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CONSTANT PV OUTPUT BY USING DUAL CONVERTERS FOR DC APPLICATION

by

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A THESIS

Submitted to the graduate faculty of The University of Alabama at Birmingham,
in partial fulfillment of the requirement for the degree of
Master of Science in Electrical Engineering

BIRMINGHAM, ALABAMA

2017

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2017

CONSTANT PV OUTPUT BY USING DUAL CONVERTERS
FOR DC APPLICATION

ABDULLAH ALGHAMDI

ELECTRICAL AND COMPUTER ENGINEERING

ABSTRACT

The energy from solar panels can be improved to extract more power by using DC-DC converters operating in continuous mode. DC-DC converters which generate fixed DC voltage were selected to observe the photovoltaic operation at maximum power point (MPP).

In this thesis, a boost converter and a buck converter are cascaded to step-up then step-down voltage from a photovoltaic (PV) array with changeable voltage, irradiance, and temperature, to a 24 V DC. The filtering parameters of the converter were computed and the means which is used as a switch is a metal oxide semiconductor field effect transistor (MOSFET) with a switching frequency of 10 KHz. However, the I-V (current-voltage) characteristic of the PV array is affected by irradiation and temperature, which have a nonlinear relationship. Therefore, the duty cycle needs to be calculated and changed to turn the converter to the maximum power available. The change in irradiation and temperature give different MPP at various curves.

The algorithm of the MPP tracking (MPPT) operation was achieved by using the Incremental Conductance (IC) method to provide high tracking accuracy and faster response. The entire system has been designed using MATLAB Simulink Program and simulation results are presented to show the efficacy of the proposed scheme.

DEDICATION

I dedicate this master thesis to my family, my teachers, and my friends who have provided full support throughout my life and always had faith in my success.

ACKNOWLEDGEMENT

Firstly, I would like to express my deepest appreciation for the entire Electrical and Computer Engineering Department at the University of Alabama at Birmingham, that helped me in my master’s degree journey. They are always helpful and provided me with the means to learn more.

I would also to express my sincere gratitude to my supervisor Dr. Mohammed Haider for his help and guidance throughout the course teaching. His experience in renewable energy gave me more knowledge in this area and allowed me to take this thesis in the solar energy subject.

Finally, I want to thank my family, and friends, especially my parents and wife who have been supporting and encouraging me during all this period. They provided me with the right environment to study and concentrate on my goals.

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CHAPTER 1

PROJECT OBJECTIVES AND BACKGROUND

1. Introduction

Renewable sources of energy have now become essential due to the high usage of fossil fuels on the earth. Utilizing and exhausting fossil fuels leads to increased pollution and emissions of greenhouse gases, such as carbon dioxide, into the atmosphere [1]. In addition to their negative environmental effects, fossil fuels are not renewable resources. However, future energy sources need to be practical, sustainable, and renewable. Renewable sources of energy such as photovoltaics (PV), hydropower, solar thermal power, wind power, and biomass are eco-friendly and free of pollution. The most common issues with renewable sources of energy are based on their development cost and efficiency.

Of the various renewable sources of energy, solar energy is the most prevalent. Solar energy is generated by using solar panels, which are made of photovoltaic cells that convert sunlight into electricity [2]. These solar panels can be used as applications to battery chargers and grid-connected PV systems. Solar energy is mainly used because it creates less pollution, requires less maintenance, and it is available for free throughout the world [3]. However, the primary challenge is to convert sunlight into electricity efficiently because this depends on real-time environmental conditions, such as solar irradiance and temperature [4].

In the market, there are several types of PV panels with an average efficiency of 8% to 12% when converting available sunlight into electricity [5]. Many techniques were recently introduced to enhance the efficiency of photovoltaic panels [6], one of them being the use of MPPT algorithms. These methods require a DC-to-DC converter, either a boost or a buck converter, or any other type of DC -to- DC converter. Additionally, using MPPT is necessary in order to control the converter operation and duty cycle.

This project aims to develop a DC-to-DC boost converter and buck converter with a closed loop proportional-integral (PI) controller and to perform an IC MPPT algorithm to confirm that the maximum amount of power is received from the PV panel.

The entire system has been designed using the MATLAB Simulink Program and simulation results are presented to show the efficacy of the proposed scheme. Comparative study on MPPT algorithms recommends Incremental-Conductance (IC) as a suitable option because it is accurate and can track the MPP under rapid variations of atmospheric conditions in an easy way [7].

2. Literature review

Solar energy systems are still a somewhat new and growing technology, which is moving in many directions. It is useful in many places such as homes, energy, water, and heating. Here is a list of some existing research about solar power systems:

- The first paper is “Closed Loop DC-DC Boost Converter with Inverter for Small Scale Generation Plan.” In this article, the authors used an input of 24 volts DC from DC supply and an output of 373 AC by using a boost converter to increase the voltage. The authors also used two level inverters to convert

DC voltage to AC voltage. The authors used feedback PI to keep the output constant, but they did not use a PV cell model or MPPT. [8]

- The second paper is “Design and Simulation of Closed Loop Boost Converter for Voltage Regulation of PV System.” In this article, the authors used two methods: an open loop and a closed loop. In the first method, they chose an input of 22 to 28 V DC, and each voltage had higher output by using a boost converter. The PWM was the control switch, but the output was not constant because it was an open loop method. The second method was a closed loop where the input varied from 22 to 26 V DC voltage and the output was consistent because using the PWM technique can maintain a constant voltage. [9]
- The third paper is “Circuit Simulation for Solar Power Maximum Power Point Tracking with Different Buck-Boost Converter Topologies.” This article is about the development of a circuit simulation model for MPPT analysis that uses different converters, such as four-switch buck-boost DC/DC, SEPIC, and Zeta converters. The simulation consisted of a PV model, a buck-boost converter to increase the input from the PV system to a higher output, and a fuzzy logic MPPT controller.[10]
- The fourth paper is “Maximum Power Point Tracking Simulation Based on Perturb and Observe Algorithm for PV Array Using Boost Converter.” This article is about the use of a PV system with a boost converter and P&O MPPT.[11]

In my thesis, I did a modeling of a PV panel, a boost converter with IC MPPT, and a buck converter with PI, which was different from other models. It has the advantage of a constant output at 24 DC voltage, which will be used to power small devices like lights, laptops, cell phones, and any other devices that can be run with 24-DC voltage.

3. Thesis aims and objectives

The main object of this thesis is to design and develop a solar power system by using MPPT, including DC-to-DC converters, in a closed loop to get a constant output. This thesis aims to develop DC-DC boost and buck converters with a closed loop feedback and to perform MPPT to make sure that maximum power can be received from the PV panel.

Literature review on MPPT algorithms recommends IC as a suitable option because it is accurate and it can go to the MPP under rapid variations of atmospheric conditions in an easy way. The objectives as outlined are to:

- Choose a PV modelling module.
- Specify the MPP after obtaining the I-V characteristic.
- Select and design a DC-to- DC converter in a closed loop.
- Size components of the selected DC-DC converters.
- Select a convenient MPPT method to receive maximum power from the PV.
- Implement the system in MATLAB Simulink program.

4. Thesis layout

This thesis is divided into 5 chapters:

- **Chapter 1:** Project Objectives and Background

  The first chapter covers the introduction, literature review, aims and objectives, thesis layout, background, types of solar cells, DC-to-DC converters, and MPP Tracking.

- **Chapter 2:** Methodology

  The second chapter provides more detail about the PV, MPPT, IC, and boost and buck converters.

- **Chapter 3:** Proposed Design and Simulation Results

  he third chapter presents the simulation and performance of the polycrystalline PV type at different temperatures and radiation levels, as well as the PV characteristics and the maximum power achieved. Finally, PV modeling is implemented by using the MATLAB Simulink Program.

- **Chapter 4:** Conclusion and Further Work

  The fourth chapter presents the results of this work and its conclusions, with some recommendations for future work.

5. Background

5.1 Solar panel

A solar panel can also be called a photovoltaic (PV) panel. Most are made from silicon and other materials. A solar panel is designed to convert sunlight into electric energy. The main purpose for solar panels is to use the converted electric energy for heating or for producing electricity directly [12].

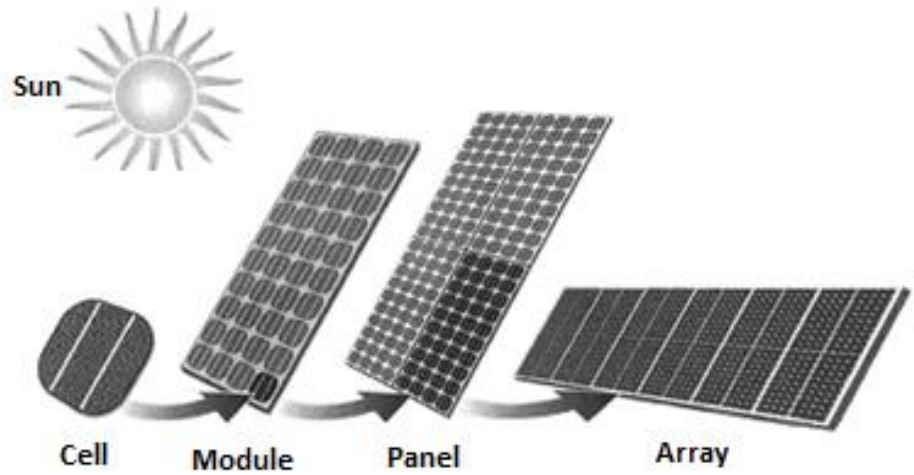


Fig. 1. Solar Cells, Modules, Panel and Arrays configuration types [13].

The above Fig. 1 shows the difference between solar cells, modules, panels and arrays, as well as their configuration types. PV arrays consist of several PV panels [12]. The PV panel contains numerous solar cells connected in parallel or series circuits. This connection depends entirely on the application and on how much voltage or current is required for the load [14]. Therefore, voltage and current levels are used when referring to the PV panel, not to individual PV cells. A series connection can be used when the operating voltage is low (at millivolts) and the current is high. Thus, a series arrangement helps to increase the output voltage by adding the voltage of each cell for each string. On the another hand, a parallel cell connection can be used to increase the current in the PV panel because it will add the current for each cell, but this is less common [14].

5.2 Operation

PV cells are composed of semiconducting materials. Generally, this consists of silicon doped with a slight quantity of impure atoms that can convert the electromagnetic radiation into electrical energy. The cell consists of a positive (P) and a negative (N) layer making a P-N junction as seen in Fig.2. Sunlight produces energy in the form of photons.

When sunlight hits the N-type silicon layer, the minority carriers inside the P-N junction are generated and move to the P-side. This flow of carriers creates electrical current and makes the conversion of solar energy into electrical energy possible [15].

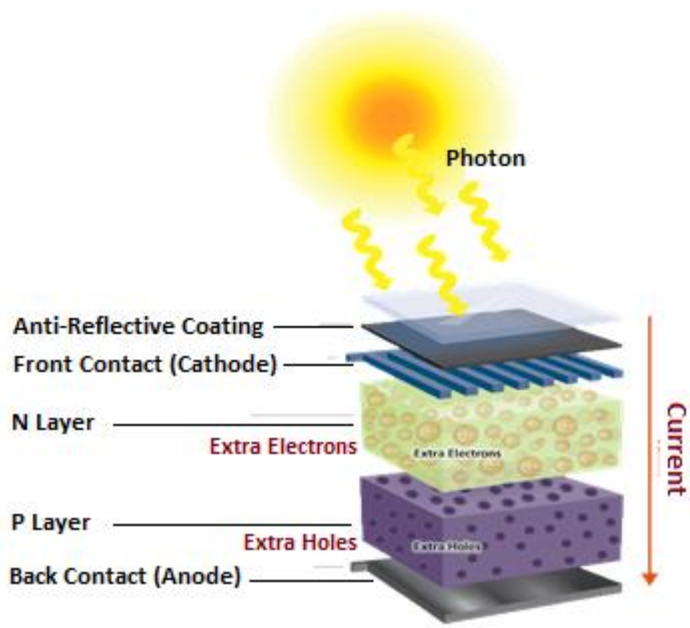


Fig. 2. Silicon PV Module Structure [16].

5.3 Equivalent Circuit of a Solar Cell

Connecting the diode in parallel with a current source can make an electrical module that produces the mean of all photovoltaic sources, as seen in Fig. 3. The generator current depends on the semiconductor material used for the cell as it represents the current source.

Cell physical effects at the silicon P-N junction are dependent on the rectifying diode. The I-V characteristic equation of an ideal circuit can be:

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_o}.\left(\mathrm{e}^{\frac{\mathrm{V}}{\mathrm{n}\,V_T}} - 1\right) \qquad (1)$$

Where I_L the current on the PV module and I_D is the diode current which is proportional to the saturation current and is given by the equation (2):

$$I_D = I_o.\left(e^{\frac{V}{n\,V_T}} - 1\right) \qquad (2)$$

V is the voltage imposed on the diode.

$$V_T = k\,.{}^{T_c}/_{q} \qquad (3)$$

I_o is the reverse saturation or leakage current of the diode (A), $V_T = 26\,mV$ at 300 K for the silicon cell, T_c is the absolute cell temperature (K), k is Boltzmann's constant $(1.381\times10^{-23} J/K)$, q is the electron charge $(1.602\times10^{-19}\ C)$. V_T is called the thermal voltage because of its dependence on absolute temperature. n is the number of PV cells connected in series, multiplied by the ideality factor. The ideality factor depends on the PV cell technology.

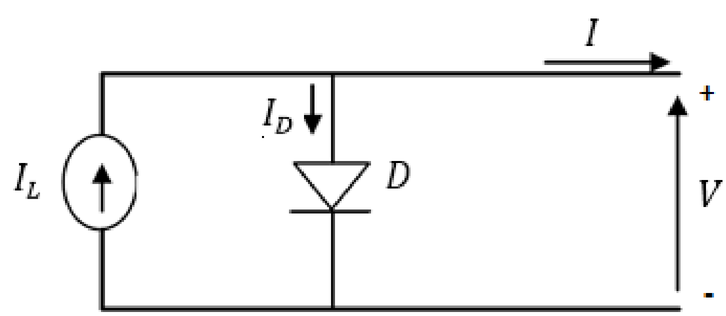
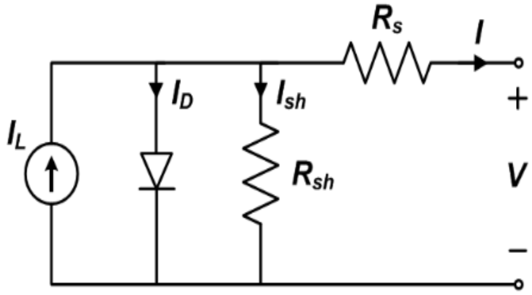
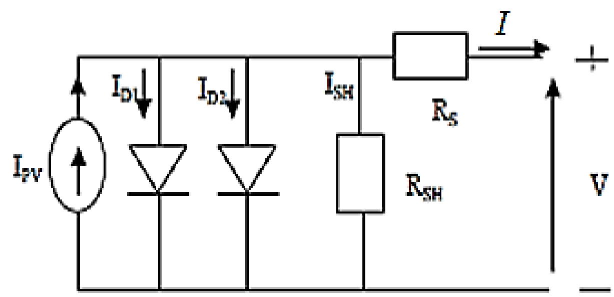


Fig. 3. Ideal Equivalent Circuit for a PV Cell [17].

Fig. 4(a) illustrates the PV model in real-world conditions because series and parallel resistors in solar panels can explain the power dissipation in the cell. Under ideal conditions, R_{sh} is infinite so the current can only flow to the load because there is no other alternate path while R_s is zero. Therefore, there is no further voltage drop before going to the load. The higher R_s will make the V_{oc} and the power drop. The lower R_{sh} will make the I_{sc} and the power drop. [18]-[19]-[20]



(a). PV Cell Equivalent Circuit and Shunt Losses Based on One Diode.



(b). PV Cell Equivalent Circuit Based on Two Diodes

Fig. 4. PV Cell Equivalent Circuits and shunt losses - Dual Diode Based Circuit - Diode Based Circuit [21]- [22].

