ANALYSIS AND COMPARISON OF THE ONE, TWO AND THREE DIODE MATHEMATICAL MODELS OF PHOTOVOLTAIC CELL

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A PROJECT REPORT PRESENTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING, COLLEGE OF ENGINEERING AND ENGINEERING TECHNOLOGY, MICHAEL OKPARA UNIVERSITY OF AGRICULTURE, UMUDIKE, IN PARTIAL FULFILLMENT OF THE AWARD OF BACHELOR OF ENGINEERING IN THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING.

DECEMBER, 2022.

CERTIFICATION

This project is the original work approved and supervised by ENGR. UKOIMA KELVIN and carried out by JOHN GOODNEWS OSONWA (MOUAU/EEE/16/93349/) in partial fulfillment of the requirements for the award of Bachelor of Engineering Degree in Electrical and Electronics Engineering in the Department of Electrical and Electronics Engineering.

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DECLARATION

We certify that this project work 'Analysis and comparison of the one, two and three diode mathematical models of photovoltaic cells' written by **JOHN GOODNEWS OSONWA(MOUAU/EEE/16/93349)** has been found acceptable for the award of Bachelor of Engineering Degree in Electrical and Electronic Engineering.

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EXTERNAL EXAMINER

DEDICATION

This project is dedicated to God Almighty for his love and care and my parents for support and encouragement.

ACKNOWLEDGEMENT

I thank God Almighty for giving me grace, inspiration and wisdom to complete this programme.

I sincerely thank my project supervisor ENGR. UKOIMA KELVIN, who took his time to supervise me thoroughly in this project work. Honestly this project wouldn't have been possible without your assistance, Sir. Thanks for the encouragement, I really appreciate it.

I also appreciate our amiable head of the department, Engr. DR. I.K ONWUKA for the transformation he has brought to this department.

Special thanks also goes to all the lecturers in electrical and electronics engineering department for their relentless effort in directing me towards academic excellence.

To my family, especially my dad, mum and siblings thank you very much for ever being behind my quest. May God bless you all with long life and prosperity.

Finally, to all my friends in Michael Okpara University of Agriculture, may God bless you all.

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ABSTRACT

Photovoltaic (PV) systems are used for obtaining electrical energy directly from the sun. In this report, a solar cell unit, which is the most basic unit of PV systems, is mathematically modeled and its behavior is simulated in detail using Matlab. Three models are presented: the one diode model, two diode model and three diode models. Non-linear mathematical equations governing the I-V and P-V characteristics are derived and simulated using the Matlab looping iterative method. Comparison is made between all models (one, two and three-diode) for design verification. Results obtained show that as the number of diodes increases in a PV cell model, the open circuit voltage and maximum power decreases for a given set of PV cell parameters. The short circuit current remained at a fixed value irrespective of the number of diodes. It is recommended that future work seeks to optimize the one, two and three-diode models to find the conditions under which all the three models produce identical simulation results.

CHAPTER 1

INTRODUCTION

1.0 Background of Study

The current voltage (IV) and power voltage (PV) characteristic of a PV cell is not linear and is dependent on external conditions of the environment. These conditions include solar radiation and ambient temperature. Since the output characteristics of a PV array aren't linear, it is complicated to understand them (Yunus *et. al.,* 2018). As a result, a variety of methods have been researched for the analysis of the performance of photovoltaic systems. An ideal option for analyzing the performance PV cells is to make use of an equivalent circuit. A good equivalent circuit should be as simple as possible (Yunus *et. al.,* 2018). The results obtained using a given PV cell equivalent circuit and the manufacturers I-V P-V characteristics on the data sheet should show a good agreement. Changes in environmental conditions should also be accurately simulated in the model of the equivalent circuit. The short-circuit current and open-circuit voltage equations of the solar cell are obtained and are used for simulations. The sensitivity of the short-circuit current and open-circuit voltage to environmental changes are analyzed through simulation (Yunus *et. al.,* 2018).

The purpose of a mathematical model is to look for an accurate mathematical model that closely represents the real-life system. To make it easy for testing suitability, an approximate mathematical model is needed to avoid spending capital before production (Gordana, 2017). The modeling process allows identification and better understanding the characteristics of the components and it provides support in decision making. The design of a perfect model is complex and time consuming. A sufficiently appropriate model should be between complexity and accuracy (Gordana, 2017). A good equivalent model is expected to be as uncomplicated as possible. In this work, we present three models of a photovoltaic system and comparison is made between all three models. An accepted option for the analysis of photovoltaic systems is the use of an approximate equivalent circuit. A mathematical photovoltaic model to be used for simulation should be a model which gives the best representation of the I-V P-V characteristic of the PV manufacturers when parameters of the physical PV module are used as input values in the mathematical model. The results obtained in the choice of model of equivalent circuit and the electrical characteristics provided by the manufacturer data sheet should show a good agreement.

The output characteristics of PV arrays (V-I characteristics and V-P characteristics) are not linear and are also highly dependent on environmental conditions.

Environmental conditions are identified by some factors such as solar irradiation, ambient temperature and partial shading conditions of PV arrays. Since the output characteristics of a PV array aren't linear, it is complicated to understand them. That is why there are a variety of methods developed for performance analysis of a PV array. Preferred option for performance analysis of a PV array is the use of an equivalent circuit. A good equivalent circuit should be as simple as possible. The results obtained in the modeling of the equivalent circuit and the electrical characteristics provided by the manufacturer data sheet should show a good agreement. The model of equivalent circuit should also accurately be able to simulate the changes in environmental conditions. In this work, a solar cell unit is. The equations of open-circuit voltage and short-circuit current of the solar cell are acquired and these equations are used for simulations. The open circuit voltage and short circuit current parameters' sensitivity to environmental changes are analyzed through simulation.

1.2 Problem Statement

The purpose of a mathematical model is to look for an accurate mathematical model that closely represents the real-life system. When an approximate mathematical model is available it is easier to test the system for suitability without spending money prior to the fabrication. The modeling process allows identification and better understanding the characteristics of the components and it provides support in decision making. The design of a perfect model is complex and time consuming. A sufficiently appropriate model should be between complexity and accuracy. In this report, we present three models of a photovoltaic system and comparison is made between all three models. Preferred option for performance analysis of a PV array is the use of an equivalent circuit. A good equivalent circuit should be as simple as possible.

1.3 Aim and Objectives

The aim of this work is to simulate and compare the various mathematical photovoltaic models. The objectives are:

1. To study existing literature on photovoltaic systems
2. Mathematically model a photovoltaic cell using one diode
3. Mathematically model a photovoltaic cell using two diodes
4. Mathematically model a photovoltaic cell using three diodes
5. Compare the various photovoltaic models.

1.4 Project Scope

This work is limited to the mathematical design and simulation of photovoltaic cells. Focus will be on using one diode, two diodes and three diodes.

1.5 Significance of project

This work will help influence the choice of a suitable mathematical model of a photovoltaic system that closely represents the real-life system so that a computer simulation can test the system outputs under various input conditions, as well as to test the system for stability.

1.6 Project Organization

Chapter 1 discusses the background study, problem statement, aim and objectives, project scope, and the significance of the project. Chapter 2 gives a well detailed literature review and some of the related works done by other authors. Chapter 3 explained the three mathematical models. Chapter 4 discusses the simulation result. Chapter 5 gives the conclusion and recommendation of the project.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of Photovoltaic Models

The equivalent circuit of a solar cell is investigated in many prior works. Erdem and Erdem (2013) proposed a distance learning experiment for a PV cell model using MATLAB. Green (1981) focuses on fill factor formulae. Phan and Chan (1984) are among the first who provide an analytical solution for a PV model. However, they do not consider parameters variation and have a limited range for a1. Further proposals for PV models can be found in (Liu and Dunford, 1985; Gow and Manning, 1999). Walker (2001) uses a MATLAB PV model to study MPPT converter technologies. (De Blas et al., 2002) and (Xiao et al., 2004) further enhance the PV models adding new perspectives, while (King et al., 2019) proposed a model available online using an extensive set of experimental data. De Soto et al. (2006) propose a model for a PV array, while Schlosser and Ghitas (2006) analyze the AC parameters of the PV cell. Villava et al. (2009) developed an accurate algorithm for finding the PV model parameters at the reference temperature. Kim et al. (2009) concentrates on transient analysis based on a grid-connected PV system. (Di Piazza and Vitale, 2010) investigated different shadowing conditions. A model dedicated to monocrystalline PV panels is proposed by Jung and Ahmed (2010); Kim and Choi (2010) introduce an interesting way for finding the PV cell parameters. Advanced mathematics is used in (Salam and Ishaque, 2011) for the same purpose while Saloux et al. (2011) elaborate explicit parameters finding around MPP. Further models are also proposed by Cuce and Cuce (2011) and Tian et al. (2012). Cubas and Pindado (2014) use Lambert W-function for PV cell parameters extraction and they also provide an LTSpice model based on these parameters. In a recent paper, Aller et al. (2017) propose an estimation of the PV parameters that can be used in inverters power control.

2.2 The Photovoltaic System (Solar Cell)

A photovoltaic cell is composed of many layers of materials, each with a specific purpose. The most important layer of a photovoltaic cell is the specially treated semiconductor layer (Robert and Louis, 1999). It is comprised of two distinct layers (p-type and n-type), and is what actually converts the Sun's energy into useful electricity through a process called the photovoltaic effect (see below). On either side of the semiconductor is a layer of conducting material which "collects" the electricity produced. Note that the backside or shaded side of the cell can afford to be completely covered in the conductor, whereas the front or illuminated side must use the conductors sparingly to avoid blocking too much of the Sun's radiation from reaching the semiconductor. The final layer which is applied only to the illuminated side of the cell is the anti-reflection coating. Since all semiconductors are naturally reflective, reflection loss can be significant (Thomas and Jain, 2004). The solution is to use one or several layers of an anti-reflection coating (similar to those used for eyeglasses and cameras) to reduce the amount of solar radiation that is reflected off the surface of the cell (Thomas and Jain, 2004).

