Title:

Abstract:

1. Introduction

As a promising solution in the clean energy, photovoltaic (PV) systems have drawn great attention recently. An accurate PV system model is the kernel in the PV system optimization. Furthermore, a fast and accurate model is more attractive when real time applications, such as to capture the PV system characteristics with ever-changing shadings, are required.

A PV system model needs to consider mismatches across solar cells in PV systems. Mismatches have to be considered for two reasons. First, a PV system has numerous solar cells - a PV system consists of thousands of PV modules, and each PV module consists of cascaded and paralleled solar cells. Thus, solar cell mismatches are inevitable. Second, PV systems are vulnerable to mismatches. Mismatches, such as temperature variations, non-uniform cell aging, and non-uniform shading across the cells, can cause power losses and solar cell damages [ref Mismatch]. The non-uniform shading is also known as the Shading Effects [SE]. Shading Effects lead to the largest output power reduction and cell damage [SE]. Furthermore, the shading on PV module is always changing. It needs a fast PV system model. (**How do we state in this paper, we only focus on shading effects and ignore other mismatches?)**

The bypass diode is another essential part in a PV module, and has to be modeled accurate in a PV module model. Bypass diodes are connected in parallel to solar cells. Figure 1 shows a solar cell chain with 3 bypass diodes. Bypass diodes have been proven to be an effective solution to compensate for consequences cause by mismatches. [ref BP]



Fig. 1. A PV module with 1 solar cell chain, which consists of 12 solar cells and 3 colonies.



Fig. 2. The One-Diode Model of a Solar Cell

A PV system’s model is based on PV module models. The existing PV module models are equivalent circuit models [solor cell model]. Generally, a solar cell is modeled as a circuit, with a current source, diodes and resistors. [solar cell models] A well-accepted solar cell model is shown in Figure 2. [One-diode model] It is referred to as the One-Diode model in this paper. A PV module model is then modeled by cascaded and paralleled One-Diode solar cell models, along with the bypass diodes according to the PV module’s configuration. Each One-Diode solar cell has its own parameters to model the mismatches. This PV module model offers great accuracy. We refer this model as the Ground Truth (GT) model throughout this paper. An example is as in Figure 1. It is a PV module with a single solar cell chain that consists of 12 solar cells and 3 bypass diodes. Therefore, its GT model has 12 One-Diode models and 3 diode models. The major drawback of the GT model is its computational time. The GT model’s complexity is proportional to the number of solar cells. Consequently, the reduction of PV module model’s complexity is appealing.

In this paper, we propose two PV module models to solve the above problem. The first model is call the Colony-Wise (CW) model. A ***colony*** is defined as a bypass diode plus all its paralleled solar cells, as shown in the circle in Figure 1. The number of colonies inside a PV module equals its quantity of bypass diodes. Solar cells inside of each colony are lumped into at most two ***macro cells***. The macro cell is modeled as the One-Diode model. Compared with the GT model, the CW model remains high accuracy, while its complexity is only proportional to the number of bypass diodes in a PV module.

We proposed a second N-Colony (NC) model to further reduce the complexity. The N-Colony model models a PV module with at most N colonies, where N is the number of bypass diodes in a module’s cascaded solar cell chain. All solar cells inside each colony are only modeled by one ***super cell***. This super cell is again modeled by the One-Diode model. The NC model achieves constant computational complexity with acceptable accuracy.

The NC model can become a four-dimensional table-based model when there are two bypass diodes in a solar cell chain. This bypass diode configuration can be found in several commercial PV modules [PV spec refs.] This is the first table-based PV module model to capture shading effects by our knowledge. It enables capturing the rapidly-changing shading effects, while still maintains high accuracy by using embedded computing.

The rest of this paper is organized as follows. Section 2 presents the One-Diode solar cell model, and how to represent shading effects with this model. These are the preliminaries of our proposed PV module models. Section 3 and Section 4 introduce and validate the Colony-Wise model and the N-Colony Model respectively. Section 5 compares these two new models with the Ground Truth model. Finally, Section 6 concludes the paper.

1. Preliminaries
   1. One-Diode Solar Cell Model

A well-accepted way to model a solar cell is through an equivalent circuit [10]. This is also denoted as the One-Diode model in the paper. It has one current source and a diode in parallel as shown in Figure 2 in Section 1.

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

where is the photovoltaic (PV) current and is the reverse saturation current of the diode D. is the diode quality factor, is the Boltzmann coefficient, is the cell operating temperature, and q is the unit electronic charge. is the equivalent serial resistance of the cell and is the shunt resistance [11]. Note that the macro cell and the super cell are also modeled as the One-Diode model. The subscript represents all parameters are from the solar cell One-Diode model to make a difference in notation. These parameters can be extracted from manufacturer specifications or from the measured I-V curves of solar cells.

