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Modeling and Analysis of Solar Arrays for Grid Connected Systems with Maximum Power Point Tracking

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Modeling and Analysis of Solar Arrays for Grid Connected Systems with Maximum Power Point Tracking

By

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A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Electrical Engineering
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Thesis Chair: Dr. Issa Batarseh

ABSTRACT

The shrinking of the world's energy sources has prompted an unprecedented interest in renewable and clean energy sources such as photovoltaic (solar) arrays. Already popular in space and some industrial power system applications, photovoltaic arrays have yet to become a viable source of energy for most terrestrial applications. For several decades now, engineers have been striving to design reliable and affordable solar array based power systems. One popular approach to achieve reliability is the integration of Maximum Power Point Tracking (MPPT) technology in solar power system design.

The purpose of this study was to gain more insight into the nature of photovoltaic arrays, in order to help engineers improve solar array systems efficiency and reliability. To this end, a detailed analysis and modeling of the electrical properties and parameters of solar arrays have been presented. Shading effects on solar arrays, as well as the benefits of incorporating MPPT technology in photovoltaic systems have also been studied. Finally an application of MPPT to grid connected systems will be introduced as part of the ongoing efforts of the Power Electronics Lab at the University of Central Florida to participate in the 2005 Future Energy Challenge.

ACKNOWLEDGEMENTS

My sincere gratitude goes to Dr. Issa E Batarseh who has given me a chance to work in his Power Electronics research lab. He has been a great mentor and I am looking forward to continue my educational journey under his guidance. I would also like to particularly acknowledge Dr. Christopher Iannello who has introduced me to Dr. Batarseh and the world of Power Electronics at an early stage of my engineering education. My special thanks go to my fellow students and researchers in the UCF Power Electronics lab; especially the members of the Air Force Research Project and the Solar Array Inverter design group. I would also like to thank Rebecca L. Hayman for working with me on solar array modeling, Kevin Lynn, Senior Research Engineer at the Florida Solar Energy Center, for helping me with solar array experiments, and Dr. Kasemsan Siri for his insight and guidance on the solar array inverter system design.

I could not have completed this first phase of my educational journey without the support of my family. I can never thank them enough for their spiritual, moral and financial supports. And to all my friends who have inspired and supported me in many ways, I am much indebted.

I dedicate this work to the memory of my late father, Toussaint A. Mensah, who taught me at an early age to always seek excellence in any thing I do.

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The photosphere, which is less than 700 km thick, constitutes the visible part of the sun. Above the photosphere is the sun's atmosphere, which is made up of the chromosphere and the corona. Nuclear reactions constantly occur inside the sun, leading to the production of light. Light is responsible for life on earth and is also very important for the operation of photovoltaic cells.

1.2.1 Light generation: the proton-proton chain

Sunlight is generated through a process called nuclear fusion. During nuclear fusion, hydrogen nuclei go through a fusion process to produce helium nuclei, neutrinos and photons, which constitute the basic particles of light. Part of the hydrogen mass is also converted to energy that is radiated away from the sun. The sun's core is a very hot and unstable region where hydrogen atoms, the most dominant elements, are broken into protons and electrons. The instability is the result of a pulling force between the sun's elements. This attractive force pulls the mass of the planet together and it is so strong that it overcomes the repulsive force, which exists between some of the separated hydrogen nuclei or protons. Two protons then combine under the influence of this force to produce a deuteron, an electron neutrino and a positron.

Proton + proton --------> deuteron + positron + electron neutrino + energy

Next, the deuteron will collide with another proton to create helium and a photon

Deuteron + proton --------> light helium + photon + energy

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LIST OF ABBREVIATIONS

A- Amperes

AC- Alternative Current

AU- Astronomical Unit

DC- Direct Current

IEEE- Institute of Electrical and Electronics Engineers

MPPT- Maximum Power Point Tracking

RMS- Root Mean Square

STC- Standard Testing Conditions

^{0}K- Degree Kelvin

^{0}C- Degree Celsius

V- Volts

W/m^{2}- Watts per square meter

I-V curve- Current vs. Voltage curve

P-V curve- Power vs. Voltage curve

PV- Photovoltaic

CHAPTER ONE

1 INTRODUCTION TO PHOTOVOLTAIC ARRAYS

1.1 Introduction

For years, most of the world has been relying on coal, oil and natural gas as primary energy sources. The expenses generated by processing these energy sources as well as their negative impact on the environment have sprung an interest in clean energy sources such as photovoltaic arrays for electrical energy generation. The principle behind solar arrays technology can be traced back to 1839, when Edmond Becquerel realized that some materials could produce electricity once exposed to light [1]. It was only until a century later that photovoltaic arrays became practical as they were being used as primary sources of electrical power for space satellites and for some remote industrial applications on earth. Over the years, there has been an increase in the usage of solar arrays thanks to the many advantages they offer over traditional power generation. The fuel, which consists of solar radiation, is free, imperishable, and does not require any special treatment. Solar arrays also require little maintenance and they succeed at delivering power to remote locations such as orbiting satellites, or any other place on earth where it is impossible or very expensive to run power distribution lines. These are just

some attractive features that have contributed to the proliferation of photovoltaic systems.

To effectively supply electrical power using solar arrays, the photovoltaic technology must be very efficient, reliable and affordable enough so that everyone could benefit from it. Currently, electricity from photovoltaic arrays costs about $0.25 per KWh, while generation using coal costs about $0.03 to $0.04 per KWh. [2] Efforts are underway to reduce the cost of photovoltaic systems and one way to achieve lower cost is to design efficient power electronics interface systems based on Maximum Power Point Tracking (MPPT) technology. In order to design these MPPT systems, it is necessary to get a better understanding of solar arrays. This study, which has been aimed toward a better understanding of the operating principles of solar arrays, thus comes as a guide to Power Electronics designers specializing in photovoltaic systems applications.

1.2 The Sun as an electrical energy source

The sun, closest star to earth, is about $1.5*10^8$ km (approximately $9.3*10^7$ miles) away. [3] It has a radius of approximately $6.9*10^5$ km and a mass of $1.9*10^{27}$ metric tons. At the center of the sun is the core, which occupies about 1.6% of its total volume. [3] The core is where the sun's energy is produced. Above the core, the radiation and convection layers allow the produced energy to reach the sun's surface also known as the photosphere.

The photosphere, which is less than 700 km thick, constitutes the visible part of the sun. Above the photosphere is the sun's atmosphere, which is made up of the chromosphere and the corona. Nuclear reactions constantly occur inside the sun, leading to the production of light. Light is responsible for life on earth and is also very important for the operation of photovoltaic cells.

1.2.1 Light generation: the proton-proton chain

Sunlight is generated through a process called nuclear fusion. During nuclear fusion, hydrogen nuclei go through a fusion process to produce helium nuclei, neutrinos and photons, which constitute the basic particles of light. Part of the hydrogen mass is also converted to energy that is radiated away from the sun. The sun's core is a very hot and unstable region where hydrogen atoms, the most dominant elements, are broken into protons and electrons. The instability is the result of a pulling force between the sun's elements. This attractive force pulls the mass of the planet together and it is so strong that it overcomes the repulsive force, which exists between some of the separated hydrogen nuclei or protons. Two protons then combine under the influence of this force to produce a deuteron, an electron neutrino and a positron.

Proton + proton --------> deuteron + positron + electron neutrino + energy

Next, the deuteron will collide with another proton to create helium and a photon

Deuteron + proton --------> light helium + photon + energy

Two light helium nuclei will then combine to form a heavy helium nucleus and 2 proton nuclei. Meanwhile, the positron created in the first reaction will combine with a free electron to produce another photon

Light helium + light helium --------> helium + 2 protons + photon + energy

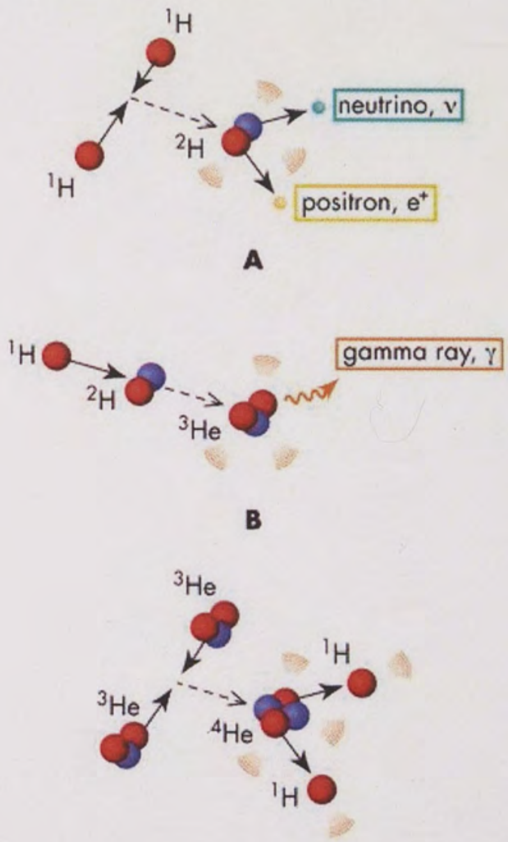


Figure 1.1 Proton-Proton Chain diagram [18]

1.2.2 Solar spectrum

An important element to consider in the manufacturing and testing of solar cells is the solar spectrum at the location where the cells will be used. In 1900, Max Planck derived a function that describes a blackbody radiation spectrum. The function, best known as Planck's law, relates a blackbody's

radiated energy per unit area to a certain range of wavelength. Considering that the sun can also be described as a blackbody with a temperature T = 5800^{0}K, one can use Planck's law to plot the solar irradiation density according to formula (1.1)

$$w(\lambda) = \frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}} - 1} \qquad (1.1)$$

Where,

h = 6.63*10^{-34} Watt sec^2 (Planck's constant)

k = 1.38*10^{-23} Joules/Kelvin (Boltzmann's constant)

c = 3*10^8 m/s (speed of light)

λ = wavelength

w = is power density or power radiated by unit area and unit wavelength in Watt/m^3

T = temperature in Kelvin

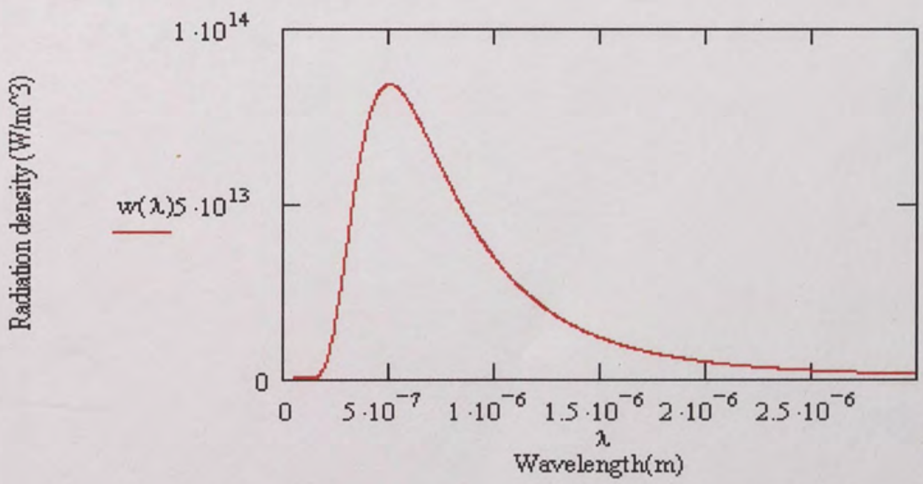


Figure 1.2 Solar Radiation density curve at the sun's surface

Integrating equation (1.1) for all range of wavelength gives the total irradiance in W/m^2 at the sun's surface as shown by the following MathCAD computation.

$h := 6.63 \cdot 10^{-34}$ $\qquad$ $k := 1.38 \cdot 10^{-23}$

$T := 5800$ $\qquad$ $c := 3 \cdot 10^{8}$

$$w(\lambda) := \frac{2 \cdot \pi \cdot h \cdot c^2 \cdot \lambda^{-5}}{e^{\frac{h \cdot c}{\lambda \cdot k \cdot T}} - 1}$$

$$E := \int_0^{\infty} w(\lambda)\, d\lambda$$

$$P := E \text{ float}, 3 \;\rightarrow 6.37 \cdot 10^{7}$$

$$P = 6.37 \times 10^{7}$$

The sun's irradiance, computed using MathCAD, is $P = 6.37*10^7$ W/m^2.By the time the energy radiated from the sun travels 1 Astronomical Unit (1 A.U. = $1.5*10^8$ Km = Earth-Sun distance), the spectrum shown in figure 1.1 changes. An infinite number of spectra can be defined depending on a location in the solar system. For any angle θ corresponding to the zenith angle (angle

between the sun and a straight up line perpendicular to the earth) of the sun, one can define any Air Mass (AM) spectrum AM_x, [3] where

$$x = \frac{1}{\cos\theta} \qquad (1.2)$$

The most important spectra to this study are AM_0 and $AM_{1.5}$. AM_0, by convention, is the spectrum for space solar cells, while $AM_{1.5}$ is used for terrestrial solar cells. $AM_{1.5}$ corresponds to a zenith angle $\theta = 48.19^o$

1.2.2.1 AM_0: solar spectrum for space solar cells

AM_0 or Air Mass Zero is the irradiance corresponding to the sunlight's spectrum just outside earth's atmosphere. Theoretically, the analytical function for this spectrum can be computed and plotted by taking into account:

1. < d > the distance between Earth and Sun
2. < R > the sun's radius
3. < P > the total solar irradiance previously computed.

Assuming that the sun radiates uniformly in all directions, we can compute, using MathCAD, the solar irradiance < S > corresponding to the AM_0 spectrum. < S > is in W/m^2 and is known as the Solar Constant.

$$P := 6.37 \cdot 10^{7} \qquad R := 6.96 \cdot 10^{8} \mathrm{m} \qquad d := 1.5 \cdot 10^{11} \mathrm{m}$$

$$S := P \cdot \frac{R^2}{d^2}$$

$$\boxed{S = 1.371 \times 10^{3}}$$

S is in units of W/m².

A function I(λ) that ideally describes the solar irradiation density corresponding to AM_0 can now be derived.

$$h := 6.63 \cdot 10^{-34} \qquad T := 5800 \qquad k := 1.38 \cdot 10^{-23}$$

$$P := 6.37 \cdot 10^{7} \qquad S := 1.371 \cdot 10^{3} \qquad c := 3 \cdot 10^{8}$$

$$w(\lambda) := \frac{2 \cdot \pi \cdot h \cdot c^2 \cdot \lambda^{-5}}{e^{\frac{h \cdot c}{\lambda \cdot k \cdot T}} - 1}$$

$$I(\lambda) := w(\lambda) \cdot \frac{S}{P}$$

$$I(\lambda) \text{ float}, 3 \rightarrow \frac{8.07 \cdot 10^{-21}}{\lambda^{5.} \cdot \left(\exp\left(\frac{2.49 \cdot 10^{-6}}{\lambda^{1.}} \right) - 1. \right)^{1.}}$$

$$\boxed{I(\lambda) := \frac{8.07 \cdot 10^{-21}}{\lambda^{5.} \cdot \left(\exp\left(\frac{2.49 \cdot 10^{-6}}{\lambda^{1.}} \right) - 1. \right)^{1.}}}$$

The ideal solar spectrum for AM_0 is plotted below using I (λ)

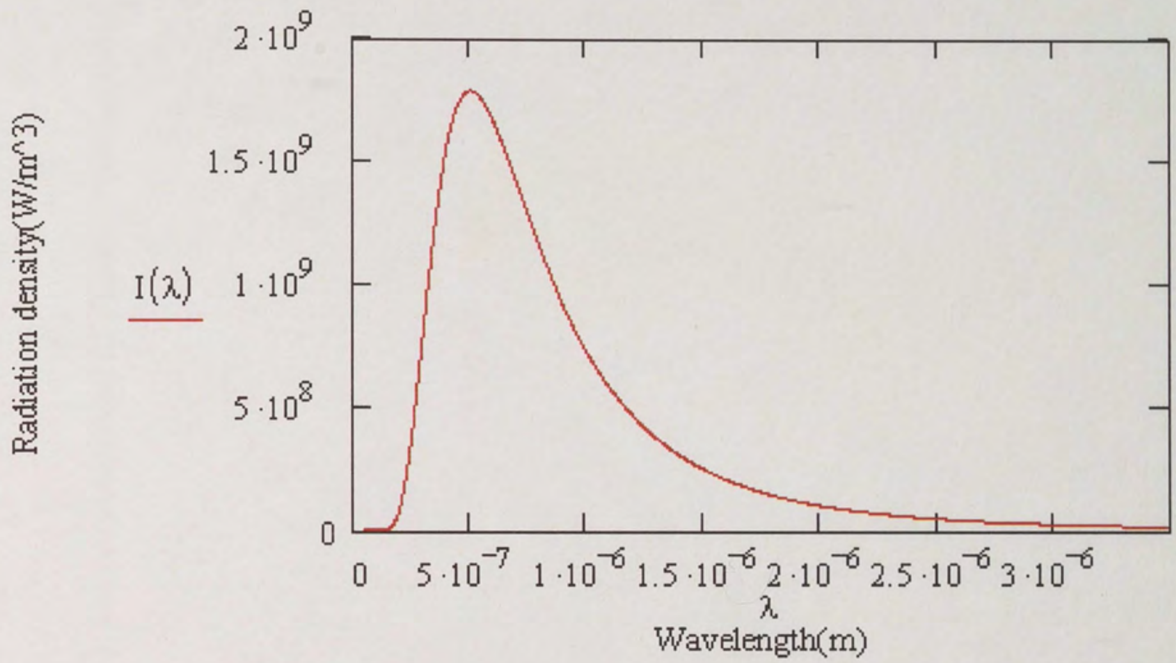


Figure 1.3 Ideal Solar Radiation density curve at the edge of earth's atmosphere

As a mean to approximate the solar constant <S> and validate the derivation of I (λ), the integration of I(λ) for all wavelengths yields $S = 1.36*10^3$ W/m^2 as shown in the following computation

$$I(\lambda) := \frac{8.07 \cdot 10^{-21}}{\lambda^{5.} \cdot \left(\exp\left(\frac{2.49 \cdot 10^{-6}}{\lambda^{1.}} \right) - 1. \right)^{1.}}$$

$$\int_0^{\infty} I(\lambda)\, d\lambda \text{ float}, 3 \rightarrow 1.36 \cdot 10^{3}$$

The actual AM_0 spectrum does not look as smooth as the one depicted in figure 1.2. Below is a plot of the actual spectrum based on data published by the National Renewable Energy Laboratory. [4]

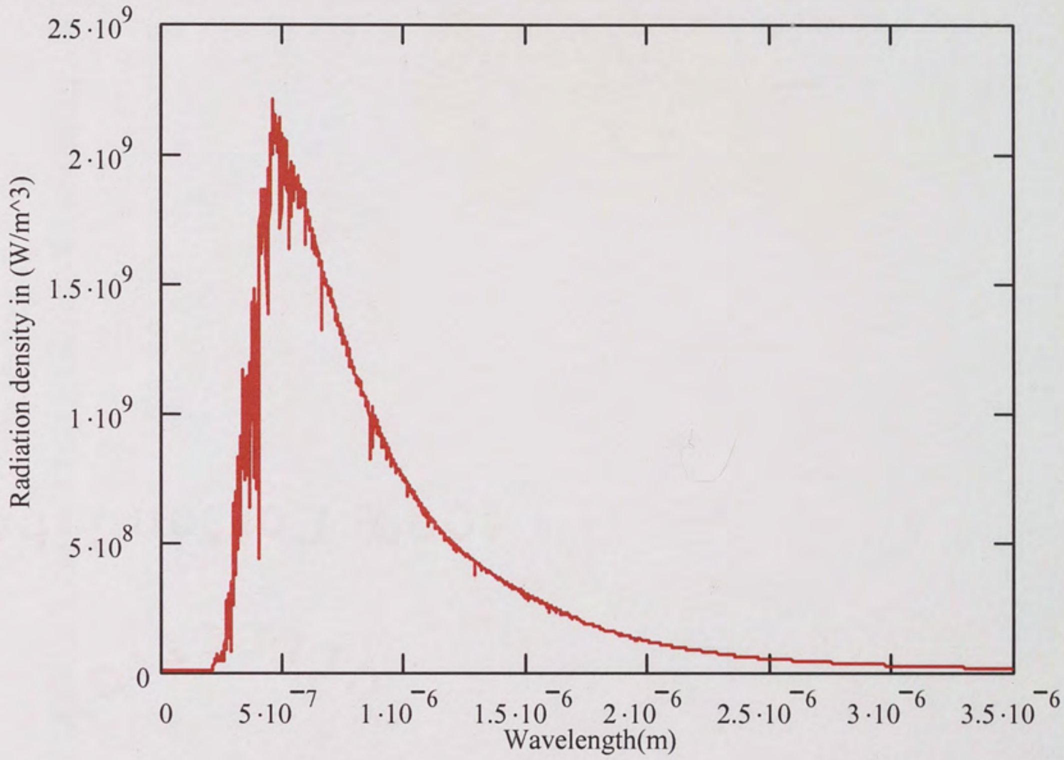


Figure 1.4 Solar Radiation density curve at the edge of earth's atmosphere

The actual AM_0 spectrum shows some minor absorption at specific wavelengths. As sunlight moves through earth's atmosphere, these absorptions become more and more intense.

1.2.2.2 AM $_{1.5}$: solar spectrum for terrestrial solar cells

The spectrum corresponding to $AM_{1.5}$ is the standard spectrum for terrestrial solar cells. Based on data published by the National Renewable Energy Laboratory, [5] a plot has been obtained and shown in figure 1.4

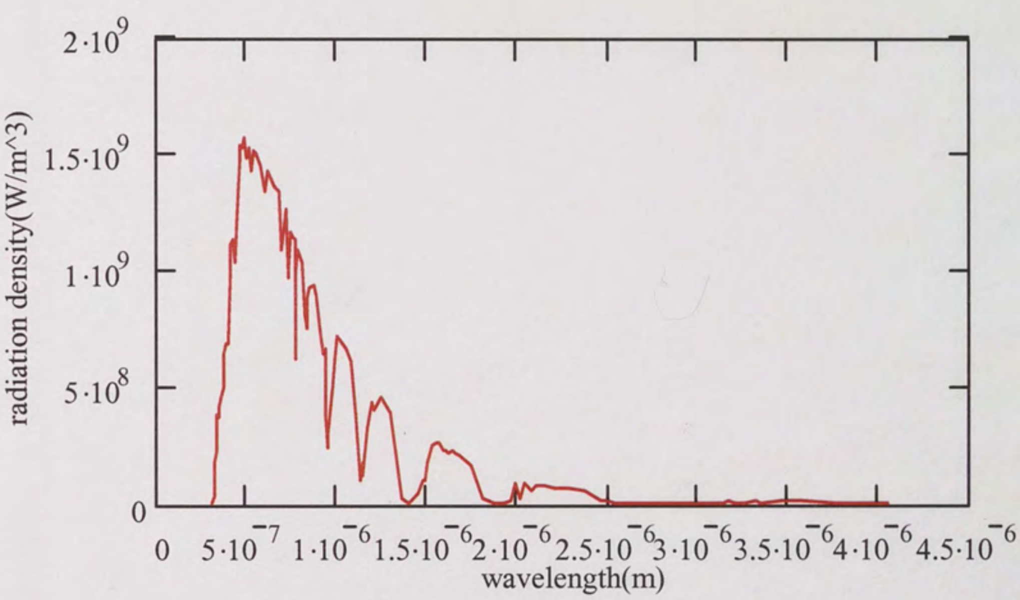


Figure 1.5 Solar Radiation density curve on earth

This spectrum shows several wavelength absorptions. Power densities for several wavelengths have been greatly attenuated. The available irradiance from this spectrum is about 1000 W/m^2.

1.3 Solar cells

1.3.1 Physical description

Solar cells are semiconductor materials made out of p or n type material into which impurities are added to form p-n layers. These layers are the most important part of every cell because they mark the starting and ending points of electrons movement. The p-n layers are sandwiched by front and back metallic grids, which facilitate the electron flow to and from any load or circuitry that is connected to the cell. The top of the cell is made out of an anti reflective coat to retain as much light as possible. Finally, a glass cover protects the entire cell surface from any damage.

1.3.2 Photovoltaic effect

The photovoltaic effect is the foundation of solar cells operation. Illuminated solar cells absorb a certain percentage of sunlight; the rest of the incident light is either reflected or passes right through the cell. As photovoltaic cells absorb sunlight, the photons, which contain energy corresponding to different wavelengths of the solar spectrum, come to contact with electrons in the p-n layers. The photon's energy is then transmitted to the electrons. When a photon's energy is high enough, it can break the bond between an electron and its atom. The electron becomes free and can therefore move through the semiconductor layers, thus generating electric current.

1.3.3 Brief history of photovoltaic cells

Photovoltaic cells go back to 1839 when French Physicist Edmond Becquerel discovered that some materials could produce electricity when they are exposed to light. From 1839 to 1954, several scientists did intensive theoretical and experimental work on the photovoltaic principle. In 1880, selenium solar cells were introduced; their efficiency was 1 to 2%. In 1954, Pearson, Chapin, and Fuller, all researchers at Bell Laboratory introduced the first practical cells: the efficiency then was 4.5%. In 1958, solar cells were used for the first time in Space exploration to power Vanguard I, the second American satellite. Since then, much effort has been put into developing solar cells. Nowadays, cell's efficiency have are in the range of 15 to 20%.

CHAPTER TWO

2 MODELING OF SOLAR CELLS: EXAMPLE OF A POLYCRISTALLINE SILICON SOLAR CELL

Solar cells are current generators made of semiconductor materials into which impurities are introduced to create p-type and n-type regions. Therefore, solar cells may be ideally modeled as a current source in parallel with a diode. A more realistic model is shown in figure 2.1 and depicts the main electrical elements of solar cells, such as those made of polycrystalline silicon. [6]

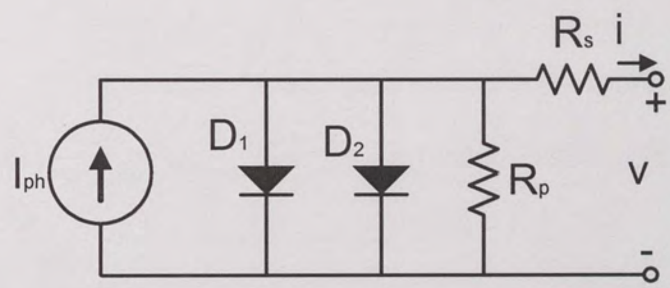


Figure 2.1 Simplified Equivalent circuit of a solar cell

The cell's output current <i> is given by the following empirical equation

$$i = I_{ph} - I_{S1}(e^{\frac{q(V+iR_S)}{kT}} - 1) - I_{S2}(e^{\frac{q(V+iR_S)}{AkT}} - 1) - \frac{V+iR_S}{R_P} \qquad (2.1)$$

where

q = $1.6*10^{-19}$ C; electron charge

k = $1.38*10^{-23}$ J/K ; Boltzmann's constant

V is the array's output voltage

T is the cell's ambient temperature in degree Kelvin

From these electrical elements come six electrical parameters associated with the cell, namely the photo current (I_{ph}), the saturation current (I_{s1}) for diode D1, the saturation current (I_{s2}) for diode D2, the quality factor (A) for diode D2, the series resistance (R_s), and the shunt or parallel resistance (R_p).

