

A MATLAB-Simulink-Based PV Module Model and Its Application Under Conditions of Nonuniform Irradiance

Kun Ding, XinGao Bian, HaiHao Liu, and Tao Peng

Abstract—The performance of a photovoltaic (PV) module is mostly affected by array configuration, irradiance, and module temperature. It is important to understand the relationship between these effects and the output power of the PV array. This paper presents a MATLAB-Simulink-based PV module model which includes a controlled current source and an S-Function builder. The modeling scheme in S-Function builder is deduced by some predigested functions. Under the conditions of nonuniform irradiance, the model is practically validated by using different array configurations in testing platform. The comparison experiments indicate that I - V and P - V characteristic curves of simulation match the measurements from outdoor experiment well. Under the conditions of nonuniform irradiance, both simulation and experiment show that the output power of a PV array gets more complicated due to multiple peaks. Moreover, the proposed model can also simulate electric circuit and its maximum power point tracking (MPPT) in the environment of MATLAB-Simulink. The experiments show that the proposed model has good predictability in the general behaviors of MPPT under the conditions of both nonuniform and uniform irradiance.

Index Terms—MATLAB-Simulink, model, nonuniform irradiance, photovoltaic (PV) array.

I. INTRODUCTION

WITH a spurt in the use of renewable energy sources, photovoltaic (PV) power generation is being employed in many applications. Conventionally, a PV system consists of solar PV arrays and electric converters. A PV array is formed by series/parallel combination of solar modules. Some operating conditions result in nonuniform irradiance of PV array, such as shadows, clouds, dirt, debris, bird droppings, different orientations and tilts, and so on. If several solar cells in a series PV module are mismatched due to nonuniform irradiance, these cells will limit the output current of normal cells. This leads to decrease of the output power, even generates hot-spot and causes damage to these cells. To avoid the destructive effects of hot-spot, a bypass diode is connected in parallel with a PV module

or parallel with some series-connected solar cells in a PV module, which creates a replacement path [1]. The output power of mismatched cells is cut off when the bypass diode works. The output characteristics will be more complicated when the PV array is mismatched, and it causes some energy loss [2]–[5]. To obtain maximal PV installation output power, it is very important to reveal PV characteristics under condition of nonuniform irradiance.

To model solar cell, the one-diode model has been proposed [6], and some researchers have studied how to extract parameters for the model [7], [8]. For a higher accuracy, two-diode model has been studied for years [9], [10]. In these research works, some methods were developed to determine the electrical parameters in these models. The electrical characteristics of a solar cell/PV module derived from those proposed models match the experimental data well when irradiance is uniform. However, these models cannot be directly used when irradiance is nonuniform.

Models for a solar cell or module based on the Shockley diode equation in MATLAB are presented, and some accurate electrical models of the PV module were modeled and demonstrated under uniform irradiance in MATLAB [11], [12]. The simulation results showed that it has excellent correspondence to manufacturer's specified curves when the P - V curve has unique power peak.

Electrical characteristics of the PV module under uniform or nonuniform irradiance have been analyzed in [2], [13]–[18]. Their results indicate that nonuniform irradiance on PV modules leads to more complicated characteristics of PV array, e.g., multiple power peaks appear in the P - V curves.

Some published PV module models, which presented some ways to improve the accuracy of the model, focused on the electrical characteristics of PV modules under conditions of nonuniform irradiances. Part of the work has been done, such as a model to simulate circuit topology and its control strategy under conditions of uniform irradiance [2], [13], [15], [17], [18].

However, the issue of modeling a flexible PV module model using MATLAB to validate new maximum power point tracking strategies under the conditions of nonuniform irradiance was seldom covered [19]–[21]. To achieve a simulation kit of this issue, a simple but accurate enough PV module model using MATLAB-Simulink was proposed in this paper. It is derived from a one-diode model with some parameters in the main formula, which could make calculating easier. The proposed model can not only be combined to simulate PV array by series/paralleled connection, but also be employed to simulate

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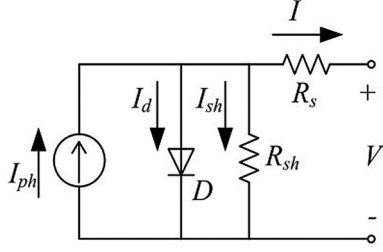


Fig. 1. Equivalent circuit of a single solar cell.

an electronic circuit and its control strategy, especially under conditions of nonuniform irradiance.

II. PHOTOVOLTAIC MODULE MODELING

A. Mathematical Equation of a Solar Cell

There are many equivalent circuits of a solar cell, where the single-diode and two-diode models could be the most widely used. Since the single-diode model is simple and accurate enough in many cases [7], [8], it is applied in this paper. Its equivalent circuit with series and parallel resistance is shown in Fig. 1 [22].

The symbols in Fig. 1 are defined as follows:

- I_{ph} : photocurrent;
- I_d : current of parallel diode;
- I_{sh} : shunt current;
- I : output current;
- V : output voltage;
- D : parallel diode;
- R_{sh} : shunt resistance;
- R_s : series resistance.