In order to create low power remote and independent electronic devices it is necessary to collect and convert energy directly from the environment. This is very important in order to maintain a continuous operation. A good solution is the use of a photovoltaic device (Edwardo Lorenzo, 1994). A photovoltaic (PV) cell converts the solar energy into the electrical energy by the photovoltaic effect. The heat does not participate constructively in this process. Heat actually limits the performance of these fine layers, and the presence of excess heat is a sign of deterioration in a PV cell. Most solar cells are built from silicon, and the presence of impurities influences their performance. Solar cell efficiencies vary from 6% for amorphous silicon-based solar cells to (Nelson, 2003) 42.8% with multiple-junction research lab cells. Solar cell energy conversion efficiencies for commercially available multicrystalline Si solar cells are around 14-19%. The major advantages of using PV cells are: short lead time for designing and installing a new system, output power matching with peak load demands, static structure, no moving parts, longer life, no noise, high power capability per unit of weight, inexhaustible and pollution free, highly mobile and portable because of its light weight. Solar arrays are used in many terrestrial and space applications (Mitchell and Mitchell, 1992). For best utilization, the photovoltaic cells must be operated at their maximum power point (MPP). However, the MPP varies with illumination, temperature, radiation dose and other aging effects. The block diagram typically used for battery charger is presented in figure 2.2. The weather and load changes cause the operation of a PV system to vary almost all the time. A dynamic tracking method is necessary to ensure maximum power is extracted from the PV cells. Due to the mismatch between load line and operating characteristic of the solar cells, the power available from the solar cells is not always fully extracted (Edwardo Lorenzo, 1994; Vivek & Sawle, 2015). This can be demonstrated by figure 2.1. Maximum power point tracking (MPPT) is a control technique to adjust the terminal voltage of PV panels so that maximum power can be extracted (Ronald and Gregory, 2007)

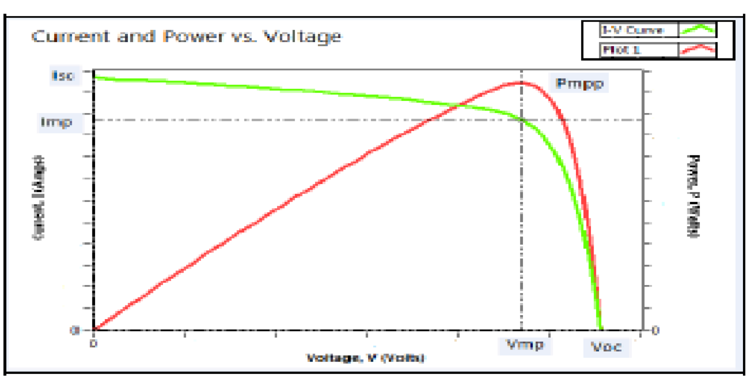


Figure 2.1: Typical I-V and P-V characteristics of photovoltaic cell.
Source: (Nelson, 2003)

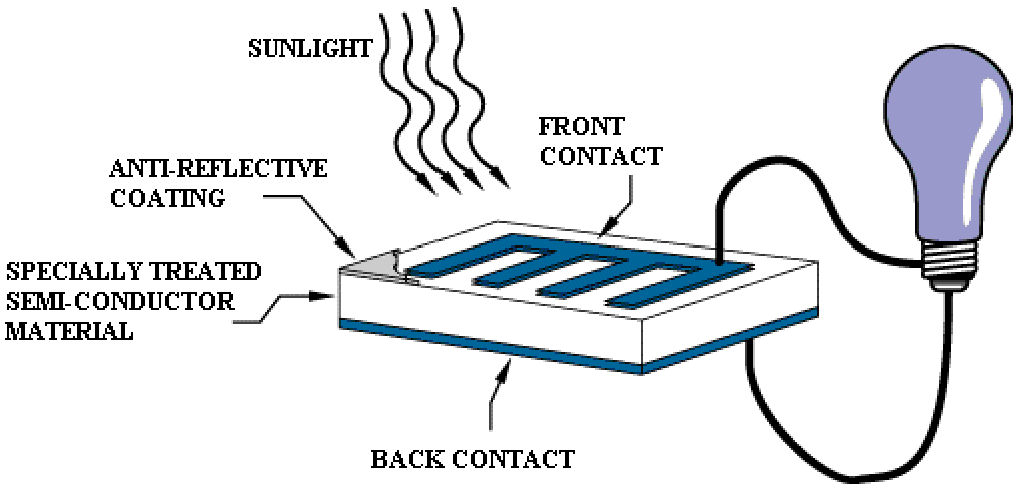


Figure 2.2: Basic solar cell
Source: (Nelson, 2003)

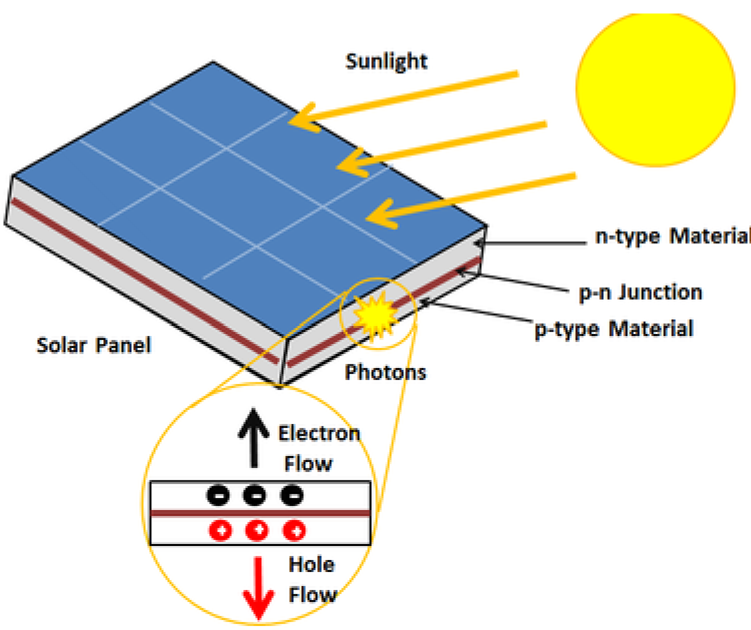


Figure 2.3: Working principle of a solar cell
Source: (Nelson, 2003)

Solar cells convert sunlight directly into electricity. Solar cells are often used to power calculators and watches. They are made of semiconducting materials similar to those used in computer chips. When sunlight is absorbed by these materials, the solar energy knocks electrons loose from their atoms, allowing the electrons to flow through the material to produce electricity. This process of converting light (photons) to electricity (voltage) is called the photovoltaic (PV) effect.

Solar cells are typically combined into modules that hold up to 72 cells; a number of these modules are mounted in PV arrays that can measure up to several meters on a side (Nelson, 2003). These flat-plate PV arrays can be mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. Several connected PV arrays can provide enough power for a household; for large electric utility or industrial applications, hundreds of arrays can be interconnected to form a single, large PV system.

Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Thin film technology has made it possible for solar cells to now double as rooftop shingles, roof tiles, building facades, or the glazing for skylights or atria. The solar cell version of items such as shingles offer the same protection and durability as ordinary asphalt shingles.

The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energies will work efficiently to create electricity, and much of it is reflected or absorbed by the material that makes up the cell. Because of this, a typical commercial solar cell in 2019 has an efficiency of about 19-22 percent, meaning about one-fifth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, and that means higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry, NREL researchers, and other U.S. Department of Energy (DOE) laboratories, and they have made significant progress. The first solar cells, built in the 1950s, had efficiencies of less than 4% (Edwardo Lorenzo, 1994; Jenny Nelson, 2003).

2.3 The P – N Junction

The p–n junction is a boundary or interface between two types of semiconductor materials, p-type and n-type, inside a single crystal of semiconductor. The "p" (positive) side contains an excess of holes, while the "n" (negative) side contains an excess of electrons in the outer shells of the electrically neutral atoms there. This allows electrical current to pass through the junction only in one direction. The p-n junction is created by doping, for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant). If two separate pieces of material were used, this would introduce a grain boundary between the semiconductors that would severely inhibit its utility by scattering the electrons and holes.

p–n junctions are elementary "building blocks" of semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place. For example, a common type of transistor, the bipolar junction transistor, consists of two p–n junctions in series, in the form n–p–n or p–n–p; while a diode can be made from a single p-n junction. A Schottky junction is a special case of a p–n junction, where metal serves the role of the p-type semiconductor.

2.4 The Shockley Diode Equation

The Shockley diode equation or the diode law, named after transistor co-inventor William Shockley of Bell Telephone Laboratories, gives the I–V (current-voltage) characteristic of an idealized diode in either forward or reverse bias (applied voltage):

$$I_D = I_O\left[exp^{\frac{qV}{nkT}} - 1\right] \tag{2.1}$$

I_D = Diode current; V = Output voltage; q = Electron charge; n = Diode factor; k = Boltzmann constant; T = Operating temperature; I_O = Diode saturation current;

The equation is called the Shockley ideal diode equation when n, the ideality factor, is set equal to 1. The ideality factor n typically varies from 1 to 2 (though can in some cases be higher), depending on the fabrication process and semiconductor material and is set equal to 1 for the case of an "ideal" diode (thus the n is sometimes omitted). The ideality factor was added to account for imperfect junctions as observed in real transistors. The factor mainly accounts for carrier recombination as the charge carriers cross the depletion region.

2.5 The Photovoltaic Effect

The photovoltaic effect is a process that generates voltage or electric current in a photovoltaic cell when it is exposed to sunlight. These solar cells are composed of two different types of semiconductors—a p-type and an n-type—that are joined together to create a p-n junction. By joining these two types of semiconductors, an electric field is formed in the region of the junction as electrons move to the positive p-side and holes move to the negative n-side. This field causes negatively charged particles to move in one direction and positively charged particles in the other direction (Nelson, 2003). Light is composed of photons, which are simply small bundles of electromagnetic radiation or energy. When light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an electron of the semiconducting material, causing it to jump to a higher energy state known as the conduction band. In their excited state in the conduction band, these electrons are free to move through the material, and it is this motion of the electron that creates an electric current in the cell (Eduardo, 1994).

