PHOTOVOLTAIC EMULATOR ADAPATABLE TO IRRADIANCE, TEMPERATURE AND PANEL-SPECIFIC I-V CURVES

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TITLE: Photovoltaic Emulator Adaptable to Irradiance, Temperature
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ABSTRACT

Photovoltaic Emulator Adaptable to Irradiance, Temperature and Panel Specific I-V Curves

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This thesis analyzes the design and performance of a photovoltaic (PV) emulator. With increasing interest in renewable energies, large amounts of money and effort are being put into research and development for photovoltaic systems. The larger interest in PV systems has increased demand for appropriate equipment with which to test PV systems.

A photovoltaic emulator is a power supply with similar current and voltage characteristics as a PV panel. This work uses an existing power supply which is manipulated via Labview to emulate a photovoltaic panel. The emulator calculates a current-voltage (I-V) curve based on the user specified parameters of panel model, irradiance and temperature. When a load change occurs, the power supply changes its current and voltage to track the calculated I-V curve, so as to mimic a solar panel. Over 250 different solar panels at varying irradiances and temperatures are able to be accurately emulated. A PV emulator provides a controlled environment that is not affected by external factors such as temperature and weather. This allows repeatable conditions on which to test PV equipment, such as inverters, and provides a controlled environment to test an overall PV system.

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Chapter 1 : Introduction

1.1 Need For PV Emulator

There has been tremendous growth in installed photovoltaic (PV) systems in the past decade. Utility scale photovoltaic systems installations have had an average annual growth rate of 102% from 2004 through 2009 [1]. Fig. 1-1 shows the growth of the solar industry from 1995 to 2009. The increased penetration of PV systems has caused new problems for photovoltaic equipment manufacturers. Some issues that are faced with the increased PV penetration are unintended islanding, the role of photovoltaics in power system voltage regulation, coordination with existing protection systems and transient stability during a fault ride through [2]. A more sophisticated way of testing PV equipment is needed.

Figure 1-1: Worldwide Solar PV Installed Capacity [1]

Currently, when testing photovoltaic equipment such as an inverter, the inverter is either directly connected to real PV modules or a programmable power supply is used. The problem with connecting to a real PV module is that its electric characteristics are constantly changing based on a variety of factors including irradiance and temperature.

This constant fluctuation makes it difficult to isolate the variables affecting the PV hardware. Conversely, when using programmable power supplies the voltage and current are set to static values that do not change. The programmable power supply does not react similarly enough to a real PV module. A PV emulator is a nice medium between using a real PV module and using a programmable power supply. PV emulators simulate a PV module more accurately than the programmable power supply and provide a more controlled environment with which to test PV hardware when compared to a real PV module.

A controlled environment to test photovoltaic equipment is difficult since outside conditions are always changing. A PV panel's electrical characteristics will change based on a variety of factors including the amount of irradiance received, temperature of the panel, and the material used to make the PV panel. A PV emulator will simulate the current and voltage characteristics of a photovoltaic panel under these various conditions, but will provide more control to allow better testing of PV equipment. Within the PV emulator the panel type, irradiance and temperature is user specified. For example, to determine how the PV system will react to a Sunpower 205-BLK module at an irradiance of 500W/m^2 at 20°C , the user will specify these parameters to the PV emulator. The user can then individually change either the irradiance or temperature and determine how these factors affect the piece of PV hardware being tested. Having consistent electrical characteristics will allow the analysis and optimization of PV systems [3]. The increased control that a PV emulator provides allows for more sophisticated measurements of maximum power point tracking (MPPT) algorithms of inverters, as well as their total harmonic distortion (THD) and power factor (PF) control under various conditions.

Hundreds of solar panels are available for purchase. It would be prohibitively expensive to buy each type of panel and test individually. A PV emulator would be able to simulate many different types of solar panels, under various temperature and weather conditions. By simply changing the PV panel type within the emulator, a new solar panel can be simulated without the hassle of purchasing a new PV panel and connecting the panel to the PV hardware to be tested.

1.2 Applications

A wide range of PV emulators have been developed over the years. Several different hardware implementations and control algorithms have been used to emulate a solar panel. These PV emulators were developed using custom built power supplies or modified versions of commercially available power supplies. Most of these PV emulators take a mathematical model of a solar cell which is based on specific cell parameters and calculate the emulator's voltage and current characteristics based on this model. The mathematical model approach allows for the simulation of a solar panel under various irradiances and temperatures.

Previous hardware implementations for a PV emulator include the use of op-amps to create the control system for the PV emulator [4]. Others utilize a DSP board and a digital control system to control the PV emulator [5]. Some emulators have used a single reference solar cell and a current amplifier to emulate a whole PV module [6]. Some have used a look-up-table method where discrete values of the solar panel's current and voltage values are stored within memory. These points are linearly interpolated to control the PV emulator [7]. This thesis will take an off-the-shelf power supply and use it to emulate a solar panel.

PV emulators have been developed for commercial and educational purposes. Some of these emulators are modular so that they can be connected in series or in parallel to further simulate a whole PV array system. PV emulators have also been used to test the photovoltaic systems on space satellites [8]. Due to the extreme conditions in outer space, designers would like to quickly and accurately simulate how their PV system will behave in space. Thus PV emulators are their best and most practical option.

1.3 Solar Panel Physics

Photovoltaic cells produce electrical power through the photoelectric effect. They convert light energy into electrical energy [9] . A solar cell is essentially a diode, which is composed of a p-type and an n-type semiconductor sandwiched together, as seen in Fig. 1-2. There is a wide range of doping elements used to compose a solar cell. The choice of these doping elements affects how efficient the solar cell is at converting light energy into electrical energy and also determines how expensive the solar cell is to manufacture. The type of doping elements used to create different types of solar cells will be discussed in a later section.

Figure 1-2: Solar Cell P-N Junction

Fig. 1-3 shows the electronic band structure of a PV cell. Since solar cells are composed of semiconductors there is a small band gap between the conduction and valence bands. Equation 1.1 shows the photon energy of specific wavelength of light and Equation 1.2 shows the minimum amount of energy needed for an electron to jump from the valence band into the conduction band [10]. A photon with energy larger than the bandgap must strike the solar cell in order to remove the electron from the cell and produce current.