The I - V equation of Fig. 1 is showed as

$$I = I_{ph} - I_0 \left\{ e^{\frac{q(V+R_s I)}{AKT}} - 1 \right\} - \frac{V + R_s I}{R_{sh}} \quad (1)$$

where I_0 is the reverse saturation current of the diode, q is the electron charge (1.602×10^{-19} C), A is the curve fitting factor, and K is Boltzmann constant (1.38×10^{-23} J/K).

B. Model of a PV Module

If a solar cell type tends to have an I - V curve in which the slope at short circuit is almost zero, the value of R_{sh} can be assumed to be infinite [23]. In this case, the last term in (1) could be ignored. And taking I_{ph} as I_{SC} , (1) will become [22]

$$I = I_{SC} - I_0 \left(e^{\frac{q(V+R_s I)}{AKT}} - 1 \right) \quad (2)$$

where I_{SC} is the short-circuit current.

Equation (2) is valid for a solar cell. For the accurate application of this equation for a PV module, the term of $q(V + R_s I)/AKT$ is changed to $q(V + R_s I)/N_s AKT$, in which N_s is the number of series-connected solar cells in a PV module. Then, (2) will become

$$I = I_{SC} - I_0 \left(e^{\frac{q(V+R_s I)}{N_s AKT}} - 1 \right). \quad (3)$$

A simple PV module model will be derived from (3) in this section.

When a PV module is in an open-circuit situation, $I = 0$ and the item $q/N_s AKT$ in (3) will be solved as follows:

$$\frac{q}{N_s AKT} = \frac{\ln\left(\frac{I_{SC}}{I_0} + 1\right)}{V_{OC}} \quad (4)$$

where V_{OC} is the open-circuit voltage of a PV module.

Substituting (4) into (3), we get

$$I = I_{SC} \left[1 - \frac{I_0}{I_{SC}} \left(e^{\ln\left(\frac{I_{SC}}{I_0} + 1\right) \frac{(V+R_s I)}{V_{OC}}} - 1 \right) \right]. \quad (5)$$

Defining $k = I_{SC}/I_0$ and simplifying (5), we get

$$I = I_{SC} \left[1 - \frac{1}{k} (k + 1) \frac{V+R_s I}{V_{OC}} + \frac{1}{k} \right]. \quad (6)$$

Normally, the value of k is very large because I_0 is far less than I_{SC} . Some terms in (6) could be ignored, and then a simple I - V equation is deduced

$$I = I_{SC} \left(1 - k \frac{V+R_s I}{V_{OC}} - 1 \right). \quad (7)$$

Under standard test condition (STC), which consists of a PV module temperature of 25 °C and an in-plane irradiance of 1 000 W/m² with spectral distribution conforming to an AM1.5 spectrum, (7) could be rewritten as follows:

$$I_{ref} = I_{SC,ref} \left(1 - k_{ref} \frac{V_{ref} + R_s I_{ref}}{V_{OC,ref}} - 1 \right) \quad (8)$$

where I_{ref} is the output current under STC, $I_{SC,ref}$ is the short-circuit current under STC, V_{ref} is the output voltage under STC, $V_{OC,ref}$ is the open-circuit voltage under STC, and k_{ref} is the coefficient of k under STC.

Parameters at maximum output power point (MPP) under STC could be given to solve the coefficient of k_{ref}

$$k_{ref} = \left(\frac{V_{MPP,ref} + R_s I_{MPP,ref}}{V_{OC,ref}} - 1 \right) \sqrt{1 - \frac{I_{MPP,ref}}{I_{SC,ref}}} \quad (9)$$

where $V_{MPP,ref}$ is the output voltage at MPP under STC and $I_{MPP,ref}$ is the output current at MPP under STC.

As temperature increases, the output voltage of the PV module decreases with the p-n junction voltage temperature dependence. Therefore, the open-circuit voltage of the PV module has a negative temperature coefficient. It is known that higher temperature results in larger photocurrent. Consequently, the output current of the PV module has a characteristic of positive temperature coefficient.

It is clear that the output voltage and current of a PV module change with irradiance [22]. Hence, the effect of changes of temperature and irradiance should be considered in the PV module model. To achieve electrical characteristic of a PV module in various temperature and irradiance, a method of current-voltage translation recommended by Hermann and Wiesner [24] is used in this paper. The mathematical expressions for correction of current and voltage in this method are

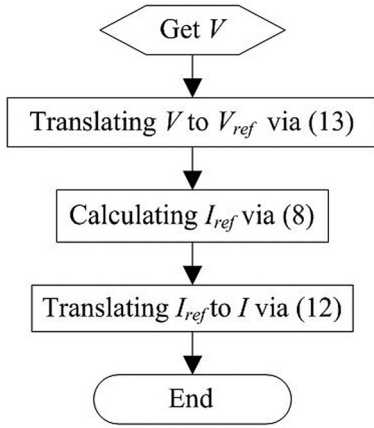


Fig. 2. Flow of calculating the output current of a PV module.

$$I_{SC} = I_{SC,ref} [1 + \alpha(T - T_{ref})] \frac{S}{S_{ref}} \quad (10)$$

$$V_{OC} = V_{OC,ref} \left[1 + a \ln \frac{S}{S_{ref}} + \beta(T - T_{ref}) \right] \quad (11)$$

where T is the PV module temperature, T_{ref} is the reference PV module temperature under STC, S is the in-plane solar irradiance, S_{ref} is the reference irradiance under STC, α is the temperature coefficient of I_{sc} , β is the temperature coefficient of V_{oc} , and a is the irradiance correction factor of V_{oc} .

