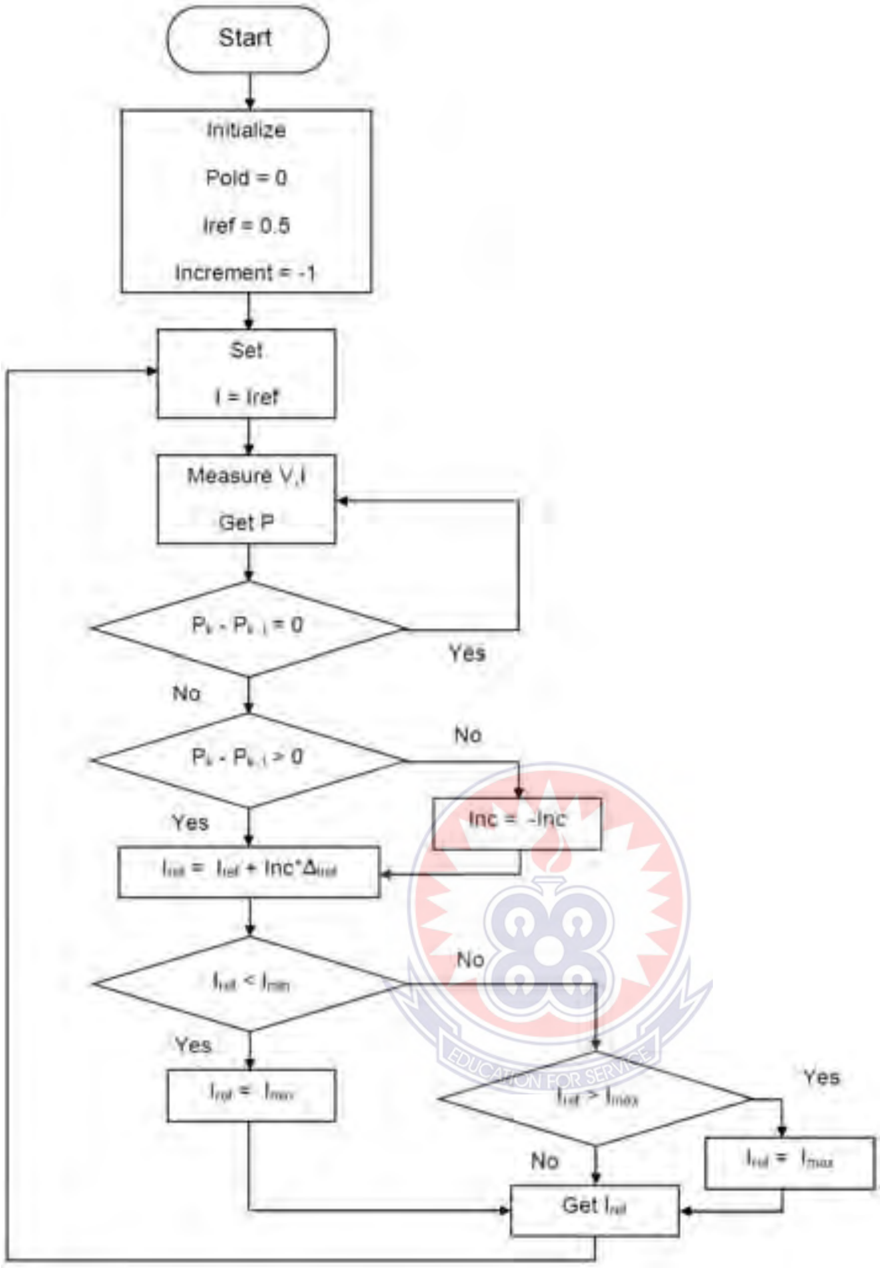

Figure 2. 3: Flow Chart of P&O Algorithm

2.3.1.1 P&O MPPT Techniques

About three (3) main methods of P&O perturbation have been proposed and used. These are:

1. Reference voltage perturbation [18]
2. Reference current perturbation [19], and
3. Direct duty ratio perturbation [20]

In reference voltage perturbation, the PV array output voltage reference is used as the control parameter in conjunction with a controller (usually a PID controller) to adjust the duty ratio of the MPPT power converter. The PI controller gains are tuned while operating the system at a constant voltage equal to the STC value of the MPP voltage. These gains are kept constant while the reference voltage is controlled by the MPPT algorithm.

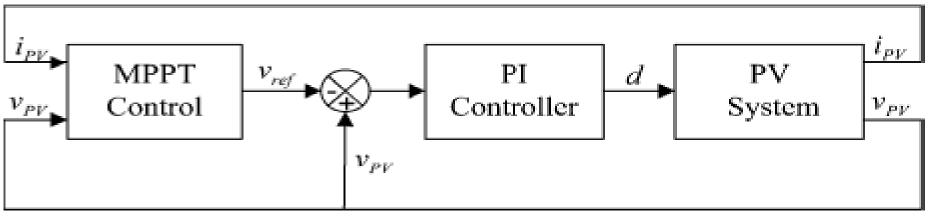

Figure 2. 4: Block diagram of MPPT with reference voltage control.

Similarly, the reference current perturbation approach uses the PV array output current reference as the control parameter. Due to its slow transient response to irradiance changes and high susceptibility to noise and PI controller oscillation, reference current control is not widely used.

The direct duty ratio perturbation uses duty ratio of the MPPT converter directly as the control parameter.

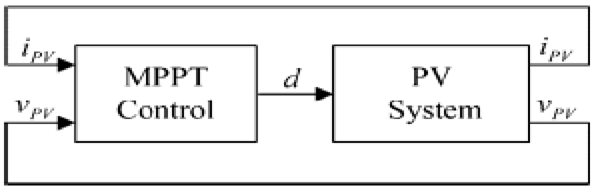

Figure 2. 5: Block diagram of MPPT with direct duty ratio control.

According to studies done by [21] and [17], reference voltage perturbation has a faster response to irradiance and temperature transients. However, it loses stability if operated at a high perturbation rate or if low pass filters are used for noise rejection from the array current and voltage feedback signals. This noise has significant impact on the algorithm performance and consequently on the energy utilization, especially with low step sizes where the system response to noise is comparable to that of MPPT perturbations. The energy utilization efficiency of the experimental system was calculated at 97.2% for slow changing solar irradiance. The energy utilization efficiency is marginally lower at 97% for rapidly changing irradiance due to the energy loss during the confusion and recovery periods when irradiance changes.

Again, [21] and [17] concludes that direct duty ratio control offers better energy utilization and better stability characteristics at a slower transient response and worse performance at rapidly changing irradiance. System stability is not affected by using low-pass feedback filters. Higher energy utilization efficiency was achieved with direct duty ratio control due to the lower impact of noise and the absence of the oscillation resulting from the PI controller. The calculated energy utilization efficiency of the experimental system was about 99%and 97.9%for the slow and rapidly changing irradiance, respectively. In addition, direct duty ratio perturbation allows the use of high perturbation rates up to the PWM rate without losing the global stability of the system.

Paper [21] adds that noise has significant impact on the algorithm performance, especially with low step sizes where the system response to noise is comparable to that of MPPT perturbations.

2.3.1.2 Drawbacks

A drawback of P&O is that, at steady state, the operating point oscillates around the MPP giving rise to the waste of some amount of available energy; moreover, it is well known that the P&O algorithm can be confused during those time intervals characterized by rapidly changing atmospheric conditions [22].

2.3.2 Incremental Conductance MPPT Algorithm

Incremental conductance method uses two sensors, that is voltage and current sensors to sense the output voltage and current of the PV array [23]. Algorithm works by comparing the ratio of derivative of conductance with the instantaneous conductance [24]. When this instantaneous conductance equals the conductance of the solar then MPP is reached. The basic equations of this method are as follows:

$$\frac{dI}{dV} = -\frac{I}{V} \quad \text{at MPP,} \qquad (2.0)$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad \text{left of MPP, and} \qquad (2.1)$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad \text{right of MPP} \qquad (2.2)$$

where I and V are the PV array current and voltage respectively

The left-hand side of the equations represents the Incremental conductance of the PV module, and the right-hand side represents the instantaneous conductance. From the three equations it is obvious that when the ratio of change in the output conductance is equal to the negative output conductance, the solar array will operate at the MPP. In other words, by comparing the conductance at each sampling time, the MPPT will track the maximum power of the PV module [25]. Considering that both the voltage and current are sensed simultaneously, the error due to change in insulation is eliminated. However the complexity and the cost of implementation increase.

2.3.2.1 Flow Diagram

The incremental conductance method can be represented by the following flow chart [26]

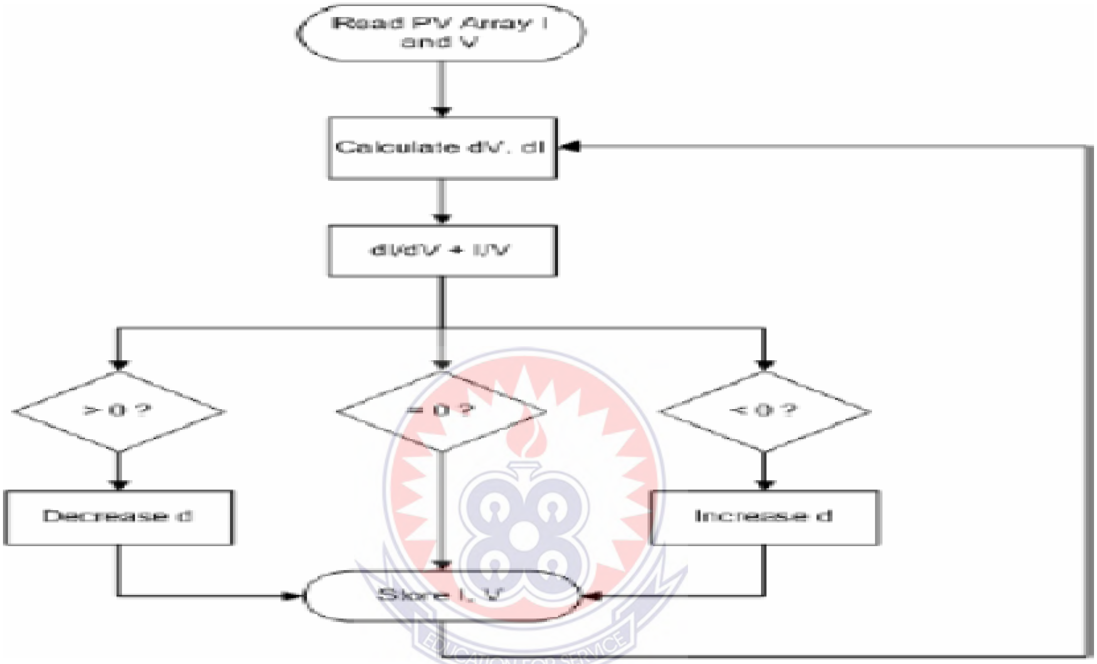

Figure 2. 6: Incremental conductance flow algorithm

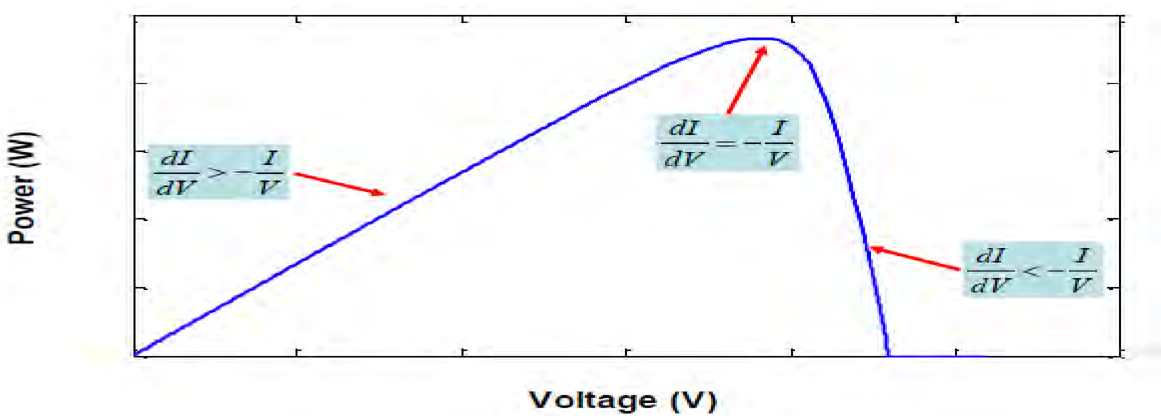

Figure 2. 7: Incremental conductance graph of output power against voltage

2.3.2.2 Drawbacks

The drawbacks of the MPPT techniques are [23]

1. They can easily lose track of the MPP if the solar insulation level changes rapidly.
2. The voltage and current around the MPP in the steady state are not constant. This is due to the fact that the control is discrete hence the voltage and current at the MPP oscillate around it.
3. The system performance is affected by step size and the perturbation frequency, thereby limiting the step values and perturbation frequencies to a smaller test set [21].