2.6 Solar Cell Efficiency

Efficiency is a design concern for photovoltaic cells, as there are many factors that limit their efficiency. The main factor is that 1/4 of the solar energy to the Earth cannot be converted into electricity by a silicon semiconductor. The physics of semiconductors requires a minimum photon energy to remove an electron from a crystal structure, known as the band-gap energy. If a photon has less energy than the band-gap, the photon gets absorbed as thermal energy. For silicon, the band-gap energy is 1.12 electron volts. Since the energy in the photons from the sun cover a wide range of energies, some of the incoming energy from the Sun does not have enough energy to knock off an electron in a silicon PV cell (Nelson, 2003). Even from the light that can be absorbed, there is still a problem. Any energy above the band-gap energy will be transformed into heat. This also cuts the efficiency because that heat energy is not being used for any useful task. Of the electrons that are made available, not all of them will actually make it to the metal contact and generate electricity. This is because some of them will not be accelerated sufficiently by the voltage inside the semiconductor. Because of the reasons listed, the theoretical efficiency of silicon PV cells is about 33%.

There are ways to improve the efficiency of PV cells, all of which come with an increased cost. Some of these methods include increasing the purity of the semiconductor, using a more efficient semiconducting material such as Gallium Arsenide, by adding additional layers or p-n junctions to the cell, or by concentrating the Sun's energy using concentrated photovoltaics. On the other hand, PV cells will also degrade, outputting less energy over time, due to a variety of factors including UV exposure and weather cycles. A comprehensive report from the National Renewable Energy Laboratory (NREL) states that the median degradation rate is 0.5% per year (Nelson, 2003).

2.7 Types of PV Cell

Photovoltaic cell can be manufactured in a variety of ways and from many different materials. The most common material for commercial solar cell construction is Silicon (Si), but others include Gallium Arsenide (GaAs), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). Solar cells can be constructed from brittle crystalline structures (Si, GaAs) or as flexible thin-film cells (Si, CdTe, CIGS). Crystalline solar cells can be further classified into two categories—monocrystalline and polycrystalline, as shown in figure 2.4. As the names suggest, monocrystalline PV cells are composed of a uniform or single crystal lattice, whereas polycrystalline cells contain different or varied crystal structures. Solar cells can also be classified by their number of layers or "p-n junctions". Most commercial PV cells are only single-junction, but multi-junction PV cells have also been developed which provide higher efficiencies at a greater cost (Robert and Louis, 1999).

2.8 Monocrystalline Silicon Cell

The first commercially available solar cells were made from monocrystalline silicon, which is an extremely pure form of silicon. To produce these, a seed crystal is pulled out of a mass of molten silicon creating a cylindrical ingot with a single, continuous, crystal lattice structure. This crystal is then mechanically sawn into thin wafers, polished and doped to create the required p-n junction. After an anti-reflective coating and the front and rear metal contacts are added, the cell is finally wired and packaged alongside many other cells into a full solar panel. Monocrystalline silicon cells are highly efficient, but their manufacturing process is slow and labour intensive, making them more expensive than their polycrystalline or thin film counterparts (Robert and Louis, 1999).

2.9 Polycrystalline Silicon Cell

Instead of a single uniform crystal structure, polycrystalline (or multicrystalline) cells contain many small grains of crystals (see figure 2.4). They can be made by simply casting a cube-shaped ingot from molten silicon, then sawn and packaged similar to monocrystalline cells. Another method known as edge-defined film-fed growth (EFG) involves drawing a thin ribbon of polycrystalline silicon from a mass of molten silicon. A cheaper but less efficient alternative, polycrystalline silicon PV cells dominate the world market, representing about 70% of global PV production in 2015.

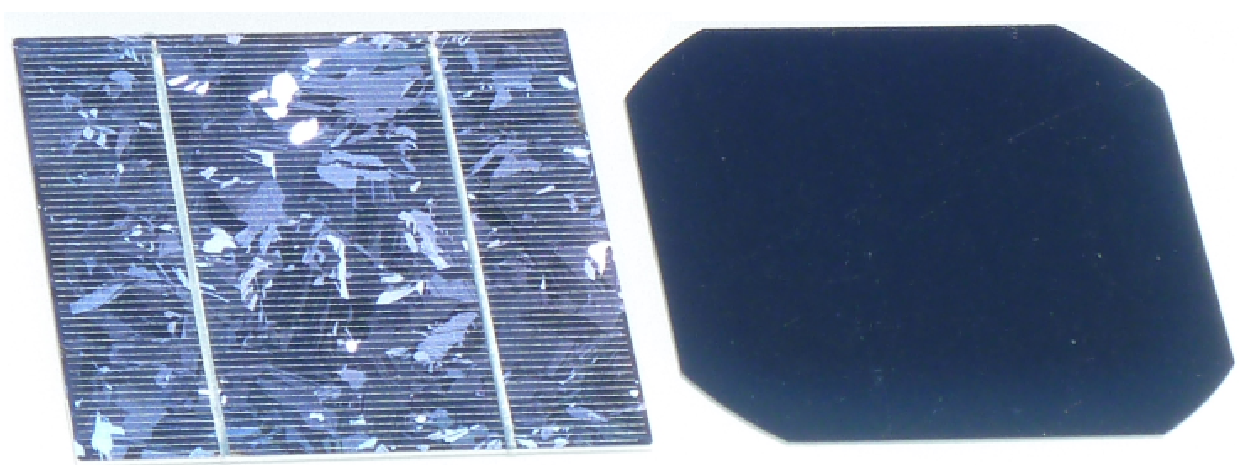


Figure 2.4: Types of PV cells
Source: (Suthar *et. al.,* 2013)

2.10 Characteristics of Photovoltaic Cell

Photovoltaic cells generally demonstrate a nonlinear I-V and P-V characteristics which vary with the solar irradiation and cell temperature. The most important fundamental parameters used for characterizing the photovoltaic cell are: short circuit current ISC, open circuit voltage VOC, Maximum Power Point (MPP), efficiency (η) and Fill Factor (FF).

Short circuit current: It is the current that reduces the effect of impedance in the circuit. When the cell is short circuited,

negligible current flows in the diode. It is calculated when V=0. However, it is largest amount current produced from the PV cell due to the photon excitation.

$$I_{L(v=0)} = I_{sc} \tag{2.2}$$

Open circuit voltage: It is voltage which is not connected to any load in a circuit and no current passing through the cell. It is calculated when the voltage is equal to zero. Moreover, it is the maximum voltage difference across the PV cell when I=0.

Mathematically,

$$V_{OC} = \frac{n_s nkT}{q} In\left[\frac{I_L}{I_O} + 1\right] \tag{2.3}$$

Maximum Power Point: It is the operating point where the power is maximum across the load. Mathematically,

$$P_m = V_m I_m \tag{2.4}$$

2.11 Modeling of the Photovoltaic Cell

A solar cell is the building block of a solar panel as well as the fundamental unit of a PV cell. A PV cell is created by the combination of many solar cells in series and parallel. Solar cells which are connected in series are used to increase the output voltage and the cells in parallel will produce a higher current. The electrical characteristics of the solar cell differ barely from a diode, the relationship between the cells terminal voltage and current is represented by the Shockley equation

$$I_D = I_O\left[exp^{\frac{qV}{nkT}} - 1\right] \tag{2.5}$$

Generally, a photovoltaic cell is a silicon semiconductor junction device composed of a p-n junction almost identical to a diode. It converts sunlight directly into electricity. When the P-N junction is visible to light, photons with energy greater than band gap energy of the semiconductor are absorbed creating the electron hole-pairs which are proportional to the incident irradiation. In the dark, the I-V output characteristics of a PV cell is similar to that of a diode. When the cell is short circuited, this current flows in the external circuit; when open circuited, this current is shunted internally by the intrinsic P-N junction diode. The characteristics of this diode, therefore, set the open circuit voltage characteristics of the cell. The equivalent circuit of a simple PV cell can be modeled by a current source in parallel with two diodes, a parallel resistor indicating a leakage current and a series resistor expressing an internal resistance to the current flow. See (Eduardo, 1994; Nelson, 2003)

2.11 SOME SOLAR ASTRONOMY

2.11.1 Solar Elevation Angle

The elevation angle is the altitude of the sun. It is the angular height of the sun in the sky measured from the horizontal plane (Nelson, 2003). In the morning, the elevation is 0° at sunrise. When the sun is directly overhead, it is 90°. Maximum elevation angle occurs at 90º. This is a vital consideration in the design of pv systems (Nelson, 2003). The angle of elevation changes continuously throughout the day. It depends specifically on the day of the year and the latitude of the location and (Nelson, 2003). The formula for solar elevation angle is given in equation (2.6).

$$\psi = sin^{-1}(cos\alpha cos\beta cos\gamma + sin\beta sin\gamma) \qquad (2.6)$$

γ is the local latitude, α is the angle hour and β is the angle of declination of the earth.

2.11.2 Solar Azimuth Angle

The azimuth angle can be defined as the direction of the sun rays projection on the horizontal plane and compass between the true north (Nelson, 2003). To determine the sun's position at a particular date and time on a particular location, knowledge of the elevation angle with respect to the plane and azimuth angle is essential (Nelson, 2003). In the Northern hemisphere, the sun is directly south at noon. This implies that the azimuth angle $A_z = 0^o$. The sun rises at the east and sets at the west at the equinoxes regardless of the latitude. This makes the azimuth angles 90° at sunrise and 270° at sunset (Nelson, 2003). The formula for solar azimuth is given in equation (2.7).

$$\zeta = cos^{-1}\left(\frac{sin\beta cos\gamma - cos\alpha cos\beta sin\gamma}{cos\psi}\right) \quad (2.7)$$

$$\beta = 23.45 sin\left(\frac{2\pi}{365}(284 + d)\right) \quad (2.8)$$

d is the day of the year

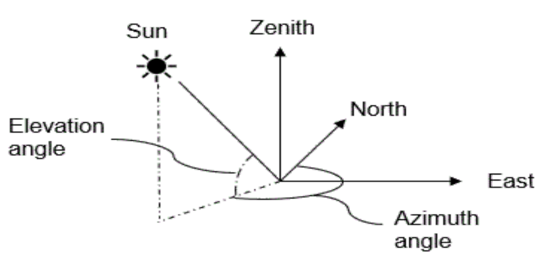


Figure 2.5: Azimuth angle: north=0, east=90, south=180, west=270 degree. Source: (Nelson, 2003)

CHAPTER 3

METHODOLOGY

This section presents the methods used in modeling a photovoltaic cell

3.1 Mathematical Modeling of Photovoltaic Cell

This section presents a framework for the modeling and simulation of PV cells. First, the basic form of a PV cell is studied. Physical laws governing the basic uint are formulated. This is followed by simulations and verification of the design