The translation equations in this method are [24]

$$I = I_{ref} \frac{I_{SC}}{I_{SC,ref}} \quad (12)$$

$$V = V_{ref} + (V_{OC} - V_{OC,ref}) + R_s (I_{ref} - I). \quad (13)$$

A flow to calculate the output current of the PV module in various temperature and irradiance is presented in Fig. 2 based on equations from (8)–(13).

To simplify the procedure in Fig. 2, (12) and (13) are substituted into (8) to get a new expression of I_{ref}

$$I_{ref} = I_{SC,ref} \left(1 - k_{ref} \frac{V - V_{OC} + R_s I_{ref} \frac{I_{SC}}{I_{SC,ref}}}{V_{OC,ref}} \right) \quad (14)$$

where I_{ref} could be solved by a numerical method in MATLAB easily.

Although the proposed model is derived by simplification and the flow in Fig. 2 is also simple, the proposed model is still good enough to assist people to understand the behavior of a PV module.

C. PV Module Model in MATLAB-Simulink

The block diagram of the MATLAB-Simulink-based PV module model is shown in Fig. 3(a), where the proposed model and the flow in sector B are implemented by an S-Function builder with three inputs and one output. $S1$ is irradiance, T is the temperature of the PV module, V is the output voltage of the PV module, and I_{out} is the output current of the PV module. I_{out} connecting to a controlled current source is used for sim-

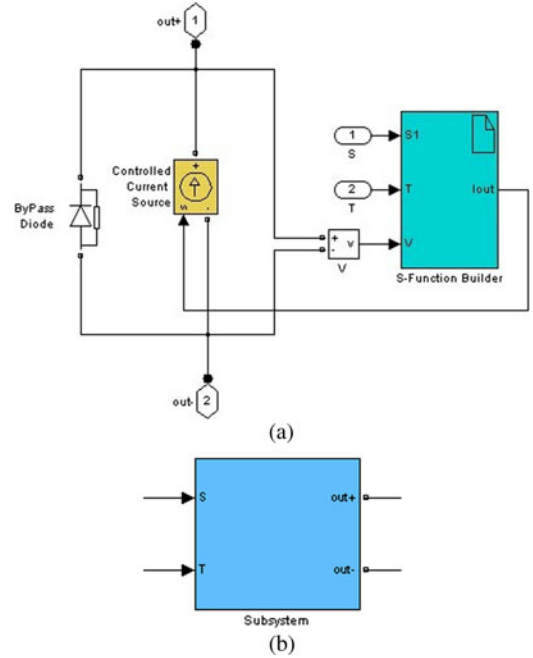


Fig. 3. PV module model in MATLAB-Simulink. (a) Block diagram of the PV module model. (b) PV module model in a subsystem.

ulating the output current of the PV module. A bypass diode is connected in parallel with the controlled current source.

For the sake of convenience, all components in Fig. 3(a) are incorporated into a subsystem block in following steps.

Step 1: Enclose the blocks and connect lines in Fig. 3(a) within a bounding box.

Step 2: Choose the option of create subsystem from the Edit menu. MATLAB-Simulink replaces the selected blocks with a subsystem block, which is shown in Fig. 3(b).

The subsystem block in Fig. 3(b) will be a basic PV module mode of MATLAB-Simulink in this paper. In the subsystem block, port of out + is the positive terminal of the PV module, port of out- is the negative terminal of the PV module, port of S is the in-plane irradiance, and T is the temperature of the PV module. The subsystem blocks can be connected in series/parallel according to the actual PV array; then it can be simulated in MATLAB-Simulink.

Fig. 4 shows the details of the screen shot of a S-Function builder block [see Fig. 3(a)]. The pane of port/parameter displays the ports and parameters that the dialog box specifies for the target S-function; they are $S1$, $T1$, V , and I_{out} . All ports are in complexity of real and dimension of 1-D. The S-code for the implementation of the proposed flow in Fig. 2 resides in the output pane. The S-code is presented in the Appendix.

III. EXPERIMENTAL VALIDATION OF THE MODEL

This section describes the procedure and results using the proposed MATLAB-Simulink based model. It is important to understand how the model works under different conditions.