2.1 Photocurrent (I_{ph})

When a semiconductor material is exposed to light, there is an energy transfer between the incident photons and the electrons inside the material. Depending on the strength of the photon's energy, an electron may migrate to a higher energy state or break the bond it has with an atom. When such bond is broken, the electron is free to move through the material, thus producing electric current. Electrons motion depends on several factors such as ambient temperature and solar irradiance. Photocurrent, temperature and solar irradiance can all be mathematically related by the following equation [6]:

$$I_{ph} = K_0 E(1 + K_1 T) \qquad (2.2)$$

Where

K_0 = -5.729*10^{-7}

K_1 = -0.1098

E = solar irradiance in W/m^2

T = solar cell's temperature in degree Kelvin

Using Simulink, graphs illustrating the variations in photocurrent with respect to ambient temperature and solar irradiance has been obtained and shown in figures 2.2 and 2.3.

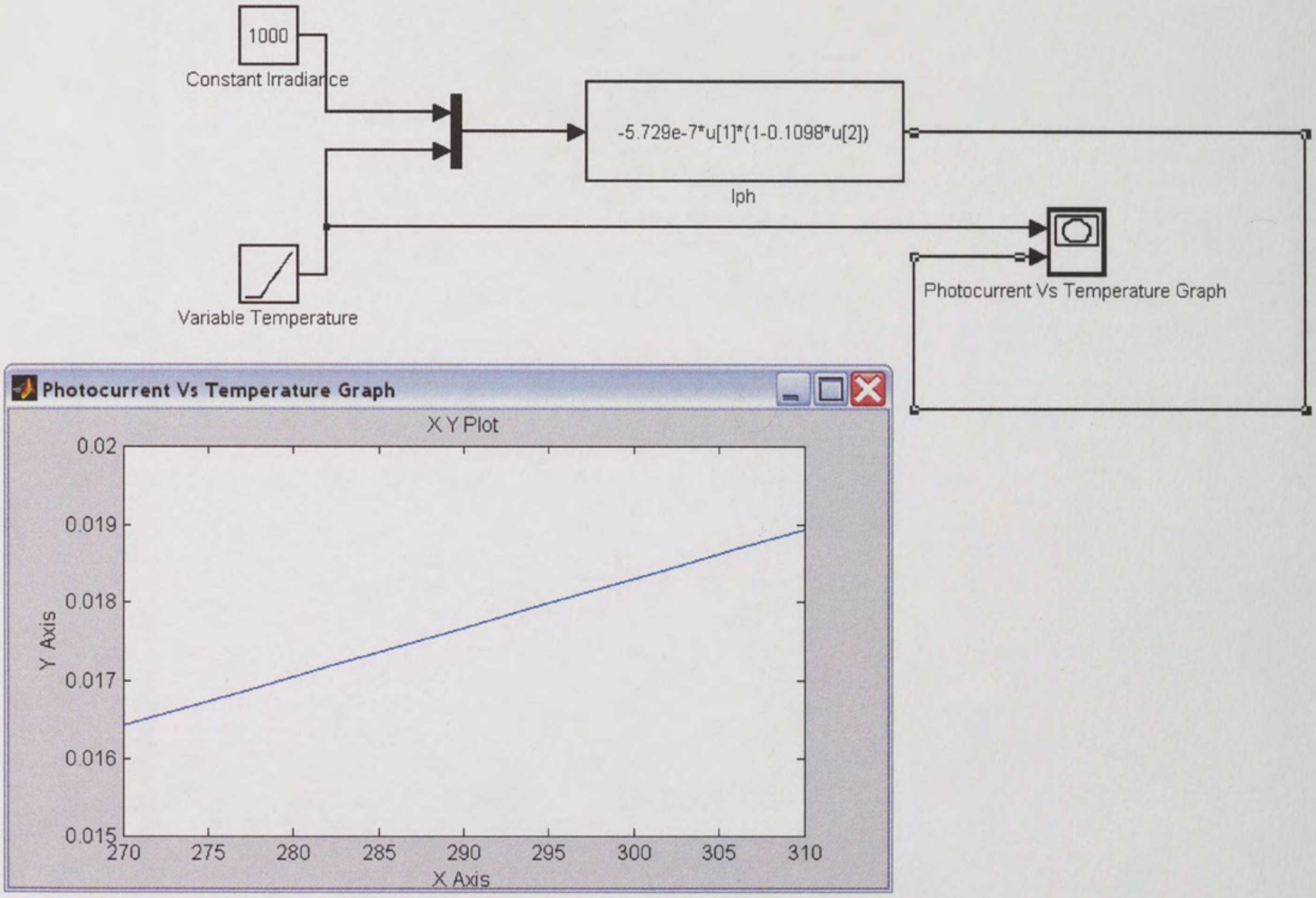


Figure 2.2 Simulink block and Graph of Iph (Amps) vs. Temperature for constant E = 1000 W/m² and $0 \leq T \leq 310^0K$

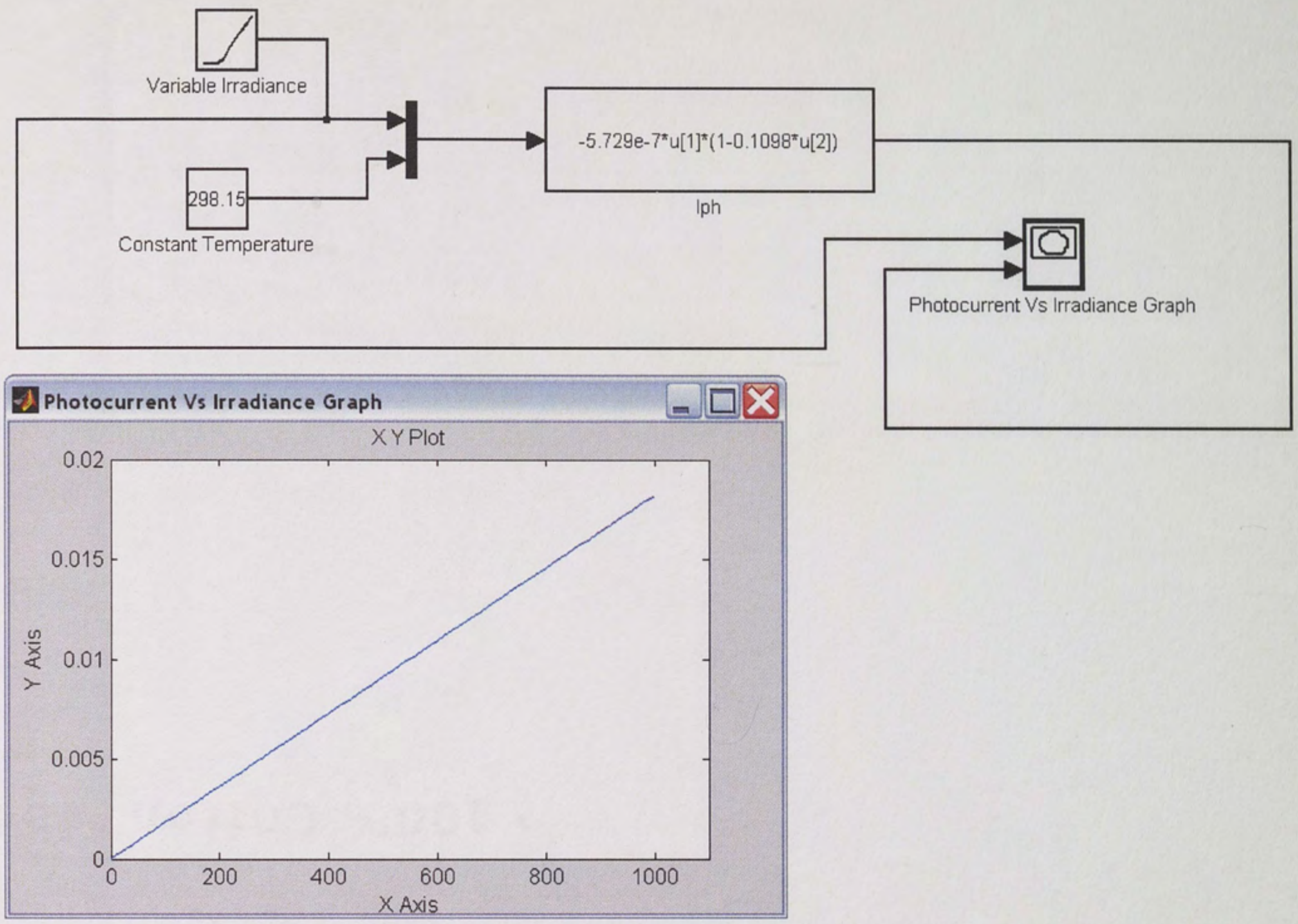


Figure 2.3 Simulink block and Graph of Iph (Amps) vs. Irradiance for constant T = 298.15^{0}K and

$0 \leq E \leq 1000W/m^2$

2.2 Saturation currents I_{S1} and I_{S2}

Semiconductors devices such as solar cells are made of p-type or n-type materials into which impurities are added to form p-n layers, which lead to p-n junctions. These junctions inside a solar cell can be modeled as diodes. A single solar cell operation depends on low voltages ranging from 0.1 to 0.5 volts [7]. In that voltage range, the traditional exponential relation between a diode's current and voltage cannot be detected. Instead two kinds of saturation currents are observed; one due to a charge diffusion process and the other due to a recombination process [7]. Gow and Manning [6] have performed some experiment and have come up with the following mathematical expressions relating these saturations current to the cell's temperature

$$I_{S1} = K_2 T^3 e^{\frac{K_3}{T}} \qquad (2.3)$$

$$I_{S2} = K_4 T^{\frac{3}{2}} e^{\frac{K_5}{T}} \qquad (2.4)$$

Where

$K_2 = 44.5355$

$K_3 = -1.264*10^4$

$K_4 = 11.8003$

$K_5 = -12.637*10^3$

The following Simulink graphs illustrate the variations of these saturation currents with cell's temperature.

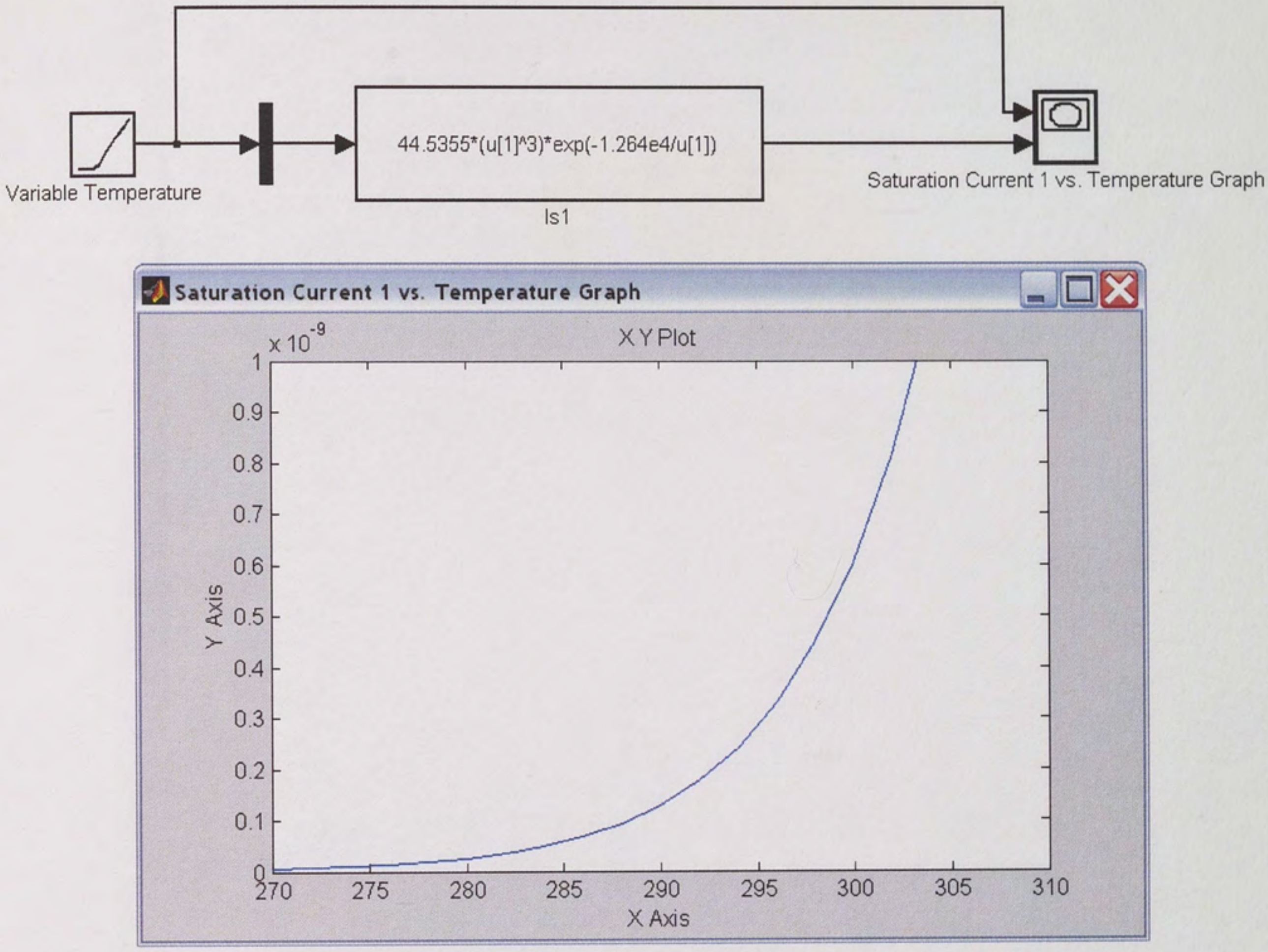


Figure 2.4 Variation of Diode D1 saturation current with temperature for $270^0K \leq T \leq 300^0K$

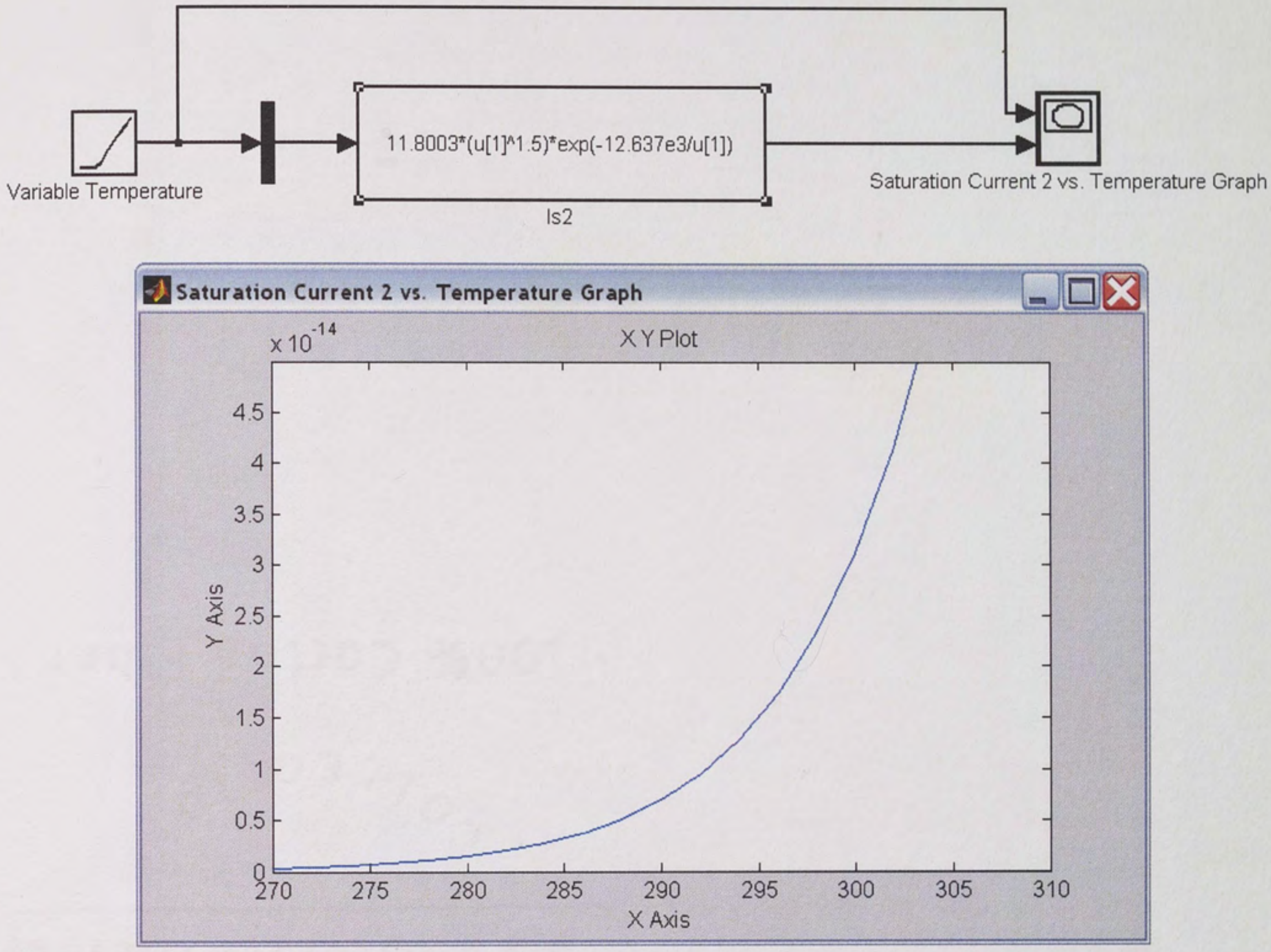


Figure 2.5 Variation of Diode D2 saturation current with temperature for $270^0K \leq T \leq 300^0K$

2.3 Diode quality factor

Without getting too much into semiconductor's theory, the diode quality factor can be described as a factor that accounts for the Shockley-Read-Hall recombination current in the p-n junction depletion regions of the solar cell [6] It is mathematically expressed by equation 2.5

$$A = K_6 + K_7 T \qquad (2.5)$$

For modeling the double exponential model of polycrystalline silicon cells, $K_6 = 2$ and $K_7 = 0$ [6].

2.4 Series resistance (R_s)

This type of resistance represents all the distributed resistance elements in the solar cell such as ohmic contact and semiconductor contact interfaces. In a broad sense, R_s accounts for all internal dissipative electrical losses that occur within the cell. The series resistance in units of Ohms is mathematically described by the following equation: [6]

$$R_S = K_8 + \frac{K_9}{E} + K_{10} T \qquad (2.6)$$

Where

$K_8 = 1.47$

$K_9 = 1.6126*10^3$

$K_{10} = -4.474*10^{-3}$

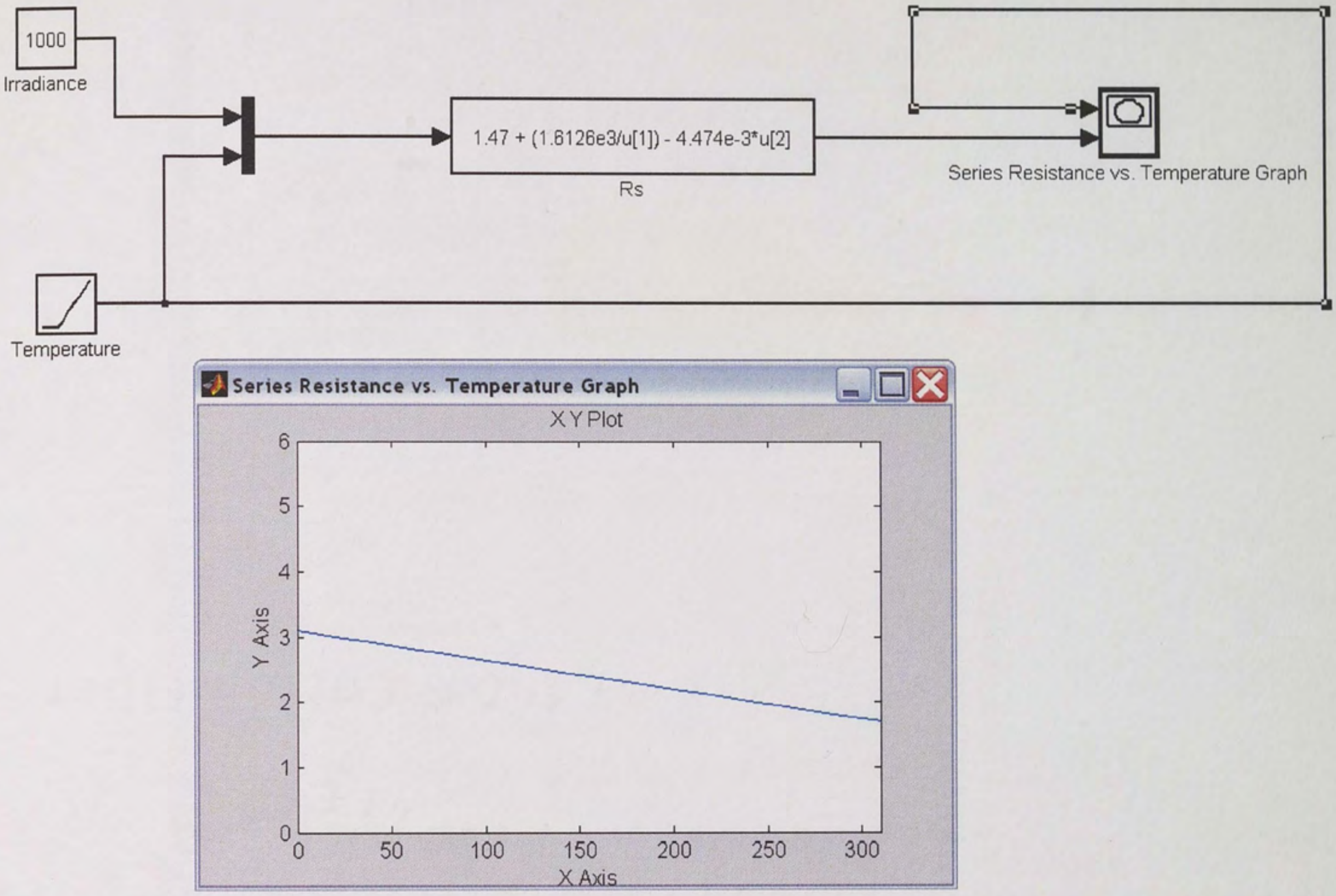


Figure 2.6 Variation of Series Resistance (Ohms) with temperature for constant irradiance of $E = 1000W/m^2$ and $0^0K \leq T \leq 300^0K$

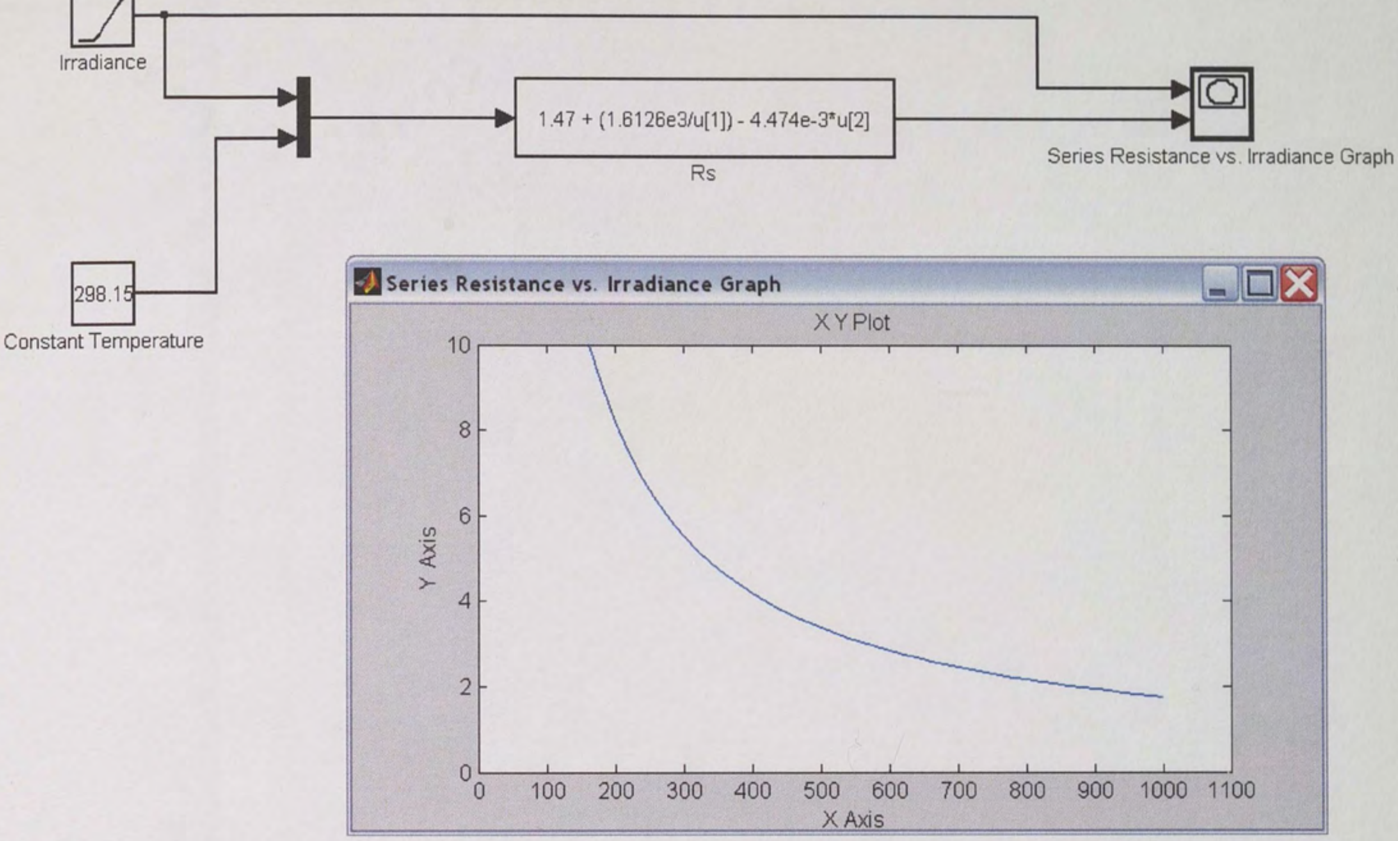


Figure 2.7 Variation of Series Resistance (Ohms) with solar irradiance $0 \leq E \leq 1000$ W/m^2 at temperature T = 298.15^{0}K