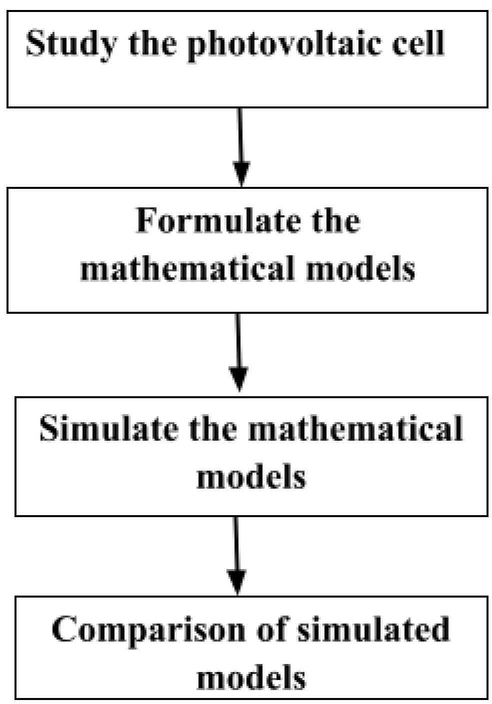


Figure 3.1: Research framework

3.1 The One-Diode-Model for PV cells

The One-Diode -Model is the simplest and the most used model for PV cells (figure 3.1). The simplified equivalent circuit of a solar cell consists of a diode and a current source which are connected in parallel. The current source generates the photo current *IPh*, which is directly proportional to the solar irradiance Fs[W/m2], ambient temperature Ta [ºC], and two output parameters: current Is [A] and voltage Vs [V]. The p-n transition area of the solar cell is equivalent to a diode. The characteristic equation of the one diode model could be derived from Kirchhoff's current law:

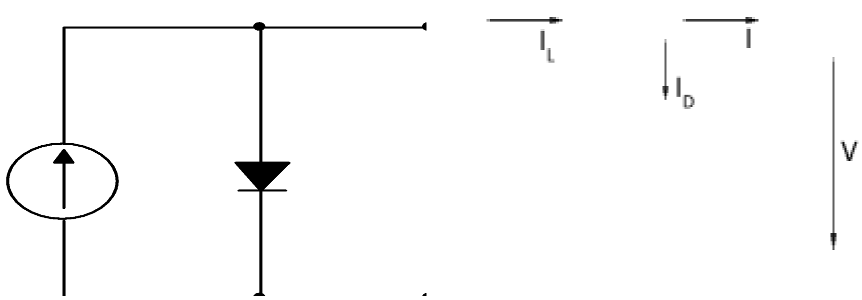


Fig. 3.1: Ideal single-diode model

I_L = Photocurrent; I_D = Diode current; I = Output current; V = Output voltage; q = Electron charge; n = Diode factor; k = Boltzmann constant; T = Operating temperature; I_O = Diode saturation current; I_{sc} = Short circuit current; V_{oc} = Open circuit voltage; R_S = Series resistance; R_{SH} = Shunt resistance; P = Power

From Fig.1, using Kirchhoff's current law,

$$I = I_L - I_D \qquad (3.1)$$

The Shockley equation for an ideal diode is given by:

$$I_D = I_O\left[exp^{\frac{qV}{nkT}} - 1\right] \qquad (3.2)$$

$$\Rightarrow I = I_L - I_O\left[exp^{\frac{qV}{nkT}} - 1\right] \qquad (3.3)$$

For n_s number of cells,

$$I = I_L - I_O\left[exp^{\frac{qV}{nn_sKT}} - 1\right] \qquad (3.4)$$

The open circuit voltage and short circuit current can be used to characterize a photovoltaic cell.

The short circuit current I_{SC} is obtained when V = 0 in (3.4)

Thus,

$$I_{SC} = I = I_L \qquad (3.5)$$

The open circuit voltage V_{OC} is obtained when I = 0 in (3.4)

$$I_L = I_O\left[exp^{\frac{qV}{nkT}} - 1\right]$$

$$V_{OC} = \frac{n_s nkT}{q} In\left[\frac{I_L}{I_O} + 1\right] \qquad (3.6)$$

Power

$$P = IV = \left[I_L - I_O\left[exp^{\frac{qV}{nn_skT}} - 1\right]\right]V \qquad (3.7)$$

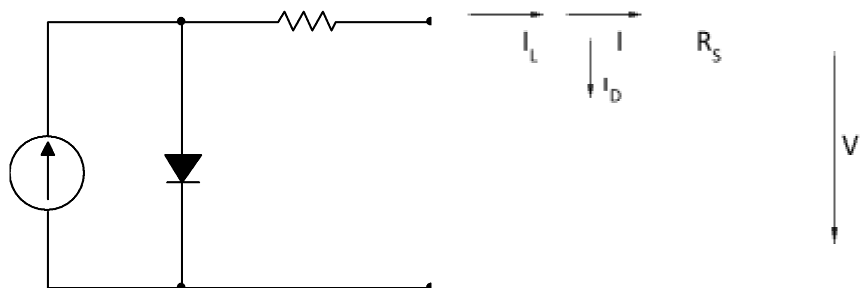


Fig. 3.2: Single-diode model with series resistance

Using similar procedures in equations 1 – 7 in the analysis of Figure 3.2, we obtain:

$$I = I_L - I_D$$

$$I = I_L - I_O\left[exp^{\frac{q(V+In_sR_S)}{n_snkT}} - 1\right] \quad (3.8)$$

$$I_{SC} = I_L - I_O\left[exp^{\frac{qI_{SC}R_S}{nkT}} - 1\right] \quad (3.9)$$

$$V_{OC} = \frac{n_snkT}{q} In\left[\frac{I_L}{I_O} + 1\right] \quad (3.10)$$

$$P = \left[I_L - I_O\left[exp^{\frac{q(V+In_sR_S)}{n_snkT}} - 1\right]\right]V \quad (3.11)$$

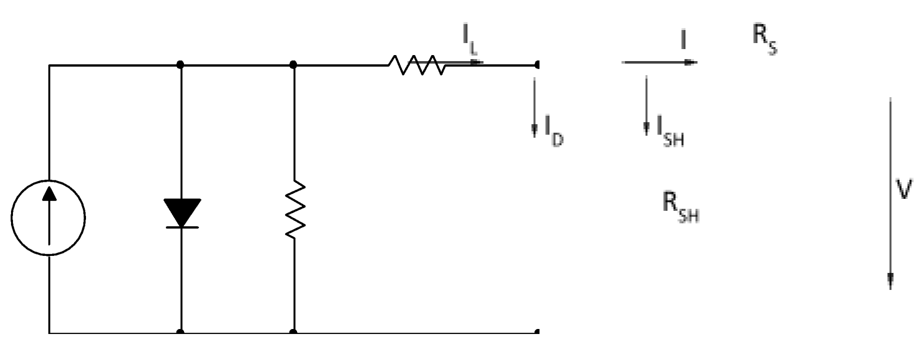


Fig. 3.3: Single-diode model with series and shunt resistances

$$I = I_L - I_D - I_{SH} \quad (3.12)$$

$$I_{SH} = \frac{V+IR_S}{R_{SH}} \quad (3.13)$$

$$I = I_L - I_O\left[exp^{\frac{q(V+IR_S)}{nkT}} - 1\right] - \frac{V+IR_S}{R_{SH}} \quad (3.14)$$

For n_S cells;

$$I = I_L - I_O\left[exp^{\frac{q(V+In_sR_S)}{n_snkT}} - 1\right] - \frac{V+In_sR_S}{n_sR_{SH}} \quad (3.15)$$

3.2 The Two-Diode-Model for PV cells

The single-diode model does not cater for the recombination effect of a diode. To solve this problem, another diode is added in parallel. The two-diode model is shown in figure 3.4 below

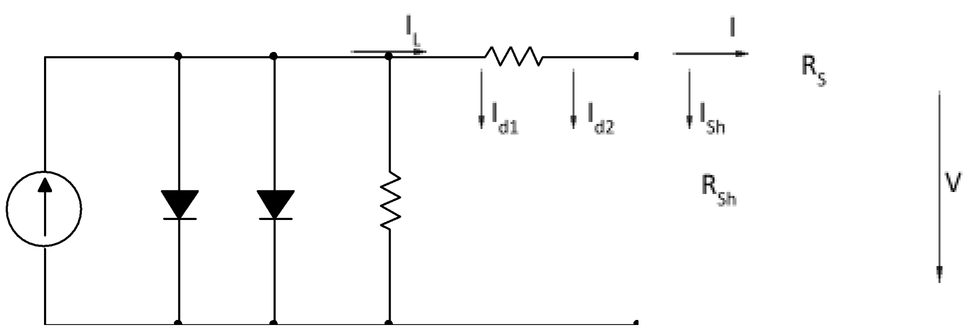


Fig.3. 4: Double-diode model with series and shunt resistances

$$I = I_L - I_{D1} - I_{D2} - I_{SH} \quad (3.16)$$

$$I = I_L - I_{O1}\left[exp^{\frac{q(V+IR_S)}{n_1kT}} - 1\right] - I_{O2}\left[exp^{\frac{q(V+IR_S)}{n_2kT}} - 1\right] - \frac{V+IR_S}{R_{SH}} \quad (3.17)$$

3.3 THREE DIODE MODEL

In the one and two-diode models highlighted above, internal losses and voltage drops caused by the inflow of current in a PV cell were represented in the model by the series resistance. The shunt resistance caters for the leakage current to ground in a practical PV cell. A single-diode model does not cater for the recombination effect of a diode; hence, another diode is added in parallel to form the two-diode model. In this section, a third diode is added in parallel to the existing two-diode model and a study of its effects on the I-V and P-V characterization is presented. Two models are presented: 1. A model with only series resistance and 2. A model with both series and shunt resistances.