A PV module, EGing-50W, produced by EGING PV with 36 series-connected monocrystalline cells, is chosen to evaluate the proposed model in this paper. The electrical characteristics

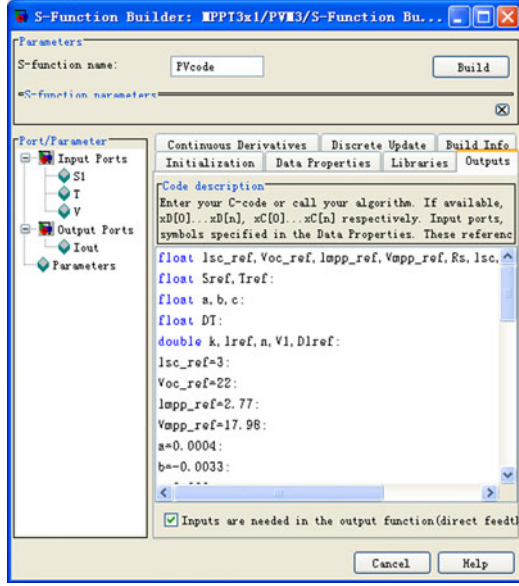


Fig. 4. Screen shot of S-Function builder.

TABLE I
ELECTRICAL CHARACTERISTICS OF EGING-50W

Parameter	Variable	Value
Maximum power	P_{MPP}	50W
Voltage at Pmax	V_{MPP}	17.98V
Current at Pmax	I_{MPP}	2.77A
Short circuit current	I_{SC}	3A
Open circuit voltage	V_{OC}	22V
Temperature coefficient of I_{SC}	a	0.04%/°C
Temperature coefficient of V_{OC}	β	-0.33%/°C

specifications under STC from manufacturer are shown in Table I.

The parameters of series resistance R_s , irradiance correction factor a in (11), and coefficient k_{ref} in (8) have to be determined.

It is well known that the derivative of the PV module power with respect to the PV module voltage is zero at MPP. An additional equation to obtain an analytical solution for R_s can be achieved [25]. The following formula can be obtained at MPP:

$$\left. \frac{dI}{dV} \right|_{V=V_{MPP}} = -\frac{I_{MPP}}{V_{MPP}}. \quad (15)$$

On the other hand, the derivative of (7) with respect to V brings

$$\frac{dI}{dV} = -I_{SC} \frac{1 + R_s \frac{dI}{dV}}{V_{OC}} k^{\frac{V + R_s I}{V_{OC}} - 1} \ln k. \quad (16)$$

Equation (16) could be rewritten at MPP as follows:

$$\left. \frac{dI}{dV} \right|_{V=V_{MPP}} = -I_{SC} \frac{1 + R_s \frac{dI}{dV} \Big|_{V=V_{MPP}}}{V_{OC}} k^{\frac{V_{MPP} + R_s I_{MPP}}{V_{OC}} - 1} \ln k. \quad (17)$$



Fig. 5. Flexible testing platform.

Substituting (9) and (15) into (17) under STC, an expression of R_s will be obtained as follows:

$$R_s = \frac{V_{MPP,ref} + \frac{I_{MPP,ref}(V_{OC,ref} - V_{MPP,ref})}{(I_{SC,ref} - I_{MPP,ref}) \ln(1 - \frac{I_{MPP,ref}}{I_{SC,ref}})}}{I_{MPP,ref} + \frac{I_{MPP,ref}^2}{(I_{SC,ref} - I_{MPP,ref}) \ln(1 - \frac{I_{MPP,ref}}{I_{SC,ref}})}}. \quad (18)$$

R_s of a PV module EGing-50W is 0.085 Ω by substituting the parameters in Table I into (18) and the coefficient k_{ref} is 3 047 214 by using (9). R_s is assumed to be a constant at its reference value under STC [23].

To determine the irradiance correction factor a , parameters in Table I and measured open-circuit voltage at 21.2 V under testing conditions of irradiance at 330 W/m² with module temperature at 14 °C are substituted into (11). Consequently, the irradiance correction factor for selected PV module is 0.066.

To evaluate the proposed model, a flexible testing platform was built up on the rooftop of Hohai University campus, which is shown in Fig. 5.

There are two frames in the platform. Three PV modules of EGing-50W are installed on each frame. These PV modules could be series-/parallel-connected flexibly. A programmable electrical load (model: ARRAY 3711A) is used, which can be controlled by users. For example, a procedure to get the I - V curve of a PV module is proposed as follows. First, electrical load is set in the current model. Second, electrical load changes automatically with fixed interval of limitation current from zero to short current; in this process, the output voltage and current of the PV module are logged synchronously. In the duration, a series of measurement data of current and voltage could be obtained from ARRAY 3711A by PC via communication of RS232. Finally, the I - V curve could be obtained.

A solar power meter (model: TES-1333) is used to measure instant irradiance.

A. Study Case of a Single PV Module

To evaluate the availability of the proposed model, three measurement I - V curves and P - V curves of single EGing-50W PV module under outdoor condition are selected to compare the results of simulation using the proposed model. Testing conditions are irradiance at 220 W/m² with module temperature at 30.5 °C, irradiance at 465 W/m² with module temperature at 45 °C, and irradiance at 890 W/m² with module temperature at 50 °C.