The incremental algorithm is less confused by noise and system dynamics compared to the P&O algorithm. However, contrary to general perceptions, it exhibits worse confusion than the P&O algorithm in rapidly changing weather conditions [21]. Both algorithms offer high energy utilization efficiencies of up to 99% depending on weather conditions. The efficiency is marginally lower for rapidly changing irradiance due to the energy loss during the confusion and recovery periods.

Various methods exist for MPPT determination aside the above. Popular among them are:

- Constant Voltage MPPT Algorithm
- Open and short-circuit MPPT algorithm
- Fuzzy Logic Control Based MPPT Algorithm
- Neural Network Based MPPT Algorithma

CHAPTER THREE

FORMULATION AND CIRCUIT DESIGN

This section deals with solar PV systems with more focus on their integration in grid systems as well as the design requirements and optimisations.

3.1 The Solar PV Structure – Basic Review

Figure 3.1 shows the block diagram of the proposed method. It uses buck boost converter to adjust the output voltage of the PV panel. Buck Boost Converter is capable of stepping up or stepping down the output voltage from the source voltage. The converter is controlled by PID with two inputs and one output and the system performance is optimized by perturb and observe method. The inputs are fed by voltage and current of the PV terminals, while the output provides duty cycle for the buck boost converter. Buck Boost converter controls the output voltage by varying the duty cycle *K,* of the switch. Duty cycle refers to ratio of the conduction time and the total switching period [21].

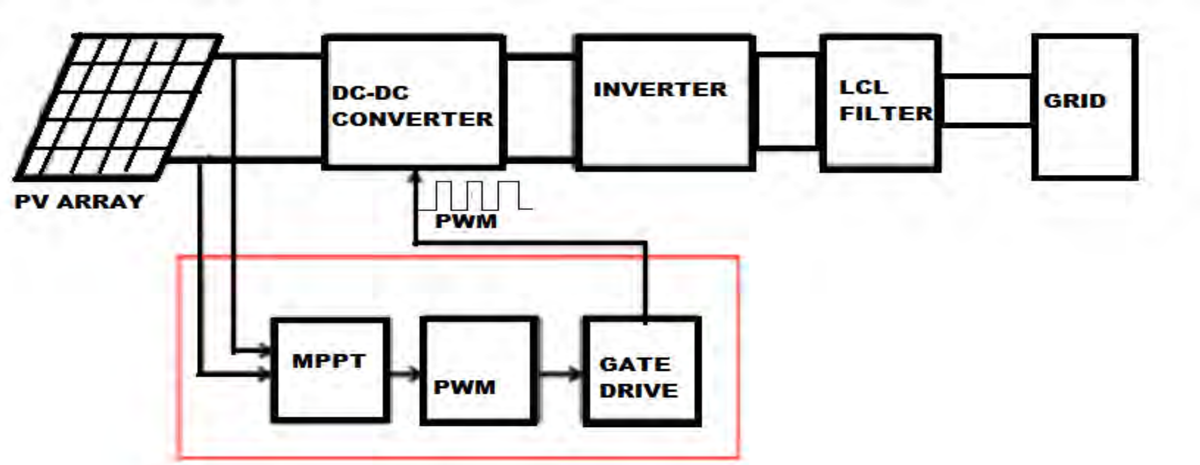

Figure 3. 1: MPPT in a solar PV system

3.1.1 PV Cell Structure

The models of solar cell are categorized as p-n semiconductor junction. When exposed to light, then a DC current is generated. The generated current depends on solar irradiance, temperature, and load current [21]. The typical equivalent circuit of PV cell is shown in the figure 3.2.

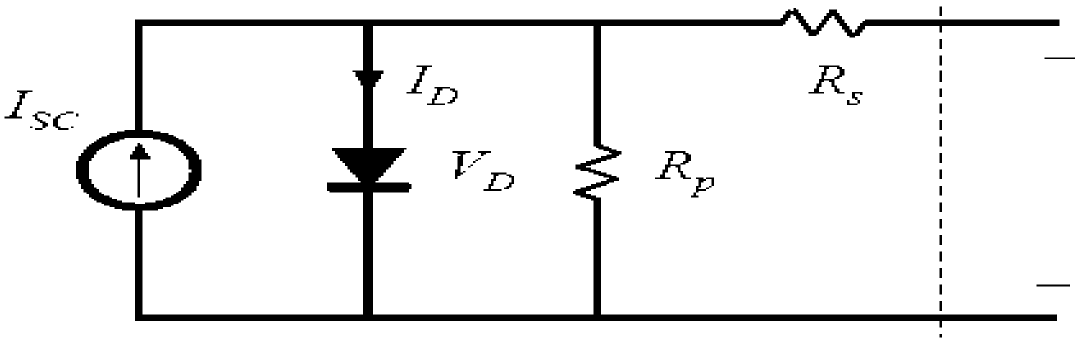

Figure 3.2 PV Cell equivalent circuit

The basic equations describing the I-V characteristic of the PV model are given below:

$$0 = I_{SC} - I_D - \frac{v_d}{R_P} - I_{PV} \qquad (3.0)$$

$$I_D = I_0(e^{V_D/V_T} - 1) \qquad (3.1)$$

$$V_{PV} = V_D - R_S I_{PV} \qquad (3.2)$$

In Figure 3.2, R_S is the equivalent series resistance of the module (unknown) and R_P is the equivalent parallel resistance (unknown), so they have to be calculated. Figure 3.3 originates the IV curve seen in the I-V curve. From the curve certain effects can be deduced:

a) Open- circuit (V_{OC}, 0).

b) Short circuit (0, I_{SC}).

c) Maximum power point (V_{MPP}, I_{MPP}).

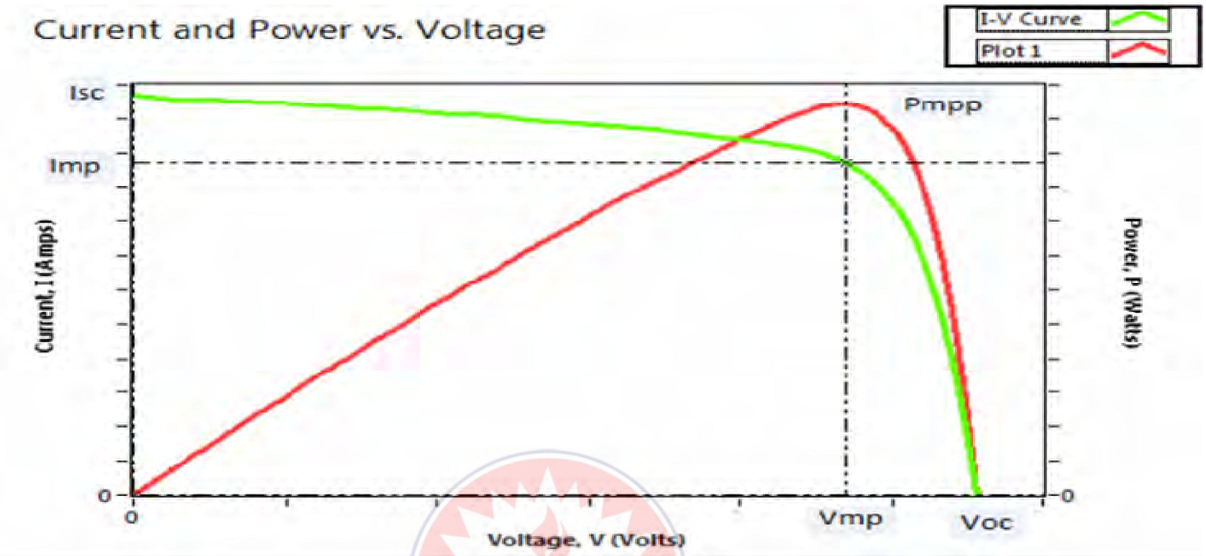

Figure 3. 3: I-V and P-V characteristics of solar cell

3.2 DC-DC Converter

The output voltage of the solar PV is usually of a small value, incapable of supporting the consumer devices. Hence, a DC-DC converter is employed to boost the voltage to a rated value. The boost converter steps up the input voltage magnitude to a required output voltage magnitude without the use of a transformer. The main components of a boost converter are an inductor, a diode and a high frequency switch. These in a co-ordinated manner supply power to the load at a voltage greater than the input voltage magnitude. The control strategy lies in the manipulation of the duty cycle of the switch which causes the voltage change.

In other cases, other types of converters can be used to achieve similar results such as the buck converter which steps down the voltage. The choice of DC-DC converter generally depends on the job description. In PV systems, the boost oriented converter is most preferred because of the need to boost the PV generator voltage. This study makes use of the buck-boost converter. As such, the rest of this section looks at the operation of the boost converter.

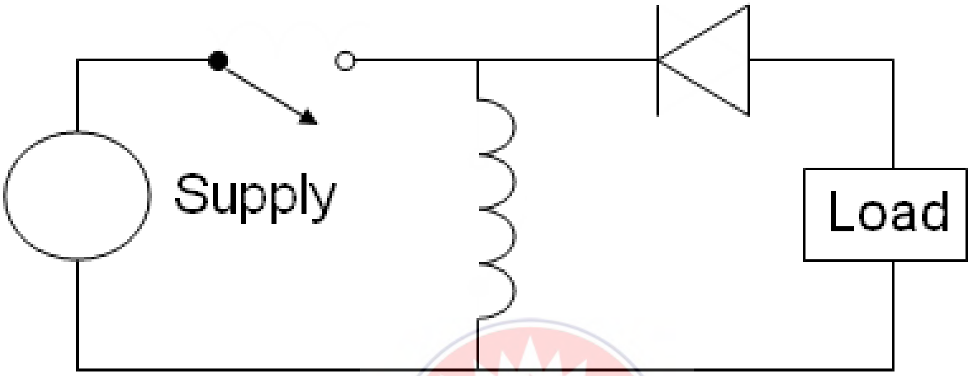

Figure 3. 4: Simple DC-DC buck-boost converter

The **buck–boost converter** is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is equivalent to a fly back converter using a single inductor instead of a transformer. Two different topologies are called inverting and buck–boost converter. Both of them can produce a range of output voltages, from an output voltage much larger (in absolute magnitude) than the input voltage, down to almost zero.

