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AND COMPUTER ENGINEERING

Environmental Effects on the Operation of Triple-Junction Flexible Photovoltaic Panels

by

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Abstract of the Thesis

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Supervised by Dr. Steven McGarry
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This thesis contains a complete description of a solar photovoltaic experiment to monitor and predict the performance of solar technology in the temperate climate in Ontario. An experiment was designed and built to monitor weather data and determine the operating characteristics of the modules using high-resolution equipment. The data gathered were used in

the one-diode model to predict the power produced by the modules. A large sample of data was not achievable due to the experiment taking place during the winter where snow and a low solar angle heavily reduced the module performance. Results were nevertheless obtained for a Uni-Solar PVL-144 thin-film triple junction amorphous silicon module, and the power predicted was within 25% of what was measured. The module efficiency was found to be 7% - 8% and the ideal tilt angle for Ottawa to be $50^\circ \pm 10^\circ$. The findings presented in this thesis form a basis for future work in characterizing other types of solar modules in the Ontario climate, as well as furthering research in snow accumulation effects on photovoltaic systems.

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List of Symbols and Abbreviations

PV	Photovoltaic	1
E_g	Band gap energy	5
k	Wave vector	6
Δk	Change in momentum	6
ϕ	Photon flux	6
AM	Air mass	7
$c-Si$	crystalline-Silicon	7
$m-Si$	multicrystalline-Silicon	7
$a-Si$	amorphous-Silicon	7
$GaAs$	Gallium arsenide	7
$CdTe$	Cadmium telluride	7
$CIGS$	Copper indium gallium di-selenide	7
I_{ph}	Photocurrent	8
R_s	Series resistance	8
R_{sh}	Shunt resistance	8
R_L	Load resistance	8
μI_{SC}	Temperature coefficient of short circuit current	8
I_D	Diode current	8
I_0	Reverse saturation current	9
k_B	Boltzmann's constant	9
G	Solar irradiance	11
I_{SC}	Short circuit current	11
I_{MPP}	Current at maximum power point	12
V_{OC}	Open circuit voltage	12
V_{MPP}	Voltage at maximum power point	12
IAM	Incidence angle modifier	18
θ_b	Solar beam incidence angle	18

α	Light absorption coefficient	24
λ	Wavelength of light	25
σ	Conductivity	32
<i>MPP</i>	Maximum power point	37
<i>MPPT</i>	Maximum power point tracker	39
<i>FF</i>	Fill factor	38
<i>GHI</i>	Global horizontal irradiance	59

Chapter 1

Introduction

Solar PV (photovoltaic) panels are being hailed more and more by clean-energy proponents as a means to solve future energy requirements, while lowering dependence on non-renewable energy resources. The association of solar panels with clean energy, as well as a desire to boost employment in the renewable energy sector, helped to encourage the Government of Ontario to introduce the FIT (Feed-In Tariff) program. The FIT program offers a subsidized rate for electricity injected into the grid that comes from a renewable source, like solar.

The push for solar technology by government programs, individuals, or companies wanting to be more environmentally responsible, has increased the need for being able to accurately characterize their performance. Research into solar cell performance has progressed fairly rapidly, but it takes place primarily in the climates of the Southwest United States. The temperate climate in Ontario requires extra considerations for a higher latitude, colder temperatures, and more frequent precipitation in the form of either

rain or snow.

Modeling the expected performance of a PV system is incredibly useful when either a particular budget, or a minimum power requirement is a major design consideration. An ideal model of a PV system would be able to take average historical weather data for a given location and predict the amount of power that would be generated in a particular configuration of PV modules. In practice, this is difficult to do because of all the variables involved, such as changing weather trends, differing material properties, inaccurate data, and many others.

Understanding the basic principles of all the components in a solar PV system, and how they behave in different operating conditions is essential for quantifying the way they will function together. It is also important to have a fine control over data collection for both the planning stages of the PV system, and for continuously monitoring its performance to update models as necessary.

The objective of this thesis is primarily to define a mathematical model of a PV module. The one-diode model is described in detail, along with several corrections used by the industry-standard software, PVSyst [10]. The data collected are analyzed and various parameters are extracted to be populated into the model. From a different set of data, the model is used to predict the performance of the modules compared to measured values in order to quantify its accuracy. As part of the predictive model, a set of design considerations are found to guide the design of a PV array in Ottawa to help mitigate snow accumulation and improve power generation in the winter months.

The second objective is to describe the design of a complete system featuring a photovoltaic module with a test load, and a fully automated monitoring system. This system was constructed with custom hardware and a full-featured software environment to record enough data to construct a mathematical model. The monitoring system was completed in November 2013, and was functioning correctly by the end of December. The majority of the data were collected in the first two weeks of January 2014, during a period of good weather.

Finally, in order to achieve these objectives, a background description of the general operating principles of photovoltaic technology is discussed. A review of how climate and physical location affect the performance characteristics of several of the most common types of commercial modules is presented. Various cell chemistries are compared in terms of how they convert light energy into electrical energy, as well as their construction methods. Important performance metrics are also described, such as fill factor, band gap, parasitic resistances, and maximum power point.

The reported experiment is a starting point for a research platform on solar photovoltaics. Additionally, the specific operating concepts of various photovoltaic cells discussed in this thesis could be useful to someone looking for more advanced knowledge of the subject.

Chapter 2

Background

2.1 Modeling

2.1.1 Basic Operation of a PV Cell

A basic PV cell consists of a p-doped bulk semiconductor with a shallow n-doped layer on top. These layers form a depletion region between themselves, which creates an electric field that separates the free charge carriers. The p-n structure is the same as in a diode, with similar operating characteristics. When a photon interacts with a semiconductor, an electron-hole pair is formed. The electric field of the depletion region causes the electron to drift towards the n-doped layer and similarly, the hole is attracted to the p-doped layer; technically a more correct way of describing this is that bound electrons from the p-doped region are attracted towards the newly formed hole. The newly released charge carriers are swept across the depletion region, separating from one another and collecting in opposite regions of the

cell. This separation of charge carriers causes a voltage to build up across the depletion region.

Metal contacts are placed on the front and back of the cell to allow the built-up carriers to be collected. The voltage built up between the front and back contacts of the cell under illumination is called the open-circuit voltage. If the contacts are shorted together and the cell illuminated, then the current generated is called the short circuit current.

Figure 2.1.1: Semiconductor band structures

In order for a photon to be absorbed, it must have at least the energy of the semiconductor band gap. The band gap energy is material-dependent, and several relevant examples are shown in Table 2.1. It has been found that the typical solar spectrum received through the atmosphere is most efficiently converted by materials with a band gap of about $E_g = 1.5eV$ [6]. Examining the data in Table 2.1, the ideal materials for PV cells would be amorphous silicon, gallium arsenide and indium phosphide. All these materials have been used for constructing PV cells, and those relevant to this thesis will be discussed further in Section 2.3.

The final piece of relevant information to the band gap energy, E_g , is its

structure. When a photon interacts with a semiconductor, the energy of the photon must be larger than the band gap of the material in order to free an electron from the valence band and promote it to the conduction band. The band structure shown in Figure 2.1.1a is an example of a direct band gap material, where the valence maximum is directly below the conduction minimum. The x-axis in Figure 2.1.1 is the crystal momentum, or wave vector, k . The momentum offset of the bands is the key difference between direct and indirect band gaps. An electron can be promoted from the valence to the conduction band in an indirect band gap material only when its momentum is conserved. The photon energy can be equal to or greater than the band gap, but in order for an electron to be excited into the conduction band it also must absorb a phonon. A phonon absorption is required due to the momentum difference between the bands, and is shown in Figure 2.1.1b as Δk .

A way to characterize the ratio of generated current (photocurrent) in a PV cell to the amount of light incident on the cell is called the internal quantum efficiency and is given by Equation (2.1.1) [11].

$$\text{Quantum Efficiency} = \frac{j}{q\phi} \quad (2.1.1)$$

Where:

j : photocurrent density in Amperes per unit area [Am^{-2}]

q : elementary charge in Coulombs [C]

ϕ : photon flux in photons per second per unit area [$N_{photons}s^{-1}m^{-2}$]

The irradiance of a cell, in Watts per unit area, is dependent on the average photon energy as well as the number of photons per second. A

convenient measure of the average irradiance arriving at Earth is the AM(air mass) standard, described in Section 2.2.1.

Material	Band Gap (eV)	
Ge	0.66	indirect
c-Si	1.12	indirect
m-Si	1.12	indirect
a-Si	1.7	direct
GaAs	1.42	direct
InP	1.34	direct
InGaAsP	0.35-2.17	direct
CdS	2.42	direct
CdTe	1.5	direct
CIGS	1.04-1.67	direct

Table 2.1: Various PV cell materials and their band gap energies [6][7][8][9].

2.1.2 One-Diode Model

A more complete model than what was described in 2.1.1 of a solar cell's function is the one-diode model, shown in Figure 2.1.2. The one-diode model is also used in the popular solar panel modeling program, PVSyst, developed by Andre Mermoud of the University of Geneva [1].

Figure 2.1.2: Schematic of the One-Diode model [1].

It has been found that the One-Diode model predicts thin-film cell per-

formance, including a-Si and CdTe multijunction cells, as accurately as it does for c-Si. Other modeling approaches exist (such as a Three-Diode model), but many of them produce inconsistent results. Mermoud et al. found that the One-Diode model was always able to give a full set of accurate parameters for the cell.[10]

The incident photons on a cell generate electron-hole pairs in the diode structure. The electric field within the depletion region causes a photocurrent, I_{ph} , to form, which is impeded by a series resistance, R_s , as the carriers propagate through the cell materials. The free carriers have a possibility of recombining along crystal boundaries and defects, represented by the diode and the shunt resistor, R_{sh} [12] [13]. The remaining current I , passes through the load, R_L , and creates a voltage potential, V .

To simplify the equation for I , each part will be described individually and then combined in Equation (2.1.6). The generated photocurrent, I_{ph} , is calculated with respect to reference values of irradiance, photocurrent and cell temperature in Equation (2.1.2).

$$I_{ph} = \frac{G}{G_{ref}} \cdot (I_{phref} + \mu_{ISC}(T_C - T_{Cref})) \quad (2.1.2)$$

Where:

G : irradiance in watts per unit area [Wm^{-2}]

μ_{ISC} : temp. coefficient of short circuit current in Amperes per Kelvin [AK^{-1}]

T_C : cell temperature in Kelvin [K]

The current through the forward-bias diode, $I_D[A]$ is modeled using the

simplified diode model in Equation (2.1.3). [10]

$$I_D = I_0 \left(\exp \left[q \frac{V + I \cdot R_s}{N_{cs} \cdot \gamma \cdot k_B \cdot T_C} \right] - 1 \right) \quad (2.1.3)$$

Where:

I_0 : reverse saturation current in Amperes (see (2.1.4)) [A]

q : elementary charge in Coulombs [C]

R_s : series resistance of the cell in Ohms [Ω]

N_{cs} : number of cells in series in the module [unitless]

γ : diode ideality factor [unitless]

k_B : Boltzmann's constant in Joules per Kelvin [JK^{-1}]

T_C : temperature of cells in Kelvin [K]

The reverse saturation current, I_0 , from Equation (2.1.3) is calculated with respect to reference values of current and temperature. This dependence is shown in Equation (2.1.4). [10]

$$I_0 = I_{0_{ref}} \cdot \left(\frac{T_C}{T_{C_{ref}}} \right)^3 \cdot \exp \left[\frac{q \cdot E_g}{\gamma \cdot k_B} \cdot \left(\frac{1}{T_{C_{ref}}} - \frac{1}{T_C} \right) \right] \quad (2.1.4)$$

Where:

$I_{0_{ref}}$: reference saturation current in Amperes [A]

$T_{C_{ref}}$: reference temperature of cells in Kelvin [K]

E_g : band gap energy in electron volts [eV]

k_B : Boltzmann's constant in Joules per Kelvin [JK^{-1}]

The final part of the one-diode model is the current through the shunt resistance, I_{sh} . This resistance models the non-ideality property of solar cells that allows separated electron-hole pairs to recombine through crystal boundaries [12][13]. The effect of shunt resistance is given in Equation

(2.1.5). [10]

$$I_{sh} = \frac{V + I \cdot R_s}{R_{sh}} \quad (2.1.5)$$

Where:

R_s : series resistance of the PV cell string in Ohms $[\Omega]$

R_{sh} : shunt resistance of the PV cell string in Ohms $[\Omega]$

Combining all the contributions to the current in Equations (2.1.2), (2.1.3), and (2.1.5) yields the full one-diode model. The full model for Figure 2.1.2 is given in simplified terms in Equation (2.1.6).

$$\begin{aligned} I &= I_{photocurrent} - I_{diode} - I_{shunt} \\ I &= I_{ph} - I_0 \left(\exp \left[q \frac{V + I \cdot R_s}{N_{cs} \cdot \gamma \cdot k \cdot T_C} \right] - 1 \right) - \frac{V + I \cdot R_s}{R_{sh}} \end{aligned} \quad (2.1.6)$$

The one-diode model does not take into account partial shading, and assumes all cells are constructed with identical physical parameters. For more detail on partial shading and the steps taken to mitigate its effects on commercial units, see Section 2.2.2.

2.2 Meteorological Influences and Monitoring

2.2.1 Factors Affecting Panel Output Power

There are many factors affecting the operation of PV systems, and each affects several different aspects of performance. The following sections describe the dependencies in terms of their base effects, separating the inter-related performance metrics.

Solar Irradiance and Atmosphere

The most important factor in PV system performance is the solar irradiance that reaches the panels. The irradiance incident on the Earth's atmosphere is AM0, which is equal to $G(0) = 1367 \text{ W m}^{-2}$ [6]. The average irradiance for most places on the Earth is AM1.5, which represents the remainder of the sun's light after having passed through the distance of one and one half atmospheres of air. AM1.5 is used instead of AM1.0 because AM1.0 only applies when the sun is directly overhead, which can never happen in Ottawa. The AM1.5 surface irradiance is $G(1.5) = 963 \text{ W m}^{-2}$, corresponding to a solar angle of about 48 degrees [6].

