Title
Efficient yet Accurate Models for Photovoltaic Modules with Shading Effects

Author
Tu, Tianheng

Publication Date
2014

UNIVERSITY OF CALIFORNIA

Los Angeles

Efficient yet Accurate Models for Photovoltaic Modules with Shading Effects

A thesis submitted in partial satisfaction

of the requirements for the degree of Master of Science

in Electrical Engineering

by

Tianheng Tu

2014

ABSTRACT OF THE THESIS

Efficient yet Accurate Models for Photovoltaic Modules with Shading Effects

by

Tianheng Tu

Master of Science in Electrical Engineering

University of California, Los Angeles, 2014

Professor Lei He, Chair

Mismatches between solar cells, such as shading effects, significantly reduce the output power of a photovoltaic (PV) module. An effective method to maintain power output in the presence of these mismatches is to add bypass diodes. However, existing modeling approaches cannot efficiently model PV modules with bypass diodes in place. Starting with an equivalent circuit model of a PV module, we develop a Colony-Wise model to reduce the model complexity while maintaining the same accuracy compared to the well-accepted Ground Truth model. To further reduce the model complexity, a Two-Colony model with a constant computational complexity is developed. We analyze the accuracy of the Two-Colony model by comparing its Power-Voltage (P-V) curves to the results generated by the Ground Truth model. Experimental results show that the maximum output power values have an average

error of 3.4% and average correlation of 0.962 with respect to the Ground Truth model’s results.

Paulo Tabuada

Sudhakar Pamarti

Lei He, Committee Chair

University of California, Los Angeles

2014

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my advisor, Professor Lei He, for his guidance and advice as I worked on this thesis. I would like to acknowledge Professor Chien-Nan Liu from National Central University, Taiwan for his help on the circuit modeling and verification methods during his visit to UCLA. Finally, I would like to thank my parents for their support and love.

Chapter 1

INTRODUCTION

As the demand for clean energy has been increasing over the last two decades, photovoltaic (PV) systems are now widely adopted in a multitude of fields, such as distributed power generators and stand-alone micro grid systems [1]. However, the output power of a PV system or a solar panel (a panel consists of several PV modules, and a module in turn consists of cascaded and paralleled solar cells) is significantly reduced by mismatches between solar cells, such as temperature variations, non-uniform cell aging, and partial shading across the PV modules [2], [3]. Consequently, modeling the power loss in a PV system due to these mismatches is critical for design and operation. Among all mismatches, we focus on shading effects because they lead to the greatest power reduction [3]. Shading effects are the effects that a PV module experiences when there is partial shading on the module (e.g. the shadow of a cloud or an obstacle covers a part of a PV module). However, it should be noted that our methods can be extended to alternative mismatches.

In addition to power output reduction, shading effects can damage solar cells due to hot-spot formation (the shaded cells are overheated by the forward bias current generated by the unshaded cells) [4], [5], [6]. In order to alleviate these problems, adding bypass diodes to

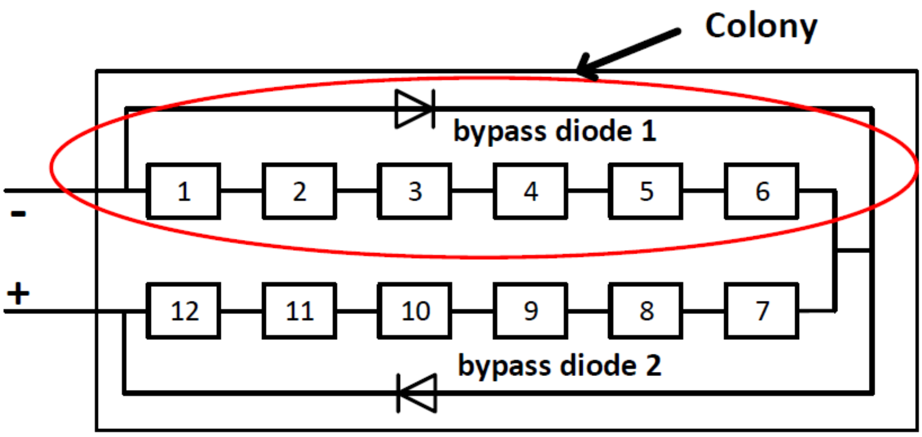


Figure 1: An Example of Bypass Diodes Configuration [4]

bypass the shaded cells, as shown in Figure 1, has been proven effective [2], [4], [7], [8], [9].

In addition, the partial shading on a PV module varies because of the changing position of the sun or the movement of a cloud. The time-varying nature of shading causes output power variation, which prohibits the optimal usage of a PV system [4]. When the output power of a utility scale PV system is injected into the power grid, it needs to be near-constant. A good model for PV modules can capture fluctuations of the output power of a PV system in real time and work with other supplemental power generators to make the PV system's output power close to constant. In addition, in order to use a PV system optimally, the load needs to be adjusted according to the maximum power point tracking (MPPT) system to achieve the maximum output power [2]. The PV module model is a key module in the MPPT system, which can estimate the Power-Voltage curve and the maximum output power [2]. Consequently, an accurate and efficient model for PV modules with shading effects is critical.

A widely used equivalent circuit model for a solar cell consists of a current source, a diode and resistors [3], [7], [10]. It is referred to as the One-Diode model throughout this thesis. The One-Diode model will be discussed in detail in Chapter 2.1. Since a PV module is a combination of solar cells, it can be modeled by a matrix of One-Diode models with additional bypass diodes. This model consisting of One-Diode models and bypass diodes is the well-accepted PV module model [2], [3], and is referred to as the Ground Truth model throughout this thesis. The output power of a solar farm (consisting of thousands or more PV modules) needs to be calculated using this model in real time to capture the time-varying shade. However, the computational complexity of the Ground Truth model grows in proportion to the number of solar cells. Such model complexity is not affordable in a real time system. Consequently, further reduction of the PV module model's complexity is necessary.

To solve the above problem, we first develop a Colony-Wise PV module model, in which a colony is a bypass diode plus all its paralleled solar cells, as shown in the circle in Figure 1. Under the assumption that a cell is either fully shaded or has no shade, solar cells in parallel with the same bypass diode (i.e., a colony) can be lumped into two macro-cells. One macro-cell represents all the shaded solar cells in a colony and the other represents the unshaded ones. Chapter 3 provides details that show this reduction procedure results in no accuracy loss. To further reduce the complexity of the PV module model, a Two-Colony model is developed. Chapter 4 shows the procedure to lump all the solar cells in a PV module into two colonies. Because this model only uses two colonies to model a single PV module, it has a constant computational complexity. Additionally, it is still able to maintain high accuracy.