3.2.1 The Inverting Topology

The output voltage is of the opposite polarity than the input. This is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that, the switch does not have a terminal at ground; this complicates the driving circuitry. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) because the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

3.2.2 Buck (step-down) converter combined with a boost (step-up) converter

The output voltage is typically of the same polarity as the input, and can be lower or higher than the input. Such a non-inverting buck-boost converter may use a single inductor which is used for both the buck inductor and the boost inductor, [29] it may use multiple inductors but only a single switch as in the SEPIC and Ćuk topologies [29].

3.2.2.1 On and Off-states

During the on state the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this state, the capacitor supplies energy to the output load.

However, during the off state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

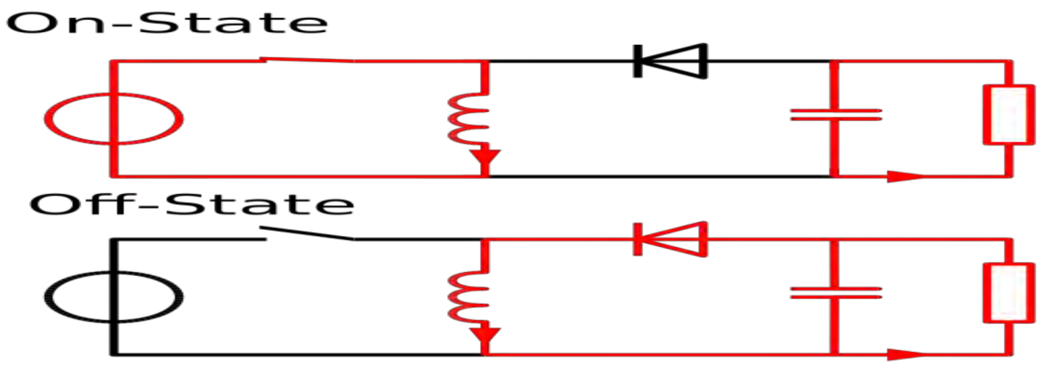

Figure 3. 5: Buck-boost converter operation (a) on-state (b) off-state

Like the buck and boost converters, the operation of the buck-boost is best understood in terms of the inductor's "reluctance" to allow rapid change in current. From the initial state in which nothing is charged and the switch is open, the current through the inductor is zero. When the switch is first closed, the blocking diode prevents current from flowing into the right hand side of the circuit, so it must all flow through the inductor. However, since the inductor doesn't like rapid current change, it will initially keep the current low by dropping most of the voltage provided by the source. Over time, the inductor will allow the current to increase slowly by decreasing its voltage drop. Also during this time, the inductor will store energy in the form of a magnetic field.

The duty cycle and output voltage can be found from the equation:

$$D_{boost} = 1 - \frac{V_{inmin} \times \cap}{V_{out}} \tag{3.3}$$

The inductance and output capacitance can also be found as

$$L > \frac{V_{inmin}^2 \times (V_{out} - V_{inmin}^2)}{Fsw \times Kind \times Iout \times V_{out}{}^2} \tag{3.4}$$

$$Cout = \frac{Iout \times Dboost}{Fsw \times \Delta Vout} \tag{3.5}$$

C_{out}= Output capacitor

V_{in}max = Input voltage at maximum power point

V_{out} = desired output voltage

V_{in}min = minimum input voltage

I_{out} = desired output current

F_{sw} = switching frequency of the converter

L = selected inductor value

K_{ind} = estimated coefficient that represents the amount of inductor ripple current relative to the maximum output current.

A good estimation for the inductor ripple current is 20% to 40% of the output current, or

$0.2 < K_{ind} < 0.4$

The purpose of L_1 and C_{in} are to filter out ripple current

3.2.2.2 Selecting the Input Capacitance

The minimum value for the input capacitor is normally given in the data sheet. This minimum value is necessary to stabilize the input voltage due to the peak current requirement of a switching power supply. The best practice is to use low - equivalent series resistance (ESR) ceramic capacitors. The dielectric material must be X5R or better. Otherwise, the capacitor loses much of its capacitance due to dc bias or temperature. The value can be increased if the input voltage is noisy.

3.2.3 Buck versus boost in a PV system

In grid connected systems with varying input from the source (like PV or wind), the input voltage might be either higher or lower than the AC voltage. This makes both buck and boost operation necessary, depending on the input voltage. Both converter topologies are applicable for Maximum power point tracking (MPPT). In real systems, however, the boost converter is the one most utilized. Normally the DC link voltage will be at least 350 V, and if enough modules cannot be connected in series to obtain this voltage level in small systems, a boost stage is necessary. It has been presented in earlier studies that the efficiency for a boost converter operating in CCM (Continuous Conduction Mode) varies slightly for varying duty cycle, while the efficiency variation for a buck converter is considerable. For a boost converter the current through the inductor will equal the input current, while for a buck converter it will equal the output current.

3.3 DC-AC Inverter

A solar inverter, or PV inverter, converts the variable direct current (DC) output of a photovoltaic (PV) solar panel into a utility frequency alternating current (AC) that can be fed into a commercial electrical grid or used by a local, off-grid electrical network. The output of the PV array or the DC-DC converter is DC. This DC has to be converted to AC so it can be consumed by connected loads. It is a critical basic operating component in a photovoltaic system, allowing the use of ordinary AC-powered equipment.

Figure 3. 6: PV grid-connected inverter

3.3.1 Features of DC-AC Inverter

- High efficiency during practical load operation
- Maximum reliability
- High temperature rating

Modern inverters use oscillator circuits to accomplish the inversion process. They're made with transistors or semiconductors, so there's no longer the need for a spring arm flipping back and forth to alternate the current as was the case in old-fashion types [31].

There are two basic types of inverters which are; thyristor based line-commutated inverters (TLCI) and pulse width modulated (PWM) voltage source inverters. Many existing PV systems make use of TLCI-type inverters because of its modest cost, availability for even higher power levels and familiarity with the technology. If this inverter connects directly to the PV array, the current drawn from the array can be controlled by varying the firing angle. This type of inverter is commonly used in grid connected PV systems [31].

Development in IGBT (Insulated Gate Bipolar Transistor) and MOSFET (Metal Oxide Semiconductor Field Effect Transistor) toward considerably higher power ratings, together with fast real time digital control have resulted in the use of high quality sinusoidal PWM voltage source inverter in PV systems. The greater flexibility of these inverters and the use of microprocessors provide the opportunity to configure the inverter for particular application easily and appropriately. In these inverters the magnitude of the input dc voltage is essentially constant in magnitude and it is possible to control both the output voltage and frequency of the inverters. This is achieved by Pulse Width Modulation of the inverter switches and hence such inverters are called PWM inverters [31].

The three-phase grid-connected voltage source inverter has six IGBT as switching devices and an output L-filter reducing the current distortion.

Solar inverters have special functions adapted for use with photovoltaic arrays, including maximum power point tracking and anti-islanding protection among others

3.3.2 Inverter Selection

The selection of the inverter for the installation will depend on:

i. The energy output of the ray

The peak power of the array is calculated using the following formula:

Array Peak Power = Number of modules in the array x the rated maximum power (P_{mp}) of the selected module at STC.

ii. The matching of the allowable inverter string configurations with the size of the array in kW

In order to facilitate the efficient design of PV systems the inverter nominal AC power output cannot be less than 75% of the array peak power and it shall not be outside the inverter manufacturer's maximum allowable array size specifications.

iii. The size of the individual modules within that array

Inverters currently available are typically rated for:

- maximum DC input power i.e. the size of the array in peak watts
- maximum DC input current
- maximum specified output power i.e. the AC power they can provide to the grid

iv. Whether the system will have one central inverter or multiple (smaller) inverters.

If the array is spread over a number of roofs that have different orientations and/or tilt angles then the maximum power points and output currents will vary. If economic, installing a separate inverter for each section of the array which has the same orientation and angle will maximise the output the total array. This could also be achieved by using an inverter with multiple maximum power point trackers (MPPTs). Multiple inverters allow a portion of the system to continue to operate even if one inverter fails. Multiple inverters allow the system to be modular, so that increasing the system involves adding a predetermined number of modules with one inverter. Multiple inverters better balance phases in accordance with local utility requirements.

The potential disadvantage of multiple inverters is that in general, the cost of a number of inverters with lower power ratings is generally more expensive [32]. While the most suitable type of inverter will be dependent on the installation scenarios; generally speaking 3-phase string inverters offer the widest range of applications in terms of residential to large commercial installations [32] and are thus preferred for this study.

3.3.3 Maximum Voltage Window

At the coldest daytime temperature the open circuit voltage of the array shall never be greater than the maximum allowed input voltage for the inverter [32]. The open circuit voltage (V_{oc}) is used because this is greater than the MPP voltage and it is the applied voltage when the system is first connected (prior to the inverter starting to operate and connecting to the grid).

Some inverters provide a maximum voltage for operation and a higher voltage as the maximum allowed voltage. In this situation, the MPP voltage is used for the operation window and the open circuit voltage for the maximum allowed voltage.

In early morning, at first light, the cell temperature will be very close to the ambient temperature because the sun has not had time to heat up the module. Therefore, the lowest daytime temperature for the area where the system is installed shall be used to determine the maximum *Voc*.

This is determined by the following equation:

$$Vmax\_oc = Voc - STC + [\gamma v \times (Tmin - TSTC)] \quad (3.6)$$

where:

Vmax_oc = Open circuit voltage at minimum cell temperature, volts

Voc - STC = Open circuit voltage at STC, volts

γv = voltage temperature Vocco-efficient ,- V/°C

Tmin = expected min. daily cell temperature, °C

TSTC = cell temperature STC, °C

It is recommended that the designer use the minimum temperature for the area where the system will be installed.

3.3.4 Types of DC-AC Inverters

Many types of inverters exist in design and implementations based on the system requirements. The following are the popular ones among them [32].

i. **Micro inverter**: (converts the DC electricity produced by a single solar panel).

ii. **String Inverter**: (most commonly used in home and commercial solar power systems).

iii. **Central Inverter**: (they are basically just very large string inverters).

3.3.5 Multilevel Inverter

These converters consist of several PV strings that are connected with dc–dc converters to a common dc–ac converter [33].This topology features several advantages such as the independent tracking of the MPP of each string to the existing plant. This converter topology can reach peak efficiencies up to 96% [34]. The multilevel voltage source inverters' unique structure allows them to reach high voltages with low harmonics without the use of transformers. The use of a multilevel converter to control the frequency, voltage output (including phase angle), and real and reactive power flow at a dc/ac interface provides significant opportunities in the control of distributed power systems. The general function of the multilevel inverter is to synthesize a desired ac voltage from several levels of dc voltages. For this reason, multilevel inverters are ideal for connecting either in series or in parallel an AC grid with renewable energy sources such as photo-voltaic or fuel cells or with energy storage devices such as capacitors or batteries. Additional applications of multilevel converters include such uses as medium voltage adjustable speed motor drives, static VAR compensation, dynamic voltage restoration, harmonic filtering, or for a high voltage dc back-to-back intertie.

