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# Development of an improved computer model for organic photovoltaic cells

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**Abstract**— This paper reports on an improved diode approximation-based model for PVs which is tested on three different organic PV (OPV) modules: AgGrid, AgNW and Carbon OPV. The model can emulate the electrical characteristics of the three cells accurately, facilitating the deployment in system models. Analytical I-V and P-V curves obtained with the model are compared with outdoor test data and demonstrate high correlation.

**Keywords**—organic photovoltaic cells, PV model, fill factor

## I. INTRODUCTION

In recent years, environmental concerns and decreasing costs have motivated research on renewable energy sources (RESs) for power generation. One technology that has been paramount in the transition to RES has been the photovoltaic (PV) cell. PV panel absorbs photons emitted by the sun and convert them into electrical energy without any emissions. As it can be deployed anywhere, it has gained significant attention [2], and the cost of utility-scale solar PV has dropped by two thirds between 2010 and 2015 [3].

The first generation of PV materials were based on silicon; however, thin-film technologies were developed to reduce the cost (known as the second generation). More recently, a third generation was developed based upon excitonic materials and covers a much broader range of technologies including organic photovoltaics (OPVs), dye-sensitised solar cell (DSSC), perovskite and quantum dots [4]. The comparison of different material PV modules and systems under varying operating conditions is a complex task, primarily due to the following factors: manufacturing cost, varying size of the panels, and environmental conditions (irradiance, temperature, cloudiness etc.) [5].

The above problems have been overcome by development of PV emulators, which are power electronic circuit-based models [6]. It can duplicate the nonlinear current-voltage (I-V) characteristic of PV model in a computational simulation environment. In literature, various PV emulators have been reported but such a device still comprises three main parts: PV model, control strategy and power converter [5, 7-9]. In terms of testing the features of different PV materials accurately, the model is the key component.

In [6], the authors proposed an electrical circuit-based PV model to derive its I-V characteristic by using Kirchhoff current law [10]. The circuit is mainly comprised of a diode, a current source, a shunt, and a series resistor. It can be applied for most PV modules, however, for low fill factor (FF) material PV cells, such as OPVs, this model presents some limitations and cannot be used.

This paper will propose an improved diode approximation-based model to replicate three different OPV cell module types. The circuit model and mathematic equations will be described in Section II. The simulation

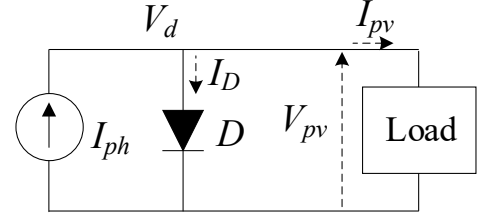


Fig. 1 Simplified PV model [1].

results are shown in Section III. The PV modules performance in terms of voltage, current and power have been monitored in an outdoor environment [11] and they will be compared with model obtained in MATLAB/Simulink in Section IV.

## II. PV MODEL DESCRIPTION

An Organic photovoltaic cell is based upon a donor-acceptor absorbing layer with transport layers and electrical contacts applied either sides of the absorbing layer. The donor-acceptor layer absorbs the incoming photons and if the energy absorbed by the electron is equal or greater than the bandgap, an exciton is formed. At the interface between the donor-acceptor materials, the exciton can be separated to enable current flow in the device. A diode approximation-based model can be used to model the electrical behaviour of OPVs, which can either be a simplified model for ideal cells, or a complete model for real environment tested PV cells.

### A. Ideal cell equivalent circuit model

An ideal solar cell equivalent circuit is as shown in Fig. 1. It is modelled by means of a current source generating current  $I_{ph}$ , representing the electrons from PV material, and a diode is connected in parallel. The diode current  $I_D$  can be expressed by Shockley's diode equation as

$$I_D = I_o \left[ \left( e^{\frac{qV_{pv}}{nkN_sT_c}} \right) - 1 \right] \quad (1)$$

where  $q$ = electron charge,  $V_{pv}$ = terminal voltage,  $n$ = junction ideality factor,  $k$ = Boltzman constant,  $N_s$ = number of cells in series per module,  $T_c$ = actual cell temperature. The reverse saturation current  $I_o$  is

$$I_o = \frac{I_{sc}}{e^{\frac{qV_{oc}}{nkN_sT_c-1}}} \quad (2)$$

where  $V_{oc}$ = open circuit voltage,  $I_{sc}$ = short circuit current in reference temperature.