There is a voltage drop in the solar cells when the current passes through the semiconductor to the output contact. It happens when there is series resistance, where the parallel resistance affects the current leakage at the cell edges. [21]- [22]- [23]

The output current of the solar cell is given by equation (4) [22]:

$$I = I_L - I_o.\left(e^{\frac{V}{n\,V_T}} - 1\right) - \frac{V + I.R_S}{R_{Sh}} \qquad (4)$$

I is the output current of the solar cell and V is the output voltage of the solar cell. I_o represents the saturation current, T is the cell temperature, V_T is given in equation (3), R_S

is the solar cell's series resistance, and R_{Sh} is the shunt resistance. The resistance values can be calculated by using equations (5) and (6). [23].

$$R_S = \frac{dV}{dI} \; at \; V_{OC} \tag{5}$$

$$R_{Sh} = \frac{dV}{dI} \; at \; I_{SC} \tag{6}$$

Where a is the diode's ideally factor, V_{OC} is the open-circuit voltage and I_{SC} is the current in the open-circuit voltage.

However, Fig. 4(b) shows the PV module with an additional diode added in parallel with a single diode, as in Fig. 4(a). The extra diode is attached to provide more accuracy in the I-V characteristic. Therefore, it is more accurate than using a single diode, but it requires more complex equations [21]- [22]- [23].

5.4 I-V Characteristic for Solar Cell

On the P-V (Power-Voltage) curve as shown in Fig. 5, there is a peak point called Maximum Power Point (MPP). This point is the maximum amount of power that solar panels can generate and can be found on the I-V curve at the point (V_m , I_m). Another parameter that can be read from the I-V curve is the V_{oc}, which is a voltage, and can be measured by the open circuit. At the open circuit condition, there is no flow current, and it can be seen at point (V_{OC}, 0) of the I-V curve. The next parameter is the I_{SC} value that can be measured at the short circuit condition (V = 0) at point (0,I_{SC}) on the I-V curve. I_{SC} can be calculated by using equations (7) and (8) [15]- [24]. As stated in equation (7), it rises with increasing temperature, as will be discussed later [25].

$$V_{OC} = \frac{nkT}{q} \ln\left(\left(\frac{I_{sh}}{I_O} + 1\right)\right) \qquad (7)$$

$$I_{SC} \approx I_L \,(\mathrm{v} = 0) \qquad (8)$$

Fig. 5 shows the MPP generated by the solar cell for an I-V characteristic. This is the desired point of power that the PV module needs in order to operate ON at all times, using MPPT. The role of the MPPT technique and algorithm will be discussed later in this section.

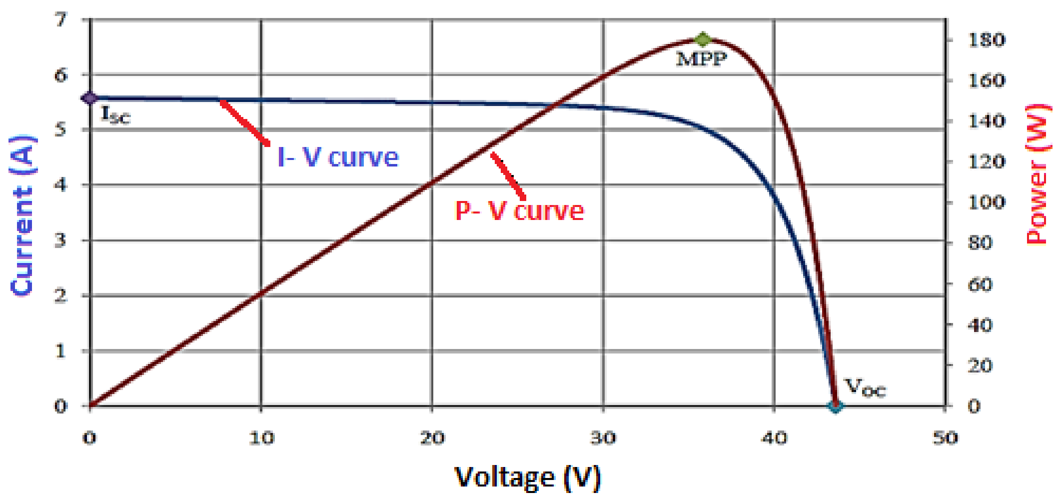
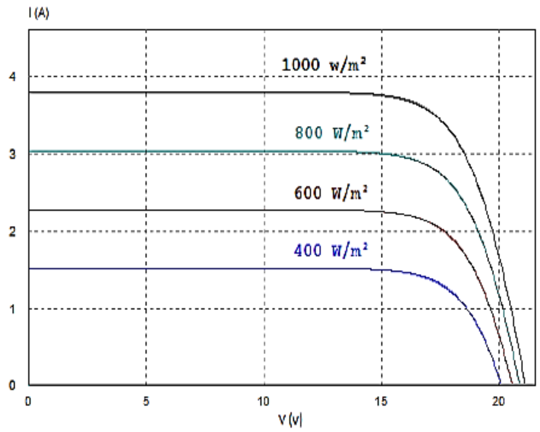


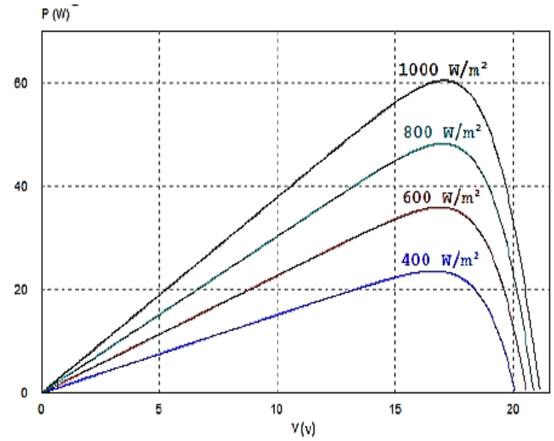
Fig. 5. Sample of Maximum Power for an I-V Characteristic.

5.5 Effect of irradiation

Irradiance is a major factor that greatly affects the power generated by solar panels. In order to present the effect of solar radiation variation, the PV panel model present in Fig. 4(a) is simulated in Ref [26] for different values of irradiation (G) at T=25 °C.



(a). I-V characteristics for different solar irradiation



(b). P-V characteristics for different solar irradiation

Fig. 6. I-V and P-V characteristics for different solar irradiation [26].

As shown in Fig. 6, the PV panel current is highly dependent on solar irradiation. Nevertheless, the voltage increased by 1 V when the irradiation was increased from 400 W/m² to 1000 W/m².

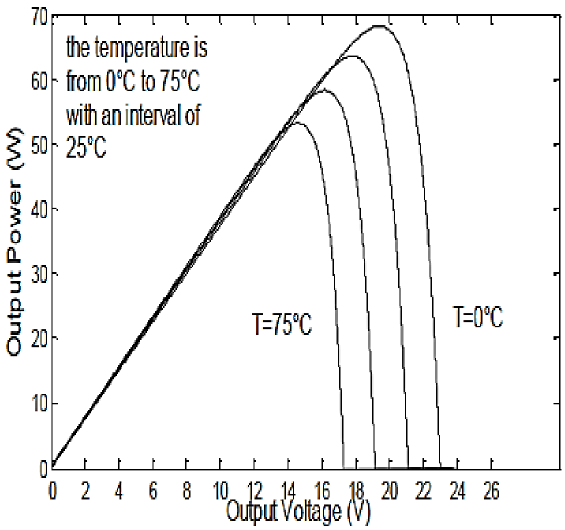
5.6 Effect of temperature

The temperature effect is inversely proportional to the irradiation effect. As temperatures increase, the value of power decreases due to the limits of an electronic devices' ability to operate at higher temperatures. This temperature parameter greatly affects the V_{oc} value that is explained by equation (9) [27]:

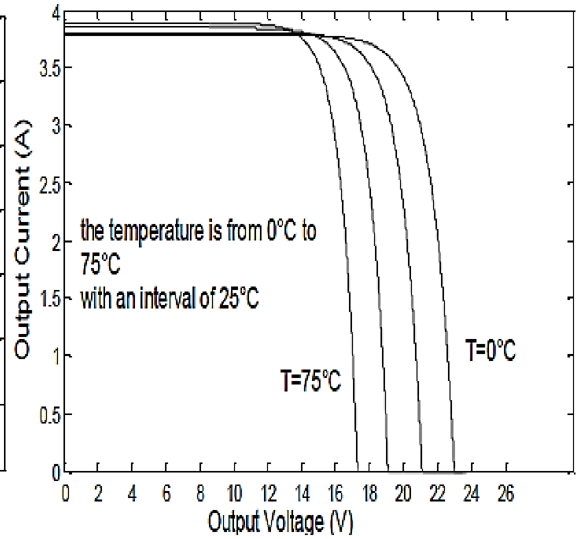
$$V_{oc} = m * V_T \ln\left(\frac{I_{sh}}{I_s}\right) \qquad (9)$$

Where as V_T is the thermal voltage, I_{sh} is the current related to the R_{sh} resistance and I_s is the current related to the R_s resistance.

In order to present the effect of temperature variation, the PV panel model presented in Fig. 4(a) is simulated in Ref [21] for different temperature values. In Fig. 7(a) and Fig. 7(b), the P-V and I-V characteristics under constant irradiance (G=1000 W/m²) with varying temperatures are presented, respectively. From these figures, when the operating temperature increases, the output current increases dramatically while the output voltage decreases marginally, which results in a net reduction in power with a rise in temperature.



(a). Curve P-V at G=1000 W/m2 for various Temperatures



(b). Curve I-V at G=1000W/m2 for various Temperatures

Fig. 7. I-V and P-V characteristics for various temperature at G=1000 W/m² [21].

6. Types of solar cell panel

The variety of available solar energy technologies is characterized by efficiency, price, durability, and flexibility, depending on the specifics need for a given project. Photovoltaic solar technology generates energy because substances such as silicon generate an electrical current when they absorb sunlight in a process called photovoltaic effect. Like semiconductors, solar PV technology needs purified silicon to achieve the best efficiency, and the crystal silicon purification process often drives up the price of photovoltaic solar manufacturing [28]. The three most common PV modules are:

1- Monocrystalline silicon solar PV

2- Polycrystalline silicon solar PV

3- Amorphous and thin film silicon solar PV

6.1 Monocrystalline silicon solar PV

Monocrystalline silicon cells are the best technology for efficiency, as measured by watts output, depending on the size of the panel. Each model is made from thin slices (wafers). Wafers are made of a single crystalline material extracted from pure molten silicon. There are two colors: black or iridescent blue. Fig. 8. shows the monocrystalline panel. This type of model, however, requires a careful manufacturing process at high temperatures. This makes it expensive to manufacture. The efficiency of this module is in the range of 15% to 18% and a $7\ m^2/1\ kW$ surface area is required. [29].

Fig. 8. Monocristalline silicone Solar PV [28].

6.2 Polycrystalline silicon solar PV

Polycrystalline silicon solar PV modules, sometimes called multi-crystalline PV modules, are made of multiple fragments of silicon that are melted together to form wafers on the panel. This process is called casting because pure molten silicon is used [12].

Fig. 9 shows a polycrystalline panel. The crystal is not ideal as it has varying structures, sizes, and shapes. Therefore, polycrystalline is 11% to 15% less efficient than monocrystalline silicon. The advantages of polycrystalline are that it is much simpler and has a lower overall cost, which means the manufacturers are able to use less silicon for a polycrystalline panel than they would for a monocrystalline panel. Finally, the surface area required for polycrystalline silicon is normally 8 m^2/kWp and the color sometimes will be blue. [29]

Fig. 9. Polycrystalline silicone Solar PV [28].

6.3 Amorphous and thin film silicon solar PV

Amorphous silicon is the first thin film PV model to be commercially produced. It is entirely different from the previous two because it is made without crystalline silicon. Because a thin film is being used, these models get lower temperatures than crystalline silicon. This makes them less expensive and less efficient than crystalline silicon. Fig.10 shows a thin film panel. Thin film has efficiency of around 6% to 8%. Because they have low efficiency, the area can cover 16 m^2/kWp. The advantage of this is type of solar panel is that it can work on cloudy days. [29]

Fig. 10. Thin Film silicon solar PV [28].

6.4 Other cells and materials

Materials other than silicon can be used to develop solar cells. The efficiency rate is higher than others, which is around 10% to 12%. The advantages of this design are similar to the thin film design, such lower cost. [29]

7. Maximum power point tracking

This is the fundamental subsystem in PV systems because it is necessary in order to get the highest power from the PV array. If the converter is switched, it can be used to maximize the output. All of the different methods of tracking MPP have their advantages and disadvantages in terms of cost, accuracy, complexity, and convergence speed. A DC-DC converter with a controlled duty cycle is required. Constant voltage (CV), P&O, and IC are the most commonly used methods in a commercial product. [30]. IC is assumed to be an improved version of P&O, but it is more complex. P&O is a popular method because it can be implemented easily and it is suitable for any PV array. The IC is very complicated other than perturbation and observation (P&O).

7.1 Constant Voltage Method

The CV method is the simplest method to track the MPP. A voltage measurement with a simple loop control is used to reach the MPP. The operating point of the PV array should match the voltage at MPP, which is around 70% to 80% of the PV open circuit voltage. Equation (10) computes the voltage at the MP. [31]

$$V_{MPP} = m\, V_{OC} \qquad (10)$$

Where:

- V_{MPP} is the voltage at MPP.
- m is the scale factor.
- V_{OC} is open circuit voltage.

When the solar radiation changes, the MPP voltage varies slightly, but more change occurs when the PV temperature changes. Thus, this method is suitable for locations where there is little variation in temperature.

To match the PV array voltage to voltages at MPP, the voltage reference V_{REF} must be equal the voltage value of MPP or another best-fixed voltage [31]. The requirement of the constant voltage algorithm makes it possible to measures the voltage. This voltage needs to control the duty cycle as shown in Fig. 11

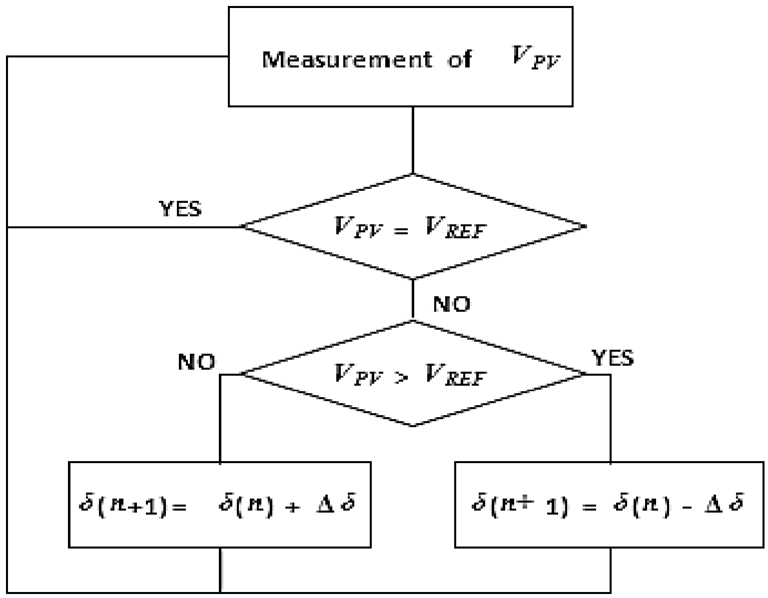


Fig. 11. Constant Voltage Flow Chart.

7.2 Perturbation and Observation P&O

The P&O technique is based on the slope or gradient of the P-V curve (gradient m = dP/dV). As shown in Fig. 12, the P-V curve can be divided into two areas at the point of MPP. One is the negative gradient (right side) and the other is the positive gradient (left side). When the operating voltage on the left side (positive gradient) [30], it must be increased to get the MPP and vice versa [32]. The positive gradient can be obtained when dP and dV are the same sign (both are positive or both are negative) and the negative gradient can be obtained when dP and dV have different signs (dP is positive while dV is negative or vice versa). This technique compares the current measurement to the previous measurement to obtain dP or dV. [30]- [33]

P&O uses a fixed step to increase or decrease the voltage on the I-V curve for tracking the maximum (optimal) power. There are two methods for these steps. The first method uses a small step where the mean oscillation will be reduced and tracking will be slow. The second method uses a bigger step where the mean oscillation will be greater. Although the scheme can track the process quickly, it also increases the power loss. [18]-[30]

It can be modified using a decreasing step (not fixed step) so that the tracking process will be faster and have smaller oscillation in a steady state [30]. Fig. 13 shows a flowchart of the P&O algorithm and explains the P&O process.