* 1. Shading Effects Representation in One-Diode model

Shading effects are the non-uniformly received solar irradiance for each solar cell in a PV module. Since the received solar irradiance directly determines the photovoltaic current in the One-Diode model, shading effects can be represented as each solar cell has its own .

* 1. Notations and Definitions

Without loss of generality, we assume the PV module to be *mSnP*, which means this module has paralleled solar cell chains and cascaded solar cells for each chain. The number of bypass diodes for each solar cell chain is . One PV module has bypass diodes.

We also define the shading level of a solar cell as its . Therefore, for the solar cell in the chain, we have:

The total number of different shading levels within one PV module is denoted as . Note that when , there is not shading effects. The maximum of is .

1. Colony-Wise PV Module Model
   1. Colony-Wise Model Equivalent Circuit Diagram



Fig 3. (a) One colony with solar cells (b) One colony model in Colony-Wise model (c) Circuit diagram of a colony modeled by Colony-Wise model

One colony in a PV module can be represented in the form of Figure 3 (a). Let us assume that this colony has solar cells. to denotes shading level of each solar cell. The Ground Truth model models each solar cell with a One-Diode model. In the Colony-Wise model, all solar cells are lumped into at most two macro cells as shown in Figure 3 (b). If , there is only one macro cell, and all the solar cells are lumped into this macro cell. Otherwise, all cells are lumped into two macro cells according to their shading levels (SLs). The two macro cells are also modeled by the One-Diode model, with their shading levels and . The superscript denotes the parameters are from macro cells. Section 3.2 details the generation of parameters in the Colony-Wise model from the Ground Truth model.

* 1. Colony-Wise Model Parameter Generation

Heuristically, we pick up the two most representative cells within each colony to build the Colony-Wise model. They are the basis of the two macro cells. One cell (Max Macro Cell) has the maximum shading level , and the other (Min Macro Cell) has the minimum shading level .

Two counters and counts the numbers of cells belongs to each macro cells. Note that . If a cell’s SL is close to , it belongs to Max Macro Cell; otherwise, it belongs to Min Macro Cell. In addition, we have:

The circuit diagram of a colony modeled by the Colony-Wise model is shown in Figure 3. (c). We can derive the circuit parameters for Max Macro Cell and Min Macro Cell based on these two counters. This model reduction is shown in Table 1.

Table 1. Model Reduction Relation for Colony-Wise Model

|  |  |  |
| --- | --- | --- |
| Parameter | Max Macro Cell | Min Macro Cell |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

The superscript denotes these parameters are from the Macro Cell.

* 1. Proof of Colony-Wise Model

**We don’t have it right now, can show several experimental results to see the curve is really determined by the max and min SLs.**

1. N-Colony PV Module Model
   1. N-Colony Model Equivalent Circuit Diagram

For a PV module with homogenous bypass diode distribution (each chain of the solar cell has same number of bypass diodes, and these bypass diodes have the same configuration), we can further lump the PV module model into the N-Colony model. The notation N stands for number of bypass diodes for each chain.

The N-Colony Model consists of N **Super Colonies**. Each super colony consists of one bypass diode and one Super Cell. The Super Cell is again modeled by the One-Diode Model. The equivalent circuit diagram for one such colony is shown in Figure 4. (a). The N-Colony model of one PV module is shown in Figure 4. (b).

The N-Colony model is an experimental model. The parameters of the modeled need to be curve fitted from the ground truth model. The details of parameter generation is shown in the Section 4.2.



Figure 4. (a) Equivalent circuit of one super colony in the N-Colony model (b) Diagram of the N-Colony model of a PV module

* 1. N-Colony Model Parameter Generation
     1. Super Colony Generation

First, we determine the Shading Level, also known as the of each super colony.

In Section 3.2, we get the and of each colony. Note that when the cells are identical within a colony, equals . The notation represents the colony in the column in a PV module.

For the chain of solar cell, we have the SL sequence: . We reorder this sequence into:, such that . We define the All Min Matrix in (6):

Where is the number of chain in a PV module.

Then, for the Super Colony in the N-Colony model, its is generate by the Equation (6):

* + 1. Cell Shading Ratio, Colony Shading Ratio and Shading Ratio

We define three parameters: the Cell Shading Ratio (), the Colony Shading Ratio () and Shading Ratio (). N-Colony parameters are generated from , and depends on and . For a PV module that has bypass diodes in a solar cell chain, we have , and

and are defined as in (7):

(7)

Where is the number of solar cell with shading level . A solar cell has shading level when its satisfies:

Where is the column this solar cell belongs to.

is the number of colonies with shading level . The definition of a colony of shading level is similar to the Equation (8):

Where is the column this colony cell belongs to, and is defined in Equation (4).