The  $I_{ph}$  is depending on the cell temperature and irradiance according to the following relationship:

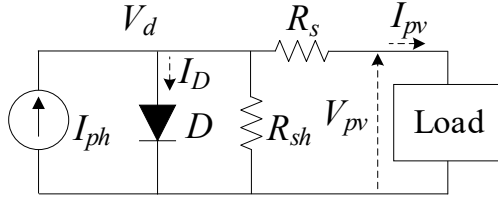


Fig. 2 Complete PV model.

$$I_{ph} = I_{sc} + k_i(T_c - T_{ref}) \frac{S}{S_{ref}} \quad (3)$$

where  $k_i$  = temperature coefficient of photon current,  $T_{ref}$  = reference cell temperature,  $S$  = actual cell irradiance,  $S_{ref}$  = reference cell irradiance.

Therefore, according to Kirchhoff current law the terminal current is expressed as

$$I_{pv} = I_{ph} - I_D \quad (4)$$

### B. Improved equivalent circuit

In non-ideal PVs, there are two parasitic parameters that cannot be neglected; shunt and series resistances. They can impact the shape of the I-V characteristics and efficiency of cells. For example, when the PV material generates photon current, the shunt resistors will lead to a reduction in current flow, and in consequence, the current that flows to the load will reduce. Therefore, the shunt and series resistances should ideally be infinite and zero, respectively, to eliminate their effect. In this paper, in addition to the current source and diode, the internal series and shunt resistors are added to simulate the PV cells more realistically [12]. The complete equivalent model circuit is as shown in Fig. 2. The terminal current for the improved model can be described by:

$$I_{pv} = I_{ph} - I_D - I_{sh} \quad (4)$$

where the current flowing through shunt resistance is  $I_{sh}$  and calculated as

$$I_{sh} = \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (5)$$

In this circuit, due to the losses drawn by the resistances, the diode current  $I_D$  and  $I_{ph}$  are modified as follows:

$$I_D = I_o \left[ \left( e^{\frac{q(V_{pv} + I_{pv}R_s)}{nkN_sT_c}} \right) - 1 \right] \quad (6)$$

$$I_{ph} = \left[ I_{sc} + \frac{I_{sc}R_s}{R_{sh}} + k_i(T_c - T_{ref}) \frac{S}{S_{ref}} \right] \quad (7)$$

Thus, the terminal current  $I_{pv}$  is derived as

$$I_{pv} = I_{sc} + k_i(T_c - T_{ref}) \frac{S}{S_{ref}} - I_o \left[ \left( e^{\frac{q(V_{pv} + I_{pv}R_s)}{nkN_sT_c}} \right) - 1 \right] - \frac{V_{pv} + (I_{pv} - I_{sc})R_s}{R_{sh}} \quad (8)$$

### III. MATLAB MODEL

The above proposed mathematic model is implemented in MATLAB/Simulink. The values of the constants are listed in Table I, while  $N_s$ ,  $N_{sh}$ ,  $R_s$ ,  $R_{sh}$ ,  $T_c$ ,  $S$ ,  $V_{oc}$  and  $I_{sc}$  are all customisable and can be defined in the simulation environment, as illustrated in Fig. 3. They will be selected and listed for each OPV cells in the next section. Based on the values of these parameters, the mathematic model will determine the value of  $I_{pv}$  to be sent to a controlled voltage source. On the right-hand side, a voltage source is connected to provide enough potential difference for the photon current flowing.