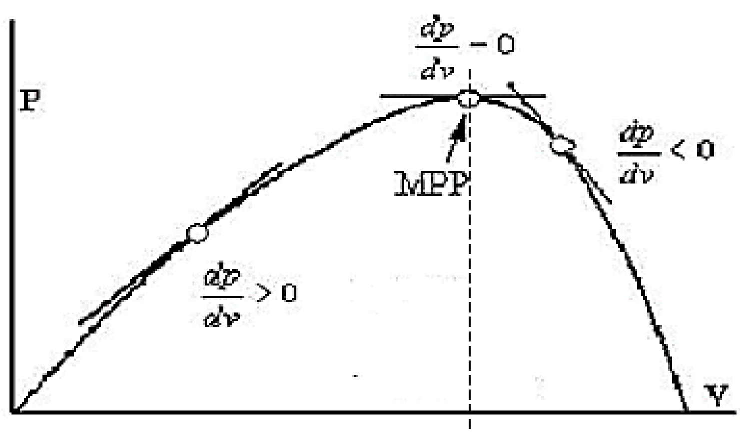


Fig. 12. P&O Algorithm MPP at Maximum [33].

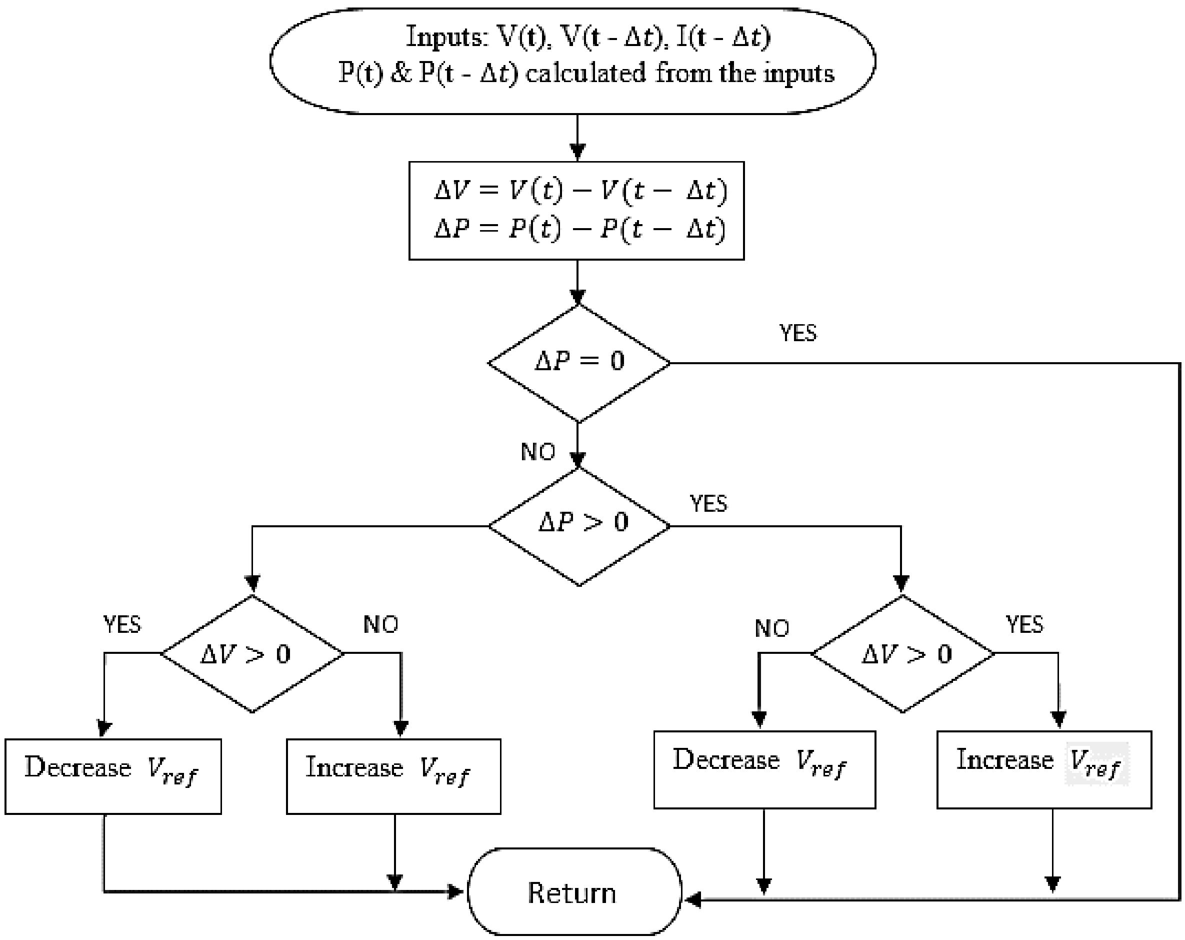


Fig. 13. Flowchart Showing the P&O Algorithm [30].

7.3 Incremental Conductance

Incremental-Conductance (IC) is a method often applied in PV systems. IC uses the same technique as P&O, however, it is a more modern method. In this process, the MPP is tracked by comparing the instantaneous and incremental conductance of the PV array. This is related to the voltage. If the voltage increases or decreases, then MPP has been reached. When the right value has been reached, the incremental conductance will stop to update. This method uses a fixed step size to update the voltage and a bigger step for fast tracking, as shown in the equations (11) and (12) [34]. Each system has some advantages and some disadvantages. The disadvantage of the IC system is that this method is similar to P&O. For this approach to obtain a fast response and accurate output, a steady state performance is required [34]. In order to measure this, two sensors must be used: one for voltage and one for current. Fig. 14 shows the IC flowchart [30].

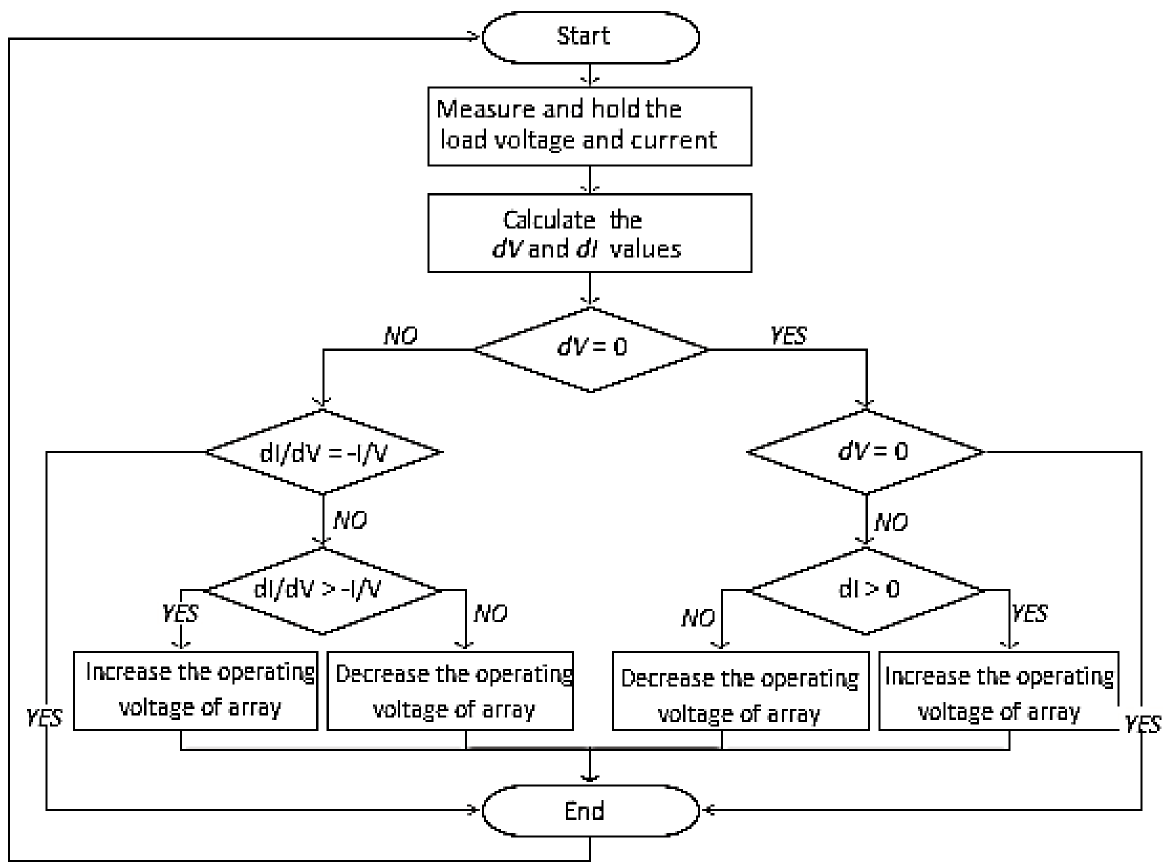


Fig. 14. Flowchart Showing the IC Algorithm [34].

$$\left.\begin{array}{l} \frac{dP}{dV} = 0, \qquad at\ MPP \\ \frac{dP}{dV} > 0, Left\ of\ MPP \\ \frac{dP}{dV} < 0, right\ of\ MPP \end{array}\right\} \tag{11}$$

$$\left.\frac{dP}{dV}\frac{d(IV)}{dv} I + V\ \frac{dI}{dV}\ \frac{dI}{dV}\right\} \tag{12}$$

From equations (11) and (12), we can obtain the equation (13) so that:

$$\begin{array}{ll} \frac{dI}{dV} + \frac{I}{V} = 0, & at\ MPP \\ \frac{dI}{dV} + \frac{I}{V} > 0, & left\ of\ MPP \\ \frac{dI}{dV} + \frac{I}{V} < 0, & right\ of\ MPP \end{array} \tag{13}$$

8. DC-DC Converters

The solar panel output voltage is variable and changeable because of varying radiation and temperatures. Therefore, a DC-to-DC converter is required. The DC-DC converter is connected between the solar panels and the load to get better output power. To get the desired output voltage, the PV panel must be connected to a DC-DC converter. Therefore, electric powered DC-to-DC converters are the central subsystem to interface with the DC energy resources, which optimizes power flow or MPP. [35]

The DC-DC converters have many types. For example, boost or buck or buck-boost converters. Step-up is another name for a boost converter and step-down is another name for a buck converter. The purpose of the boost converter is to increase the output voltage to a higher level and to decrease the output current until it reaches the MPP current.

The purpose of the buck converter is to reduce the output voltage to a lower level and to increase the output until it reaches the desired output current. [36]

Each converter has some advantages and disadvantages. The output of the PV panel is changeable because solar irradiance and temperature are unstable. Therefore, the boost and buck converter must have an individual switch [36].

In recent years, most designs use a step-up converter to get high voltage in order to connect with the grid. Additionally, the output of the boost converter was constant in some designs, but not all of them use MPPT or, if the design used MPPT, the output of the boost converter was inconsistent [36]. In the next section, the boost and buck converters will be discussed in greater detail as they will be used as an example in this thesis.

Boost Converter

A boost converter, also called a step-up converter, is a converter where the input voltage goes inside the converter causing the output to be higher than the input. [37]-[38]. A simplified circuit diagram of a boost converter is shown in Fig. 15 and the main current and voltage waveforms are shown in Fig. 16 [39].

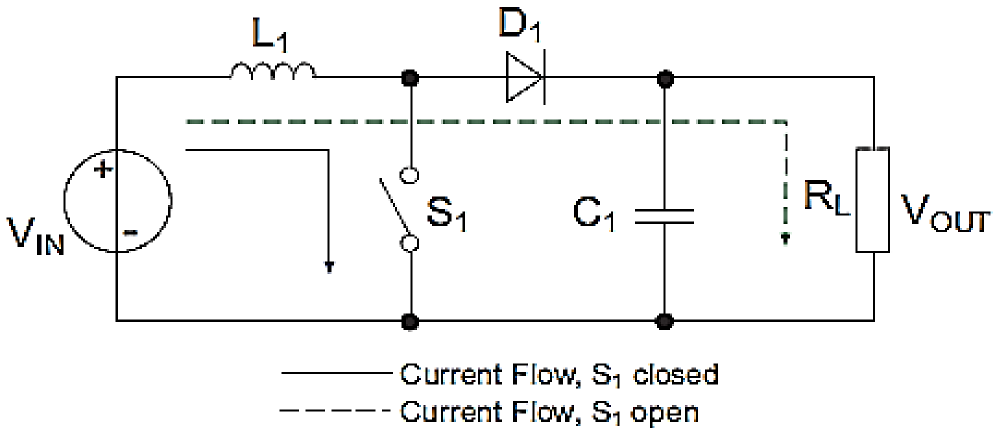


Fig. 15. DC-DC Boost Converter [39].

There are two different modes of operating the boost converter: continuous or discontinuous inductor current mode. In the continuous mode, as seen in Fig. 16, the current goes through the inductor during the whole switching cycle in a steady state. In contrast, in the discontinuous mode, the inductor current begins from zero for a time, then increases to peak value before returning to zero for each switching cycle [38].

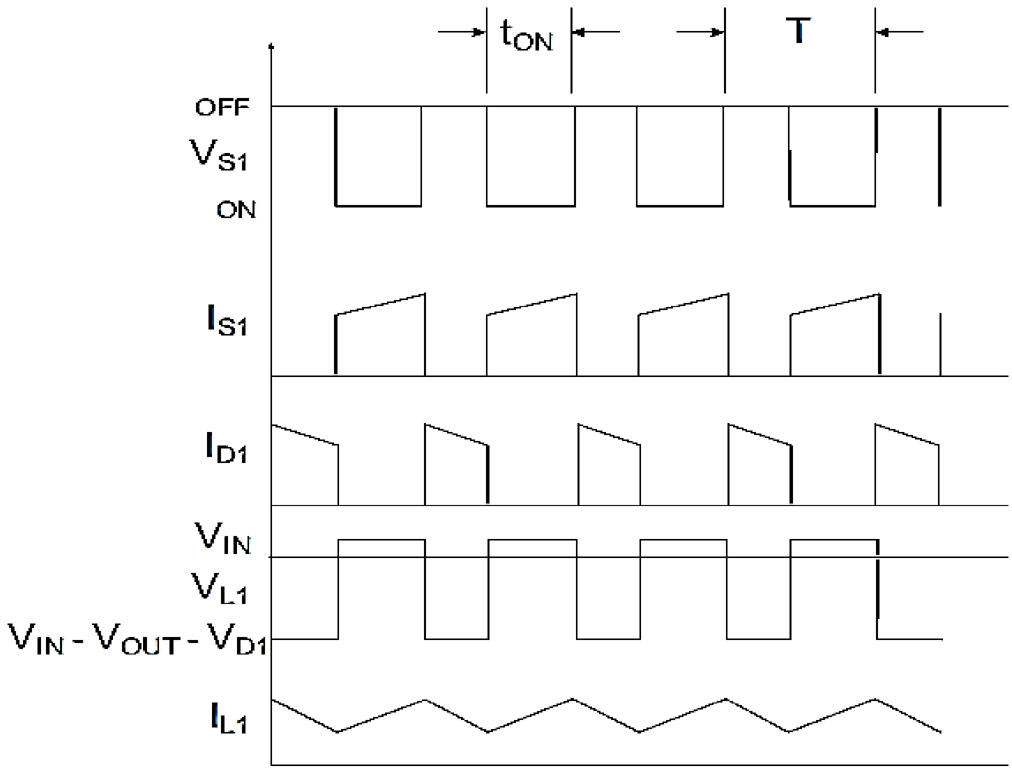


Fig. 16. Boost Converter Operation in Continuous [39].

8.1 Buck Converter

Typically the solar panel is connected in series to get a high voltage. In some cases, the high voltage needs to be stepped-down, which requires the use of a buck converter. The name of the buck converter comes from the fact that the input voltage is bucked in amplitude to give a lower output voltage. It is a non-isolated converter and provides necessary local voltage from a higher voltage, but with the advantages of simplicity and lower cost. It is a principle based on switching the input voltage for a period of time through to the output voltage, a process called proportional–integral (PI). PI of the switching frequency is used to control the MOSFET gate to get the desired output voltage. In an ideal scenario, the output from the converter cannot be accepted because it has ripples and is unstable. Therefore, it is necessary for capacitors and an inductor to be added to the converter to smooth the voltage and current. The inductor L is used to ensure that the current i_L is in a continuous current waveform to the load where the capacitor C is used to smooth the voltage ripples. Thus, the regulated DC output is smoothed and repaired by the inductor and capacitors. [40]. A simplified circuit diagram of a buck converter is shown in Fig. 17 and the main current and voltage waveforms are shown in Fig. 18 [39].