The rest of this thesis is organized as follows. Chapter 2 presents the preliminaries of the solar cell modeling and effects of bypass diodes. Chapter 3 introduces and validates the Colony-Wise model. Chapter 4 develops and presents the Two-Colony model. Chapter 5 compares these two new models with the Ground Truth model. Chapter 6 concludes the thesis and discusses future work.

Chapter 2

PRELIMINARIES

2.1 One-Diode Model

One way to model a solar cell is to use an equivalent circuit with a current source and a diode in parallel as shown in Figure 2. This model was developed in [10] and is called the One-Diode model in this thesis.

For the One-Diode model, the Current-Voltage (I-V) curve of the solar cell is as follows [11]:

$$I = I_{ph} - I_s \left[\exp\left(q \frac{V + R_s I}{NkT} \right) - 1 \right] - \frac{V + R_s I}{R_{sh}} \quad (1)$$

where I_{ph} is the photovoltaic (PV) current and I_s is the reverse saturation current of the diode D. N is the diode quality factor , k is the Boltzmann constant, T is the cell operating temperature and q is the unit electronic charge. R_s is the equivalent serial resistance of the cell and R_{sh} is the shunt resistance [11]. These parameters can be extracted from manufacturer specifications or from the measured I-V curves of solar cells.

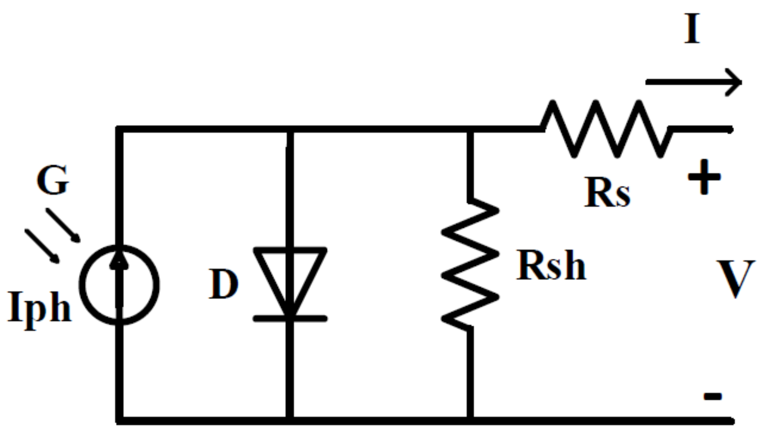


Figure 2: One-Diode Model for a Solar Cell

2.2 Impacts of Bypass Diodes

Shading effects are defined as the non-uniform solar irradiances across the PV module and are the major cause for a drop in energy yield in the PV system. Bypassing the shaded cells with bypass diodes has been proven to be effective in mitigating power loss [4].

One way to model a PV module with shading effects is as follows. For a certain solar cell, its current source value in Equation 1 is determined by its shading level (degree of the shading) as in [13]. Thus, if the shading pattern and shading strengths are known, the One-Diode equivalent circuit model of each cell in the PV module is known. By solving all the equations together with the additional bypass diode configuration (for example, see Figure 1), the I-V curve for the solar module can be extracted. This method is well-accepted [2], [3] and is called the Ground Truth model in this thesis.

The major limitation of the Ground Truth model is that each solar cell needs to be modeled as a One-Diode model. Applying the model to every solar cell causes the number of nonlinear equations to grow proportionally to the number of solar cells. Thus, the model of a solar farm (consisting of thousands or more PV modules) has high complexity and requires a long simulation time and significant computational resources. Consequently, the real time calculation of a solar farm's output power is very difficult to be achieved based on the One-Diode model [12].

We illustrate the impact of bypass diodes in several experiments below by comparing the P-V curves using different bypass diode configurations. A chain of 12 solar cells is set up with the same specifications as in [13]. We extract the P-V curve of this chain with a variety of bypass diodes added. To show that these diodes can effectively mitigate shading effects, one solar cell (randomly picked) is fully shaded while others are unshaded. The P-V curves of this solar cell chain under various bypass diode configurations (modeled by the Ground Truth model) are shown in Figure 3. It shows the impact of the number of bypass diodes in a PV module.

In our experiment, each bypass diode has the same number of solar cells in parallel. For example, with two bypass diodes, there are six parallel solar cells to each diode; when there are three bypass diodes, there are four parallel solar cells to each diode. It is easy to see from

Figure 3 that as the number of bypass diodes increases, the loss of maximum output power of the solar cell chain decreases. Note that when there is only one bypass diode (the bypass diode is parallel to the load directly), there is no compensation. Thus, for each solar cell chain, two or more bypass diodes are needed. In this thesis, we assume that each solar cell chain has two bypass diodes in a PV module for simplicity. This configuration is the most popular configuration that can be found in the market [4], [14]. Furthermore, the P-V curves have the same behavior characteristic (they all have two humps) with two or more bypass diodes. It should be noted that our models, in fact, can be extended to a chain with more than two bypass diodes and this extension is ongoing work. In addition, deciding the optimal bypass diode configuration is also left to be future work.