2.5 Cell shunt resistance (Rp)

Some of the solar cell's electrical energy gets lost due to internal cell leakage paths that exist through the cell's outer edge and p-n junction. These leakage paths are not uniform in the cell and they are accounted for by the cell's shunt resistance in ohms according to equation (2.7)

$$R_P = K_{11} e^{K_{12} T} \qquad (2.7)$$

Where

$K_{11} = 2.303*10^{6}$

$K_{12} = -2.812*10^{-2}$

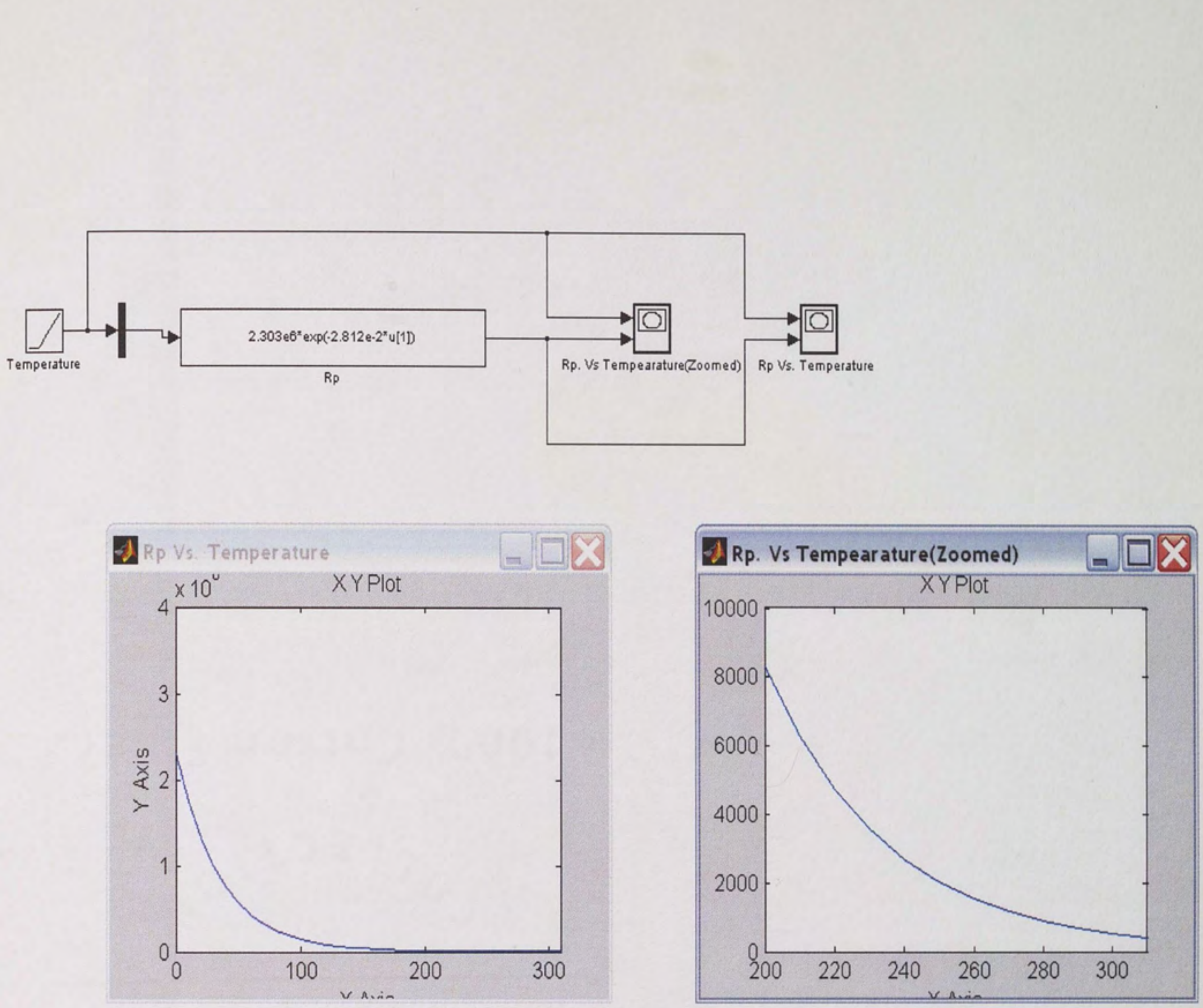


Figure 2.8 Variation of Shunt Resistance (Ohms) with temperature $0 \leq E \leq 300^0K$

2.6 Development of a numerical model of a polycrystalline silicon solar array

The basic building blocks of solar arrays are photovoltaic modules which are series combinations of individual solar cells. Photovoltaic modules are often combined in series-parallel configuration to create solar arrays. In this sense, solar arrays can be regarded as series-parallel combinations of solar cells. Solar arrays often incorporate bypass and blocking diodes, whose purpose is to limit power losses. Bypass and blocking diodes will be discussed in chapter three. For now let's idealize solar arrays by considering the series-parallel combinations of individual solar cells. Assuming that an array is made of N_p cells in parallel and N_s cells in series, its I-V equation can be derived from the single cell I-V equation (2.1) by scaling the single cell's current by a factor of N_p, and its voltage by a factor of N_s.

$$I = N_p \left[Iph - I_{s1}\left(e^{\frac{q(\frac{V}{Ns}+\frac{I}{Np}Rs)}{kT}} - 1\right) - I_{s2}\left(e^{\frac{q(\frac{V}{Ns}+\frac{I}{Np}Rs)}{AkT}} - 1\right) - \frac{\frac{V}{Ns}+\frac{I}{Np}Rs}{Rp} \right] \quad (2.8)$$

Where

I = Array's output current

V = Array's output voltage

Np = number of cells in parallel

Ns = number of cells in series

I_{ph}, I_{s1}, I_{s2}, R_s, R_p, q, k, A, T have all been previously defined.

Even though it is simple to implement a solar array configuration in circuit analysis programs such as Pspice and Multisim, other types of analysis such as the economic analysis of a Maximum Power Point Tracking system presented in chapter 4, which may require numerical packages such as Matlab, Simulink, or MathCAD often do not offer any simple way to implement an implicit expression such as equation (2.8). The problems associated with the implementation of the solar array I-V curve can be overcome by:

- Performing a re-arrangement of the circuit configuration of a single cell shown in Figure 2.1
- Scaling the output current of the single cell by a factor of N_p and the output voltage by a factor of N_s

2.6.1 Re-arrangement of a single cell's equivalent circuit

The following steps can be taken to develop a model that does away with the implicit nature of a solar array's I-V equation.

Step 1: Combine the current source I_{ph} and the shunt resistance R_p into a voltage source Vinput in series with the same resistance R_p

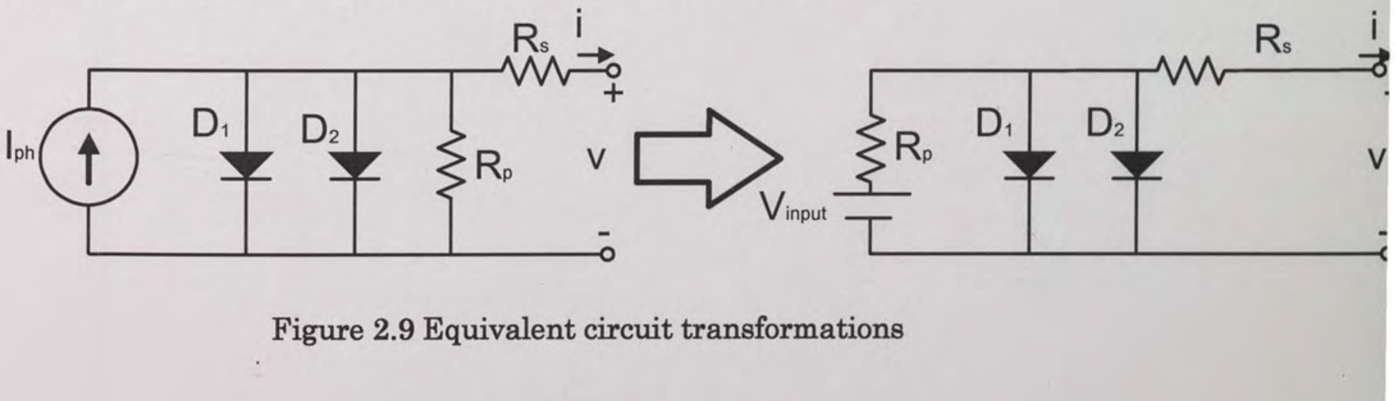


Figure 2.9 Equivalent circuit transformations

Step2: Derive the output current as a function of the output voltage v

By considering a voltage drop v_{diode} across the diodes D1 and D2, the output current < i > can be derived as

$$i = \frac{V_{input} - v_{diode}}{R_p} - i_{D1} - i_{D2} \qquad (2.9)$$

The diode currents i_{D1} and i_{D2} are given by the following exponential relation between a diode's voltage and current

$$i_{D1} = I_{S1}(e^{(\frac{q*v_{diode}}{k*T})} - 1) \qquad (2.10)$$

$$i_{D2} = I_{S2}(e^{(\frac{q*v_{diode}}{A*k*T})} - 1) \qquad (2.11)$$

The variables q, k, and T have been previously defined.

Finally, the output voltage < v > can be related to the output current < i > as

$$v = v_{diode} - i * R_S \qquad (2.12)$$

For a given set of solar irradiance E and ambient temperature T, and using the solar cell's parameters equations, one can easily implement equation 2.12 to obtain the output characteristic curves (current-voltage and power-voltage) of a solar cell as demonstrated by the following MathCAD manipulations. The following example uses an irradiance of $E = 1000W/m^2$ and a temperature K $= 300^0K$

$E := 1000$ $T := 298.15$

$q := 1.6 \cdot 10^{-19}$ $k := 1.38 \cdot 10^{-23}$

Photocurrent

$K_0 := -5.729 \cdot 10^{-7}$ $K_1 := -0.1098$

$I_{ph} := K_0 \cdot E \cdot (1 + K_1 \cdot T)$ $I_{ph} = 0.018$

Saturation Currents for Diodes D1 and D2

$K_2 := 44.5355$ $K_4 := 11.8003$ $K_5 := -12.637 \cdot 10^3$

$I_{s1} := K_2 \cdot T^3 \cdot e^{\left(\frac{K_5}{T}\right)}$ $I_{s2} := K_4 \cdot T^{\left(\frac{3}{2}\right)} \cdot e^{\left(\frac{K_5}{T}\right)}$

$I_{s1} = 4.619 \times 10^{-10}$ $I_{s2} = 2.377 \times 10^{-14}$

Diode Quality Factor

$K_6 := 2$ $K_7 := 0$

$A := K_6 + K_7 \cdot T$

$A = 2$

Series Resistance

$K_8 := 1.47$ $K_9 := 1.6126 \cdot 10^3$ $K_{10} := -4.474 \cdot 10^{-3}$

$R_s := K_8 + \left(\frac{K_9}{E}\right) + K_{10} \cdot T$ $R_s = 1.74$

Shunt Resistance

$K_{11} := 2.303 \cdot 10^6$ $K_{12} := -2.812 \cdot 10^{-2}$

$R_p := K_{11} \cdot e^{\left(\frac{K_{12}}{T}\right)}$ $R_p = 2.303 \times 10^6$

Equivalent circuit calculations

$V_{input} := I_{ph} \cdot R_p$

Diode voltage Drop Range v

This range is the variable in this derivation

Currents calculation

$$i_1(v) := \frac{V_{input} - v}{R_p}$$

First diode current

$$i_{d1}(v) := I_{s1} \cdot \left[-1 + e^{\left(\frac{q \cdot v}{k \cdot T}\right)} \right]$$

Second diode current

$$i_{d2}(v) := I_{s2} \cdot \left[-1 + e^{\left(\frac{q \cdot v}{A \cdot k \cdot T}\right)} \right]$$

Solar cell output current

$$i_{output}(v) := i_1(v) - i_{d1}(v) - i_{d2}(v)$$

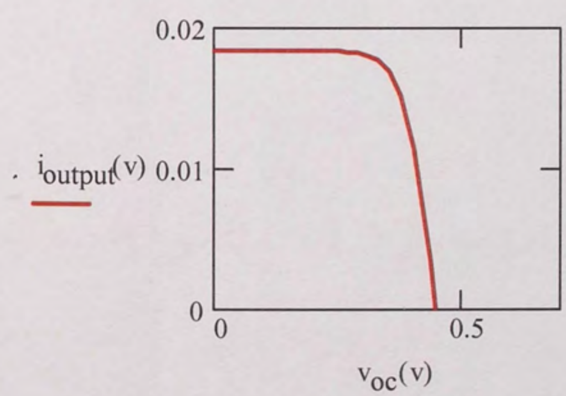
Solar cell open ciruit voltage

$$v_{oc}(v) := v - i_{output}(v) \cdot R_s$$

Solar Cell output powei

$$P_{output}(v) := i_{output}(v) \cdot v_{oc}(v)$$

Solar Cell I-V curve



Solar Cell P-V curve

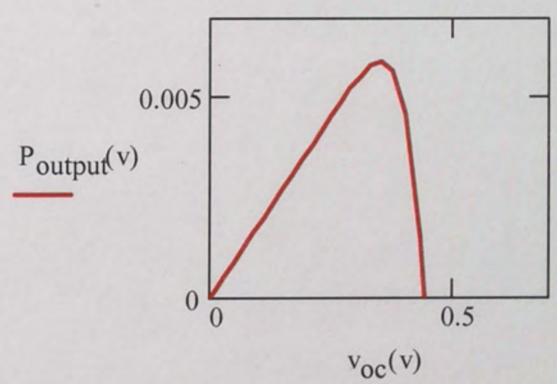


Figure 2.10 Output characteristic curves of a polycrystalline silicon solar cell

2.7 Experimental results: output characteristic curves of a polycrystalline silicon solar array module.

To validate the mathematical model developed in Section 2.6, an I-V curve tracer has been used to perform a series of tests at the Florida Solar Energy Center (www.fsec.ucf.edu). The experimental apparatus consists of:

- Solarex SX 65 U photovoltaic module
- Daystar photovoltaic I-V curve tracer connected to the Solarex module
- Computer connected to the Daystar I-V curve tracer for data collection

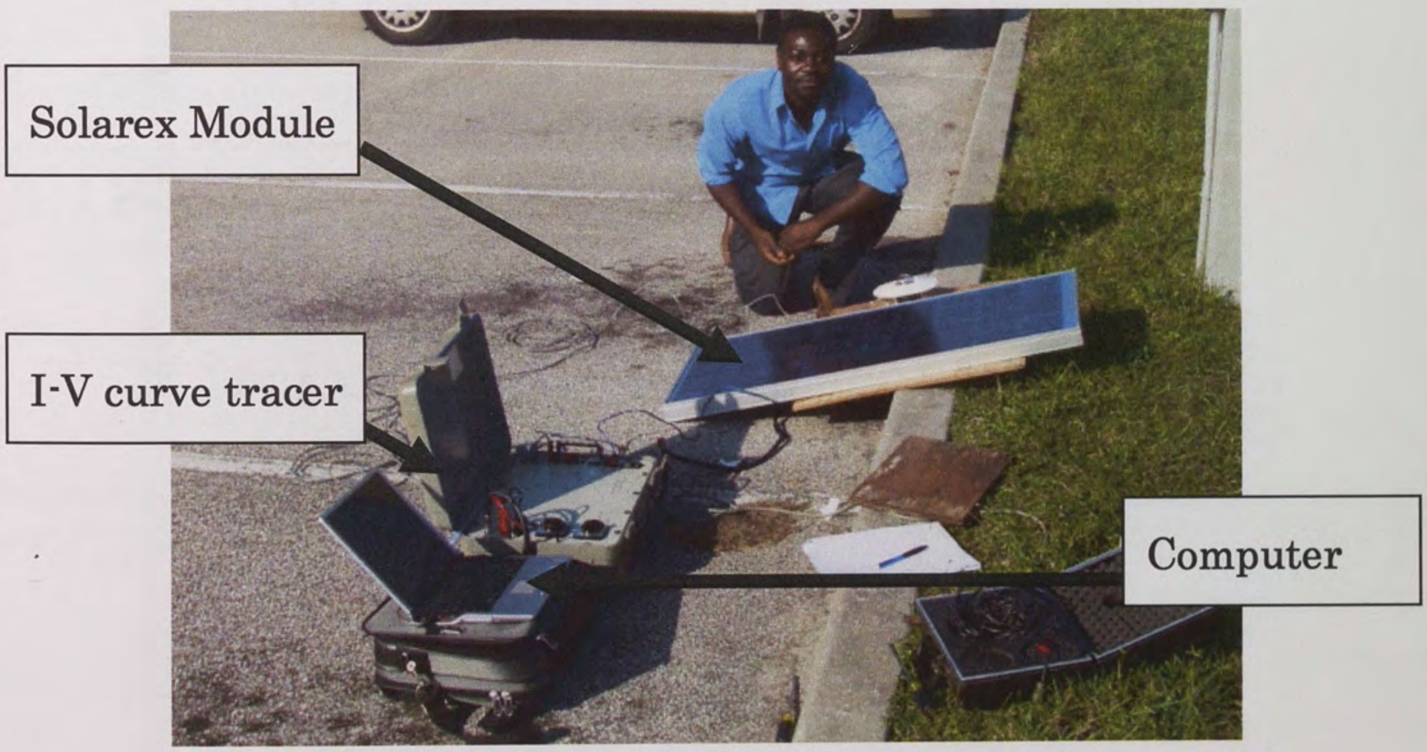


Figure 2.11 Experimental Apparatus

2.7.1 Elements of the experiment

2.7.1.1 Solar irradiance and cell's temperature

Solar Irradiance and Ambient Temperature constitute the input parameters to the solar array model. Solar arrays data sheets usually describe parameters measured at Standard Test Conditions (STC). STC in the photovoltaic industry refers to a testing condition at an irradiance of E = $1000W/m^2$ and a cell temperature of T = 25^0C. Because of atmospheric conditions, the test performed at the Florida Solar Energy Center will not necessarily be done under STC. However the input parameters of the model developed in section 2.6 can be changed to reflect the experimental environment.

2.7.1.2 Open circuit voltage

The Open circuit voltage (V_{OC}) is the voltage measured across the photovoltaic module when the output current is zero. The open circuit voltage represents the upper limit of the module's operating voltage range.

2.7.1.3 Short circuit current

The short circuit current is the current that flows through the module when its outputs are shorted, or when the module's load voltage is zero. This current can, for all practical purposes, be approximated by the photogenerated current I_{ph}. The short circuit current represents the upper limit of the module's operating current range.

2.7.1.4 Maximum power

This is the maximum power than can be drawn from the array under STC. The actual maximum power can increase or decrease depending on the level of sunshine.

2.7.1.5 Voltage and current at maximum power point

These two parameters are of great importance to power electronics interface system designers, since reliable photovoltaic systems are designed to operate at maximum power point.

2.7.1.6 Specifications of the Solarex SX 65 U module

The Solarex SX 65 U, a solar module consisting of 36 polycrystalline silicon solar cells in series, has the following specifications under STC

- Maximum Power: $P_{max} = 65$ W
- Open Circuit Voltage: $V_{oc} = 21.5$ V
- Short Circuit Current: $I_{sc} = 4.06$ A
- Voltage at Maximum Power Point: $V_{mpp} = 17.2$V
- Current at Maximum Power Point: $I_{mpp} = 3.77$A

2.7.1.7 Daystar I-V curve tracer

The I-V curve tracer records the solar irradiance and module's temperature, and automatically applies a varying load across the solar module to produce the current vs. voltage curve.

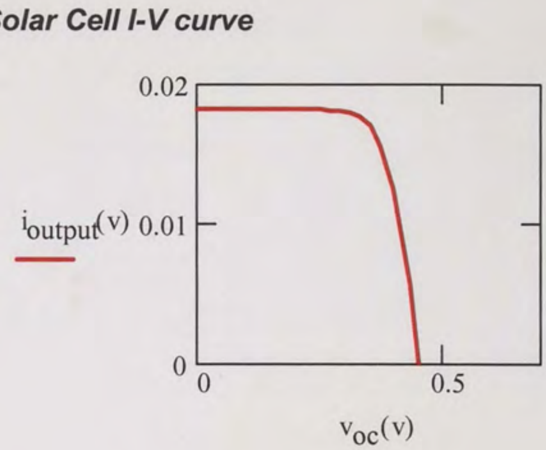
2.7.1.8 Computer

A Sony VIAO laptop computer was used on site to record data provided by I-V curve tracer, via a serial cable.

2.7.2 Experimental results

2.7.2.1 Comparison of manufacturer's datasheet values and values derived from modeling the Solarex SX 65 U under STC

Since the Solarex SX 65 U is a polycrystalline silicon based module, it constitutes a good candidate to test the previously derived mathematical model. Before proceeding to the test, let's adjust the mathematical model to reflect the manufacturer's datasheet. The model has been based on experiments performed by Manning and Gow on a relatively small size cell, whose area has not been revealed by the authors. [6] Since the Solarex provides a short circuit current of 4.06A as compared to the 0.018A produced by the cell of the mathematical model (figure 2.11), one can conclude that the area of the Solarex cells is bigger than the area of the cells used by Manning and Gow by a factor of X = 4.06/0.018 = 226. Based on the fact that parallel connected cells produce more current, it is then obvious that 1 cell on the Solarex corresponds to 226 cells in parallel on the model.



$$i_{output}(0) = 0.018$$

$$i_{output}(0.445) = 3.048 \times 10^{-3}$$

Figure 2.12 Computation of open circuit voltage and short circuit current using i-v curve

Furthermore, the open circuit voltage of a cell using the mathematical model is V_{OC} = 0.445V as shown in figure 2.11. The open circuit voltage of the Solarex cell using the datasheet is

$$V_{OC\_SOLAREX} = 21.5V/36 = 0.6\ V$$

Based on the fact that series connected cells produce a bigger output voltage, one can conclude that one Solarex cell corresponds to Y = 0.6/0.445 = 1.35 model cells in series. Since the Solarex module consists of 36 cells in series, its equivalent in the mathematical model will be an array of 49 cells in series (49 = 36*Y) and 226 cells in parallel. Shown in figure 2.12 are the I-V and P-V curves of an array of N_s = 49 series cells and N_p = 226 parallel cells, generated by running the mathematical model in MathCAD. Solar irradiance and cells temperature are respectively E = 1000W/m^2 and T = 298.15^{0}K to conform to STC.

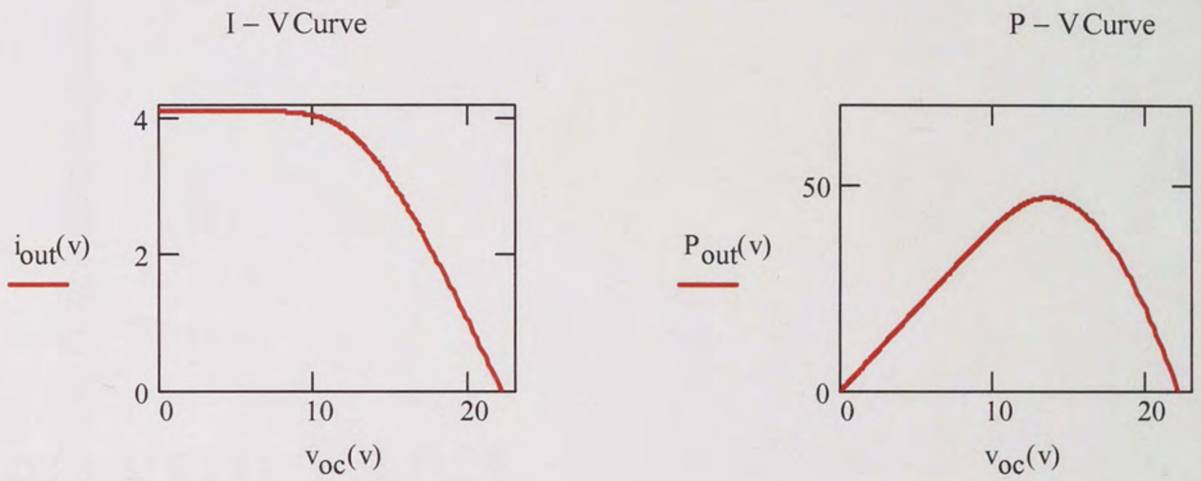


Figure 2.13 I-V and P-V curves for mathematical model of Solarex SX65U (49-by-226 cells)

Figure 2.12 should be a scaled up and non distorted version of figure 2.9, which showed the output curves for a single solar cell. This is not however the case for two main reasons:

- A single cell may be considered as an array of 1-by-1 cell
- Any array , which is a scaled version of that cell must preserve the squared aspect of the cell

Instead of directly implementing a 49-by-226 cells array, the following procedures should be taken:

- Implement a 49-by-49 cells array
- Scale the output current and output power of the array by a factor of F = 226/49

These new steps lead to better modeling results as shown in figure 2.13

$$N_s := 49 \qquad\qquad N_p := 49$$

$$i_1(v) := \frac{(V_{input} - v)}{R_p}$$

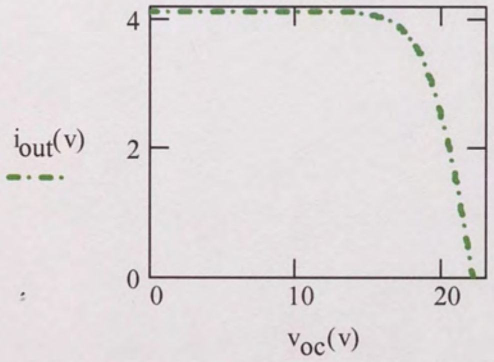
$$i_{d1}(v) := I_{s1}\cdot\left[-1 + e^{\left(\frac{q\cdot v}{k\cdot T\cdot N_s}\right)}\right] \qquad i_{d2}(v) := I_{s2}\cdot\left[-1 + e^{\left(\frac{q\cdot v}{A\cdot k\cdot T\cdot N_s}\right)}\right]$$

$$i_{output}(v) := N_p\cdot\left(i_1(v) - i_{d1}(v) - i_{d2}(v)\right)$$

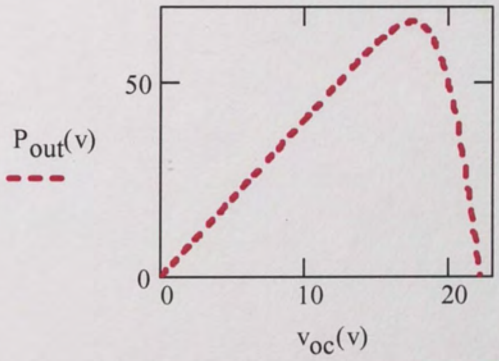
$$v_{oc}(v) := v - i_{output}(v)\cdot R_s \qquad P_{output}(v) := i_{output}(v)\cdot v_{oc}(v)$$

$$i_{out}(v) := 226\cdot\frac{i_{output}(v)}{49} \qquad P_{out}(v) := 226\cdot\frac{P_{output}(v)}{49}$$

I – V Curve



P – V Curve



$i_{out}(0) = 4.109$

$i_{output}(22.035) = 4.187 \times 10^{-4}$

$i_{out}(19.025) = 3.731$

$P_{out}(19.025) = 65.699$

$P_{out}(19.05) = 65.67$

$P_{out}(19.025) = 65.699$

Figure 2.14 Corrected I-V and P-V curves for mathematical model of Solarex SX65U (49-by-226 cells)

The following conclusions can be drawn from figure 2.13

- The short circuit current provided by the model is I_{sc} = 4.109A
- The open circuit voltage provided by the model is V_{oc} = 22.035V
- The maximum power, using the concavity of power curve is P_{mpp} = 65.699 W
- The voltage at maximum power point for the model is V_{mpp} = 19.025 V
- The current at maximum power point for the model is I_{mpp} = 3.731 A