R is defined as:

Where , and are the weighing factors that need to be curve fitted. Note that we need to make sure all s are greater then zero.

Therefore, for a PV module with bypass diodes on each chain, parameters are required to be curve fitted.

* + 1. Other Parameters

Once we have all s, we can generate all N-Colony model parameters based on Table 2.

Table 2. Model Reduction Rules for Super Colony

|  |  |
| --- | --- |
| Parameter | Super Colony i |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

Where and are the parameters of the bypass diode in the super colony. The superscript denotes these parameters are from the super colony.

* + 1. Curve Fitting of Weighting Factors

The goal of the N-Colony model is to minimize the error of its Power-Voltage (PV) curve from the curve generated by the Ground Truth model. In addition, we care about the maximum power point (MPP), which is the optimal operation point of a PV module. Therefore, the objective function of the curve fitting is described in (10).

where is the relative error of the maximum power point (MPP) and is the correlation of the two curves. If we have two P-V curves, and , with each curve consisting of sampled points and , , then the CORR of the two curves is defined in (11)

where and are the average value for all and . Note that the closer CORR is to 1, the more similar the two curves are.

In addition, to quantify the impacts of these two terms, they have to be normalized. MPP has already been normalized because its value is between 0 and 1. However, CORR has a range of -1 to 1. The term is the normalization term used in (10). Furthermore, and are weights that are used to count for the impacts of CORR and MPP after normalization. In our experiment, they are both set to 0.5 to make the effects of CORR and MPP equal.

* 1. Table-based N-Colony Model

The N-Colony model has high efficiency. Furthermore, if there are only 2 bypass diodes in a solar cell chain, we can build a Table-based model.

Under the above assumption when , only four key variables: , , and , are enough to derive all parameters in the N-Colony model. For a mSnP PV module, the combination of equals , equals and both and equal , where is the number of shading levels a PV model have. Therefore, this model can be pre-calculated and stored into a four-dimensional table. In addition, computing time for each variable-combination is constant, which makes the table build-up time to be scalable. For a given shading pattern, the P-V curve can be estimated by table lookup according to the four variables. Fetching data from table needs only a small and constant complexity, which is very efficient.

5 Experimental Results

5.1 Experiment Settings

In this section, we compare three models for PV modules in terms of maximum power output and P-V curves. These models are the Ground Truth (GT) model, the Colony-Wise (CW) model, and the N-Colony (TC) model. Without losing generality, we assume that all the cells that have the same shading level within one PV module are adjacent to each other.

To compare the accuracy of each model to the ground truth, we compare the P-V curves from CW and NC models with that from the GT model.

We use an array to represent the multilevel shading effects:

We use a array, which has the same length of , to specify the percentage of cells with such shading level within mSnP module.

For example, for the shading level , there are cells have this shading level.

In this experiment, we assume . To cover multiple scenarios, we use three arraies. , ,. Therefore, for each solar module, we have three different cases. For each case, 100 random shading patterns of this shading ratio are evaluated for the three PV-module models.

Each of the three models (GT, CW and TC) is instantiated with three PV module settings: 20s2p, 20s4p and 30s2p. Each serially connected solar cell chain has two or three bypass diodes.

We use the same solar cell parameters as in [13] for all the three PV module models. Diode quality factor =, diode saturation current =, serial resistance = and shunt resistance=. The bypass diode has the quality factor =and saturation current =.

The circuit simulations are conducted in HSPICE. The computer that we use has an Intel i5 2.4GHz CPU, and 8GB memory.

For the NC model, 20 shading patterns are used to curve fit the weighting factors in Equation (9). The resulting parameters are used to validate the PV module models through the rest of shading patterns. We implemented the gradient descent search to achieve the curve fitting. The curve-fitted parameters of the NC model are shown in Table 3. Although they are different for different PV modules, the complexity overhead is reasonable because a solar farm usually has a small number of PV modules types.

TABLE 3. Weighting Factors of the N-Colony Model

|  |  |  |  |
| --- | --- | --- | --- |
|  | 20s2p (2 bp) | 20s4p (2 bp) | 30s2p (2 bp) |
|  | *0.75, 0.22, 0.06* | *0.71, 0.24, 0.06* | *0.75, 0.31, 0.04* |
|  | 20s2p (3 bp) | 20s4p (3 bp) | 30s2p (3 bp) |
|  | *0.39,0.17,0.08* | *0.38,0.19,0.09* | *0.39,0.15,0.08* |
|  | *0.40,0.20,0.08* | *0.42,0.21,0.09* | *0.40,0.17,0.08* |

Furthermore, α is always larger than β and γ under all conditions. This shows that has a larger impact on PV module modeling than . is the dominant factor in a PV module’s output power. This implies that the PV module generates less power when the shade covers more colony while the area of the colony remains the same. Similar observation can also be found in other references [2], [4], [10].