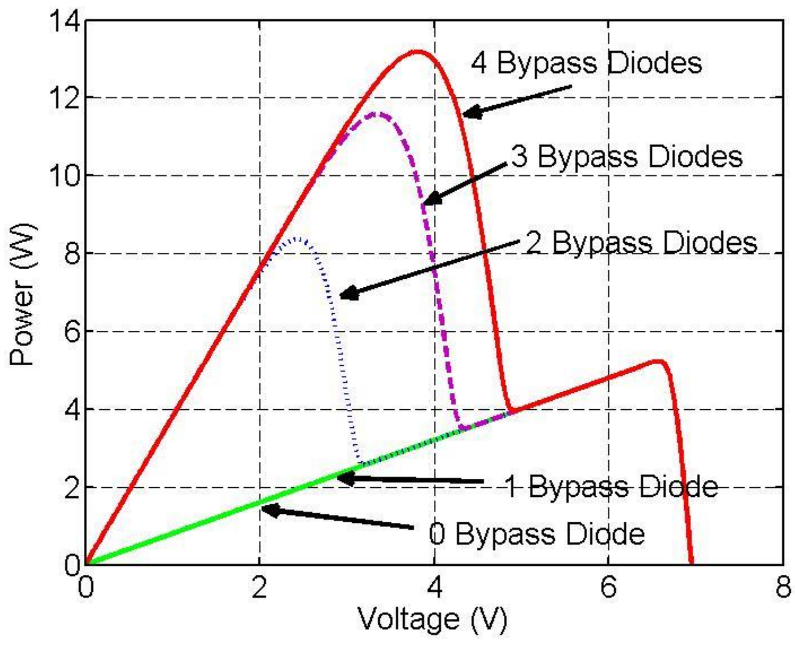


Figure 3: Impacts of Bypass Diodes Numbers

Chapter 3

COLONY-WISE PV MODULE MODEL

In order to reduce the complexity of the PV module model, we develop a Colony-Wise (CW) method. Without loss of generality, we assume the setting of the PV module to be *mSnP*, which means the module has *n* paralleled solar cell chains and *m* cascaded solar cells for each chain. Each chain has two uniformly inserted bypass diodes. A colony is defined as one bypass diode with all the solar cells in parallel to it (for example, there are two colonies in Figure 1). Therefore, a PV module has *2n* colonies. Furthermore, we assume a solar cell is either shaded or completely unshaded. We will show that the Colony-Wise model can reduce the solar module model's computational complexity down to *O(4n)* from *O(mn)*. Because *m* is usually much larger than *n* [13], the model's efficiency is greatly improved.

3.1 Properties for Colony-Wise Model

Property 1: Switching the positions of any two solar cells within one colony does not affect the I-V characteristic.

Proof: To prove this property, we first start with a simple example. Colony 1 in Figure 4 has one unshaded cell and one shaded cell. Colony 2 switches the positions of the two cells.

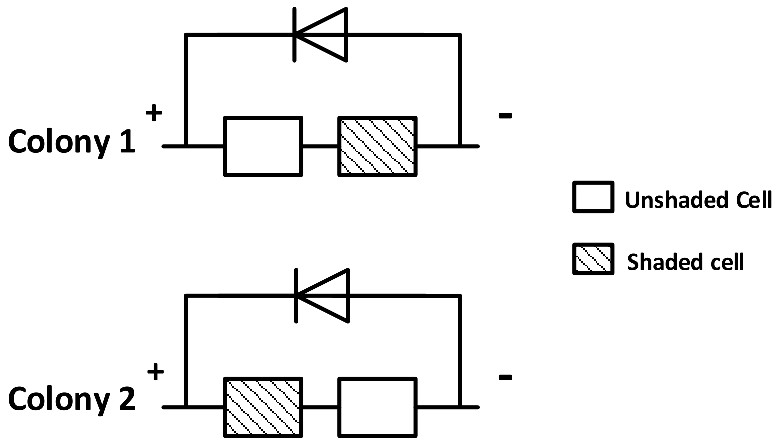


Figure 4: Illustration of Property 1

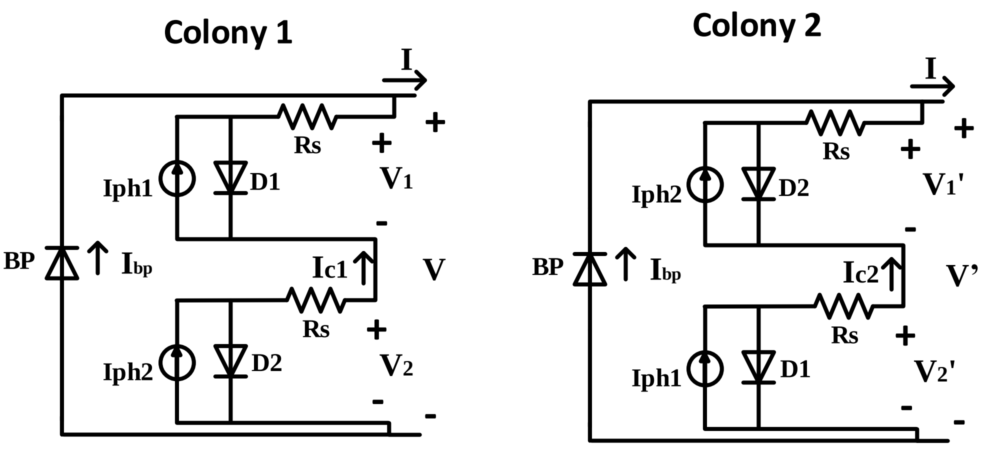


Figure 5: Detailed Circuits Model of the Example for Property 1

The equivalent circuits of these two colonies are shown in Figure 5. Because the shunt resistors are very large and therefore have limited impact on [7], they are ignored for simplicity of the proof. To show that the two models are equivalent, we show that the I-V curves of colony 1 and colony 2 are the same. To find the I-V curve, one can sweep the entire range of I and find the corresponding V.

Each colony has two working regions. The voltage across the colony is either positive (no current on bypass diode) or negative (current on bypass diode and shaded cell is bypassed). Note that a negative output voltage may occur. In Chapter 2, we stated that using bypass diodes is effective only when a chain has at least 2 bypass diodes. When the bypass diode is active (has current on it), the corresponding colony has negative voltage and other colonies in the same chain have positive voltages. However, the voltage across the entire chain is always positive.

In the positive voltage case, there is no current on the bypass diode. Thus, $I = I_c$, where I_c is the current flowing through the cascaded solar cell (e.g. I_{c1} and I_{c2} in Figure 5). Figure 5 shows that the two cascaded solar cells have two difference current sources. The maximum current through this chain is determined by the lowest current source (photovoltaic current of the shaded cell - I_{ph2}). Thus the maximum I_c = I_{ph2}. When I is injected into both the colonies, the voltages of colony 1 and colony 2 will be (2)

$$V = V_1 + V_2 = \left[\frac{NkT}{q}\ln\left(\frac{I_{ph1} - I}{I_s} + 1\right) - R_s I\right] + \left[\frac{NkT}{q}\ln\left(\frac{I_{ph2} - I}{I_s} + 1\right) - R_s I\right]$$

$$V' = V_1' + V_2' = \left[\frac{NkT}{q}\ln\left(\frac{I_{ph2} - I}{I_s} + 1\right) - R_s I\right] + \left[\frac{NkT}{q}\ln\left(\frac{I_{ph1} - I}{I_s} + 1\right) - R_s I\right] \quad (2)$$

where V_1 and V_2 are the voltages of the unshaded cell and the shaded cell in colony 1, and V_1' and V_2' are the voltages of the shaded and unshaded cells in colony 2. Other parameters are defined the same as in Equation 1. Equation 2 shows that $V = V'$.