Figure 1-3: Conduction and Valence Band

$$\frac{hc}{\lambda} = \phi + eV \quad (1.1)$$

$$\lambda_{\min} = \frac{hc}{\phi} \quad (1.2)$$

Where

E is the photon energy

h is Planck's Constant ($6.626068 \times 10^{-34} \text{ m}^2 \text{ kg / s}$)

c is the speed of light in a vacuum ($3 \times 10^8 \text{ m/s}$)

λ is wavelength

ϕ is the work function of photo-electric threshold

$\lambda_{\min}$ is minimum wavelength to remove an electron from the material

Fig. 1-4 shows the Shockley-Queisser Limit. It is the maximum possible efficiency of a solar cell based on bandgap. When the bandgap is too high, not enough photons have the amount of energy necessary for electrons to cross the bandgap. When the bandgap is too low, electrons are easily able to jump from the conduction band to the valence band. The photons however, have much more energy than necessary for the electrons to jump the gap and the remaining energy is lost to relaxation of electrons to the band edges and energy lost in the tradeoff between low radiative recombination versus high operating voltage as seen in Fig. 1-5 [11].

Figure 1-4: Shockley-Queisser Limit [12]

Figure 1-5: Breakdown of Shockley-Queisser Limit [13]

From Fig. 1-5, the black portion is the Shockley-Queisser limit and the green portion is losses associated to relaxation of electrons to the band edges of the P-N junction. Relaxation of electrons to the band edges occurs when a photon with more energy strikes the cell with a much lower bandgap. For a 1eV bandgap material, the same electron-hole pair will be created if either a 3eV photon or 1.01eV photon strikes the solar cell. The extra 2eV from the 3eV photon is wasted. The blue portion of the curve is related to power losses due to electron-hole recombination. The pink portion is power wasted from photons that are below the bandgap. Power is wasted because it is energy not being absorbed by the solar cell material. Note that the Shockley-Queisser Limit is based on a single P-N junction tuned to absorb visible light. The limit can be exceeded by using tandem solar cells that will be described in a later section [13].

Fig. 1-6 shows the solar radiation spectrum for direct light at the top of the atmosphere and at sea level. A solar cell is designed to absorb a portion of this spectrum. As seen from the figure, a large amount of spectral irradiance is available in the visible spectrum (390nm-700nm) as opposed to UV (>750nm) and infrared light (<390nm). Solar cells are designed to absorb as much of the visible spectrum as

possible. The visible spectrum has the most spectral irradiance compared to other types of light and therefore solar cells should be optimized to harvest this type of light in order to convert the most amount of light energy into electrical energy [14].

Figure 1-6: Solar Radiation Spectrum [15]

Temperature is a large factor in the performance of a solar cell. The maximum allowable voltage across a solar cell is equal to the bandgap voltage, this occurs when the temperature of the cell is at 0 Kelvin [11]. As temperature increases, the bandgap and voltage across the cell decreases. Since the bandgap has decreased, it takes less light energy to free electrons from the solar cell and there will be a slight increase in the output current. However, a more drastic decrease in the output voltage occurs with increasing temperature and the overall output power of the solar cell decreases. A solar cell's output power increases as irradiance increases and temperature decreases. Therefore ideal locations for PV panels are in cold climates that receive lots of sunlight [16].

Chapter 2 : Thesis Objectives

The goals of this thesis are to:

1. Develop an understanding of the factors affecting PV cell performance
2. Calculate a current-voltage(I-V) curve based on these factors
3. Control an off-the-shelf power supply to follow the calculated I-V curve
4. Determine the speed and accuracy of the PV emulator

A diagram for the hardware implementation for the PV emulator is illustrated in Fig. 2-1. It consists of a computer with Labview and a power supply. Labview will receive user specified parameters such as panel type, irradiance, and temperature, and will calculate the I-V curve for the power supply to follow. Labview will be used to control the power supply for its relative ease to communicate with hardware devices, ease of constructing sophisticated graphical user-interfaces, and extensive library for performing specific array manipulations and mathematical calculations.

Figure 2-1: PV Emulator Hardware Setup

PV panel manufacturer I-V curves will be compared to those created by the emulator to evaluate the accuracy of the calculated curves. To test that the power supply is able to follow the I-V curve correctly, a power decade resistor box is connected to the power supply. The resistance will be varied from a large resistance to a small resistance to have the PV emulator sweep through the I-V curve. The speed at which the emulator is able to change its current and voltage based on a change in load will need to be minimized as much as possible to emulate the real-time response of an actual solar panel.

The PV emulator will eventually be used to test future senior projects and master's theses that deal with photovoltaics and serve as an aid for students to learn about the electrical characteristics of solar panels. The emulator must be user friendly to give the user an intuitive feel as to how a real solar panel would react to changes in temperature and irradiance. Purchasing a commercially available emulator will be prohibitively expensive, but developing a custom built PV emulator from an off-the-shelf power supply and a computer with Labview will provide a relatively affordable PV emulator for use in future renewable energy labs.

Chapter 3 : Modeling a Solar Panel

3.1 Basic Diode Model

The goal of the photovoltaic emulator is to have its output current and output voltage follow the diode equivalent model as closely as possible. From Fig. 3-1, several models can be made with increasing complexity to model a PV module. The PV emulator will be using the simplified model to simulate a solar panel. The practical model will not be used since shunt resistance is negligible in modules and calculations become more complex for calculating output current and voltage. Equations 3.1-3.7 are the basic equations that were used to model a solar cell [17].

Figure 3-1: Solar Cell Model

$$I = I_{ph} - I_d - I_{Rsh} \quad (3.1)$$

Expanding upon I_{ph} , I_d , and I_{Rsh} yields Eq 3.2:

$$I = I_o e^{\frac{V_{oc}}{n_s V_t}} + \frac{V_{oc}}{R_{sh}} - I_o \left(e^{\frac{q(V+IR_s)}{n_s V_t}} - 1 \right) - \frac{(V+IR_s)}{R_{sh}} \quad (3.2)$$

where:

$$V_t = \frac{AkT_{stc}}{q} \quad (3.3)$$

$$I_o = \left(I_{sc} - \frac{V_{oc} - I_{sc} R_s}{R_{sh}} \right) e^{-\frac{V_{oc}}{n_s V_t}} \quad (3.4)$$

$$I_{ph} = I_o e^{\frac{V_{oc}}{n_s V_t}} + \frac{V_{oc}}{R_{sh}} \quad (3.5)$$

$$I_d = I_o \left(e^{\frac{q(V+IR_s)}{n_s V_t}} - 1 \right) \quad (3.6)$$

$$I_{Rsh} = \frac{(V+IR_s)}{R_{sh}} \quad (3.7)$$

where:

R_s is the series resistance (Ω)
 R_{sh} is the shunt resistance (Ω)
 V_t is the thermal voltage (V)
 k is the Boltzmann constant (J/K)
 q is the electron charge (C)
 T : is the cell temperature ($^{\circ}\text{C}$)
 T_{stc} : is the cell temperature at standard test conditions($^{\circ}\text{C}$)
 n_s : is the number of series cells in the module
 A : is the ideality factor of the diode
 I_{ph} : is the photogenerated current (A)

From equation 3.1, the current leaving the solar panel (I) is equal to the photogenerated current (I_{ph}) minus the diode current (I_d) and shunt resistance (I_{rsh}). The photogenerated current is the current created from photons striking the PV cell and releasing electrons from the material. Equation 3.2 is the expanded form of equation 3.1 and is the general equation used to control the PV emulator. Equations 3.3 through 3.7 are calculated coefficients that compose equation 3.2. Fig 3-2 is the calculated I-V curve obtained when equation 3.2 is plotted as a function of the solar panels output current and output voltage [17].