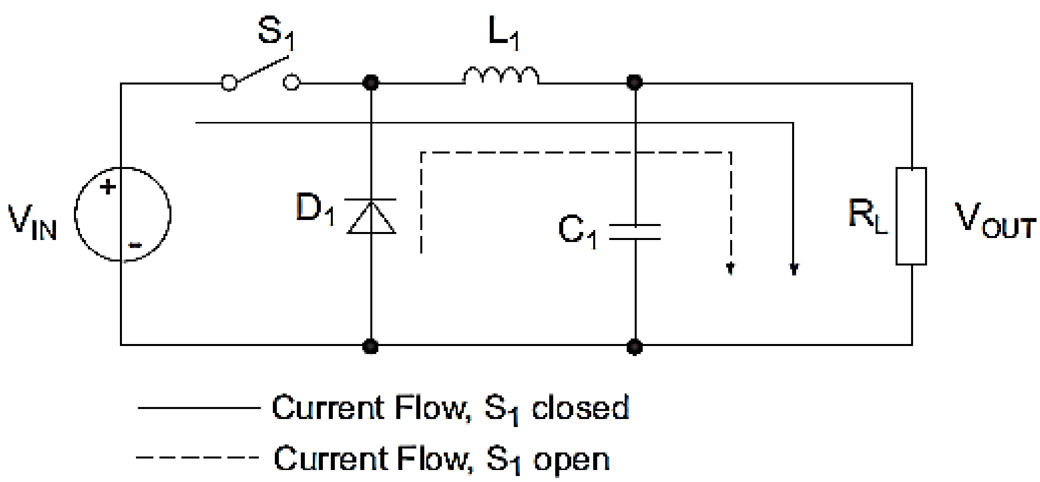


Fig. 17. DC-DC Buck Converter [39].

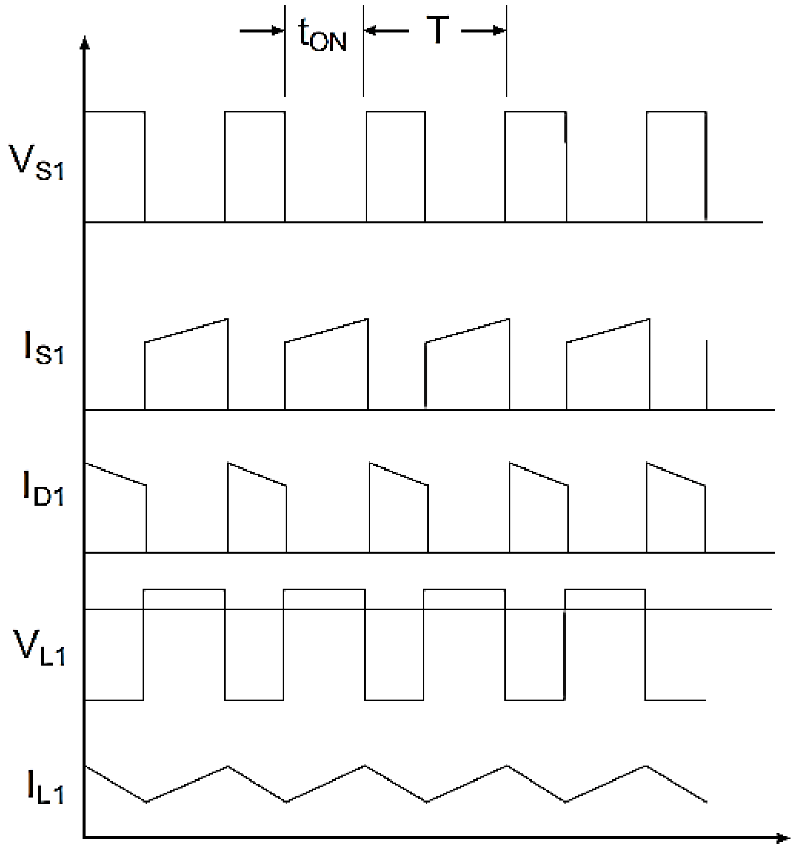


Fig. 18. Buck Converter Operation in Continuous [39].

8.2 Other DC-DC Converters

There are other types of DC-DC converters such as buck-boost, Fly back, Cuk, and push-pull converters. The buck-boost converter, or step-up/down power stage, is a modern non-isolated converter as shown in Fig. 19. It is used when the output voltage is not constant. Its name was taken from the buck and boost converters' power stage because it uses both cases.

However, the Cuk converter is a combination of a boost and a buck converter, as shown in figure 1.20. The Cuk converter is similar to a buck-boost converter circuit and can deliver an inverted output. The Fly back does not use inductance. Instead, it uses a transformer and the transformer ratio must be considered in order to calculate the output voltage. Finally, the push-pull converter is used in applications that require more than one switch and for high power applications. [37]

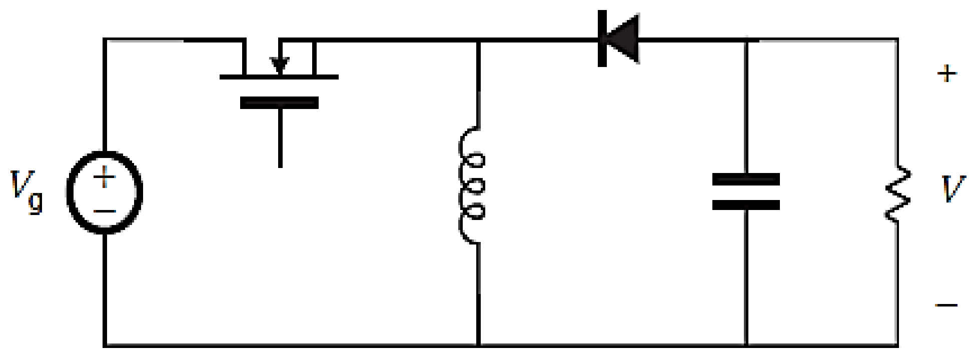


Fig. 19. DC-DC Buck-Boost Converter [37].

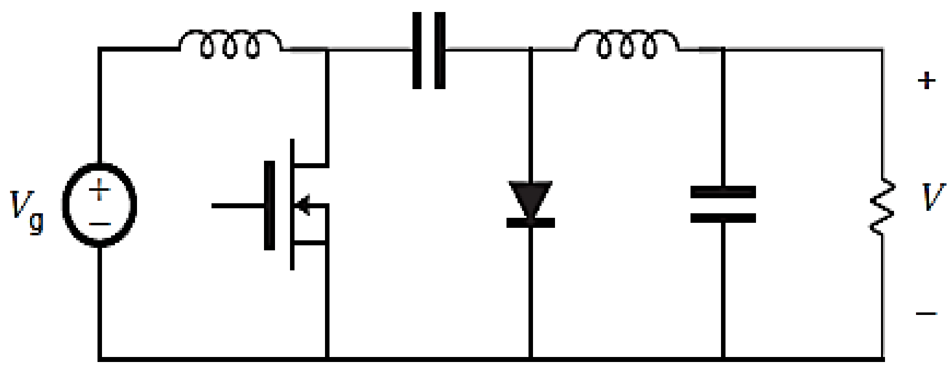


Fig. 20. DC-DC Cuk Converter [37].

CHAPTER 2

METHODOLOGY

1. PV system

This project focuses on subsystems for extracting the maximum amount of power from a solar panel, as shown in Fig. 21: the PV arrays, DC-DC converters, MPPT (IC) controller and (DC Applications) load. PV cells will convert solar radiation into electrical energy, making a nonlinear (voltage-current) V-I characteristic. The PV cells' output is an uncontrolled DC voltage. Thus, it cannot be connected directly to the load; it needs to be controlled in order to smooth the output voltage. Additionally, the MPPT method needs to be implemented to extract maximum power from the PV module.

The converters and MPPT algorithm are used to implement MPPT to make the output voltage constant, and to remove the ripples. The DC-DC boost converter and buck converter closed loop PI are achieved between the solar panel and load to step-down the voltage to the load requirement. The MPPT is then fed from the voltage and current so that their input comes from the PV of the output of the solar panel. This allows for the extraction of individual MPP [29].

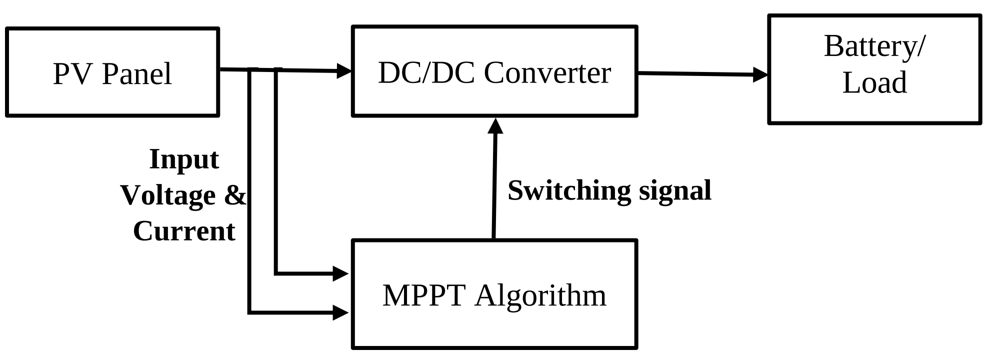


Fig. 21. Block diagram of the whole system

2. MPPT

In this thesis, I will use IC method because:

- Most other techniques are explained in fewer articles. This point of the IC process is comparatively common.
- The efficiency of the MPPT will change over time, even if the PV system degrades or if other site specific conditions change.

3. Boost Converter

3.1 Operating

The main principle is working on a boost converter that acts as an inductor to hold changes in current. When the start is charged, it acts as the load and absorbs energy. When the start is discharged, it acts as an energy source. During the discharge phase, the voltage produced is deepened to the rate of change in the current. [38]-[41]

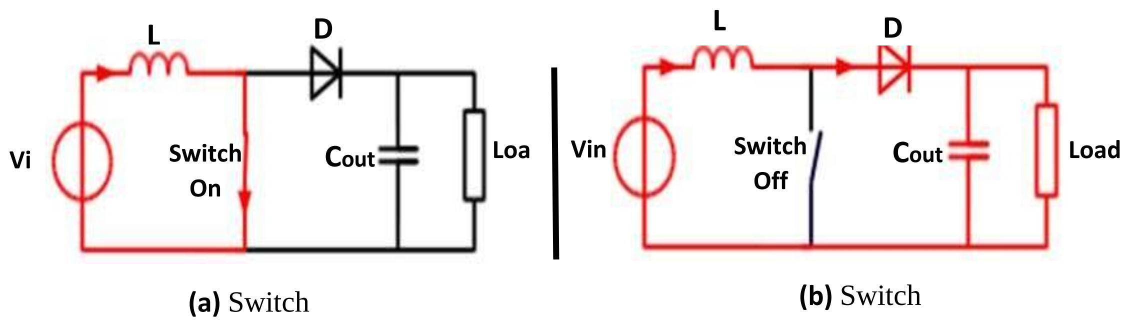


Fig. 22. The boost converter, ON, and OFF state.

Fig. 22 presents the main function of a boost converter in two different states:

- When the switch S is in the On-state, it is closed. The inductor current stores some energy by creating a magnetic field and current flows clockwise through the inductor. Fig. 22(a).

- When the switch S is in the Off-state, it is open. There is only one path for the inductor current to go through the diode, and the energy stored before will be released, producing a higher voltage. Fig. 22(b).

When the switch S is in the On-state, as seen in Fig. 22, it is closed. That produces the input voltage V_i that appears across the inductor, which is the reason why a change in current I_L flowing through the inductor for a period time can use this equation [35]:

$$\frac{\Delta I_L}{\Delta t} = \frac{V_{in}}{L} \qquad (14)$$

The end of the On-state, the increase of I_L is, thus:

$$\Delta I_{LOn} = \frac{1}{L}\int_0^{DT} V_{in}\, dt = \frac{DT}{L} V_{in} \qquad (15)$$

The duty cycle is D. It shows the part of the commutation period time T during the time when the switch is On. When D is 0, S is OFF. When D is 1, S is ON. The inductor current flows to the load when the S is in the OFF-state. The voltage will be a drop in the diode when at zero. Also, the capacitor can get enough voltage to remain constant. As seen in equation (16), the evolution of I_L is: [35]- [38]

$$V_{in} - V_{Out} = L\,\frac{dI_L}{dt} \qquad (16)$$

Thus, the difference of I_L during the Off-period time is:

$$\Delta I_{LOff} = \int_{DT}^{T} \frac{(V_{in} - V_{Out})dt}{L} = \frac{(V_{in} - V_{Out})(1-D)T}{L} \qquad (17)$$

Continuous mode will be operating in this converter, and the stored energy in each of components has to be similar to the beginning and the end of a commutation cycle. We can use equation (18) to calculate the stored energy in the inductor: [35]

$$E = \frac{1}{2} L I_L^2 \qquad (18)$$

From equation (18), we can conclud that the overall change in the current is zero:

$$\Delta I_{LOn} + \Delta I_{LOff} = 0 \qquad (19)$$

Substituting ΔI_{LOff} and $\Delta I_{Lon}$by their for:

$$\Delta I_{LOn} + \Delta I_{LOff} = \frac{V_{in}\, DT}{L} + \frac{(V_{in} - V_{Out})(1-D)T}{L} = 0 \qquad (20)$$

From equation (20), we obtain the transformation ratio $V_{out}/\, V_i$:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \qquad (21)$$

From equation (21), The Duty Cycle D is :

$$D = 1 - \frac{V_{in}}{V_{out}} \qquad (22)$$

3.2 Converter Switch

The switch can be a MOSFET, BJT, IGBT or JFET. It must have a fast switching time to avoid loss during switching. MOSFET has three legs called drain, gate, and source.

The MOSFET switch is controlled through the gate pin by application of MPPT. Therefore, the converter can control the output voltage by varying the MPPT signal to control the OFF and ON conditions. [35]

Schottky diodes must be used in order to reduce loss. The maximum output current is the same as the forward current rating:

$$I_F = I_{out(max)} \qquad (23)$$

Therefor:

- I_F is average forward current of the rectifier diode.
- I_{OUT} is output current (max).

The equation (24) can check the power dissipation of the rectifier diode:

$$P_{loss}(diode) = I_F * V_F \qquad (24)$$

Where V_F is the average forward voltage of the rectifier diode.

3.3 Inductor

Estimate the inductor ripple current is 20% to 40% [35]

$$\Delta I_L = \times\, I_{out(max)} \times (20\%\ to\ 40\%) \times \frac{V_{out}}{V_{in}} \qquad (25)$$

The critical inductance value of the boost converter is given by the equation (26) [35]:

$$L = \frac{V_{in}\,(V_{out} - V_{in})}{\Delta\, I_L * f_{sw} * V_{out}} \qquad (26)$$

Where:

- V_{in} is the input voltage.
- V_{out} is the desired output voltage.
- f_{sw} is the designed switching frequency.
- ΔI_L is inductor ripple current.

3.4 Output capacitor

The current store to the output circuit is discontinuous. Therefore, to limit the output voltage ripple, a big filter capacitor is required. When the diode is off, the filter capacitor should supply the output DC to the load. [35]

$$C_{out(min)} = \frac{D * I_{out(msx)}}{\Delta\, V_{out} * f_{sw}} \qquad (27)$$

Where:

- $C_{out(min)}$ is the output capacitance (minimum).
- ΔV_{out} is the ripple of output voltage.
- f_{sw} is switching frequency in kHz.
- $I_{out(msx)}$ is minimum output current.
- D is the duty cycle.

The selection of C_{min} must be higher than the calculated value to make sure that the converter's output voltage ripple remains within the specific range and that its equivalent series resistance (ESR) is low. ESR can be minimized by connecting many capacitors in parallel. Therefore, it can be assumed that the ESR is calculated using the following equation (28): [35]

$$\Delta V_{out(ESR)} = ESR * \frac{I_{out(\max)}}{1-D} + \frac{\Delta I_L}{2} \approx 5\,\%\, V_{out} \qquad (28)$$

4. Buck Converter

4.1 Operation Principle

Fig. 23 shows the circuit and offers the most significant part of a buck converter without feedback controller. The common inductor L and capacitor C filter are used to reduce the ripple of the output to a low level, which is caused by the converter switch. The inductor smooths the current crossing into the inductor and load, whereas the capacitor reduces the voltage ripple over the load [12].

