Efficient Photovoltaic Module Models

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Abstract

Abstract— Bypass diodes are added to photovoltaic (PV) modules to compensate for power loss under shading effects. However, existing models cannot efficiently model PV modules with bypass diodes. In this paper, we develop an efficient Colony-Wise model with the nearly the same accuracy as the Ground Truth (GT) model, but its calculating time is reduced by 5.81 times on average. Furthermore, a more efficient N-Colony model is proposed, which has an average 5.15% maximum power point error, and an average power-voltage curve correlation of 0.96, and uses about $1/16$ calculating time when compared to the GT model. To the best of our knowledge, the Colony-Wise model and the N-Colony model are the two most efficient models for real-time solar energy prediction.

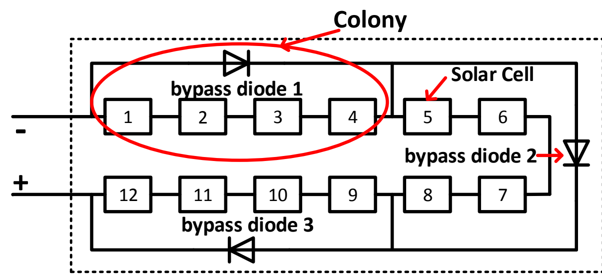

Fig. 1. A PV module with 1 solar cell chain, which consists of 12 solar cells and 3 colonies.

I. 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 [1, 2], 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 [3]. The non-uniform shading is also known as the Shading Effects [4, 5]. Shading Effects lead to the largest output power reduction and cell damage [4]. Furthermore, the shading on PV module is always changing. It needs a fast PV system model.

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 [6].

A PV systems model is based on PV module models. The existing PV module models are equivalent circuit models [7, 8]. Generally, a solar cell is modeled as a circuit, with a current source, diodes and resistors. A well-accepted solar cell model is shown in Figure 2. 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 modules configuration. Each One-Diode solar cell has its own parameters to model 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 models complexity is proportional to the number of solar cells. Consequently, the reduction of PV module models 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 re-

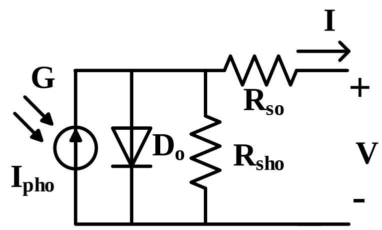

Fig. 2. The One-Diode model of a solar cell.

duce 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 modules 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.

Our major contribution is that these two models can model PV module of various configurations and with shading effects accurately and efficiently.

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

II. Preliminaries

A. The One-Diode Solar Cell Model

A well-accepted way to model a solar cell is through an equivalent circuit [7]. This model 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 I.

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

$$I = I_{ph_o} - I_{s_o}[exp(q\frac{V + R_{s_o}I}{N_o kT}) - 1] - \frac{V + R_{s_o}I}{R_{sh_o}} \quad (1)$$

where I_{ph_o} is the photovoltaic (PV) current and I_{s_o} is the reverse saturation current of the diode D. N_o 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_o} is the equivalent serial resistance of the cell and R_{sh_o} is the shunt resistance [7]. Note that the macro cell and the super cell are also modeled as the One-Diode model. The subscript o 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.

B. Shading Effects Representation in the 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 I_{ph} in the One-Diode model, shading effects can be represented as each solar cell has its own I_{ph}.

C. Notations and Definitions

We describe a PV module's configuration as the following. Without loss of generality, we assume the PV module to be $mSnP$, which means this module has n paralleled solar cell chains and m cascaded solar cells for each chain. The number of bypass diodes for each solar cell chain is n_{bp}. One PV module has $n * n_{bp}$ bypass diodes.

We use shading level SL to describe the shading effects. One SL is defined as the I_{ph} of a solar cell in the One-Diode model. Therefore, for the i^{th} solar cell in the j^{th} chain, we have:

$$SL_{ij} = I_{ph}(i, j) \quad (2)$$

All the shading levels together on a PV module represent its shading effects. The total number of different shading levels within one PV module is denoted as n_{SL}. Note that when all the solar cells have the identical photovoltaic current, $n_{SL} = 1$. This means there is not shading effects. The maximum of n_{SL} is $m * n$, when each of the solar cell has its own unique shading level.