Figure 3-2: Example I-V Curve

Important points on the I-V curve are the open circuit voltage, short-circuit current, and maximum power point. The open circuit voltage is the maximum voltage that the module can output and the short-circuit current is the maximum current that the module can output. The maximum power point is the largest amount of power that the PV panel can deliver. The power of the I-V curve is obtained through Ohms law ($P = V \cdot I$). Since the short-circuit current is at 0V, there is no power output from the PV

module at I_{sc} . Similarly, at V_{oc} , the open-circuit voltage, the associated current is 0A and therefore there is no power output from the PV module. At the maximum power point both the voltage and current are maximized to provide the largest amount of power from the PV module. V_{mp} is the voltage value at P_{max} and I_{mp} is the current value at P_{max} . Depending on the load connected to the PV panel, the module voltage and current will fall somewhere in between a curve created between the 3 points of I_{sc} , P_{max} , and V_{oc} .

3.2 Increasing Model Complexity

To more accurately replicate a solar panel, several factors have to be included into the model. These factors are irradiance, cell temperature, series resistance, and the diode ideality factor. These parameters affect the shape of the I-V curve which will be discussed further in this section. The photogenerated current (I_{ph}) is affected by both irradiance and temperature as seen in equation 3.8 [18]:

$$I_{ph} = (I_{sc} + K_1(T_c - T_c^{ref})) \frac{G}{G_{nom}} \quad (3.8)$$

where:

I_{sc} is the short circuit current (A)
 K_1 is the short circuit current temperature coefficient (A/°C)
 T_c is the cell temperature (°C)
 T_c^{ref} is the cell reference temperature (Typically 25 °C)
 G is the solar irradiance (W/m²)
 G_{nom} is the nominal solar irradiance (1000 W/m²)

Equation 3.8 is similar to the photogenerated current in equation 3.5. However, this equation shows the relationship between temperature and irradiance to the photogenerated current. As seen from the equation, as temperature increases I_{ph} will increase slightly due to K_1 , the short-circuit current temperature coefficient. Depending on the solar panel type, K_1 will range from 2μA/°C to 4mA/°C. So for a short-circuit current temperature coefficient of 4mA/°C, and temperature of 50°C, there will only be a

100mA increase in photogenerated current. Irradiance however affects I_{ph} much more dramatically. From the equation, the photogenerated current will scale proportionally to the irradiance. Equation 3.8 affects Equation 3.2, the equation used to create the I-V curve, by altering the photogenerated component of the equation based on temperature and irradiance.

Figure 3-3: Effect of Irradiance on I-V Curve

Fig. 3-3 shows the I-V curve of a module being exposed to different amounts of irradiance. The short circuit current is greatly affected by changes in irradiance whereas the open circuit voltage remains somewhat constant. The current scales proportionally as described previously. When looking at the diode equivalent model, as more light strikes the solar cell a larger current is outputted by the current source which represents the photogenerated current as seen in Fig. 3-1.

Temperature affects the diode saturation current (I_0). As the temperature changes, the value of I_0 will change accordingly. This affects equation 3.2, the overall equation to model the PV module. Equations 3.9 and 3.10 show how temperature affects I_0 [18]:

$$I_0(T) = I_0(T_{stc}) \left(\frac{T}{T_{stc}} \right)^{\frac{3}{n}} e^{\frac{qV_{oc}(T_{stc})}{nk \left(\frac{1}{T} - \frac{1}{T_{stc}} \right)}} \quad (3.9)$$

where:

$$I_0(T_{stc}) = \frac{I_{sc}(T_{stc})}{\left(e^{\frac{qV_{oc}(T_{stc})}{nkT_{stc}}} - 1 \right)} \quad (3.10)$$

V_q is the band gap voltage (V)
 n is the diode ideality factor

Fig. 3-4 shows the effect of temperature on a solar cell. From Fig. 3-4, it can be seen that the open circuit voltage is greatly affected by changes in temperature whereas the short circuit current increases slightly as previously discussed. Table 3-1 shows typical diode ideality factors and band gap voltages for various solar cell materials. Panels with large band gap voltages are affected more by changes in temperature than panels with smaller band gap voltages. This is due to the differing length in bandgap as discussed in the previous solar cell physics section. A large band gap voltage will cause an even larger spread between the open circuit voltages as temperature increases.

Figure 3-4: Effect of Temperature on I-V Curve

Table 3-1: Diode Ideality Factor and Band Gap Voltage [14]

Diode Ideality Factor (n) and Band Gap Voltage (E _g)		
Cell Type	n	E _g
Mono-Si	1.026	1.12
Poly-Si	1.025	1.14
a-Si:H	1.8	1.65
a-Si:H tandem	3.3	2.9
a-Si:H triple	3.09	1.6
CdTe	1.5	1.48
CIS	1.5	1
AsGa	1.3	1.43

Figure 3-5 shows the effect of changing the diode ideality factor (n). As the diode ideality factor increases, a longer bend in the knee of the I-V curve occurs. Also maximum power point on the I-V curve begins to decrease. The diode ideality factor affects the diode saturation current (I_0) as seen in equation 3.9. The range of the ideality factor is from 1 to 2, where $n=1$ is an ideal diode, and $n=2$ is a non-ideal diode. As the ideality factor approaches 2, more defects are introduced into the material and more recombination (electron/hole elimination) occurs [19]. As seen in Table 3-1, different

solar cell materials have differing diode ideality factors. The materials with diode ideality factors greater than 2 are multi-junction cells. These types of cells have multiple p-n junctions layered on top of each other instead of a single p-n junction. This increases the value of the ideality factor.