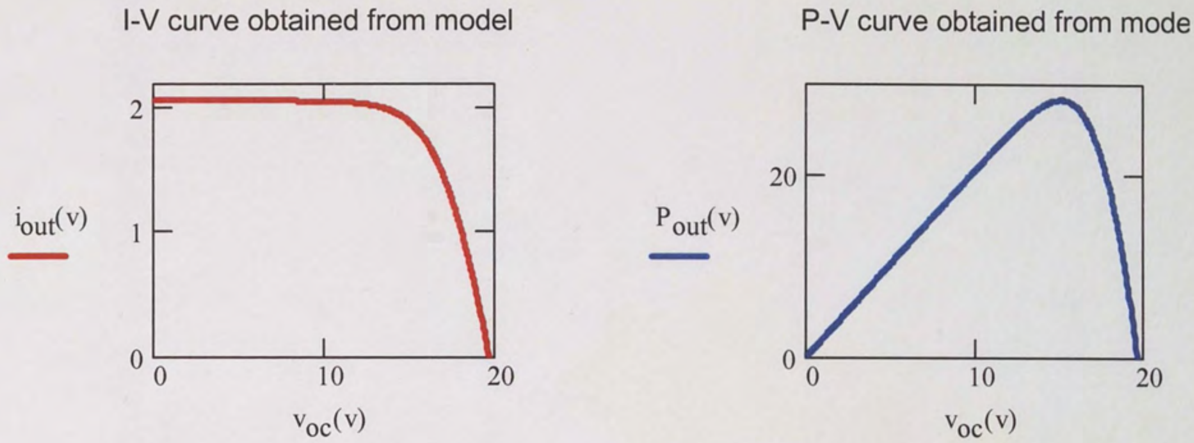
The following table provides a comparison between datasheet values and values derived from the model

Parameter	Datasheet value	Model Value	Error
Pmax(W)	65	65.699	1.08%
Voc(V)	21.5	22.035	2.49%
Isc(A)	4.06	4.109	1.21%
Vmpp(V)	17.2	19.025	10.61%
Impp(A)	3.77	3.731	-1.03%

Table 2.1 Comparison between model values and datasheet values

2.7.2.2 Comparison of experimental values and values obtained from modeling the Solarex SX 65 U at E = 479.5W/m^2 and T = 37.5^{0}C (310.65^{0}K)

Values obtained from the Daystar I-V curve tracer are presented in appendix A. Curves obtained form the experiment as well as curves obtained from the model for the experimental conditions(E = 479.5W/m^2 and T = 310.65^{0}K) using MathCAD are presented as follow:



$i_{out}(0) = 2.056$ $P_{out}(16.5) = 28.207$

$i_{out}(16.25) = 1.9$ $P_{out}(16.25) = 28.176$

$i_{out}(19.6) = 0.075$ $P_{out}(16.5) = 28.207$

Figure 2.15 I-V and P-V curves for mathematical model of Solarex SX65U at E = 479.5 W/m^2 and T = 310.65^{0}K

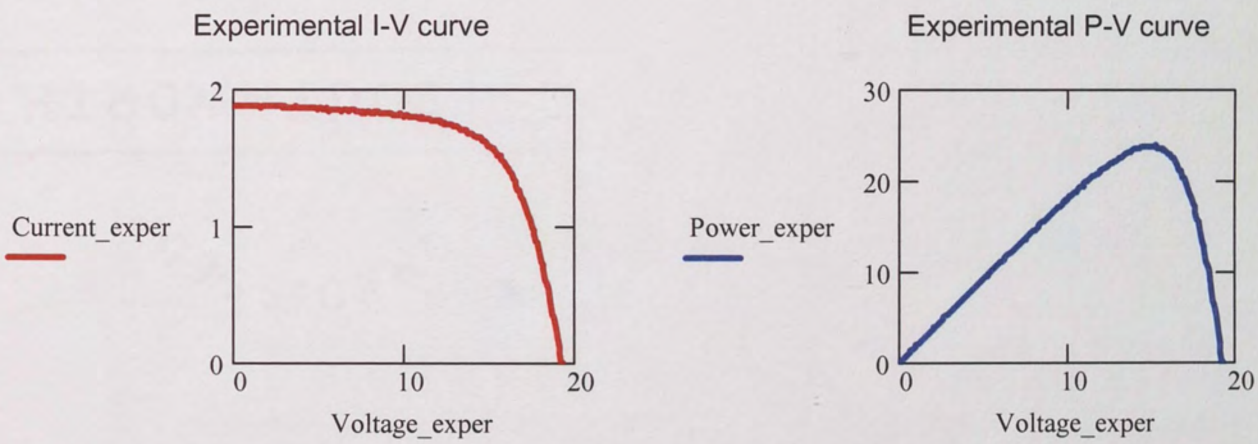


Figure 2.16 Experimental I-V and P-V curves of Solarex SX65U for E = 479.5 W/m^2 and T = 310.65^{0}K

The following conclusions about the Solarex module can be drawn from figure 2.15 and Appendix A:

- Short Circuit Current is I_{SC} = 1.88 A
- Open Circuit Voltage is V_{OC} = 19.25 V
- Maximum Power is P_{mpp} = 23.8W
- Voltage at maximum power is V_{mpp} = 14.5 V
- Current at maximum power is P_{mpp} = 1.64A

From figure 2.14, the following conclusions can also be drawn:

- The short circuit current provided by the model is I_{sc} = 2.056A
- The open circuit voltage provided by the model is V_{oc} = 19.6V
- The maximum power, using the concavity of power curve is P_{mpp} = 28.2 W
- The voltage at maximum power point for the model is V_{mpp} = 16.25 V
- The current at maximum power point for the model is I_{mpp} = 1.9 A

Comparison of data obtained from experiment and modeling are presented as follow:

Parameter	Experiment	Model Value	Error
Pmax(W)	23.8	28.2	18.49%
Voc(V)	19.25	19.6	1.82%
Isc(A)	1.88	2.056	9.36%
Vmpp(V)	14.5	16.25	12.07%
Impp(A)	1.64	1.9	15.85%

Table 2.2 Comparison between model values and experimental values

2.7.2.3 Discussion of Results

There are some discrepancies between the modeling and experimental results as shown in the error columns of both tables 2.1 and table 2.2. These discrepancies may be due to the following reasons:

- The fundamental formulas used in the developing the model are derived from Manning and Gow[6], who may have used a silicon material whose characteristics are different from the silicon used by Solarex to manufacture their modules
- Calibration errors on the Daystar I-V curve tracer may lead to irradiance and temperature values that may have deviated from the real environmental condition values. Same calibration errors may lead to distortion in the recorded values of electrical parameters, such as Maximum Power, Open Circuit Voltage, Short Circuit Current, etc...
- There may be power loss in the Solarex module due to manufacturing defect or random and undetected shading patterns. Even though extra precautions have been taken to avoid significant shading on the module, there is always the possibly of getting slight shading from factors such as dust, atmospheric humidity, clouds, reflection of solar radiations, etc...

CHAPTER THREE

3 ANALYSIS OF POWER LOSS MECHANISMS IN SOLAR ARRAYS

As mentioned in section 2.6, the main elements of a photovoltaic array are solar modules, bypass diodes, and blocking diodes. Solar modules are series connection of individual solar cells. Bypass diodes limit power losses and heating in a solar array when the array is not uniformly illuminated. Blocking diodes prevent battery discharge into the solar array in case the array is connected to a battery bank. Battery banks are usually incorporated into a solar array system as backup energy storage elements in instances there is not enough solar radiation to provide adequate power to the loads. For a solar array to operate at its optimum, all cells must be electrically balanced. Set aside manufacturing defects, one of the most important cause of electrical imbalance and power loss in solar arrays is shading. Shading can be uniform or partial over the surface of an array and is usually the result of clouds, dust, or shades of elements being powered by the arrays.

3.1 Effect of shading on electrical parameters of solar cells

Shading occurs when for any reason; the total available solar irradiance does not penetrate the solar array (uniform shading) or when part of the array or cell's surface is covered by an opaque object, which prevents light penetration

(partial shading). The study of shading effects on individual cells will be limited only to electrical parameters that play an important role when cells are connected together to form a module or an array. These parameters include:

- Short circuit current
- Open circuit voltage
- Series and shunt resistances.

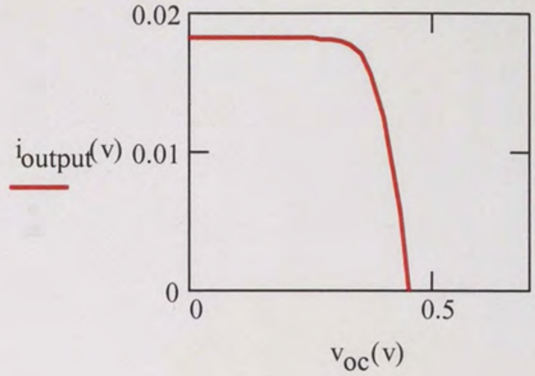
3.1.1 Short circuit current

The short circuit current is the current produced by the cell when its output voltage is zero. Using equation 2.1, the short circuit current I_{sc} is expressed as:

$$I_{SC} = i(0) = I_{ph} - I_{S1}(e^{\frac{q(I_{SC}R_S)}{kT}} - 1) - I_{S2}(e^{\frac{q(I_{SC}R_S)}{AkT}} - 1) - \frac{I_{SC}R_S}{R_P} \tag{3.1}$$

This short circuit current is approximately equal to the photogenerated current as shown in figure 3.1 where short circuit and photogenerated currents have been computed for standard test conditions (STC) using equations developed in chapter 2.

Solar Cell I-V curve



$i_{output}(0) = 0.018$

$I_{ph} = 0.018$

Figure 3.1 Computation of short circuit current using I-V graph for E = 1000 W/m² and T = 298.15°K

Since $I_{SC} = I_{ph}$, the short circuit current can now be expressed as

$$I_{SC} = I_{ph} = K_0 E(1 + K_1 T) \tag{3.2}$$

The constants K_0, and K_1 have been previously defined in chapter 2. In the event of uniform shading, it can be implied from equation 3.2 that at constant operating temperature, the cell's short circuit current will decrease linearly at a rate of

$$r = K_0(1 + K_1 T) \tag{3.3}$$

In the case of partial shading, it is useful to think of the cell as a set of several identical micro cells in parallel. Since irradiance is in units of Watts per square meters, the bigger the surface of the cell, the more power and therefore, the more current the cell can deliver. Since current adds up in

parallel connected systems, the short circuit current in this case will be proportional to the illuminated surface of the cell and it can be expressed as

$$I_{SC}(n) = I_{SC}(0) * (1 - n) \qquad (3.4)$$

Where

Isc (0) is the short circuit current produce by a non shaded cell for a particular value of irradiance and temperature

<n> is the percentage of the cell that is covered or shaded.

3.1.2 Open circuit voltage

The open circuit voltage is the voltage at the terminals of the solar cell when the output current is zero. Using the double exponential equation 2.1 to solve for this voltage can be cumbersome. However, to show the dependence of the open circuit voltage of any cell on solar irradiance, let's use the ideal solar cell model, which consists of a current source in parallel with a diode as shown in figure 3.2

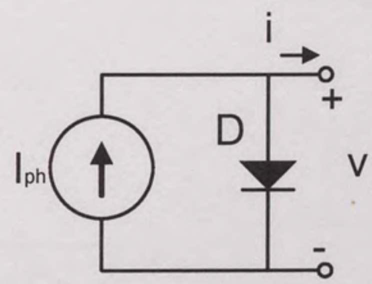


Figure 3.2 Ideal circuit model of a solar cell

The output current of the ideal model is given by

$$i = I_{ph} - I_S(e^{\frac{qV}{kT}} - 1) \tag{3.5}$$

Where

I_{ph} is the photogenerated current

I_s is the diode D saturation current

$q = 1.6*10^{-19}$ C; electron charge

$k = 1.38*10^{-23}$ J/K; Boltzmann's constant

V is the array's output voltage

T is the cell's temperature in degree Kelvin

Solving equation 3.5 for i = 0 yields to the expression for open circuit voltage V_{OC}

$$V_{oc} = \frac{kT}{q}\ln(\frac{I_{ph}}{I_S} + 1) \tag{3.6}$$

As previously shown, the photogenerated current I_{ph} depends on solar irradiance and is sensitive to shading; therefore, the open circuit voltage which depends on the photocurrent is also sensitive to shading.

3.1.3 Resistances

The resistance mainly affected by shading is the series resistance. The series resistance is inversely proportional to solar irradiance as shown by equation 2.6 and illustrated in figure 2.6. As solar irradiance decrease the series

resistance increases thus limiting the output current. The shunt resistance is typically very large and does not depend on irradiance.

3.2 Effect of shading on solar arrays

Arrays usually experience two kinds of shading: uniform shading and partial shading, also called non-uniform shading. In uniform shading conditions, the surface of the array gets a limited amount of solar irradiance and as a result, the array produces less power. Partial shading on the other hand not only limits the output capabilities of the solar PV array, but it is also the source of severe power losses and heating. The I-V curve of a partially shaded Solarex module, based on data presented in appendix B is shown below.

Figure 3.3 Solarex module partially shaded a piece of plywood

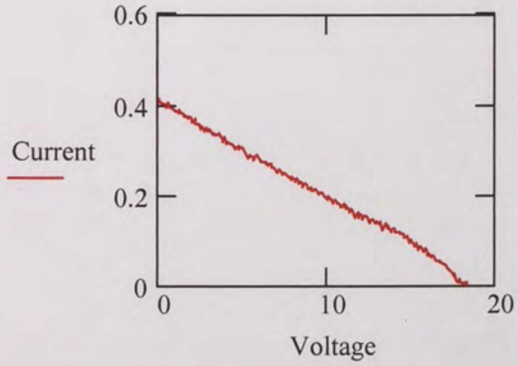


Figure 3.4 I-V curve of Solarex module partially shaded a piece of plywood

To better understand the power loss mechanisms in a shaded solar array or module, a Pspice simulation has been performed on a virtual 5 series connected cells module under uniform and partial shading conditions.

3.2.1 Pspice simulation of shaded modules

The output current and power of a partially shaded and uniformly shaded modules will be compared against those of a uniformly illuminated module at STC (E = $1000W/m^2$, T = 298.15^oK). Each module consists of 5 cells connected in series. A commercial module usually has 33 to 36 series connected cells; however, for simulation purposes, a five cell module is sufficient enough to illustrate power loss mechanisms. The uniformly shaded module consists of cells, which are 87% illuminated with respect to the uniformly illuminated module. Using the mathematical model, the following essential parameters have been computed:

- I_{ph} = 16mA
- R_s = 1.99 Ohms
- R_p = $2.3*10^6$ Ohms

The partial shading (or non-uniform) pattern has been selected as follows:

Cell#1: 100% illuminated (I_{ph} = 18.3mA, R_S = 1.75 Ohms, and R_p = $2.3*10^6$ Ohms)

Cell#2: 87% illuminated (I_{ph} = 16mA, R_S = 1.99 Ohms, and R_p = $2.3*10^6$ Ohms)

Cell#3: 75% illuminated (I_{ph} = 14mA, R_S = 2.29 Ohms, and R_p = $2.3*10^6$ Ohms)

Cell#4: 45% illuminated (I_{ph} = 8.18mA, R_S = 3.72 Ohms, and R_p = $2.3*10^6$ Ohms)

Cell#5: 95% illuminated (I_{ph} = 17mA, R_S = 1.83 Ohms, and R_p = $2.3*10^6$ Ohms)

Simulation results are as follow:

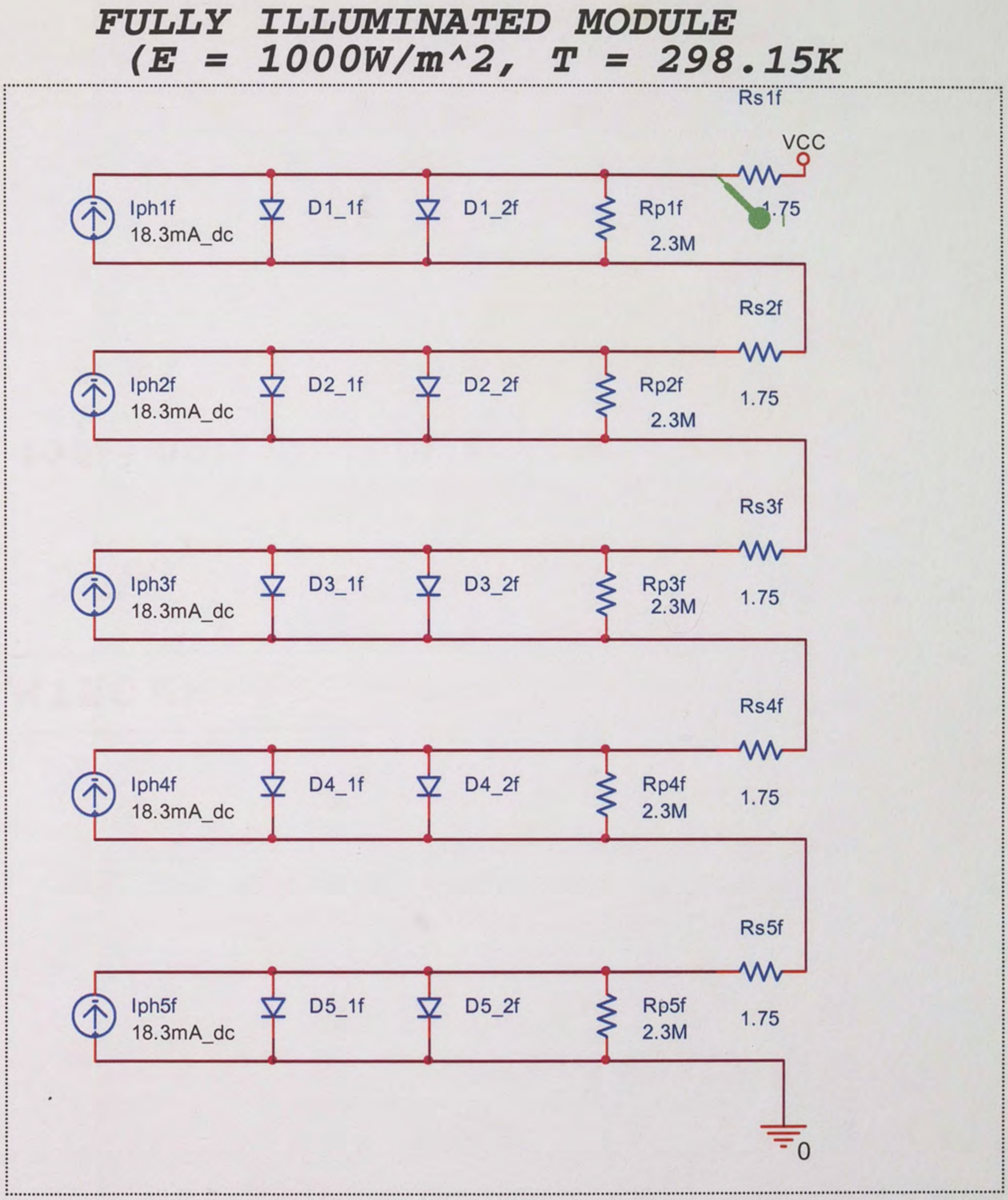


Figure 3.5 Pspice schematic of a fully illuminated module

PARTIALLY SHADED MODULE

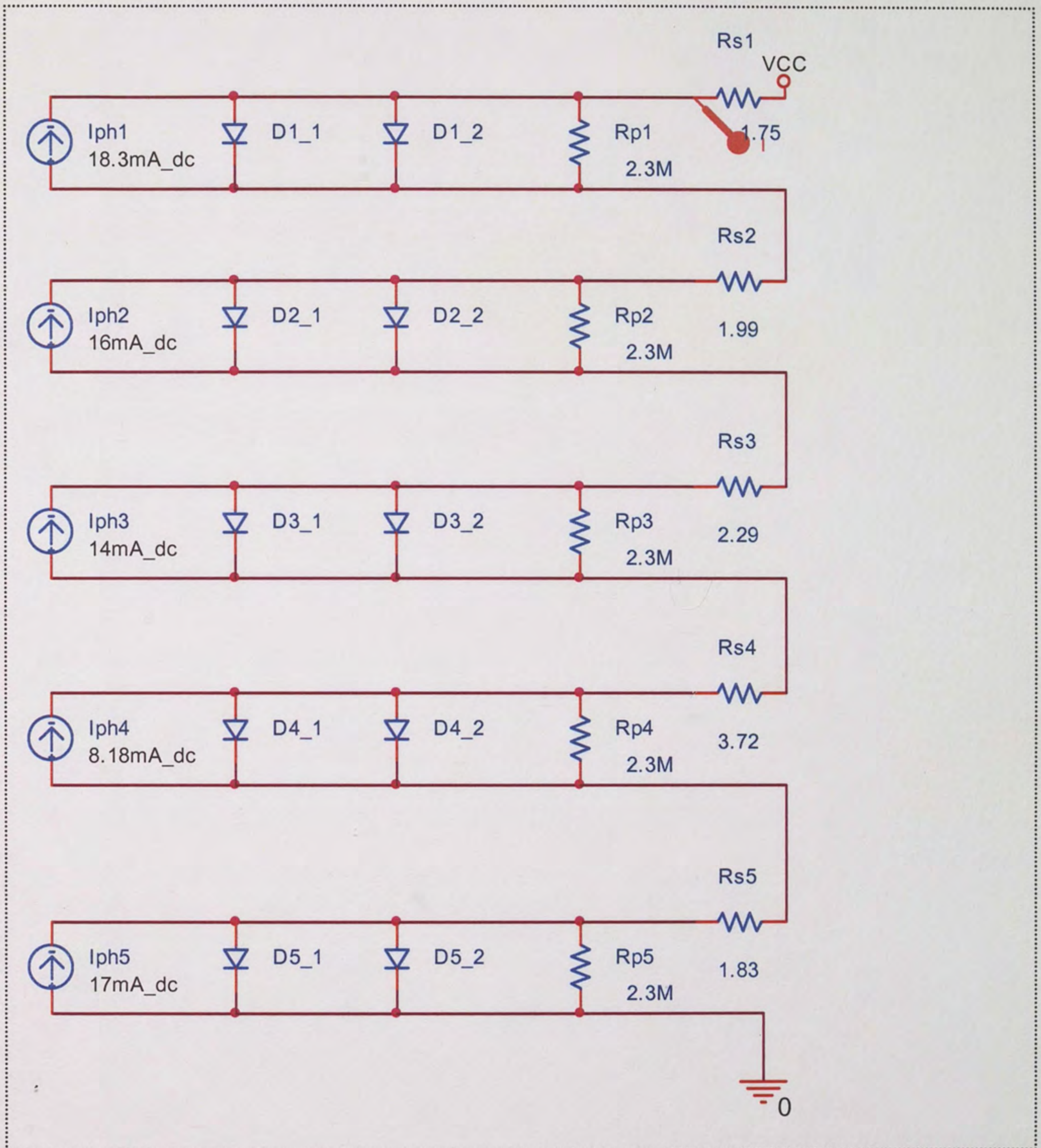


Figure 3.6 Pspice schematic of a partially shaded module

UNIFORMLY SHADED MODULE

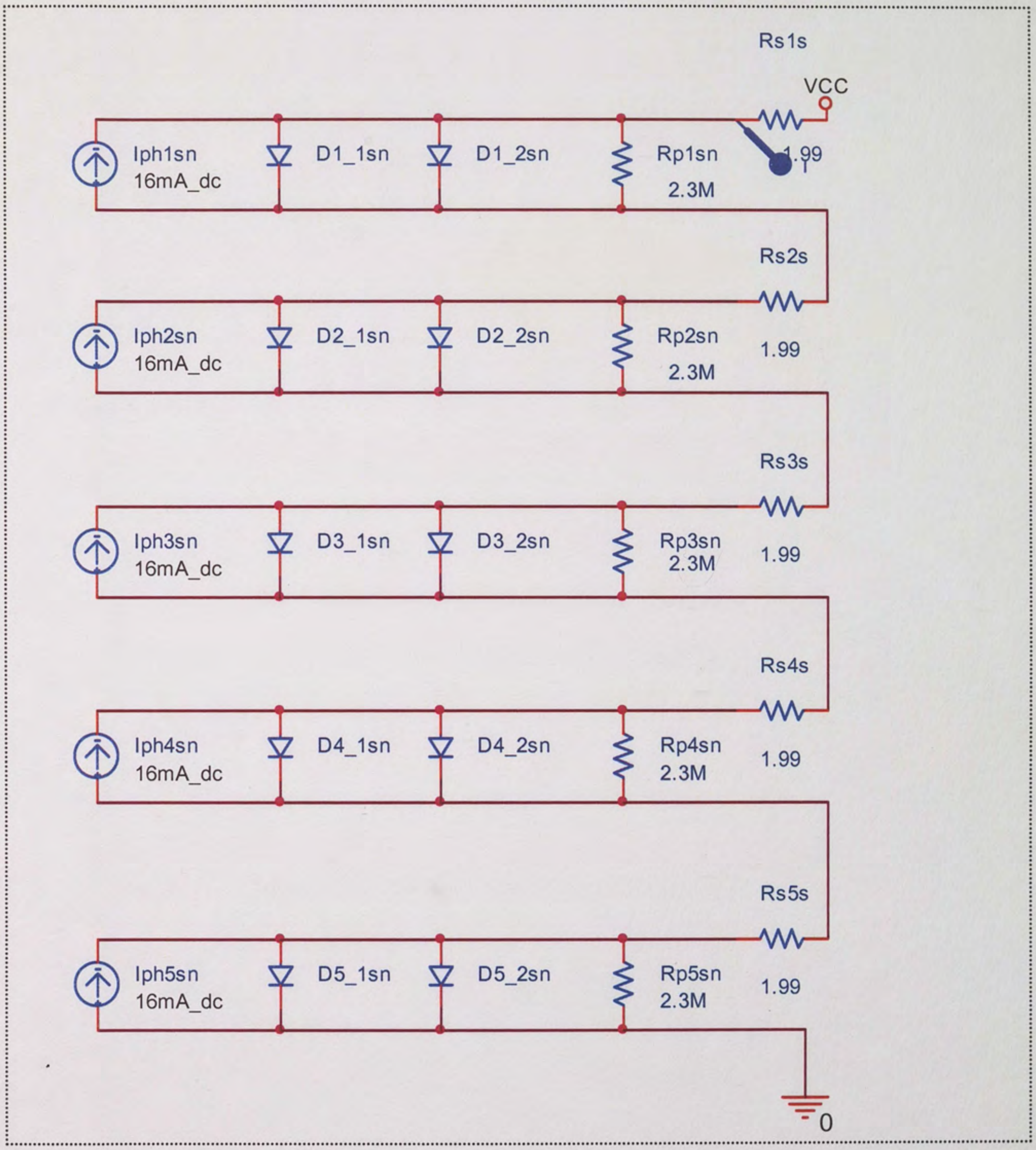


Figure 3.7 Pspice schematic of a uniformly shaded module

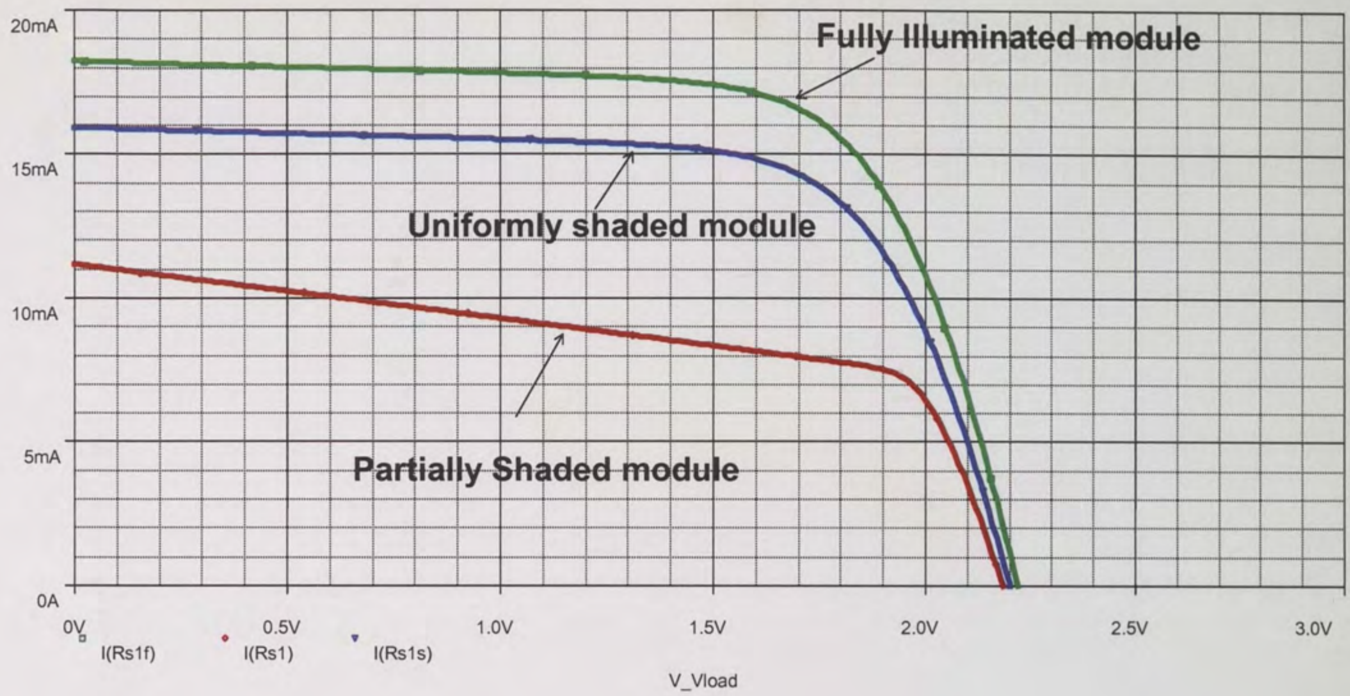


Figure 3.8 Current vs. Voltage curves of Pspice simulated modules

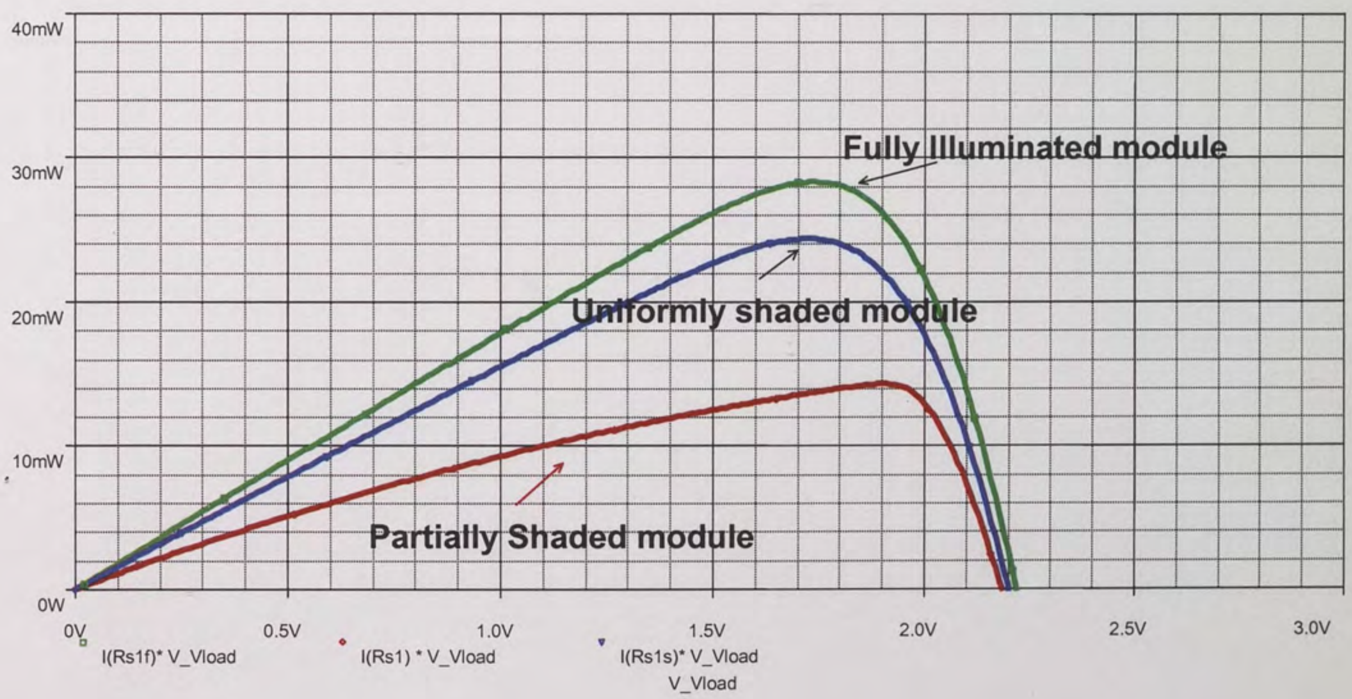


Figure 3.9 Power vs. Voltage curves of Pspice simulated modules

It can be concluded from the above simulation results that the partially shaded module produces less power than the uniformly shaded module does. The excess of power loss in the partially shaded module is due to electrical imbalance among the cells. Under normal operating conditions, each cell in the module must produce the same amount of current because of the series connection. However, since the module is not uniformly shaded, each cell has different currents coming out of their terminal. As a result, the output current of the module is limited by the output current of the least illuminated cell, which was cell#4 in the simulation. Moreover, as shown in figure 3.10, unlike the rest of the cells in the module, cell#4 is producing negative power; in other words, cell#4 is dissipating power for in the operating voltage range of the cell (0V to 2.2V). On the other hand, no cell is dissipating power in the fully illuminated and uniformly shaded modules as shown in figures 3.11 and 3.12 in the operating voltage range.

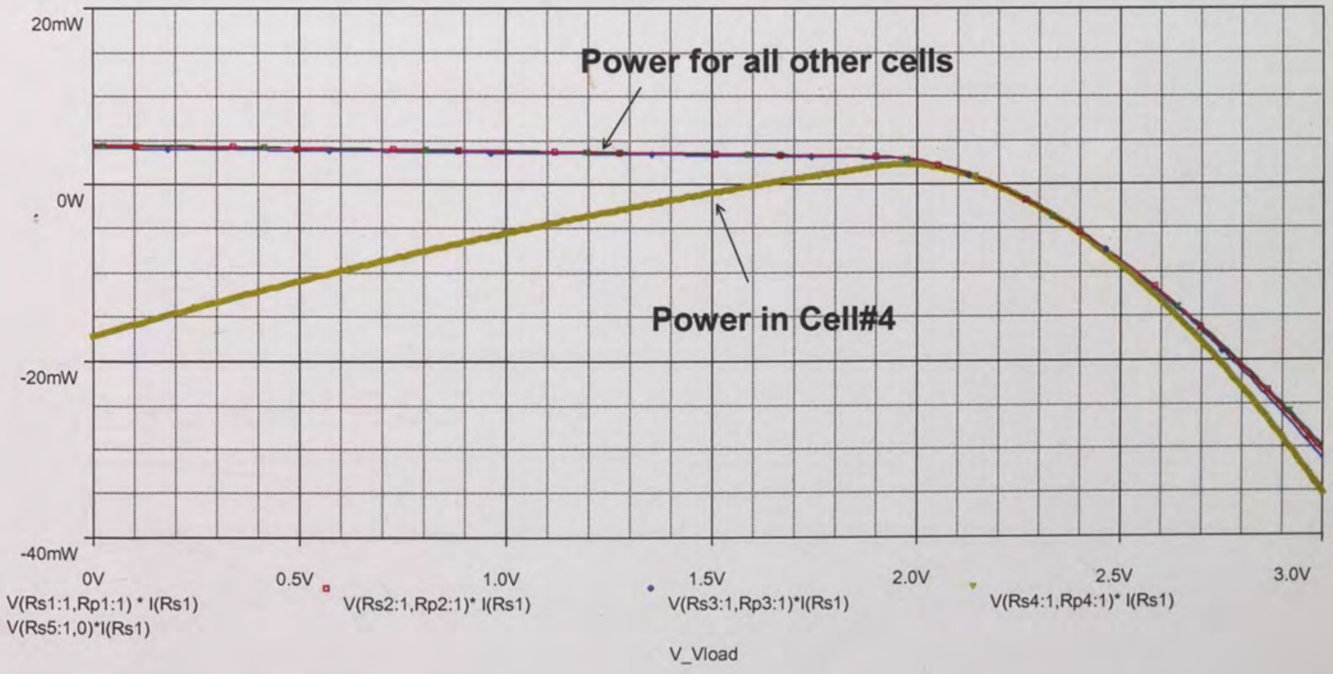


Figure 3.10 Power dissipation pattern in cell#4 of partially shaded module

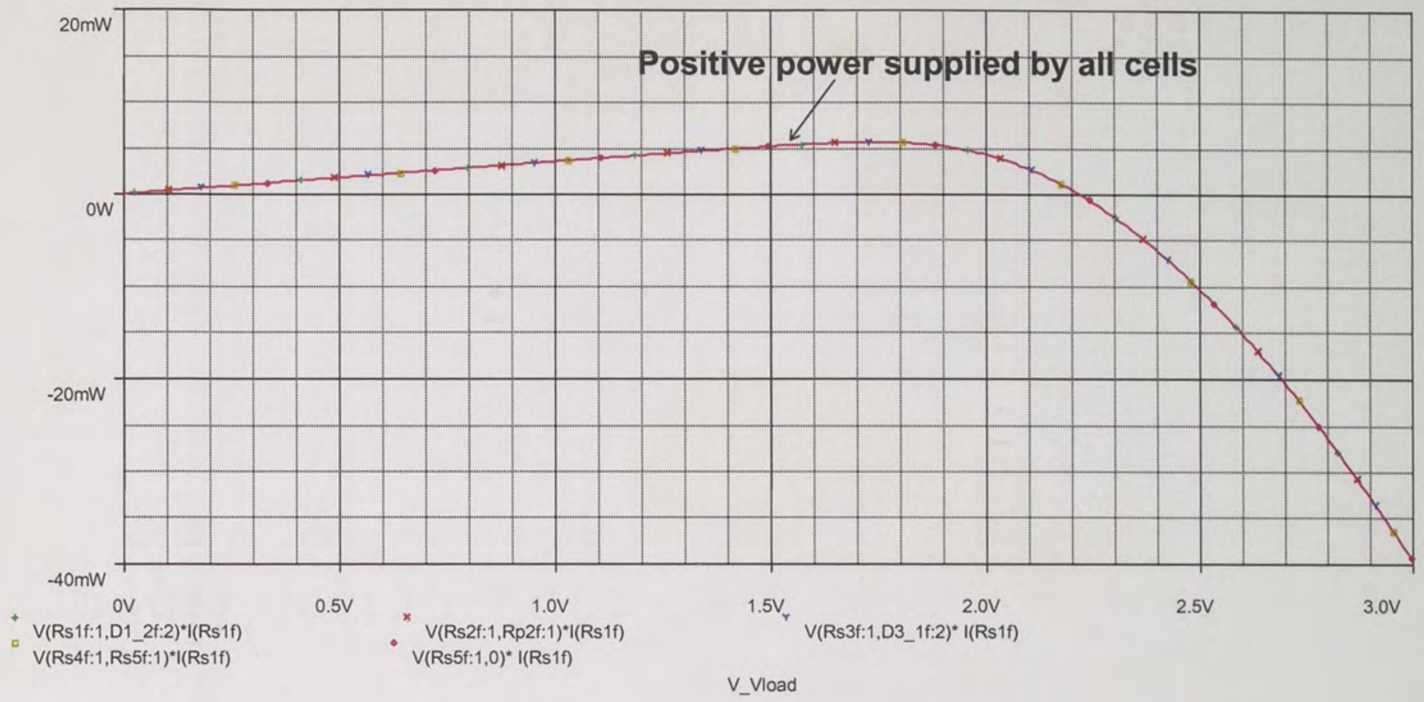


Figure 3.11 Power production in each cell of the fully illuminated module

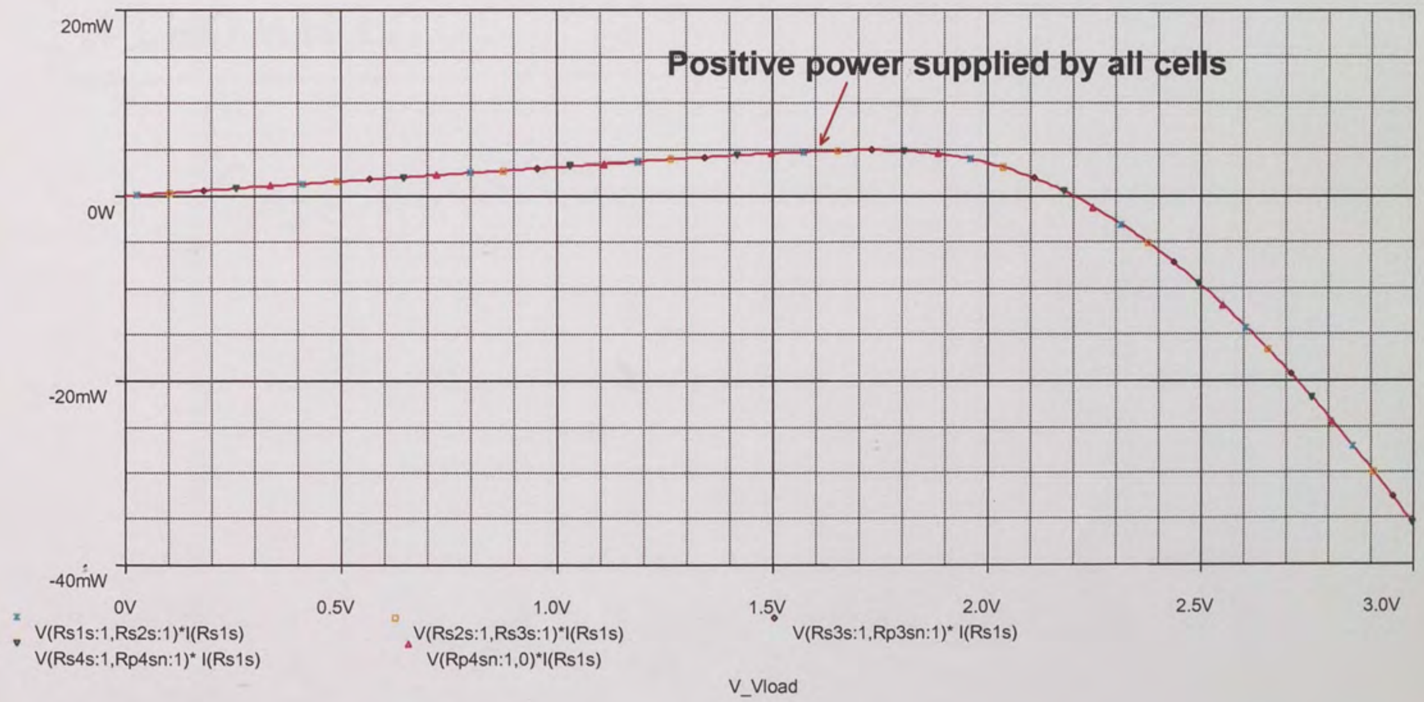


Figure 3.12 Power production in each cell of the uniformly shaded module

Since partial shading is more likely to occur than any other type of shading, photovoltaic designers usually incorporate bypass diodes in solar arrays to

limit the power losses in the least illuminated cells. In addition to bypass diodes, blocking diodes are also used to prevent storage batteries to discharge into the solar array or to prevent a string to feed current back into another parallel connected string in case shading introduces electrical mismatches. A typical solar array configuration is shown in figure 3.13. Depending on the size of the array, it may be more cost effective to connect the bypass diodes across modules instead of connecting them across each cell.

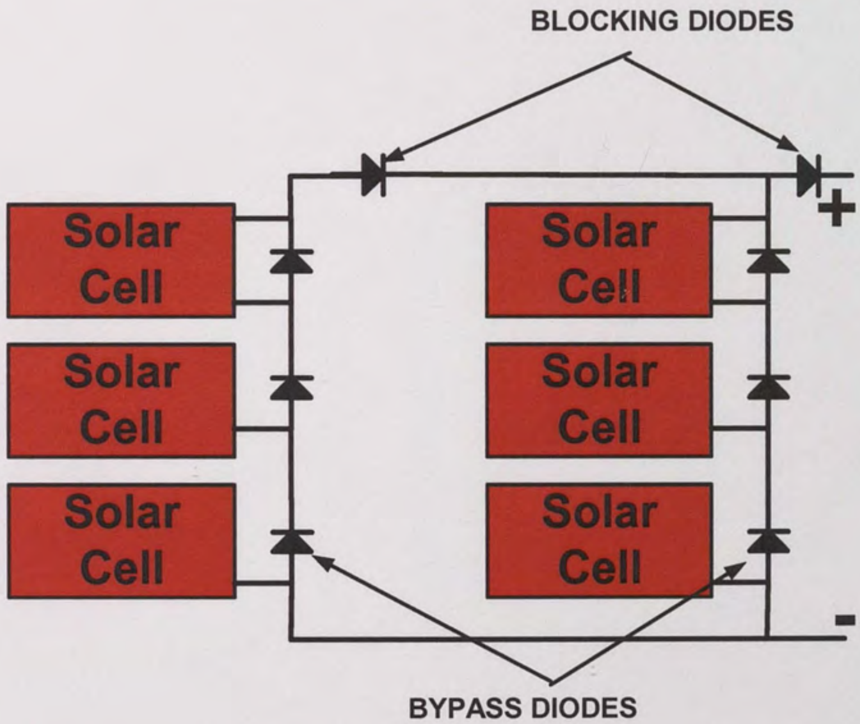


Figure 3.13 Typical solar array configuration

To illustrate the benefits of using bypass diodes, the partially shaded module and a similarly shaded module incorporating bypass diodes have been simulated and results are as presented in the following figures.

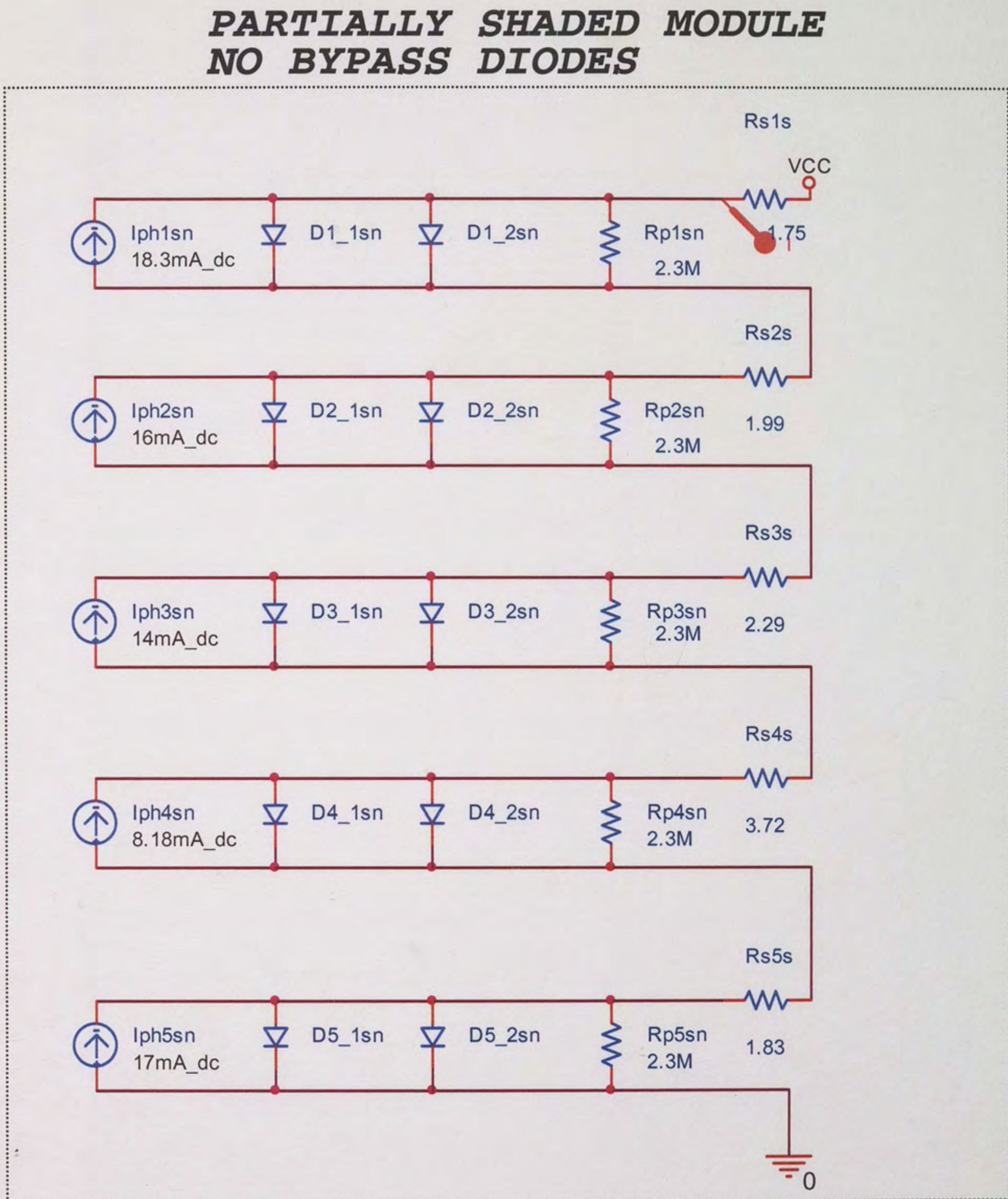


Figure 3.14 Pspice schematic of a partially shaded module without bypass diodes

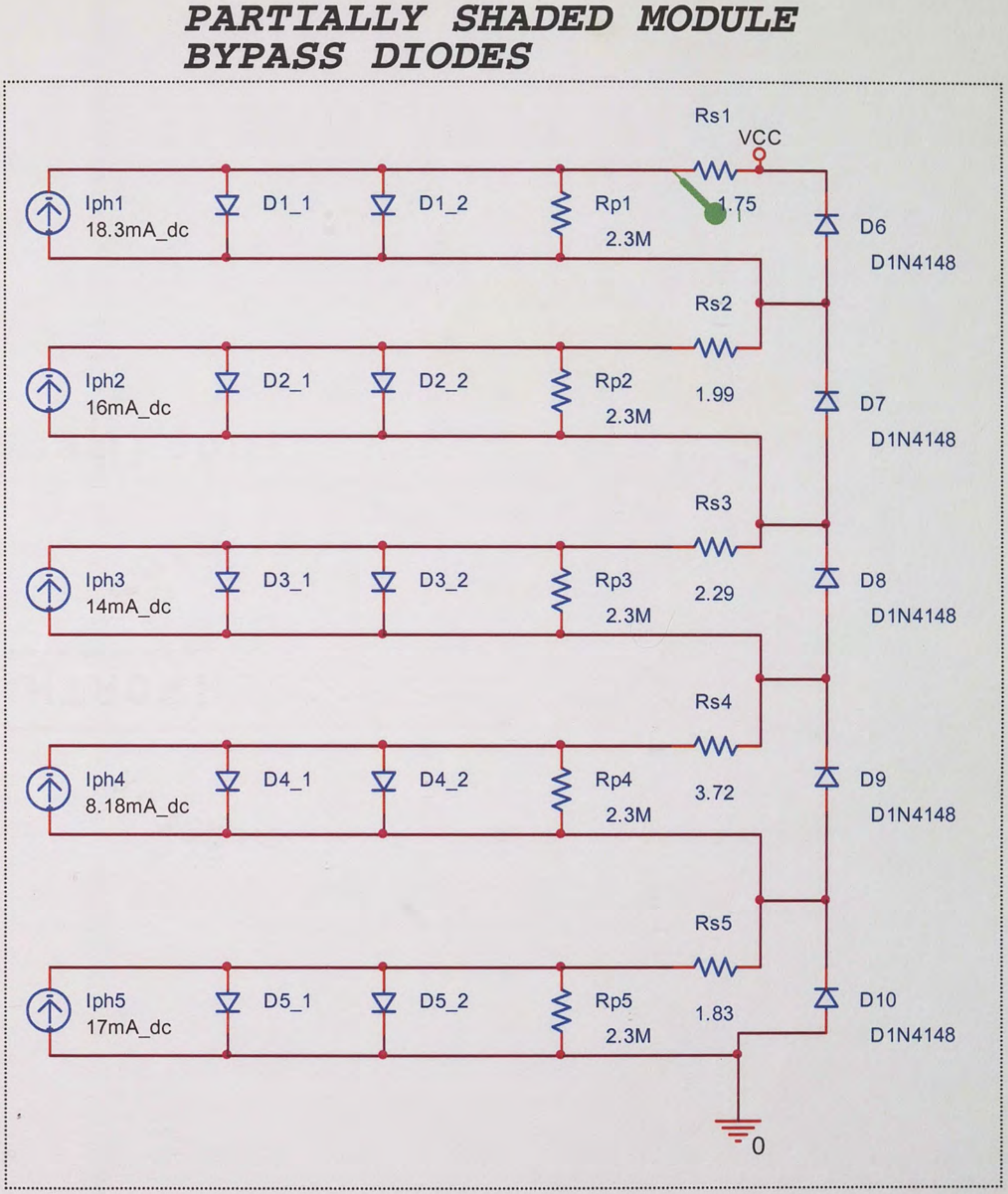


Figure 3.15 Pspice schematic of a partially shaded module with bypass diodes

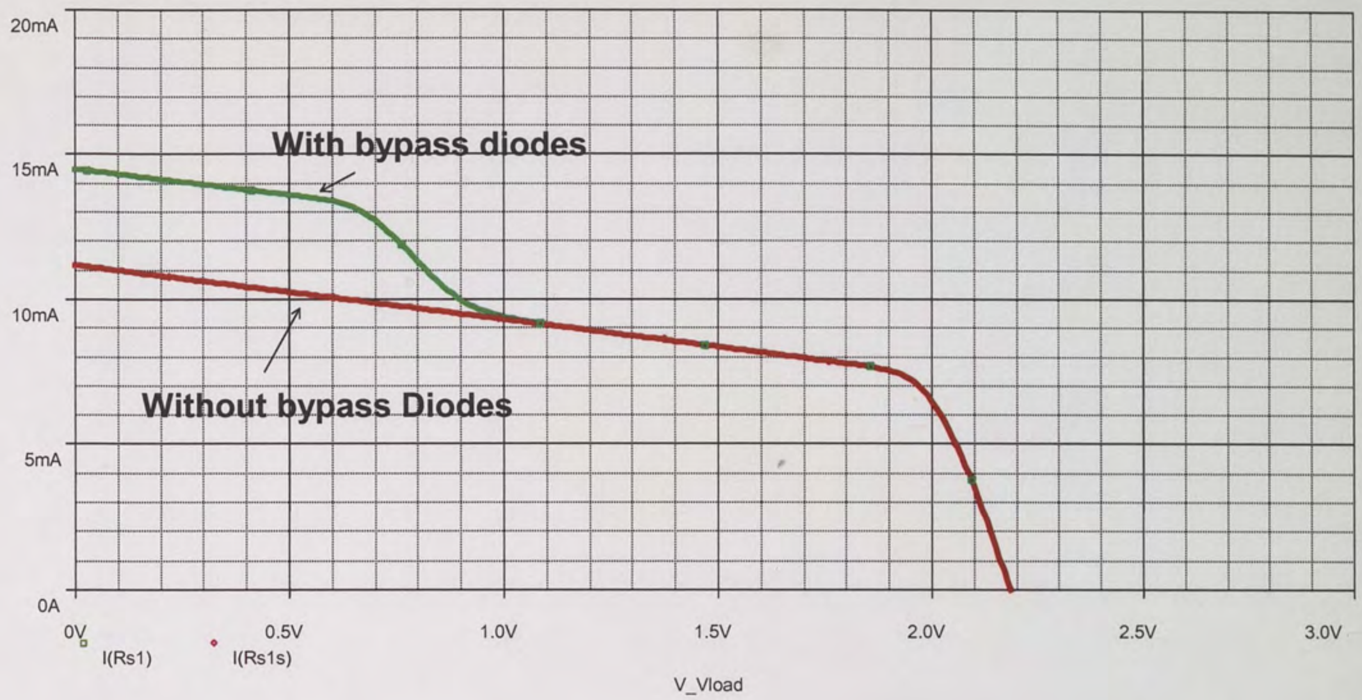


Figure 3.16 Pspice simulation results: Current-Voltage curves for two partially shaded module: one with bypass diodes and the other without bypass diodes.