Figure 2.2.1: Plot of current versus irradiance over a wide range of solar and atmospheric conditions. Plot is for m-Si and only to illustrate an example of an $I - G$ relationship for PV. Important points are blue (I_{SC}) and red (I_{MPP}). Figure reprinted from King et al., Photovoltaic Array Performance Model, 2004.[2]

As the irradiance on a PV panel increases, the current through the load

Figure 2.2.2: Plot of voltage versus irradiance over a wide range of solar and atmospheric conditions. Plot is for m-Si and only to illustrate an example of a $V - G$ relationship for PV. Figure reprinted from King et al., Photovoltaic Array Performance Model, 2004.[2]

has been shown to increase linearly, as the red I_{MPP} (maximum power point current, see Section 2.4.1) data points in Figure 2.2.1 show. Similarly, Figure 2.2.2 shows the relationship between irradiance and cell voltage at V_{OC} and V_{MPP} (maximum power point voltage). These plots are given as examples of the relationships that current and voltage share with irradiance and may not necessarily be accurate representations of a-Si cells. The ‘effective irradiance’, E_e , in these plots is a statistical average and derived from I_{SC} , which means that the I_{SC} data points are linear with E_e . As demonstrated by King et al., the I-G and V-G relationships are uniform under load and independent of irradiance [2] as shown in Figures 2.2.1 and 2.2.2, respectively.

The set of IV curves from a typical solar cell for several values of irra-

Figure 2.2.3: A set of typical IV curves of a solar cell showing the irradiance dependence of voltage and photocurrent.

diance is shown in Figure 2.2.3. It should be noted that the curves tend to have a uniform shape for mid-range values of irradiance. The general trend is that I_{MPP} and V_{MPP} both increase linearly as irradiance increases, but the current is significantly more affected. See Section 2.4.1 for more details on I_{MPP} , V_{MPP} , I_{SC} , and V_{OC} .

2.2.2 Panel Shading

Shading can come from many different sources, and is defined as anything blocking the beam component of sunlight from reaching a solar cell. Under most forms of shading during the day, there will still be a diffuse component of light illuminating a cell. This diffuse component can be modeled as an isotropic source of irradiance, as if atmospheric conditions were overcast [14].

Typical shading sources include the horizon, buildings, trees, snow and ice, fallen leaves and other debris. Ideally, a solar panel installation would

be placed with minimum shading from buildings or trees. Snow and ice accumulation are also important considerations when designing a solar panel system in Ontario or any other temperate climate where these weather conditions are common during the winter months. Snow and ice covering is safe for solar panels as long as they are properly supported, but for some modules there must be safety precautions in place to protect against partial shading. If one cell in a module is not generating enough power, then the module current will flow through that cell, potentially causing thermal damage.

If one cell is shaded to the point where it can no longer produce as much photocurrent as the other cells in a series string, it will begin to enter a reverse voltage situation. All of the current generated by the other cells will begin to dissipate through the shaded cell causing it to heat up, this is known as a hot spot condition [10]. At a certain temperature, the cell will be destroyed and the entire module must be replaced since all the cells within the module are connected in series. A solution to this problem is to place a bypass diode across several cells in the module. If a reverse condition were then to happen, the protection diode would start to conduct after $-0.7V$, safely dissipating the reverse current [15]. Unfortunately the entire sub-module connected across this diode would be cut off from contributing power to the system, but module destruction is a far worse event. It has been shown that for a crystalline silicon (General Electric GE PV-165, in particular) solar panel's bypass diode to begin conducting, only 20%-30% of the cell needs to be shaded [15]. For crystalline silicon panels, where typically each cell's total area is only about the size of a hand, a fallen leaf

could easily cause a cell to reverse bias without a bypass diode.

A far less destructive form of shading is where an entire solar panel is shaded evenly, such as for clouds, snow, ice, dust or the sun going behind a building or horizon. The only way to mitigate building shading is to place the solar panels out of the path of the sun, and as for the horizon, there are no common practical solutions.

Cloud cover can also affect the stability of the grid due to sudden drops in injected power. PV power in Ottawa can be sporadic in nature due to the weather systems in its temperate climate compared to more arid places such as the Southwestern United States. If Ontario is going to increase its reliance on solar energy, then the cloud issue will need to be overcome in order to provide a stable power grid.

Accumulation of dust on the surface of a solar panel can also reduce performance depending on many factors. Dust can be electrostatically attached to a glass surface, and salts in the dust particles can dissolve in moist air, dew, or light rains. When the panels later dry, the salt adheres to the glass, similar to cement. In order to remove this cemented dirt, manual cleaning can be performed, or the panel can be left to a heavy rain or melting snowfall. Transmissivity of glass has been shown to be reduced by 1%-10% each month depending on environmental conditions such as rain, wind and the amount of airborne particles. Studies have found that panel shadings of 10% can reduce total power output by up to 50%. Many materials and coatings have been tested to mitigate soiling but the majority either accumulate more dirt, degrade under UV exposure, or are more difficult to manually clean than untreated glass.[16]

There has been little research on shading as a result of snow and ice accumulation. Of the research on the subject, O'Rourke's report for the US Department of Energy [17] primarily covers snow accumulation on roof-mounted panels. Ross' report for Natural Resources Canada [18] provided a detailed analysis of snow and ice accumulation, mitigation technologies, and the effects of snow and ice on the operating characteristics of PV modules. More recent work on snow accumulation includes that of Andrews et al., describing various aspects of snow accumulation on solar panels during the 2010/2011 winter in Kingston. The findings in this paper reveal a range of about 0.5%-3.5% yearly power loss attributable to snow [19].

2.2.3 Panel Orientation

The effects of panel orientation in a PV system are best described by using an eye diagram, such as the one given in Figure 5.2.2 for Ottawa, Canada. The eye diagram shows all possible positions of the sun throughout the year (shaded in yellow) in rectangular coordinates. This particular diagram describes the experiment set up for this thesis, with the panels oriented directly South (azimuth = 0°) and the black dashed shading curves at the bottom representing inter-module shading. Finally, this eye diagram illustrates several commonly known points about the Earth-Sun system for the Northern Hemisphere:

- (Point 1) The Sun is at it's highest altitude at 12:00 on June 22. In Ottawa, this corresponds to $\sim 68^\circ$
- (Point 4) The Sun's altitude at 12:00 is equal to the location's latitude ($\sim 45^\circ N$) on the Equinoxes (March 20 and September 23)

- (Point 7) The highest altitude of the Sun on December 22 is $\sim 16^\circ$ at 12:00 in Ottawa.

One common layout for a PV system is referred to as a ‘shed’, which is the type being investigated in this thesis. There are many other possible arrangements, all with their own uses depending on the particular needs of the system, but their descriptions are beyond of the scope of this thesis.

The shed arrangement is where PV modules are mounted on a flat surface and tilted to a certain angle from the horizontal. An assumption typically made is that the modules are infinitely long, treating the extra solar irradiance on the edges as negligible [10]. An example of a shed configuration is shown in Figure 5.2.1, corresponding to the one in this experiment. In the side-profile figure, the blue lines are the active portions of the cells, black are part of the structure, and yellow are the Sun’s beam component at the limit before inter-module shading starts to happen.

Inter-module shading in a shed configuration is when the Sun’s beam component is blocked, either partially or fully, by another module. As Figure 5.2.1 shows, this effect begins when the Sun is lower than 22.7° in altitude. Only the front panel, with respect to the Sun, is unaffected by this shading. Another consideration with any orientation of module is when the Sun is behind the plane of the modules around sunrise and sunset. At this solar position, as well as with inter-module shading, the only component of irradiance is the diffuse component; the Sun’s beam is fully blocked [10].

In addition to considerations for tilt angle of modules, another important factor is azimuth angle. The compass direction that the modules face

determines what time the Sun passes behind the plane of the modules, corresponding to the blue lines in Figure 5.2.2. In Ottawa and other northern temperate locations, the Sun is always less than 90° in altitude and towards the South at noon, so the ideal azimuth angle is exactly South. For many places within the Southern Hemisphere, the ideal azimuth would be North, and between the tropics, panels could be mounted horizontally to capture the midday Sun roughly overhead.

Tilt and azimuth angles combine to determine with what angle the beam component of the solar irradiance strikes the PV cell surface. A popular model for this effect is the IAM (incidence angle modifier), standardized by ASHRAE (the American Society of Heating, Refrigeration, and Air Conditioning), and given in Equation (2.2.1) [20][21]. The IAM is directly multiplied by the beam, diffuse and albedo reflected components of solar irradiance and then summed to get the total effective irradiance. It is acceptable to approximate IAM_D (diffuse) and IAM_R (reflected) as 0.1 for most practical purposes [22].

$$IAM(\theta_b) = 1 - b_0 \cdot \left(\frac{1}{\cos(\theta_b)} - 1 \right) \quad (2.2.1)$$

Where:

b_0 : empirical parameter depending on the panel surface [unitless]

θ_b : solar beam incidence angle from the normal in degrees $[\circ]$

The b_0 parameter in Equation (2.2.1) is determined empirically, and for PV modules is typically given to be $b_0 = 0.05$ [10][23] or $b_0 = 0.07$ [22] for crystalline silicon with a glass top layer. An additional consideration with

the ASHRAE Model of IAM is that it cannot be accurately applied to angles beyond $\theta_b > 80^\circ$ [22]. Other models trade simplicity for a more accurate physical description at large incidence angles. Some of these models include the Physical Model by De Soto et al. in 2006 [24], the Martin and Ruiz Model by Martin and Ruiz in 2001 [25], and the Sandia Model by King et al. in 2004 [2]. Though it should be noted that the Sandia Model produces non-physical values for $10^\circ - 45^\circ$ due to it being a polynomial model [21].

Temperature

The temperature dependence of current and voltage in a PV cell is complex because of its influences at the material level. The photocurrent in Equation (2.1.2) has a linear dependence on temperature and the diode current in Equation (2.1.3) has both an inverse exponential dependence on temperature and a T^3 factor from the I_0 component. Parasitic resistances, R_s and R_{sh} , within the cell will also increase with temperature, though increasing R_{sh} has a beneficial effect on current. The voltage and current will increase as a result of R_{sh} increasing, however, the voltage across the load will also decrease due to a higher R_s .

Single junction cells with high band gaps suffer lower losses at an elevated operating temperature [26] than lower band gap materials. The loss is due to temperature increasing the number of thermally-generated electron-hole pairs, and is an $I \propto T^3$ factor in Equation (2.1.4), the diode reverse saturation current. This temperature dependence is reduced by higher band gap materials because they produce fewer thermally-generated carriers for recombination. A PV cell's voltage is also proportional to its band gap,

so as cell voltage increases, total current decreases and parasitic losses are reduced due to the $P = I^2R$ relation [27].

Conveniently, most manufacturers of commercial solar panels will provide temperature coefficients of their modules for various operating points. Most commonly provided are derating percentages of I_{SC} and V_{OC} . Sometimes the MPP voltage and current temperature deratings are also provided by the manufacturer of the panel. The availability of this information is beneficial because it promotes transparency in marketing panels, and it keeps the consumer informed.

Relative Humidity

Relative humidity is the saturation level of water vapor in air, and it can potentially play a role in solar panel performance. Air with a higher percentage of water vapor can absorb sunlight more than dry air, which reduces the beam component of irradiance on solar cells. High humidity can also contribute to long term damage of encapsulant materials and possibly permeate panel sealants and damage cells directly. Heat trapping is another issue with humidity that can reduce cell efficiency, as climates with high humidity will have higher air temperatures.[28]

2.2.4 Data Sampling

It is fortunate that most meteorological phenomena take place on a time scale of minutes and hours, so that any equipment monitoring them does not need to be fast at taking measurements. Likely the shortest event that could have an effect on PV module output is a passing cloud, where the

sun can be blocked and then visible again within a few seconds to a few minutes. Due to the short duration, periodic clouds are of little concern when building models to estimate monthly and yearly energy production.

An important decision when setting up data monitoring for any experiment is with what frequency should measurements be taken. For periodic data, the Nyquist rate is typically acceptable, but weather phenomena are inherently random. A trade-off must be chosen between collecting the maximum amount of data possible and amount of time and space required to process and store them. One of two compromises are typically chosen; to under-sample the data, or to sample at a higher rate and take an average.

Riley et al., quantified these two methods by measuring irradiance and came up with several conclusions [29]:

- For days with little variability there is negligible difference between averaging and under-sampling
- For days with high variability the mean absolute error is about 50% higher with under-sampling than it is with averaging. The daily energy prediction error is 2-2.5 times larger with under-sampling.
- For high variability days, under-sampling produces errors spread above and below zero, but averaging errors are always above zero

Based on the conclusions of Riley et al., the preferred method of recording data is to sample at a high rate and average the data to a manageable rate [29].

2.3 PV Cell Technologies

The photoelectric effect is the ability to generate a voltage across a material under illumination, and is the core principle on which all PV cells operate. Although this effect was fully explained by Einstein in 1921, it was not until 1954 that the first PV cell for the visible spectrum was constructed by Chapin, Fuller, and Pearson at Bell Labs [30]. Currently, PV cells are being fabricated using many different materials and fabrication technologies, some of which are discussed in the following sections. A summary of the top-performing research cells of each type is reported and updated by NREL (National Renewable Energy Laboratory) and shown in Figure 2.3.1 [3].

Figure 2.3.1: Top research cells and their efficiencies. Figure reprinted from NREL National Center for Photovoltaics, Research Cell Efficiency Records, 2013.[3]

2.3.1 Silicon-Based PV

The first PV cell with what might be called ‘modern efficiency’ was made from silicon by Chapin et al. a few years after the first transistor was built in the same laboratories. Today, commercial silicon PV cells are widely available in several different forms, giving a wide range of performance for different applications.

Crystalline Silicon

With the thriving microelectronics industry basing their technologies in crystalline silicon wafers, it is only logical that silicon would make an ideal candidate for PV technology. Silicon is abundant in the Earth’s crust, and pure silicon wafers are inexpensive and readily available due to the existing integrated circuit industry. Processing silicon wafers for solar cells is simple and does not require such advanced fabrication technology as is used for complex microelectronics.