TABLE I. LIST OF DEFINED CONSTANTS

Term	Value
$q$	$1.6 \times 10^{-19} \text{ C}$
$k$	$1.38 \times 10^{-23} \text{ J/K}$
$n$	1.47
$k_i$	$1.7 \times 10^{-3} \text{ A/K}$
$T_{ref}$	25 °C
$S_{ref}$	1000 W/m <sup>2</sup>

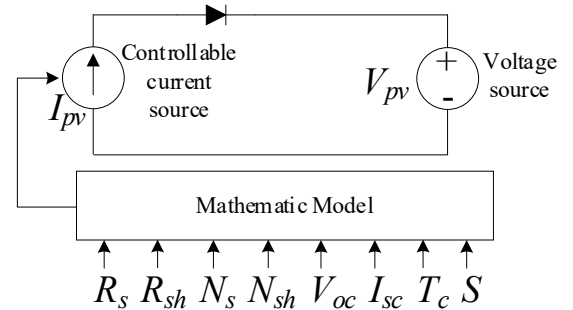
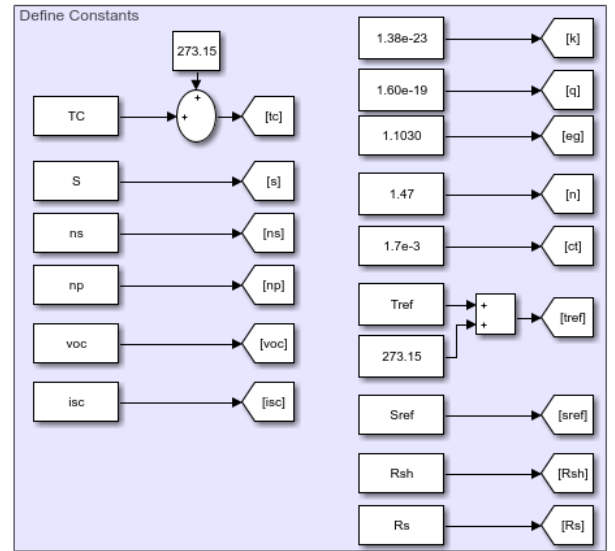
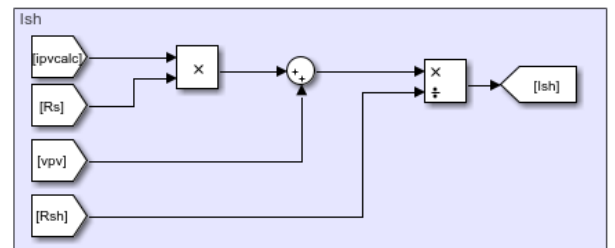


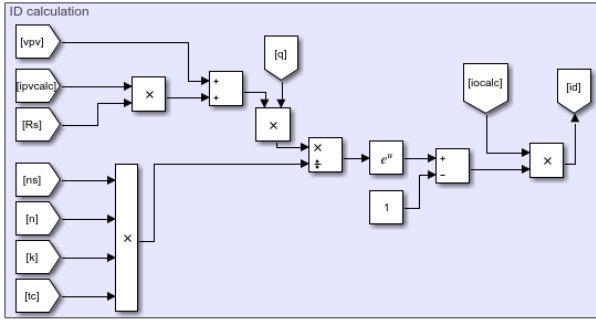
Fig. 3 PV mathematic model and simulation circuit



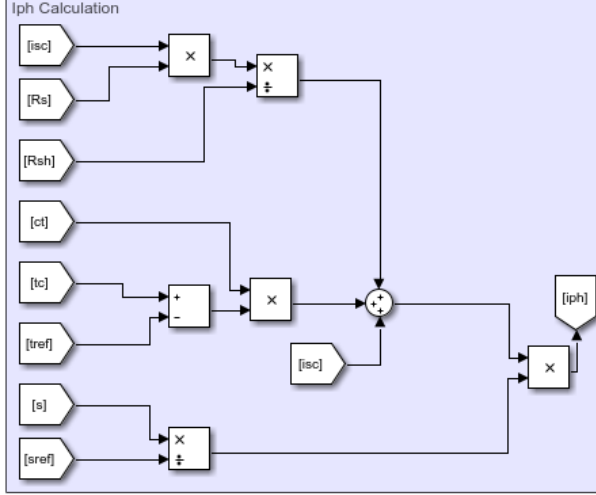
(a)



(b)



(c)



(d)

Fig. 4 Details of the model: (a) Defined parameters, (b) Shunt current  $I_{sh}$ , (c) Diode current  $I_D$  and (d) Source current  $I_{ph}$ .