3.4 Grid-connected Filter

An LCL (inductor-capacitor-inductor) filter is often used to interconnect a voltage source inverter (VSI) to the utility grid in order to filter the harmonics produced by the inverter. A filter is required between an inverter and the grid, imposing a current-like performance for feedback control and reducing harmonics of the output current. A simple series inductor can be used, but the harmonic attenuation is not very pronounced. In addition, a high voltage drop is produced and the inductor required in the design is very bulky [35]. Commonly a high-order LCL filter has been used in place of the conventional L-filter for smoothing the output currents from a VSI [35], [36]. The LCL filter achieves a higher attenuation along with cost savings, given the overall weight and size reduction of the components. LCL filters have been used in grid-connected inverters and pulse-width modulated active rectifiers [37], because they minimize the amount of current distortion injected into the utility grid. Good performance can be obtained in the range of power levels up to hundreds of kW, with the use of small values of inductors and capacitors [37]. The higher harmonic attenuation of the LCL filter allows the use of lower switching frequencies to meet harmonic constraints.

3.4.1 Filter Types

In order to stabilize the energy output and to give it some defined shape and value, the power converter must be connected to the output of the solar panel. For this purpose of application is the most suitable choice voltage source inverter (VSI). In order to suppress or reduce negative effects the filter is connected between the converter and the network. The filter must be designed precisely, because it must have sufficient attenuation at the inverter's switching frequency and it must not bring oscillations to the whole system.

The output filter reduces the harmonics in generated current caused by semiconductor switching. There are several types of filters [38]. The simplest variant is filter inductor connected to the inverter's output. But also combinations with capacitors like LC or LCL can be used.

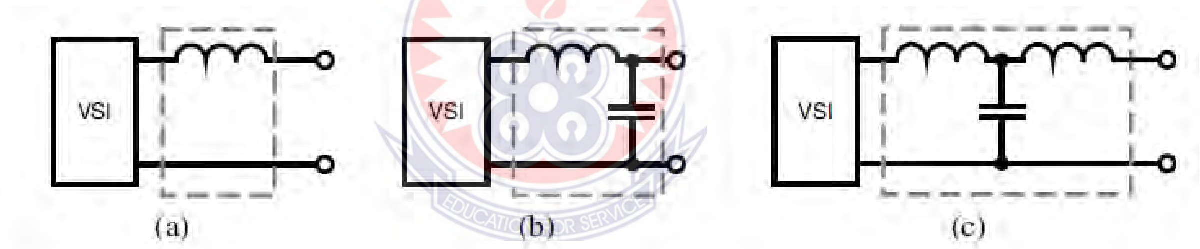

Figure 3. 7: Filter types (a) L (b) LC (c) LCL filters respectively

i. **L-filter:** The L-filter is the first order filter with attenuation 20 dB/decade over the whole frequency range. Therefore the application of this filter type is suitable for converters with high switching frequency, where the attenuation is sufficient. On the other side inductance greatly decreases dynamics of the whole system converter-filter.

ii. **LC-filter:** The LC-filter is the second order filter and it has better damping behaviours than L-filter. This simple configuration is easy to design and it works mostly without problems. The second order filter provides 12 dB per octave of attenuation after the cut-off frequency f_0, it has no gain before f_0, but it presents a peaking at the resonant frequency. Transfer function of the LC-filter is

$$F(s) = \frac{1}{1 + s \cdot L_F + s^2 \cdot L_F \cdot C_F} \tag{3.7}$$

The design of the filter is a compromise between the value of the capacity and inductance. The high capacity has positive effects on the voltage quality. On the other hand higher inductance value is required to achieve demanded cut-off frequency of the filter. Connecting system with this kind of filter to the supply grid, the resonant frequency of the filter becomes dependent on the grid impedance and therefore this filter is not suitable too.

iii. **LCL-filter:** The attenuation of the LCL-filter is 60 dB/ decade for frequencies above resonant frequency. Therefore lower switching frequency for the converter can be used. It also provides better decoupling between the filter and the grid impedance and lower current ripple across the grid inductor. Therefore LCL-filter fits to our application. The LCL filter has good current ripple attenuation even with small inductance values. However it can bring also resonances and unstable states into the system. Therefore the filter must be designed precisely according to the parameters of the specific converter.

3.4.2 Designing the LCL Filter

Several characteristics must be considered in designing a LCL filter, such as current ripple, filter size and switching ripple attenuation. The reactive power requirements may cause a resonance of the capacitor interacting with the grid. Therefore, passive or active damping must be added by including a resistor in series with the capacitor. In this work, the passive damping solution has been adopted, but active solutions can also be applied.

The following parameters are needed for the filter design: VLL-line to line RMS voltage (inverter output), V_{ph} -phase voltage (inverter output), P_n - rated active power, VDC-DC link voltage, f_g-grid frequency, F_{sw}-switching frequency, F_{res}-resonance frequency. The base impedance and base capacitance are defined by (3.9) and (3.10). Thus, the filter values will be referred to in a percentage of the base values

$$Z_b = \frac{E_n^2}{P_n} \tag{3.8}$$

$$C_b = \frac{1}{2\pi f_g Z_b} \tag{3.9}$$

For the design of the filter capacitance, it is considered that the maximum power factor variation seen by the grid is 5%, indicating that the base impedance of the system is adjusted as follows: $C_f = 0.05\ C_b$. A design factor higher than 5% can be used, when it is necessary to compensate the inductive reactance of the filter [38].

The inverter side inductor L_i can be found as

$$L_i = \frac{V_{DC}}{6F_{sw} \times \Delta I_{Lmax}} \tag{3.10}$$

Where; ILmax is 10% ripple of the rated inductor current.

The LCL filter should reduce the expected current ripple to 20%, resulting in a ripple value of 2% of the output current [39].

The grid side inductor can then found as

$$L_g = \frac{(\frac{1}{ka})^{0.5}+1}{(2\pi f_{sw})^2 \times C_f} \tag{3.11}$$

Where Ka is the desired attenuation and C_f =0.01 / 0.05 C_b

In the technical literature many articles on the design of the LCL filters [4, 5] shows the important parameter of the filter is its cut-off frequency. The cut-off frequency of the filter must be minimally one half of the switching frequency of the converter, because the filter must have enough attenuation in the range of the converter's switching frequency. The cut-off frequency must have a sufficient separation from the grid frequency, too. The cut-off frequency of the LCL filter can be calculated as

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \tag{3.12}$$

The LCL filter is usually vulnerable to oscillations too and it will magnify frequencies around its cut-off frequency. Therefore the filter is added with damping. The simplest way is to add damping resistor. In general there are four possible places where the resistor can be placed in series/ parallel to the inverter side inductor or series/parallel to filter capacitor. The value of the damping resistor can be calculated as

$$R_{sd} = \frac{1}{3\omega_{res} C_f} \tag{3.13}$$

The resistor reduces the voltage across the capacitor by a voltage proportional to the current that flows through it. The LCL filter is found to be more reliable and efficient [40].

CHAPTER FOUR

IMPLEMENTATION

4.1 MODELLING THE SYSTEM

4.1.1 The MATLAB/ SIMULINK ENVIRONMENT

To design and analyse the PV system, the MATLAB/ SIMULINK environment was used. The software allows building and simulation of the system in real-time. The software was used to model the PV system all and other components.

4.1.2 THE PV SYSTEM

The solar PV panel was modelled as shown in figure 4.1

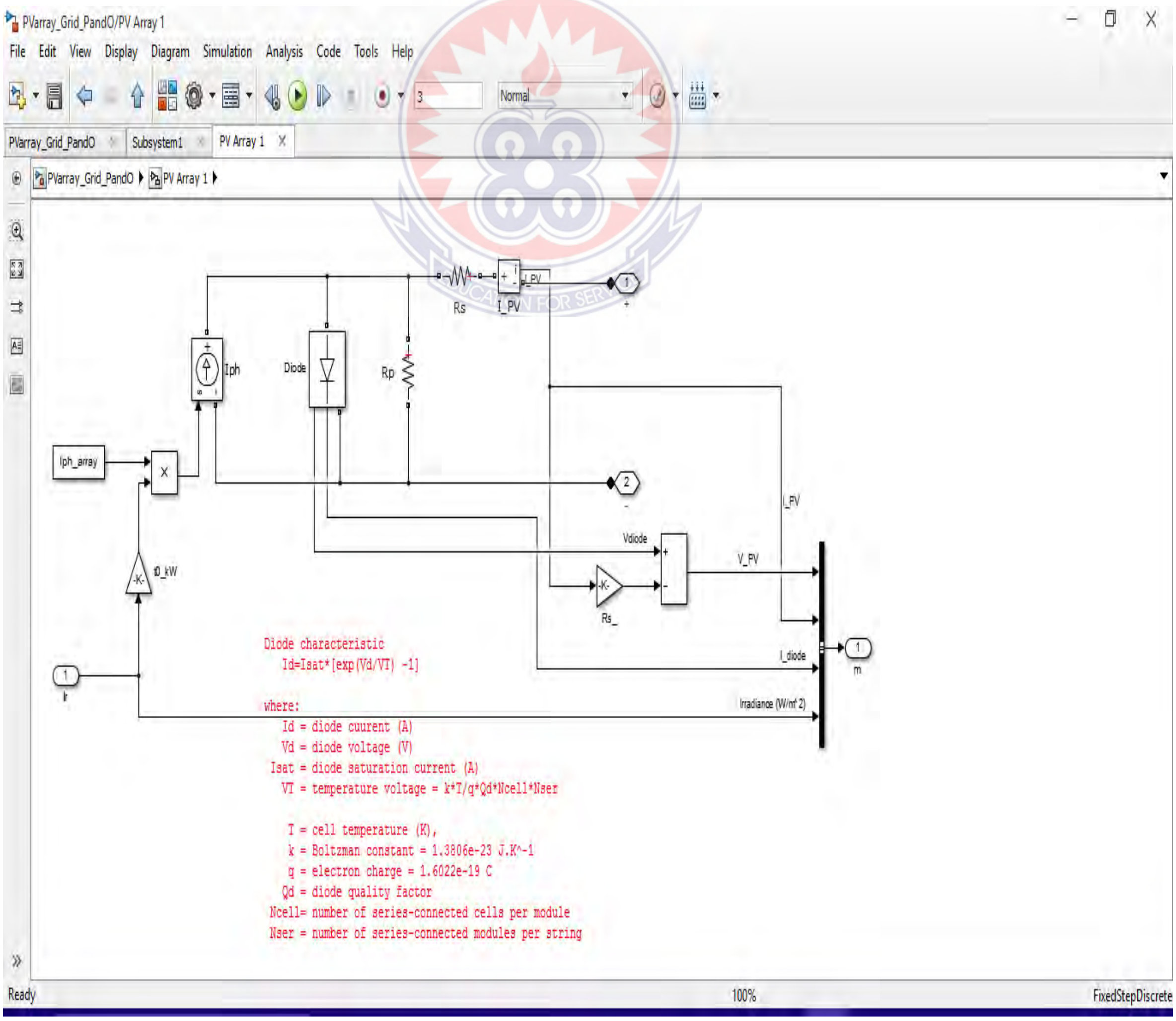

Figure 4. 1: Solar PV model

The model above can be compared to Figure 3.2 where the PV is modelled as a current source with a diode and Shunt resistor as well as a series resistor as seen. The system models one cell. SIMULINK then allows the computation of a number of cells in series and parallel by setting the parameters. In this system, the array consists of 5 strings of 33 series-connected modules connected in parallel. Each cell generates 305.2 W. Hence the total generated power is

P = 33*5*305.2 W= 50.4 kW (4.0)

This 50-kW PV array of the model uses 330 Sun Power modules (SPR-305).