For a PV module with n_{SL} multilevel shadings, we can use a I_{ph} sequence and a ratios sequence to represent shading effects:

$$\begin{aligned} SLs &= \{I_{ph1}, I_{ph2}, \ldots, I_{phn_{SL}}\} \\ ratios &= \{r_1, r_2, \ldots, r_{n_{SL}}\} \end{aligned} \quad (3)$$

where the ratios r_i represents the percentage of solar cells that has I_{phi}. Therefore, in a $mSnP$ PV module, there are $m*n*r_i$ solar cells that have I_{phi}.

III. The Colony-Wise PV Module Model

A. The Colony-Wise Model Equivalent Circuit Diagram

One colony in a PV module can always be represented as in Figure 3 (a). Let us assume that this colony has n_c solar cells. SL_1 to SL_{n_c} denotes shading level of each solar cell. Recall that the Ground Truth model models each solar cell with a One-Diode model. Differ from the GT model, in the Colony-Wise model, all n_c solar cells are lumped into at most two macro cells as shown in Figure 3 (b). If $SL_1 = SL_2 = \cdots = SL_{n_c}$, there is only one macro cell. Then all of the n_c 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 as SL^m_{max} and SL^m_{min}. The superscript m denotes the parameters are from macro cells. Section III B details the generation of parameters of the Colony-Wise model from the Ground Truth model. SL^m_{max} and SL^m_{min} are defined as the following:

$$SL^m_{max} = \max_{i \in n_c} SL_1, SL_2, \ldots, SL_{n_c} \quad (4)$$

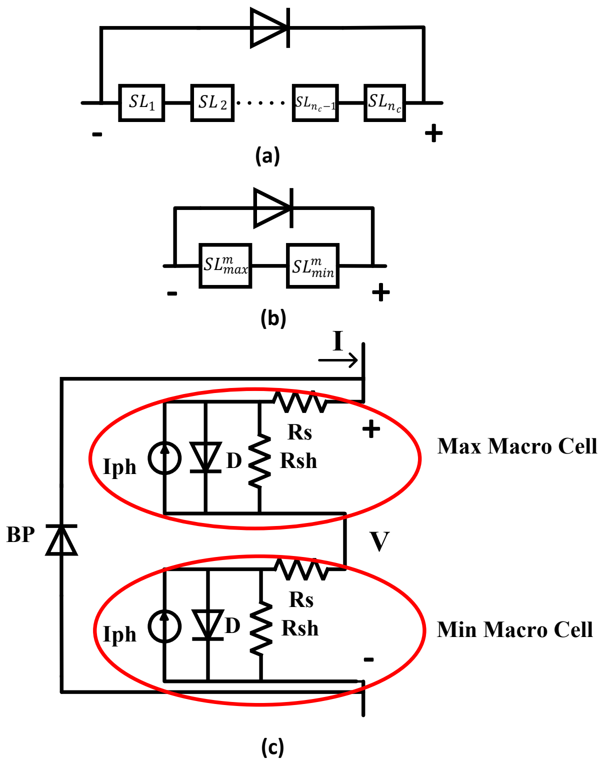

Fig. 3. (a) One colony with n_c solar cells (b) One colony model in Colony-Wise model (c) Circuit diagram of a colony modeled by Colony-Wise Model

$$SL^m_{min} = \min_{i \in n_c} SL_1, SL_2, \ldots, SL_{n_c} \tag{5}$$

B. Parameter Generation of The Colony-Wise Model

Heuristically, we pick up the two most representative solar cells within each colony to build the Colony-Wise model. These two cells are the basis of the two macro cells - the Max Macro Cell and the Min Macro Cell. These two macro cells are circled in the Figure 3 (c). One cell (to build the Max Macro Cell) has the maximum shading level SL^m_{max}, while the other cell (to build the Min Macro Cell) has the minimum shading level SL^m_{min}.

n_{max} and n_{min} counts the numbers of cells that belong to each macro cells within one colony. Note that:

$$n_{max} + n_{min} = n_c \tag{6}$$

The belonging of a cell depends on the shading level threshold:

$$thres = \frac{1}{2}(SL^m_{max} + SL^m_{min}) \tag{7}$$

For a solar cell, if its $SL \geq thres$, it belongs to the Max Macro Cell; otherwise, it belongs to the Min Macro Cell.