A crystalline silicon PV cell is fabricated on a standard silicon wafer several hundred microns thick and typically of p-type doping. The top layer is thin and heavily doped with an n-type element such as phosphorus or arsenic, shown in Figure 2.3.2. The n+ layer needs to be heavily doped because metal ‘fingers’ (commonly made from silver) are layered on top to provide a current path into the cell and a high dopant concentration reduces this series resistance, R_s . Too much doping however, will result in a smaller depletion region, which will reduce the active volume for absorption of light and generation of electron-hole pairs. For the back contact, a common

Figure 2.3.2: A typical crystalline silicon PV cell structure.

practice is to spread aluminum paste and heat it until the aluminum diffuses into the back to provide a low-resistance p+ region, a metal contact for the cell, and a reflective surface for light that passes through to the back of the cell.[6]

As described in Section 2.1.1, silicon is an indirect band gap (see Figure 2.1.1b) material, which causes it to have a low absorption coefficient, $\alpha \approx 10^2 \text{cm}^{-1}$ to 10^4cm^{-1} in the visible spectrum [31]. The thickness of silicon required to absorb a significant amount of light is $x \gg 1/\alpha$, or $1\mu\text{m}$ to $200\mu\text{m}$. The Beer-Lambert Law given in Equation (2.3.1) describes the amount of light that penetrates to a given material depth. For crystalline silicon, the absorption depths of various wavelengths are plotted in Figure 2.3.3, where each line represents the absorption of a different part of the

visible spectrum.

$$I(x) = I_0 \cdot \exp(-\alpha \cdot x) \quad (2.3.1)$$

Where:

x : material depth from the surface in centimetres $[cm]$

I : intensity of light at a particular depth in arbitrary units

α : absorption coefficient in inverse centimetres $[cm^{-1}]$

Equation (2.3.1) can be used to determine the amount of light absorbed after a particular depth to generate the plot in Figure 2.3.3:

$$\text{Absorbed light} = 1 - \exp(-\alpha \cdot x)$$

Figure 2.3.3: Crystalline silicon depth is plotted against the amount of light absorbed for $\alpha = 10^2 cm^{-1}$, $10^3 cm^{-1}$, and $10^4 cm^{-1}$ corresponding to wavelengths $\lambda = 1.0 \mu m$, $0.8 \mu m$, and $0.5 \mu m$, respectively. The absorption coefficient of the red line is also approximately the wavelength corresponding to the band gap of c-Si

Despite the low absorption coefficient, crystalline cells have an advantage of greater efficiency per unit area over other silicon PV technologies. The crystal structure has a low defect density which reduces recombination sites and helps to increase quantum efficiency. A low defect density also increases shunt resistance, and decreases the series resistance of the cell. The increase in efficiency of crystalline cells comes at the cost of reducing the active area of a module; since crystalline cells are fabricated with circular wafers, gaps are left when the cells are arranged in a rectangular module. Overall, most commercial crystalline silicon PV modules perform at approximately 10%-16% efficiency [31]. These modules are also more expensive than other forms of silicon PV due to the increased price of crystalline silicon wafers and the equipment required to fabricate them.

Multicrystalline Silicon

Due to the difficulty of growing single-crystal silicon wafers, crystalline silicon modules tend to be more expensive than other silicon modules. A popular compromise is to melt pure silicon (often with dopant added) and cool it slowly in blocks. This casting method produces large columns of randomly oriented single crystals on the order of a few millimetres in diameter. These blocks can be cut into thin wafers that are mostly single crystals extending from the front to the back of the wafer and are considered ‘pretty good’ for use in PV cells.

Multicrystalline PV cells function similarly to crystalline, and are processed using the same techniques, but the primary differences are: [6]

- Multicrystalline cells can be made rectangular and packed edge-to-edge in modules, covering a greater percentage of the module's surface area than circular crystalline cells
- Multicrystalline cells tend to have lower shunt resistance due to the defects along grain boundaries, reducing usable current
- Crystalline cells can be textured to trap light by dipping in KOH (forming inverted pyramids on the surface) but multicrystalline cells can't due to the random orientation of grains.

Given that the cost of producing multicrystalline wafers is lower than that of crystalline, and the active area per module is increased, multicrystalline PV is an excellent choice for consumers. The commercial modules offered also tend to only be about 1% less efficient than their crystalline counterparts [6], which suggests that in the future there won't be much demand for consumer grade crystalline panels.

Amorphous Silicon

While crystalline and multicrystalline silicon are similar in operation, amorphous silicon is different in both fabrication techniques, and operation. The most important difference is that amorphous silicon is deposited as a thin film, typically using PECVD (plasma-enhanced chemical vapor deposition) onto a non-silicon substrate [11]. The result is a film of 'microcrystalline' silicon with many dangling bonds that are passivated by hydrogen atoms [6]. Passivation is necessary to reduce recombination losses, although recombination of carriers will still be higher in amorphous silicon than in single crystal.

PECVD works by using a radio frequency (or sometimes direct current) high voltage discharge to ionize a gas containing silicon, which is deposited on a substrate placed in the low-pressure chamber. The typical gas used is silane (SiH_4), but gasses containing dopant atoms such as phosphine (PH_3) or diborane (B_2H_6) can also be used for depositing doped layers of silicon [11]. Amorphous silicon PV cells can be made significantly thinner than cells made from silicon wafers because they can be grown onto a substrate such as glass, metal, or a flexible material. Thin cells are also more efficient because of their direct band gap of 1.7eV with a corresponding absorption coefficient of $\alpha > 10^5 cm^{-1}$ [6] for wavelengths $> 730nm$. The high absorption coefficient means that amorphous silicon cells can be made 400nm thick and still absorb at least 98% of light shorter than 730nm, as shown in Figure 2.3.4 using Equation (2.3.1)

Absorption depth of amorphous silicon for light shorter than 730nm

Figure 2.3.4: Amorphous silicon depth is plotted against the amount of light absorbed for $\alpha = 10^5 cm^{-1}$ corresponding to wavelengths shorter than $\lambda = 730nm$

A PV cell made from amorphous silicon is commonly made with a p-i-n structure (p-type intrinsic n-type) rather than a p-n junction. The intrinsic layer is added to create a wide depletion region with as few dopant atoms as possible, because doped amorphous silicon has low carrier mobilities and lifetimes [6]. If electron-hole pairs are generated within the undoped intrinsic layer, the electric field will cause them to drift apart with less likelihood of recombining than if they were generated in a doped region. Another key difference in cell design for amorphous silicon is that it should be made with the p-type material exposed to illumination rather than n-type. For thicknesses $> 200nm$, amorphous silicon is less efficient when the n-layer is illuminated [11] because most absorption happens within the first $100nm$. The concentration of holes increases towards the p-layer because they have a slower drift velocity and longer distance to travel than electrons, this buildup weakens the electric field and increases recombination [11].

Figure 2.3.5: A typical amorphous silicon p-i-n cell structure.

A typical p-i-n structure for an amorphous silicon PV cell is shown in Figure 2.3.5, with an intrinsic region of usually $200nm - 500nm$ and doped n- and p-type regions only about $10nm - 30nm$ thick. A PV cell designed this way could achieve an efficiency close to 10%, under laboratory conditions.[32]

Amorphous silicon has the ability to be alloyed with other elements to produce a different band gap energy. It is possible to do this with crystalline silicon but not as easily, since the crystal structure must be maintained and there are few choices of elements that produce the desired band gap with matching lattice sizes. A large enough lattice mismatch between materials means they could de-laminate or large defects could be introduced, but this is not the case with amorphous silicon.

To raise the band gap, carbon or oxygen can be alloyed with the amorphous silicon and to lower it, germanium is used [32]. Lowering the band gap has a practical limit of about $1.4eV$ for 40% germanium, beyond which, the material becomes optically and electrically useless. Currently, there are no manufacturers using carbon or oxygen to raise the band gap of amorphous silicon and harness the blue end of the spectrum.[11]

With the ability to easily alter the direct band gap, a short absorption depth, and low cost of manufacture, amorphous silicon is an excellent choice for PV cells. Since the layers are built up, one on top of the other using PECVD, amorphous cells can be grown on top of one another and connected in series. If the band gaps of each cell are tuned to absorb blue light at the top, and red light at the bottom, they can efficiently convert more of the solar spectrum into usable power. Such a structure is shown in Figure 2.3.6.

Figure 2.3.6: A typical triple-junction structure for amorphous silicon PV cells.

Staebler-Wronski Effect

One strange property of amorphous silicon PV cells, noticed in 1977 by Staebler and Wronski [33] is the effect in amorphous silicon that bears their names. The SWE (Staebler-Wronski Effect) causes a reduction in the photocurrent and dark current within amorphous silicon PV cells after being exposed to light. It was also observed that when highly doped, amorphous silicon is less susceptible to the effect than with lighter doping. [33]

It was not clear to Staebler and Wronski what was causing the degradation, though they believed it had something to do with dangling bonds in the silicon, which was later shown to be correct [34]. The method in which the dangling bonds form is not currently known, but it is likely that hydrogen within the silicon plays a role when exposed to light for the first few hundred hours [34][11].

Deng and Schiff showed in 2003 that the SWE degraded several Uni-Solar

triple junction PV cells by 15% and some Uni-Solar single junction cells by 30% after 1000 hours [11]. After this degradation time, the efficiency became stable again and didn't worsen. It is interesting to note that the effect is consistently worse on single junction cells than triple junction.

The SWE is non-permanent, it was shown that annealing at temperatures above 150°C for a few minutes can completely restore cell efficiency [33]. Lower temperatures can also cause an annealing effect where conductivity is based on activation energy $E_a = 0.87\text{eV}$ in the Arrhenius equation $\sigma = \sigma_0 \exp(E_a/kT)$ [33]. It has been observed that in the summer months, the efficiency closely follows the daily mean temperature with a difference of about 1% increased efficiency during the summer [11]. There have been many efforts to reduce or eliminate the SWE but most add a large amount of cost and complexity to the fabrication process of amorphous silicon [34].

2.3.2 Other PV Chemistries

There are many compounds that can be used to make PV cells besides silicon; some of them are listed in Table 2.1 with their band gaps, and some are described in the following sections. Beyond those listed here, are other technologies still in the research stage, such as organic films and dye-sensitized PV cells. All of these cells are represented in Figure 2.3.1 comparing their laboratory efficiencies.

Gallium Arsenide

The current champion PV cell is made with GaAs wafers in a three-layer design that uses either a lens or curved mirror to concentrate solar irradiance

onto the cell. GaAs is referred to as one of the III-V group of materials because Ga (group-III element) and As (group-V element), when alloyed together, form a semiconductor material with which PV cells can be made.

A major advantage of GaAs is that it can be alloyed with other III-V elements to change the band gap. AlGaAs can be made with a high enough band gap that it is transparent to most of the solar spectrum, creating a window into the cell. Other elements commonly used are indium, nitrogen and phosphorus. Some alloys of GaAs can be made to match the lattice of germanium, allowing it to be used as the bottom cell in a multi-junction configuration with its low band gap.[32]

The direct band gap of GaAs gives it a high absorption coefficient, comparable to that of amorphous silicon, meaning that most of the solar spectrum can be absorbed in a few hundred nanometres of material. The high absorptivity of a GaAs cell has the same problem as a crystalline silicon cell, where its thickness causes efficiency to drop due to increased recombination rate and higher series resistance [6]. It is therefore often desirable to deposit thin GaAs films using MOCVD (metalorganic chemical vapor deposition) onto another substrate, such as silicon or germanium.

The limiting factor of GaAs is the cost of both the materials and the equipment to produce PV cells comparable to or better than silicon. As seen in Figure 2.3.1, GaAs PV is moderately more efficient than silicon, and only begins to excel when the light is concentrated. GaAs is also well-suited for power generation in space on satellites and robots that need to run for a long time. Silicon devices are susceptible to damage from radiation, which is common outside the Earth's magnetic field. GaAs is found to be resilient to

radiation, thought to be due to an annealing process that takes place when high-energy electrons strike a crystal defect [6].

Copper Indium Gallium (di)Selenide

Another choice for thin-film PV cells is CIGS (CuInGaSe), which is a direct band gap semiconductor material that is easily and inexpensively sputtered onto various substrates. Due to its direct band gap, CIGS has a high absorption coefficient and can convert about 90% of solar irradiance into free carriers with $2\mu\text{m}$ of material. The band gap can be engineered by adjusting the concentration of gallium from CuInSe_2 with $E_g = 1.04\text{eV}$ to CuGaSe_2 with $E_g = 1.67\text{eV}$. The optimum tends to be about 35% gallium, producing a band gap of 1.3eV which exhibits a high quantum efficiency for light of wavelength $0.5\mu\text{m} - 1\mu\text{m}$. [32]

Figure 2.3.7: A typical CIGS thin film cell structure.

CIGS PV cells are sputtered at temperatures typically below $550^{\circ}C$ due to thermal expansion problems with substrates such as stainless steel and soda lime glass [26]. The back contact is formed first, and is almost always molybdenum, followed by the CIGS layer with the desired concentration of gallium. When the CIGS layer is deposited in the heat of the sputtering chamber, some of the selenium diffuses into the molybdenum and forms $MoSe_2$, a good ohmic contact [35]. Since CIGS is a p-type semiconductor, the n+ contact is provided by a layer of cadmium sulfide with a band gap of $2.4eV$, making it transparent to most solar irradiance [6]. The top layer is a transparent conducting oxide, typically zinc oxide doped with aluminum. A schematic of a typical CIGS structure is shown in Figure 2.3.7.

The top performing CIGS cells have achieved efficiencies of over 20% in the laboratory, which is the highest for any thin-film PV cell. Work is being done to increase efficiency by using specialty glass substrates to allow deposition temperatures of up to $650^{\circ}C$ or more. The current problem with CIGS is their operating temperature coefficients are almost as low as crystalline silicon. At operating temperatures of $50^{\circ}C$, the power loss of CIGS cells can be 20% or more.[26]

Cadmium Telluride

Just below the performance of CIGS in Figure 2.3.1, are cadmium telluride thin film PV cells. This material is a direct band gap semiconductor of $E_g = 1.45eV$ with an absorption coefficient on the order of $10^5 cm^{-1}$ for light above the band gap energy [32][6]. The absorption depth for the visible spectrum of CdTe is close to that of amorphous silicon shown in Figure 2.3.4.

The advantage of CdTe is that it can absorb wavelengths as long as $825nm$ ($E_g = 1.45eV$), where amorphous silicon can only absorb those shorter than $730nm$ ($E_g = 1.7eV$) due to its higher band gap energy.

Figure 2.3.8: A typical cadmium telluride thin film n-p cell structure.

The standard cell layout for CdTe is the reverse of amorphous silicon and CIGS, using an n-p structure applied to a transparent superstrate of typically soda lime glass. The glass is coated with a transparent conducting oxide, such as SnO_2 or In_2O_3 by physical vapor deposition. A thin ($< 100nm$) n+ layer of cadmium sulfide can be sputtered or deposited in a chemical bath. The p-type CdTe is sputtered, or more commonly deposited using CSS (close space sublimation) to a thickness no more than a few microns.[32]

CSS deposition is similar to sputtering except the source material is rapidly heated, often by high-power halogen lamps or resistive wire in a vacuum chamber. The material sublimates into a gas and is deposited on the

target, which is held close to the source, often on the order of millimetres.[36]

The CdTe cell is finished off by sputtering a p+ layer of Sb_2Te_3 and molybdenum to provide an ohmic contact to the back of the cell [32]. The layout of a typical CdTe cell is shown in Figure 2.3.8.