Figure 3-5: Effect of Diode Ideality on I-V Curve

R_s is the series resistance between cells. The series resistance affects the diode saturation current as seen in equation 3.4. Fig. 3-6 shows the effects of changing R_s on the module's I-V curve. As the series resistance is increased, the slope between the voltage at maximum power (V_{mp}) and the open circuit voltage (V_{oc}) decreases. Increasing the series resistance makes the solar cell appear less like an ideal voltage source at higher cell voltages. Note that the open circuit voltage stays the same as the series resistance changes.

Figure 3-6: Effect of Series Resistance on I-V Curve

3.3 PV Power

A PV modules' output power can be obtained by multiplying the output voltage to its corresponding output current ($P=V \cdot I$). A power curve can be obtained by plotting the calculated power versus voltage. Fig. 3-7 shows a typical power curve for a PV panel. Inverters generally want to harvest energy at the solar panels' maximum power point using a tracking algorithm so that they can harvest the most amount of power from the solar panel. Fig. 3-7 further shows an I-V curve with its maximum power point along with the equivalent power curve with its maximum power point. The largest value on the power curve is equivalent to the maximum power point on the I-V curve. From Fig. 3-7 the red asterisk denotes where the maximum power point is on the power curve and on the I-V curve. If an inverter is not operating its tracking algorithm at the maximum power point, it is not maximizing the amount of electrical energy it could harvest[9].

Figure 3-7: PV Power of a Solar Cell

Like the I-V curve, the power curve is a way to look at the output characteristics of a PV module. Fig. 3-8 shows the effect of irradiance upon the power curve and Fig. 3-9 shows the effect of temperature on the power curve. As the irradiance striking the cell decreases, the power curve will scale proportionally. The maximum power point of the solar cell will also change [9]. If an inverter is connected to the PV module, its tracking algorithm needs to account for the change in the maximum power point in order to harvest the most amount of energy.

Figure 3-8: Effect of Irradiance on Power Curve

Figure 3-9: Effect of Temperature on Power Curve

3.4 Fill Factor

Apart from efficiency, fill factor (FF) is another key parameter when evaluating a solar cell's performance. Fill factor is the ratio of the actual maximum obtainable power, ($V_{mp} \times I_{mp}$) to the theoretical power, ($I_{sc} \times V_{oc}$). Typical commercial solar cells have a fill factor greater than 0.70. Lower grade cells, have a fill factor between 0.4 and 0.7 [20]. The fill factor can be determined graphically as seen in Fig. 3-10. Mathematically the fill factor is defined as

$$FF = \frac{P_{max}}{P_{Theoretical}} = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \quad (3.11)$$

Figure 3-10: Fill Factor of a Solar Cell

The shunt and series resistance losses affect the amount of fill factor. It determines how square the I-V curve of a solar cell is. A cell with 100% fill factor has little to no resistive losses. Solar cells can be thought of as a current source at low output voltages, where a constant current is outputted over a varying load voltage. As the output voltage is increased and the dark saturation current begins to dominate the output characteristics of the panel, and the panel will behave more like a voltage source. The panel will provide a relatively constant voltage for a given load current.

The model that has been discussed is for a single photovoltaic cell. A photovoltaic module is composed of a series-parallel combination of individual photovoltaic cells [18]. Fig. 3-11 shows the diode equivalent model of an entire PV module. Similar to Fig. 3-1, the practical model includes both series and shunt resistances, while the simplified models only accounts for the series resistances. The ideal does not account for either the series or shunt resistance losses. Adding cells in series increases the overall voltage of the module as seen in Fig. 3-12 and adding cells in parallel increases the amount of overall current of the module as seen and Fig. 3-13. When adding cells in series it can be thought of like adding batteries in series where the voltages of each individual battery will add together. When adding cells in parallel it can be thought of like adding batteries in parallel where the currents of each individual battery will add together.

Figure 3-11: Solar Panel Diode Model

Figure 3-12: Effect of Adding Cells in Series

Figure 3-13: Effect of Adding Cells in Parallel

3.5 Panel Types

There are several different types of solar panel materials available. The main types of solar cells are thin film, crystalline silicon, and multijunction cells [9]. These various types of solar cells will be simulated with the PV emulator. Background information for each type of cell is needed to show how each type of technology creates a different I-V curve. The advantages and disadvantages of each type of solar cell are outlined below.

3.5.1 Thin Film

Thin films have the lowest efficiencies compared to other types of cells, the tradeoff however is that they are the cheapest type of solar cell to manufacture [9]. A layer of thin film ranges from a few nanometers to tens of micrometers. The cheaper price of these cells is a result of the smaller amount of material needed to make them as well as the manufacturing techniques used to make them. There are several different chemistries used to make thin film solar panels. Below is a list of some materials used to make thin film solar cells

- Amorphous Silicon
- Polycrystalline Silicon
- Nanocrystalline Silicon
- Cadmium-Telluride
- Copper-Indium
- Gallium-Arsenide.

3.5.2 Crystalline Silicon Cells

There are two types of crystalline silicon cells. They are monocrystalline and polycrystalline silicon cells. Monocrystalline silicon cells are made from single-crystal wafers similar to many high-end integrated circuits. Monocrystalline cells are relatively expensive to manufacture, however they provide a high efficiency rate of converting light energy to electrical energy [9]. Polycrystalline silicon cells are cast from ingots of silicon. They are less expensive to produce than monocrystalline cells but are less efficient.

3.5.3 Multijunction Cells

Multijunction cells are composed of several P-N junctions stacked on top of one another. Each layer is able to convert a specific region of sunlight into electricity. By splitting up the spectrum of light that is converted into electricity, higher efficiencies are achieved. Each layer is connected in series with the next and therefore the same current is transmitted through each layer. Consequently, the bandgaps that compose each layer must be chosen so that the current from each layer match [21]. The increase in layers adds more steps in the manufacturing process, and therefore multijunction cells are the most expensive to produce. They are generally used for specialized purposes such as space applications or for light concentrators.

Fig. 3-14 shows efficiencies for various solar cell types. Multi-junction cells currently have the highest efficiencies followed by crystalline cells and then thin-film technologies. New emerging solar cells such as inorganic cells are relatively new. However there is plenty of upside to these and they could potentially provide either a cheaper or more efficient alternative to existing solar cell technologies.