The details of the mathematic model are shown in Fig. 4; constants and variable parameters are defined in Fig. 4(a).  $I_{sh}$  in (5) is calculated as shown in Fig. 4(b),  $I_D$  is in (c) and  $I_{ph}$  is in (d). Finally,  $I_{pv}$  can be derived as  $(I_{ph} - I_D - I_{sh})$ .

#### IV. SIMULATION RESULTS

Three different OPV cells are simulated and are called ‘AgGrid’, ‘AgNW’ and ‘Carbon’. These are differentiated by their electrode design and the internal design of these three modules is reported in [4]. The outdoor test data of the three cells is then compared with simulation results. For AgGrid and AgNW, 8 cells are monolithically connected in series, while for Carbon has 16 cells. The parameters selection and calculation of cell resistances and temperature are shown in the following subsections.

##### A. Parameters selection

The values of the parameters shown in Fig. 3 are based on the different OPV features. The shunt and series resistances  $R_s$  and  $R_{sh}$  are calculated based on the slopes of PV cell I-V characteristic curve, as shown in Fig. 5.

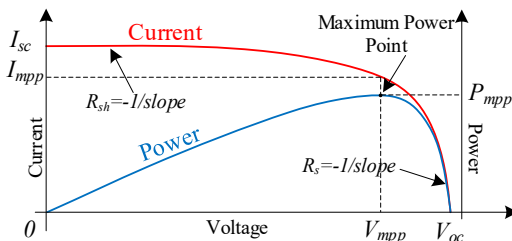


Fig. 5 I-V and P-V curves with highlighted parameters

In terms of the OPV cell temperature  $T_c$ , it is calculated according to the following equation:

$$T_c = T_{ot} + kS \quad (9)$$

where  $T_c$  is the PV module temperature,  $T_{ot}$  is outdoor temperature,  $S$  is irradiance and  $k$  is Ross Coefficient which can be obtained from previous outdoor tests, as shown in Fig. 6 [11]. Following by the calculations shown above, the outdoor temperature and module temperature parameters for the three outdoor tested OPVs can be obtained and shown in Table II, and the rest are in Table III.

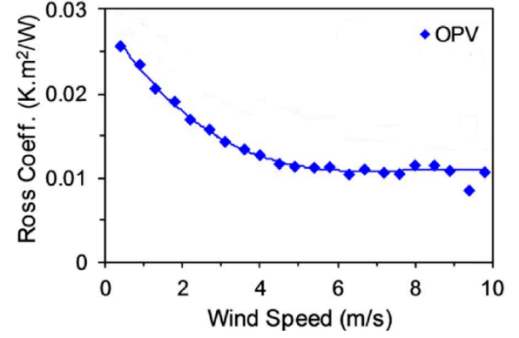


Fig. 6 OPV Ross Coefficient [11].

TABLE II. OPV PARAMETERS FOR TEMPERATURES CALCULATION

	AgGrid	AgNW	Carbon
$T_{ot}$	18.2 °C	11.2 °C	18.3 °C
$S$	831 W/m²	1006.66 W/m²	949.2 W/m²
Wind speed	5.8 m/s	4 m/s	2.2 m/s
$k$	0.0101 K* m²/W	0.013 K* m²/W	0.02 K* m²/W
$T_c$	26.59 °C	24.29 °C	37.28 °C

TABLE III. OTHER PARAMETERS

	AgGrid	AgNW	Carbon
$N_s$	8	8	16
$N_{sh}$	1	1	1
$R_s$	63 Ω	25 Ω	479 Ω
$R_{sh}$	516 Ω	651 Ω	1420 Ω
$V_{oc}$	4.19 V	4.55 V	7.65 V
$I_{sc}$	20.40 mA	53.86 mA	8.52 mA

##### B. Results comparisons

The MATLAB/Simulink results and experimental data from outdoor test results of the AgGrid OPV cells, AgNW OPV cells and Carbon OPV cells are compared in Fig. 7, Fig. 8 and Fig. 9, respectively. In all the graph, (a) shows the I-V curves and (b) shows the P-V curves. The blue curves represent the results obtained with the MATLAB/Simulink model, the red curves are the outdoor test results.