2.4 PV Cell Operation

2.4.1 Maximum Power Point

A solar cell has many possible operating points along its characteristic IV curve and is determined by the load on the cell. If the illuminated cell is unconnected, then the voltage potential between the terminals is V_{OC} and is the highest voltage that can be produced under the respective panel irradiance. Conversely, if the terminals are shorted together then the resulting current is I_{SC} and is the highest current producible under that irradiance. In both cases of V_{OC} and I_{SC} , the total output power is zero watts. V_{OC} and I_{SC} are shown on the plot of a typical solar cell IV curve in Figure 2.4.1.

In order to optimize useful power from the cell, a load must be selected such that the product of current and voltage is maximized, regardless of solar irradiance. This operating condition is called the MPP (Maximum Power Point) and is shown in Figure 2.4.1. The area defined between the origin, I_{MPP} , and V_{MPP} is the power produced in that cell. Tracking the maximum power point is essential because solar irradiance directly alters the IV curve of a PV cell, with more current generated at higher irradiances. In a real-world PV installation, the irradiance is never constant and can change drastically throughout the day.

Figure 2.4.1: A typical IV curve of a solar cell showing V_{OC} , I_{SC} , MPP and total power (area from the origin to MPP)

As discussed in Section 2.2.1, the IV curve is altered by the irradiance on the cell. Figure 2.2.3 shows that increased irradiance gives a small boost to the cell voltage and a large boost to the generated current. The larger dependance on irradiance of the photocurrent causes the MPP to shift more in current and less in voltage when irradiance changes.

Fill Factor

The FF (fill factor) of a cell is the ratio of the maximum power produced by an ideal PV cell to a real cell. The parasitic series and shunt resistances are responsible for the non-ideal performance. Generally, fill factor can be used to quantify any reduction in performance, such as dust accumulating on the surface of a module [28]. The calculation of fill factor is given in Equation

(2.4.1).

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}} \quad (2.4.1)$$

For the case of amorphous silicon thin films, annealing using hydrogen or helium plasma produced cells with better fill factors and suffered less degradation due to the Staebler-Wronski effect [12].

2.4.2 MPP Tracking Algorithms

A voltage-based MPPT is the simplest possible solution for harvesting power from PV cells. This method assumes a linear relationship between V_{MPP} and V_{OC} [37], so with a measurement of V_{OC} , the power point can be easily selected. The presently accepted V_{MPP} range for most PV cells is $0.71V_{OC}$ to $0.78V_{OC}$ [37]. The optimal V_{MPP} to V_{OC} ratio for a particular cell can be determined from an IV curve ahead of time, or for commercial panels, taken from the manufacturer's recommendations.

Once the optimal ratio has been determined and the PV cell is in operation, the load can be switched off and V_{OC} measured. The tracking device switches the load back on and monitors the cell voltage, actively altering the load to keep the cell operating at the optimal voltage. Maintaining a PV cell's optimal operating voltage can be done with a DC/DC switching converter, which rapidly pulses current through an inductor-capacitor circuit, emulating a variable load resistor.

To track the MPP as panel irradiance changes, the controller can periodically open circuit the cell and recalculate the MPP. This measurement should only take one or two seconds, and will not cause a significant a power

disruption if many cells are operating together with independent trackers. This MPPT method is simple to implement, but only ever operates close to the MPP, since the target voltage is only an approximation of the true V_{MPP} .

To improve the accuracy of finding the V_{MPP} , an IV curve can be measured at intervals throughout operation at the cost of extra time spent not generating power [37]. The measured IV curve will reveal the exact MPP but will only be valid for the cell conditions at the time of measurement.

The obvious drawback to these MPPT methods is that environmental conditions can change rapidly. For example clouds could block the sun, or debris that is covering cells could fall off. A better solution is one where the MPPT can respond quickly to changes in cell irradiance.

A more advanced tracking algorithm is called P&O (Perturb and Observe), which is able to find the MPP and dynamically adjust it for any change in irradiance. The P&O algorithm remembers the previous power of the cell, compares it to the current power, and adjusts the V_{MPP} in the direction that causes the power to increase. The biggest limitation to this algorithm is that it does not always respond well to rapid changes in irradiance [38].

New MPPT techniques are continuously being developed to achieve a faster response to changing irradiance, and also to more accurately find the MPP and hold the load there. A few notable techniques are fuzzy logic, neural network, dP/dV feedback control and incremental conductance [37]. A key factor in choosing a particular MPPT algorithm is the amount of sensor and computational power required to operate it. If one algorithm

can provide more efficient tracking but the extra energy it produces is less than the extra energy required to run it, then it is less efficient.

2.4.3 AC Inverters

For most PV applications, the goal is to harvest as much power as possible from the Sun and convert it into AC power that can be used in a building, or fed into the existing power grid. This section will briefly describe a few key points about inverters in sufficient detail for the scope of this thesis.

The inverter is a device that converts the high voltage DC power from the PV modules into AC power that can be used in standard home or building circuits. A common practice is to attach several modules in series to form a ‘string’ with a maximum voltage close to the maximum voltage supported by the inverter. Having a high voltage reduces ohmic losses in the DC wiring. If there are several strings in the system, and the inverter can handle their current contributions, then they are all connected in parallel.

The MPPT algorithm is typically built into the inverter’s control system and is responsible for loading the strings [37]. This means that each string should be comprised of only identical cells, receiving the same irradiance [6] or else losses will occur within the string, as discussed in Section 2.2.2.

One solution becoming more common is to use a buck/boost converter on each module to bring the low DC panel voltage up to a higher level. When the voltage is increased at the panel, long cable runs of low-voltage DC can be minimized, which reduces loss. The second advantage of DC/DC converters is that each panel has its own MPPT and can be oriented differently, receive a different level of irradiance or shading, or even be a different

technology from the rest of the system. This eliminates the need to match modules in a string and every panel can be boosted to the same voltage and contribute its current to the inverter in parallel. This solution is more expensive due to the added components, but can produce a more steady supply of power during shading events, or if the operator decides to add additional modules into the system at a later time.

Chapter 3

Apparatus

For this thesis, an array of solar photovoltaic modules was donated by Enfinity Canada and installed on a rooftop at Carleton University. A weather station and pyranometer were mounted nearby to measure and record various local atmospheric and solar irradiance data on the top of the roof. Data from these sensors were digitized and fed to a computer using USB and RS-232 connections to be collected and recorded by software.

3.1 The Solar Array

3.1.1 Uni-Solar PVL-144 Modules

An array of 20 Uni-Solar PVL-144 modules were mounted to the rooftop of the Mackenzie Engineering Building (Block 1). The modules were mounted to a metal subframe which was secured to the roof using concrete ballast. Due to the layout of the HVAC components already on the roof, the array was organized with all 20 modules lined up one behind the other so that

only one front module would not receive shading from another module. This layout does, however, provide a simple way of precisely determining shading effects on the modules at any amount of shading by comparing the output of the front panel to that of the second.

The PVL-144 modules are made from triple-junction amorphous silicon, printed on a thin stainless steel substrate and encapsulated with a polymer film. The published specifications of these modules are shown on the IV curve in Figure 3.1.1. The peak design power is 144W at AM1.5 conditions, resulting in a fill factor of:

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

$$FF = \frac{33.0V \cdot 4.36A}{46.2V \cdot 5.3A}$$

$$FF = 0.59$$

Figure 3.1.1: IV curve labeled with the published specifications of a Uni-Solar PVL-144 module used in this experiment.

Each module has 22 cells connected in series, and with $V_{OC} = 46.2V$, the voltage produced by each cell is roughly $V_{OC_{cell}} = 2.1V$. Each of these cells is equipped with a bypass diode, which means that once a cell is shaded enough that the diode begins to conduct, only that cell is cut off from the rest of the module. Many other commercial modules have bypass diodes connected across multiple cells, so even if only one cell is shaded, the module will lose the contribution of several unshaded cells (sometimes 12 or more depending on the manufacturer).

An inverter was not used in this experiment in order to have more control of the electrical measurements and MPPT algorithm. If an inverter was used, the modules would likely have been connected into two parallel strings of 10 modules in series. Connecting 10 PVL-144 modules in series would yield a V_{OC} of $462V$, which is reasonable for a system of this size ($2.8kW$) in terms of reducing ohmic losses from high DC currents. Additionally, most inverters have a maximum DC input voltage of $500V - 600V$ depending on the model, meaning 20 modules in series would not be possible.

3.1.2 Panel Tilt and Orientation

Locating the array on the roof of a multistorey building is useful for eliminating shading from ground-based objects. Shown in Figure 3.1.2, is the location of modules on the roof, which was chosen to be as far as possible from all the HVAC units. Maximizing the space around the array avoids radiant heat and shading from the rooftop units, but the array also can't be too far away from the location where cables drop into the building to reduce ohmic losses.

Figure 3.1.2: Location of the PV array on the roof of the Mackenzie Building at Carleton University. DC power cables and sensor data cables were brought into the building through the gray box in the left corner.

The chosen location happened to be ideal for facing the array to the South. Several compass readings were taken and corrected for magnetic declination in order to align the mounting frames 0° in azimuth (South) $\pm \sim 3^\circ$ reading and alignment error. The PVL-144 thin film modules are branded ‘Power Tilt’ and glued to a 15° angle piece of sheet metal. The angle is set by the factory, not user-adjustable, and there was no option of specifying a different angle. Uni-Solar claims the 15° angle is for ‘increased performance’, though there is no mention of what this is compared to.

It is likely that the factory-tilt of 15° will not be ideal for Ottawa because the angle of solar altitude is always less than 70° . Another argument for a tilt angle in the range of $40^\circ - 60^\circ$ is to help reduce snow accumulation on the modules and increase available sunlight through albedo (reflection off the ground) effects of fallen snow [19]. Further analysis of higher tilt angles is presented in Section 5.2.

3.2 Data Collection

The data collection apparatus consisted of two parts; the Vaisala WXT520 weather station using the supplied WeatherVIC software, and a custom-written C++ application to interface with custom circuitry through a LabJack digital-to-analog converter.

3.2.1 Vaisala WXT520 Weather Station

The WXT520 is able to accurately measure temperature, relative humidity, barometric pressure, wind speed and direction, and average rainfall. The sensors are not user-adjustable and are delivered pre-calibrated from the manufacturer. The weather station is designed to interface over an RS-232 serial connection to a computer running the proprietary WeatherVIC application. WeatherVIC enables real-time monitoring of weather conditions and records them in a data file along with the time the measurement was taken at.

The weather station was secured to a custom-built mount, shown in Figure 3.2.1, following the recommendations of the manufacturer. The mount was located close to the PV array but not so close as to shade any of the modules.

3.2.2 LabJack U12 Monitoring

The digital-to-analog converter used for monitoring this experiment and controlling the operating point of the modules is a LabJack U12. The LabJack converts a voltage connected into one of its analog ports into a 12-bit digital

Figure 3.2.1: Weather station (white object) and pyranometer (black domed object) mounted to the roof near the PV array.

signal and transfers it to a computer through a USB connection. The LabJack can also output a low-current analog voltage up to 5V over one of two analog output ports. In this experiment, several devices were connected to the LabJack to be monitored and controlled by the computer.

Current and Voltage Sensing

The primary monitoring device is a custom-built current and voltage monitoring circuit using a FET as a dummy load for a PV module. A schematic drawing of the circuit is shown in Figure 3.2.2. The voltage was measured using a high-resistance voltage divider of $> 1M\Omega$ which is more than 10^6 times the resistance of the terminals through the current sensor, ensuring

that voltage drop across the sensor is negligible. An Allegro ACS713-20A Hall Effect current sensor was directly connected to the PV module positive terminal. The negative terminal of the sensor was then connected through the drain of an STMicroelectronics STP80NF12 n-channel MOSFET and back to the negative terminal of the PV module.

Figure 3.2.2: Schematic drawing of the PV module current and voltage monitor with FET for a dummy load.

To measure the operating voltage of the PV module, a voltage divider must be used to reduce the peak voltage at the LabJack analog input, as it is limited to $\pm 10V$ in single-ended configuration. The voltage divider resistors were chosen to meet the criterion of being $> 1M\Omega$ but also being able to divide $50V$ or more down to a voltage that would not come close to the maximum of the LabJack. The chosen resistors were (as measured with

a precision ohmmeter):

$$R_1 = 1.194M\Omega$$

$$R_2 = 38.26k\Omega$$

with a voltage divider ratio of:

$$V_{PV} = V_{in} \frac{38.26k\Omega}{1.194M\Omega + 38.26k\Omega}$$

$$V_{PV} = 0.031 \cdot V_{in}$$

Reducing the measured voltage to 3% of the input ensures that even if several modules were connected in series accidentally, the LabJack would not be damaged. Another important consideration is that the analog inputs of the LabJack have an input impedance on the order of $100k\Omega$, low in comparison to the impedance of the voltage divider. The LabJack User's guide suggests compensating for the input impedance by assuming a current source of I_{in} given by [4]:

$$I_{in} = 8.1815 \times 10^{-6} \cdot V_{in} - 11.67\mu A \quad (3.2.1)$$

Where:

V_{in} : measured voltage reported by LabJack in volts [V]

The complete voltage sensing schematic diagram, including the input current source in Equation (3.2.1) is shown in Figure 3.2.3 and Figure 3.2.4. The voltage sensed by the LabJack can then be scaled by Equation (3.2.2) to give the PV module voltage, V_{PV} . For a full derivation, see Appendix

A.1.

$$V_{PV} = V_{in}(41.97564) - 13.93398V \quad (3.2.2)$$

Where:

V_{in} : measured voltage reported by LabJack in volts [V]

Figure 3.2.3: Equivalent circuit of voltage divider with LabJack input current I_{in} [4].

The Hall effect current sensor is connected between the PV module output and the FET, which is the primary path to ground for the module current. The sensor is designed to output $185mV/A$ at high impedance and is connected to one of the single-ended analog input pins of the LabJack. Another analog input pin on the LabJack is being used to directly monitor the $+5V$ regulator output voltage. Monitoring this rail is necessary because the Hall effect current sensor output depends on the level of its VCC pin.

Figure 3.2.4: Completed voltage and current sensing circuit with FET to control module operating point.

Solar Irradiance Sensing

The solar irradiance is measured with an Apogee SP-110 pyranometer mounted to a pole, with an almost-unobstructed view of the horizon. The SP-110 requires no external power source and outputs a differential voltage that closely resembles an ideal voltage source. No special circuitry is necessary with this signal, as the LabJack can read two analog input ports in differential mode with various gain levels, to increase measurement resolution.

The SP-110 was calibrated by the manufacturer to output $200\mu V/Wm^{-2}$ peak-to-peak, and is not user-adjustable. The maximum output voltage of the pyranometer is $0.4V_{diff}$ for an irradiance of $2000Wm^{-2}$, which is roughly double the maximum solar irradiance anywhere on the Earth's surface. The pyranometer was fixed horizontally to the same mount as the weather station in order to measure the full-sky irradiance.