Figure 3-14: Efficiencies of Various Solar Technologies [22]

Chapter 4 : Power Supply

4.1 Power Supply Background Information

Since the power supply is the main piece of hardware, a basic understanding of how a power supply operates is essential. DC power supplies have two modes of operation, continuous voltage mode and continuous current mode [23]. As seen in Fig.4-1, when in continuous voltage (CV) mode the power supply will output a constant voltage, at varying currents. The amount of current is determined by the load connected to the power supply.

Figure 4-1: Continuous Voltage Mode of a Power Supply

Fig. 4-2 shows the power supply in continuous current (CC) mode. In this mode the power supply outputs a specified amount of current at various voltages. The outputted voltage is determined by the load.

Figure 4-2: Continuous Current Mode of a Power Supply

As seen in Fig. 4-3, the power supply will switch between continuous current mode and continuous voltage mode depending on the resistance connected to the power supply. The point at which the power supply switches from CV to CC is determined by the maximum supply current which is specified by the user. If the load requires a larger amount of current than the maximum supply current, the power supply will enter CC mode and limit the current to the maximum supply current.

Figure 4-3: Operating Between CC and CV Mode

4.2 Power Supply Selection

A power supply was selected so that it will be able to emulate most solar panels, be inexpensive and have the capability to interface with a computer. Based on these requirements the BK Precision 9153 power supply was selected. This power supply's maximum output voltage is 60V and maximum output current is 9A. Solar panels with open-circuit voltages above 60V or short-circuit currents above 9A cannot be emulated. Based on the Sandia PV database, 284 different panels will be able to be emulated. The power supply's USB interface allows for uncomplicated communication within Labview between the computer and power supply.

Figure 4-4 shows the hardware implementation of the PV emulator. The top piece of hardware is the BK Precision 9153 Power supply. It is connected to a power resistor decade box. The decade box is varied from a large resistance to short circuit. This tests if the algorithms developed in Labview will control the power supply well enough to mimic a solar panel and follow the calculated I-V curve from the open-circuit voltage to the short-circuit current.

Figure 4-4: PV Emulator Hardware Setup

4.3 Why a DC Electronic Load Should Be Avoided

A DC electronic load should be avoided. A power resistor decade box is the preferred method to test the PV emulator. A DC electronic load has three modes of operation, constant current, constant voltage, and constant resistance. Constant current mode and constant voltage mode operate similarly to the power supply's constant current and constant voltage mode, but instead of sourcing voltage or current, the DC load will sink a certain amount of voltage or current. When the electronic load is in constant resistance mode, the load senses both voltage and current. It adjusts both voltage and current to create a constant resistance based on Ohms law, $R = V/I$ as seen in Fig. 4-5.

Figure 4-5: Resistance Mode of Power Supply

The output from the power supply could potentially oscillate between constant current voltage mode and constant current mode if it were connected to a DC load. When the resistance of the DC load is low enough to exceed the maximum supply current, the power supply enters continuous current mode. The power supply's output voltage will decrease because it is now be in CC mode. The DC load will then sense this change in voltage and will decrease the load current to maintain the same resistance value. The power supply will in turn sense this drop in load current and will enter continuous voltage mode where voltage the returns to its original value. The DC load will again sense the increase in voltage and increase load current to maintain the same resistance value. The power supply will repeat this loop and will switch between constant current mode and constant voltage mode. The output current and output voltage will oscillate as the power supply and load try to match what the other demands. This oscillation can be minimized or even eliminated if the selected power supply is drastically faster than the voltage and current sensing of the DC load.

Chapter 5 : Design

The basic algorithm to model a photovoltaic module was obtained from an existing model that had been developed in Matlab [17]. The algorithm obtained from the Matlab code was modified to allow the emulation of various solar panels from the Sandia PV database in Labview. It retrieves specific PV panel parameters such as the panel material, V_{oc} , I_{sc} , and diode ideality. These parameters are used by the mathematical model to create the I-V curve for the PV emulator. The Labview model has the ability to change the I-V curve based on the simulated irradiance and temperature as well as the specific PV model type. Below are flowcharts showing how the algorithm of the PV emulator operates. Figure 5-1 shows the basic algorithm on calculating the I-V curve.

The inclusion of the series resistance parameter into the diode model makes the solution to the panel current iterative. Newton's method is used for its fast convergence to iteratively solve for the output current [24]. The algorithm calculates a single output current based on a desired voltage. The full I-V curve is then produced by creating a voltage array which contains elements from 0 Volts to the open-circuit voltage and the PV model is then used to calculate an array of corresponding currents. The equations from Chapter 2: Modeling A Solar Panel were used to calculate the current values based on a voltage. The calculated I-V curve, which is an array composed of discrete voltages and their corresponding current values, will be used by the main PV emulator algorithm to control the power supply's output characteristics.

Figure 5-1: Algorithm to Calculate I-V Curve

5.1 Power Supply Algorithm Design

There were two algorithms that were considered to control the power supply. One was using an I-V curve look-up-table and another involves finding an intersection point between a resistive load line and the I-V curve. These two algorithm schemes were personally developed. The final algorithm chosen used was the resistive line method. Both methods are described below.

5.1.1 Look-Up-Table Method

A table with all the voltage and current values to form the I-V curve would be used to control the power supply. With this method, the current outputted by the power supply is measured. This current value is found in the look-up-table along with the corresponding voltage. The power supply is then set to this new voltage. Sensing the current and changing the voltage is done continually to mimic the output characteristics of a solar panel. Problems occur with this method when the current is near the linear constant current region. When the PV emulator is approaching the linear constant current region and the load current increases momentarily above the short-circuit current, the power supply will measure a current that is not within the look-up-table. The algorithm will search for the largest value of current in its LUT, which is the short circuit current and try to adjust the voltage to 0V. The look-up-table method works well when operating well below the short-circuit current, but fails to provide the correct output once the PV emulator operates near this region. A flowchart of the look-up-table method can be seen in Fig. 5-2.

Figure 5-2: Flow Chart of Look-Up-Table Method

5.1.2 Resistance Line Method

Similarly to the look-up-table method, a table with all the voltage and current values to form the I-V curve would be used to control the power supply. However, instead of measuring the outputted current and using the LUT to find the corresponding voltage, a line is drawn from the origin to the measured current value. The slope of this line is equal to the resistance connected to the power supply. The intersection point between the resistance line and the I-V curve is the operating point. An algorithm is used to find this intersection point and the power supply's voltage is changed accordingly. Since this method is not looking for a specific current to what is being measured from the power supply, it does not have the instability that the look-up-table method has. It is able to operate in all regions of the I-V curve, from the linear current region to the maximum power point region, to the voltage source region. The resistance line and I-V curve must have a large amount of data points so that when the two lines intersect there is a single point where they intersect. The resistance line and I-V curve are created using 50,000 data points so that an accurate intersection point can be made. Fig 5-3 shows the algorithm of the resistance line method.