In the negative voltage case, the bypass diode provides extra current to increase the colony output current, reducing the impact of current source mismatch between the two cells. A current I is injected into the two colonies to determine the voltage outputs. Since the maximum current the two solar cells can provide is I_{ph2}, we have:

$$I = I_{bp} + I_c = I_{bp} + I_{ph2} \tag{3}$$

where I_{bp} is the current through the bypass diode. Equation 3 can be applied to both of the colonies.

$$V = \frac{N_{bp}kT}{q}\ln\left(\frac{I - I_{c1}}{I_{sbp}} + 1\right)$$

$$V' = \frac{N_{bp}kT}{q}\ln\left(\frac{I - I_{c2}}{I_{sbp}} + 1\right) \tag{4}$$

where N_{bp} is the quality factor of bypass diode and I_{sbp} is its saturation current. Other parameters are defined the same as in Equation 1. Since $I_{c1} = I_{c2} = I_{ph2}$, we have $V = V'$.

Therefore, under all situations, the I-V curves of colony 1 and colony 2 are the same. By the same reasoning, the location invariance property holds true when a colony has a different number of cells.

Property 2: n Cascaded identical One-Diode modeled solar cells can be lumped into a single One-Diode modeled solar cell.

Proof: We first show the lumping rules of Property 2, then prove the rules. The rules are presented in Table 1.

Table 1: Model Reduction Rules for Homogenous Cells in a Colony

Parameter	I_{ph}	I_s	N	R_s	R_{sh}
Value	I_{pho}	I_{so}	$n * N_o$	$n * R_{so}$	R_{sho}

The first row in Table 1 is the lumped One-Diode model parameters. The second row is the mapping relation to the original un-lumped solar cell model. The subscript *o* means the parameters are from the original model. For example, if the diode quality factor in the original cell is N_o, then the quality factor of the lumped model of *n* original solar cells is $N = n * N_o$.

In order to prove this property, we start with two identical solar cells. Figure 6 shows the procedure of lumping two cascaded identical cells into one cell. Since the two cells are identical, the voltage across each cell is *V/2*, and the current flowing inside the cell is *I*. For each cell, the *I*-*V* relation is shown in (5):

$$I_{ph} - I - \frac{\frac{V}{2} + R_{so}I}{R_{sho}} = I_{so}\left[\exp\left(q\frac{\frac{V}{2} + R_{so}I}{N_o kT}\right) - 1\right] \tag{5}$$

(3) can be rewritten as (6)

$$I_{ph} - I - \frac{V + 2R_{so}I}{2R_{sho}} = I_{so}\left[\exp\left(q\frac{V + 2R_{so}I}{2N_o kT}\right) - 1\right] \tag{6}$$

By replacing $2R_{so}$ by R_o, $2R_{sho}$ by R_{sh}, and $2N_o$ by *N*, Equation 6 is the same I-V relation as a single One-Diode model of the circuit in Figure 6.

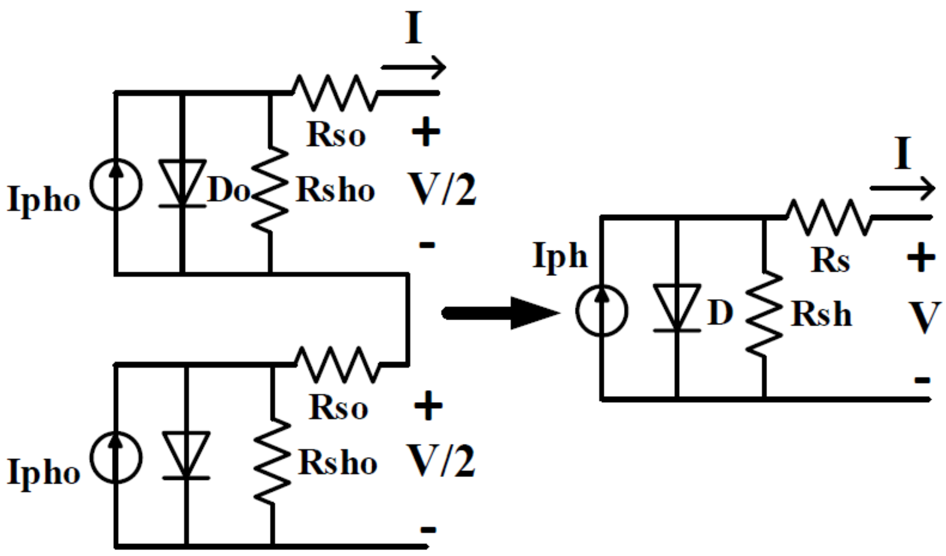


Figure 6: Two Cascaded Homogenous Cells Lumped into One Cell

For *n* cascaded solar cells, the same methodology can be applied to prove Property 2.

3.2 Lumping to the Colony-Wise Model

An *mSnP* solar module model is lumped into a Colony-Wise (CW) model, which consists of *2n* colonies. Each colony in the CW model has no more than two macro cells. A macro cell is the abstraction of a group of identical solar cells within a single colony, and it can be modeled by the One-Diode solar cell model. The formation of the CW model has two steps. First, because of Property 1, all shaded solar cells within one colony can be moved such that shaded cells are adjacent to each other, and unshaded cells are adjacent to each other. Second, because of property 2, all shaded cells can be lumped into one macro cell that can be the One-Diode model, and all unshaded cells into another macro cell. The procedure is illustrated in Figure 7. If all the cells are identical in terms of shading within a colony, then they form only one macro cell. Figure 8 gives an example of the transform procedure from an *mSnP* PV module model into a CW model. The size of the macro cell in Figure 7 and Figure 8 represents the number of cells lumped into this macro cell. The larger the size is,