3.2.3 C++ Code

The primary data gathering logic was implemented in C++ using a DLL library supplied by the LabJack Corporation as an interface to the device. The code was executed by a scheduler on the monitoring computer that was also running the WeatherVIC software. The majority of the code was original work with exception to modified example code supplied by the LabJack Corporation [4] for interfacing with the DLL library.

See Appendix B for the complete code listings of all 3 files. The code is divided into *LJBase.cpp* and its header file, *LJBase.h*, which define a custom *LJBase* object that maintains a connection with a LabJack device. The main program is called *main.cpp*, and is responsible for instantiating the object and containing the monitoring logic.

LJBase Class

The *LJBase* class defines function pointers for accessing a DLL file which is provided by LabJack [4]. The class provides temporary storage for values sent to and received by the LabJack device, some of which are hard-coded, and some are accessible through public functions. Three public void functions are defined: *analog_update*, *analog_read*, and *diff_read*. The *analog_update* function sends a particular voltage from the analog output pin on the LabJack to the gate of the load FET, directly connected to it. When the *analog_read* function is called, 4 LabJack analog channels are sampled and the voltages are returned by array reference. The *diff_read* function does the same thing as *analog_read*, except only two channels are sampled, each

comprised of a differential pair.

Main Function

The main program contains all the functions required to sample data through *LJBase*, apply scaling, generate IV curves, write data to files, control the maximum power point tracking, and keep synchronized with the clock. After the initial setup, the program waits for 04:00 and then starts gathering one data point every second, scaling and writing it to a file. Additionally, the MPPT algorithm is run after every data sample to ensure the module is operating at peak output. An IV curve is generated every 10 minutes, with the raw data being saved to a separate file containing all the IV curves in one day (108 of them). Every hour, a new file is created to minimize data loss if the computer should lose power, and also to enable easy remote monitoring using the Dropbox cloud-storage software.

The initial setup defines all necessary variables and timers, then waits until the time is 04:00 to ensure that measurements are being taken before the Sun rises. The program then enters the main loop which repeats the following until it determines that it is time to exit (either by failure or the time is 22:00):

1. Check if it is 22:00, if so then exit
2. Check if it has been more than 1 hour since the current file was created, if so then make a new file
3. Check if has been more than 10 minutes since an IV curve was recorded, if so then record an IV curve

4. Wait until the clock ticks
5. Make 10 measurements from the LabJack at $20ms$ intervals
6. For each parameter, drop the highest and the lowest value, and average the remaining
7. For each parameter, apply the correct scaling to its average value
8. Add the scaled voltage and current to a queue containing the 3 most recent samples
9. Run the MPPT algorithm (see Section below)
10. Write the samples to a file along with the Unix time
11. Go to 1

When the main loop exits, the currently open file is closed and the LabJack analog output pin connected to the FET is reset to $0V$, stopping all current from the PV modules.

MPPT Algorithm

The tracker was designed as a P&O (perturb and observe) algorithm and modified to respond to trends in the last 3 samples, as opposed to only the most recent sample with many simpler P&O algorithms. It was found after several trials of a simple P&O algorithm that there was too deep of an oscillation due to small fluctuations in measured samples. To make the algorithm more smooth, a queue structure was created so that the FET acting as a load resistor wouldn't allow more current until the the power was definitely increasing. Another feature of this algorithm is that no current

is allowed to flow until the open circuit voltage has reached a threshold of $15V$.

The modified P&O algorithm starts turning on the FET once the open circuit voltage threshold has been reached, starting by increasing the gate voltage in $0.1V$ increments, then increments of $0.01V$ once it has reached $3V$. During this time, the last 2 changes in module power are checked, and if they have both increased, then the FET voltage is moved one increment in the direction that it last went. If a decrease in module power was recorded, then the FET voltage moves in the opposite direction. If the power neither increased or decreased in both intervals, then the FET voltage is left where it is. This third state allows the system to smooth out any measurement noise and only change the operating point when it is certain that the modules are not operating at the maximum power point.

Chapter 4

Experimental Results

The IV curve of a photovoltaic module can be used to determine many characteristics about its cells. The fill factor is a good way to quantify how close the module operates to an ideal cell, and only requires knowing the operating point, short circuit current and open circuit voltage. The shunt and series resistances are not directly measurable from outside the cell but can be estimated from the slope of the IV curve near I_{SC} and V_{OC} , respectively.

This experiment attempted to monitor a triple-junction amorphous silicon PV panel in various environmental conditions. Due to several equipment issues, a year-round analysis was infeasible, however, data have been gathered from several days of operation to extract the required parameters for a cell model. The recorded weather conditions include: clear and cloudy sky, each with and without a layer of snow on the module, partly cloudy, and during a snowfall.

4.1 Clear and Cloudy Performance

The optimal conditions for measuring PV module parameters is direct sunlight without clouds, snow, or haze. Because the data collection took place in the Ottawa winter, these optimal conditions were rare, but enough data were collected to analyze the performance of the module.

4.1.1 Clear Sky

Clear sky conditions were present on January 3rd and 9th, after all the snow had been manually removed from the panel. The solar irradiance on those days peaked at approximately 400Wm^{-2} , shown in blue in Figure 4.1.1 along with the power produced by the module, shown in red. IV curves from various times during each day illustrate the performance of the module at different irradiance levels, shown in Figure 4.1.2.

Figure 4.1.1: Irradiance and power generated over two clear-sky days.

The curves in Figure 4.1.1 show some discontinuities from glitches in the measurement software. This glitch caused the IV measurement code to run extra iterations, so any data recorded during that time had lost the MPP. For

Figure 4.1.2: IV curves at 4 different irradiance levels on two clear-sky days.

illustrative purposes, these glitch measurements were removed from Figure 4.1.1a and left alone in Figure 4.1.1b. Another unnatural point in Figure 4.1.1a is around 09:00, where the snow-covered module was uncovered, and is discussed in Section 4.2.

To ensure that the pyranometer data are correct in Figure 4.1.2, another source for GHI (global horizontal irradiance) data was found at the University of Ottawa’s SUNLAB Solar Test Site [39][5]. Irradiance data for Ottawa are available from a calibrated pyranometer, and a plot of SUNLAB’s measured irradiance is reproduced in Figure 4.1.3 for January 3, 2014.

It is clear that the pyranometer data are accurate and Figure 4.1.1 reveals that the MPPT algorithm works well, where generated electrical power smoothly follows the solar irradiance. The only exception is the IV measurement glitch present at the start of every hour due to a C++ programming error.

Figure 4.1.1b also reveals how the MPPT behaves when the irradiance is low. The output current was held at zero while V_{OC} increased, until

Figure 4.1.3: Irradiance data measured with a calibrated pyranometer on January 3rd by SUNLAB. Figure reprinted from the University of Ottawa SUNLAB Solar Test Site with permission [5].

it reached 15V at about 07:30, when the FET turned on to allow current flow and power to be generated. This increase in output power is only gradual and not proportional to the irradiance while the module is over 50% shaded. At about 08:15, the solar beam illuminated more than 50% of the cell area, as discussed in Section 5.2 (Figure 5.2.2), and less current was absorbed by the shaded area of each cell. After the shading threshold, output current began to proportionally follow the solar irradiance. The same effect happened again starting around 15:15, although there was also some cloud cover during this time. It should be noted that the bypass protection diodes do not conduct during the morning and evening shaded times because every cell is equally shaded. The protection diodes are only necessary when a small number of cells in the whole module are shaded, while the others are producing power.

Measured throughout the day, the IV curves in Figure 4.1.2 show the diode response of the module at different irradiance levels. The reason for the difference in the distribution of points along each curve is because the algorithm that samples the IV data was still being adjusted in the days between the 3rd and 9th. Another issue with the curves is the inaccuracy of measurements at low current levels, which is due to the limitations of the data collection equipment.

4.1.2 Fill Factor

The fill factor, described in Section 2.4.1, can be calculated with the IV curves in Figure 4.1.2. A sample calculation using Equation (2.4.1) is given in Appendix C.1 and summarized in Table 4.1.

Irradiance (Wm^{-2})	Fill Factor
150	0.56
200	0.58
250	0.56
300	0.56
350	0.55
395	0.53
400	0.50
Average	0.55

Table 4.1: Fill factors for several IV curves from January 3rd and 9th.

The average fill factor value measured is 0.55, and is a reasonable measurement because the published fill factor is 0.59 (shown in Section 3.1.1)

4.1.3 Module Efficiency

An important factor in characterizing any PV module is how efficiently it can convert solar irradiance into usable electrical power. The collected irradiance data are in Wm^{-2} , so the measured electrical power through the load just needs to be scaled to the active area of the PV module. Appendix C.2 shows an example calculation of module efficiency, and a summary of module efficiency is given in Table 4.2 for several different measured irradiances.

Irradiance (Wm^{-2})	Load Power (W)	Efficiency
100.2	4.3	2.0%
150.5	18.4	5.7%
200.6	27.7	6.4%
299.9	46.8	7.2%
397.0	68.5	8.0%
414.9	69.9	7.8%

Table 4.2: Module efficiencies calculated for several irradiances.

The reported efficiency of the PVL-144 panels in the Uni-Solar literature is 6.7%, but PVSyst reports an efficiency of 7.86% [10]. Both of these efficiencies are based on an irradiance of $1000Wm^{-2}$, but the measurements shown in Table 4.2 only report up to $414.9Wm^{-2}$. It can still be seen that the calculated efficiencies at higher irradiances agree more with PVSyst than they do with the Uni-Solar literature. Another observation from these data is that as the irradiance falls below $200Wm^{-2}$, the efficiency of the module begins to drop off significantly. Below $100Wm^{-2}$, very little power is being produced at all.

4.1.4 Clouds and Overcast Sky

In the afternoons of January 3rd and 9th, there were times when the solar irradiance dropped, most obviously at around 14:15 in Figure 4.1.1a. These drops were caused by clouds passing overhead, creating temporary overcast conditions where the output power dropped roughly in proportion to the irradiance.

One fully overcast day was January 4th, with irradiance plot shown in Figure 4.1.4. The peaks on this plot show when the clouds thinned but there was never any direct sunlight. It is clear that some power was generated throughout the day, but only about 30% of what was generated on January 3rd. This reduction in power is why a clear sky is important to efficient solar generation, even despite amorphous silicon cells theoretically outperforming crystalline in diffuse light.

Figure 4.1.4: Irradiance and power generated on January 4th (overcast).

4.2 Module Under Accumulated Snow

January 3rd presented the opportunity of a clear day to compare the production of power of a snow-covered module to an uncovered module. At about 09:10, an undisturbed layer of snow, 15 *cm* deep at the top and 23 *cm* deep at the bottom of the cell was manually removed. Figure 4.2.1 is an image illustrating the snow depth prior to its removal. The system continued to gather data during the snow removal process, which took about 10 minutes. The plot in Figure 4.2.2 shows the generated power rapidly increasing as snow is removed from the module one cell at a time.

Figure 4.2.1: Image of the experimental PV module (the second one from the front) partially uncovered with snow, showing depth of 15 *cm* – 23 *cm*. January 3, 2014

An attempt at measuring an IV curve before the snow was removed showed that a negligible amount of light was reaching the module under ~ 20 *cm* of snow. The IV curve after snow removal is the 250Wm^{-2} (blue) data set in Figure 4.1.2a, but there were no reliable data gathered while

Figure 4.2.2: Plot showing power generated before and after the removal of snow from a module. January 3, 2014

snow was covering the module. This lack of light penetration through snow is best shown in Figure 4.2.2, where the panels produce no power (compared to the morning of January 9) until the snow is removed.

An example of module performance in clear sky conditions and buried under snow, was December 30th, 2013. On this day there was as much snow as January 3rd, but without any cloud, allowing for the maximum amount of light to reach the module. The plot in Figure 4.2.3 shows power generated throughout the day, and the only interruption of sunlight was a cloud at around 14:15. This plot shows that under $\sim 20\text{ cm}$ of snow, only a small amount of diffuse light reaches the module to produce a peak of 0.5 W , with an irradiance of almost 400 W m^{-2} , compared to 65 W four days later.

Snow accumulation on PV panels is drastically affected by both the wind

Figure 4.2.3: Solar irradiance and generated power on December 30th, a clear day with the module buried under snow.

and the height of the module off the ground. Figure 4.2.4 shows several multicrystalline modules mounted on a 45° angle, with the bottom several inches off the ground. The m-Si modules had snow covering almost half of their area and were on the same rooftop as the ones in this experiment. The angle and lack of a gap between them and the ground is the likely reason that they were covered more by blown snow, than accumulation alone. Contrastingly, the a-Si modules that were mounted at shallow angles close to the ground were completely buried in snow. Under these particular snow coverings, a-Si modules were generating effectively no power, while the m-Si modules were still theoretically capable of generating about half their nominal output power.

Figure 4.2.4: Image of a multicrystalline PV module half-covered with blown snow. January 3, 2014

Chapter 5

Modeling

5.1 Module Parameters

Determining parameters to use in the mathematical model is important for ensuring the model produces accurate data. Some parameters are given by the manufacturer, such as cell area and temperature coefficients. Others, like diode ideality, series and shunt resistance must be estimated, either by inference of performance graphs, or based on known values for similar solar cells.

5.1.1 Shunt and Series Resistance

Since PVSyst [10] is such a widely used and accepted tool for planning a PV installation, several features of its one-diode model were used as a basis for the model described in this chapter. PVSyst uses several empirical measurements to approximate the relationship between R_{sh} and irradiance, since R_{sh} has been found to increase exponentially in a-Si cells with increas-

ing irradiance [10]. The model presented here must assume a constant value of R_{sh} due to the extra data collection required during the summer months where solar irradiance is higher.

On a solar cell IV curve, close to the short circuit current, the shunt resistance can be estimated by the inverse of the slope. Similarly, the series resistance can be estimated from the inverse slope near the open circuit voltage. Figure 5.1.1 shows example IV plots from January 3rd and 9th where R_{sh} and R_s were estimated. These two days were chosen because they had clear skies at 12:00 when irradiance was highest. Appendix C.3 shows example calculations of both resistances, with the results summarized in Table 5.1.

Sample	R_{sh} (Ω)	R_s (Ω)
Jan 3 ($350Wm^{-2}$)	166.7	6.71
Jan 3 ($395Wm^{-2}$)	147.1	7.40
Jan 9 ($400Wm^{-2}$)	106.4	6.10
Average	140.1	6.74

Table 5.1: Shunt and series resistances calculated for several IV curves from January 3rd and 9th.