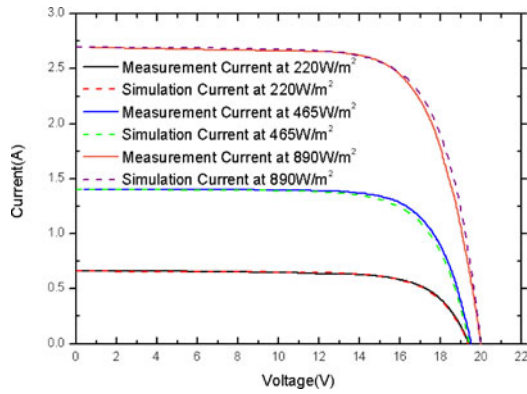


Fig. 6. Simulation and measurement I - V curves with various irradiance.

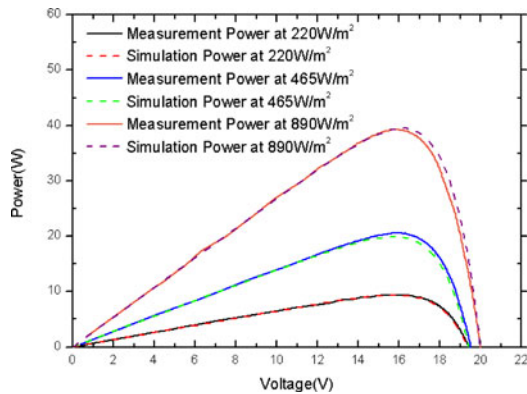


Fig. 7. Simulation and measurement P - V curves with various irradiance.

In these study cases, the solid lines show measurement curves and dashed lines show simulation curves in Figs. 6 and 7. These figures show good agreement between measurement curves and simulation curves.

B. Study Case of a PV Array Under the Conditions of Nonuniform Irradiance

To evaluate the performance of the proposed model under nonuniform irradiance conditions, the following experiments and simulations have been carried out.

Given three PV modules in one frame of the testing platform are connected in series to obtain the I - V and P - V characteristics under the conditions of nonuniform irradiance. The corresponding simulation diagram is shown in Fig. 8. Three PV module models are employed; the models are named PVM1, PVM2, and PVM3, respectively, and they have their own inputs of temperature and irradiance. An adjustable resistance R_{load} is tied with the output of this series as load.

To achieve different in-plane irradiance of each PV module, several pieces of translucent plastic are employed to decrease in-plane irradiance of the PV module. These tests under the conditions of nonuniform irradiance are carried out in following steps.

Step 1: wait duration of stable clear sky.

Step 2: cover PV module by using translucent plastic as soon as possible.

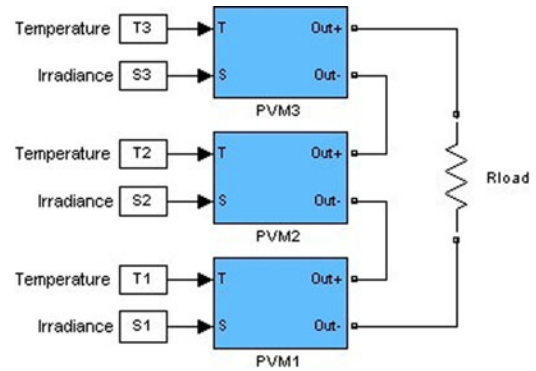


Fig. 8. Diagram of three PV modules connected in series.

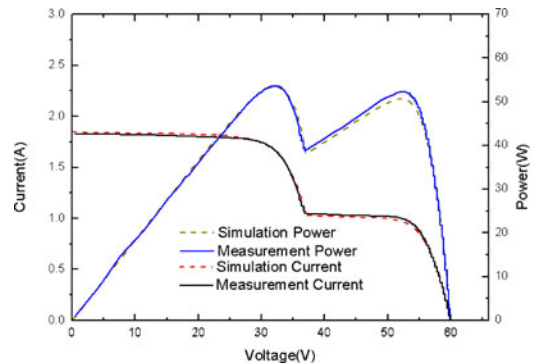


Fig. 9. I - V and P - V curves of test A.

Step 3: measure irradiance as soon as possible.

Step 4: measure I - V curves as soon as possible.

Because of thermal inertia, the temperature of PV modules is the same. In other words, the process of achieving nonuniform irradiance causes fixed temperature in the same studied case.

Fig. 9 shows the I - V and P - V characteristics under the different irradiance as follows: $S1 = 340 \text{ W/m}^2$, $S2 = 612 \text{ W/m}^2$, and $S3 = 612 \text{ W/m}^2$. The module's temperature is 39°C . It is named test A. There are two power peaks in Fig. 9. It should be noticed that the temperature of all PV modules are the same due to covering quickly and measuring immediately.

Another experiment and corresponding simulation have been implemented too. The incident irradiance of three modules is different, with $S1 = 578 \text{ W/m}^2$, $S2 = 827 \text{ W/m}^2$, and $S3 = 990 \text{ W/m}^2$. The module's temperature is 47°C . It is named test B; there are three power peaks in Fig. 10.