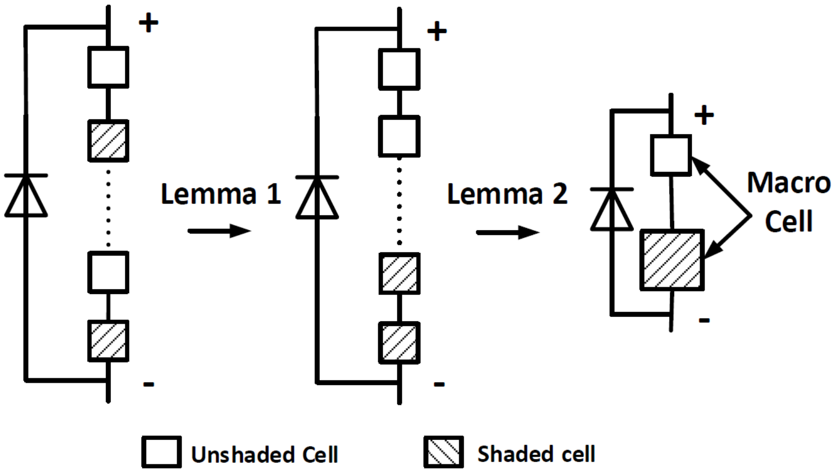


Figure 7: Procedure of Colony Lumping

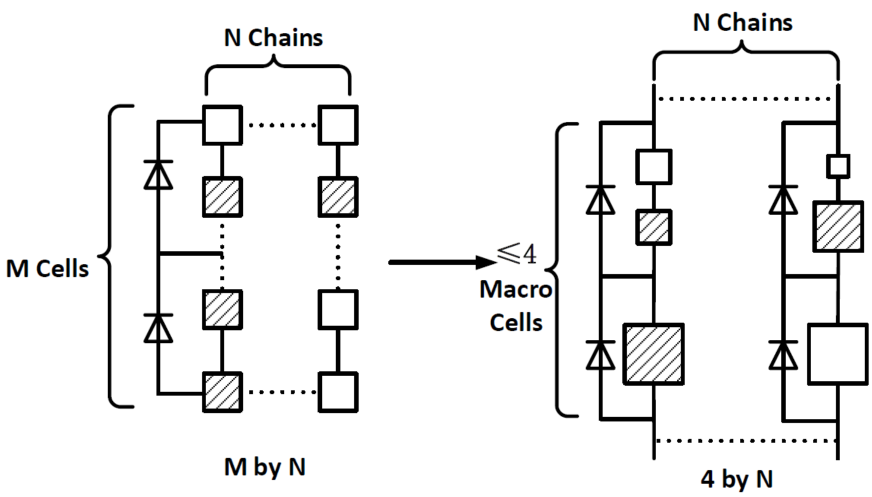


Figure 8: An Example of Building Colony-Wise Model

the more homogenous solar cells are lumped. Finally, the *mSnP* PV module is lumped into *n* chains, where each chain has at most 4 macro cells. Because *m* is usually much larger than *n* [13], the CW model has much lower computational complexity compared with the Ground Truth model. In addition, the CW model has no accuracy loss compared with the Ground Truth model because the transformation by property 1 and property 2 has no loss in accuracy.

Chapter 4

TWO-COLONY PV MODULE MODEL

To further reduce the complexity of the PV model, we propose a heuristic Two-Colony (TC) model. The TC model consists of two colonies. Each colony has one bypass diode and one super cell that can again be modeled by the One-Diode model. One colony represents all the unshaded cells in a solar module while the other colony represents all the shaded cells. Figure 9 illustrates the equivalent circuit model of a PV module using the TC model.

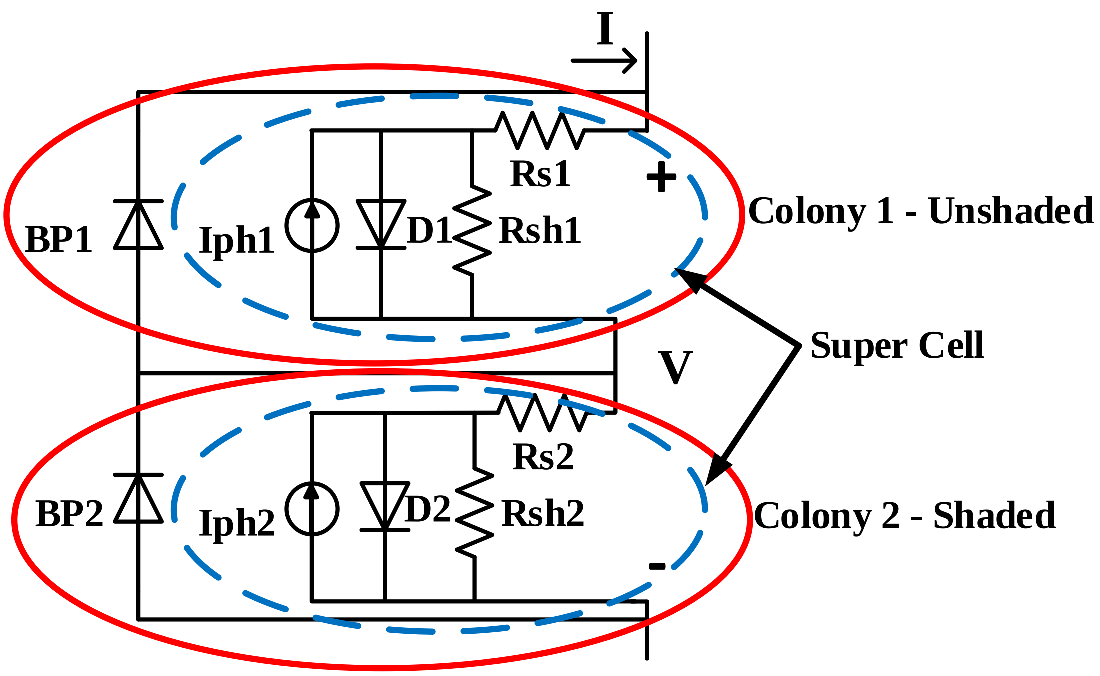


Figure 9: Equivalent Circuit Diagram of Two Colony Model

The parameter of the TC model depends on the shading pattern of the PV module. We develop a heuristic method to extract these parameters. We define the Cell Shading Ratio

(CER) and Colony Shading Ratio (COR) of an *mSnP* solar module as (7)

$$CER = \frac{\#shaded\_cell}{m * n}, \qquad COR = \frac{\#shaded\_colony}{\#colony} \tag{7}$$

where $\#shaded\_cell$ is the total number of shaded cells, $\#shaded\_colony$ is the total number of colonies which have shaded cells and $\#colony$ is the number of entire colonies in a PV. Then, we derive the Shading Ratio Factor (R), which is a linear combination of CER and COR. The Shading Ratio Factor represents the shading effects on a PV module. Equation 8 shows the relationship among the three factors.

$$\begin{gathered} R = \alpha(CER) * COR + \beta * CER + \gamma(CER) \\ \alpha(CER) = \begin{cases} \alpha_1, & if\ 40\% \le CER \le 60\% \\ \alpha_2, & otherwise \end{cases} \\ \gamma(CER) = \begin{cases} \gamma_1, & if\ CER \le 50\% \\ \gamma_2, & otherwise \end{cases} \end{gathered} \tag{8}$$

where R is the Shading Ratio Factor used in the lumping rules. α, β and γ are the parameters that need to be fit to a curve. They change as the CER varies. The curve fitting process is as follows: for a specific PV module, we use different shading ratios and conduct experiments with the TC model and the Ground Truth model (GT). The TC model is the training object and the GT model is the ground truth. The objective function of the curve fitting process is described in (9), and aims to minimize the error between the two P-V curves generated by the two models.