The resistances measured are reasonable because a-Si panels are known to have low shunt resistance, on the order of 100Ω , and series resistances higher than in c-Si cells [10]. The values for R_s presented in Table 5.1 are several times higher than the value suggested by PVSyst, 1.11Ω , likely because the estimation method used in Figure 5.1.1 is only good as an approximation. In reality, a more accurate value of R_s is not obtainable from an IV curve [10].

(a) January 3, 2014

(b) January 9, 2014

Figure 5.1.1: IV curves on two clear sky days showing data and slopes used to calculate shunt and series resistances.

5.1.2 Diode Ideality Factor

The ideality factor, γ , is used to model second order effects in the diode equation, although it doesn't have a large impact on the shape of a solar cell's

IV curve [10]. It is typically chosen as a value between 1 and 2 for crystalline and multicrystalline silicon, but up to 3 times that for triple-junction cells due to their structure of three cells in series. Since the ideality factor is usually chosen to fit the diode model to a measured curve, it wouldn't make sense to take that approach here. Instead, $\gamma = 4.2$ will be used, as suggested by the PVSyst empirical model for PVL-144 modules [10].

5.1.3 Reference Photocurrent

The photocurrent produced is dependent on irradiance and temperature of the cells, and is given by Equation (2.1.2). This equation can be solved to find the reference photocurrent, $I_{ph_{ref}}$, as a function of the given irradiance, temperature and the manufacturer-specified temperature coefficient, μ_{ISC} . Solving the photocurrent equation for $I_{ph_{ref}}$ produces Equation (5.1.1):

$$\begin{aligned} I_{ph} &= \frac{G}{G_{ref}} \cdot (I_{ph_{ref}} + \mu_{ISC}(T_C - T_{C_{ref}})) \\ I_{SC}(G_{ref}, T_{C_{ref}}) &= \frac{G_{ref}}{G_{ref}} \cdot (I_{ph_{ref}} + \mu_{ISC}(T_{C_{ref}} - T_{C_{ref}})) \\ I_{SC}(G_{ref}, T_{C_{ref}}) &= I_{ph_{ref}} \end{aligned} \tag{5.1.1}$$

The photocurrent when $V \approx 0$ is approximately the short circuit current, I_{SC} , so $I_{ph_{ref}} = I_{SC}$ at G_{ref} and $T_{C_{ref}}$.

5.2 Panel Tilt and Shading

PVSyst has a useful tool to help visualize module shading based on the physical dimensions of a PV array. The dimensions of the PVL-144 modules

were measured and input into the software to produce Figure 5.2.1. The complete array of solar modules is arranged in what is called a shed layout, and the figure shows that shading effects will start to happen when the sun is below 22.7° in altitude.

Figure 5.2.1: A side profile view of the shed layout for this experiment. Module tilt and active cell areas are shown to affect shading limits on each module behind the front. Plot generated using PVSyst.

PVSyst can also use the module dimensions to generate an eye diagram for visualizing the altitude and azimuth angles that the sun makes with an observer for every day of the year. PVSyst will generate an eye diagram for any location based on coordinates, and one for Ottawa at latitude $45.2^\circ N$ is given in Figure 5.2.2.

The PV modules are mounted on a non-adjustable tilt angle of 15° . The tilt is important for rain and melting snow to slide off, and it minimizes inter-module shading. Even at a latitude of $45^\circ N$ the tilt angle appears to be suitable for mounting on a horizontal surface as shown:

Figure 5.2.2: An eye diagram showing solar altitude and azimuth angles, over one year for Ottawa. The diagram also includes inter-module shading limits for this experiment. Plot generated using PVSyst.

At noon on June 22 the Sun hits the modules at angle

$$\begin{aligned}\theta_{\text{June22}} &= 90^\circ - \text{latitude} + \text{Earth tilt} + \text{module tilt} \\ \theta_{\text{June22}} &= 90^\circ - 45.2^\circ + 23.5^\circ + 15^\circ \\ \theta_{\text{June22}} &= 83.3^\circ \text{ from the cell surface}\end{aligned}$$

but at noon on December 22 the Sun hits the modules at angle

$$\begin{aligned}\theta_{\text{December22}} &= 90^\circ - 45.2^\circ - 23.5^\circ + 15^\circ \\ \theta_{\text{December22}} &= 36.3^\circ \text{ from the cell surface}\end{aligned}$$

For a module tilt of 15° , both θ_{June22} and $\theta_{\text{December22}}$ are consistent with Figure 5.2.2 and increasing the tilt angle to 30° would reduce IAM losses [25]. Using the same logic and arguments from Section 3.1.2 and Andrews et al.[19], other tilt angles can be investigated. For example, a module tilt of 50° produces $\theta_{\text{June22}} = 118.3^\circ$ and $\theta_{\text{December22}} = 71.3^\circ$, giving a worst-

case noon solar angle of less than 30° from normal incidence. The practical downside to a larger tilt is that to achieve the same shading limit of 22.7° , the horizontal distance between modules would have to be increased from 57 cm to 89 cm . The increased module spacing reduces the effective ground area coverage by almost half and requires a larger physical space to position the array.

The panel tilt is not the only factor causing IAM losses; in all but the winter months, the beam component of the sun is highly attenuated by the azimuthal incidence angle of the module array during the first and last few hours of sunlight. The net effect of the altitude/azimuth IAM losses and partial module shading is that the majority of the power generated before 09:00 and after 15:00 is from diffuse irradiation. Figures 4.1.1 also show this (for the winter months), and further investigation can be done to show it for the spring, summer and fall as well.

5.3 Model of PV Performance

The one-diode model in Section 2.1.2 can now be populated with the data collected in this experiment to estimate the potential power generated from a non-ideal PV module. Having collected data only in Ottawa during the winter where solar irradiance is lower due to atmospheric effects, the accuracy might be reduced in the summer, or at a different latitude.

5.3.1 Photocurrent

The photocurrent can be calculated using Equation (2.1.2) from reference values of irradiance and photocurrent (using the relation in Equation (5.1.1)) for reference values of G , T_C , and I_{SC} :

$$I_{ph} = \frac{G}{G_{ref}} \cdot (I_{ph_{ref}} + \mu_{ISC}(T_C - T_{C_{ref}}))$$

Where:

$$G_{ref} : 350Wm^{-2}$$

$$I_{ph_{ref}} : 2.144A$$

$$\mu_{ISC} : 0.001AK^{-1}$$

$$T_{C_{ref}} : 248K$$

This gives:

$$I_{ph}(G, T) = \frac{G}{350Wm^{-2}} \cdot (2.144A + 0.001AK^{-1}(T_C - 248K)) \quad (5.3.1)$$

5.3.2 Diode Forward Current

The diode forward current can be calculated using Equation (2.1.3) from several material constants and the operating current and voltage:

$$I_D = I_0 \left(\exp \left[q \frac{V + I \cdot R_s}{N_{cs} \cdot \gamma \cdot k_B \cdot T_C} \right] - 1 \right)$$

Where:

$$\begin{aligned}
I_0 &: \text{calculated in Equation (5.3.3)} \\
q &: 1.602 \times 10^{-19} C \\
R_s &: 6.74 \Omega \\
N_{cs} &: 22 \\
\gamma &: 4.2 \\
k_B &: 1.381 \times 10^{-23} JK^{-1}
\end{aligned}$$

This gives:

$$I_D(I_0, V, I, N_{cs}, T_C) = I_0 \left(\exp \left[125.5 CKJ^{-1} \frac{V + I \cdot 6.74 \Omega}{N_{cs} \cdot T_C} \right] - 1 \right) \quad (5.3.2)$$

5.3.3 Diode Reverse Saturation Current

The diode reverse saturation current can be calculated using Equation (2.1.4) from reference temperature and saturation current (determined empirically from PVSyst for PVL-144 modules), and material constants:

$$I_0 = I_{0_{ref}} \cdot \left(\frac{T_C}{T_{C_{ref}}} \right)^3 \cdot \exp \left[\frac{q \cdot E_g}{\gamma \cdot k_B} \cdot \left(\frac{1}{T_{C_{ref}}} - \frac{1}{T_C} \right) \right]$$

Where:

$$\begin{aligned}
I_{0_{ref}} &: 11 nA \\
T_{C_{ref}} &: 298 K \\
q &: 1.602 \times 10^{-19} C \\
E_g &: 1.7 eV \\
k_B &: 8.617 \times 10^{-5} eV K^{-1}
\end{aligned}$$

This gives:

$$I_0(T_C) = 11 nA \cdot \left(\frac{T_C}{298 K} \right)^3 \cdot \exp \left[7.525 \times 10^{-16} CK \cdot \left(\frac{1}{298 K} - \frac{1}{T_C} \right) \right] \quad (5.3.3)$$

5.3.4 Shunt Current

The shunt current can be calculated using Equation (2.1.5) from the operating point, series, and shunt resistances:

$$I_{sh} = \frac{V + I \cdot R_s}{R_{sh}}$$

Where:

$$\begin{aligned} R_s &: 6.74\Omega \\ R_{sh} &: 140.1\Omega \end{aligned}$$

This gives:

$$I_{sh}(V, I) = \frac{V + I \cdot 6.74\Omega}{140.1\Omega} \quad (5.3.4)$$

5.3.5 Full Model

Assembling Equations (5.3.1) through (5.3.4), yields the full PV performance model of module current. The full model is given in Equation (5.3.5), and is implicitly defined for load current, I_{load} , meaning that an estimate must be made and a solution iterated.

$$\begin{aligned} I_{load} = & \\ = & \frac{G}{350Wm^{-2}} \cdot (2.144A + 0.001AK^{-1}(T_C - 248K)) \\ & - \left(11nA \cdot \left(\frac{T_C}{298K} \right)^3 \cdot \exp \left[7.525 \times 10^{-16}CK \cdot \left(\frac{1}{298K} - \frac{1}{T_C} \right) \right] \right) \\ & \cdot \left(\exp \left[125.5CKJ^{-1} \frac{V + I \cdot 6.74\Omega}{N_{cs} \cdot T_C} \right] - 1 \right) \\ & - \frac{V + I \cdot 6.74\Omega}{140.1\Omega} \end{aligned} \quad (5.3.5)$$

The calculation for Equation (5.3.5) was made in Microsoft Excel, but

could be implemented as easily in Matlab or C. Unfortunately, equipment problems coupled with snowfall, had prevented the gathering of accurate clear sky data since January 9th, so no large amount of data exists to compare this model against. For illustrative purposes, the best that can be done at this time is to compare against two irradiance measurements that were not used to derive any model parameters; January 3rd $308Wm^{-2}$ and January 9th $295Wm^{-2}$. Table 5.2 summarizes the comparison between the PV performance model and these two points.

Sample	$G (Wm^{-2})$	$T_C (K)$	$I_{load} (A)$	$V_{load} (V)$	$P (W)$	% error
Jan 3	308	247	1.372	34.28	47.03	
Model	308	247	1.438	24.4	35.1	25%
Jan 9	295	262	1.453	28.22	41.00	
Model	295	262	1.362	26.7	36.4	11%

Table 5.2: PV performance model compared against two measurements from January 3rd and 9th.

To generate the results given in Table 5.2, the measured ambient temperature was input, along with the solar irradiance, into the PV performance model. An initial operating voltage and current were assumed, and then the voltage was swept until a maximum power was found. This process is analogous to the MPPT algorithm discussed in Section 3.2.3.

Chapter 6

Concluding Statements

In this thesis, a simulated solar photovoltaic system was reviewed and characterized. An array of Uni-Solar PVL-144 PV modules was selected and placed on the roof of a building with careful consideration to shading and orientation. A complete monitoring system was developed that could autonomously operate and measure the characteristics of a module. A weather monitoring station with pyranometer was also installed alongside the PV modules and tied into the monitoring and control system. Finally, all the data collected were analyzed to extract characteristics of the modules for the one-diode equation as a predictive model of performance.

The monitoring system consisted of hardware to both control the operating point of a module, and to monitor its performance at that point. The hardware portion was designed to have minimal electrical influence on the PV modules, and simple enough to expand the number of modules under investigation if necessary. The software featured a custom algorithm for tracking the maximum power point, and recording the voltage, current,

and solar irradiance. Every 10 minutes, the program would sweep the load resistance to obtain an IV curve of the module before resuming tracking the MPP.

Various methods were used to extract empirical parameters about the PV modules, and some had to be taken from accepted values in literature. The parameters were applied to the PV performance model to allow for an iterative analysis needing only the cell temperature and solar irradiance, with an initial voltage and current assumption. The model was based primarily on data obtained through measurements of the system, but did require some use of commonly accepted values where extraction from data was infeasible or inaccurate.

In comparisons between the PV performance model and real-world data, the model underestimated the maximum power point voltage, and by extension the maximum power. This discrepancy is likely due to the high series resistance in the exponential term of the diode forward current, causing the term to rapidly inflate if initial conditions were estimated too high. In order to find a more accurate resistance, more data collection is required at higher irradiances, to correct the runaway forward current term.

Although writing software was not the primary focus of this thesis, the data collection and MPPT algorithms performed well. The MPPT algorithm converged on a point within 10 seconds and had minimal oscillations about that point during operation. A visual examination of the operating point on an IV curve during testing showed that the computed point was indeed correct, or at least reasonably close.

The data collection problems mentioned in Chapter 4 began in mid-

January, when the value of the filter capacitor for the ACS713 current sensor was changed from $12pF$ to $0.1\mu F$. After this change, the reported current was incorrect, especially at currents higher than $1A$, which rendered the power measurements inaccurate and IV curves unusable.

For the data that were collected and analyzed, the measured parameters for the one-diode model were reasonably accurate and produced estimates of power within 25% of what was measured. The effects of clouds and an overcast sky were discussed, but more measurements are needed in order to conclusively determine any quantitative results. The Uni-Solar literature reports a module efficiency of 6.7% but the data measured in this experiment suggest an efficiency in the range of 7% - 8% for irradiances above $300Wm^{-2}$.

Snow cover was also shown to have a strong impact on the power produced, where a 20 *cm* thick layer causes effectively no power to be generated. The 15° tilt angle of the modules from the manufacturer was one of the primary reasons for a large accumulation of snow. If the modules had been mounted at a steeper angle, there would be more of a chance for snow to fall off and they would also be oriented more perpendicular to the sun, reducing IAM losses. The modules would need to be placed further apart, taking up more roof area, but increasing the tilt to $50^\circ \pm 10^\circ$ would likely be ideal for Ottawa's location and climate. If the location is suitable, another option is to mount the modules as 'sun-shields' on the side of a building which allows for high-tilt angles and eliminates inter-module shading.

This experiment lays the groundwork for a more in-depth investigation to draw a complete model for yearly performance of different types of solar technologies. Module tilt is another important factor for temperate climates

that can be investigated further for its impact on snow accumulation and low solar altitude angles. The basis for producing an empirical model of rain, snow, and cloud effects on PV modules was described in this thesis, but not fully carried out due to the extra equipment necessary.