There are two operating modes in the buck converter, similar to the boost converter: continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In this thesis, the CCM is highlighted. Fig. 23 describes the operating principle of CCM. There are two positions for a switch—closed (ON) and open (OFF) —on a buck converter. When the switch is closed (ON), the diode is reverse-biased, which means the current cannot flow into it. When the current crosses into the inductor, the inductor increases because the energy is being stored. While the switch is open (OFF), the diode becomes forward-biased. Therefore, the inductor keeps the current in the load. Therefore, the inductor is performing as a source. In the open (OFF) circuit, the inductor has energy. This energy will decrease, and the current will fall slowly. [37]-[42]

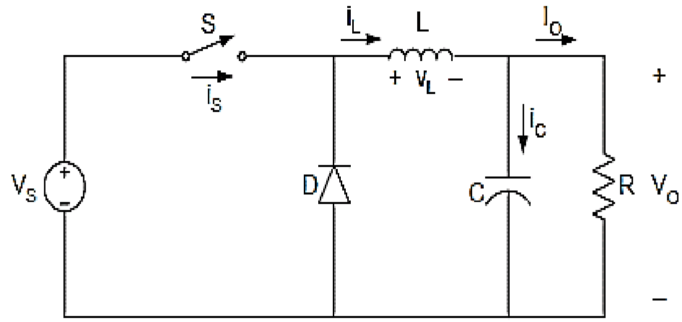


Fig. 23. Operating Principle of Buck Converter

Fig. 23 can be adjusted by combining the PI feedback controller. The PI feedback controller changes the duty cycle to look for a smooth output voltage by comparing the voltage reference with a part of the output voltage. The duty cycle will be decreased by using the controller when the output voltage increases to reduce the regulated output. The duty cycle will be increased by using the controller when the output voltage is reduced to keep up a suitable output level.[37]. Equation (29) computes the stored energy (E) in the inductor [42]:

$$E = \frac{1}{2} L * {I_L}^2 \qquad (29)$$

Where L is the inductor and I_L is the current passing through the inductor. Therefore, I_L can be calculated according to the law of induction, as shown in equation (30) [42]:

$$V_L(t) = L.\frac{dI_L}{dt} \qquad (30)$$

Whereas, the voltage across the inductor is V_L and can be calculated by equation (31) [35] :

$$V_L = V_D - V_{out} = V_S - V_{out} \qquad (31)$$

Where V_D is the voltage across the diode, V_s is the input voltage and V_{0ut} is the output voltage. Thus, the rise in current in the inductor during its ON state is given by equation (32):

$$\frac{dI_L}{dt} = \frac{V_L}{L} = \frac{V_s - V_{out}}{L} \qquad (32)$$

Moreover, when the switch is OFF state, the current decrease and is given by equation (33) [42]:

$$\frac{dI_L}{dt} = \frac{V_L}{L} = \frac{-V_{0ut}}{L} \qquad (33)$$

The duty cycle D is given by the equation (34):

$$V_{0ut} = D.\, V_S \qquad (34)$$

Therefore, the duty cycle D is :

$$D = \frac{V_{out}}{V_s} \qquad (35)$$

Where V_s is the input voltage (minimum) to maximize the switching current. The D varies according to the supply voltage and desired output voltage, and is measured as a percentage, which represents the ON state of the switching converter.

4.2 Converter Switch

The converter switch is mainly a transistor switch and it has two state conditions: ON or OFF. The transistor switch can be MOSFET, BJT, IGBT or JFET. It should have a fast switching time to avoid loss during switching. In the buck converter case, the most suitable switch is MOSFET because it is fit for a low voltage application with high switching frequency [43]. The MOSFET is controlled through the gate pin by application of PI. When the switch is in the ON state, the voltage across the inductor and load is equal to the supply voltage. On the other hand, when the switch is in the OFF state, the voltage passing the load is same as the voltage across the inductor. Power MOSFETs are therefore an excellent example of a high switching frequency with low voltage application. Equation (36) computes the switching current of the MOSFET [42]:

$$I_{switch} = I_{out} * \delta \qquad (36)$$

Where δ is the duty cycle.

The forward current of the rectifier diode need to be equal to the output current at maximum as shown in equation (37) [42]:

$$I_F = I_{out} * (1 - \delta) \qquad (37)$$

Power losses of the rectifier diode can be checked by the equation (38) [35]:

$$P_{loss}(diode) = I_F * V_F \qquad (38)$$

Where V_F is the average forward voltage of the rectifier diode.

4.3 Inductor

The mission of the inductor is to look after the current percentage when the current is going through the inductor and to control the current ripples. Therefore, when the current starts to go down, the inductor acts as a source. The switch resistance limits high peaks of current [42]. Therefore, in the OFF-state condition, the inductor supplies the load to get the desired output voltage. When the inductor is small, the results will get higher losses in the switch, because there is a large current ripple. [37]

The voltage V_L at the inductance is given by equation (39), V_L will be equal to V_{out} [42]:

$$V_L = L * \frac{dI_L}{dt} \qquad (39)$$

$$V_L = L * \frac{\Delta I_L}{(1-\delta)T} = V_{out} \qquad (40)$$

Therefore, the inductor L is given by equation (41) [42]:

$$L = \frac{V_{out} * (V_{in} - V_{out})}{f_{sw} * \Delta I_L * V_{in}} = \frac{V_{out} * (1-\delta)}{f_{sw} * \Delta I_L} \qquad (41)$$

Where:

- V_{in} is the input voltage.
- V_{out} is the desired output voltage which V_L when a switch is Off.
- f_{sw} is the designed switching frequency.
- ΔI_L is the estimated inductor ripple current.

Estimate the inductor ripple current at 20% to 40 % [42].

$$\Delta I_L = (20\% \ to \ 40\%) * I_{out} \qquad (42)$$

Calculate the inductor peak current I_{pk} as seen in equation (43) [42]:

$$I_{pk} = I_{out} + \frac{\Delta I_L}{2} \qquad (43)$$

4.4 Capacitor Output

To minimize the voltage overshoot, ripples over the load and filtering require the use of a capacitor. It filters like currents away from the load. The designer specifies the allowed overshoot and ripples.

The three elements that need to be considered for capacitor design are the value of capacitance(C), equivalent series resistance (ESR), and equivalent series inductance(ESL). Using these four equations (44), (45), (46) and (47): [42]

$$\Delta I_{c\,out} = \frac{V_{out}}{f_{sw}} \cdot \frac{1-\delta}{L} \qquad (44)$$

$$\Delta Q_{cout} = \frac{T_{sw}}{2} \cdot \frac{1}{2} \cdot \frac{\Delta I_L}{8 \,.\, fsw} \qquad (45)$$

$$\Delta V_{cout} = \frac{\Delta Q_L}{Cout} = \frac{\Delta I_L}{8 \,.\, C_{out} \cdot f_{sw}} \qquad (46)$$

$$C_{out} = \frac{\Delta I_L}{8 \,.\, \Delta V_{cout} \cdot f_{sw}} \qquad (47)$$

It Is;

- C_{out} is the output capacitance (minimum).
- ΔV is the ripple output voltage.

ESR causes power dissipation in the capacitor when current ripples pass through it. This might lead to a reduction of the capacitor’s life and efficiency because of the increase in temperature. Thus, a capacitor greater than calculated from equation (47) must be selected. Therefore, it can be assumed that the ESR is as in equation (48): [42]

$$\Delta V_{cout} = ESR * V_{out} \approx 5\% \, V_{out} \qquad (48)$$

4.5 Input capacitor

As stated earlier, the output of the PV voltage has ripples due to the change in temperature and solar irradiation. Therefore, it is necessary to replace the input capacitor in parallel with the voltage supply to minimize ripples produced by the solar panel. The ripples have an adverse effect on the output, as the input voltage is proportional to the output current. ESR on the input capacitor, should be considered by selecting a greater capacitor value than the calculated one. Equation (49) computes the value of the input capacitor while considering the ripples limit.

$$C_{in} = \frac{I_{out}}{f_{sw} * \Delta V_{input}} (\delta - \delta^2) \qquad (49)$$

Where:

$$\Delta V_{input} = ESR * V_{Input} \approx 5\% \, V_{\mathrm{input}} \qquad (50)$$

CHAPTER 3

PROPOSED DESIGN AND SIMULATION RESULTS

1. PV Modelling

In this section, a PV module based on one diode is simulated using the MATLAB SIMULINK PROGRAM [44]. Fig. 24 demonstrates the PV cell modeling based on the project's PV design.

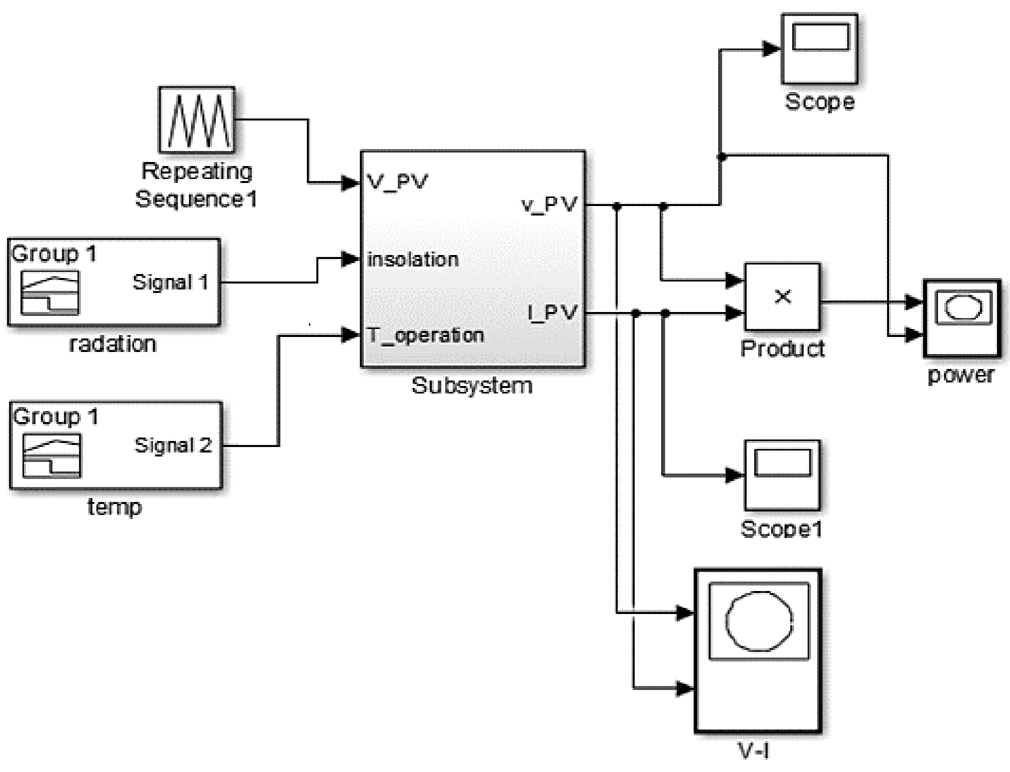


Fig. 24. PV Cell Modeling by MATLAB SIMULINK

The 234.9 W PV array of the detailed model uses SunPower modules (SPR-234.9). The array consists of 1 string of 36 series-connected modules connected in parallel (8456.4 W). The model of the PV-array block can be seen in Fig. 25. The model parameters are:

- Number of series-connected cells: 36
- Open-circuit voltage: V_{oc}= 48.4 V
- Short-circuit current: I_{sc} = 6.18 A
- Voltage and current at maximum power: V_{mp} =40.5 V, I_{mp}= 5.8 A

The Block parameters PV Array can be seen in Fig. 26.

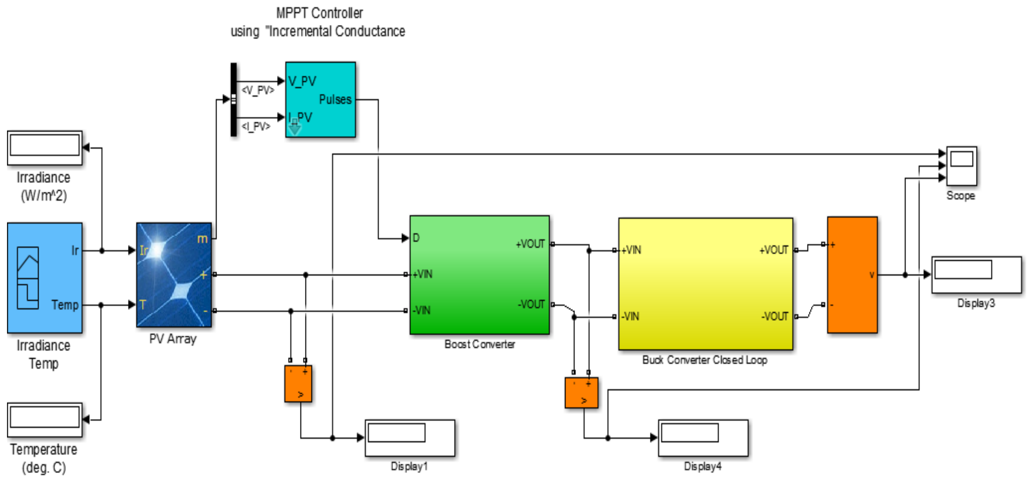


Fig. 25. PV Model Using MATLAB Simulink

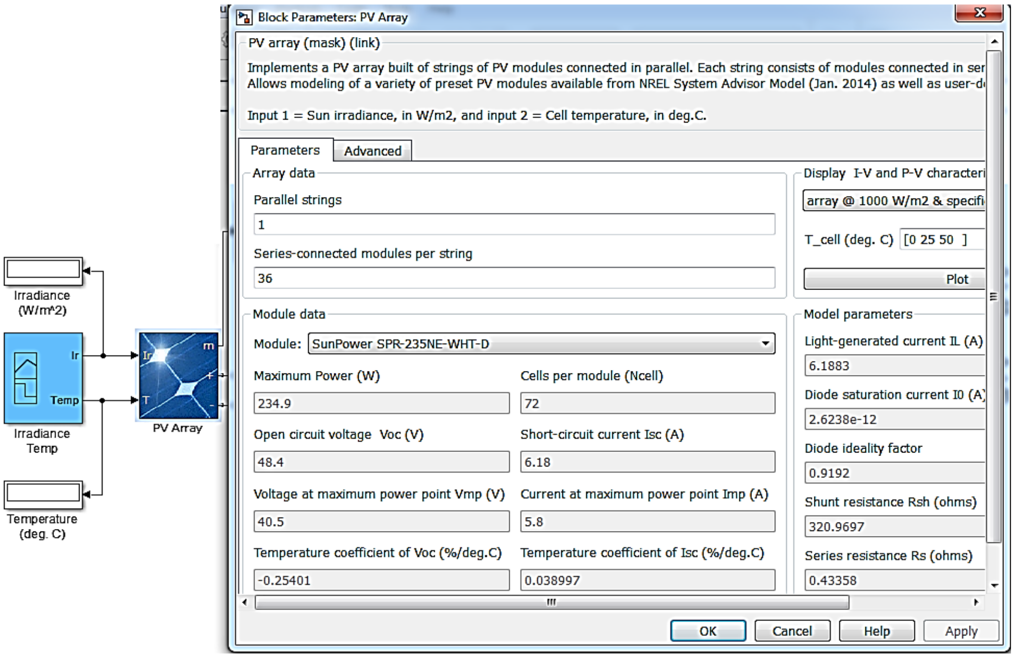


Fig. 26. Block parameters: PV Array.

2. Irradiance and Temperature Inputs

The PV array block menu plots the P-V and I-V characteristics for the whole array and one module. The characteristics of the SunPower-SPR234.9 array. Four profiles of irradiance were used to simulate irradiance on the solar array. The run was a variable irradiance at 1000W/m^2, 250W/m^2, and back to 1000W/m^2 as seen in Fig. 27.