Obviously, the numbers of power peaks depend on in-plane irradiance levels in the series of PV modules. Note that the short-circuit current of each PV module under different irradiance is different; the associated bypass diode would be conducted when the passing current is greater than its short-circuit current. That means the PV module is cut off and is not able to produce any electricity power. So, different in-plane irradiance levels in the series of PV modules might cause different numbers of power peaks depending on how many PV modules are bypassed.

Given a PV array which consists of six PV modules arranged into two parallels, each having three modules connected in series. The corresponding simulation diagram is shown in Fig. 11.

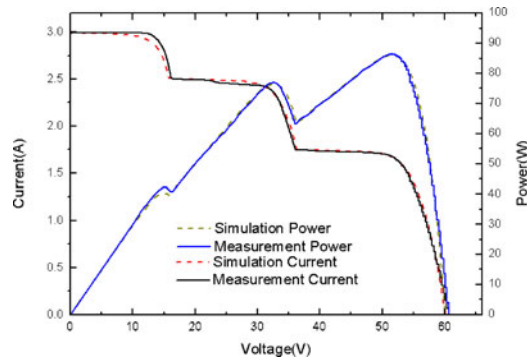


Fig. 10. I - V and P - V curves of test B.

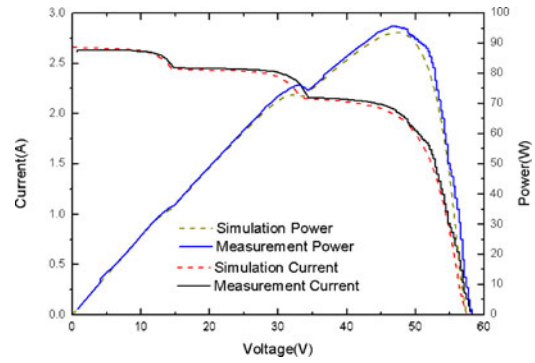


Fig. 13. I - V and P - V curves of test D.

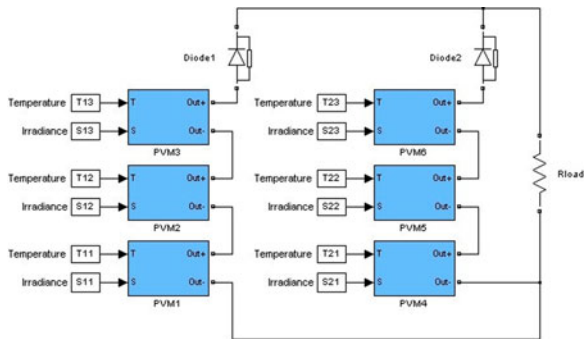


Fig. 11. Diagram of a 3×2 PV array.

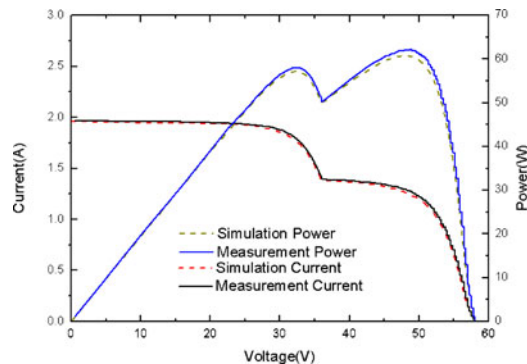


Fig. 12. I - V and P - V curves of test C.

Each of six PV module models can be controlled by their own inputs of irradiance and temperature.

Fig. 12 shows the I - V and P - V curves under different irradiance as follows: $S_{11} = 325 \text{ W/m}^2$, $S_{12} = 325 \text{ W/m}^2$, $S_{13} = 138 \text{ W/m}^2$, $S_{21} = 325 \text{ W/m}^2$, $S_{22} = 325 \text{ W/m}^2$, and $S_{23} = 325 \text{ W/m}^2$. The modules temperature is 38°C . It is named test C; there are two power peaks in Fig. 12.

Another experiment and corresponding simulation have been implemented for evaluating the 3×2 PV array. The in-plane irradiances of three modules are different: $S_{11} = 440 \text{ W/m}^2$, $S_{12} = 370 \text{ W/m}^2$, $S_{13} = 275 \text{ W/m}^2$, $S_{21} = 440 \text{ W/m}^2$, $S_{22} = 440 \text{ W/m}^2$, and $S_{23} = 440 \text{ W/m}^2$. The modules temperature is 46°C . It is called test D, where three power peaks are shown in Fig. 13.