The circuit diagram of a colony modeled by the Colony-Wise model is as shown in Figure 3 (c). We can derive the parameters of Max Macro Cell and Min Macro Cell based on n_{max} and n_{min}. This model reduction is shown in Table I.

TABLE I
MODEL REDUCTION RULE FOR THE COLONY-WISE MODEL

Parameter	Max Macro Cell	Min Macro Cell
I^m_{ph}	SL^m_{max}	SL^m_{min}
I^m_s	I_{s_o}	I_{s_o}
N^m	$n_{max} * N_o$	$n_{min} * N_o$
R^m_s	$n_{max} * R_{s_o}$	$n_{min} * R_{s_o}$
R^m_{sh}	R_{sh_o}	R_{sh_o}

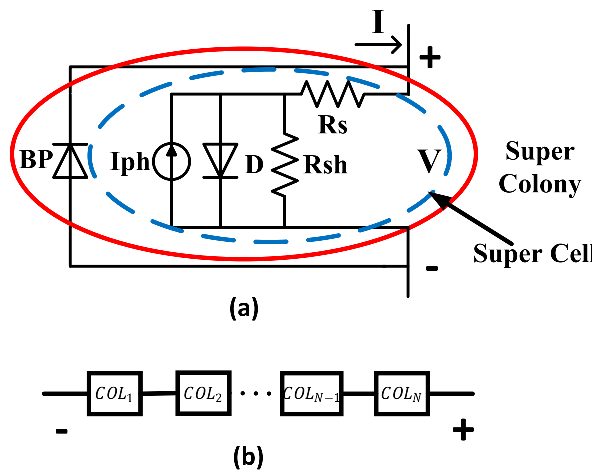

Fig. 4. (a) Equivalent circuit of one super colony in the N-Colony model (b) Diagram of the N-Colony model of a PV module

IV. THE N-COLONY PV MODULE MODEL

A. The N-Colony Model Equivalent Circuit Diagram

For a PV module with homogenous bypass diode distribution (each chain in a PV module has the same number of bypass diodes, and these bypass diodes have the same configuration), we can further lump a PV module into the N-Colony model. The notation N stands for the number of bypass diodes in each chain. Recall from Section II C, $N = n_{bp}$.

The N-Colony Model consists of N *super colonies*. Each super colony consists of one bypass diode and one *super cell*. The super sell is as circled in Figure 4, and 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 a $mSnP$ PV module is as shown in Figure 4 (b).

The N-Colony model is an heuristic model based on experiments. The parameters of the modeled need to be curve fitted from the Ground Truth model. The details of parameter generation is shown in the next sub-section.

B. Parameter Generation of the N-Colony Model

B.1 Super Colony's Shading Level Generation

First, we determine the shading level of each super colony. It is also the I_{ph} of the One-Diode model in the super cell.

According to Equation 4 and5, we can calculate the $SL^{(i,j)}_{max}$ and $SL^{(i,j)}_{min}$ of each colony. Note that when the cells are identical within a colony, $SL_{max}^{(i,j)} = SL_{min}^{(i,j)}$. The notation (i, j) represents the i^{th} colony in the j^{th} column in a PV module.

We define a matrix namely the All Min Matrix (M_{am}) to record all $SL_{max}^{(i,j)}$s and $SL_{min}^{(i,j)}$s. M_{am} is an ordered matrix, and is formed as the following. For the j^{th} chain of a PV module, we have the a SL sequence for all the colonies within this chain: $SL_{min}^{(1,j)}, SL_{min}^{(2,j)} m \ldots, SL_{min}^{(n_{bp},j)}$. We then reorder this sequence into: $SL^{(1,j)}, SL^{(2,j)}, \ldots, SL^{(n_{bp},j)}$, such that:

$$SL^{(1,j)} \leq SL^{(2,j)} \leq \cdots \leq SL^{(n_{bp},j)} \tag{8}$$

The All Min Matrix then is defined accordingly:

$$M_{am} = \begin{bmatrix} SL^{(1,1)} & \ldots & SL^{(1,n)} \\ \ldots & \ldots & \ldots \\ SL^{(n_{bp},1)} & \ldots & SL^{(n_{bp},n)} \end{bmatrix} \tag{9}$$

where n is the number of chain in a $mSnP$ PV module.