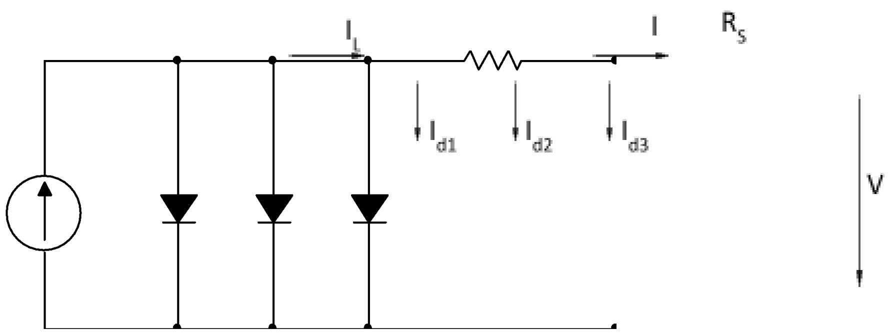


Fig.3. 5: Three diode model with series resistance

Using similar arguments in equations 1 – 4 and equation 13, the following is obtained.

$$I = I_L - I_{D1} - I_{D2} - I_{D3} \quad (18)$$

$$I = I_L - I_{O1}\left[exp^{\frac{q(V+IR_S)}{n_1kT}} - 1\right] - I_{O2}\left[exp^{\frac{q(V+IR_S)}{n_2kT}} - 1\right] - I_{O3}\left[exp^{\frac{q(V+IR_S)}{n_3kT}} - 1\right] \quad (3.19)$$

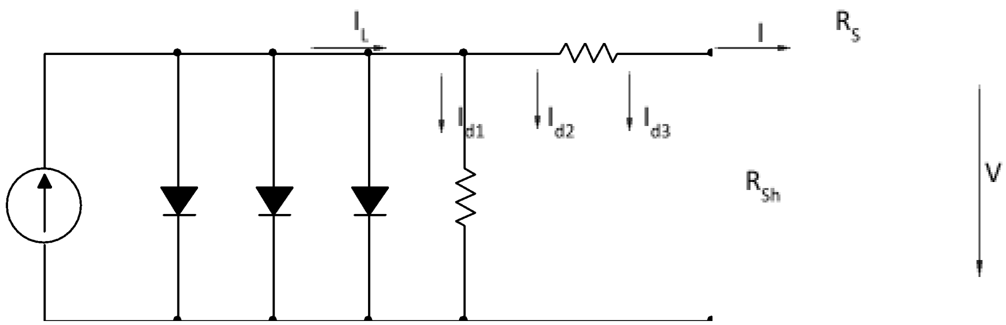


Fig. 3.6: three-diode model with series and shunt resistances

$$I = I_L - I_{D1} - I_{D2} - I_{D3} - I_{SH} \quad (3.20)$$

$$I = I_L - I_{O1}\left[exp^{\frac{q(V+IR_S)}{n_1 kT}} - 1\right] - I_{O2}\left[exp^{\frac{q(V+IR_S)}{n_2 kT}} - 1\right] - I_{O3}\left[exp^{\frac{q(V+IR_S)}{n_3 kT}} - 1\right] - \frac{V+IR_S}{R_{SH}}$$

(3.21)

3.4 SIMULATION MODELS

In this section, the mathematical models used for simulation in Matlab is presented. The general equations for the diode saturation current, I_O and the nominal diode saturation current, I_{ON} are standard formulas obtained from (Nelson, 2003). This was then extended to the case of the one, two and three diode models using subscripts 1, 2 and 3. The simulations were then performed using Matlab looping iterative method. The results are presented in chapter 4.

Case 1a: Model with no shunt resistance for single diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] \; I_{O1} = I_{ON1}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] \; I_{ON1} = \frac{I_{SCN}}{exp\left(\frac{V_{OCN}}{nV_{TN}}\right) - 1} \; I = I_L$$

(3.22)

Case 1b: Model with no shunt resistance for two diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] I_{O1} = I_{ON1}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] I_{O2} = I_{ON2}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\right.\right.$$

(3.23)

Case 1c: Model with no shunt resistance for three diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] I_O = I_{O1} = I_{O2} = I_{O3} = I_{ON}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] I_{ON} = I_{O}$$

(3.24)

Case 2a: Model with shunt resistance for single diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] I_{O1} = I_{ON1}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] I_{ON1} = \frac{I_{SCN}}{exp\left(\frac{V_{OCN}}{nV_{TN}}\right)-1}\; I = I_L - I_{O1}\left[exp^{\frac{q(V+IR_s}{n_1 kT}}\right.$$

(3.25)

Case 2b: Model with shunt resistance for a two diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] I_O = I_{O1} = I_{O2} = I_{ON}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] I_{ON} = I_{ON1} = I$$

(3.26)

Case 2c: Model with shunt resistance for a three diode model

$$I_L = \frac{G}{G_N}\left[I_{LN} + K_I\left(T - T_N\right)\right] I_O = I_{O1} = I_{O2} = I_{O3} = I_{ON}\left(\frac{T}{T_N}\right)^3 exp\left[\frac{qE_g}{nk}\left(\frac{1}{T_N} - \frac{1}{T}\right)\right] I_{ON} = I_{ON1} = I_{ON2} = I_{O}$$

(3.27)

Table 1: PV cell parameters

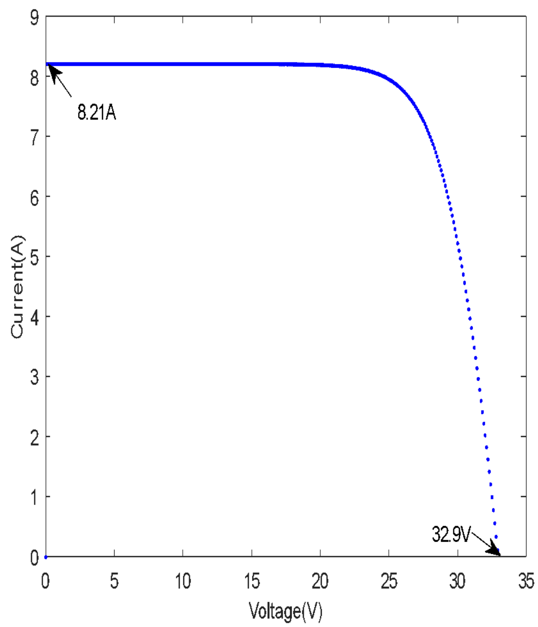
Parameters	Values
k	1.38065e-23 J/K
q	1.602e-19 C
Iscn	8.21 A
Vocn	32.9 V
Ki	0.0032 A/K
T	25+273 K
Tn	25+273 K
Gn	1000 W/m^2
n	1.3 ($1 \leq n \leq 2$)
Eg	1.12 J
G	1000 W/m^2
Rs	0.2 Ω
Rsh	415 Ω

CHAPTER 4

SIMULATION RESULTS

CASE 1: MODEL WITH NO SHUNT RESISTANCE

1a: Single Diode Model



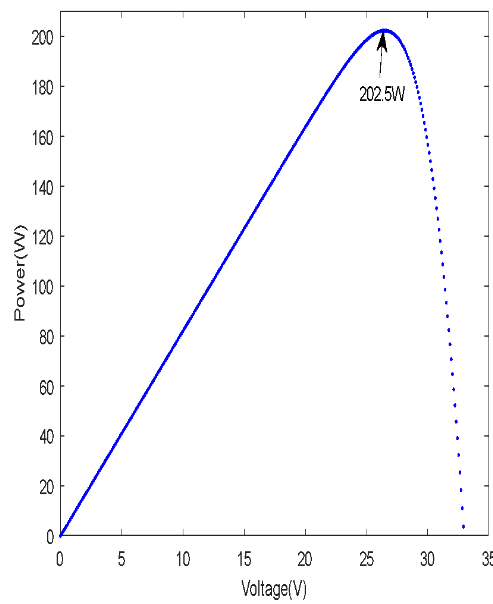
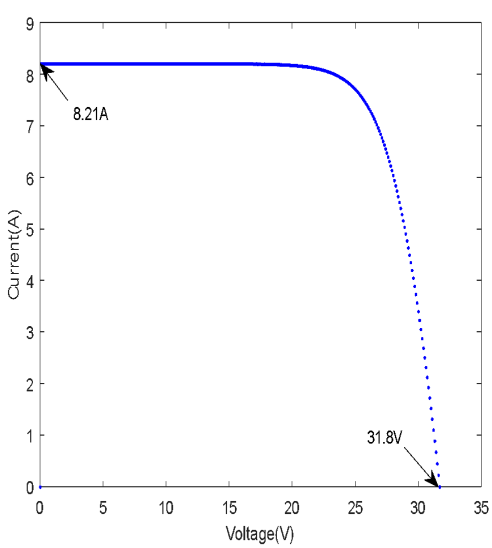