6.1 Recommendations

If this experiment were to be repeated, I would recommend a few modifications to the data collection hardware. The largest source of error was the LabJack and its low input impedance resulted in noisy data. The LabJack simplifies interfacing with the computer, so it would be preferable to use a low-noise op-amp on each of its single-ended inputs, rather than selecting a different datalogging interface. When the differential inputs of the LabJack were used, there seemed to be less noise in the values read by the software, so single-ended signals could also be replaced with a differential measurement.

Another recommendation is to collect data with a wide range of irradiances in order to more accurately determine series and shunt resistance of the modules. A correct value of series resistance is important, as a value that is too large will cause the model's current to diverge due to the exponential term.

Having a large dataset is helpful for accuracy, but with the slow rate of change in the weather conditions, measuring at one-second intervals was too much data to collect and analyze. I believe accuracy could be improved if measurements were taken at longer intervals and averaged over one minute. Reducing the data to once per minute would bring the number of data

points from over 60000 to over 1000. The IV curve algorithm also needs to be improved to produce a more evenly distributed set of points to further reduce the amount of data processing.

6.2 Future Work

This experiment should be continued by following the recommendations in Section 6.1, and gathering lower-interval data on a PV module. More modules could be analyzed with different PV chemistries or manufacturers, by adding more datalogging circuits. The data collection software could benefit from a more user-friendly interface, and the output format could be made to simplify the data analysis.

Another necessary effort would be to obtain a more diverse data set in order to ensure the model parameters are accurate. The results would also be improved by allowing for at minimum, one complete year of data collection, while monitoring several modules at once. Having multiple identical modules is necessary for quantifying the effects of snow cover as long as snowfall is able to be manually removed when necessary. Once more accurate data collection techniques are in place, it would be relatively simple to add corrections to the one-diode model to predict cell temperature if only the ambient temperature were available. The temperature prediction could be extended to include the effects of wind and rain, given that the weather station already monitors these parameters.

Finally, it would be extremely beneficial to monitor the same modules mounted on different tilt angles. This would enable a more accurate predic-

tion of the best angle to reduce snow accumulation and increase generated power on winter days when the Sun is at a lower altitude angle. Having this information would be valuable to those involved in Ontario's FIT program, and any other consumer in Ontario wishing to install a PV system.

Appendix A

Derivations of Equations

A.1 Voltage Sensor

The voltage divider layout in Figure 3.2.3 can be solved to find the unknown PV module voltage V_{PV} :

given:

- V_{in} : measured voltage reported by LabJack in volts [V]
- I_{in} : input current given by Equation (3.2.1) in Amperes [A]
- R_1 : upper resistor [$1.194M\Omega$]
- R_2 : lower resistor [$38.26k\Omega$]

Using Kirchhoff's Current Law

$$I_{R_1} = I_{R_2} + I_{in}$$

using Ohm's Law

$$\begin{aligned}\frac{V_{PV} - V_{in}}{R_1} &= \frac{V_{in}}{R_2} + I_{in} \\ \frac{V_{PV}}{R_1} &= \frac{V_{in}}{R_1} + \frac{V_{in}}{R_2} + I_{in} \\ V_{PV} &= V_{in} + V_{in} \frac{R_1}{R_2} + R_1 I_{in}\end{aligned}$$

substituting I_{in} with Equation (3.2.1)

$$\begin{aligned}
V_{PV} &= V_{in} + V_{in} \frac{R_1}{R_2} + R_1 (8.181 \times 10^{-6} \mathcal{U} \cdot V_{in} - 11.67 \mu A) \\
V_{PV} &= V_{in} \left(1 + \frac{R_1}{R_2} + 8.181 \times 10^{-6} \mathcal{U} \cdot R_1 \right) - R_1 (11.67 \mu A) \\
V_{PV} &= V_{in} \left(1 + \frac{1.194 M\Omega}{38.26 k\Omega} + 8.181 \times 10^{-6} \mathcal{U} \cdot 1.194 M\Omega \right) \\
&\quad - 1.194 M\Omega \cdot 11.67 \mu A \\
V_{PV} &= V_{in} (41.97564) - 13.93398 V
\end{aligned}$$

Appendix B

C++ Code

This appendix section is all the raw C++ code used in data collection.

B.1 LabJack Class Header

Listing B.1: LJBase.h

```
1 //LJBase.h
2 // Written by Kevin Graff, December 2013
3 // with excerpts from LabJack Corporation used with
  permission.
4 // Available at: http://labjack.com/support/u12/examples/dev
  -C
5 // LabJack standard header:
6 //-----
7 //
8 // LabJack U12 Legacy driver example using dynamic linking.
  Tested on
9 // Dev-C++ 4.9.9.2, but should work with any Windows C
  compiler.
10 //
11 // support@labjack.com
12 // 8/2005
13 //-----
14 //
15 #include <stdio.h>
16 #include <wtypes.h>
17 #ifndef LJBASE_H //check for previous inclusion
18 #define LJBASE_H //establish header guard
19
```

```

20 typedef long (CALLBACK *tAISample) (long*, long, long*, long,
    long, long, long*, long*, long, long*, float*);
21 typedef long (CALLBACK *tAOUpdate) (long*, long, long, long, long
    *, long*, long, long, unsigned long*, float, float);
22
23 class LJBase
24 {
25     public:
26         LJBase();
27         void analog_update(float ao0);
28         void analog_read(float voltages[]);
29         void diff_read(float voltages[]);
30
31         //Define a variable to hold a handle to the loaded DLL.
32         HINSTANCE hDLLInstance;
33
34         //Define variables for functions we will use.
35         tAISample m_pAISample;
36         tAOUpdate m_pAOUpdate;
37
38     private:
39         long idnum;
40         long stateIO;
41         long ov;
42         long channels[4];
43         long diffchannels[1];
44         long gains[4];
45         long trisD, trisIO, stated;
46         unsigned long count;
47 };
48 #endif

```

B.2 LabJack Class

Listing B.2: LJBase.cpp

```

1 //LJBase.cpp
2 // Written by Kevin Graff, December 2013
3 // with excerpts from LabJack Corporation used with
    permission.
4 // Available at: http://labjack.com/support/u12/examples/dev
    -c
5 // LabJack standard header:

```

```

6  //-----
7  //
8  // LabJack U12 Legacy driver example using dynamic linking.
   Tested on
9  // Dev-C++ 4.9.9.2, but should work with any Windows C
   compiler.
10 //
11 // support@labjack.com
12 // 8/2005
13 //-----
14 //
15 #include "LJBase.h"
16
17 //First define structures that have the same format as the
   desired function prototype.
18
19 //Constructor
20 LJBase::LJBase ()
21 {
22     //try and load the DLL.
23     if (hDLLInstance = LoadLibrary("ljackuw.dll"))
24     {
25         //If successfully loaded, get the address of the
           desired functions.
26         m_pAISample = (tAISample)::GetProcAddress(hDLLInstance,
           "AISample");
27         m_pAOUpdate = (tAOUpdate)::GetProcAddress(hDLLInstance,
           "AOUpdate");
28     }
29     else
30     {
31         printf("\nFailed to load DLL\n");
32     }
33
34     idnum=-1; //reset this before each call
35     stateIO=0; //not using this
36     ov=0; //reset this before each call
37     trisD=0; //doesn't get modified by dll calls
38     trisIO=0; //doesn't get modified by dll calls
39     stateD=0; //not using this
40     count=0; //not using this
41
42     channels[0]=0; //doesn't get modified by dll calls
43     channels[1]=1;
44     channels[2]=2;

```

```

45  channels[3]=3;
46  diffchannels[0]=10;
47  gains[0]=0; //doesn't get modified by dll calls
48  gains[1]=0; //7= +/- 1V range on differential voltage
49  gains[2]=0;
50  gains[3]=0;
51 }
52
53 void LJBase::analog_update(float ao0)
54 {
55     long errorcode=0;
56
57     idnum=-1;
58     /*
59     if(ao0 > 0.0)
60     {
61         printf("\n\nWARNING! YOU ARE ABOUT TO SET GATE VOLTAGE
62             TO %f\n\nPress Enter to proceed.\n\n",ao0);
63         getchar();
64     }
65     */
66     errorcode = m_pAOUpdate(&idnum,0,trisD,trisIO,&stated,&
67         stateIO,1,0,&count,ao0,0);
68     if(errorcode > 0)
69     {
70         printf("\nAOUpdate... Error = %d\n",errorcode);
71     }
72
73 void LJBase::analog_read(float voltages[])
74 {
75     long errorcode=0;
76     idnum=-1;
77     ov=0;
78     voltages[0]=0;
79     voltages[1]=0;
80     voltages[2]=0;
81     voltages[3]=0;
82
83     errorcode = m_pAISample(&idnum,0,&stateIO,0,0,4,channels,
84         gains,0,&ov,voltages);
85     if(errorcode > 0)
86     {
87         printf("AISample... Error = %d\n",errorcode);
88     }

```

```

87     if(ov > 0)
88     {
89         printf("\nAISample... Overvoltage Detected!\n");
90         ov=0;
91     }
92
93 }
94
95 void LJBase::diff_read(float voltages[])
96 {
97     long errorcode=0;
98     idnum=-1;
99     ov=0;
100    voltages[0]=0;
101    voltages[1]=0;
102    voltages[2]=0;
103    voltages[3]=0;
104
105    gains[0]=7; //doesn't get modified by dll calls
106    gains[1]=7; //7= +/- 1V range on differential voltage
107    gains[2]=7;
108    gains[3]=7;
109
110    errorcode = m_pAISample(&idnum,0,&stateIO,0,0,1,
111        diffchannels,gains,0,&ov,voltages);
112    if(errorcode > 0)
113    {
114        printf("Differential AISample... Error = %d\n",
115            errorcode);
116    }
117    if(ov > 0)
118    {
119        printf("\nDifferential AISample... Overvoltage Detected
120            !\n");
121        ov=0;
122    }
123
124    gains[0]=0;
125    gains[1]=0;
126    gains[2]=0;
127    gains[3]=0;
128 }

```

B.3 Main Program

Listing B.3: main.cpp

```
1 //main.cpp
2 // Written by Kevin Graff, December 2013
3 //-----
4 //
5 // Assuming to be scheduled to start at 0400hours for Ottawa
6 // 's sunrise
7 // on June 21st at 0514hours.
8
9 #include "LJBase.h"
10 #include <stdio.h>
11 #include <wtypes.h>
12 #include <iostream>
13 #include <fstream>
14 #include <time.h>
15 #include <string>
16 #include <dirent.h>
17 #include <stdlib.h>
18
19 using namespace std;
20
21 const float TAMBIENT = 22.0; //degC
22 const float VTURNON = 15.0; //turn on voltage
23 const float EPS = 0.0000001; //smallest division displayed
24 // on output
25 const int IVINTERVAL = 10; //interval in minutes between IV
26 // characteristic measurements
27
28 // Returns in Volts
29 float vScale(float voltage)
30 {
31     return ((voltage * 41.97564144) - 13.93398);
32 }
33
34 // Returns in Amps
35 float iScale(float voltage, float vref)
36 {
37     // remove zero current output voltage and divide by v-i
38     // ratio
39     return ((voltage - (vref * 0.1)) / 0.185);
40 }
```

```

38 // Returns in W/m^2
39 float pyroScale(float pyroReading)
40 {
41     return (pyroReading * 5000.0);
42 }
43
44 float average10(float arg[])
45 {
46     float highest=arg[0];
47     float lowest=arg[0];
48     float sum = 0;
49
50     for(int i = 0; i < 10; i++)
51     {
52         sum+=arg[i];
53         if(arg[i] > highest) { highest = arg[i]; }
54         if(arg[i] < lowest) { lowest = arg[i]; }
55     }
56     sum-=highest;
57     sum-=lowest;
58     //debug line
59     //printf("highest: %f lowest: %f\n",vScale(highest),
60             vScale(lowest));
61     return (sum/8.0);
62 }
63
64 float average3(float arg[])
65 {
66     float sum = 0;
67
68     for(int i = 0; i < 3; i++)
69     {
70         sum+=arg[i];
71     }
72     return (sum/3.0);
73 }
74
75 float power(float voltage, float current)
76 {
77     return voltage*current;
78 }
79
80 //When this returns, volts[2] and amps[2] become ready for
81 //overwrite

```



```

80 void MPPT(LJBase &labjack, float *volts, float *amps, float
    &pwr, float *vGate)
81 {
82     /* Conventions:
83         volts[2] is the most recent measurment
84         volts[0] is the oldest measurement
85         vGateHistory -> 0=unchanged, +tive=went up, -tive=went
            down
86     */
87
88     pwr = power(volts[2], amps[2]);
89     float dpwr[2]; //delta power
90     dpwr[1] = (pwr - power(volts[1], amps[1]));
91     dpwr[0] = (pwr - power(volts[0], amps[0]));
92
93     if(volts[1]==0.0 && volts[0]==0.0) //zero power, start at
        open circuit with a kick
94     {
95         vGate[2]=0.01;
96     }
97     else if((vGate[2] < 3.0) && (volts[2] >= VTURNON))
98     {
99         vGate[2]+=0.1;
100    }
101    else if(volts[2]>=VTURNON) //Start tracking at V_open-
        circuit = VTURNON
102    {
103        if(vGate[2] - vGate[1] > 0) //vGate went up
104        {
105            if((dpwr[1] < 0) && (dpwr[0] < 0)) //power went down
                twice, so decrease vGate
106            {
107                vGate[2]-=0.01;
108            }
109            else if ((dpwr[1] > 0) && (dpwr[0] > 0)) //power went
                up twice, so increase vGate
110            {
111                vGate[2]+=0.01;
112            }
113            else //power fluctuated so keep vGate the same
114            {
115                vGate[2]=vGate[1];
116            }
117        }
118        else if(vGate[2] - vGate[1] < 0) //vGate went down

```

```

119     {
120         if((dpwr[1] < 0) && (dpwr[0] < 0)) //power went down
            twice, so increase vGate
121         {
122             vGate[2]+=0.01;
123         }
124         else if ((dpwr[1] > 0) && (dpwr[0] > 0)) //power went
            up twice, so decrease vGate
125         {
126             vGate[2]-=0.01;
127         }
128         else //power fluctuated so keep vGate the same
129         {
130             vGate[2]=vGate[1];
131         }
132     }
133     else //vGate didn't change
134     {
135         if((dpwr[1] < 0) && (dpwr[0] < 0)) //power went down
            twice
136         {
137             if(vGate[1] - vGate[0] > 0) //vGate went up, so
                decrease it
138             {
139                 vGate[2]-=0.01;
140             }
141             else //vGate went down or stayed the same, so try
                increasing it
142             {
143                 vGate[2]+=0.01;
144             }
145         }
146         else if ((dpwr[1] > 0) && (dpwr[0] > 0)) //power went
            up twice
147         {
148             if(vGate[1] - vGate[0] < 0) //vGate went down, so
                decrease it
149             {
150                 vGate[2]-=0.01;
151             }
152             else //vGate went up or stayed the same, so try
                increasing it
153             {
154                 vGate[2]+=0.01;
155             }