Finally, for the i^{th} super colony in the N-Colony model, its I_{ph}^{i} is generate by Equation 10:

$$I_{ph}^{i} = \sum_{j=1}^{n} M_{am}(i, j) \tag{10}$$

B.2 Cell Shading Ratio, Colony Shading Ratio and Shading Ratio

We define three variables: the Cell Shading Ratio (c_r), the Colony Shading Ratio (C_R) and Shading Ratio (R) of a N-Colony model. Parameters in N-Colony are generated from R, and R depends on c_r and C_R. For a PV module that has n_{bp} bypass diodes in a solar cell chain, we have $c_r^1, c_r^2, \ldots, c_r^{n_{bp}}$, $C_R^1, C_R^2, \ldots, C_R^{n_{bp}}$ and $R^1, R^2, \ldots, R^{n_{bp}}$ for a PV module.

c_r and C_R are defined as in Equation 11:

$$\begin{aligned} c_r^i &= \frac{\#i^{th}\ lv\ cell}{m * n} \\ C_R^i &= \frac{\#i^{th}\ lv\ colony}{n * n_{bp}} \end{aligned} \tag{11}$$

where $\#i^{th}\ lv\ cell$ is the number of solar cells with shading level i. A solar cell has shading level i when its SL satisfies:

$$M_{am}(i-1, j) \geq SL \geq M_{am}(i, j) \tag{12}$$

where j is the column this solar cell belongs to.

Similarly, $\#i^{th}\ lv\ colony$ is the number of colonies with shading level i, which is defined as in Equation 13 :

$$M_{am}(i-1, j) \geq SL_{min} \geq M_{am}(i, j) \tag{13}$$

where j is the column this colony cell belongs to, and SL_min is defined in Equation 5.

R is defined as:

$$R^i = \begin{cases} \alpha_i * c_r^i + \beta_i * C_R^i + \gamma_i & \text{if } i \neq n_{bp} \\ 1 - \sum_{j=1}^{n_{bp}-1} R^i & \text{otherwise} \end{cases} \tag{14}$$

where α_i, β_i and γ_i are the weighing factors that need to be curve fitted. Note that we need to make sure all R^is are greater then zero.

Therefore, for a PV module with $n * n_{bp}$ bypass diodes on each chain, $(n*n_{bp}-1)*3$ parameters are required to be curve fitted.

TABLE II
MODEL REDUCTION RULE FOR THE N-COLONY MODEL

Parameter	Super Colony i
I_{ph}^s	I_{ph}^i
I_s^s	$I_{s_o} * n * R^i$
N^s	$N_o * m * R^i$
R_s^s	$R_{s_o} * m/n * R^i$
R_{sh}^s	$R_{sh_o}/n * R^i$
$I_{s_{bp}}^s$	$I_{s_{bp_o}} * n * R^i$
N_{bp}^s	$N_{bp_o} * n * R^i$

B.3 Parameters in the N-Colony Model

Once we have all R^is and I_{ph}^is, we can generate all N-Colony model parameters based on Table II. In Table II $I_{s_{bp}}^s$ and N_{bp}^s are the parameters of the bypass diode in the super colony. The superscript s denotes the corresponding parameters are from the super colony.

B.4 Curve Fitting of the Weighting Factors

The goal of the N-Colony model is to minimize the error between its Power-Voltage (PV) curve and 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 Equation 15.

$$Obj = w_1 * 0.5 * (2 - CORR) + w_2 * Error_{MPP} \tag{15}$$

where $Error_{MPP}$ is the relative error of the maximum power point (MPP) and CORR is the correlation of the two curves. If we have two P-V curves, namely 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 Equation 16.

$$CORR = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{16}$$

where $\bar{x}$ and $\bar{y}$ are the average value for all x_i and y_i. Note that the closer $CORR$ is to 1, the more similar the two curves are.

In addition, to quantify the impacts of these two optimization goals, they have to be normalized. MPP has already been normalized because its value is between 0 and 1. However, CORR has a range between -1 and 1. Therefore, the $0.5*(2-CORR)$ term is the normalization term used in Equation 15. Furthermore, w_1 and w_2 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 impacts of CORR and MPP equal.