Fig. 4.1: I-V Characteristic

Fig. 4.2: P-V Characteristic

1b: Two Diode Model



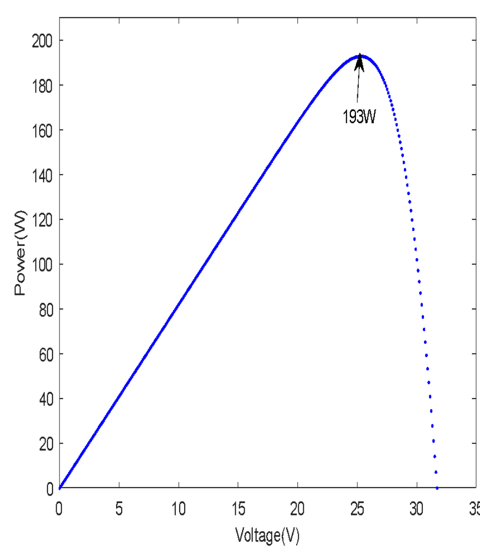


Fig. 4.3: I-V Characteristic

Fig. 4.4: P-V Characteristic

1c: Three Diode Model

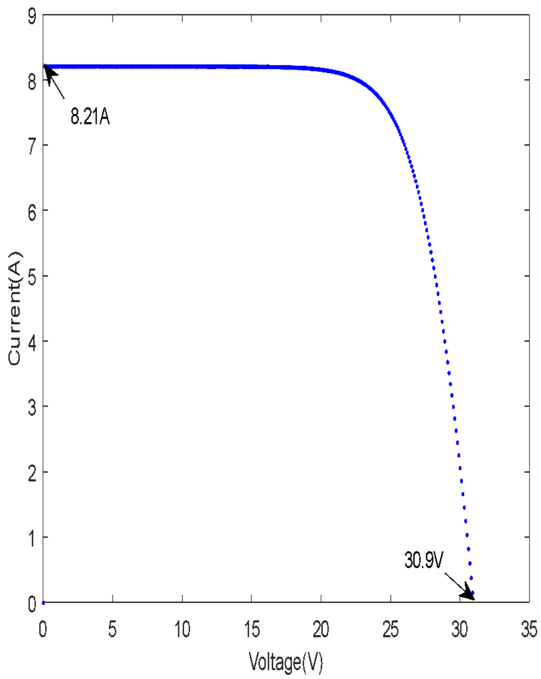


Fig. 4.5: I-V Characteristic

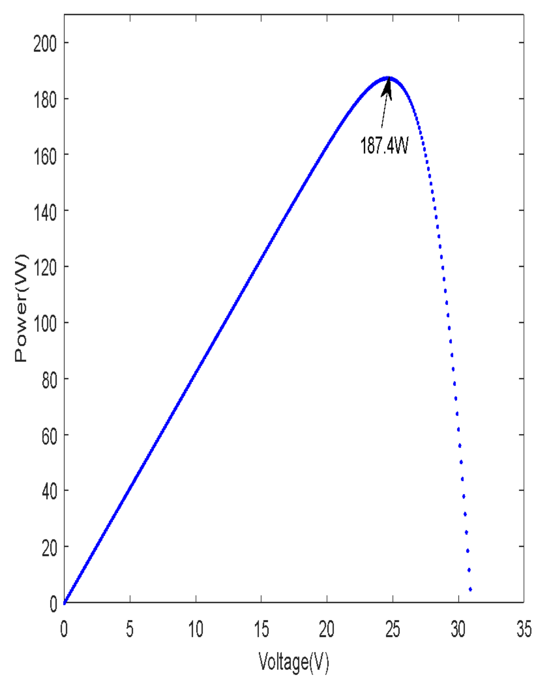


Fig. 4.6: P-V Characteristic

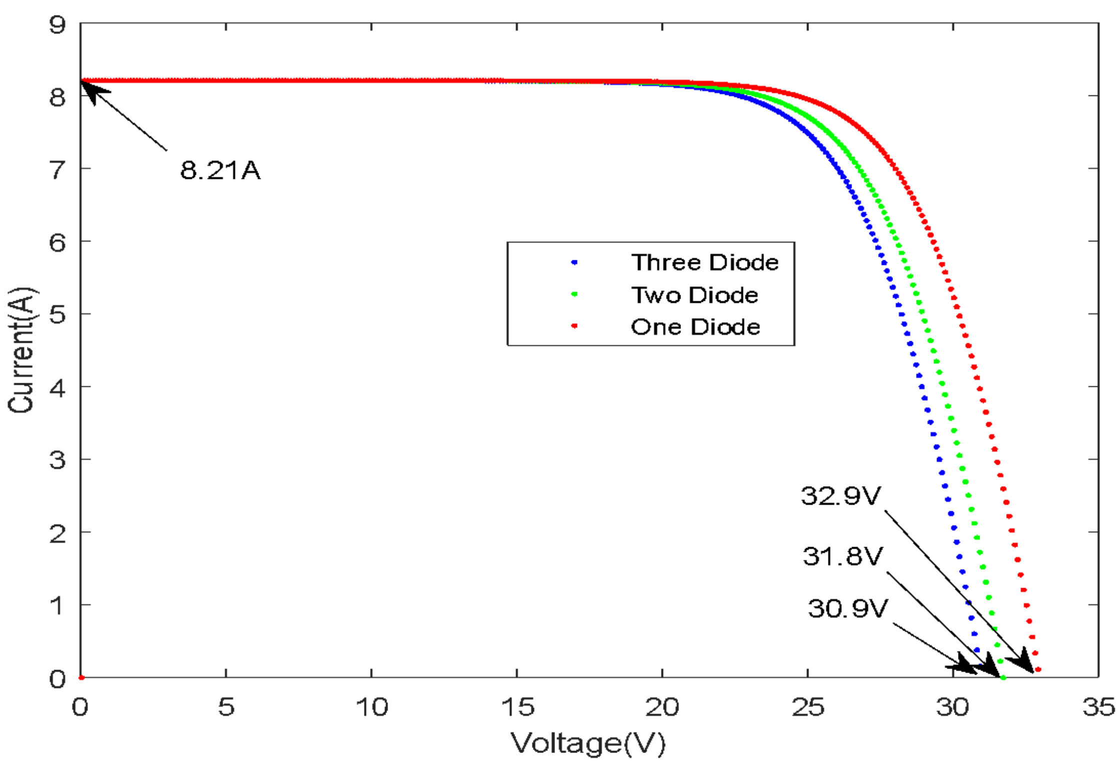


Fig. 4.7: I-V Characteristic of the One, Two and Three Diode Models

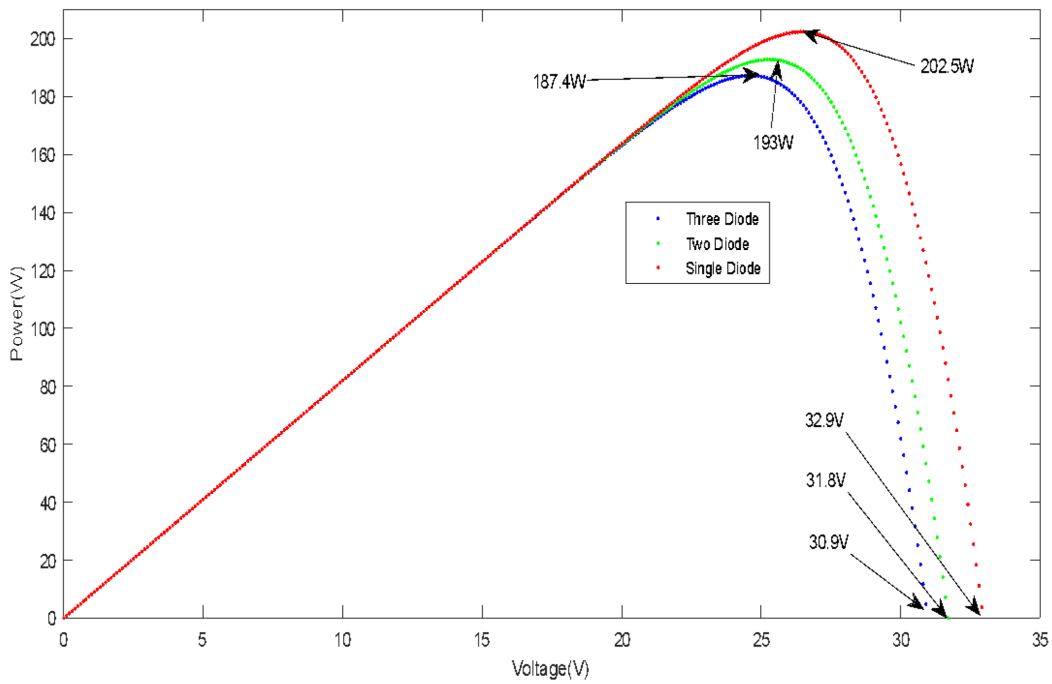


Fig. 4.8: P-V Characteristic of the One, Two and Three Diode Models

Table 1: Model with no shunt resistance

Model	**I_{SC} (A)**	**V_{OC} (V)**	**P_{MAX} (W)**
One Diode	8.21	32.9	202.5
Two Diode	8.21	31.8	193
Three Diode	8.21	30.9	187.4

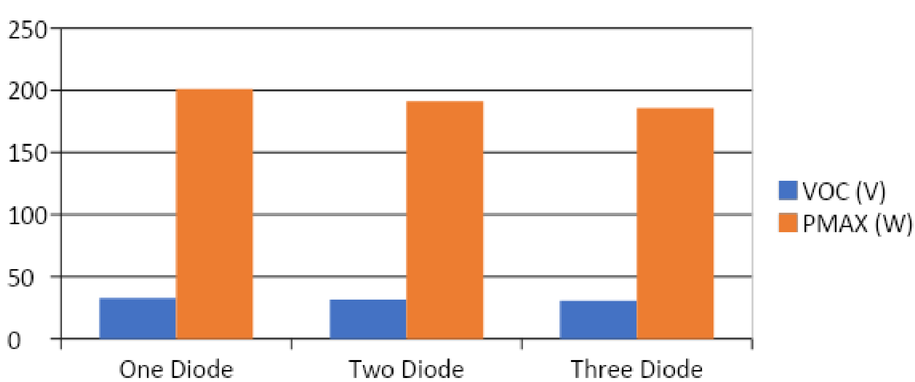
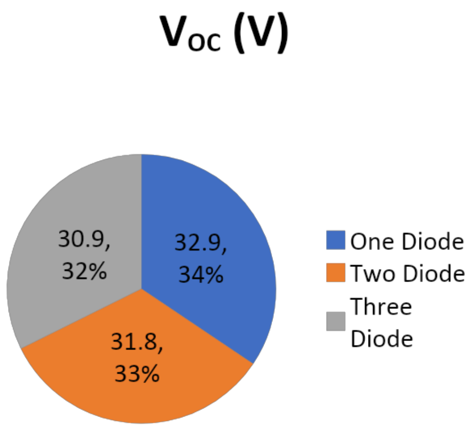


Fig. 4.9a: One, Two and Three Diode Models without Shunt Resistance Bar Chart



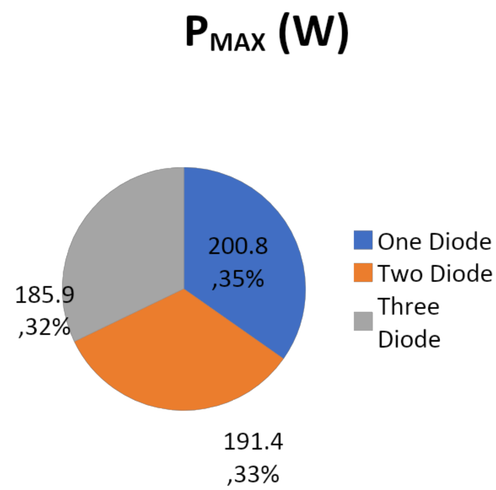


Fig. 4.9b: Open Circuit Voltage of the One, Two and Three Diode Models without Shunt Resistance Bar Chart

Fig. 4.9c: Maximum Power of the One, Two and Three Diode Models without Shunt Resistance Bar Chart