Although in-plane irradiance on one of the series-connected PV modules is the same, multi-peaks occur in both experiment

TABLE II
COMPARISON OF MEASUREMENTS AND SIMULATION RESULTS AT POWER PEAKS

Test		V_{mpp} (V)			P_{mpp} (W)		
		Meas-urement	Simul-ation	Error (%)	Meas-urement	Simul-ation	Error (%)
Test A	Peak 1	32.2	31.8	-1.24	53.7	53.4	-0.56
	Peak 2	52.7	52.1	-1.14	52.4	50.7	-3.24
	Peak 3	14.9	14.8	-0.67	42.2	40.4	-4.27
Test B	Peak 2	32.7	32.5	-0.61	77.0	76.5	-0.65
	Peak 3	51.5	51.5	0.00	86.7	86.2	-0.58
Test C	Peak 1	32.0	32.5	1.56	58.0	57.1	-1.55
	Peak 2	48.7	47.8	-1.85	62.2	60.7	-2.41
Test D	Peak 1	14.8	14.5	-2.03	36.4	35.5	-2.47
	Peak 2	33.1	31.7	-4.23	76.1	72.7	-4.47
	Peak 3	47.2	47.1	-0.21	95.8	93.6	-2.30

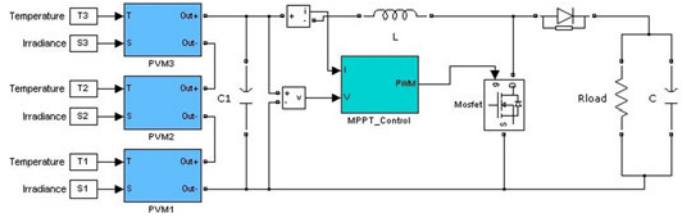


Fig. 14. Simulation schematic of boost topology using the proposed model.

and simulation due to nonuniform irradiance on another series-connected PV module.

Parameters at power peaks from test A to test D are compared in Table II.

Figs. 9 and 10 as well as Figs. 12 and 13 show multi-peaks of PV array output power under the conditions of nonuniform irradiance, and simulation results are in accordance with the results of experiment. The peak power errors are shown in Table II.

C. Study Case of a Combining Model With DC/DC Converter

To verify the suitability of the proposed model combining with dc/dc converter, a simulation schematic is presented in Fig. 14. It consists of series-connected three PV module models and a boost circuit. The boost circuit is a typical dc/dc converter, and the parameters are set as follows:

$$L = 1.7 \text{ mH}; R_{load} = 86 \Omega; C = 470 \mu\text{F}; \text{ and } C1 = 10 \mu\text{F}$$

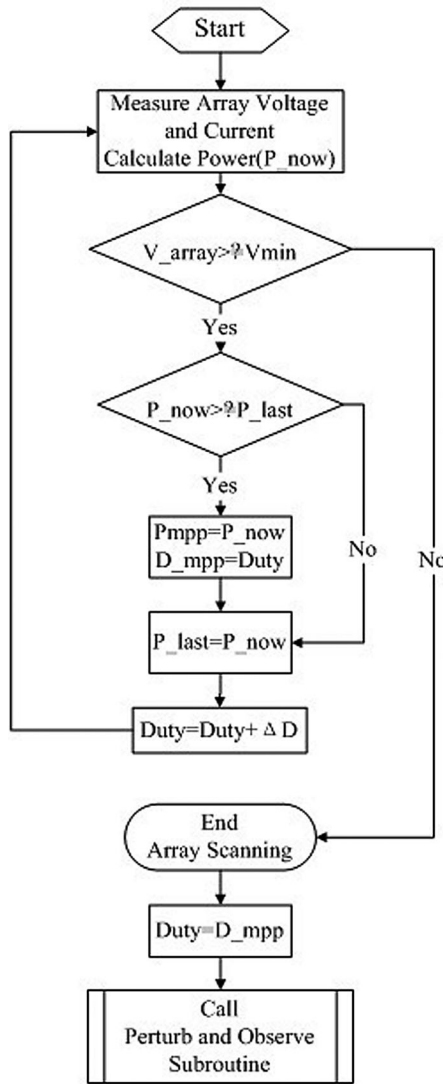


Fig. 15. Flow of GMPPT.

For comparison, the testing platform is configured as the same layout of the simulation schematic in Fig. 14.

A same global maximum power point tracking (GMPPT) strategy is applied in both simulation and testing platform. There were some complicated GMPPT strategies [26]. For convenience, a simple strategy is adopted; its flow is shown in Fig. 15.

Some parameters in the control flow are as follows: initial duty of pulsewidth modulation is 0.125, V_{min} is 27 V, ΔD is 0.020, duty step in perturb and observe method is 0.020, and control period is 10 ms.

First, a case of uniform irradiance is implemented to verify whether the proposed model can work well under normal condition, in which irradiance is 940 W/m^2 and module temperature is 30°C . There is only one power peak at around 140 W in this case.

Fig. 16 shows simulated and measured results of a PV array in the process of GMPPT in this case. In the beginning part of the process, the GMPPT strategy scans the output power of a

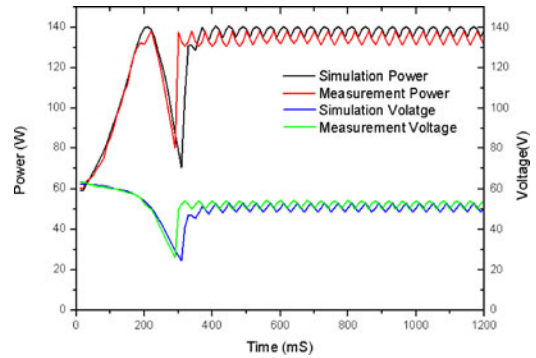


Fig. 16. Results of simulation and experiment in the case of uniform irradiance.