The key results of the cells are listed in Table IV, including maximum power ( $P_{mp}$ ), voltage at the maximum power ( $V_{mp}$ ), current at the maximum power ( $I_{mp}$ ), and the Fill Factor ( $FF$ ), calculated as follows:

$$FF = \frac{P_{mp}}{V_{oc}I_{sc}} \quad (10)$$

From the results, it can be observed that both the waveform shapes and the key results from the simulation and test data are match closely.

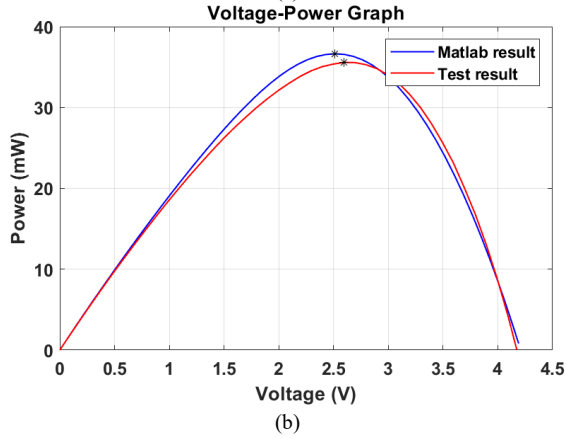
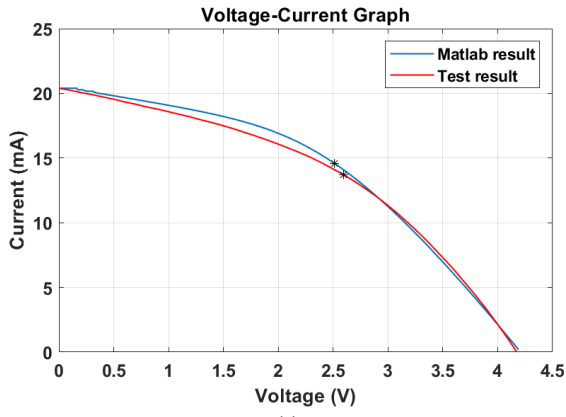


Fig. 7 Comparisons of AgGrid OPV (a) I-V and (b) P-V curves.

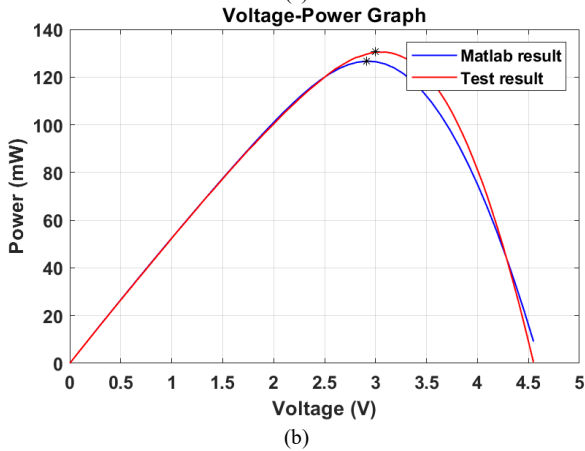
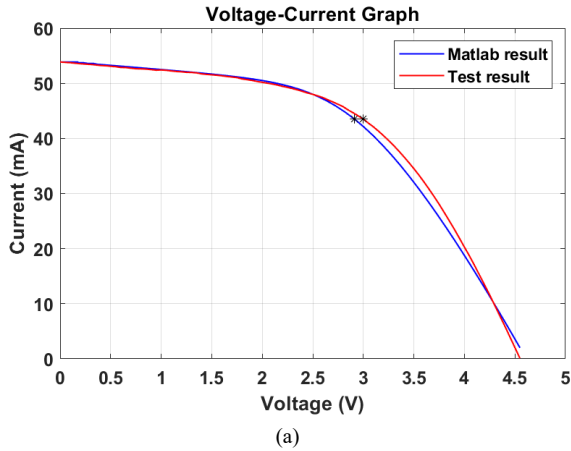


Fig. 8 Comparisons of AgNW OPV (a) I-V; (b) P-V curves.