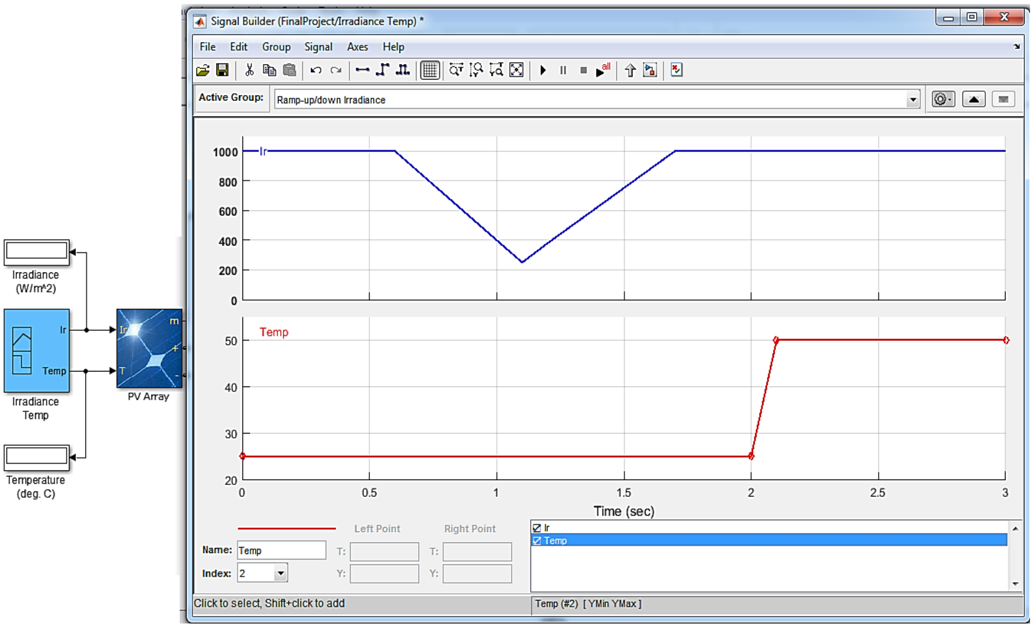


Fig. 27. Signal Builder of irradiation and temperature

Temperature was also variable at 25deg/C to 50deg/C as seen in Fig. 27. Furthermore, Fig. 28 demonstrates the V-I curve of the PV module at different radiation levels. With changes in radiation level, the current also changes, but the voltage does not change as much.

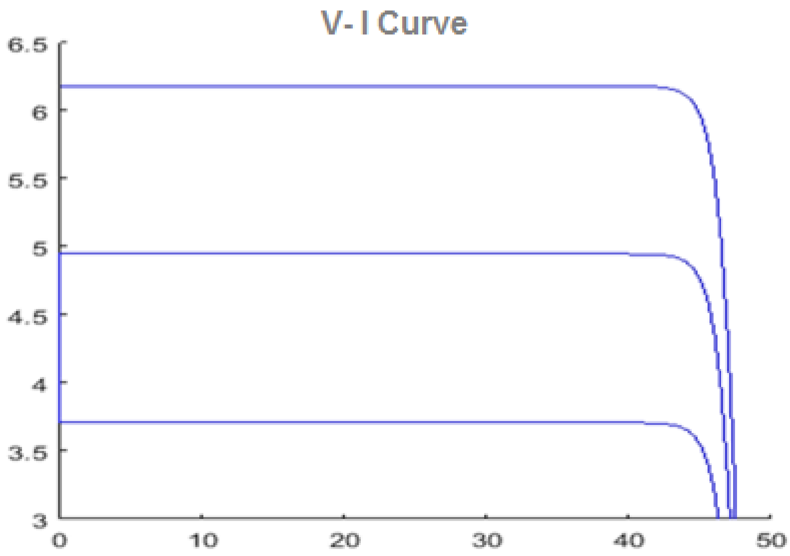


Fig. 28. The Look-Up Table Plotted by MATLAB (V-I Curve for Various Radiation Levels).

3. DC-DC Converters

Boost and buck converters are used in most of the applications that require a transient line response. They can convert the voltage source into maintained high and low voltages as a required load. In the case of the PV generator, the DC output voltage for a boost converter needs to operate at MPP and be controlled, and a buck converter needs to run by using a closed loop to get constant voltage. This requires the use of DC-DC converters. As stated earlier, DC-DC converters can be achieved by using the topology shown in Fig. 29. The boost and buck converter components–such as diode type, MOSFET, and filter element inductor and capacitors–need to be calculated and selected to maintain the required DC voltage level. In this study, the converters were implemented using MATLAB Simulink.

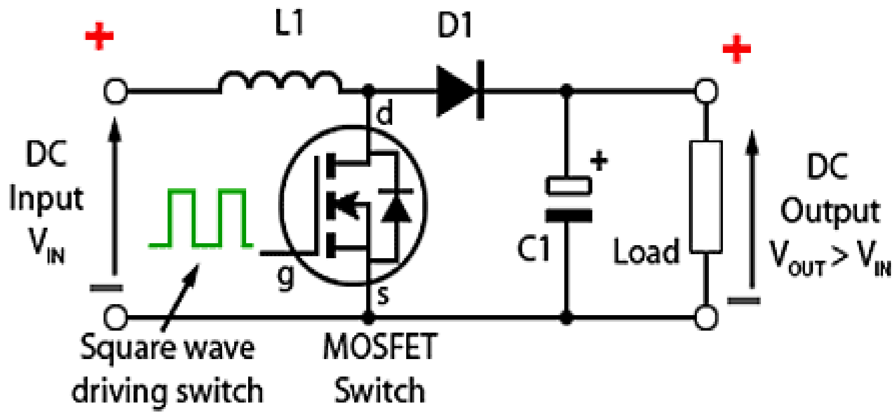


Fig. 29. Boost Converter Sample Design [45].

3.1 Boost converter design

In this section, the four components will be designed and calculated based on switching frequency, input and output voltage on a diode, converter switch, capacitors, and inductor. The output power from the PV module is 8 KW, however, the size and cost of the components depend on the switching frequency. For that reason, 10 KHZ was chosen as the switching frequency. This produced high-frequency results in the shorter period and fast switching.

3.1.1 Boost converter parameters

3.1.1.1 Converter switch design

Bipolar junction transistors are usually employed for high power applications, whereas MOSFETs are suitable for switching in low power applications.

A power MOSFET switch can improve efficiency during ON/OFF switching by minimizing dynamic losses. Thus, it was chosen for this boost converter's design to improve the overall converter performance. The selected MOSFET has advantages over other types, such as the temperature coefficient.

The MOSFET switch can be ON or OFF through the MOSFET gate, which is controlled by MPPT (IC) using a gate drive and controller. Furthermore, the PV is connected to the drain generator, while the source is connected to the diode and inductor [34].

3.1.1.2 Inductor and capacitor selection

Input and output capacitors need to be computed to minimize voltage ripples. The input capacitor is used to reduce the voltage ripples from the PV array, which normally requires a higher capacitor. Ripples are due to the change in radiation and temperature. The output capacitor (across the load) is used to reduce and control the output ripples, whereas inductance is used to maintain the current when passing through the inductor. Table 1 shows the specifications of the boost converter and Fig. 29 shows a design of a boost converter with an example of current ripples.

Table 1. DC-DC boost converter specifications

Input voltage (Max voltage of PV)	75V
Output voltage	150V
Maximum power	8kW
Switching frequency	10KHZ
Inductor current ripples	30%
Output voltage ripples	5%

We can calculate the duty cycle of the boost converter by using equation (22) from the previous chapter.

$$D = 1 - \frac{Vin}{V_{out}} = \frac{75}{150} = 0.5$$

Then, the output current can be calculated by using the following equation:

$$P_{out} = V_{out} * I_{out}$$

$$I_{out} = \frac{P_{out}}{V_{out}} = \frac{8000\ W}{150\ V} = 5.3\ \mathrm{A}$$

Since the output current is known, the current ripples can be calculated by using equation (25) from chapter 2 and thus the ripple percentage is assumed to be 30%.

$$\Delta \mathrm{I_L} = (0.2 \text{ to } 0.4) \times \mathrm{I_{out(max)}} \times \frac{\mathrm{V_{out}}}{\mathrm{V_{in}}}$$

$$\Delta I_L = 0.3 \times 5.3 \times \frac{150}{75} = 3.2\ A$$

Therefore, the inductor of boost converter can be computed by using equation (26).

$$L = \frac{V_{in}\,(V_{out} - V_{in})}{\Delta I_L * f_{sw} * V_{out}}$$

$$L = \frac{75 * (150 - 75)}{1.22 * 10000 * 150} = 3.07\ \mathrm{Mh}$$

3.1.1.3 Output capacitor

Output capacitor can be calculated by using equation 25 in chapter 3. The voltage ripples were assumed to be within the limit of 5% as stated in equation (27).

$$C_{out(min)} = \frac{D * I_{out(max)}}{\Delta\, V_{out} * f_{sw}}$$

$$C_{out} = \frac{0.5 * 2.04}{0.05 * 10000} = 5.3\ \mu\mathrm{F}$$

The ESR rating should be very small when selecting the capacitor to minimize the ripples on the output voltage. Therefore, the capacitor needs to be larger than 5.3 μF to consider the ESR and for a smoother output voltage. The series inductance is also important to look at when selecting a capacitor, but only usually for a switching frequency above 1 MHz [41].

Now, the output filter can be connected to the boost converter to reduce and control the current and voltage ripples.

3.1.1.4 Diode selection

As mentioned earlier, a diode should be used to prevent backward current flow, and in practice, the MOSFET will be burned if the diode is not used in a converter. Therefore, it is more efficient for the converter and results in faster switching speed than a normal diode. Also, the current and voltage ratings should be considered when selecting a diode. The forward current required can be calculated by equation (23).

$$\mathrm{I_f} = \mathrm{I}_{\mathrm{out(max)}}$$

$$I_f = 5.3\ A$$

3.1.1.5 Load resistor

The resistive load needs to be designed for the desired output voltage at the rated power. Since the rated power and output current are known, the resistor load value can be calculated as:

$$P_{out} = {I_{out}}^2 \times R_{load}$$

$$R_{load} = \frac{P_{out}}{{I_{out}}^2} = \frac{8000}{(5.3)2} = 285\Omega$$

Therefore, it can be used a 285Ω resistor for the load.

3.1.2 Simulation the Boost Converter

The simulation of the boost converter is probably the most important part to predict the behavior of the boost converter before it is built. The above calculations and parameter designs will be used, as seen in Table 2, to demonstrate the boost converter by using MATLAB Simulink

Table 2. Design Parameters of the Boost converter

Δ	0.5
L	3.07 µH
C_{out}	100 µF
R_{load}	285Ω

3.1.3 Boost converter with MPPT controller

In this case, a DC source will be used as the input voltage from PV modeling. This means the radiation at 1000 W/m^2 and temperature at 25 d/C are assumed to be constant. Therefore, the duty cycle at 0.5 can be used to switch the MOSFET ON and OFF. As stated earlier, when the radiation and temperature are considered, a constant duty cycle cannot be used and it will be necessary to use a controller to control the MOSFET switching.

The boost converter was built and simulated in MATLAB as seen in Fig. 30 with MPPT IC controller and input voltage 75 V at a duty cycle of 0.5 %. Initially, there was a need for an input capacitor as the input was smooth from a PV model. Fig. 32 (a) shows the PV input voltage of the boost converter.

However, the desired output voltage was 150V, which was reached in the simulation with ripples, as shown in Fig. 32 (b). These ripples were as expected and did not reach the limit of 5 % of the output voltage.

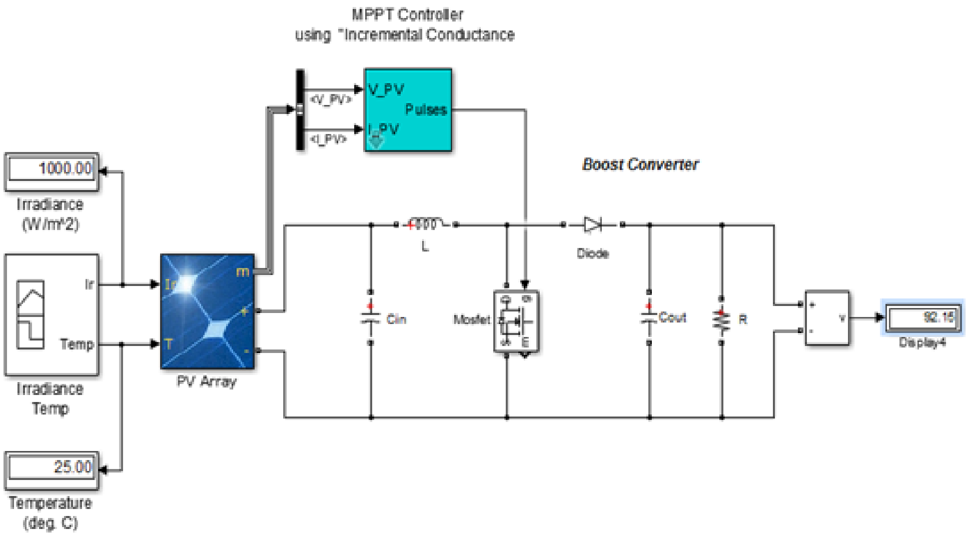


Fig. 30. DC-DC Boost Converter with MPPT Controller (MATLAB Simulink).

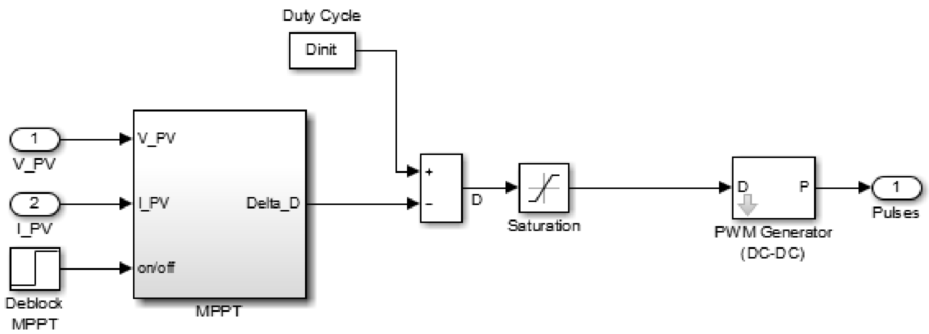


Fig. 31. MPPT Controller Block.

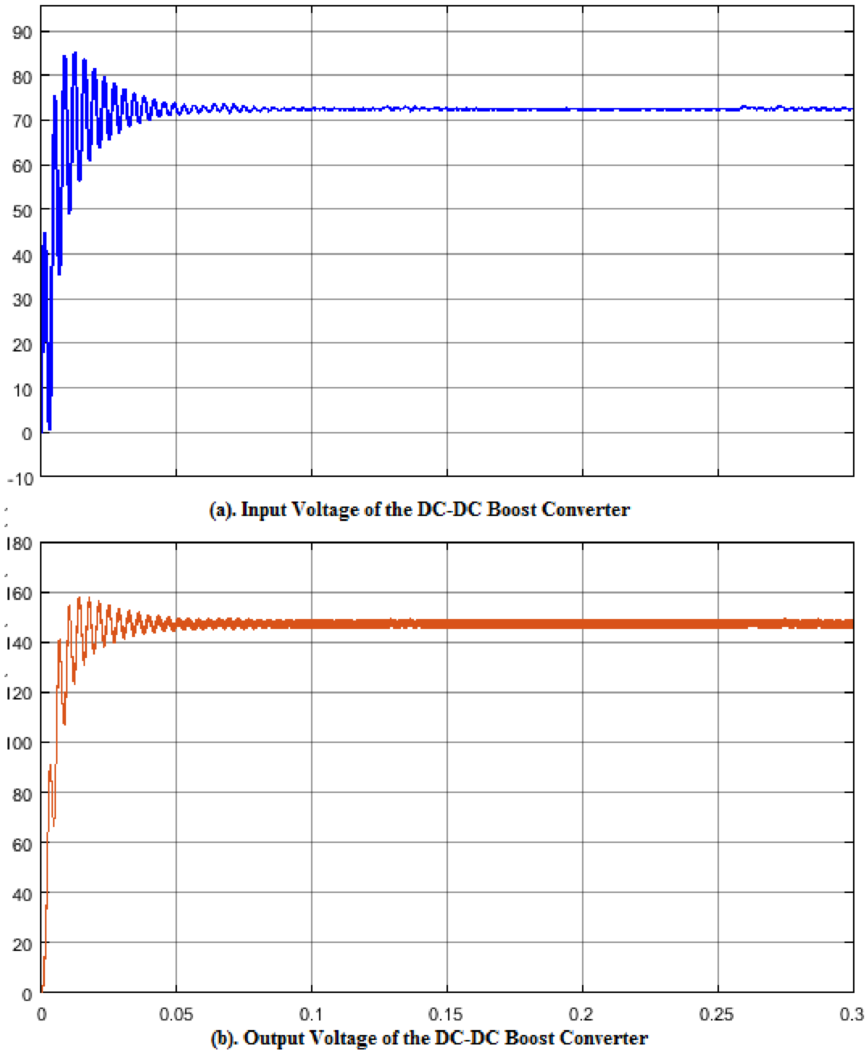


Fig. 32. Input/ Output Voltage of the DC-DC Boost Converter

3.2 Buck converter design

3.2.1 Buck converter parameters

3.2.1.1 Converter switch design

Like what is said before in boost convert. MOSFET at ON-state resistance between the drain and the source must be considered when designing a switch. For this reason, the selected MOSFET is N-channel because it has less ON-state resistance and also has a higher switching performance than P-channel.