**(Do we need to mention about the Table-Based Model? It only works when there are only two shading levels and 2 bypass diodes for each solar cell chain. Otherwise, memory will explode** )

5.2 Accuracy Comparisons

To evaluate three models’ accuracy, the average relative error of the Maximum Power Point (MPP) and the average P-V curve correlation (CORR) are compared among the three PV-module models. The MPP represents the operation point of a PV module, and the CORR shows the similarity between the estimated P-V curve and the ground truth curve.

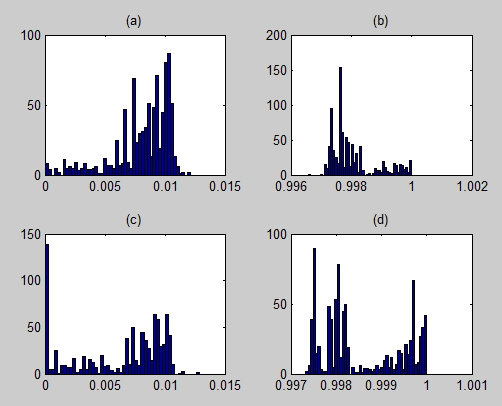
First, we compare Colony-Wise model with the Ground Truth model. Figure 4. (a) (b) shows the histogram of 900 cases’ MPP and CORR when each solar cell chain has 2 bypass diodes. The average MPP error is 0.81%, and the average CORR is 0.998. Figure. (c) (d) shows the above two specifications when there are 3 bypass diodes for each solar cell chain. The average of MPP error and CORR are 0.62% and 0.999 respectively.  


Figure. 4 Colony-Wise model error analysis (a) MPP error of 900 cases when (b) CORR of 900 cases when (c) MPP error of 900 cases when (b) CORR of 900 cases when

Then, the N-Colony model is compared with the Ground Truth model the same way. The histogram is shown in Figure 5. When there are 2 bypass diodes, the average error of MPP and CORR are 5.28% and 0.96. When there are 3 bypass diodes, these two average numbers are 1.46% and 0.91 respectively.

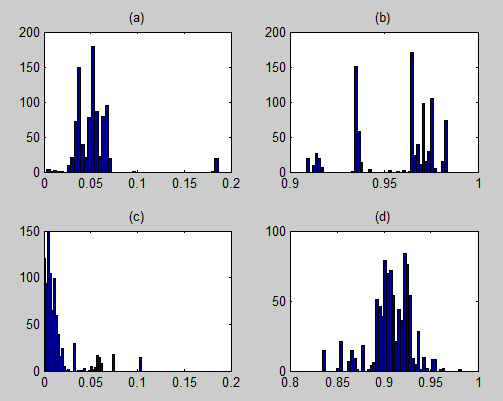


Figure. 5 N-Colony model error analysis (a) MPP error of 900 cases when (b) CORR of 900 cases when (c) MPP error of 900 cases when (d) CORR of 900 cases when

In conclusion, the Colony-Wise model can offer nearly the same accuracy as the Ground Truth model. The N-Colony model can still provide high accuracy, while its runtime is constant. It high efficiency is shown in the next sub-section.

5.3 Efficiency Comparisons

We compare the three models’ efficiency in terms of HSpice simulation time. The total run-time of the 300 cases (100\*3 ratios) for each PV module is shown in Table 4.

TABLE 4. Run Time of Three Models

|  |  |  |  |
| --- | --- | --- | --- |
| PV Module Config | GT Model | CW Model (speed up) | NC Model (speed up) |
| 20s2p (2 bp) | 1143s | 252s (4.53x) | 164s (6.97x) |
| 20s4p (2 bp) | 2106s | 441s (4.77x) | 153s (13.76x) |
| 30s2p (2 bp) | 1449s | 297s (4.88x) | 149s (9.72x) |
| 20s2p (3 bp) | 1116s | 351s (3.18x) | 243s (4.60x) |
| 20s4p (3 bp) | 2196s | 613s (3.58x) | 225s (9.76x) |
| 30s2p (3 bp) | 1656s | 432s (3.83x) | 231s (7.17x) |

As shown in Table 4, the runtime of the GT model is roughly proportional to the number of solar cells in a PV module. The runtime of the CW model is proportion to the multiplication of bypass diodes in a PV module. In addition, the runtime of the NC model is proportional to the number of bypass diodes in a solar cell chain.

The maximum speedup of the NC model is 13.76x when the PV module setting is 20s4p (2 bypass diodes). The speedup can be higher when a PV module has more paralleled solar cell chain and less bypass diodes within one solar cell chain.

6 Conclusion