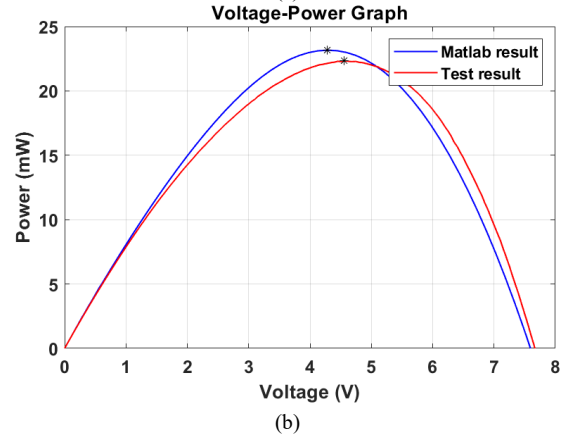
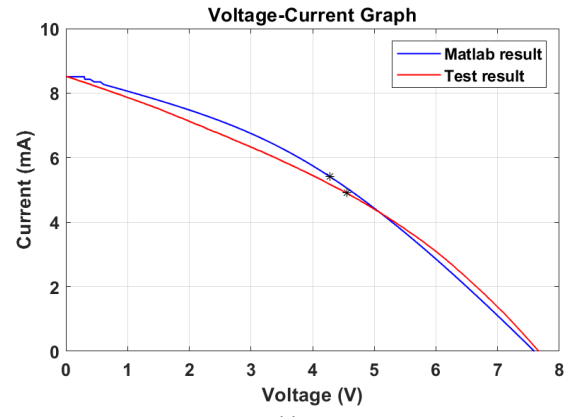


Fig. 9 Comparisons of Carbon OPV cells (a) I-V; (b) P-V curves.

TABLE IV. COMPARISONS OF OPV SIMULATION AND TEST RESULTS

		MATLAB / Simulink result	Outdoor test result	% error
AgGrid	$FF$	0.43	0.42	2.4 %
	$P_{mp}$	36.6 mW	35.6 mW	2.8 %
	$V_{mp}$	2.68 V	2.60 V	3.1 %
	$I_{mp}$	14.11 mA	13.71 mA	2.9 %
AgNW	$FF$	0.52	0.53	1.9 %
	$P_{mp}$	126.7 mW	130.54 mW	2.9 %
	$V_{mp}$	2.91 V	3.0 V	3.0 %
	$I_{mp}$	43.50 mA	43.51 mA	0
Carbon	$FF$	0.36	0.34	5.9 %
	$P_{mp}$	23.2 mW	22.3 mW	4.0 %
	$V_{mp}$	4.13 V	4.55 V	9.2 %
	$I_{mp}$	5.34 mA	4.9 mA	8.9 %

## V. CONCLUSIONS

An improved diode approximation-based PV model was proposed in the paper, which improved the accuracy of simulating low fill factor PV cells by computer software. The circuit model and mathematic equations were derived and three organic PV cells were tested and simulated: AgGrid, AgNW and Organic cells. The analytical I-V and P-V characteristic waveforms that obtained from the simulations were then compared with the outdoor experimental data. The comparison show that the simulation results are very similar to the measurement (2.8%-4% error in maximum power  $P_{mp}$ ). The use of the Ross coefficient to calculate the cell temperature also allows calculating accurate models for varying temperatures and irradiance conditions.

The next step of the research will be to apply the computer model to a power electronic-based hardware platform, to emulate the PV cell features in a real environment.

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