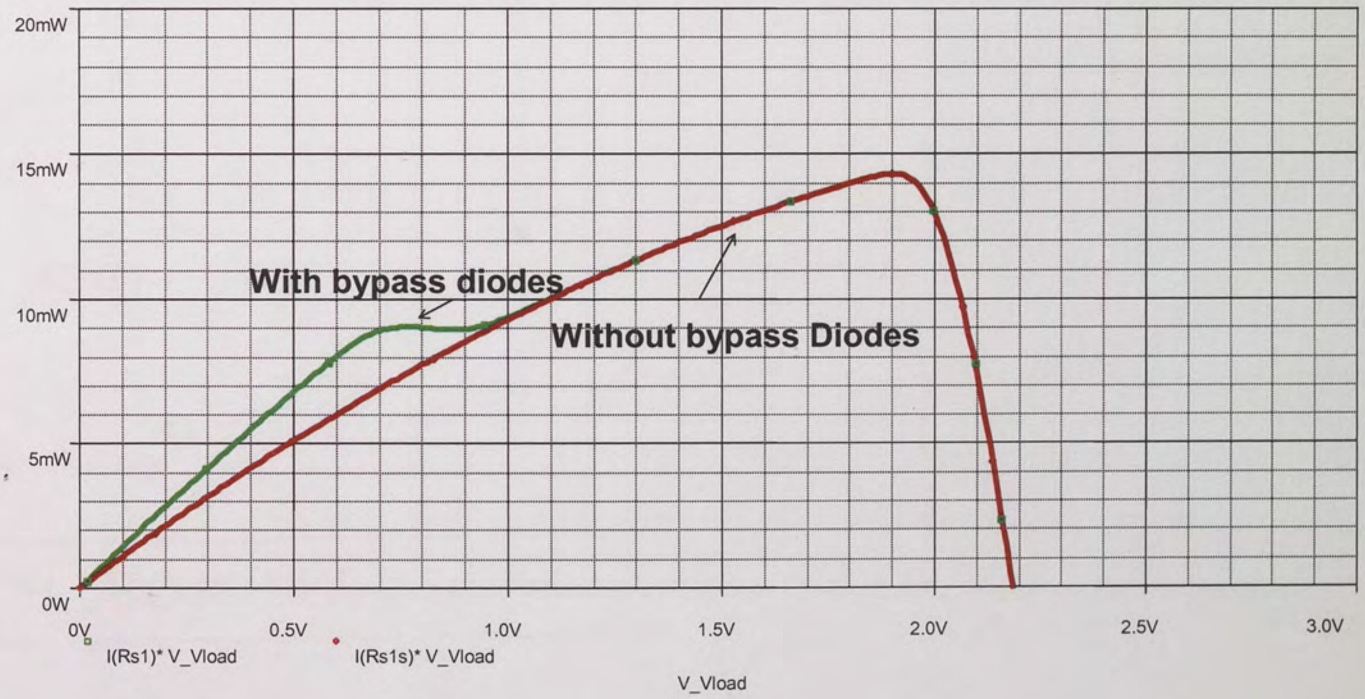


Figure 3.17 Pspice simulation results: Power-Voltage curves for two partially shaded module: one with bypass diodes and the other without bypass diodes.

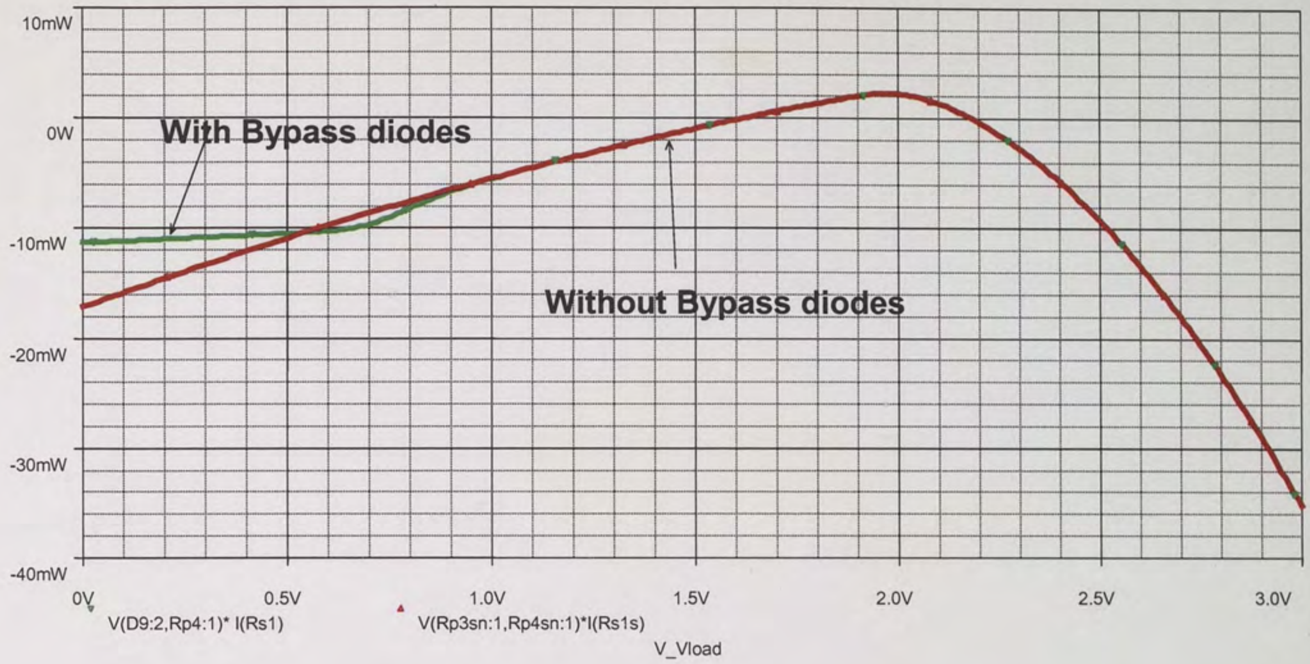


Figure 3.18 Power dissipation in cell#4, the least illuminated cell of each module.

Figure 3.16 and 3.17 illustrate the output current and power curves for the two partially shaded modules. In each case, it is clear that more power is harnessed from the module when bypass diodes are used. In figure 3.18 it is shown that the power dissipation in the least illuminated cell (cell#4) has been limited in the module incorporating bypass diodes. Not all manufacturers include bypass diodes in their modules; therefore, some precautions must be taken when selecting external bypass diodes during a solar array configuration. The smaller the turn-on voltage of the bypass diode, the better the diode limits power dissipation in shaded modules and the more power can the module can supply in partial shading conditions. To illustrate this point, another Pspice simulation has been performed. The simulation consists of two partially shaded modules with the same shading

pattern that has been used in previous simulations. This time, bypass diodes modeled with switches have been connected across each cell of each module. The turn on voltage for the bypass diodes in one of the module is V_{on} = 0.1V, while the bypass diodes of the other module have a turn-on voltage of V_{on} = 0.5V. Simulation results are as follow:

PARTIALLY SHADED MODULE
BYPASS DIODES with Von = 0.1V

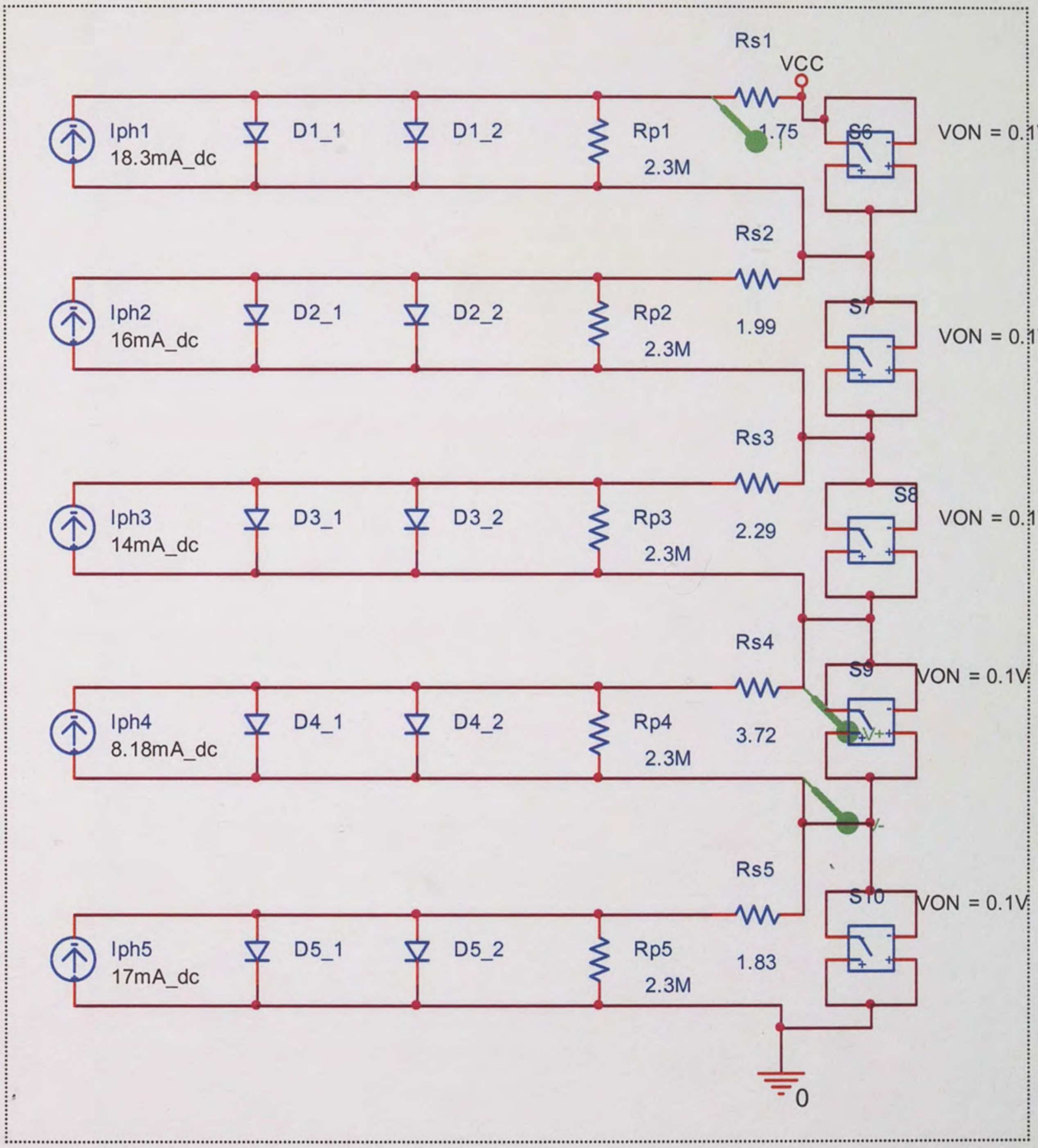


Figure 3.19 Pspice schematic of module with 0.1V bypass diodes

PARTIALLY SHADED MODULE BYPASS DIODES with Von = 0.5V

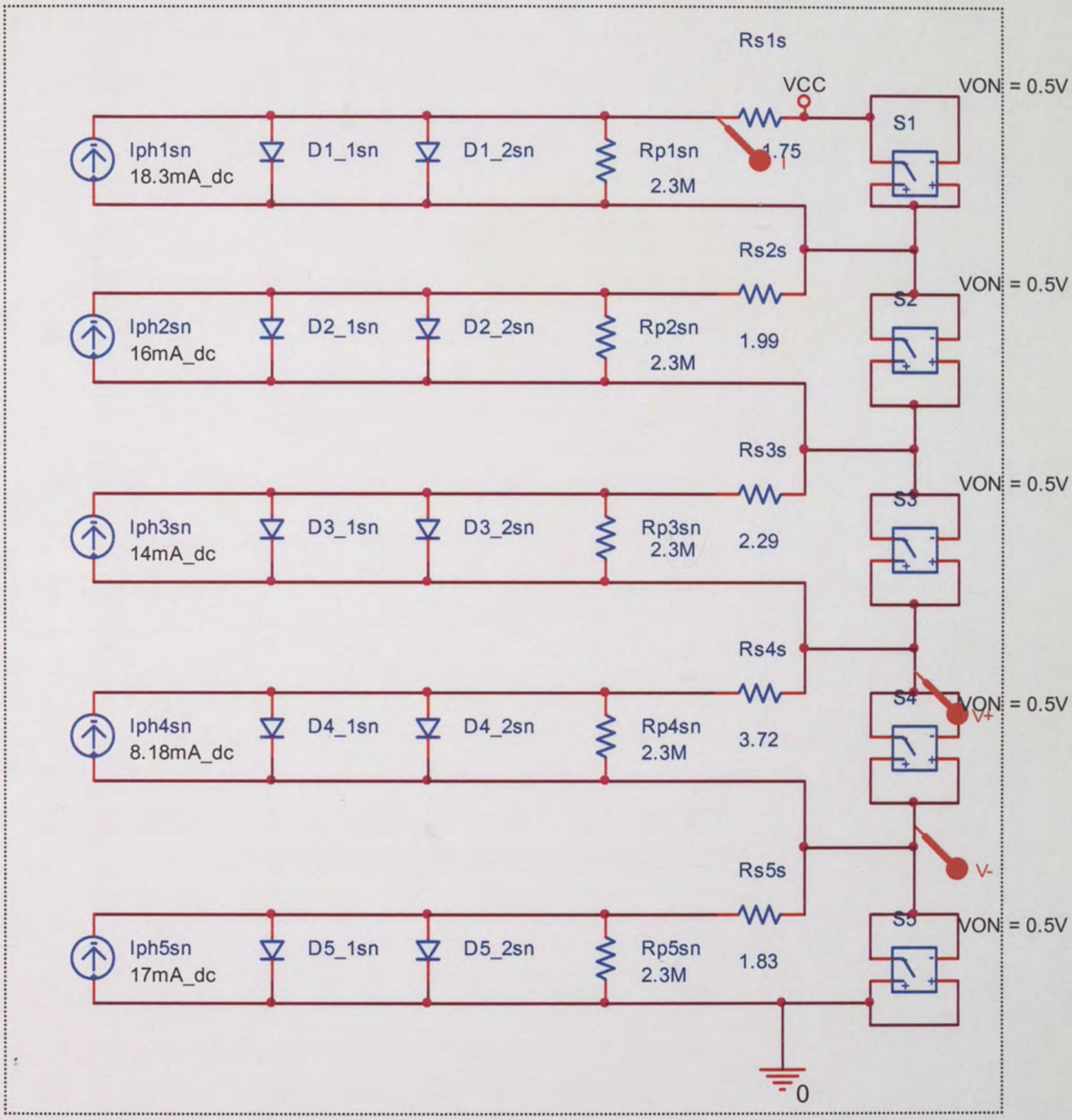


Figure 3.20 Pspice schematic of module with 0.5V bypass diodes

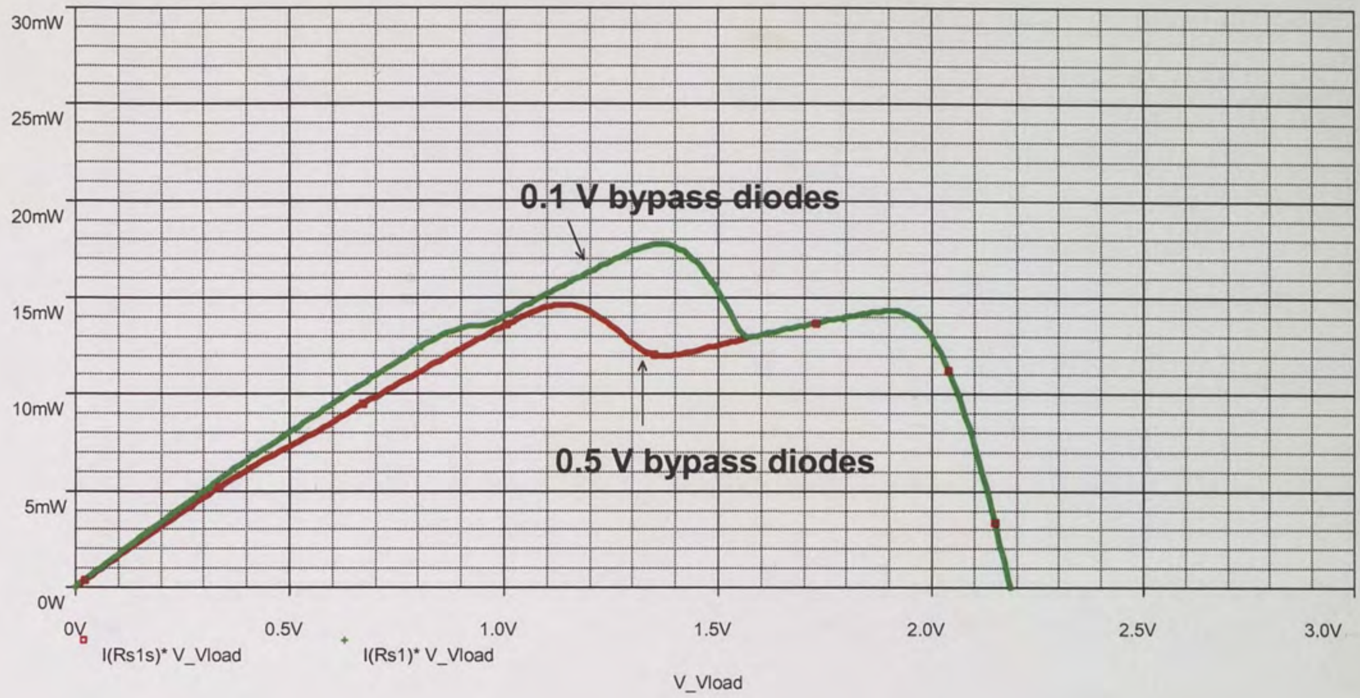


Figure 3.21 Power-Voltage curves for two partially shaded modules: one with 0.1V bypass diode and the other with 0.5V bypass diode

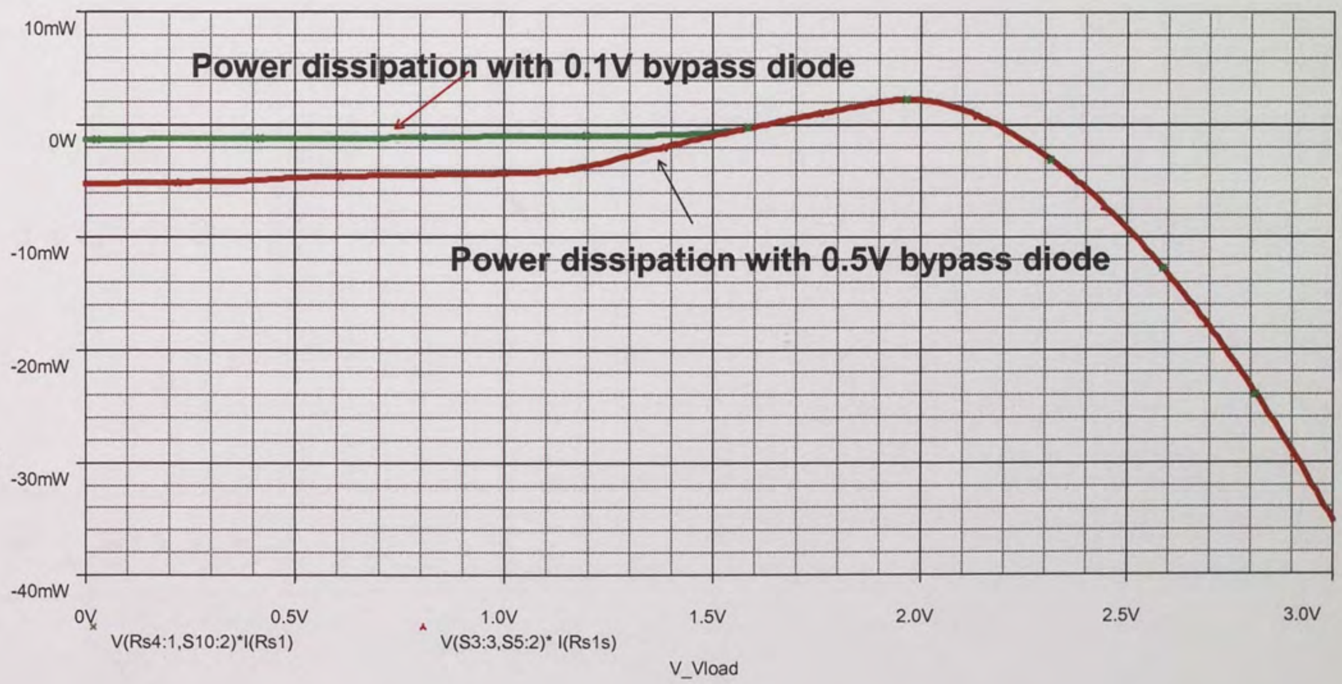


Figure 3.22 Comparison of power dissipation in cell #4 for 0.1V and 0.5V bypass diodes.

Even though bypass diodes limit power dissipation in shaded photovoltaic modules, their use lead to output power curves that have more than one extremum. This phenomenon is known as the local maxima phenomenon. A reliable photovoltaic power system must be able to track the maximum power produced by the solar array. To this end, several so-called Maximum Power Point Tracking (MPPT) techniques have been developed. MPPT systems are important in the sense that they always track maximum power even in the extreme conditions of shading. Moreover, a system that has been designed to always take advantage of maximum power may not require a big size array. The benefits of MPPT systems have been studied and presented in the next chapter.

CHAPTER FOUR

4 ANALYSIS OF MPPT SYSTEMS

4.1 Introduction to maximum power point tracking

It has been shown in chapter two that a solar array does not exhibit a constant output power over its output voltage range. The output current and power are also prone to fluctuate since they depend on a varying solar irradiance and solar cell's operating temperature. It is therefore necessary to devise a mechanism that regulates and maintains reliable output power at a solar array's terminals at any given time. This mechanism is known as Maximum Power Point Tracking (MPPT). Maximum Power Point Tracking is a technique that forces a solar array to operate at a voltage level, such that the maximum array power is delivered to the load, as needed. Popular MPPT algorithms include the Perturb and Observe, Incremental Conductance, Parasitic Capacitance, Open Circuit Testing, Curve Scanning, and Pilot Cell Algorithms. Detailed descriptions about the operating principles of these algorithms have been described by Hohm and Ropp [8]. Two main reasons drive the need to incorporate MPPT in a photovoltaic system: optimum operation of the backup batteries and proper output voltage regulation of the power converters of the photovoltaic system.

4.1.1 Optimum operation of backup batteries

Batteries are often incorporated in photovoltaic systems to compensate for power shortage when there is not enough solar irradiance. Four possible scenarios can occur in a PV system based on the available solar array power and the charging state of the batteries:

1. ***The available array power exceeds the load power demand and the battery is uncharged.***

In this case, if the array is operating at maximum power, the excess power can be used to charge the battery. An array operating at maximum power will deliver the maximum excess power to the battery; therefore, the battery will be charged as quickly as possible.

2. ***The available array power is lower than the load demand and the battery is uncharged.***

This is a disastrous situation. Insufficient power is delivered to the load. This situation is less frequent with efficient MPPT systems.

3. ***The available array power is lower than the load demand and the battery is fully charged.***

In this case, the battery will be fully or partially supporting the load. However if the array is working at maximum power point, the battery's discharge rate can be limited, thus reducing current stress on the battery. Less current stress will extend the battery's life.

4. *The available array power exceeds the load power demand and the battery is fully charged*

There is no need to track the maximum power under this condition. Only the PV system's power converters are responsible for maintaining proper output power. This mode of operation is known as Output Voltage Regulation mode. If the load demand were to suddenly increase under this mode, the array's voltage can quickly collapse unless the system include a maximum power point tracker

4.1.2 Proper output voltage regulation

When a PV system is working in Output Voltage Regulation mode, a sudden increase in the load power demand will cause the power converters to draw more current from the solar array to meet load demand. There is however a point beyond which the converters must not operate. This point corresponds to the MPPT barrier labeled in Figure 4.1. As a converter control loop is dynamically increasing the array's current to meet increasing load demand, there is a risk for the array voltage to quickly collapse. It is therefore desirable to prevent any increase in array's current to the left of the MPPT barrier and supply the remaining needed power from the batteries.

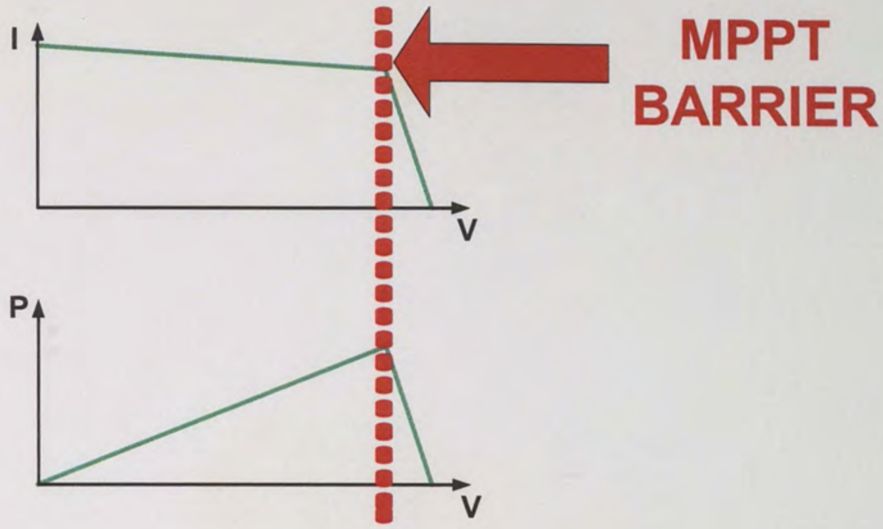


Figure 4.1 MPPT barrier

4.2 Economic analysis of MPPT systems

Efficient photovoltaic systems should incorporate a backup battery in order to supply enough power to the load, in the absence of adequate solar irradiance. Unfortunately, environmental conditions may prevent the solar array from supplying enough power to meet the load demand, even in the presence of backup batteries. This analysis consists of comparing the ability of two different photovoltaic systems (MPPT and non-MPPT) at delivering power to a load. Each system is connected to the same type of load and undergoing the same environmental constraints.