Case 2: Model with shunt resistance

2a: One Diode Model

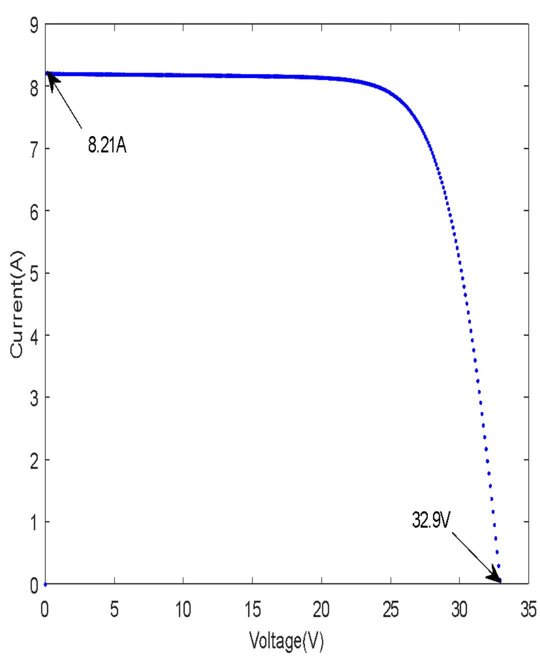


Fig 4.10: I-V Characteristic

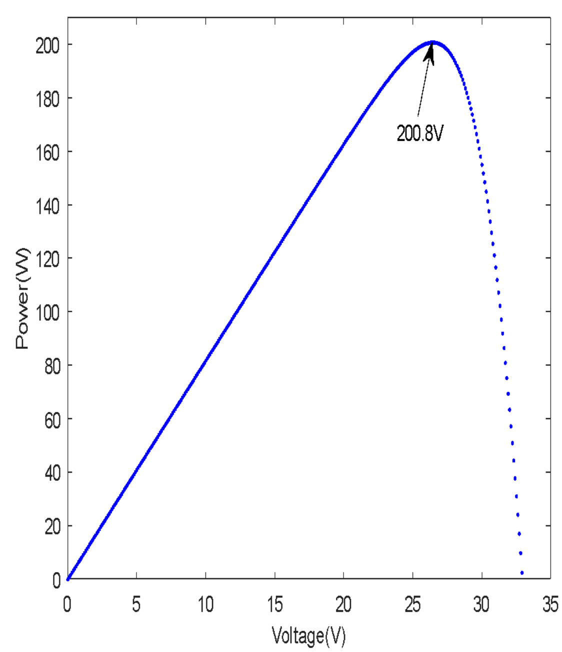


Fig. 4.11: P-V Characteristic

2b: Two Diode Model

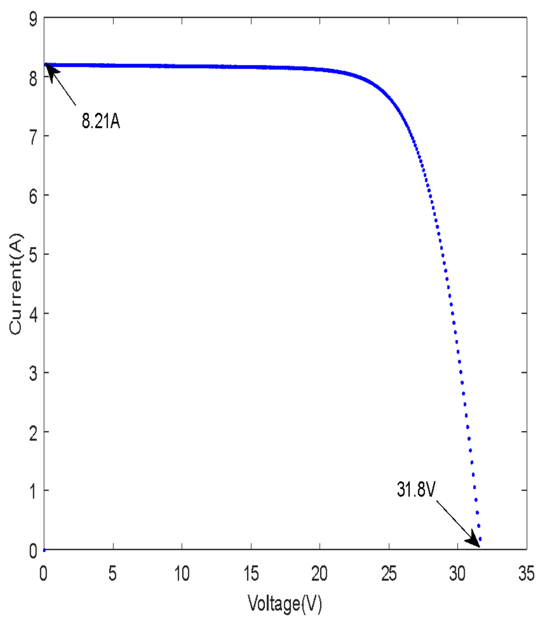


Fig. 4.12: I-V Characteristic

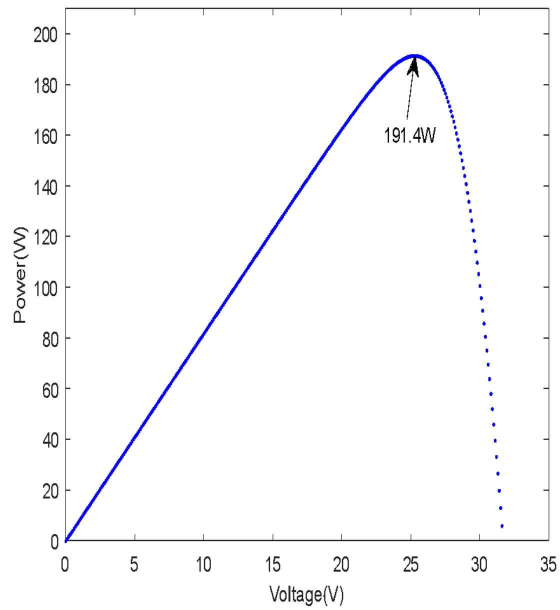


Fig. 4.13: P-V Charactersitic

2c: Three Diode Model

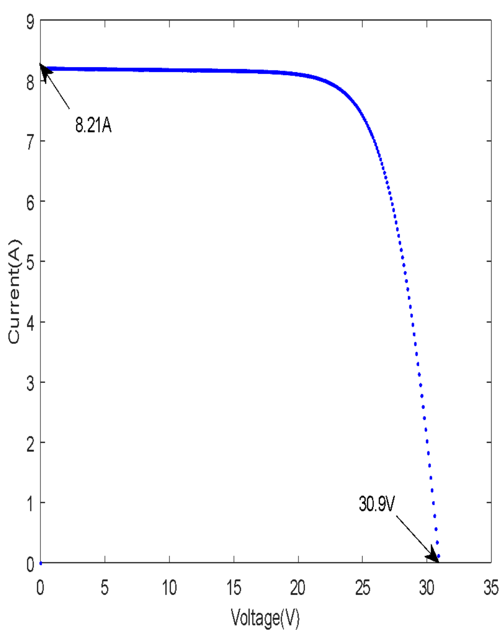


Fig 4.14: I-V Characteristic

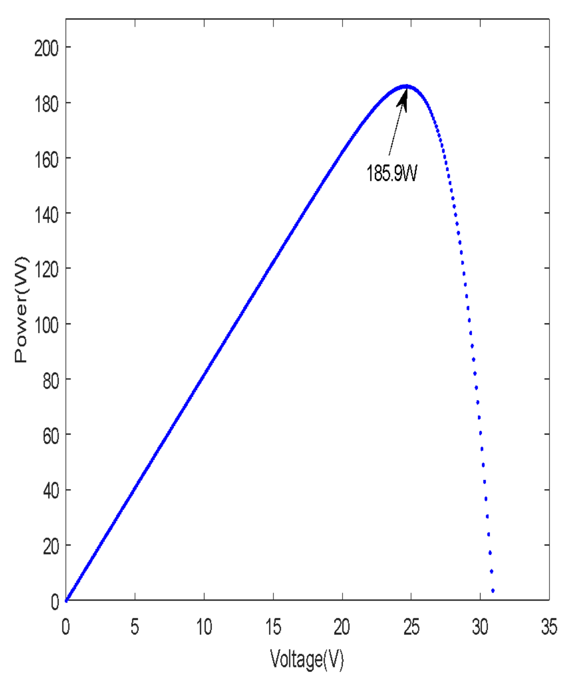


Fig 4.15: P-V Characteristic

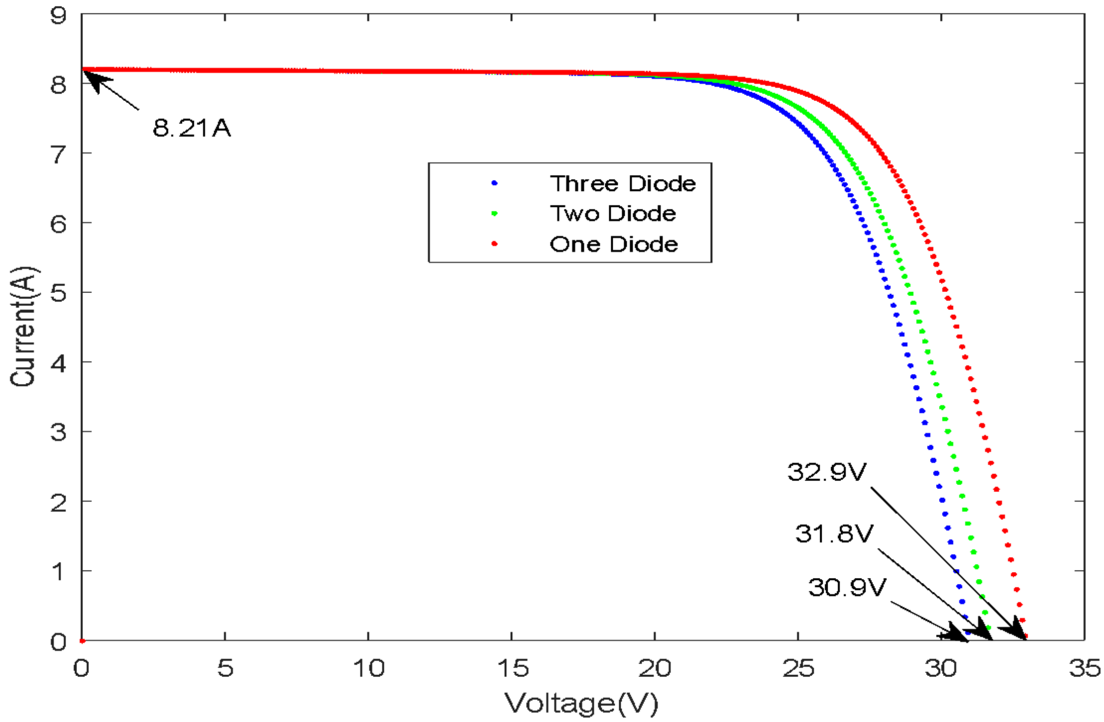


Fig. 4.16: I-V Characteristic of the One, Two and Three Diode Models

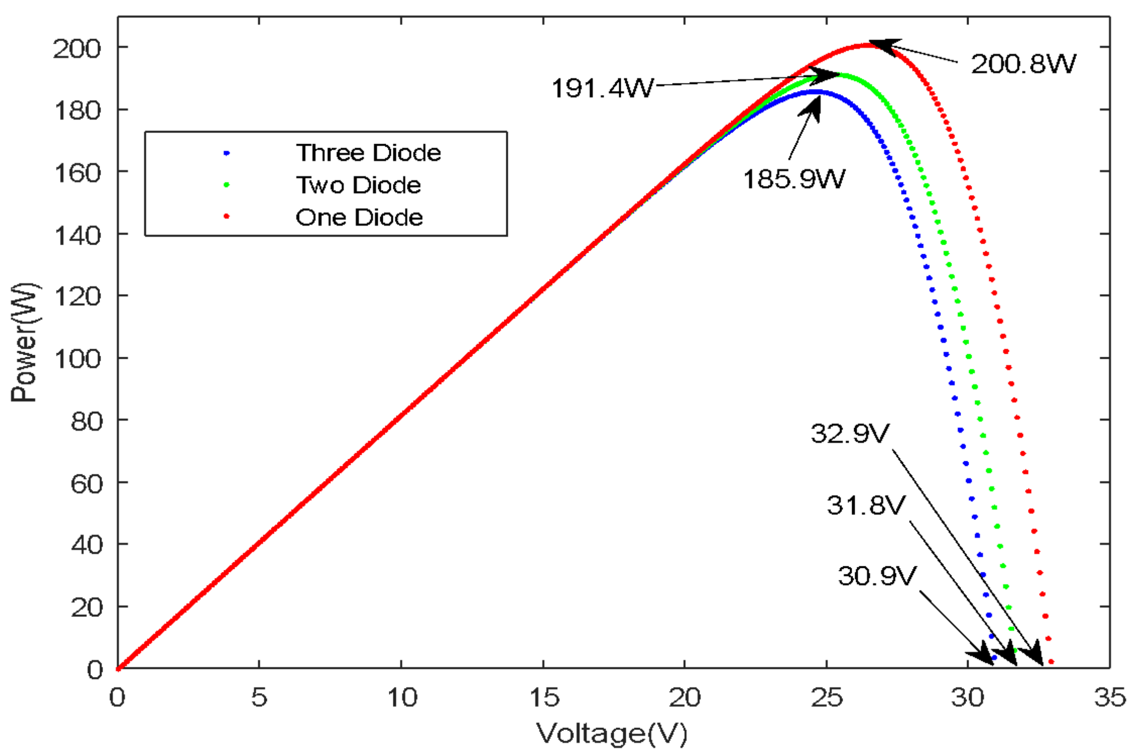


Fig. 4.17: P-V Characteristic of the One, Two and Three Diode Models

Table 2: Model with shunt resistance

Model	I_{SC} (A)	V_{OC} (V)	P_{MAX} (W)
One Diode	8.21	32.9	200.8
Two Diode	8.21	31.8	191.4
Three Diode	8.21	30.9	185.9

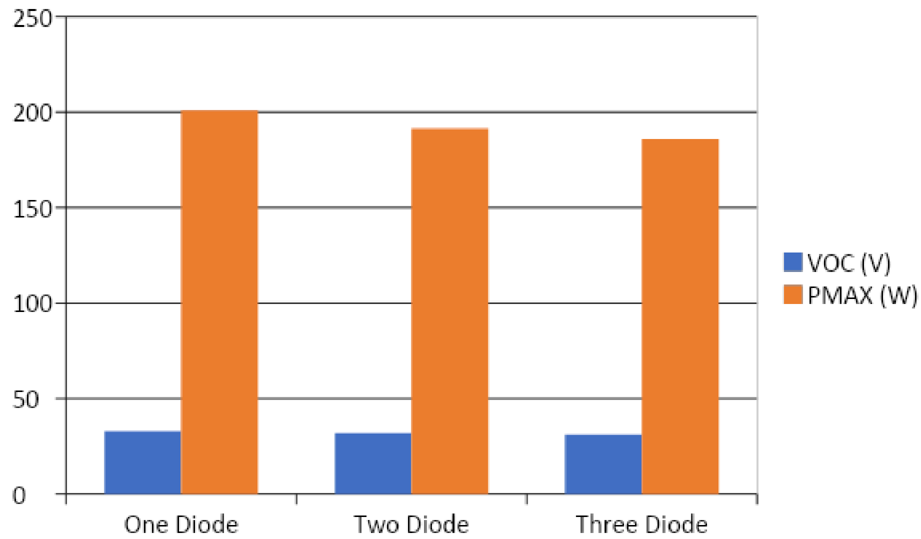
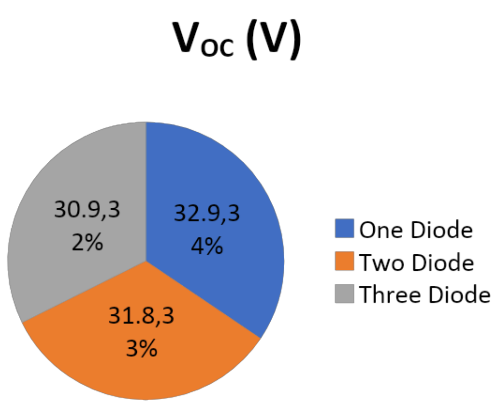


Fig. 4.18a: One, Two and Three Diode Models without Shunt Resistance Bar Chart



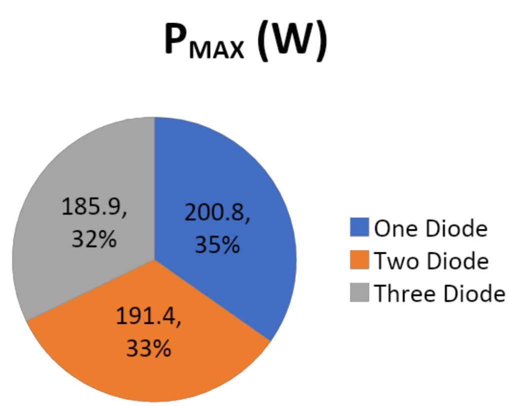


Fig. 4.18b: Open Circuit Voltage of the One, Two and Three Diode Models with Shunt Resistance

Fig. 4.18c: Maximum Power of the One, Two and Three Diode Models with Shunt Resistance

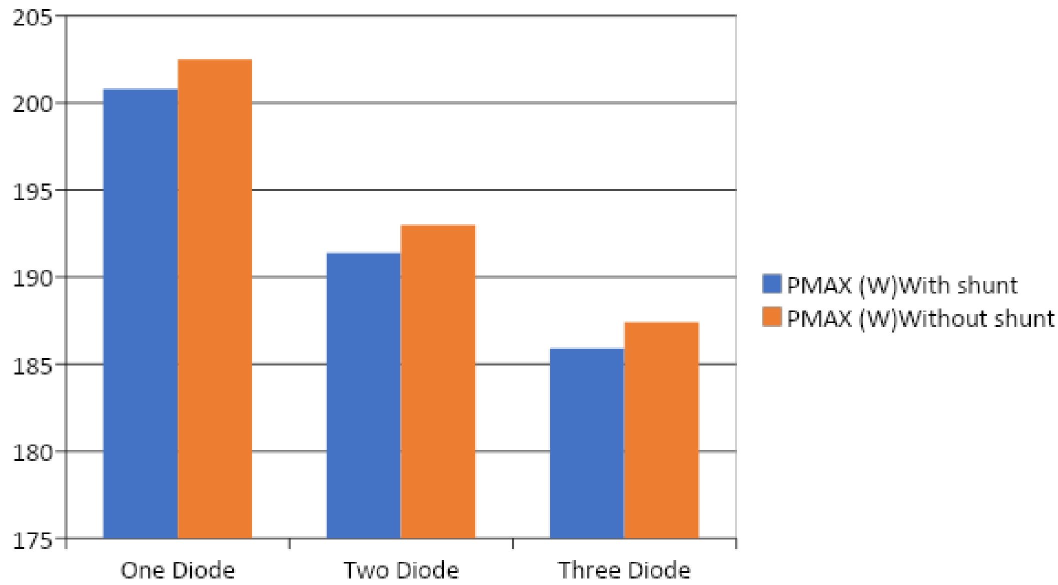


Fig. 4.19: One, Two and Three Diode Models Maximum Power with and without Shunt Resistance

Figure 4.1 and 4.2 shows the I-V P-V characteristic of a single diode model with no shunt resistance. The open circuit voltage and maximum power is 32.9V and 202.5W respectively. The two-diode model characteristic without shunt resistance is shown in figures 4.3 and 4.4. The open circuit voltage and maximum power is 31.8V and 193W respectively. Figures 4.5 and 4.6 shows that an open circuit voltage of 30.9V and maximum power of 187.4W is obtained for a three-diode model with no shunt resistance. Figures 4.7 and 4.8 shows that as the number of diodes increases, the open circuit voltage and maximum power decreases for models without shunt resistances. The I-V P-V characteristics of the one, two and three diode models without shunt resistance is summarized in table 1and figure 4.9