$$Obj = w_1 * 0.5 * (2 - CORR) + w_2 * Error_{pop} \tag{9}$$

where $Error_{pop}$ is the relative error between the two peak output power (POP) on the P-V curves and CORR is the correlation of the curves. If we have two P-V curves, X and Y, with each curve consisting of sampled points x_i and $y_i, i = 1,2, \ldots, n$, then the CORR of the two curves is defined in (10)

$$CORR = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \quad (10)$$

POP determines the operating point of a PV module and CORR represents the similarity between the curves (the closer CORR is to 1, the more similar the two curves are). POP is a value between 0 and 1. However, CORR has a range of -1 to 1. Therefore, it needs to be normalized. The $0.5 * (2 - CORR)$ term is the normalization term in (9). In (9), w_1 and w_2 are weights that are used to account for the impacts of CORR and POP after normalization. In our experiment, they are both set to 0.5 to make the effects of CORR and POP equal.

The Two-Colony Model lumping rule of an *mSnP* PV module with *2* bypass diodes per chain is summarized in Table 2. R_{so}, R_{sho}, N_o and I_{so} are the parameters from the un-lumped solar cell model (one solar cell One-Diode model's parameters in the Ground Truth model, not macro cell model). N_{bpo} and I_{sbpo} are the parameters of the bypass diode (bypass diodes parameters in the Ground Truth model). The subscript o means the parameters are from the Ground Truth model. The second and third columns show the mapping relation from original un-lumped model parameters to the Two-Colony model

Table 2: Reduction Rules for the Two-Colony Model

Parameters	Unshaded Colony	Shaded Colony
Photovoltaic Current	$I_{ph1} = maxCurrent$	$I_{ph2} = maxCurrent$
Serial Resistor	$R_{s1} = R_{so} * m/n * R$	$R_{s2} = R_{so} * m/n * (1 - R)$
Shunt Resistor	$R_{sh1} = R_{sho} * m/n * R$	$R_{sh2} = R_{sho} * m/n * (1 - R)$
Cell Quality Factor	$N_1 = N_o * m * R$	$N_2 = N_o * m * (1 - R)$
Cell Sat. Current	$I_{s1} = I_{so} * n * R$	$I_{s2} = I_{so} * n * (1 - R)$
BP Quality Factor	$N_{bp1} = N_{bpo} * 2 * R$	$N_{bp2} = N_{bpo} * 2 * (1 - R)$
BP Sat. Current	$I_{sbp1} = I_{sbpo} * n * R$	$I_{sbp2} = I_{sbpo} * n * (1 - R)$

parameters.

The photovoltaic currents of the super cells (I_{ph1} and I_{ph2}) in the TC model are the maximum and minimum current of the PV module. They are defined in (11).

$$maxCurrent = \sum_{1 \le i \le n} (maxCC_i)$$

$$minCurrent = \sum_{1 \le i \le n} (minCC_i)$$

$$maxCC_i = \begin{cases} \overline{I_{ph}}, & if\ all\ colonies\ have\ shaded\ cells \\ I_{ph}, & otherwise \end{cases}$$

$$minCC_i = \begin{cases} I_{ph}, & if\ none\ of colonies\ has\ shaded\ cells \\ \overline{I_{ph}}, & otherwise \end{cases} \quad (11)$$

where $maxCC_i$ and $minCC_i$ are the maximum and minimum currents of each solar cell chain. I_{ph} and $\overline{I_{ph}}$ are the photovoltaic currents of the unshaded and shaded solar cell, respectively.

Based on Table 2, the TC model of one PV module is given by a constant number of nonlinear equations. Therefore the model has a constant computational complexity. In addition, we will show in the next chapter that the ratio of shaded colonies (COR) has a larger impact on the model than the ratio of shaded cells (CER).

Chapter 5

EXPERIMENTAL RESULTS

5.1 Experiment Settings

In this section, we compare three models for PV module in terms of maximum power output and P-V curves. These models are the Ground Truth model (GT), the Colony-Wise model (CW), and the Two-Colony model (TC). The shading ratio is defined as the ratio of the number of shaded cells to the number of total cells in a PV module. To mimic realistic shading effects, we assume that all the shaded cells within one PV module are adjacent to each other (while this assumption is realistic in almost all cases, it does not affect the accuracy of the CW model and slightly improves the accuracy of the TC model). Thus, the shading pattern is modeled as one continuous block. For each specified shading ratio, we experimented many random shading patterns for the fixed shade area. To compare the accuracy of each model to the ground truth, we compare CW and TC models' P-V curves with the GT model's P-V curve. In order to cover different shading situations in reality, we use three categories of shading ratios: partially shaded (20%), half shaded (50%), and heavily shaded (80%). Each of the three models (GT, CW and TC) is instantiated with three PV module settings: *10s4p*, *20s4p* and *30s2p*. Each serially connected solar cell chain has two bypass diodes. The circuit simulations are conducted in HSPICE [15].

We use the same solar cell parameters as in [13] for all the three PV-module models. Specifically, diode quality factor $N = 1.5$, diode saturation current $I_s = 10^{-6}A$, serial resistance $R_s = 0.0079\Omega$ and shunt resistance $R_{sh} = 5000\Omega$. The bypass diode has the quality factor $N_{bp} = 1$ and saturation current $I_{sbp} = 10^{-6}A$ for the GT model. The difference between the One-Diode cell models of the shaded and unshaded cells is the photovoltaic current. For shaded cells, $\overline{I_{ph}} = 0.8A$ whereas for unshaded cells $I_{ph} = 1.9A$. In the experiments, 100 instances of each shading ratio (the pattern is randomized each time) are evaluated for the three PV-module models. For the TC model, 20 shading patterns are used in each shading ratio to extract the parameters of the model by curve fitting and the resulting parameters are used by the rest of shading patterns to validate the PV module models.

5.2 Results and Analysis

300 cases are tested to evaluate the proposed models for each PV module in our experiment (100 cases for each shading ratio). The parameters of the Two-Colony model are extracted using the curve fitting method described in Chapter 4. Their values with the three different PV module settings are shown in Table III.