Manufacturer specifications for one Sun Power module are:

- Number of series-connected cells : 96
- Open-circuit voltage: Voc= 64.2 V
- Short-circuit current: Isc = 5.96 A
- Voltage and current at maximum power : Vmpp =54.7 V, Impp= 5.58 A

The full specification can be found in APPENDIX A

Hence for our system with 33 series-connected modules per string and 5 parallel strings, the following were obtained.

$$V_{oc} = 64.2 * 5 = 321V \quad (4.1)$$

$$V_{mpp} = 54.7 * 5 = 273.5V \quad (4.2)$$

$$I_{sc} = 33 * 5.96 = 196.68A \quad (4.3)$$

$$I_{mpp} = 33 * 5.58 = 184.1A \quad (4.4)$$

The PV array block menu allows plotting of the I-V and P-V characteristics for one module, and for the whole array. The characteristics of the SunPower-SPR305 array are reproduced as presented in Table 4.1.

Table 4. 1: Characteristics of the SunPower-SPR305 array

MODEL CHARACTERISTICS	PARAMETER
Ncel	96
Nser	5
Npal	33
Voc	64.2 * 5 = 321V
Isc	5.96 * 33 =196.68A
Vmp	54.7 * 5 = 273.5V
Imp	5.58 * 33 = 184.1A
Rs	0.037998 Ω
Rp	993.51 Ω
Isat	1.1753*10^-8 A
Iph	5.9602 A
Qd	1.3
Sample time	Ts_power

4.1.3 The DC-DC Converter

In this study, a buck-boost converter was implemented as shown in figure 4.2 below. Duty cycle from the MPPT is fed to a pulse generator which generates the gate signalling pulses for the Insulated Gate Bipolar Transistor (IGBT).

The following parameters were set for the boost converter are presented in Table 4.2.

Table 4. 2: Buck-boost converter parameters

Inductance L_1	1mH
Inductance L_2	47μH
Internal inductor resistance	1mΩ
Capacitance C_1	2000μF
Capacitance C_2	2000μF
Diode resistance	1mΩ
Switching frequency	5kHz

The capacitor C_1 was connected between PV array and the boost circuit to reduce high frequency harmonics. Its value was set to 2000 μF.

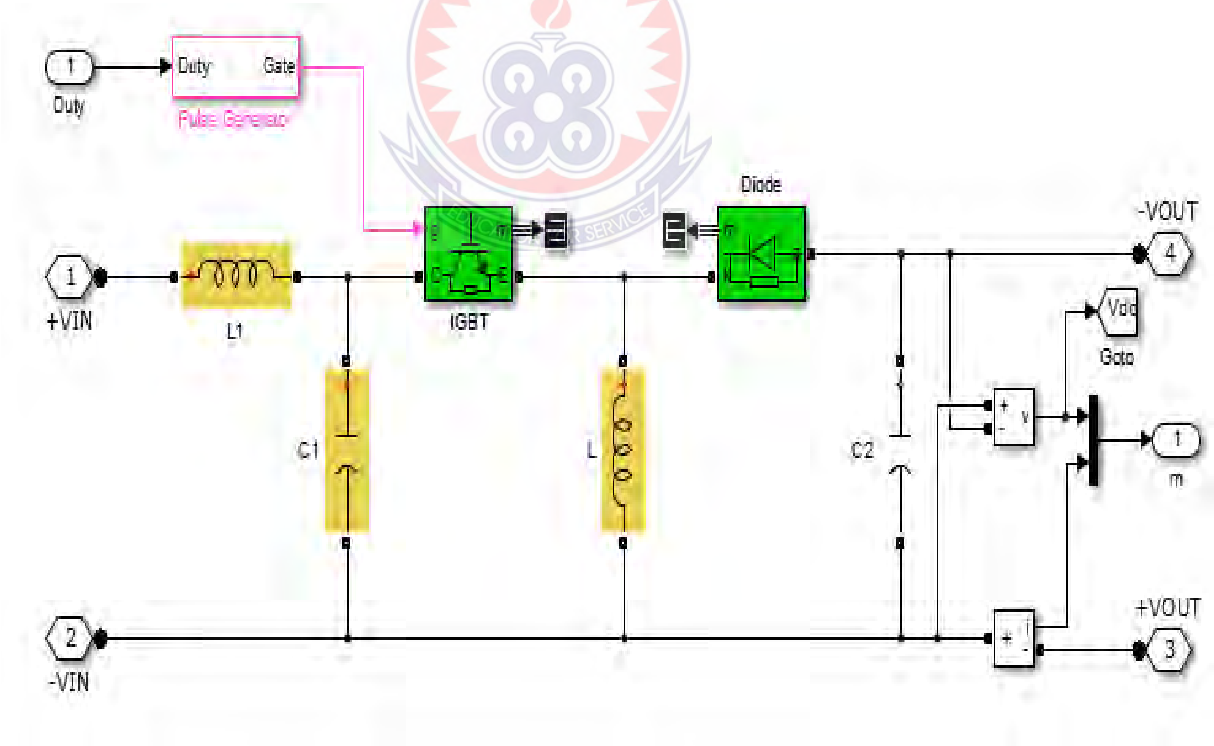

Figure 4. 2: Buck-boost converter model with physical parameters

4.1.4 The DC-AC Inverter

The three-level V_{SC} (blue blocks) regulates DC bus voltage at 240 V_{rms} and keeps unity power factor. The control system uses two control loops: an external control loop which regulates DC link voltage to +/- 340 V and an internal control loop which regulates I_d and I_q grid currents (active and reactive current components).

The Phase-Locked Loop (PLL) is used to generate square pulses to the V_{SC} which generates the alternating sine wave described.

If the firing, pulses to forced-commutated devices is blocked, the bridge operates as a diode rectifier. In this condition, the appropriate values of Rs and Cs must be used. If the model is discretized, the following formulas can be used to compute approximate values of Rs and Cs:

$$R_s > 2\frac{T_s}{C_s} \quad (4.5)$$

$$C_s < \frac{P_n}{1000(2\pi f)V_n^2} \quad (4.6)$$

Where

P_n = nominal power of single- or three-phase converter (VA)

V_n = nominal line-to-line AC voltage (V_{rms})

f = fundamental frequency (Hz)

T_s = sample time (s)

Table 4.3 presents a DC-AC inverter parameters and the VSC is designed as shown in Figure 4.3.

Table 4. 3: Dc-Ac inverter parameters

Tf	1 µS
Tt	2 µS
C	0.1µF
Vfd	0.7V
Vf	0.7V
Ron	10mΩ
Rs	100kΩ

.

The VSC is designed as shown in figure 4.3 below:

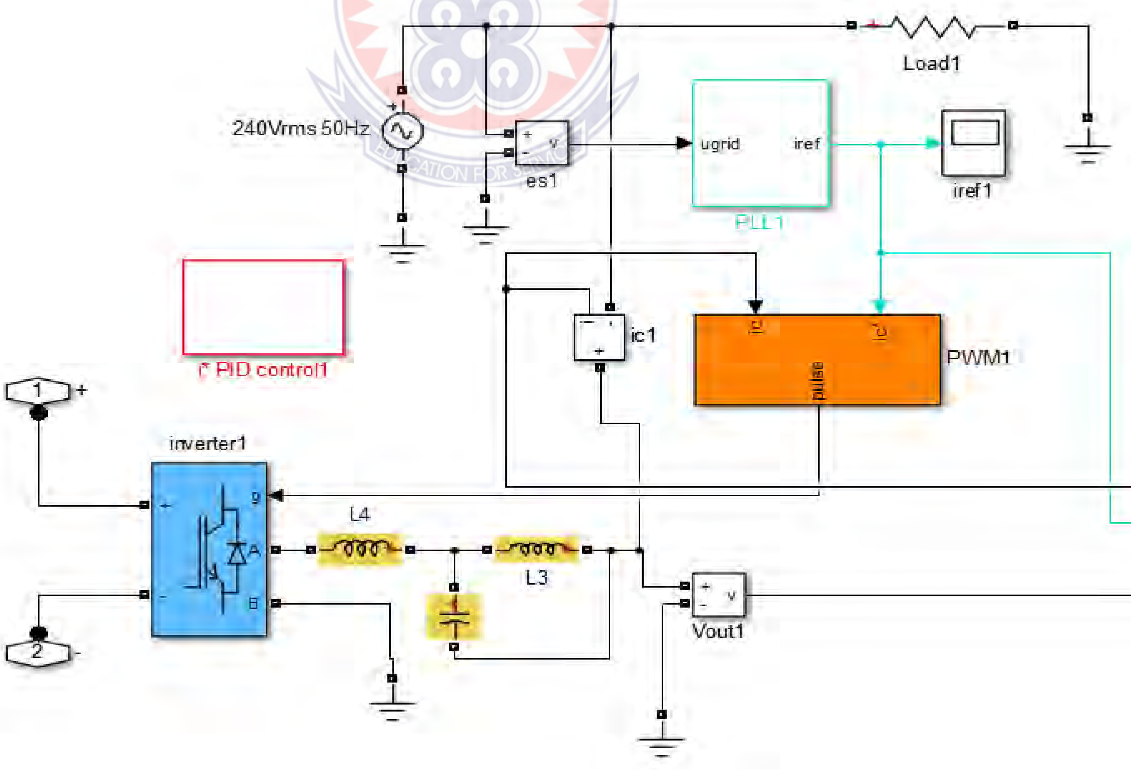

Figure 4. 3: DC-AC Inverter model

4.1.5 LCL Filter

The LCL filter as stated above should be designed to meet the system requirements. It has been found also that, its operation depends on the cut-off frequency.

To implement damping of oscillations, a damping resistor was inserted in series with the inductor on the inverter side of the system. The value, according to the formula above was found to be 2 mΩ. The filter values obtained were L_1 = 1 mH, L_2 = 0.5 mH and C = 24 µF

The designed filter is as shown in Figure 4.4.

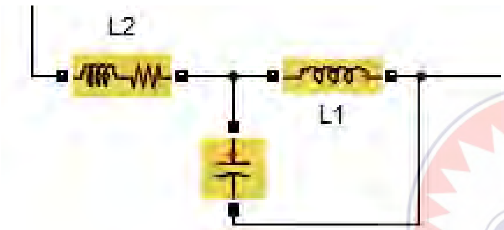

Figure 4. 4: LCL filter model

4.1.6 The Power Grid

The converted and filtered power is then fed into the modelled utility grid through a 100 KVA 260 V/ 11 kV three-phase coupling transformer. The power is fed to an 11 kV distribution feeder with a 120 KV equivalent transmission system.

4.1.7 The MPP Tracker

To execute the duty cycle perturbation of the boost converter switching frequency, the MPPT is modelled as shown in figure 4.5 below. The model's operation is actually described by a SIMULINK function block which enables the insertion of code to do the computation.