4.2.1 Non-MPPT system

The Non-MPPT system consists of a photovoltaic source connected to a constant voltage type load and a backup battery as shown in Figure 2.1. A diode is also incorporated in the system to prevent current flow from the

battery back to the photovoltaic array. The operating voltage of the load is 28V. The battery's operating voltage is 28V, when fully charged.

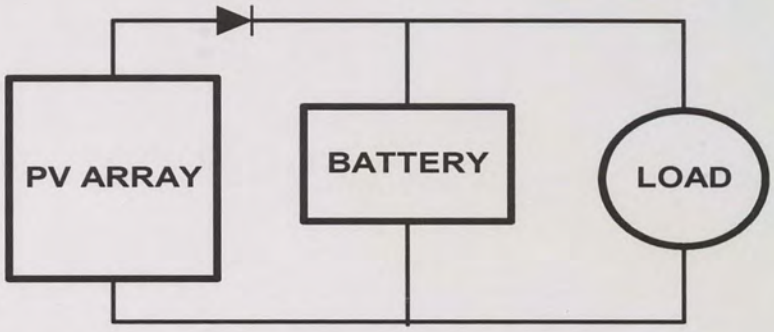


Figure 4.2 Block Diagram of a PV system without MPPT

4.2.1.1 Photovoltaic array

The configuration of the photovoltaic array has been left as a variable in the program. The user can then use a base module to configure the array to meet load demand. The base module has been configured to produce a maximum power of P_{MPP} = 500W at 28V for a solar irradiance E = 1000W/m^2 and an ambient temperature T = 300^{o}K. Environmental conditions, however, will always cause a deviation from Maximum Power at 28V.

4.2.1.2 Backup battery

The maximum capacity of the backup battery has also been left as a variable to allow the user to size the battery bank to meet load demand. It has been assumed that the battery possesses a charge controller that prevents a discharge beyond 10% of the maximum battery capacity, SOCm. This charge controller also stops any charging current flow to the battery once the SOCm

is reached during system operation. As mentioned earlier, the battery's operating voltage is 28V, at the maximum capacity specified by the user.

4.2.1.3 Load

The load operates at 28 V and its power demand can fluctuate throughout the day. Load demand patterns have been obtained from the Florida Solar Energy Center [9] for a typical Floridian household for 3 different days. The load demand has been sampled every 15 minutes for a period of 24 hours; resulting in a total of 96 samples per day.

4.2.1.4 Operating principle

The power produced by the photovoltaic array will primarily serve the load. However, since the photovoltaic power will fluctuate throughout the day, three different scenarios can occur:

1. ***The power produced by the array is greater than the load's demand***

In this case, the excess power will be channeled to charge the battery. If the battery has already reached SOCm, then this excess power will be shunted away by the battery's charge controller.

2. ***The power produced by the array is less than the load's demand***

In this case, the battery, if it holds enough charge, will compensate the power deficiency of the array to deliver appropriate power to the load. Should the battery have insufficient power, the system may experience a black-out.

3. ***The power produced by the array is exactly equal to the load demand***

In this case, the battery is bypassed and all power is channeled from the array to the load.

4.2.2 MPPT system

The MPPT system as shown in Figure 4.3 is an upgraded version of the Stand-Alone System. The MPPT block provides impedance matching between the power converter and the photovoltaic array. This impedance matching allows the power converter to always channel the maximum array power to the load bus, while maintaining a 28V operating voltage across the load and battery. In other words, the input voltage of the converter, which corresponds to the output voltage of the solar array, will be dynamically changed by the MPPT controller such that this input voltage corresponds to maximum power P_{MPP}. The converter will then be responsible to step this input voltage up or down to Vop = 28V, to supply the load.

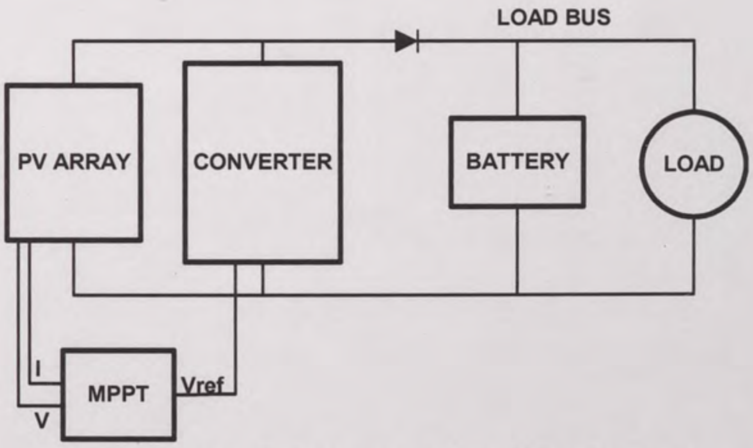


Figure 4.3 Block Diagram of the MPPT System

4.2.2.1 Operating principle

In this system, the array will always be forced by the MPPT controller to deliver maximum available power to the system. (There can also be a

configuration when maximum power is delivered only when load demand is greater than array's supply; this kind of scheme may alleviate the work of the controller when there is enough power to supply the load, but the battery charging will not be optimum) The battery controller works in the same manner as in the non-MPPT system. However, the architecture of the new system dramatically reduces the chances of system black-out thanks to the MPPT controller. In summary, the Non-MPPT system is fed with whatever power is available, while the MPPT system is always fed with maximum power.

4.2.3 Comparison

The performances of the two systems have been compared using MATLAB. A typical power demand pattern has been collected for a Florida household for 3 days from the monitoring database of Florida Solar Energy Center (FSEC). Solar irradiance and ambient temperature data have also been monitored to compute the power produced by the PV array.

4.2.4 Algorithms

4.2.4.1 Non-MPPT system

N_P = *Number of cells in parallel*

N_S = *Number of cells in series*

P_{array} = *Power produced by solar array at 28V*

P_{load} = *Load power demand at sample time*

SOC = *Maximum charge battery can hold*

SOC_m = *Maximum charge allowed on battery*

SOC_{actual} = *Actual charge of battery*

*SOCmin = 0.1*SOC = minimum charge the battery is allowed to have*

SOCm = SOC and SOCactual = SOCm Initializing state of charge of battery

$P_{battery\_max}$ = *Maximum charge that can be drawn from battery*

P_{load_need} = *Power needed to meet load demand*

P_{load_get} = *Power that battery actually provides towards load demand*

P_{supply} = *Power supplied to the load by the system*

$P_{battery\_charge\_available}$ = *Maximum available power to charge battery*

```
For each sample of Irradiance and temperature
        Compute P_array
        Get P_load
        If P_array < P_load Then
                If SOC_actual > SOCmin
                        P_battery_max = SOC_actual – SOCmin
                        P_load_need = P_load - P_array
                        If P_load_need >= P_battery_max Then
                                P_load_get = P_battery_max
                        Else
                                P_load_get = P_load_need
                        End If
                        SOC_actual = SOC_actual - P_load_get
                        P_supply = P_array + P_load_get
                Else
                        P_load_get = 0
                        P_supply = P_array
                End If
        End If
        If P_array = P_load Then
                P_supply = P_array
        End If
If P_array >P_load Then
        P_supply = P_load
```

If $SOC_{actual} < SOC_m$ *Then*

$P_{battery\_charge\_available} = P_{array} - P_{load}$

If $P_{battery\_charge\_available}$ *+SOCactual >* SOC_m *Then*

$SOC_{actual} = SOC_m$

Else$_e$

$SOC_{actual} = SOC_{actual} + P_{battery\_carge\_available}$

End If

Else

SOCactual = SOCactual

End If

End If

End For

Plot Load demand and power supplied to load on same graph.

4.2.4.2 MPPT system

N_P *= Number of cells in parallel*

N_S *= Number of cells in series*

P_{array_max} *= Maximum Power produced by solar array for each pair of Irradiance and temperature*

P_{load} *= Load power demand at sample time*

SOC = Maximum charge battery can hold

SOC_m *= Maximum charge allowed on battery*

SOC_{actual} *= Actual charge of battery*

*SOCmin = 0.1*SOC = minimum charge the battery is allowed to have*

SOCm = SOC and SOCactual = SOCm Initializing state of charge of battery

$P_{battery\_max}$ *= Maximum charge that can be drawn from battery*

P_{load_need} *= Power needed to meet load demand*

P_{load_get} *= Power that battery actually provides towards load demand*

P_{supply} *= Power supplied to the load by the system*

$P_{battery\_charge\_available}$ *= Maximum available power to charge battery*

For each sample of Irradiance and temperature

```
Compute P_array_max
Get P_load
If P_array_max < P_load Then
        If  SOC_actual  > SOCmin
                P_battery_max = SOC_actual – SOCmin
                P_load_need = P_load - P_array
                If P_load_need >= P_battery_max Then
                        P_load_get = P_battery_max
                Else
                        P_load_get = P_load_need
                End If
                SOC_actual = SOC_actual  - P_load_get
                P_supply = P_array_max + P_load_get
        Else
            P_load_get = 0
            P_supply = P_array_max
        End If
End If
If P_array_max = P_load Then
        P_supply = P_array_max
End If
If P_array_max >P_load Then
        P_supply = P_load
        If SOC_actual < SOC_m Then
                P_battery_charge_available = P_array_max - P_load
                If P_battery_charge_available +SOCactual > SOC_m Then
                        SOC_actual = SOC_m
                Else_e
                        SOC_actual = SOC_actual + P_battery_carge_available
                End If
        Else
                SOCactual = SOCactual
        End If
End If
End For
```

4.2.5 Results

For each day's load pattern, the array and battery sizes have been selected such as load demand is met in each case; then a comparison have been made to show which system demands a bigger array and battery storage size.

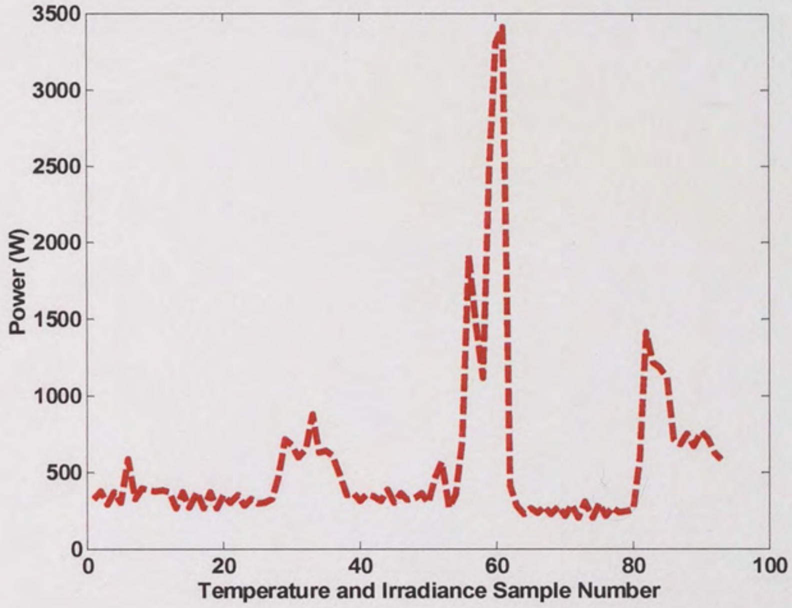


Figure 4.4 Load Power demand for November 1, 2004

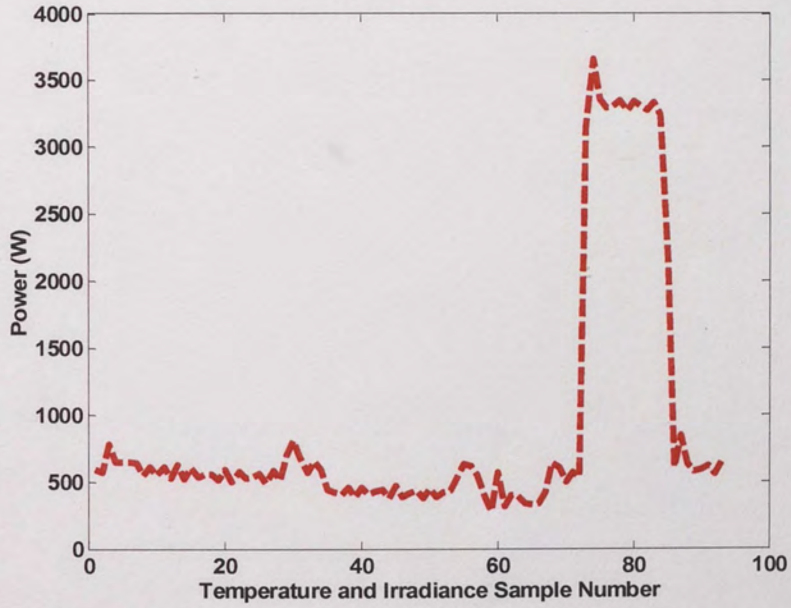


Figure 4.5 Load Power demand for November 2, 2004

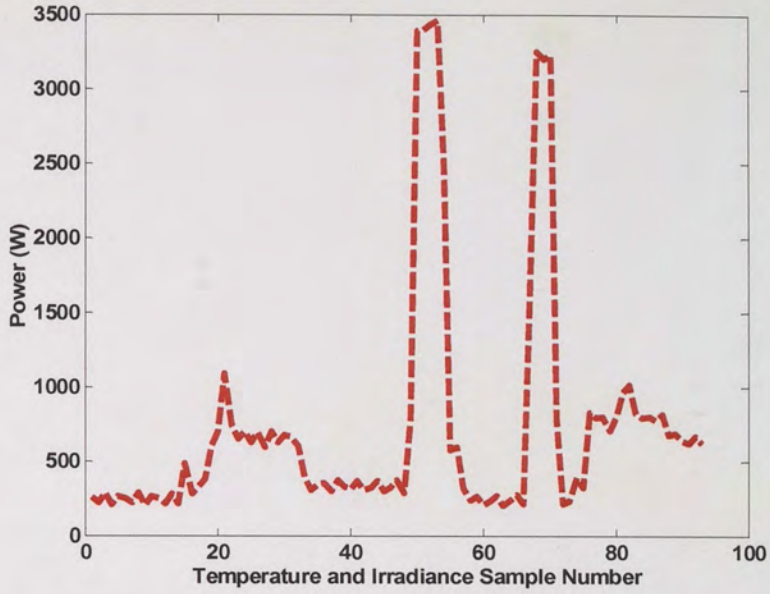


Figure 4.6 Load Power demand for November 3, 2004

Using the algorithms, it has been determined that to meet load demand, the MPPT and the non-MPPT systems require different battery storage capacities, when the array size has been limited to two parallel connected base modules. The results are presented in table 4.1 and include the savings on battery size in MPPT systems.

Date	Battery size for MPPT system(KWh)	Battery size for non-MPPT system(KWh)	Savings
11/1/2004	37.992	45.984	17.38%
11/2/2004	72.984	82.992	12.06%
11/3/2004	54.984	69.984	21.43%

Table 4.1 Comparison of systems performance

Based on the figures of table 4.1, a different type of analysis has been performed. The battery sizes of the MPPT systems have been incorporated

into the non-MPPT systems and the relative augmentation in array size have been computed using the algorithms. The results are as follow

Date	Array size for MPPT	Array size for non-MPPT
11/1/2004	2 modules in parallel	4 modules in parallel
11/2/2004	2 modules in parallel	4 modules in parallel
11/3/2004	2 modules in parallel	7 modules in parallel

Table 4.2 Augmentation in array size

It can be concluded from the above results that MPPT systems are economically more beneficial.

4.3 Application of MPPT to grid connected systems

Solar arrays can be used as primary power source for houses, thus extending the benefits of MPPT to residential applications. As a common practice, when solar arrays are used to provide power for houses, the electric grid becomes a backup power source. Such power system configuration, often referred to as Distributed Generation, is beneficial to both consumers and electric utility companies. The electric grid system is often forced to operate at or beyond its maximum rating to meet consumers ever increasing power need. A complete upgrade of the grid system could help remediate this problem, but the complexity of the power grid from both technical and business perspectives would turn any upgrade project into a difficult, if not impossible task. However, if consumers take advantage of solar array systems and generate power locally in their houses, not only will they save on their electric bill, but

they will also lessen the burden on power companies to update their transmission and distribution systems. In third world and some developing countries such as India, a failure of power companies to update their distribution systems have led to significant shortage of power. Developed countries such as the United States of America have trouble maintaining their power grid, and the blackout that affected the northeastern region of the country and part of Canada in August 2003 is one of the direct consequences. Foreseeing the potential electric power problems, the Power Electronics Society of the Institute of Electrical and Electronics Engineers (IEEE), along with other IEEE societies and the National Renewable Energy Laboratory (NREL) have sponsored a "Future Energy Challenge" competition which partly consists of developing inverter systems for use in distributed generation systems. The Power Electronics Laboratory at the University of Central Florida, one of the participants of the competition is currently developing a system whose block diagram is shown in figure 4.7

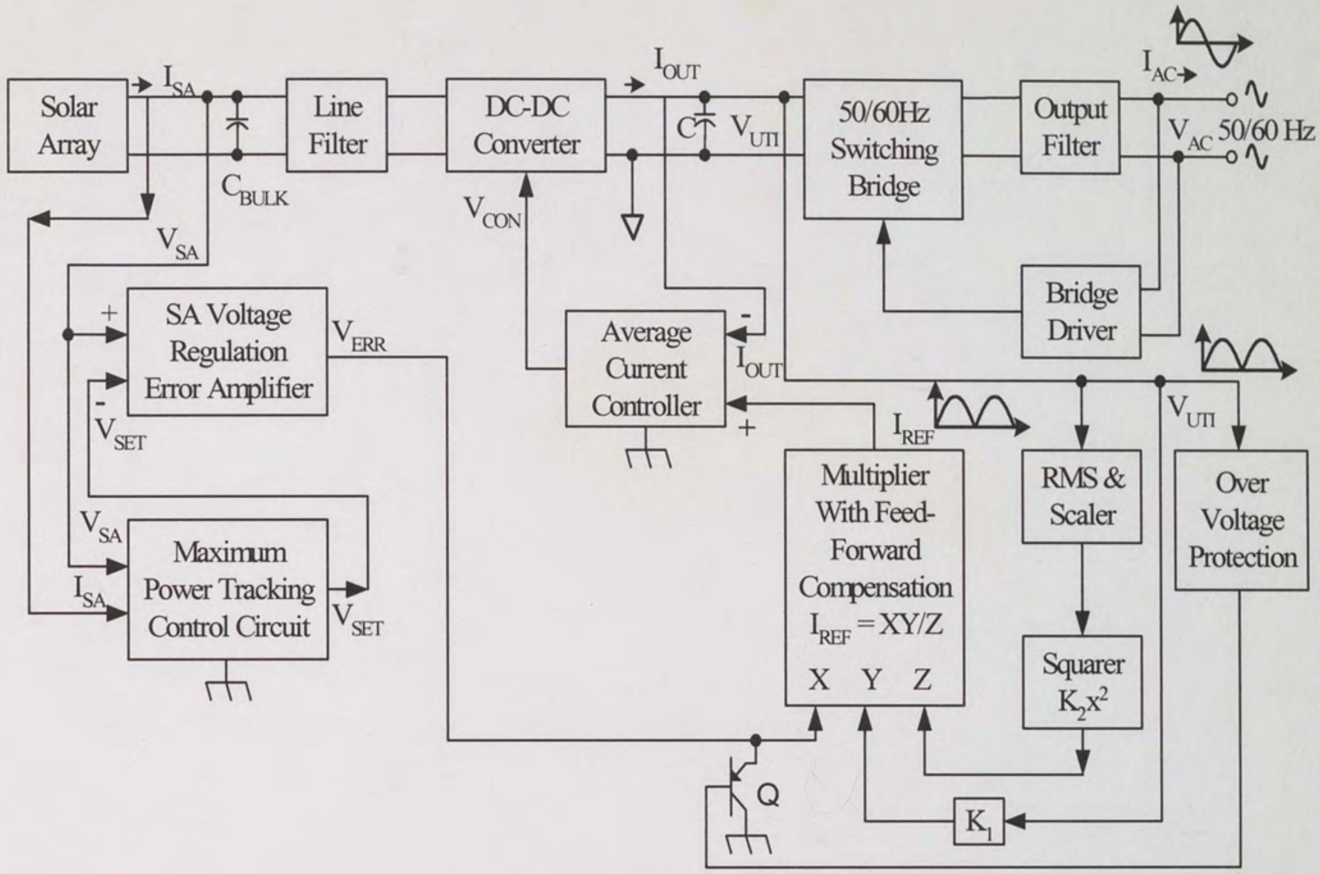


Figure 4.7 Inverter System for 2005 Future Energy Challenge

This high efficiency inverter system is unique in the sense that it achieves power conversion in only one single stage as opposed to the traditional two stage inverter topologies. The main stages of this system are:

- Maximum power tracking stage
- Power and control stage
- Protection circuits
- Grid Interface

4.3.1 Maximum power tracking stage

Employing solar-array voltage V_{SA} and solar-array current I_{SA} as the feedback signals, the Maximum Power Tracking control sub-system continuously updates the set-point voltage reference V_{SET}. The set-point voltage reference commands the solar-array voltage regulation sub-system (or SA voltage regulation error amplifier) to produce the error voltage drive signal V_{ERR} for regulation of the solar-array voltage, V_{SA}, at the level corresponding to V_{SET}. V_{ERR} signal, which is sufficiently band-limited to have negligible ac ripple voltage especially at twice the utility frequency despite the presence of AC array-voltage ripple, commands the converter output average-current regulation sub-system that controls the converter power stage to properly deliver the output current of the rectified sinusoidal wave shape, I_{OUT}.

4.3.2 Power and control stage

The power and control stage decomposed into four basic sub-systems

- DC-DC converter
- 50/60Hz switching bridge
- Average current controller
- Feed-forward compensated current reference generator

4.3.2.1 DC-DC converter

The DC-DC converter topology selection can be left to the discretion of the system designer. Most of the time, the selection of the topology is driven by the characteristics of the control stage. It is important to use a high efficiency topology since the majority of the power conversion (DC of solar array to AC to be fed into the grid and supply energy to appliances) is done by the DC-DC converter. This converter is controlled to provide a rectified sinusoid, which is later fed through a bridge driver to produce an AC signal.

4.3.2.2 50/60 Hz switching bridge

The DC-AC switching bridge sub-system provides switching control at the utility frequency to the 50/60Hz switching bridge that commutates I_{OUT} into an AC current in synchronization with the utility voltage and delivers, to the utility grid, the in-phase AC current I_{AC} with low total-harmonics distortion. The 50/60Hz switching bridge is driven by a set of switching signals derived from the utility voltage through the bridge driver circuit such that the resulting ac current I_{AC} that is converted from the converter output current I_{OUT} is always in-phase with the utility voltage.

4.3.2.3 Average current controller

The average-current regulation sub-system is part of the innermost control loop that requires the fastest control dynamics (or the highest control unity-gain bandwidth) as compared to those of the array-voltage regulation sub-

system since the system requires low harmonics distortion of the rectified sinusoidal current output. Serving as the commanding reference-current signal for the average current regulation sub-system, I_{REF} possesses the rectified sinusoidal waveform that is properly scaled from the rectified utility voltage V_{UTI}.

4.3.2.4 Feed-forward compensated current reference generator

To significantly reduce the variation of the error voltage V_{ERR} at an array power level within a utility voltage range, a feed-forward compensation technique is utilized to continuously update I_{REF} through the feed-forward compensated multiplier from which the output reference current signal I_{REF} is the scaled product of three quantities: V_{ERR}, the instantaneous value of V_{UTI}, and the inverse of the RMS squared value of V_{UTI}. Ensuring low total-harmonic distortion in the in-phase ac current I_{AC}, V_{ERR} must have negligibly small AC ripple content superimposed on its DC operating point. Therefore, the control loop gain frequency response of the solar-array regulation needs to have a relatively low unity-gain bandwidth (such as a 10Hz to 15Hz bandwidth). Consequently, the array-voltage regulation control loop is designed to be insensitive to the fundamental frequency of the array-voltage AC ripple (at 100/120Hz) but only to the DC or much lower frequency components of the solar array voltage. The compensated current reference generator consists of a root-mean-square (RMS) extraction and scaling circuit, signal squarer, and a three-input multiplier. The RMS and scaling

circuit extracts a low-pass filtered signal that has its DC component being proportional to the RMS value of the utility line voltage. The scaled RMS signal must have negligible AC components to ensure low harmonic contents of the controlled sinusoidal current supplying to the utility grid. The scaled RMS signal is squared and subsequently inversed after being fed to the Z input of the three-input multiplier circuit. The inversed squared RMS signal is used as a feed-forward compensation factor, 1/Z, for the three-input multiplier that senses, at the input Y, the rectified utility voltage signal of the rectified sinusoidal wave shape and multiplies V_{ERR} signal as input X by the product of the sensed rectified line-voltage signal (Y) and the feed-forward compensation factor (1/Z). The multiplier outputs the computed result (X*Y/Z) as the reference current signal, I_{REF} that commands the innermost control loop to regulate the DC-DC converter output current accordingly.

4.3.3 Protection circuits

The system will have the following protection circuits:

- Over voltage protection
- Over current protection

4.3.3.1 Over voltage protection

The over voltage protection will function only in Stand-Alone mode of operation because during grid-tie operation, the utility interface subsystem has a higher over voltage control priority. In the stand-alone mode, the

inverter output voltage may be excessive due to an accidental open or near open circuit load condition. Once the over voltage is detected and confirmed, the over voltage protection circuit shuts down the inverter power stage through a pull down transistor such as Q as shown in the system diagram. This shutdown function could be latched and the user reset the inverter system operation back to normal, or the system may be automatically restored after the over-voltage disappears after a certain period. Another over voltage protection supporting mode is to be part of the closed -loop control to regulate the RMS inverter output voltage V_{UTI} at the upper bound of the inverter output voltage. This usually occurs when the system is in the stand-alone mode and the system's load is not heavy enough as compared to the available array peak power. The control loop bandwidth for this inverter voltage-clamping mode is usually around 10 to 15 Hz to minimize total harmonic distortions to the inverter output current. Its phase margin at unity gain crossover frequency should be at least 45 degrees. Similar error amplifier configuration used for the solar array voltage regulation can be applied for the error amplifier used for this active clamping of the inverter output voltage. The control voltage V_{ERR} will be affected by this output voltage clamping function. As a consequence, this voltage-clamping mode causes the maximum power tracking circuit to back off its commanding set point voltage V_{SET} to reduce to its minimum level since the solar array

voltage is increased above its peak power voltage because of the reduced load demand below the array peak power.

4.3.3.2 Over current protection

The over current protection circuit works in current-limiting and over-current shut-down modes of operation. In current-limiting mode, the inverter output current has reached its current limiting threshold level, causing the current-limiting amplifier to actively pull down the control signal V_{ERR} in such a way that the feed-forward compensation produces the appropriate rectified sinusoidal reference current command I_{REF} for the average current controller. The control bandwidth for the current-limiting operation has to be around 10 to 15 Hz to reduce total harmonic distortion to the inverter output current. Its phase margin should be at least 45 degrees. The current limiting threshold reference can be assigned at 120% of rated power. This current-limiting mode protects the overly strong solar array from providing too much power to the load or the power grid. In over-current shut-down mode of operation, the instantaneous inverter current is detected and its immediate RMS value is measured for one cycle of utility frequency. If the instantaneous value of the inverter current crosses the instantaneous current reference threshold, the inverter immediately shuts down. If the immediate RMS current crosses the immediate RMS reference threshold (such as 200% of the full power current) and this over current condition sustains for a certain number of utility cycles (such as 3 cycles), the over current protection circuit

will shut down the inverter and restore the system's operation after a waiting period.