Figure 5-3: Flow Chart of Resistance Line Method

5.2 Main Algorithm

Figure 5-4 shows the main algorithm of the PV emulator. It initializes the power supply at the beginning, by choosing the communication port with which the computer and power supply will be communicating. Communication with the power supply is done using the VISA language. VISA is a high level programming language which calls lower level drivers. This language is used because it has the ability to communicate with hardware using the same command, whether the connection between the devices is USB, GPIB, or RS-232.

After establishing connection with the power supply, the algorithm determines if it is the first time running through the loop. If it is the first time, then an initial I-V curve is calculated and the power supply's maximum supply current is set to 10% above the short circuit current. The maximum supply current is set to this value so that the current does not swing wildly and output the absolute maximum current that the power supply is rated for. After creating the initial I-V curve, the voltage and current outputted by the power supply is measured. From these measurements a new voltage and current operating point is found using the resistance line method mentioned in the above section. Finally the I-V curve and operating point are displayed in a graph. The process then repeats. If the panel type, irradiance, or temperature is changed by the user a new I-V curve is calculated. This is done to minimize the amount of times the computer has to calculate an I-V curve and communicate with the power supply to improve the speed of the PV emulator.

Figure 5-4: Main PV Emulator Algorithm

Fig. 5-5 shows the GUI for the PV emulator. The GUI displays the calculated I-V curve and its operating point, a resistance line, and power curve along with its operating point. Each of these curves can be turned on or off depending on what the user would like to be displayed on the graph by pressing the buttons below the graph. The sliders to the right of the graph allow the user to change the temperature and irradiance. Above the sliders is a drop down menu where the user can select up to 284 different solar panels to emulate. Numeric values for the temperature, irradiance, output voltage, output current, and output power are displayed to the user.

As the user moves the temperature or irradiance slider up or down, the curves will change in real time to reflect the changes specified by the user. The GUI is intended to give the user an intuitive feel as to how a real solar panel would react to changes in temperature, irradiance and loads.

Figure 5-5: PV Emulator GUI

5.3 Timing

Timing is a critical component to the PV emulator. Having the algorithm compute an I-V curve and control the power supply quickly is essential. Ideally the PV emulator would react instantaneously to load changes like a real solar panel would. Since some calculations and communications between devices need to be made, the emulator will not react instantaneously. Calculation and communication times must be minimized to mimic a solar panel closely. If there is a change in the load, the PV emulator algorithm must react quickly enough so that the current and voltage being outputted by the power supply always lies on the I-V curve.

Table 5-1 shows the amount of time it takes for each section of the algorithm to run when using the BK Precision 9153 power supply. The loop for the entire emulator algorithm takes 400ms. Table 5-1 breaks up this algorithm into two components, calculating the I-V curve and setting the power supply. Calculation of the I-V curve takes 150ms while setting the power supply and graphing the curve takes 232ms. The algorithm to set the power supply and graph is further broken down into graphing, calculating the intersection point, setting the power supply voltage, and measuring the output from the power supply. Graphing and calculating the intersection point takes 12ms and 57ms respectively. Setting the power supply voltage and measuring the output from the power supply take 23ms and 160ms respectively. Measuring voltages and currents, which involve communicating to the power supply takes a relatively long time. This is because both a write and read VISA commands need to be made, instead of just the write VISA command used to set a voltage.

Table 5-1: Timing of BK Precision 9153 Power Supply

Operation	Average Time[ms]
Initializing Connection to PS	147.25
Entire Loop	400.71
Calculating IV Curve	156.93
Entire Setting PS and Graphing Portion	232.29
Graphing	12.79
Calculating Intersection Point	57.55
Setting Voltage	23.06
Measuring Current and Voltage	160.20
Closing Connection to PS	220.75

NOTE: Refer to the Appendix for the step-by-step process to obtain the algorithm timing.

Table 5-2 shows the timing of the emulator using a BK Precision XLN3640 power supply. The BK Precision XLN3640 power supply has much faster communication times as seen in the Table 5-2. The time it takes to set the voltage as well as measure the current and voltage from the power supply is reduced to 5.94ms and 20.35ms respectively, as opposed to the 23ms and 160ms timing of the BK precision 9153 power supply. Selecting a power supply that has fast communication times between the computer and the power supply is critical.

Table 5-2: Timing of BK Precision XLN3640 Power Supply

Operation	Average Time[ms]
Initializing Connection to PS	2292.80
Entire Loop	256.56
Calculating IV Curve	159.62
Entire Setting PS and Graphing Portion	114.74
Graphing	12.70
Calculating Intersection Point	45.94
Setting Voltage	5.94
Measuring Current and Voltage	20.35
Closing Connection to PS	54.67

Chapter 6 : Development Process

The process that was taken during the development of the PV emulator is described below. First an I-V curve was modeled within Matlab with varying irradiance and temperature for a single solar panel. The next step was to have Labview interface with the power supply and follow simple linear equations. Once this was achieved, then the Matlab model outlined above was adapted to work in the Labview environment. The Labview algorithm reads user inputs based on panel manufacturer, irradiance, and temperature. Panel characteristics such as the open-circuit voltage and short circuit current were obtained by looking at the Sandia PV Database and a corresponding I-V curve was calculated. The next step was optimizing the algorithm for speed and accuracy.

As outlined in Power Supply Algorithm Design section, the initial method was the look-up-table method for controlling the power supply. Although this method accurately tracked the I-V curve along the open-circuit voltage section, as the current approached the short-circuit current, the algorithm would take several iterations for the emulator to find the true operating point on the I-V curve. The emulator algorithm was then modified to use the Resistance Line method described above. This method was able to more accurately track the I-V curve at all the various regions.

There were several steps taken to resolve the speed issues of the PV Emulator. First, initial timings of each component of the algorithm were obtained. Table 6-1 shows the initial timing using the BK Precision 9153 power supply. As compared to the final timing obtained in Table 5-1, the initial timing was considerably slower. The BK Precision 9153 power supply has manufacturer provided sub-virtual instruments for Labview that allow for easy communication between computer and the power supply. These sub-

virtual instruments contain many unnecessary function calls and cause a large overhead for Labview to process. This large overhead causes the large delay times seen in Table 6-1.