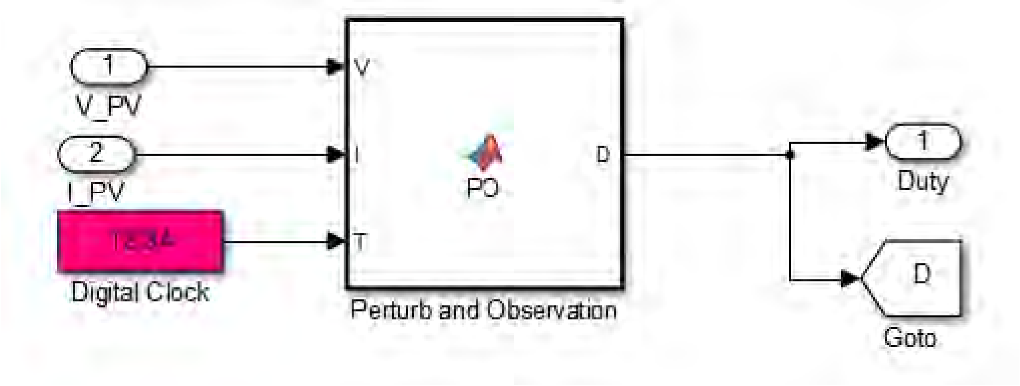

Figure 4. 5: MPPT block diagram

4.1.8 The Single-phase Grid

The grid was modelled as a single-phase load with the following parameters

Voltage: 240 Vrms

Frequency: 50 Hz

Active Power: 40 kW

Inductive Reactive Power: 5 kVar

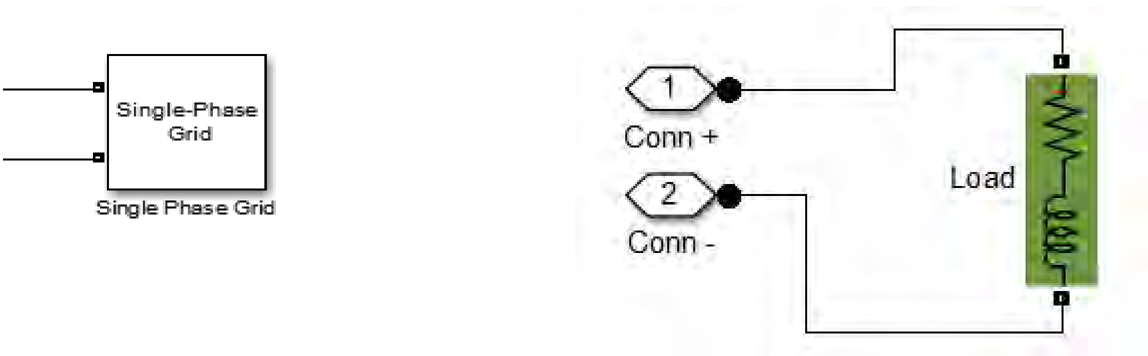

Figure 4. 6: Single-phase grid

4.1.9 Putting It Together

The entire modelled system was connected as shown in figure 4.7.

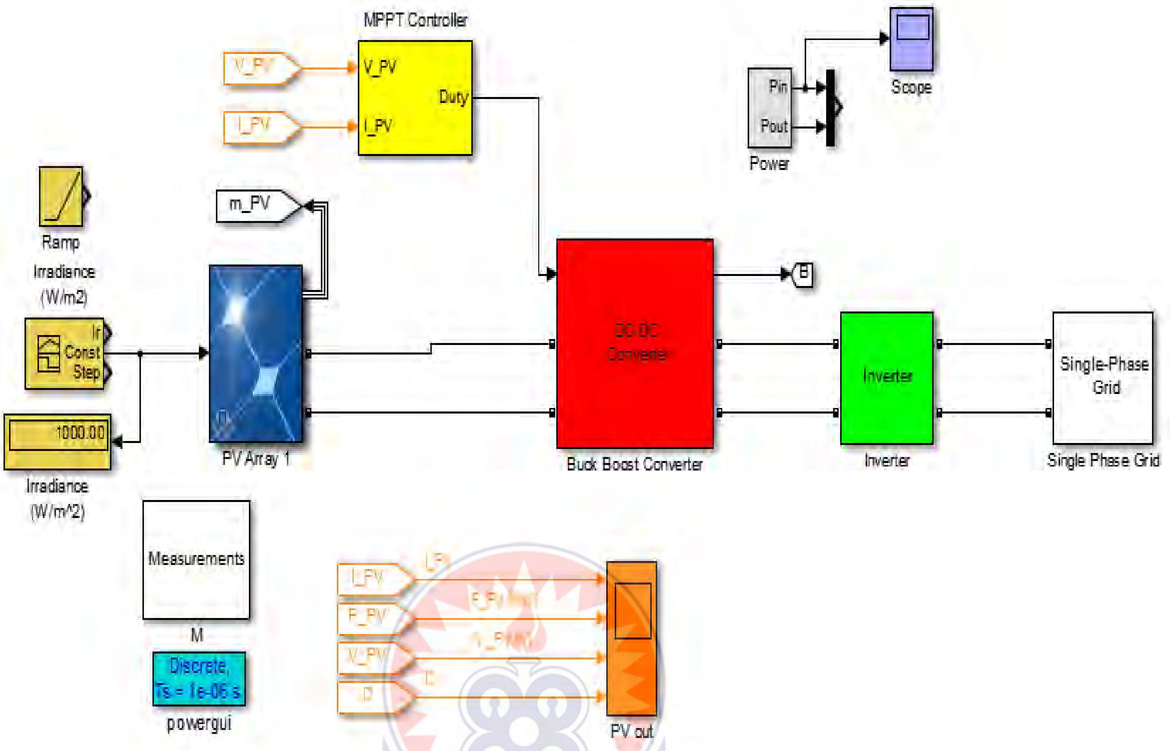

Figure 4. 7: PV system to grid

4.2 Simulation

The entire simulation was run to cater for the different forms of variations that can occur in the irradiance of the PV system that is step, and ramp response. The system was simulated for 0.2 seconds. Within this time, the irradiance was varied through step, and ramp inputs.

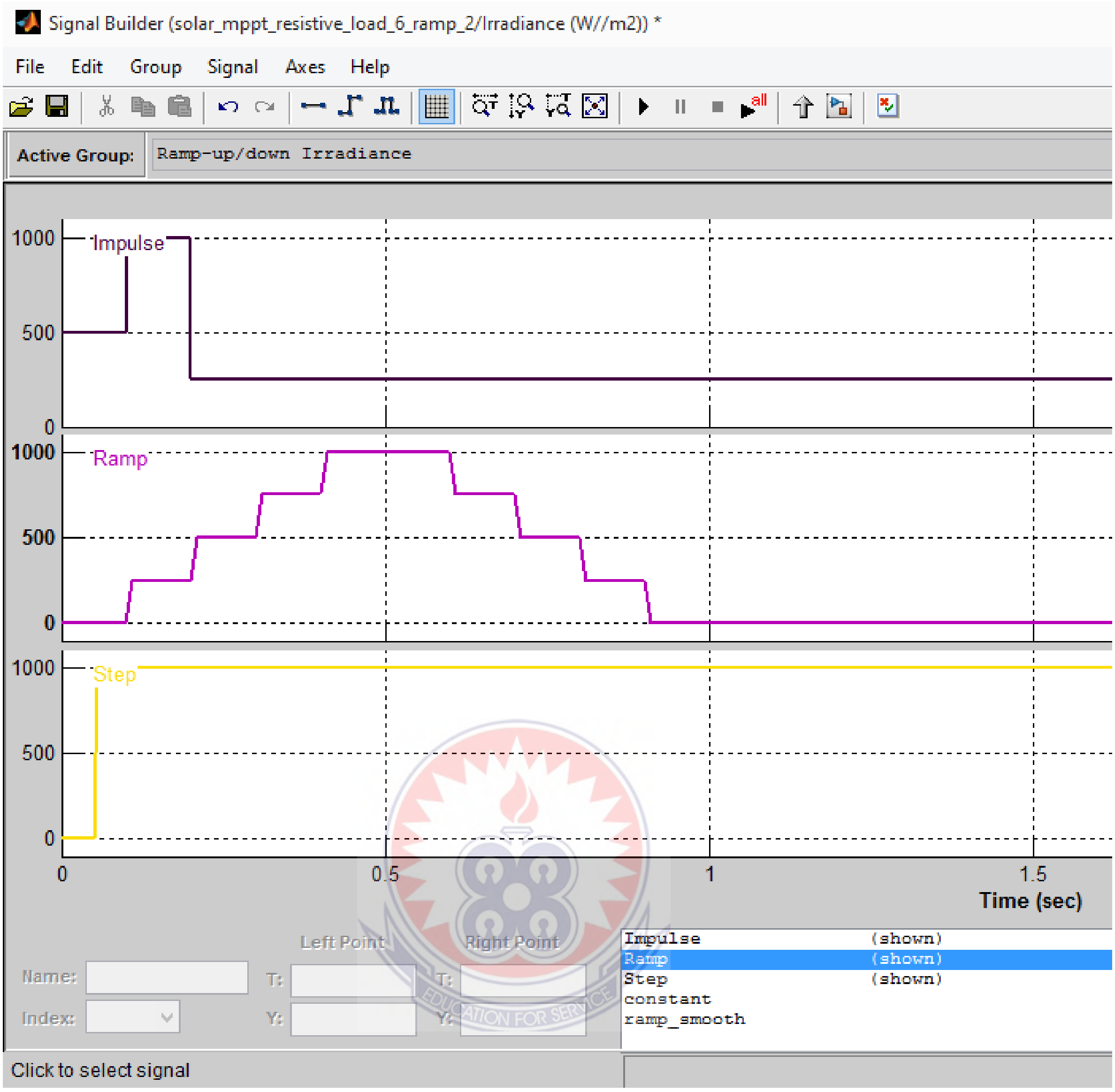

Figure 4. 8: PV system to grid

4.2.1 Initialisation

From t=0 sec, pulses to Boost and VSC converters are blocked. PV voltage corresponds to open-circuit voltage

Voc=5*64.2=321 V, (4.7).

Afterwards, the voltage drops to the MPP voltage.

The MPPT block computes the duty cycle based on the PV voltage and current. The Pulse Width Modulation (PWM) pulse generator produces pulses at 5 kHz out of the duty cycle. These pulses are then used to switch the IGBT of the DC-DC buck boost converter which charges the capacitors up to 200V as seen from the measured Vdc shown below.