```

```

156         }
157         else //power fluctuated so keep vGate the same
158         {
159             vGate[2]=vGate[1];
160         }
161     }
162 }
163 else //start turning off if V is less than VTURNON to get
      closer to Voc
164 {
165     vGate[2]-=0.01;
166 }
167
168 //Update FET gate
169 if(vGate[2] < 0.0) { vGate[2] = 0.0; }
170 labjack.analog_update(vGate[2]);
171
172 //Shift values in history
173 for(int i=0; i<2; i++)
174 {
175     volts[i]=volts[i+1];
176     amps[i]=amps[i+1];
177     vGate[i]=vGate[i+1];
178 }
179 }
180
181 int ivCurve (LJBase &labjack, time_t &rawtime, ofstream &
      file, float vGateOriginal)
182 {
183     //vGateOriginal stores the current gate voltage to resume
      tracking after this function completes
184     float vGate = 0.0;
185     float voltages[] = {0,0,0,0};
186     float vSamples[] = {0,0,0};
187     float iSamples[] = {0,0,0};
188     float vrefSamples[] = {0,0,0};
189     float avg_vSamples = 0.0;
190     float avg_iSamples = 0.0;
191     float avg_vrefSamples = 0.0;
192
193     while(1)
194     {
195         //Measure 1 datapoint and print to file
196         for(int i=0; i<3; i++)
197         {

```

```

198     labjack.analog_read(voltages);
199     vSamples[i]=voltages[1];
200     iSamples[i]=voltages[0];
201     vrefSamples[i]=voltages[2];
202     Sleep(10);
203 }
204
205 avg_vSamples = vScale(average3(vSamples));
206 avg_vrefSamples = average3(vrefSamples);
207 avg_iSamples = iScale(average3(iSamples),
    avg_vrefSamples);
208
209 if(avg_vSamples < 0) { avg_vSamples = 0.0; }
210 if(avg_vrefSamples < 0) { avg_vrefSamples = 0.0; }
211 if(avg_iSamples < 0) { avg_iSamples = 0.0; }
212
213 //Write to file
214 if (file.is_open())
215 {
216     file << rawtime << "\t" << avg_iSamples << "\t" <<
217         avg_vSamples << "\t" << vGate << endl; //endl to
        flush the stream buffer
218 }
219 else //File is closed, something went wrong
220 {
221     printf("ERROR! Could not open file for write\n");
222     return 1; //leave main loop
223 }
224
225
226 if(vGate < 1.5)
227 {
228     vGate+=0.5;
229 }
230 else if(vGate <= 2.5)
231 {
232     vGate+=0.1;
233 }
234 else if(vGate < 3.4)
235 {
236     vGate+=0.01;
237 }
238 else if(vGate <= 4.5)
239 {
240     vGate+=0.1;

```

```

241     }
242     else if(vGate >= 4.5)
243     {
244         break;
245     }
246
247     labjack.analog_update(vGate);
248 }
249
250 //Update FET gate
251 if(vGateOriginal < 0.0) { vGateOriginal = 0.0; }
252 labjack.analog_update(vGateOriginal);
253
254 return 0; //return success
255 }
256
257 main()
258 {
259     float voltages[4];
260     float diffvoltages[4];
261     float vSamples[10];
262     float iSamples[10];
263     float vrefSamples[10];
264     float pyroSamples[10];
265     float avg_vSamples;
266     float avg_iSamples;
267     float avg_vrefSamples;
268     float avg_pyroSamples;
269     float voltsHistory[] = {0,0,0};
270     float ampsHistory[] = {0,0,0};
271     float mpptPower=0;
272     float vGate[] = {0,0,0};
273     int ivCurveReturn = 0;
274
275     ofstream outfile; //holds main program output for the
                        hour
276     ofstream ivfile; //holds iv curve data for the day
277     char timeInt[sizeof(long)*10+1];
278     string timeString(timeInt);
279     string baseFilename("C:\\Dropbox\\Masters Degree\\Data\\
                        LJMonitor Data\\timestamp-");
280     string ivbaseFilename("C:\\Dropbox\\Masters Degree\\Data
                        \\LJMonitor Data\\IV-Curves\\ivdata-");
281     string filename("");
282     string ivfilename("");

```

```

283  time_t rawtime;
284  time_t oldtime;
285  struct tm newFileTime;
286  struct tm exitProgramTime;
287  struct tm starttime;
288  struct tm ivtime;
289  LJBase labjack; //new instance of LJBase Class
290
291  cout << "LJMonitor Initialized, reading time and setting
      up key times.\n" << endl;
292  time(&rawtime);
293
294  //Check if there is an error reading system time
295  if(rawtime<=0)
296  {
297      cout << "\nError reading system time!\n" << rawtime <<
          endl;
298      getchar();
299      return EXIT_FAILURE;
300  }
301
302  //Set up the start time as 03:59:59
303  starttime = *localtime(&rawtime);
304  starttime.tm_hour=3;
305  starttime.tm_min=59;
306  starttime.tm_sec=59;
307
308  //Set up the exit time as 22:00:00
309  exitProgramTime = *localtime(&rawtime);
310  exitProgramTime.tm_hour=22; //terminate the program
      whenever the time is 22:mm:ss
311  exitProgramTime.tm_min=0;
312  exitProgramTime.tm_sec=0;
313
314  cout << "Waiting until start time...\n" << endl;
315  //Wait until the start time
316  while(1)
317  {
318      if(difftime(rawtime,mktime(&starttime)) >= 0) { break;
          }
319      time(&rawtime);
320  }
321
322  //Open initial file
323  time(&rawtime);

```

```

324   ltoa(rawtime,timeInt,10);
325   timeString = timeInt;
326   filename = baseFilename;
327   ivfilename = ivbaseFilename;
328   filename += (timeString + ".csv");
329   ivfilename += (timeString + ".csv");
330   outfile.open (filename.c_str(), ios::out | ios::app);
331   ivfile.open (ivfilename.c_str(), ios::out | ios::app);
332
333   //Set the new file timer
334   newFileTime = *localtime(&rawtime);
335   newFileTime.tm_min=0;
336   newFileTime.tm_sec=0;
337
338   //Set up the iv gathering time
339   ivtime = *localtime(&rawtime);
340   ivtime.tm_min=0;
341   ivtime.tm_sec=0;
342
343   oldtime=rawtime;
344
345   cout << "Objects initialized. Entering main loop.\n\n" <<
        endl;
346   // if current time is 0 mins and 0 secs then (if a file is
        open close it) make a new file and reset newFileTime
347   // if current time is 22 hours then close the open file, set
        AN0 to 0, and exit program
348   // on timer tick (call all the data gathering stuff and do
        something with MPPT)
349   while(1)
350   {
351       //Quit program at exitProgramTime time
352       if(difftime(rawtime,mktime(&exitProgramTime)) >= 0)
353       {
354           cout << "\nIt is now after 10pm -> exiting main loop"
                << endl;
355           break; //leave main loop
356           //This is the primary exit point if all goes well
357       }
358
359       //Make a new file 1 hour after the last file
360       if(difftime(rawtime,mktime(&newFileTime)) >= 3600.0)
361       {
362           cout << "\nIt has been 3600 or more seconds since
                creation of file -> making a new one" << endl;

```

```

363
364     if(outfile.is_open())
365     {
366         outfile.close();
367     }
368     ltoa(rawtime,timeInt,10);
369     timeString = timeInt;
370     filename = baseFilename;
371     filename += (timeString + ".csv");
372     outfile.open (filename.c_str(), ios::out | ios::app);
373
374     //Reset the new file timer
375     newFileTime = *localtime(&rawtime);
376     newFileTime.tm_min=0;
377     newFileTime.tm_sec=0;
378 }
379
380 // Gather IV characteristic
381 if(difftime(rawtime,mktime(&ivtime)) >= 0)
382 {
383     if(voltsHistory[2] > 10.0)
384     {
385         printf("Gathering I-V Characteristic...\n");
386         ivCurveReturn = ivCurve(labjack, rawtime, ivfile,
387                                 vGate[2]);
388         printf("I-V Function Returned: %i\n\n",
389               ivCurveReturn);
389     }
390     else { printf("Voltage less than 10V, too low for I-V
391                 curve\n"); }
392
393     //Refresh current time
394     time(&rawtime);
395
396     //Reset the IV Characteristic timer
397     ivtime = *localtime(&rawtime);
398     ivtime.tm_min+=IVINTERVAL;
399     ivtime.tm_sec=0;
400
401     int newminute = ivtime.tm_min / IVINTERVAL;
402     newminute*=IVINTERVAL;
403     if(newminute >= 60) { newminute = 0; }
404     ivtime.tm_min = newminute;

```



```

405     //Wait until clock tick
406     while(1)
407     {
408         if(difftime(rawtime,oldtime) >= 1) { break; }
409         time(&rawtime);
410     }
411
412     //Make a measurement
413     for(int i=0; i<10; i++)
414     {
415         labjack.analog_read(voltages);
416         labjack.diff_read(diffvoltages);
417         vSamples[i]=voltages[1];
418         iSamples[i]=voltages[0];
419         vrefSamples[i]=voltages[2];
420         pyroSamples[i]=diffvoltages[0]; //differential read
421         Sleep(20);
422     }
423
424     avg_vSamples = vScale(average10(vSamples));
425     avg_vrefSamples = average10(vrefSamples);
426     avg_iSamples = iScale(average10(iSamples),
427         avg_vrefSamples);
428     avg_pyroSamples = pyroScale(average10(pyroSamples));
429
430     if(avg_vSamples < 0) { avg_vSamples = EPS; }
431     if(avg_vrefSamples < 0) { avg_vrefSamples = EPS; }
432     if(avg_iSamples < 0) { avg_iSamples = EPS; }
433     if(avg_pyroSamples < 0) {avg_pyroSamples = EPS; }
434
435     voltsHistory[2] = avg_vSamples;
436     ampsHistory[2] = avg_iSamples;
437
438     //Run the MPPT algorithm
439     MPPT(labjack, voltsHistory, ampsHistory, mpptPower,
440         vGate);
441
442     //Write to file
443     if (outfile.is_open())
444     {
445         outfile << rawtime << "\t" << avg_iSamples << "\t" <<
446             avg_vSamples << "\t" << avg_vrefSamples << "\t" <<
447             avg_pyroSamples << "\t" << mpptPower << "\t" <<
448             vGate[2] << endl; //endl to flush the stream buffer
449     }

```

```

448     else //File is closed, something went wrong
449     {
450         struct tm * errtime;
451         errtime = localtime(&rawtime);
452         printf("ERROR! Could not open file for write at %s\n"
453             ,asctime(errtime));
454         break; //leave main loop
455     }
456
457     //Console Output
458     printf("Panel Current (AI0) = %f Amps\n", avg_iSamples);
459     printf("Panel Voltage (AI1) = %f Volts\n", avg_vSamples)
460     ;
461     printf("5V Rail Voltage (A12) = %f Volts\n",
462         avg_vrefSamples);
463     printf("Pyranometer (AI4,5) = %f Watts/m^2\n",
464         avg_pyroSamples);
465     printf("Panel Power (V x I) = %f Watts\n", mpptPower);
466     printf("Gate Voltage (VO0) = %f Volts\n\n", vGate[2]);
467
468     time(&rawtime); //refresh current time
469     oldtime = rawtime;
470 };
471 //End of main loop
472
473 if(outfile.is_open())
474 {
475     outfile.close();
476 }
477
478 //reset AOx to 0
479 printf("\nEnd of File Write: Resetting AOx to 0...\n");
480 labjack.analog_update(0);
481
482 return EXIT_SUCCESS;
483 }

```

Appendix C

Sample Calculations

C.1 Fill Factor

The fill factor for any PV cell's IV curve can be found using Equation (2.4.1):

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

Where:

$$V_{MPP} : 33.12V$$

$$I_{MPP} : 1.954A$$

$$V_{OC} : 42.26V$$

$$I_{SC} : 2.474A$$

$$FF = \frac{33.12V \cdot 1.954A}{49.54V \cdot 2.474A}$$

$$FF = \frac{64.72W_{real}}{122.6W_{ideal}}$$

$$FF = 0.53$$

The fill factor for this example is 0.53, or, the power produced by this real cell is 53% of an ideal cell at this irradiance ($395Wm^{-2}$).

C.2 Module Efficiency

The module efficiency is the percentage of irradiance that is converted by the panel into electrical power through the load. The generated power in this example is $P = 68.5W$, on January 3, 2014 at the peak irradiance of $G = 397Wm^{-2}$, shown in Figure 4.1.1a. The total active area of the cells is $A = 2.161m^2$.

$$\begin{aligned} eff &= \frac{G}{\frac{P}{A}} \\ eff &= \frac{397Wm^{-2}}{\frac{68.5W}{2.161m^2}} \\ eff &= 0.0798 \end{aligned}$$

The efficiency of the modules in this example is about 8.0%.

C.3 Shunt and Series Resistances

Shunt and series resistances in this example will be calculated using data collected from the IV curve in Figure C.3.1.

Figure C.3.1: IV curve showing data and slopes used to calculate shunt and series resistances for January 3, 2014

C.3.1 Shunt Resistance

The shunt resistance of a cell can be estimated by the inverse of the slope near the short circuit current. Figure C.3.1 shows the linear slope of the curve near I_{SC} , and the data points used to calculate it. The slope is here is $-0.006AV^{-1}$ so the shunt resistance is approximately:

$$\begin{aligned} R_{sh} &= \frac{1}{slope_{I_{SC}}} \\ R_{sh} &= \frac{1}{|-0.006AV^{-1}|} \\ R_{sh} &= 166.7\Omega \end{aligned}$$

C.3.2 Series Resistance

The series resistance of a cell can be estimated by the inverse of the slope near the open circuit voltage. Figure C.3.1 shows the linear slope of the curve near V_{OC} , and the data points used to calculate it. The slope is here is $-0.149AV^{-1}$ so the series resistance is approximately:

$$\begin{aligned} R_s &= \frac{1}{slope_{V_{OC}}} \\ R_s &= \frac{1}{|-0.149AV^{-1}|} \\ R_s &= 6.71\Omega \end{aligned}$$

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