4.3.4 Grid interface

The system should be able to sense the grid voltage and be able to disconnect and reconnect under certain conditions outlined in IEEE 929 standard. The grid should remain disabled until continuous normal voltage and frequency have been maintained by the utility for a minimum of 5 minutes, at which time, the inverter is allowed to automatically reconnect the solar array system to the utility grid. Tripping conditions described in the IEEE 929 standard are summarized as follow:

- Voltage
  - Trip in 0.1 sec for V < 50%
  - Trip in 2 sec for 50% < V < 88%
  - Trip in 2 sec for 106% < V < 137%
  - Trip in 0.03 sec for V > 137%
- Frequency
  - Trip in 0.1 sec for F < 59.3 Hz
  - Trip in 0.1 sec for F > 60Hz

In addition to complying with the IEEE 929 standard, the inverter system must also meet anti-islanding conditions specified in the UL 1741 standard.

CHAPTER FIVE

5 CONCLUSION

5.1 Research summary

The work presented in this document is part of a research directed towards the development of new and expandable solar array power system architectures for space and terrestrial applications. One of these new system architectures includes parallel connected converters utilizing MPPT to maximize efficiency. The other architecture is made of a MPPT based inverter connected to the utility grid. Because of their dependence on a continuously varying solar radiation, photovoltaic arrays present unique challenge to power electronic interface systems designers. These challenges have been addressed through the modeling of all major electrical parameters of a solar array. The modeling presented in this document has shown that solar arrays internal components (current source, diodes, and resistances) are very sensitive to changes in solar irradiance and operating temperature. These changes due to irradiance and temperature lead to significant power loss in solar arrays. These power losses are usually limited by blocking and bypass diodes. The use of blocking and bypass diodes introduces irregularities in the output of solar arrays. To prevent these irregularities from affecting the stability of solar array based power systems, maximum power point tracking techniques have been integrated in the design of theses solar array systems. An immediate application of the maximum power point

tracking technology is the design of grid connected inverter systems, which will not only help consumers save on their electric bill, but will also alleviate stress on a complex utility grid already driven to operate at its maximum capacity.

5.2 Future work

The modeling presented here has been limited to polycrystalline silicon solar arrays because of their popularity. In the future, a more general modeling will be performed to reflect the behavior of not only polycrystalline arrays but also the behavior of arrays made out of any other semiconductor materials. Other issues to address in photovoltaic system design include, but are not limited to:

- Design of efficient battery storage systems to minimize blackout due to extreme shading and during nighttime
- Improvement of existing MPPT techniques
- Development of efficient and cheaper inverter systems for residential and industrial applications
- In-depth study of grid connected inverter systems to bring support and relief to an already saturated power grid.
- Integration of photovoltaic and fuel cell systems as part of an effort to promote renewable energy sources.

Appendices

6 APPENDIX A: I-V data from Daystar curve tracer

E = 479.5W/m² and T = 310.65⁰K, Current in Amperes and Voltage in Volts

Current	Voltage	Current	Voltage	Current	Voltage	Current	Voltage
1.879883	1.46E-02	1.853027	5.170898	1.799316	9.975586	1.564941	15.11719
1.875	0.117188	1.848145	5.258789	1.806641	10.09277	1.569824	15.20508
1.875	0.234375	1.853027	5.34668	1.801758	10.20996	1.538086	15.29297
1.872559	0.336914	1.855469	5.43457	1.791992	10.29785	1.525879	15.38086
1.877441	0.454102	1.838379	5.551758	1.799316	10.41504	1.513672	15.46875
1.872559	0.556641	1.843262	5.698242	1.789551	10.50293	1.51123	15.60059
1.877441	0.644531	1.84082	5.786133	1.799316	10.60547	1.489258	15.68848
1.877441	0.776367	1.84082	5.874023	1.794434	10.75195	1.477051	15.79102
1.872559	0.864258	1.845703	5.961914	1.784668	10.86914	1.455078	15.87891
1.872559	0.966797	1.843262	6.049805	1.794434	10.95703	1.430664	15.98145
1.872559	1.12793	1.845703	6.137695	1.791992	11.07422	1.42334	16.06934
1.872559	1.21582	1.843262	6.225586	1.779785	11.17676	1.386719	16.17188
1.872559	1.333008	1.838379	6.342773	1.777344	11.26465	1.381836	16.27441
1.867676	1.450195	1.84082	6.445313	1.782227	11.36719	1.345215	16.37695
1.865234	1.538086	1.843262	6.577148	1.784668	11.46973	1.320801	16.46484
1.875	1.669922	1.838379	6.679688	1.772461	11.55762	1.306152	16.55273
1.875	1.772461	1.845703	6.782227	1.772461	11.66016	1.264648	16.65527
1.870117	1.860352	1.84082	6.884766	1.77002	11.74805	1.254883	16.77246
1.870117	1.948242	1.845703	7.016602	1.767578	11.83594	1.206055	16.86035
1.867676	2.036133	1.833496	7.104492	1.767578	11.92383	1.193848	16.94824
1.872559	2.124023	1.833496	7.236328	1.762695	12.05566	1.154785	17.06543
1.870117	2.226563	1.835938	7.324219	1.755371	12.14355	1.11084	17.15332
1.872559	2.34375	1.826172	7.426758	1.75293	12.26074	1.069336	17.24121
1.872559	2.475586	1.835938	7.514648	1.743164	12.34863	1.040039	17.3584
1.870117	2.578125	1.831055	7.602539	1.740723	12.43652	0.998535	17.44629
1.870117	2.680664	1.826172	7.705078	1.740723	12.55371	0.97168	17.53418
1.872559	2.797852	1.828613	7.807617	1.73584	12.6709	0.935059	17.62207
1.862793	2.885742	1.828613	7.895508	1.738281	12.75879	0.883789	17.70996
1.867676	2.973633	1.816406	7.983398	1.721191	12.84668	0.866699	17.8125
1.860352	3.061523	1.821289	8.085938	1.723633	12.97852	0.800781	17.90039
1.865234	3.149414	1.828613	8.173828	1.723633	13.08105	0.744629	17.98828
1.862793	3.237305	1.826172	8.276367	1.713867	13.18359	0.708008	18.07617
1.860352	3.383789	1.828613	8.364258	1.706543	13.28613	0.683594	18.16406
1.85791	3.515625	1.828613	8.452148	1.706543	13.40332	0.60791	18.25195
1.870117	3.618164	1.826172	8.540039	1.70166	13.56445	0.578613	18.33984
1.865234	3.75	1.821289	8.62793	1.694336	13.65234	0.544434	18.42773
1.860352	3.852539	1.816406	8.71582	1.679688	13.75488	0.437012	18.55957
1.855469	3.955078	1.816406	8.803711	1.679688	13.84277	0.358887	18.64746
1.860352	4.042969	1.816406	8.891602	1.679688	13.94531	0.32959	18.75
1.855469	4.189453	1.813965	8.979492	1.665039	14.07715	0.266113	18.86719
1.85791	4.291992	1.82373	9.067383	1.652832	14.19434	0.180664	18.95508
1.85791	4.379883	1.818848	9.199219	1.643066	14.28223	0.107422	19.04297
1.85791	4.467773	1.809082	9.287109	1.640625	14.38477	5.62E-02	19.13086
1.862793	4.555664	1.809082	9.404297	1.640625	14.4873	-2.44E-03	19.21875
1.855469	4.658203	1.809082	9.492188	1.623535	14.58984	0	19.24805
1.85791	4.775391	1.804199	9.580078	1.61377	14.70703		
1.853027	4.863281	1.813965	9.711914	1.601563	14.82422		
1.85791	4.980469	1.801758	9.799805	1.584473	14.92676		
1.85791	5.068359	1.806641	9.887695	1.57959	15.0293		

7 APPENDIX B: I-V data from Daystar curve tracer

1 cell is partially shaded

E = 495.3W/m^2 and T = 310.25^{0}K, Current in Amperes and Voltage in Volts

Current	Voltage	Current	Voltage	Current	Voltage	Current	Voltage
0.412598	0	0.302734	4.541016	0.214844	8.964844	0.131836	13.41797
0.405273	7.32E-02	0.305176	4.614258	0.217285	9.038086	0.136719	13.49121
0.407715	0.146484	0.305176	4.6875	0.209961	9.125977	0.126953	13.56445
0.402832	0.219727	0.310059	4.760742	0.209961	9.213867	0.134277	13.6377
0.400391	0.307617	0.302734	4.833984	0.212402	9.287109	0.126953	13.71094
0.400391	0.380859	0.305176	4.907227	0.209961	9.360352	0.119629	13.78418
0.397949	0.454102	0.305176	4.980469	0.209961	9.433594	0.12207	13.85742
0.395508	0.527344	0.297852	5.068359	0.200195	9.506836	0.126953	13.93066
0.405273	0.600586	0.297852	5.15625	0.205078	9.580078	0.126953	14.00391
0.395508	0.673828	0.288086	5.229492	0.205078	9.65332	0.119629	14.07715
0.393066	0.74707	0.283203	5.302734	0.205078	9.741211	0.117188	14.15039
0.393066	0.820313	0.290527	5.390625	0.197754	9.814453	0.119629	14.23828
0.390625	0.893555	0.285645	5.463867	0.197754	9.887695	0.119629	14.31152
0.388184	0.966797	0.285645	5.537109	0.192871	9.960938	0.112305	14.38477
0.385742	1.054688	0.285645	5.610352	0.19043	10.03418	0.112305	14.45801
0.385742	1.12793	0.27832	5.683594	0.197754	10.10742	0.112305	14.53125
0.383301	1.201172	0.285645	5.756836	0.195313	10.18066	0.104981	14.60449
0.390625	1.274414	0.290527	5.830078	0.19043	10.25391	0.104981	14.67773
0.383301	1.347656	0.288086	5.90332	0.183106	10.32715	0.109863	14.75098
0.383301	1.435547	0.280762	5.976563	0.187988	10.40039	0.109863	14.82422
0.375977	1.508789	0.27832	6.049805	0.19043	10.47363	9.52E-02	14.89746
0.378418	1.582031	0.275879	6.123047	0.185547	10.54688	0.100098	14.9707
0.373535	1.655273	0.275879	6.210938	0.183106	10.63477	9.77E-02	15.04395
0.373535	1.728516	0.275879	6.28418	0.180664	10.70801	9.28E-02	15.11719

0.371094	1.801758	0.270996	6.37207	0.178223	10.78125	8.79E-02	15.19043
0.375977	1.889648	0.273438	6.445313	0.175781	10.85449	8.79E-02	15.26367
0.371094	1.962891	0.266113	6.518555	0.175781	10.92773	9.28E-02	15.33691
0.361328	2.036133	0.268555	6.591797	0.180664	11.01563	0.078125	15.41016
0.361328	2.109375	0.268555	6.679688	0.170898	11.08887	8.06E-02	15.4834
0.368652	2.182617	0.261231	6.75293	0.178223	11.16211	8.79E-02	15.55664
0.358887	2.255859	0.263672	6.826172	0.168457	11.23535	8.30E-02	15.62988
0.358887	2.329102	0.256348	6.899414	0.170898	11.30859	7.32E-02	15.70313
0.356445	2.402344	0.256348	6.972656	0.163574	11.38184	7.32E-02	15.77637
0.34668	2.475586	0.249023	7.045898	0.170898	11.45508	8.30E-02	15.84961
0.354004	2.563477	0.253906	7.119141	0.161133	11.52832	7.32E-02	15.92285
0.349121	2.636719	0.256348	7.192383	0.163574	11.60156	6.59E-02	15.99609
0.34668	2.709961	0.253906	7.265625	0.151367	11.68945	7.08E-02	16.08398
0.341797	2.783203	0.246582	7.338867	0.15625	11.7627	6.10E-02	16.15723
0.349121	2.856445	0.246582	7.412109	0.163574	11.83594	6.10E-02	16.23047
0.341797	2.929688	0.249023	7.485352	0.151367	11.90918	6.59E-02	16.30371
0.344238	3.00293	0.246582	7.558594	0.158691	11.98242	6.10E-02	16.37695
0.344238	3.09082	0.246582	7.631836	0.153809	12.05566	5.86E-02	16.4502
0.336914	3.164063	0.241699	7.705078	0.146484	12.12891	5.37E-02	16.52344
0.334473	3.237305	0.236816	7.77832	0.153809	12.2168	5.37E-02	16.59668
0.339356	3.310547	0.241699	7.866211	0.153809	12.30469	5.37E-02	16.68457
0.334473	3.383789	0.234375	7.939453	0.151367	12.37793	5.13E-02	16.75781
0.334473	3.457031	0.236816	8.012695	0.148926	12.45117	5.13E-02	16.83105
0.334473	3.530273	0.234375	8.085938	0.136719	12.52441	4.64E-02	16.9043
0.336914	3.618164	0.231934	8.15918	0.146484	12.6123	4.64E-02	16.97754
0.32959	3.691406	0.236816	8.232422	0.144043	12.68555	4.64E-02	17.05078
0.324707	3.764648	0.229492	8.305664	0.146484	12.75879	0.039063	17.12402
0.319824	3.837891	0.227051	8.378906	0.13916	12.83203	3.66E-02	17.19727

0.32959	3.911133	0.231934	8.452148	0.13916	12.90527	3.42E-02	17.28516
0.319824	3.984375	0.224609	8.525391	0.141602	12.97852	3.17E-02	17.3584
0.314941	4.057617	0.219727	8.598633	0.136719	13.05176	2.44E-02	17.47559
0.317383	4.130859	0.227051	8.671875	0.134277	13.125	1.71E-02	17.54883
0.3125	4.21875	0.224609	8.745117	0.141602	13.19824	2.69E-02	17.62207
0.314941	4.291992	0.219727	8.818359	0.12207	13.27148	9.77E-03	17.69531
0.314941	4.379883	0.212402	8.891602	0.129395	13.34473	4.88E-03	17.79785

8 APPENDIX C: Economic analysis program- MPPT system performance

```
% THIS PROGRAM COMPARES ABILITY OF STAND-ALONE AND MPPT SYSTEMS TO
MEET LOAD DEMAND

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

% Collect irradiance and temperature data from the user.    %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

irrad=xlsread('irra_nov1.xls');

temp=xlsread('temp_nov1.xls');

load_power=xlsread('load_nov1.xls');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

% ARRAY CONFIGURATION

% The solar module is to be configured to produce a maximum

% of P = 500 W at V = 28V @ AM1.5 (E = 1000W/m^2 and T =300K)

% Calculations yield the following:

% Number of cells in Series Ns = 75

% Number of cells in Parallel Np = 1061

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

% Solar Cell Constants                    %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%

q=1.602*10^-19;

k=1.38*10^-23;

k0=-5.729e-7;

k1=-0.1098;

k2=44.5355;

k3=-1.264e4;
```

```
k4=11.8003;

k5=-12.637e3;

k6=2;

k7=0;

k8=1.47;

k9=1.6126e3;

k10=-4.474e-3;

k11=2.303e6;

k12=-2.812e-2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Definition of variables

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


Np = 75;     %This is the number of cells in parallel

Ns = 75;      %This is the number of cells in series

SOC = 38000;     %This is the maximum power the battery can hold

SOCm = SOC;    %This is the maximum power (Watts) the battery is allowed to hold: The battery is initialy charged to this capacity

SOCmin = 0.1*SOC;   %This is the minimum charge the battery is allowed to hold

SOCactual = SOCm;   %The battery is initially charged at full capacity; SOCactual is actual charge of battery

efficiency = 0.9;

factor = 2122/Np;  %To preserve integrity of I-V and P-V curves

for a = 1:(length(irrad))

   v = 28;           %This is the operating voltage of the system

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% I-V and P-V equations                        %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for a=1:(length(irrad))   %a is an index pointing to each irradiance and temperature sample.PLEASE NOTE THAT Irradiance and temperature go in pairs

   Iph(1,a) = k0*irrad(1,a)*(1 + k1*temp(1,a));  %This is the photocurrent generated by a signle cell
```

Is1(1,a) = k2*(temp(1,a))^3*exp(k5/temp(1,a)); %This is the saturation current for the solar cell's PN junctions

Is2(1,a) = k4*(temp(1,a))^1.5*exp(k5/temp(1,a)); %Second Saturation current

i(1,a) = Np*(Iph(1,a) - Is1(1,a)*(exp(q*v/(k*Ns*temp(1,a)))-1)) – Is2(1,a)*(exp(q*v/(k*A*Ns*temp(1,a)))-1)) ; %This is the current generated by the solar array for any voltage v (v = 28V in this case) . The (V+ iRs) term has been dropped because it is too small compared to Rp

p(1,a) = v*i(1,a);

%This is the power generated by the solar array for any voltage v; in this case we choose 28V

end

for a=1:(length(irrad))

Iph(1,a) = k0*irrad(1,a)*(1 + k1*temp(1,a));

%This is the photocurrent generated by a single cell

Is1(1,a) = k2*(temp(1,a))^3*exp(k5/temp(1,a)); %This is the saturation current for the solar cell's PN junctions

wer =0:0.001:35; %35 being the open circuit voltage (to be calculated within the program)

iarray = Np*(Iph(1,a) - Is1(1,a)*(exp(q*wer/(k*Ns*temp(1,a)))-1)) – Is2(1,a)*(exp(q*v/(k*Ns*temp(1,a)))-1)); %This is the current generated by the solar array for any voltage v (v = 28V in this case)

parray = wer.*iarray*factor;

parray_max = max(parray);

. Parray(1,a) = efficiency*parray_max; %get power generated by array for each Irrandiance and Temperature sample and factor in system effieciency

Pload(1,a) = load_power(1,a); %get load power demand at sample time

if (Parray(1,a) < Pload(1,a)) %If power generated by array is less than load demand

if (SOCactual > SOCmin) % and if actual charge of battery is greater than 10% of maximum charge of battery

Pbattery_max(1,a) = SOCactual - SOCmin; %then we compute the maximum charge that can be drawn from the battery

Pload_need(1,a) = Pload(1,a) - Parray(1,a); % and we compute the extra power that the load needs

```
        if (Pload_need(1,a) >= Pbattery_max(1,a))        %if the extra power needed by the load
is greater or equal to the max power that can be drawn from the battery
          Pload_get(1,a) = Pbattery_max(1,a);          %then the power contributed by the
battery is equal to the max power that can be drawn from the battery
        else
          Pload_get(1,a) = Pload_need(1,a);          %otherwise, the battery provide the load
all extra power needed
        end
        SOCactual = SOCactual - Pload_get(1,a);      %Now the battery's charge has
decreased by the amount given to the load
        Psupply(1,a) = Parray(1,a) + Pload_get(1,a);          %Here we compute the power
supplied to the load ( for plotting purposes)
        if (Psupply(1,a)<0)              %Psupply must have a lower limit of zero
          Psupply(1,a) = 0;
        else
          Psupply(1,a) = Psupply(1,a);
        end
      else                              %If actual charge of battery is less of equal to 10% of
maximum battery's charge
        Pload_get(1,a) = 0;                    %then battery does not supply load with any power
        Psupply(1,a) = Parray(1,a);                  %so, power supplied to teh load is whatever
power produced by array
        if (Psupply(1,a)<0)                    %Psupply must have a lower limit of zero
          Psupply(1,a) = 0;
        else
          Psupply(1,a) = Psupply(1,a);
        end
      end
    end
    if (Parray(1,a) == Pload(1,a))                    %if power generated by array is equal to
load demand
      Psupply(1,a) == Parray(1,a);                    %then of course load will consume all
power generated
    end
    if (Parray(1,a) > Pload(1,a))                    %of power generated by array is greater than
load demand
      Psupply(1,a) = Pload(1,a);                    %then load is supplied with whatever power
it needs
      if (Psupply(1,a)<0)              %Psupply must have a lower limit of zero
```

```
            Psupply(1,a) = 0;

        else

            Psupply(1,a) = Psupply(1,a);

        end

        if (SOCactual < SOCm)                    %and if charge on battery is less than maximum
charge allowable

            Pbattery_charge_available(1,a) = Parray(1,a) - Pload(1,a); %then total charge
available to charge battery is computed

            if ((Pbattery_charge_available(1,a) + SOCactual) > SOCm)  %if by adding the total
charge available to charge battery to the actual charge in teh batter, we get a charge greater

                                                 % than the allowable maximum charge on battery

                SOCactual = SOCm;                    % then the battery will be fully charge and
the excess power will be shunted awaytween this available charge and the acutal charge on
battery

            else                                 % if the addition does not yield something greater than
the total charge allowed on battery

                SOCactual = Pbattery_charge_available(1,a) + SOCactual;  %then the new charge
on battery is computed and battery's charge is thereby updated

            end

        else                                     % if actual charge on battery is already maximum
or greater than maximum ( greater than max is not realisitic and will not happen)

            SOCactual = SOCactual;                           %battery's charge is left untouched

        end

    end


 end
plot(Psupply','b')
hold on
plot(Pload', 'r--')
xlabel('Temperature and Irradiance Sample Number')
ylabel('Power (W)')
```

9 APPENDIX D: Economic analysis program- non-MPPT system performance

```
% THIS PROGRAM COMPARES ABILITY OF STAND-ALONE AND MPPT SYSTEMS TO
MEET LOAD DEMAND

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Collect irradiance and temperature data from the user.    %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
irrad=xlsread('irra_nov1.xls');
temp=xlsread('temp_nov1.xls');
load_power=xlsread('load_nov1.xls');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ARRAY CONFIGURATION                               %
% The solar array is to be configured to produce a maximum  %
% of P = 500 W at V = 28V @ AM1.5 (E = 1000W/m^2 and T =300K)%
% Calculations yield the following:                 %
% Number of cells in Series Ns = 75                 %
% Number of cells in Parallel Np = 1061             %
% Calculations have been based on ideal solar array model to %
% simplify calculations                             %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Solar Cell Constants                              %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
q=1.602*10^-19;
k=1.38*10^-23;
k0=-5.729e-7;
k1=-0.1098;
k2=44.5355;
k3=-1.264e4;
k4=11.8003;
```

```
k5=-12.637e3;

k6=2;

k7=0;

k8=1.47;

k9=1.6126e3;

k10=-4.474e-3;

k11=2.303e6;

k12=-2.812e-2;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%

% Definition of variables                          %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%


Np = 75;     %This is the number of cells in parallel

Ns = 75;      %This is the number of cells in series

SOC = 38000;     %This is the maximum power the battery can hold

SOCm = SOC;    %This is the maximum power (Watts) the battery is allowed to hold: The
battery is initialy charged to this capacity

SOCmin = 0.1*SOC;   %This is the minimum charge the battery is allowed to hold

SOCactual = SOCm;   %The battery is initially charged at full capacity; SOCactual is actual
charge of battery

factor = 4244/Np;  %to preserve integrity if I-V and P-V curves

for a = 1:(length(irrad))

   v = 28;           %This is the operating voltage of the system

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%

% I-V and P-V equations                          %

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%

for a=1:(length(irrad))   %a is an index pointing to each irradiance and temperature
sample.PLEASE NOTE THAT Irradiance and temperature go in pairs

   Iph(1,a) = k0*irrad(1,a)*(1 + k1*temp(1,a));   %This is the photocurrent generated by a
signle cell


   Is1(1,a) = k2*(temp(1,a))^3*exp(k5/temp(1,a));   %This is the saturation current for the
solar cell's PN junctions
```

```
Is2(1,a) = k4*(temp(1,a))^1.5*exp(k5/temp(1,a));

  i(1,a) = Np*(Iph(1,a) - Is1(1,a)*(exp(q*v/(k*Ns*temp(1,a)))-1)) - Is2(1,a)*(exp(q*v/(k*Ns*temp(1,a)))-1)); %This is the current generated by the solar array for any voltage v (v = 28V in this case)

  p(1,a) = v*i(1,a);                    %This is the power generated by the solar array for any voltage v; in this case we choose 28V


  Parray(1,a) = p(1,a)*factor;          %get power generated by array for each Irrandiance and Temperature sample

  Pload(1,a) = load_power(1,a); %get load power demand at sample time

  if (Parray(1,a) < Pload(1,a)) %If power generated by array is less than load demand

    if (SOCactual > SOCmin) % and if actual charge of battery is greater than 10% of maximum charge of battery

        Pbattery_max(1,a) = SOCactual - SOCmin;     %then we compute the maximum charge that can be drawn from the battery

        Pload_need(1,a) = Pload(1,a) - Parray(1,a);      % and we compute the extra power that the load needs

        if (Pload_need(1,a) >= Pbattery_max(1,a))     %if the extra power needed by the load is greater or equal to the max power that can be drawn from the battery

          Pload_get(1,a) = Pbattery_max(1,a);       %then the power contributed by the battery is equal to the max power that can be drawn from the battery

        else

          Pload_get(1,a) = Pload_need(1,a);         %otherwise, the battery provide the load all extra power needed

        end

        SOCactual = SOCactual - Pload_get(1,a);     %Now the battery's charge has decreased by the amount given to the load

        Psupply(1,a) = Parray(1,a) + Pload_get(1,a);       %Here we compute the power supplied to the load ( for plotting purposes)

        if (Psupply(1,a)<0)             %Psupply must have a lower limit of zero

          Psupply(1,a) = 0;

        else

          Psupply(1,a) = Psupply(1,a);

        end

    else                        %If actual charge of battery is less of equal to 10% of maximum battery's charge

        Pload_get(1,a) = 0;                     %then battery does not supply load with any power

        Psupply(1,a) = Parray(1,a);                %so, power supplied to teh load is whatever power produced by array

        if (Psupply(1,a)<0)                     %Psupply must have a lower limit of zero
```

```
            Psupply(1,a) = 0;
         else
            Psupply(1,a) = Psupply(1,a);
         end
      end
   end
 if (Parray(1,a) = Pload(1,a))                          %if power generated by array is equal to load
demand
      Psupply(1,a) = Pload(1,a)                          %then of course load will consume all power
generated
   end
   if (Parray(1,a) > Pload(1,a))                          %of power generated by array is greater than
load demand
      Psupply(1,a) = Pload(1,a);                          %then load is supplied with whatever power
it needs
      if (Psupply(1,a)<0)                    %Psupply must have a lower limit of zero
            Psupply(1,a) = 0;
      else
            Psupply(1,a) = Psupply(1,a);
      end
      if (SOCactual < SOCm)                      %and if charge on battery is less than maximum
charge allowable
         Pbattery_charge_available(1,a) = Parray(1,a) - Pload(1,a);  %then total charge
available to charge battery is computed
         if ((Pbattery_charge_available(1,a) + SOCactual) > SOCm)  %if by adding the total
charge available to charge battery to the actual charge in teh batter, we get a charge greater
                                                  % than the allowable maximum charge on battery
            SOCactual = SOCm;                          % then the battery will be fully charge and
the excess power will be shunted awaytween this available charge and the acutal charge on
battery
         else                                  % if the addition does not yield something greater than
the total charge allowed on battery
            SOCactual = Pbattery_charge_available(1,a) + SOCactual;   %then the new charge
on battery is computed and battery's charge is thereby updated
         end
      else                                          % if actual charge on battery is already maximum
or greater than maximum ( greater than max is not realisitic and will not happen)
         SOCactual = SOCactual;                              %battery's charge is left untouched
      end
  end
```

```
end
plot(Psupply','g')
hold on
plot(Pload', 'r--')
xlabel('Temperature and Irradiance Sample Number')
ylabel('Power (W)')
```

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