The complexity overhead is reasonable to have different parameters for different PV modules because a solar farm usually has a small number of PV modules types. Note that in Table 3, α is always larger than β and γ under all conditions. This shows that the colony

Table 3: Parameters of Two-Colony Model

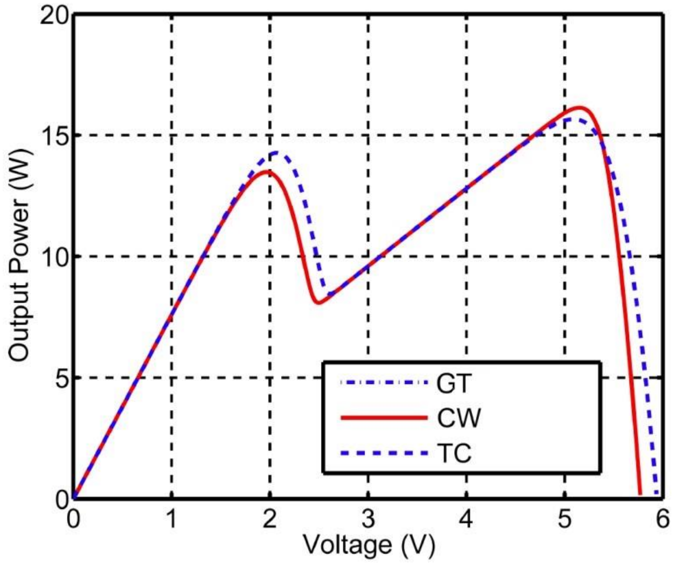
shading ratio	10s4p			20s4p			30s2p		
	α	β	γ	α	β	γ	α	β	γ
20%	0.7	-0.033	0.157	0.7	-0.167	0.183	0.69	-0.033	0.157
50%	0.6	-0.033	0.107	0.6	-0.167	0.133	0.6	-0.033	0.107
80%	0.7	-0.033	0.107	0.7	-0.167	0.133	0.69	-0.033	0.107

Table 4: Accuracy and Efficiency Comparison (Average Data of 100 Experiments)

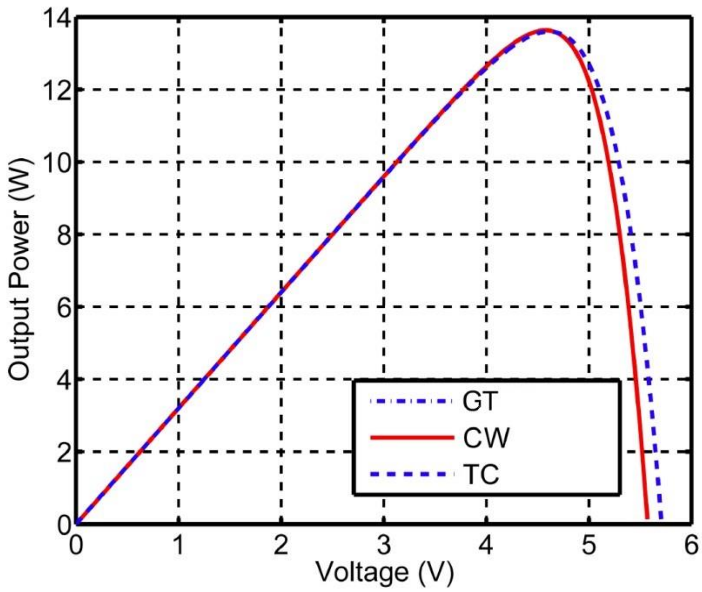
Module Size	Shading Ratio	GT	CW			TC		
		runtime(s)	POP (%)	CORR	runtime(s)	POP (%)	CORR	runtime(s)
10s4p	20%	60.58(1X)	0	1	24.55(2.47X)	4.10	0.947	9.98(6.07X)
	50%	60.31(1X)	0	1	24.51(2.46X)	4.70	0.960	9.99(6.04X)
	80%	60.66(1X)	0	1	24.72(2.45X)	0.76	0.984	9.97(6.08X)
20s4p	20%	124.15(1X)	0	1	23.59(5.26X)	3.17	0.944	9.98(12.44X)
	50%	123.51(1X)	0	1	22.61(5.46X)	5.21	0.967	9.95(12.41X)
	80%	124.21(1X)	0	1	23.82(5.21X)	0.16	0.978	9.99(12.43X)
30s2p	20%	88.41(1X)	0	1	12.86(6.88X)	2.39	0.954	10.01(8.83X)
	50%	87.73(1X)	0	1	12.46(7.04X)	5.41	0.968	9.97(8.80X)
	80%	88.89(1X)	0	1	12.65(7.03X)	0.57	0.985	9.98(8.90X)
Average			0	1	4.92X	2.94	0.966	9.11X

shading ratio (COR) has a larger impact on PV module modeling than solar cell shading ratio (CER). The COR is the dominant factor in a PV module's output power. This implies that if a shade covers more colonies, the PV module generates less power compared to the case where the same shade covers less colonies of the same PV module. Similar observation can also be found in other references [2], [4], [10].

Experimental results of model accuracy and runtime efficiency are shown in Table 4. The results of the proposed methods are compared with the Ground Truth model in terms of accuracy and efficiency. To evaluate accuracy, the average relative error in terms of peak



(a) 20% Shading Ratio



(b) 80% Shading Ratio

Figure 10: P-V Curves of 10s4p PV Module with Three Different Models

output power (POP) and the average correlation (CORR) are compared between P-V curves generated by the three PV-module models. The peak output power represents the operation point of a PV module, and the CORR shows the similarity between the estimated P-V curve and the ground truth's P-V curve. In Chapter 3, we showed that the CW model has no accuracy loss compared with the ground truth. Therefore the POP error always equals 0 and CORR always equals 1 for the CW model. On the other hand, the TC model is a heuristic model and thus experiences some accuracy loss with an average POP relative error of 2.94% and an average CORR of 0.966. Yet, the maximum power point and the entire region of the P-V curve can be estimated quickly with a high accuracy by the TC model. Figure 10 is an example of the 10s4p PV module modeled by the GT, CW and TC models.