3.2.1.2 Inductor and capacitor selection

The input capacitors do not need it because the output capacitor of the boost converter will take care of the ripples and will keep the output voltage smooth. Moreover, the output capacitor (across the load) is used to reduce and control the output ripples, whereas inductance is used to maintain the current when passing through the inductor. Table 3 shows the specifications of the buck converter.

Table 3. DC-DC Buck Converter Specifications

Input voltage (Max voltage of PV)	150 V
Output voltage	24 V
Maximum power	6 W
Switching frequency	10 KHz
Inductor current ripples	30 %
Output voltage ripples	5 %

We can calculate the duty cycle of the converter by using equation (35) from the previous chapter, which is the ratio of the output voltage across the load and input voltage.

$$V_{out} = \delta\, V_{in}$$

$$\delta = \frac{V_{out}}{V_{in}} = \frac{24\ v}{150\ v} = 0.16$$

Then, the output current can be calculated by the following equation:

$$P_{out} = V_{out} * I_{out}$$

$$I_{out} = \frac{P_{out}}{V_{out}} = \frac{6}{24} = 0.25 \text{ A}$$

Since the output current is known, the current ripples can be calculated by using equation (42) from chapter 2 and thus the ripple percentage is assumed to be 30%.

$$\Delta I_L = 30\% * I_{out}$$

$$\Delta I_L = 0.3 * 0.25 = 0.075\ A$$

Therefore, the inductor of the converter can be computed by using equation (41):

$$L = \frac{Vout * (1 - \delta)}{f_{sw} * \Delta I_L} = \frac{24 * (1 - 0.16)}{10\ K * 0.075} = 2.7\ \mu H$$

The current ripples will decrease as the inductor values increase, but the inductor current will also decrease. Thus, the inductor should be selected carefully.

However, the peak current of the inductor is also needed to be calculated to control the saturation current. It can be computed by using equation (43):

$$I_{peak} = I_{out} + \frac{\Delta I_L}{2} = 9.78 + \frac{0.075}{2} = 3.75 \text{ mA}$$

The selected inductor must not show any saturation with a peak current of 3.75 mA since the saturation current can burn the MOSFET when the current exceeds the peak value. The output capacitor can be calculated by using equation (47) in chapter 2. The voltage ripples were assumed to be within the limit of 5% as stated in equation (48).

$$C_{out} = \frac{\Delta I_L}{8\ .\ \Delta V_{cout}\ .\ f_{sw}}$$

Where:

$$\Delta V_{cout} = 5\% * V_{out}$$

$$\Delta V_{cout} = 0.05 * 24 = 1.2\ V$$

$$\Delta V_{cout} = 0.05 * 150 = 7.5\, V$$

Therefore,

$$C_{out} = \frac{0.075}{8 * 7.5 * 10\, K} = 7.972 \approx 1.25\ \mu\text{F}$$

The capacitor has some tolerance, known as ΔV_{load}, which needs to be considered when selecting a capacitor. In addition, the ESR rating should be very small when selecting the capacitor to minimize the ripples on the output voltage. Therefore, the capacitor needs to be larger than $8\, \mu F$ to consider the ESR and for, smoother output voltage. Now, the output filter can be connected to the buck converter to reduce and control the current and voltage ripples.

3.2.1.3 Diode selection

The current and voltage ratings should be considered when selecting a diode. The forward current required can be calculated by equation (37):

$$I_f = I_{out} (1 - \delta)$$

$$I_f = 0.075 (1 - 0.16) = 0.063\ \text{A}$$

3.2.1.4 Load resistor

The resistive load needs to be designed for the desired output voltage and the rated power. Thus, since the rated power and output current are known, the resistor load value can be calculated as:

$$P_{out} = {I_{out}}^2 * R_{load}$$

$$R_{load} = \frac{P_{out}}{{I_{out}}^2} = \frac{6}{0.075^2} == 2.45\ \Omega$$

Therefore, it can be used 3Ω resistor for the load.

3.2.2 Simulation the Boost Converter

The above calculations and parameter designs are used to demonstrate the buck converter closed loop by using MATLAB Simulink. Table 3 shows the configuration parameter values, which will be used with the specifications shown in Table 4.

Table 4. Design parameters of the Buck converter

Δ	0.26
L	6.053 μH
C_{out}	8 μF
R_{load}	8Ω

4. Boost and Buck converters with PI using MATLAB Simulink

The buck controller is controlled by a proportional-integral controller (PI). The purpose of the feedback PI controller is to convert the output voltage into the desired voltage by correcting the error between measurement and reference values. The PI controller will be computed based on the buck converter parameters in Table 4.

Closed loop PI control can be designed manually by using MATLAB Simulink. The steps are:

- Open PID control block
- Selecting an appropriate PI algorithm (P, PI, or PID) like what you see in the Fig. 33.

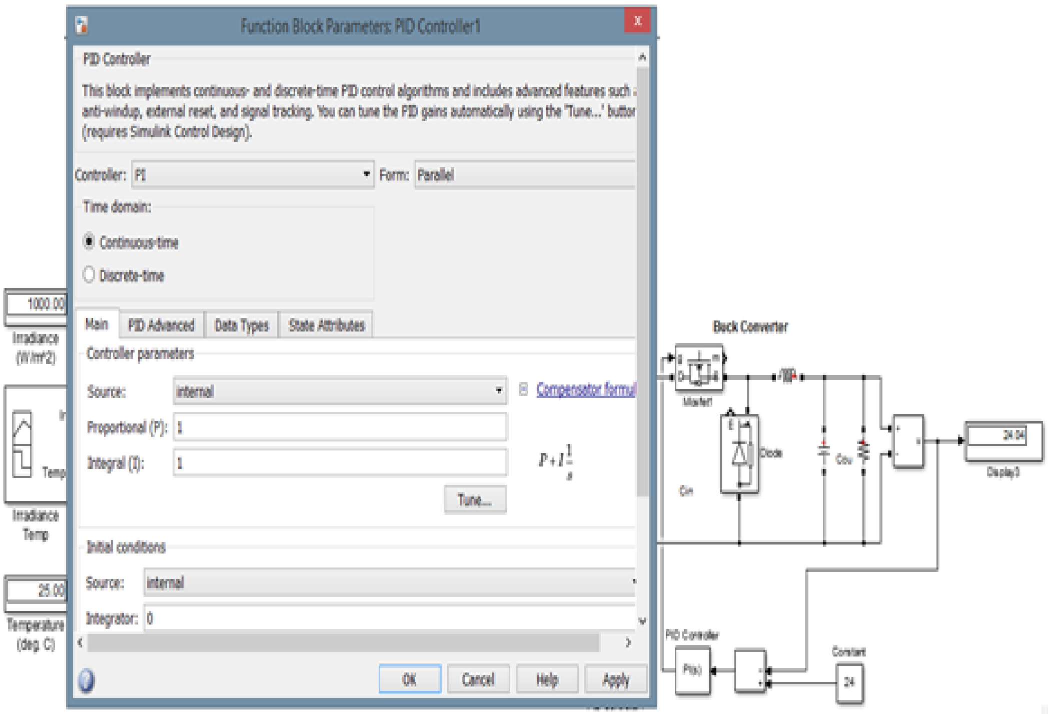


Fig. 33. Function Block Parameters PID.

- Click to (Tuning) controller gains. This will open a new window called PI tuning step plot: Fig. 34.

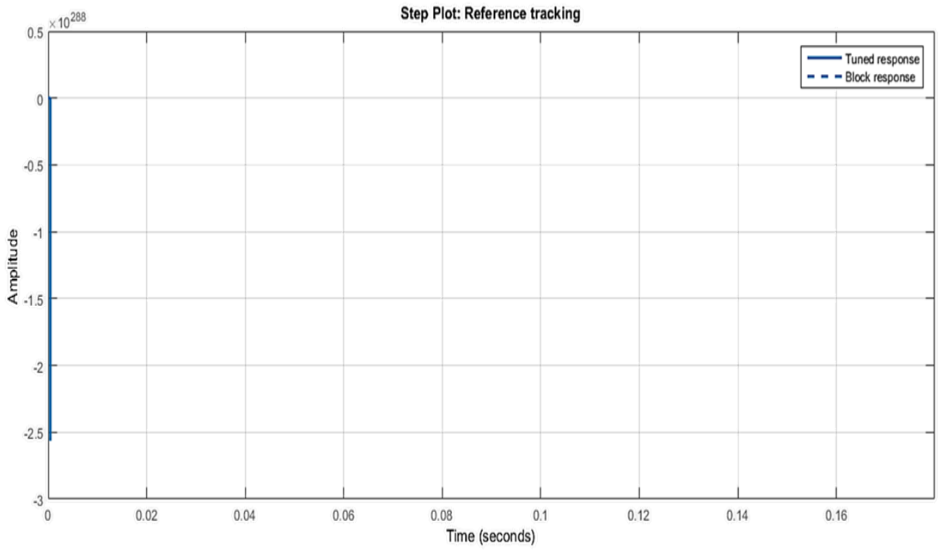


Fig. 34. PI Tuning Step Plot

- Click to Plant and select (Identify New Plan). Your screen should look like Fig. 35.

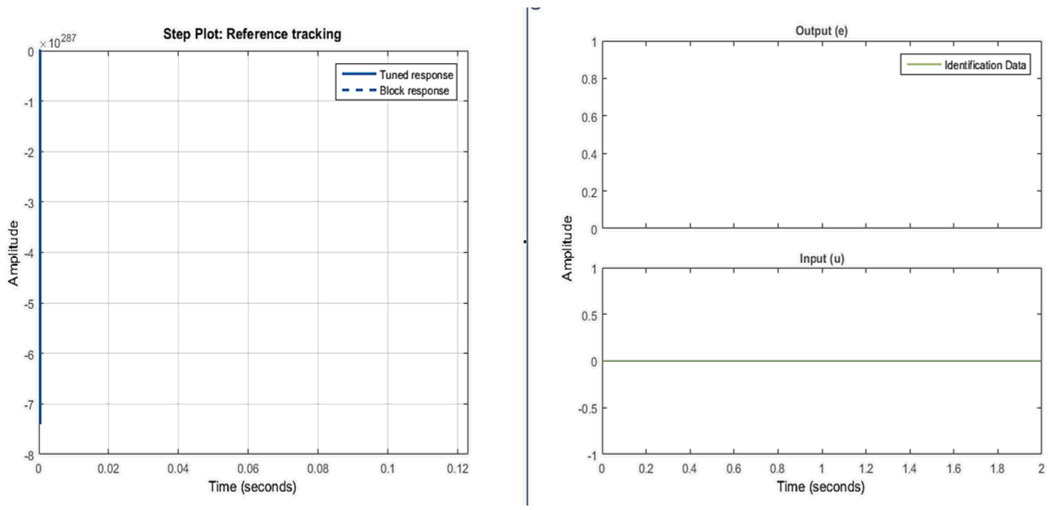


Fig. 35. New Window for New Plan.

- Then, justify the Sample Time, Offset, Onset, and Stop Times. From this window, click to signal type and click for pen next to Step. Then change the Amplitude (A) from 1 to 24. You will then see the Green line on right side change from 1 to 24. After that, click to Run Simulation and wait until it finishes. Then click Apply and Close. Fig. 36.

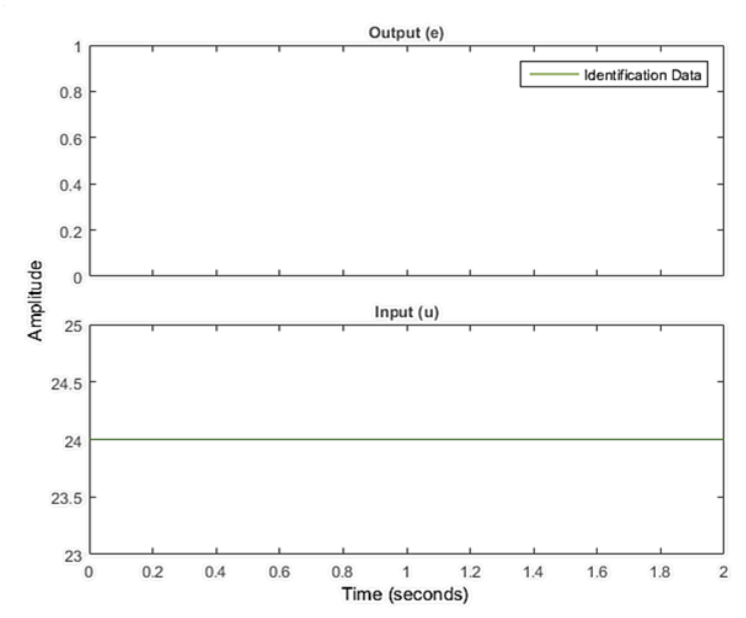


Fig. 36. Function Block Parameters PID.

- After that, click Plant Identification. Then click Auto Estimate. A new window will open. Wait until it finishes, then close the Plant identification Progress window. Fig. 37.

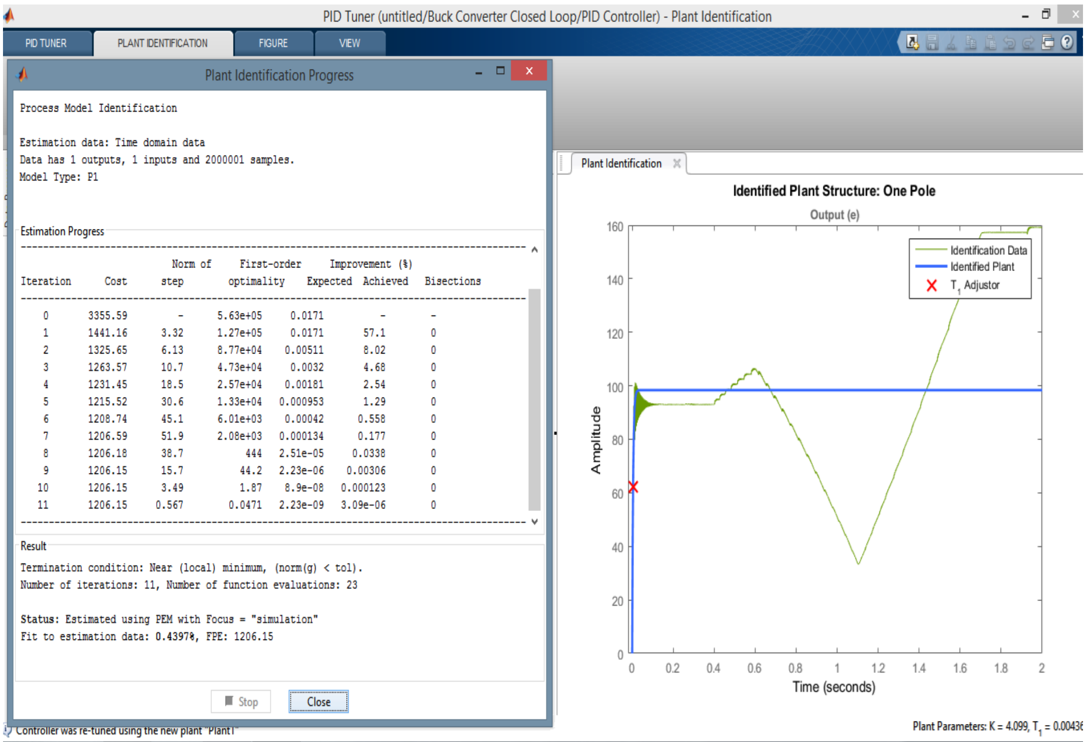


Fig. 37. Plant Identification Progress PID.