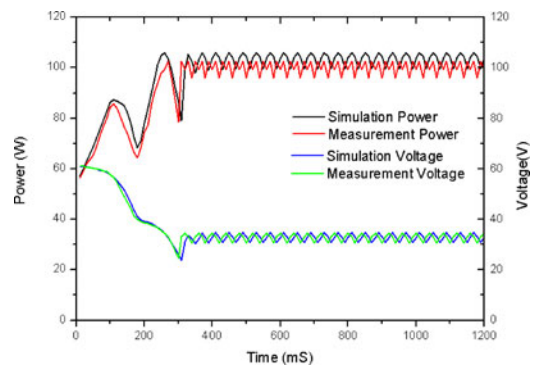


Fig. 17. Results of simulation and experiment in the case of nonuniform irradiance.

PV array in the range of output voltage from V_{oc} to V_{min} . Thus, a rough global maximum power point (GMPP) could be found. Then, the perturb and observe method [27] is used to seek and keep GMPP. The fluctuations of power and voltage in stable stage are due to duty step and control period in the perturb and observe method. The perturbing process in stable stage could be observed clearly both in experiment and simulation.

Second, a case of nonuniform irradiance is implemented, in which irradiances are different: $S_1 = 1080 \text{ W/m}^2$, $S_2 = 1080 \text{ W/m}^2$, and $S_3 = 524 \text{ W/m}^2$. The module's temperature is 32°C . There are two power peaks in this case, which are around 85 and 100 W, respectively. Both simulation and testing platform are running under the given conditions.

Fig. 17 shows results of simulation and measurement. Two power peaks occur in the stage of scanning GMPP, the higher one could be identified. The fluctuations in the stable stage are due to the same reasons in previous testing.

In this section, the proposed MATLAB-Simulink mode was tested to verify whether it could correctly simulate the behavior combining with dc/dc converter. Fig. 16 shows power and voltage curves in simulation which coincide with the curves in measurement, and the same results can be achieved from Fig. 17. Comparisons of simulation and implementation in the testing platform show that the proposed model has the ability of verifying electronic circuit and its control strategies under various conditions of different irradiance and temperature before implementation of an actual circuit.

IV. CONCLUSION

A MATLAB-Simulink based PV module model is presented in this paper, which includes a controlled current source and an S-Function builder. Various PV array simulation schematic could be created by the proposed model, and parameters of irradiance and temperature of each PV module model can be set independently. The PV array simulation model allows us to investigate the characteristics of a PV array under various conditions of different irradiance and temperature, especially under condition of nonuniform irradiance. The performance of the proposed model is validated by outdoor experimental results.

Another important performance of the proposed model is that a PV array, created by using a proposed model, allows to be combined with an electronic circuit to simulate the behavior of circuit and control strategy. It is also well validated by some outdoor experimental results.

The model is proposed not only to study the behavior of PV array, but also to validate new electronic circuit and MPPT strategies.

APPENDIX

```
Source code of S-function as follow:
float Isc_ref,Voc_ref,Impp_ref,Vmpp_ref,Rs,Isc,Voc;
float Sref,Tref;
float a,b,c;
float DT;
double k,Iref,n,V1,Dlref;
Isc_ref=3;
Voc_ref=22;
Impp_ref=2.77;
Vmpp_ref=17.98;
a=0.0004;
b=-0.0033;
c=0.066;
Rs=0.085;
Sref=1000;
Tref=25;
DT=T[0]-Tref;
Isc=Isc_ref*(S1[0]/Sref)*(1+a*DT);
Voc=Voc_ref*(1+b*DT+c*log(S1[0]/Sref));
k=pow(1-Impp_ref/Isc_ref,Voc_ref/(Vmpp_ref-Voc_ref+Rs
*Impp_ref));
Iref=1.5;
Dlref=1.5;
V1=Voc-Rs*Iref*Isc/Isc_ref+Voc_ref*log(1-Iref/Isc_ref)/lo
g(k);
//Solving (14) in paper via numerical method
for(n=0;n<50;n++)
{
    Dlref=Dlref/2;
    if(V1<V[0])
    {
        Iref=Iref-Dlref;
    }
}
```

```
else if(V1>V[0])
{
    Iref=Iref+Dlref;
}
else
{
    n=100;
}
```

```
V1=Voc-Rs*Iref*Isc/Isc_ref+Voc_ref*log(1-Iref/Isc_ref)/log(
k);
}
Iout[0]=Iref*Isc/Isc_ref;
```

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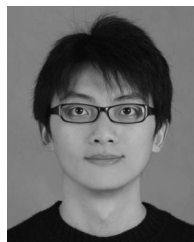
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