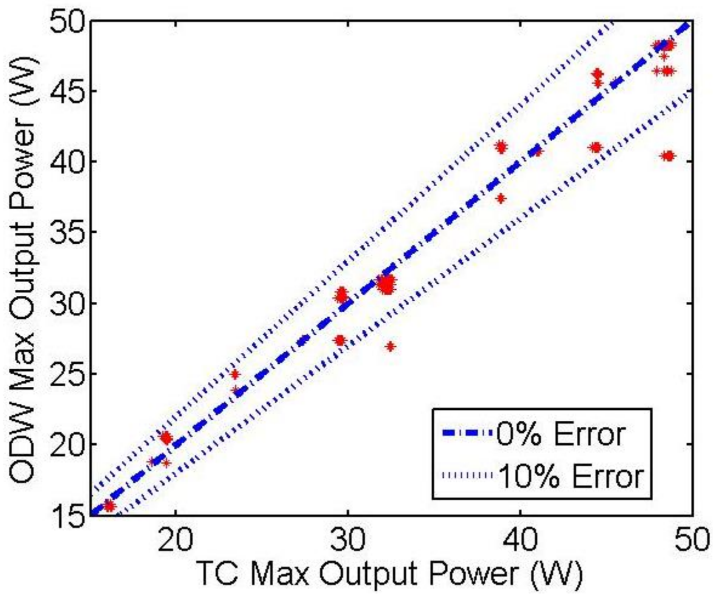


Figure 11: Scatter Plot of Peak Output Power

Figure 11 shows a scatter plot of the peak output power of the GT model and TC model. The distribution of the points shows most of the errors are around the 0% error line. 2.56% of the points have error larger than 10%. These cases happen when shades on the PV module are scattered (e.g. the shade is like a circle or zigzags). Even though these types of shades are continuous, they are rare in reality. Note that we have cases of both underestimation and overestimation for PV-modules, and this leads to some error cancelling for a solar panel or solar farm with many PV-modules and further reduces error.

We compare efficiency by the runtime of HSPICE simulation. The experiments were run on an Intel i5 2.4 GHz machine with 4G RAM. From Table 4, we see that the runtime of the GT model increases linearly as the size of the PV module. The CW model's runtime is shorter than GT model. The time is proportional to the number of solar cell chains in the module, regardless of the length of the chain. As shown in Table 4, although the 20s4p module has 2 times more solar cells than the 10s4p module, they have approximately the same CW model's runtime. In addition, the CW model's runtime of the 30s2p module is approximately one half of the 20s4p module's runtime. The runtime speedup is 4.92X on average. The TC model further reduces the complexity to a nearly constant runtime and provides a 9.11X speedup on average. In the last column in Table 4, all test cases have nearly the same runtime. It is clear that due to its constant runtime, the TC model is highly beneficial for large PV modules when compared with the GT and CW models. In the experiment, the maximum speedup is 12.44X when the PV module size is *20s4p*.

Chapter 6

CONCLUSIONS AND FUTURE WORK

In this thesis, two new PV module models are proposed, namely the Colony-Wise (CW) model and the Two-Colony (TC) model. The Colony-Wise model can efficiently capture the P-V curve of a PV module without any accuracy loss. The Two-Colony model can further reduce the model's computational complexity to a constant value, but has a limited accuracy loss (on average 2.59%). Thus, it can be used to estimate the output power of a PV module quickly with an acceptable accuracy. Such efficiency has not been reported to the best of our knowledge.

We simplify the bypass diode configurations by assuming each cascaded solar cell chain has two bypass diodes in this thesis. Considering other bypass diode configurations is our future work. We also assume that a solar cell is either fully shaded or unshaded, and do not consider multiple shading levels (e.g. a solar cell can be in complete dark shade, slight shade or no shade). Our future work will extend to these shading conditions as well as other mismatches such as aging effects and manufacturing variations. We speculate that models presented in this thesis may be extended to the aforementioned cases.

References

[1] F. Peng et al., “A novel method to estimate the maximum power for a photovoltaic inverter system,” in Power Electronics Specialists Conference, vol. 3. IEEE, 2004, pp. 2065–2069.

[2] H. Patel and V. Agarwal, “Matlab-based modeling to study the effects of partial shading on pv array characteristics,” Energy Conversion, IEEE Transactions on, vol. 23, no. 1, pp. 302–310, 2008.

[3] R. M. Sullivan, “Shadow effects on a series-parallel array of solar cells,” Greenbelt, MD, 1965.

[4] S. Silvestre, A. Boronat, and A. Chouder, “Study of bypass diodes configuration on pv modules,” Applied Energy, vol. 86, no. 9, pp. 1632– 1640, 2009.

[5] N. Femia, G. Petrone, G. Spagnuolo, and M. Vitelli, “Optimization of perturb and observe maximum power point tracking method,” Power Electronics, IEEE Transactions on, vol. 20, no. 4, pp. 963–973, 2005.

[6] E. Roman, R. Alonso, P. Iba˜nez, S. Elorduizapatarietxe, and D. Goitia, “Intelligent pv module for grid-connected pv systems,” Industrial Electronics, IEEE Transactions on, vol. 53, no. 4, pp. 1066–1073, 2006.

[7] A. Kajihara and T. Harakawa, “Model of photovoltaic cell circuits under partial shading,” in Industrial Technology, 2005. IEEE International Conference on, 2005, pp. 866–870.

[8] W. Xiao and W. G. Dunford, “A modified adaptive hill climbing mppt method for

photovoltaic power systems,” in Power Electronics Specialists Conference, 2004. PESC 04. 2004 IEEE 35th Annual, vol. 3. IEEE, 2004, pp. 1957–1963.

[9] E. Koutroulis, K. Kalaitzakis, and N. C. Voulgaris, “Development of a microcontroller-based, photovoltaic maximum power point tracking control system,” Power Electronics, IEEE Transactions on, vol. 16, no. 1, pp. 46–54, 2001.

[10] G. Walker, “Evaluating mppt converter topologies using a matlabpv model,” Journal of Electrical & Electronics Engineering, Australia, vol. 21, no. 1, p. 49, 2001.

[11] M. G. Villalva, J. R. Gazoli et al., “Comprehensive approach to modeling and simulation of photovoltaic arrays,” Power Electronics, IEEE Transactions on, vol. 24, no. 5, pp. 1198–1208, 2009.

[12] J. R. Janke, “Multicriteriagis modeling of wind and solar farms in colorado,” Renewable Energy, vol. 35, no. 10, pp. 2228–2234, 2010.

[13] S. Moballegh and J. Jiang, “Partial shading modeling of photovoltaic system with experimental validations,” in Power and Energy Society General Meeting. IEEE, 2011, pp. 1–9.

[14] W. Herrmann, W. Wiesner, and W. Vaassen, “Hot spot investigations on pv modules-new concepts for a test standard and consequences for module design with respect to bypass diodes,” in Photovoltaic Specialists Conference, 1997., Conference Record of the Twenty-Sixth IEEE. IEEE, 1997, pp. 1129–1132.

[15] Manual, Star-HSPICE. "Avant." Corp., Fremont, CA (1998).