Table 6-1: Initial Timing of BK Precision 9153 Power Supply

Operation	Average Time[ms]
Initializing Connection to PS	4914.40
Entire Loop	878.51
Calculating IV Curve	234.51
Entire Setting PS and Graphing Portion	626.28
Graphing	12.41
Calculating Intersection Point	47.87
Setting Voltage	238.64
Measuring Current and Voltage	336.33
Closing Connection to PS	319.00

To decrease the amount of time to communicate between the power supply, direct VISA read and write commands were created within Labview. These VISA commands eliminated the error queries present in the manufacturer supplied Labview sub-virtual instruments. Using the VISA commands reduced the emulator algorithm time from 238ms to 23ms to set the power supply voltage and 336ms to 160ms to measure the current and voltage.

Another section of the algorithm that was optimized for speed was calculating the I-V curve. Initially it took 234ms to compute the I-V curve, but it was reduced to 156ms. Calculating the I-V curve had several for-loops which looped through all 50,000 data points when trying to calculate the I-V curve. To reduce the amount of computations, an array of voltage values were passed into the for-loop instead of individual voltage values. Calculating the current values simultaneously in the array is much faster than calculating the current in each iteration of the for-loop.

Chapter 7 : Results

7.1 Testing Procedure

A power resistor decade box was used to determine how effective the PV emulator was at mimicking a commercially available solar panel. I-V curves generated by the PV emulator were compared to those given from a commercially available data sheet. By changing the resistance of the power resistor decade box, a sweep can be made from the open-circuit voltage to the short-circuit current of the I-V curve. The operating point of the emulator was recorded to determine the accuracy at which the output voltage and current lined up with the generated I-V curve. The equivalent setup, if an actual solar panel were used, can be seen in Fig. 7-1.

Figure 7-1: Equivalent Circuit of PV Emulator Hardware Setup

The PV emulator tracks changes in both load current and load voltage and changes the voltage accordingly so as to follow the I-V curve. Fig. 7-2 depicts what happens when a resistive load is connected to the PV emulator. A resistive load will have a linear slope due to Ohms law. The point where the resistive load and I-V curve meet is the operating point of either the solar cell or PV emulator. As the resistance of the load increases, the operating point approaches the open circuit voltage.

Figure 7-2: Resistance Line and Operating Point of Emulator

7.2 Comparison to Datasheet I-V Curves

I-V curves provided by solar panel manufactures were compared to curves calculated by the PV emulator. Fig 7-3 shows I-V curves for a Solarex MSX-60 panel. The curves shown are for temperatures of 0°C, 25°C, 50°C, and 75°C at an irradiance of 1000W/m². Fig. 7-4 shows the calculated I-V curves for the same panel along with the steady-state operating points for various resistive loads. The PV emulator is able to accurately calculate an I-V curve that is nearly identical to the manufacturer I-V curves. The steady-state operating points of the emulator, shown as black circles in Fig. 7-4, are

very close to the calculated I-V curve and therefore the emulator is able to effectively emulate this solar panel at various temperatures.

Figure 7-3: Solarex MSX-60 Manufacturer Supplied I-V Curve [25]

Figure 7-4: Solarex MSX-60 PV Emulator Calculated I-V Curve

Fig 7-5 shows I-V curves for a Sunpower 205-BLK panel. The curves shown are for varying irradiances of 1000W/m^2 , 800W/m^2 , and 500W/m^2 at 25°C and for 50°C at 1000W/m^2 . Fig. 7-6 shows the calculated I-V curves for the same panel along with the steady-state operating points for various resistive loads. The calculated I-V curves are nearly identical to the manufacturer supplied I-V curves and the steady-state operating

points of the power supply fall right on top of the calculated curves. Since the calculated I-V curves match the Sunpower I-V curves and the operating points fall on top of the calculated curves the PV emulator is able to accurately emulate this solar panel at various irradiances.

Figure 7-5: Sunpower 205-BLK Manufacturer Supplied I-V Curve [26]

Figure 7-6: Sunpower 205-BLK PV Emulator Calculated I-V Curve

Chapter 8 : Conclusion and Areas of Future Investigation

The PV emulator has the ability to emulate 284 different solar panels at various irradiances and temperatures. Based on a given load the emulator is able to output voltages and currents similar to the desired solar panel type. This thesis simulates a single solar panel. The Labview code and hardware however, can be modified to simulate an entire array of solar panels. This would allow accurate testing of larger PV equipment such as multi-kilowatt inverters and battery banks. Several power supplies would have to be put in a series-parallel combination to simulate an array of panels. The Labview program would need to be modified so it can communicate with several power supplies at once.

Another area to investigate would be to expand upon the calculation of the I-V curve. Adding parameters such as time-of-day or a location component to the emulator algorithm could be included to more accurately emulate a solar panel under real world conditions. The PV emulator would be able to simulate a solar panel as the panel goes through an entire day in a user specified region. Shading could be another potential factor that could be included into the PV emulator. Since PV panels are composed of several solar cells connected in series and parallel, partial shading of the module will affect output characteristics of the solar panel. The equations used to calculate the I-V curve in Labview need to be modified to account for the new input parameters.

Developing a custom power supply would be another area of investigation. Developing the power supply would involve power electronic design of a DC-DC converter and some digital signal processing to control the output of the power supply. The custom power supply could bring down the cost of the PV emulator and depending on the output characteristics of the designed DC-DC converter could allow the emulation of more solar panels.