V. EXPERIMENTAL RESULTS

A. Experiment Settings

In this section, we compare three models for PV modules in terms of accuracy and speed. 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

TABLE III
CURVE FITTING RESULTS OF THE N-COLONY MODEL

Weighting Factors	$60s2p$	$30s4p$	$40s2p$
$\{\alpha_1, \beta_1, \gamma_1\}$	$\{0.41, 0.17, 0.04\}$	$\{0.75, 0.22, 0.06\}$	$\{0.71, 0.27, 0.10\}$
$\{\alpha_2, \beta_2, \gamma_2\}$	$\{0.40, 0.20, 0.14\}$	NA	NA

all the cells that have the same shading level within one PV module are adjacent to each other.

We use notations from Section II (Equation 3) to represent the multilevel shading settings. In the experiment, we assume $SLs = \{2A, 1.75A, 1.5A, 1.25A, 1A\}$. In order to simulate multiple shading scenarios, we define a ration array that consist three ratios: $ratios1 = \{70\%, 10\%, 5\%, 5\%, 10\%\}$, $ratios2 = \{50\%, 10\%, 10\%, 10\%, 20\%\}$ and $ratios1 = \{20\%, 20\%, 20\%, 20\%, 20\%\}$. The three $ratios$ covers low shading, medium shading and high shading respectively. For one PV module with each shading ratio, we generate 100 random shading patterns to evaluate three models.

We instantiate three different PV modules in our experiment: $60s2p$, $30s4p$ and $40s2p$. As for the bypass diode configuration, every 15 to 20 cells have one bypass diode according to [6]. Therefore, $60s2p$ module has 3 bypass diodes for each chain, and other two modules have 2 bypass diodes for each chain. We use the same solar cell's One-Diode model parameters as in [7]. Diode quality factor $N_o = 1.5$, diode saturation current $I_{s_o} = 10^{-6}A$, serial resistance $R_{s_o} = 0.0079\Omega$ and shunt resistance $R_{sh_o} = 5000\Omega$. The bypass diode has the quality factor $N_{bp_o} = 1$ and saturation current $I_{sbp_o} = 10^{-6}A$.

The circuit simulations are conducted in HSPICE [9]. The experiment was conducted on a laptop that has an Intel $i5$ 2.4GHz CPU, and 8GB memory.

For the N-Colony model, 20 shading patterns are used to curve fit the weighting factors in Equation 15. 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. In order to jump out of the local optimal, several randomized initial points were used and we picked the best results. The curve-fitted parameters of the NC model are shown in Table III. Although they are different for different PV modules, the curve fitting overhead is reasonable because in a solar farm, the types of PV modules are usually small.

Furthermore, α is always larger than β and γ under all conditions. This shows that C_R has a larger impact on PV module modeling than c_r. C_R is the dominant factor in a PV modules output power. This implies that the PV module generates less power, when the shade covers more colonies while the area of the shade remains the same. Similar observations can also be found in other references [10, 7, 8].

B. Accuracy Comparisons Among the Three Models

To evaluate accuracy of the Colony-Wise model and the N-Colony model, the average relative error of the Maximum Power Point (MPP) and the average P-V curve correlation (CORR) are compared with the Ground Truth model. 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.

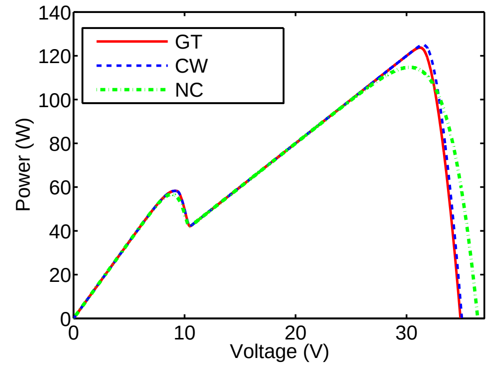

Fig. 5. An example of three P-V curves generated by three models of a same PV module configuration