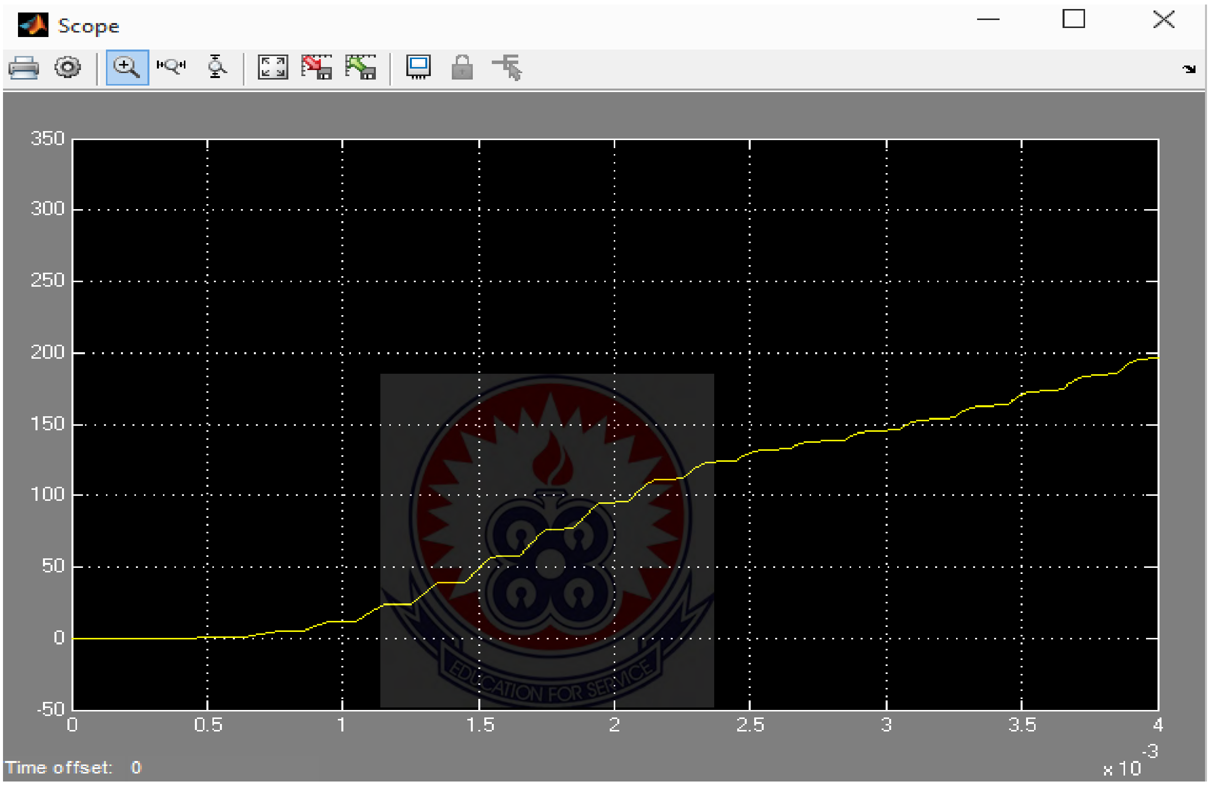

Figure 4. 9: Measured DC-DC converter output

This DC voltage is then inverted by the 1650-Hz (33*50) 3-level 2-phase VSC to generate current alternating with 340 V peak. The generated AC voltage profile for the first 0.2s is shown in figure 4.10 below.

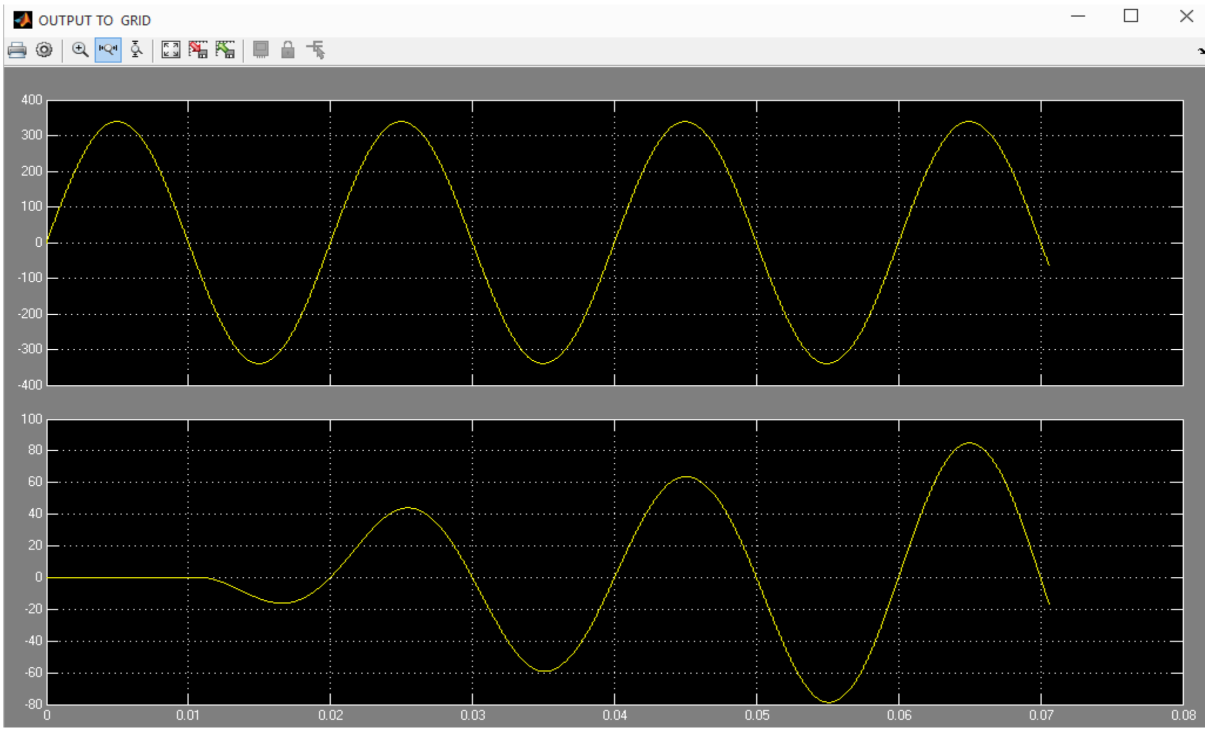

Figure 4. 10: Output AC of Inverter

CHAPTER FIVE

RESULTS AND DISCUSSION

This section describes the results observed after simulation. The system was simulated for step and ramp input irradiance and the output power and voltage characteristics observed. The response parameters were also noted as shown further below.

5.1 Step Response

The system irradiance was stepped up from an initial of 0 to 1000W/m^2 at time 0.05 seconds. The following power and voltage profiles were obtained.

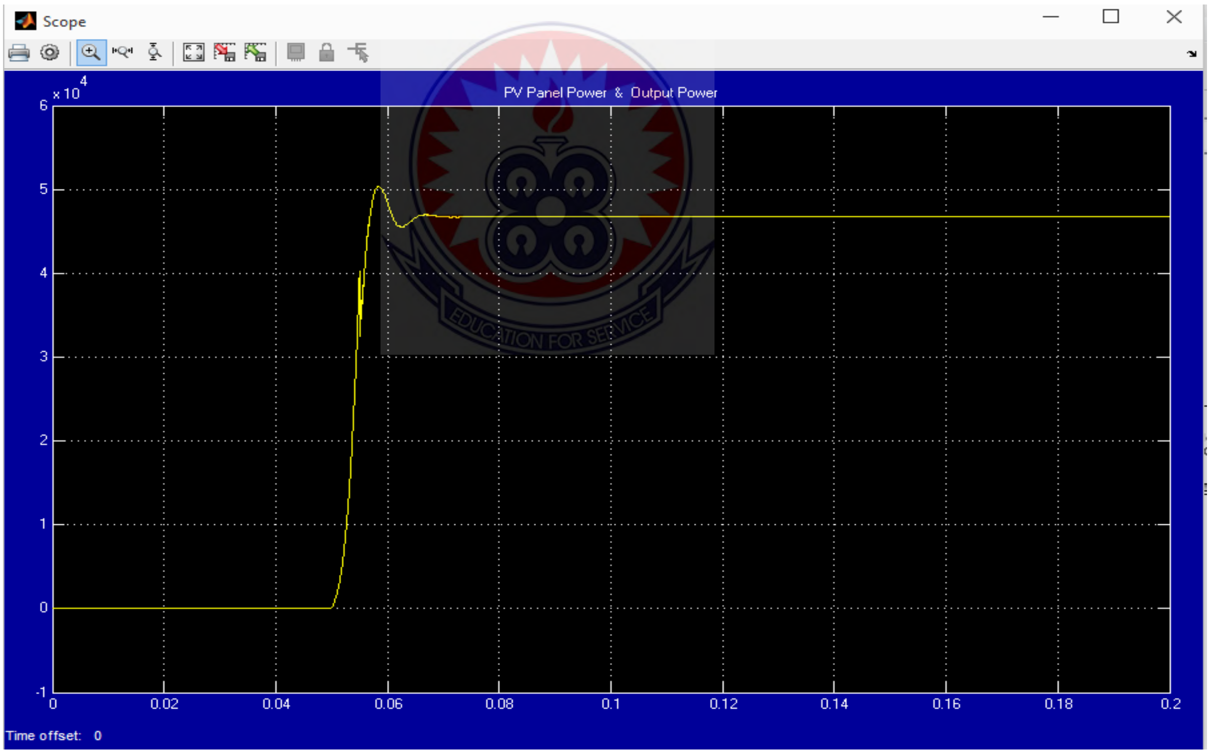

Figure: 5. 1: Power profile over 0.2 seconds

From figure 4.11 above, the PV output power at time zero where the inverter is open circuited is seen as 50.3kW. Once the inverter connects, the power drops and steps up and finally settling at 46.7kW. The results has the following response parameters

Rise time: 71ms

Settling time: 28ms

Overshoot: 7.86%

5.2 Ramp Response

The system irradiance was ramped up from an initial of 0 to 1000W/m^2 and then down to 0 as shown in figure 4.11. The setup was simulated for a second. The following power and voltage profiles were obtained.

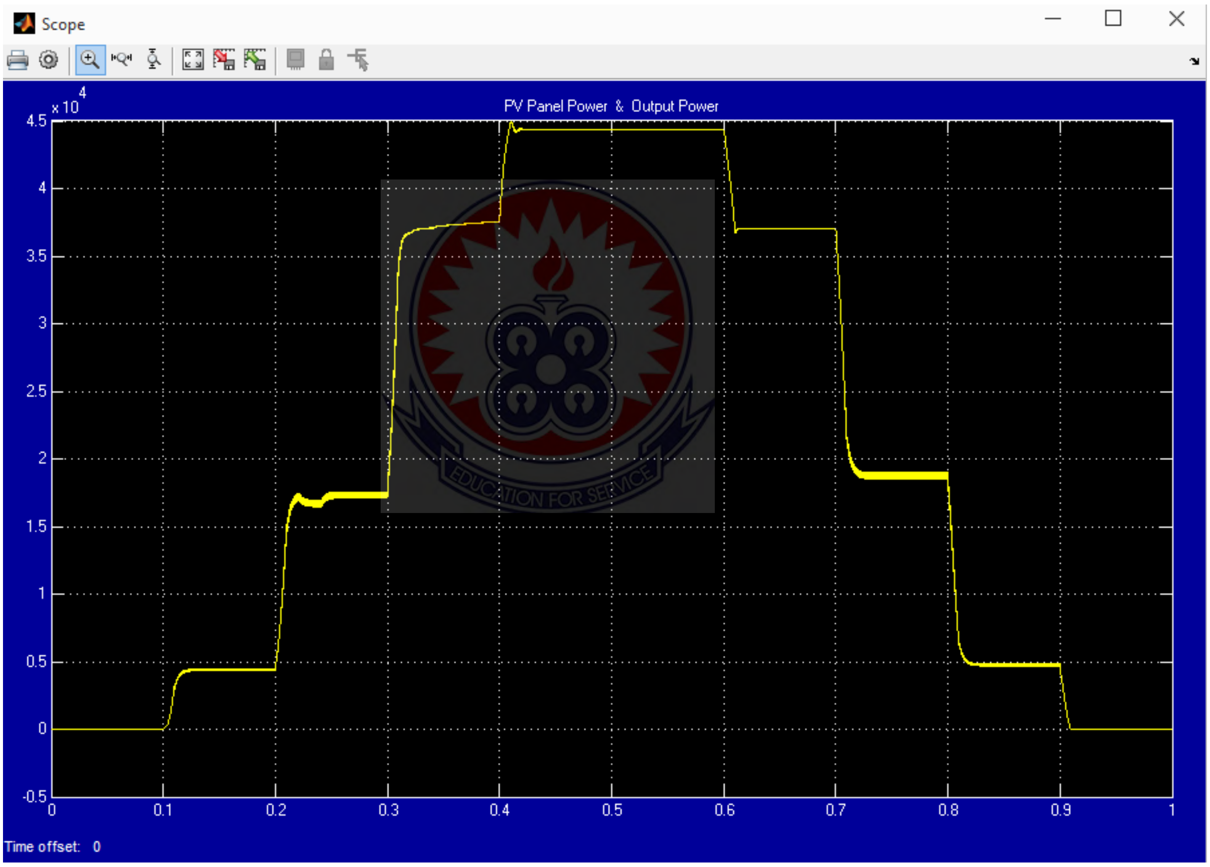

Figure: 5. 2: PV output power for ramp

From figure 4.12 above, the power variation is seen to closely follow the irradiance variation.