References

- [1] S. Ahmed, A. Jaber, and R. Dixon, "Renewables 2010 Global Status Report," *Renewable Energy Policy Network for the 21st Century (REN21)*, 2010, p. 15.
- [2] N.H. Viet and A. Yokoyama, "Impact of Fault Ride-Through Characteristics of High-Penetration Photovoltaic Generation on Transient Stability," *Power*, 2010, pp. 1-7.
- [3] Athena Energy Corp, "Solar Array Emulator 1000PV Datasheet," 2010.
- [4] J. Ollila, "A Medium PV-Powered Simulator With a Robust Control Strategy," *Control Applications, 1995., Proceedings of the 4th IEEE Conference*, 1995, p. 40.
- [5] G. Martin-Segura, J. López-Mestre, M. Teixidó-Casas, and A. Sudrià-Andreu, "Development of a photovoltaic array emulator system based on a full-bridge structure," *Electrical Power Quality and Utilization, 2007. EPQU 2007. 9th International Conference on*, IEEE, , p. 1–6.
- [6] S. Armstrong, C.K. Lee, and W.G. Hurley, "Investigation of the Harmonic Response of a Photovoltaic System with a Solar Emulator," *2005 European Conference on Power Electronics and Applications*, vol. 9, 2005, pp. 8-10.
- [7] S.S. Kulkarni, "A novel PC based solar electric panel simulator," *The Fifth International Conference on Power Electronics and Drive Systems, 2003. PEDS 2003.*, pp. 848-852.
- [8] Agilent, "E4360 Modular Solar Array Simulator Datasheet," 2011.
- [9] R. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, Taylor and Francis Group, 2010, pp. 49-52, 369-373, 407-447.
- [10] F.B. Matos and J.R. Camacho, "A model for semiconductor photovoltaic (PV) solar cells: the physics of the energy conversion, from the solar spectrum to dc electric power," *2007 International Conference on Clean Electrical Power*, May. 2007, pp. 352-359.
- [11] W. Shockley and H.J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells," *Journal of Applied Physics*, vol. 32, 1961, p. 510.
- [12] E. Yablonovitch and O. Miller, "The Influence of the $4n^2$ Light Trapping Factor on Ultimate Solar Cell Efficiency," *Optics for Solar Energy*, 2010.
- [13] Y.-H. Zhang, D. Ding, and R. Johnson, "A Semi-Analytical Model and Characterization Techniques for Concentrated Photovoltaic Multijunction Solar Cells," *Optics for Solar Energy*, 2010.

- [14] K. Araki, M. Yamaguchi, M. Kondo, "Which is the best number of junctions for solar cells under ever-changing terrestrial spectrum?," *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion*, vol. 1, 2003.
- [15] National Renewable Energy Laboratory (NREL), "Reference Solar Spectral Irradiance: Air Mass 1.5," 2002. <http://rredc.nrel.gov/solar/spectra/am1.5/> (June 9, 2011)
- [16] K. Fukae, C.C. Lim, M. Tamechika, N. Takehara, K. Saito, I. Kajita, and E. Kondo, "Outdoor performance of triple stacked a-Si photovoltaic module in various geographical locations and climates," *Photovoltaic Specialists Conference*, Jan. 1996, pp. 1227-123.
- [17] F.M. González-Longatt, "Model of Photovoltaic Module in Matlab," *II CIBELEC*, 2006, p. 1–5.
- [18] H.-liang Tsai, C.-siang Tu, and Y.-jie Su, "Development of Generalized Photovoltaic Model Using MATLAB / SIMULINK," *Proceedings of the World Congress on Engineering and Computer Science*, 2008, pp. 22-24.
- [19] W. Liu, "Diode ideality factor for surface recombination current in AlGaAs/GaAs heterojunction bipolar transistors," *IEEE Transactions on Electron Devices*, vol. 39, 1992, pp. 2726-2732.
- [20] N. Fukuda, H. Tanaka, K. Miyachi, Y. Ashida, Y. Ohashi, and A. Nitta, "Fabrication of amorphous silicon solar cells with high performance such as fill factor of 0.77 and conversion efficiency of 12.0%," *Photovoltaic Specialists Conference*, vol. 1, 1988, pp. 247-250.
- [21] S. Luque, Antonio Hegedus, *Handbook of Photovoltaic Science and Engineering*, Wiley, 2003, pp. 363-364
- [22] L. Kazmerski, "Best Research-Cell Efficiencies," *National Renewable Energy Laboratory (NREL)*, 2011. [http://en.wikipedia.org/wiki/File:PVeff\(rev100921\).jpg](http://en.wikipedia.org/wiki/File:PVeff(rev100921).jpg) (June 9, 2011)
- [23] C.F. Coombs, *Electronic Instrument Handbook*, McGraw-Hill, 1999, pp. 11.1-11.7
- [24] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *Journal of Electrical & Electronics Engineering, Australia*, vol. 21, 2001, p. 49–56.
- [25] Solarex, "Solarex MSX60 Datasheet," 1998.
- [26] Sunpower, "SPR 205-BLK Datasheet," 2007.
- [27] D.L. King, J.A. Kratochvil, and W.E. Boyson, "Photovoltaic array performance model," *Sandia Report*, 2004, pp. 1-19.

Appendices

A. Obtaining Timing Of Algorithms in Labview

Below is a step-by-step guide to obtain the elapsed time for a particular section of the PV emulator algorithm to process. It consists of using the stacked structure within the programming menu of Labview.

1. As seen in Fig. A-1, the first frame the Clock_Tick.vi is connected to an indicator to obtain the initial time.

Figure A-1: Obtaining Initial Timing

2. In Fig. A-2, the portion of the algorithm that is to be timed is put into the following frame.

Figure A-2: Portion of PV Algorithm to be Timed

3. In Fig. A-3, another frame is created and the Clock_Tick.vi and indicator is once again called to obtain the final time.

Figure A-3: Obtaining Final Timing

4. In Fig A-4, the last frame subtracts the final time from the initial time to obtain the overall elapsed time it took for the algorithm to process.

Figure A-4: Calculating Elapsed Time

B. Operating the PV Emulator

- 1) Connect power supply to computer via USB connection.
- 2) Open DEMO_PV Emulator folder on the desktop.
- 3) Open PV_EMULATOR.vi.
- 4) Press 'Run' button [ ] at top left corner of screen.
- 5) Select the type of panel from the drop down menu and select the temperature and irradiance using the sliders.
- 5) Vary the load to sweep through I-V Curve.
- 6) When finished emulating, press the stop button.

Figure B-1: GUI of PV Emulator

C. Troubleshooting

- 1) Look in PV_EMULATOR.vi and verify correct 'COM' port is selected for the USB connected power supply. (Default should be COM4).

Figure C-1: Location of Power Supply Communication Port

- 2) Verify correct path to SANDIA database.
 - a. Open 'PV_EMULATOR.vi'.
 - b. Verify the correct path for the SANDIA database csv file (i.e. Sandia PV Database.csv).

Figure C-2: Location to Change to the Sandia PV Database

- 3) Verify Power Supply Device Drivers are installed

- 4) Verify The Power Supply Labview Virtual Instruments are installed in the correct path (Note: Do this only if using Manufacturer Supplied Labview Virtual Instruments and NOT VISA commands)

Figure C-3: Location to Place Power Supply Virtual Instruments

D. Labview Block Diagrams

Figure D-1: Block Diagram for Main Algorithm

Figure D-4: Expanded View of Panel Parameter and I-V Curve Calculation

Number of Data Points
132

Figure D-5: Block Diagram for Creating I-V Curve Array

Figure D-6: Block Diagram for Resistance Line Calculation and Finding Intersection Point