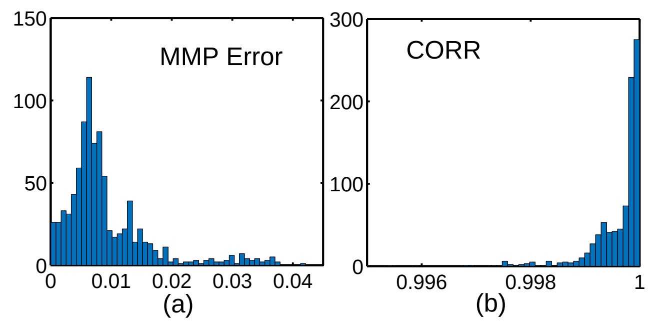

Fig. 6. (a) CW model's MPP error histogram over 900 test cases (b) CW model's CORR histogram over 900 test cases

Figure 5 shows an typical example of the P-V curves generated by the three models. The PV module is $60s2p$ with 3 bypass diodes for each solar cell chain. Compared to the Ground Truth model's P-V curve (red solid line), the Colony-Wise model (blue dashed line) has almost the same accuracy, while the N-Colony model (green dot-dashed line) sacrifices the model a little bit to trade off for the constant computational speed.

First, we compare the Colony-Wise model with the Ground Truth model over the 900 test cases. Figure 6 (a) (b) show the histogram of 900 cases MPP error and CORR. The average MPP error is 0.92%, and the average CORR is 0.999. In addition, the largest MPP error is 4.21%, 95% of MPP errors are less than 2.60%, and the lowest CORR is 0.995. The results show that the Colony-Wise model has nearly the same accuracy as the Ground Truth model.

Then, we compare the N-Colony model with the Ground

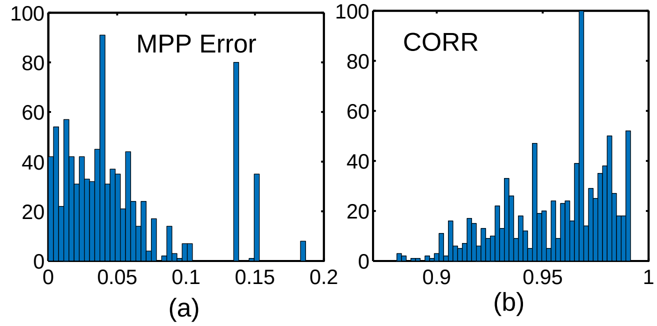

Fig. 7. (a) NC model's MPP error histogram over 900 test cases (b) NC model's CORR histogram over 900 test cases

TABLE IV
RUNTIME OF THE THREE MODELS

PV Module Config	GT	CW (Speedup)	NC (Speedup)
$60s2p$	$2216s$	$318s$ (7.0X)	$129s$ (17.2X)
$30s4p$	$1325s$	$317s$ (4.2X)	$91s$ (14.5X)
$40s2p$	$1652s$	$267s$ (6.2X)	$101s$ (16.3X)

Truth model. Figure 7 (a) shows the histogram of 900 cases MPP error and (b) shows the CORRs' histogram. The average MPP error is 5.15%, and the average CORR is 0.96. The NC model sacrifices the accuracy a little for it's constant computational complexity. There are two major reasons for the loss of accuracy. First, the NC model has constant number of component, therefore, there will be information loss when converting from the GT model to the NC model. Second, the NC model is an experimental model, which means some of its parameters are curved fitted (trained) through experiment data. The shading patterns of the large error cases are not covered in the 20 training patterns. Therefore, the NC model has larger error for these cases. To overcome this weakness, we can increase the number of training patterns.

C. Speed Comparisons Among the Three Models

We compare the three models' efficiency in terms of HSpice simulation time. The total run-time of the 300 cases for each PV module is shown in Table IV.

As shown in Table IV, 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 17.2X when the PV module setting is $60s2p$ (3 bypass diodes for each chain). The speedup can be higher when a PV module has more paralleled solar cell chain and less bypass diodes within one solar cell chain.

VI. CONCLUSIONS

In this paper, two new PV module models are proposed, namely the Colony-Wise (CW) model and the N-Colony (NC) model. The two new models can support multiple shading levels on a PV module and various PV module configuration. The Colony-Wise model can efficiently capture the P-V curve of a PV module with almost no accuracy loss. The N-Colony model can further reduce the models computational complexity to a constant value with a limited accuracy loss.

The N-Colony model is based on curve fitting. The accuracy of the model is highly related to the curve fitting process. Our future work will be finding optimal/good parameters in a high-dimensional solution space.

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