Figure 4.10 and 4.11 shows the I-V P-V characteristic of a single diode model with shunt resistance. The open circuit voltage and maximum power is 32.9V and 200.8W respectively. The two-diode model characteristic with shunt resistance is shown in figures 4.12 and 4.13. The open circuit voltage and maximum power is 31.8V and 191.4W respectively. Figures 4.14 and 4.15 shows that an open circuit voltage of 30.9V and maximum power of 185.9W is obtained for a three diode model with shunt resistance. Figures 4.16 and 4.17 shows that as the number of diodes increases, the open circuit voltage and maximum power decreases for models with shunt resistances. The I-V P-V characteristics of the one, two and three diode models with shunt resistance is summarized in table 2 and figure 4.18

In all the simulations performed, the short circuit current remained at a fixed value of 8.21A. It can be observed from figure 4.19 that the inclusion of the shunt resistance reduces the maximum power of a photovoltaic model.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.0 Conclusion

In conclusion, as the number of diodes increases, the open circuit voltage for a given set of parameters of a photovoltaic cell reduces. However, the short circuit current remains the same irrespective of the number of diodes. Also, an increase in the number of diodes reduces the maximum permissible power drawn from a PV cell. Finally, the choice of a mathematical photovoltaic model to be used for simulation depends on the model which gives the best representation of the I-V P-V characteristic of the PV manufacturers when parameters of the PV manufacturers are used as input values for the mathematical model.

5.1 Recommendation

It is recommended that future work seeks to optimize the one, two and three-diode models to find the conditions under which all the three models produce identical simulation results.

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