5.3 Impulse Response

Irradiance was stepped up and down at times 0.1 and 0.2 respectively as shown in figure 4.11. The PV output power responds appropriately as shown in figure 4.13. It can be seen that during the impulse from 1000 to 250, the PV output goes well below zero to about -2.1MW. This is because at that time, the PV output voltage is negative and well below zero.

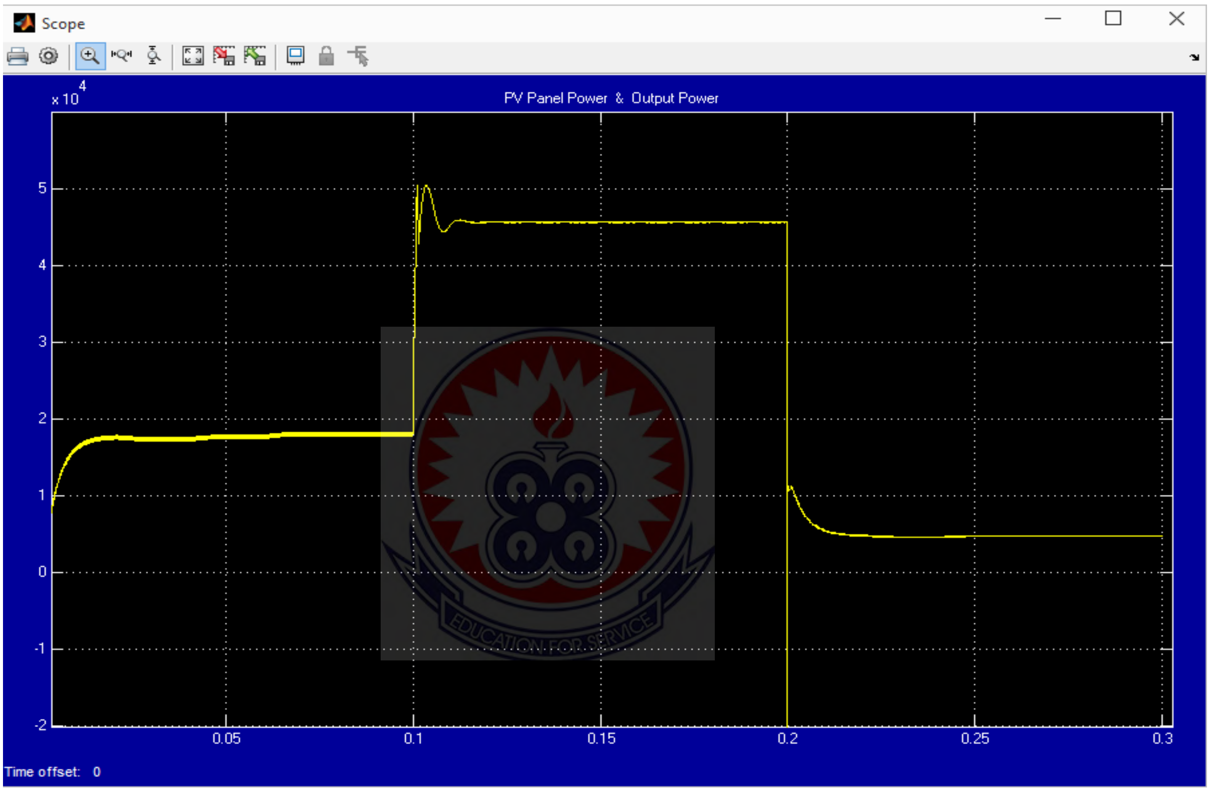

Figure: 5. 3: Scaled PV output power for impulse response

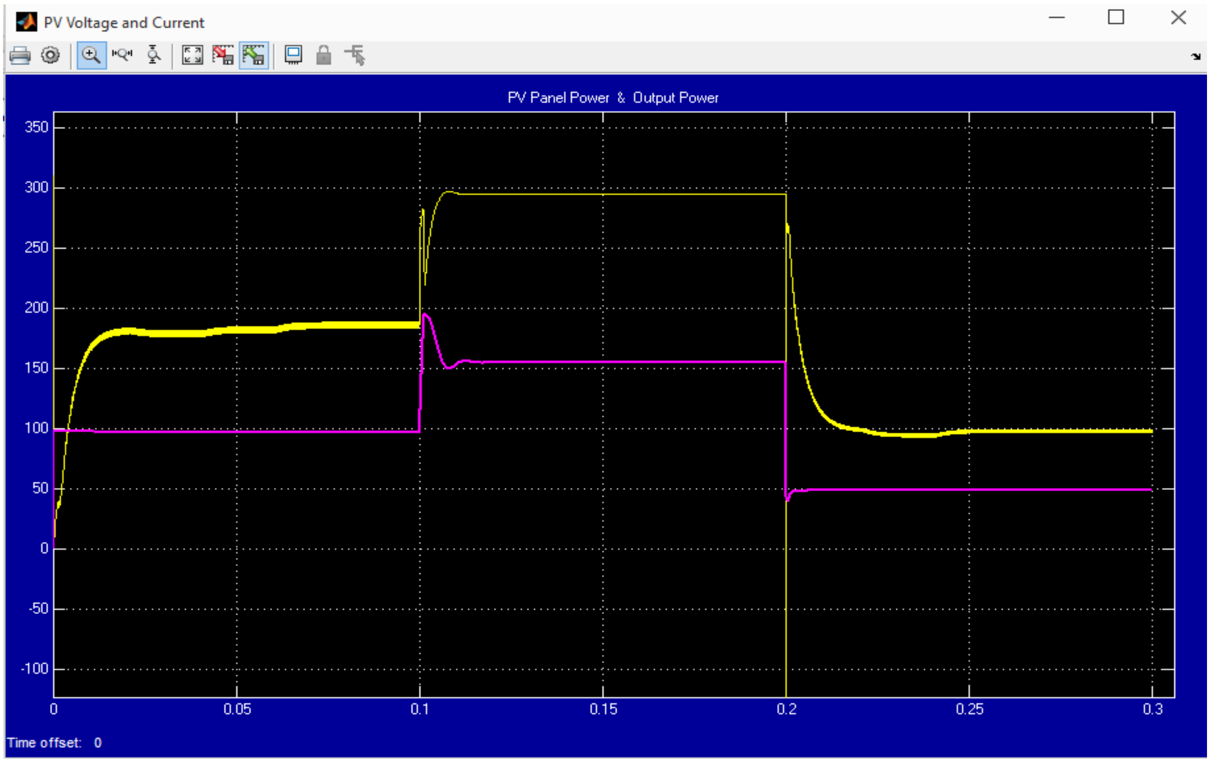

Figure: 5. 4: Scaled PV output voltage and current for impulse response

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

In this paper, the design of grid-connected PV systems has been reviewed. The individual components have been analysed and common selection criteria have been discussed.

A grid-connected PV system is modelled to study the concept of MPPT using the P&O algorithm with duty cycle perturbation while varying the irradiance for step, ramp and impulse response.

From the analysis, the system has been found to operate and supply maximum power to the grid. Also, the following observations have been made.

- Designed MPP tracker achieves its purpose
- Designed LCL filter removes harmonics successfully
- PV output is generated at unity power factor
- Frequency of the AC cycle is 50 cycles per second which is appropriate for the system in this country
- System performs well for step, ramp and impulse irradiance

MPPT fails for low impulse irradiance but quickly recovers.

6.2 Recommendation

It is obvious that the grid connected photovoltaic system has certain advantages in specified areas. The research conducted under this thesis tried to examine these features and created a model in order to simulate. The simulation model can be a starting point and can be improved in several ways for future studies.

Contrasting the proposed single phase system which has its short falls, a three phase system may be a technique to use for better accuracy.

Instead of making assumptions, using fixed values and omitting certain facts in order to reduce the complexity, allowing for more detailed studies. Multipath effects can be added for better understanding. Allowing for multipath may well produce better results. The academic studies that have been used as references in this thesis are the primary resources that can lead to future research and improvements in constructing a grid connected PV system.

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APPENDIX

A 330 SUNPOWER SPECIFICATIONS

% NREL : 2007(E)

SolarModuleSpec(Type).Desc= 'SunPower SPR-305-WHT';

SolarModuleSpec(Type).nCells= 96; % Number of cells in series

SolarModuleSpec(Type).Pmp= 305.2; % Maximum power (W)

SolarModuleSpec(Type).Vmp= 54.70; % Maximum power voltage (V)

SolarModuleSpec(Type).Imp= 5.58; % Maximum power current (A)

SolarModuleSpec(Type).Voc= 64.20; % Open circuit voltage (V)

SolarModuleSpec(Type).Isc= 5.96; % Short circuit current (A)

SolarModuleSpec(Type).TempC_Pmp= -1.154e+000; % Maximum power temp. coefficient (W/deg.C)

SolarModuleSpec(Type).TempC_Vmp= -1.860e-001; % Maximum power voltage temp. coefficient (V/deg.C)

SolarModuleSpec(Type).TempC_Imp= -2.120e-003; % Maximum power current temp. coefficient (A/deg.C

SolarModuleSpec(Type).TempC_Voc= -1.770e-001; % Open circuit voltage temp. coefficient (V/deg.C)

SolarModuleSpec(Type).TempC_Isc= 3.516e-003; % Short circuit current temp. coefficient (A/deg.C)

SolarModuleSpec(Type).Rs= 0.037998; % Series resistance of PV model (ohms)

SolarModuleSpec(Type).Rp= 993.51; % Parallel resistance of PV model (ohms)

SolarModuleSpec(Type).Isat= 1.1753e-08; % Diode saturation current of PV model (A)

SolarModuleSpec(Type).Iph= 5.9602;   % Light-generated photo-current of PV model (A)

SolarModuleSpec(Type).Qd= 1.3;   % Diode quality factor of PV model