- Click to PID TUNER and click to Update Block. After that close the window. Fig. 38.

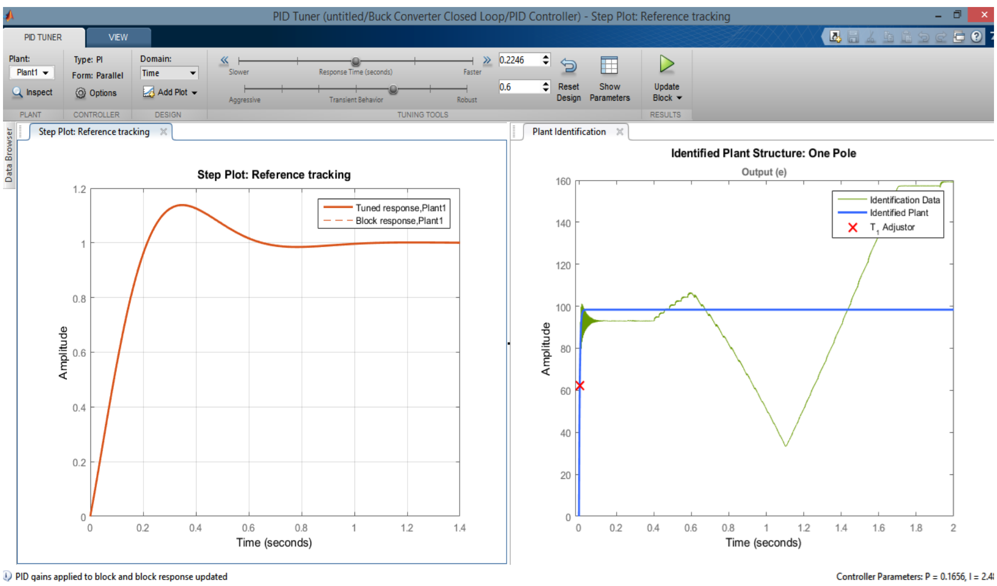


Fig. 38. PID Update Block.

- Click to (Run) closed-loop system simulation by connecting your PI Controller block to the plant model

After the controller had been computed, the controller will be added to the buck converter that was built (Fig. 39 and Fig. 40). Fig. 40 shows the buck converter with a controller to regulate the output voltage.

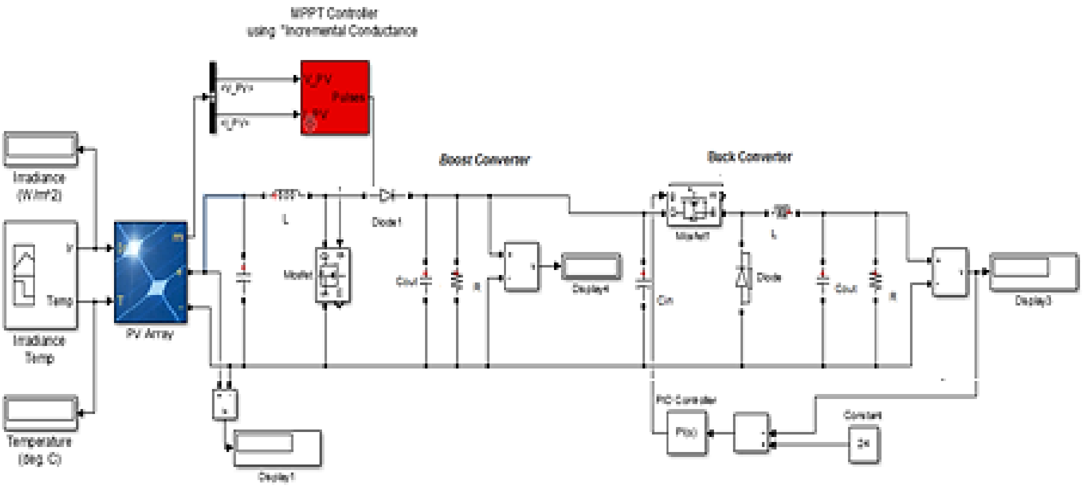


Fig. 39. PV Boost and Buck Converters with feedback Controller Using MATLAB Simulink.

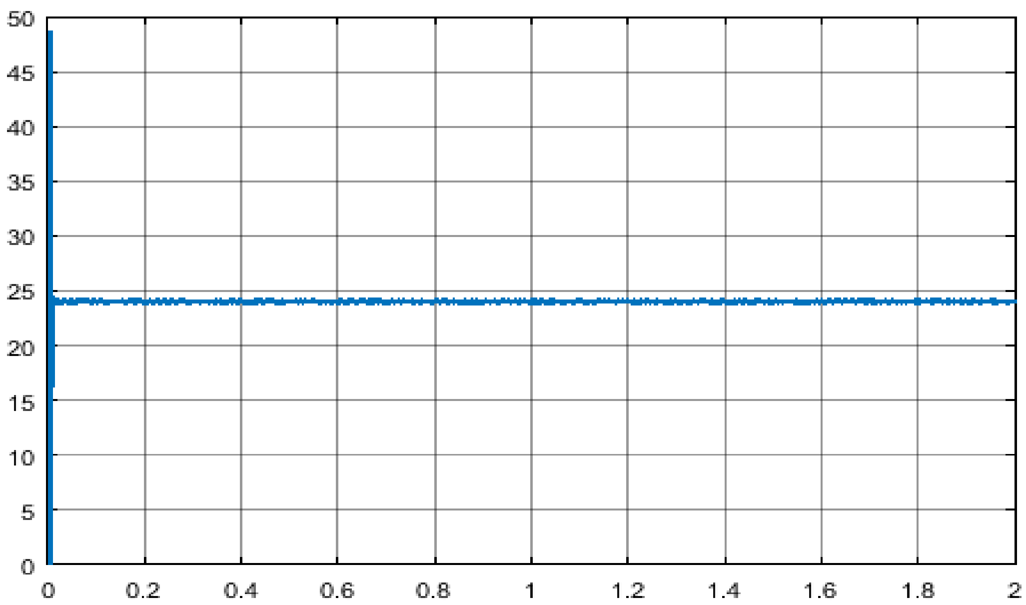


Fig. 40. Output Voltage of the Buck converter.

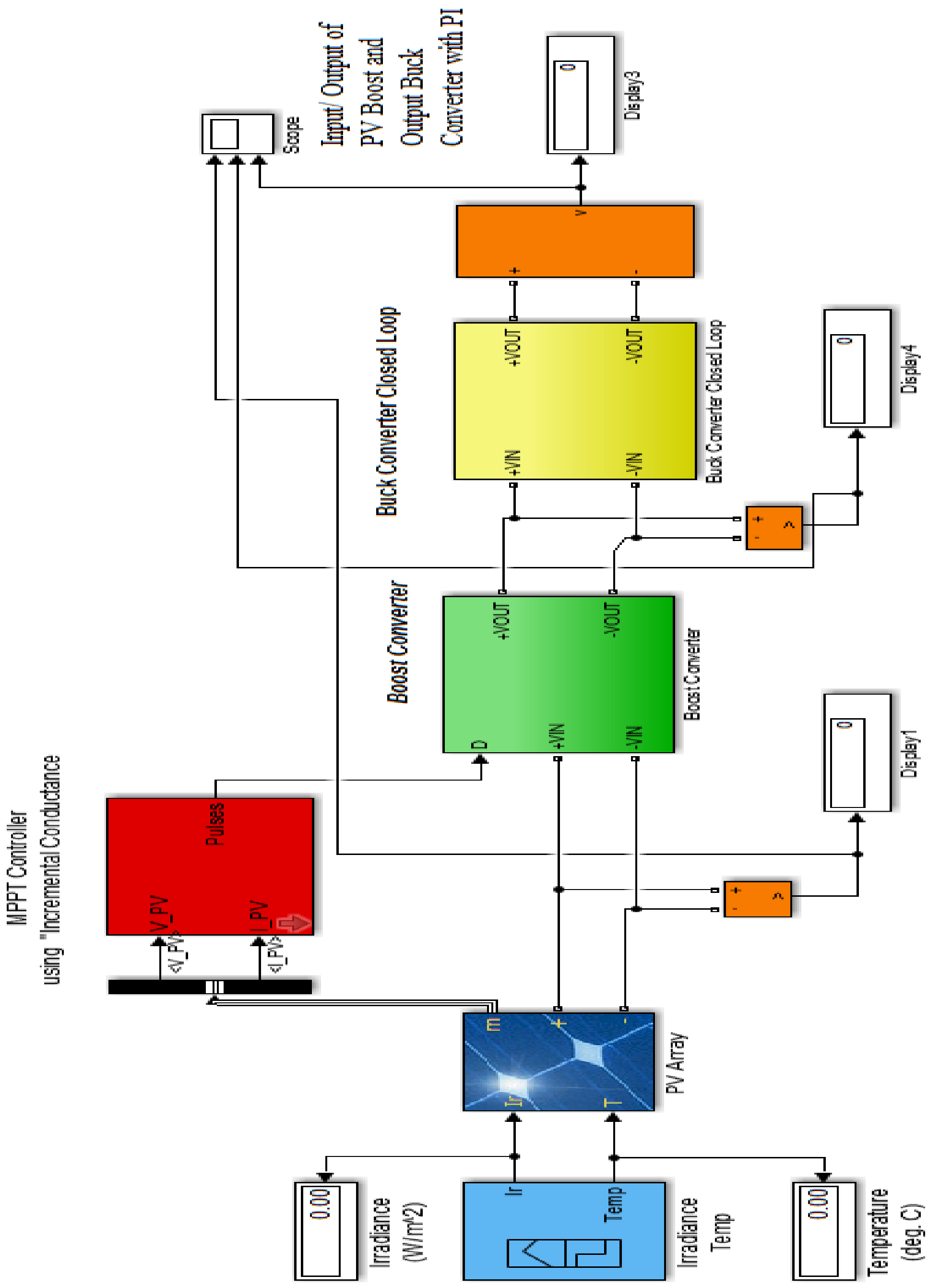


Fig. 41. PV Boost and Buck Converters blocks in MATLAB Simulink.

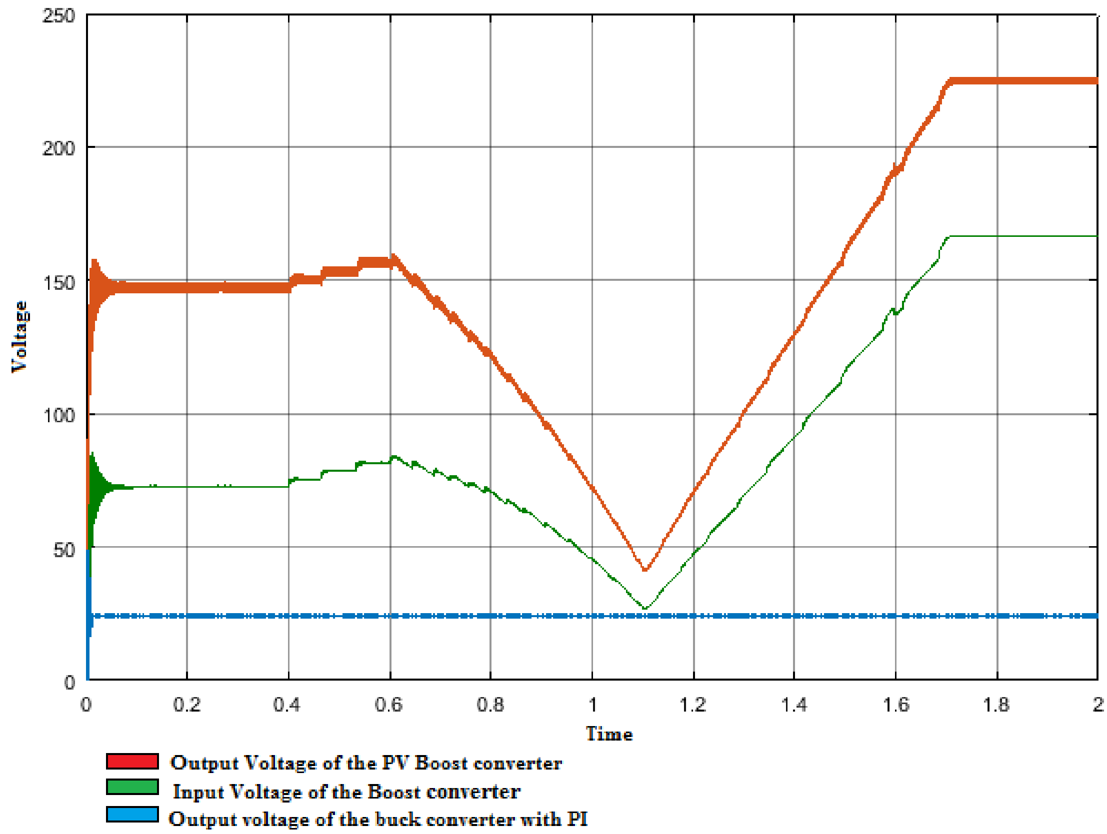


Fig. 42. Input/ Output of PV Boost Converter and Output of Buck Converter with PI.

Fig. 42 shows the simulation result of the boost and buck converters with a feedback controller. It can be seen from the input voltage (green curve) plot that, in the first 0.4 seconds, 75 V was applied and that the output of the boost converter (red curve) plot was at 150 V. Then it was switched to a higher DC voltage source of 155 V to notice the duty cycle behavior with the irradiance at 1000 W/$m^2$and temperature at 25 deg/C. During the time between 0.4 and 1.2 seconds, the irradiance and temperature changed from 1000 W/$m^2$and temperature at 25 deg/C to 250 W/$m^2$and temperature at 50 deg/C. Additionally, the input of the PV plot and output of the boost converter plot changed to a low voltage. However, the output of the buck converter with PI (blue curve) plot desired at 24 V, even when the irradiance and temperature changed from 1000 W/m^2at 25 deg/C to 250 W/m^2at 50 deg/C

CHAPTER 4

CONCLUSION AND FUTURE WORK

1. Conclusion

In this thesis, the Polycrystalline Module was simulated under different radiation conditions to get the PV performance and MPP from V-P curve. Therefore, the output power of the PV module has a significant effect on radiation levels and ambient temperature levels.

In Chapter 3, the DC-DC boost and buck converters were designed by selecting the frequency of 10 KHz. This helps to reduce the cost of the buck converter because the size of the components is reduced with an increase of frequency. It is designed with a step-down output voltage to 24 V, whereas the input voltage from the PV module varies with radiation level. The design was done properly with the desired output voltage, which was stated in Chapter 4. Output voltage ripples and inductor current ripples were found as designed within the limit of 5 % and 30 %, respectively.

However, the boost and buck converters were built by using MATLAB Simulink. There were two controllers: one MPPT controller for the boost converter and one buck converter controller were computed. The feedback controller was built by using MATLAB Simulink software. It absorbed the change in the duty cycle when the input as changed from one voltage level to another. Finally, the PV modelling was connected to the boost converter and the output of the boost converter was connected to the buck converter and simulated under different radiation levels. The output of the converter was as expected and was within the designed voltage constant. In Chapter 4, the controller with selected IC algorithm was explained and discussed. The algorithm of IC was built by using Simulink and run in MATLAB software.

Finally, I presented the result of the converter when it runs by MPPT IC for a boost converter and PI control for a buck converter.

Table 5 shows the results of our work in comparison with other research papers.

Table 5. Comparing with Other Research Papers

RF	**PV model**	**Converter**	**MPPT**	**PWM**	**Feedback**	**Vin**	**Vout**
[8]	No	Boost	No	NO	PID	24	373 AC
[9]	Yes	Boost	No	YES	Regulation	22-28	varies
[10]	Yes	Buck-Boost	YES	NO	NO	21.5	17.44
[11]	Yes	Boost	P&O	NO	NO	17.5	
This Thesis	Yes	Boost & Buck	IC	NO	YES	varies	24 DC Constant

2. Future work

For this thesis, there is still some work that can be done to improve the efficiency of the implemented system. It can also be improved in order to be used in a residential home. Therefore, some of the future works are highlighted below:

- To get better efficiency of the MPPT, comparisons of the performance of the IC algorithm with other algorithms, such as P&O algorithm, with the same photovoltaics system should be explored.

- The buck converter performance could be tested by using other controllers such as LMS (Least Mean Square).
- It would be difficult to design a DC-AC to feed AC load.
- Finally, battery storage could be added in order to meet the load demand overnight.

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