Improved Circuit Model of Photovoltaic Array

Mohamed Azab

***Abstract*—**A circuit based model of photovoltaic array (PV) suitable for simulation studies of solar power systems is proposed in this paper. The proposed model is realised using Power System Block Set under MATLAB/SIMULINK, however, it can be constructed using standard simulation software such as PSPICE. The proposed circuit model has several advantages: simple, reliable, allows simulation of basic cells, group of cells, or mismatched panels that work under different operating conditions. The obtained results of both uniform and mismatched PVs prove the validity of the proposed model to simulate the non-linear behaviour of photovoltaic array not only to understand the operation of PV systems but also to design a proper maximum power point tracker to extract the maximum possible power from the photovoltaic array.

***Keywords*—**Photovoltaic array, piecewise linear model, modelling, simulation.

I. INTRODUCTION

RENEWABLE energy sources are gaining more interest in recent years. Among them, photovoltaic (PV) panels, that offer several advantages such as requirement of little maintenance, no environmental pollution. Recently, PV arrays are used in many applications such as battery chargers, solar powered water pumping systems, grid connected PV systems, solar hybrid vehicles, and satellite power systems. In all solar power systems, efficient simulations including PV panel are required before any experimental verification. The aim of this paper is to present a circuit-based model of PV array that can be utilized in any simulation studies of such solar power systems.

II. CLASSICAL PV MODEL

A. Simplified Equivalent Circuit

A solar cell basically is a p-n semiconductor junction. When exposed to light, a current proportional to solar irradiance isgenerated. The circuit model of PV cell is iluustrated in Fig. 1. Standard simulation tools utilize the approximate diode equivalent circuit shown in Fig. 2 in order to simulate all electric circuits that contain diodes. The model is based on two-segment piecewise linear approximation. The circuit consists of R_{on} in series with voltage source V_{on}.

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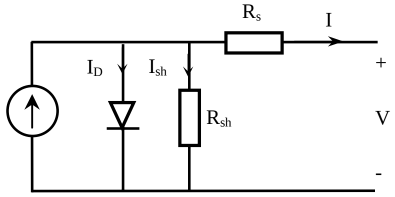

Fig. 1 Circuit model of PV solar cell

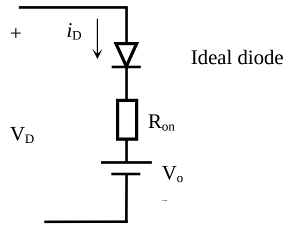

Fig. 2 Diode equivalent circuit used in Power System blockset/Simulink

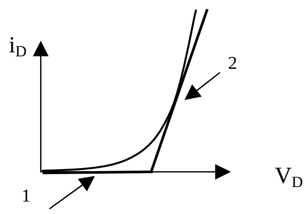

Fig. 3 Two-segment Diode model

B. Theoretical Mathematical Model

The equations that describe I-V characteristics of the solar cell based on simple equivalent circuit shown in Fig. 1, are given below;

$$I_D = I_o \left(e^{\frac{q(V + IR_s)}{kT}} - 1\right) \tag{1}$$

$$I = I_L - I_o \left(e^{\frac{q(V + IR_s)}{kT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{2}$$

Where:
I is the cell current (A).
q is the charge of electron $= 1.6x10^{-19}$ (coul).
K is the Boltzman constant (j/K).
T is the cell temperature (K).
I_L is the light generated current (A).
I_o is the diode saturation current.
R_s , R_{sh} are cell series and shunt resistance (ohms).
V is the cell output voltage (V).

III. Proposed PV Circuit Model

A. *Proposed Piecewise Linear Model*

In this paper bP 350U Solar Panel is chosen to verify the proposed circuit model. The panel has 36 series connected cells. The key specifications of the bP 350U PV Solar Panel are shown in Table I.

TABLE I
KEY SPECIFICATION OF BP SOLAR PANEL

Maximum Power	P_{max}	50 W
Voltage @ max. power	V_{max}	17.3 V
Current @ max. power	I_{max}	2.89 A
Short circuit current	I_{SC}	3.17 A
Open circuit voltage	V_{OC}	21.8 V

The piecewise linear model developed in this paper is based substituting single-diode by three-parallel diodes. Each diode is modelled as simple piecewise linear (PWL) as a voltage controlled resistor with two states ON and OFF as shown in Fig. 4. Therefore, the V-I curve of the equivalent diode of the PV cell is approximated and divided into several segments. Each diode provides two-segments of the curve. In addition, the PWL model of the PV cell can be improved by approximating the curve with more segments by connecting more diodes in parallel with suitable values of series resistances. Computation of these series resistors will be explained in the following section. Fig. 5 shows the proposed PWL model of the PV cell.

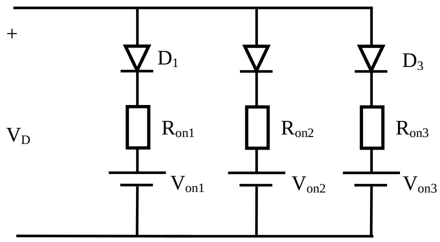

Fig. 4 Proposed PWL Model of PV diode

Basically, the model is developed to simulate single PV cell. However, it is easy to scale up the model to account for the overall PV panel which consists of 36 cells connected in series. Scaling up to simulate the bulk PV panel is carried out using two methods:

1. Bulk PV Model: Where the experimental data of bp solar panel are used to compute directly the values of diodes ON-voltages (V_{D1},V_{D2}, and V_{D3}) and series resistors (R_{on1}, R_{on2}, and R_{on3}) to account for the all 36 cells that are connected in series as given in manufacturer data sheet.

2. Single PV cell Model: the basic PV solar cell, is modelled, then the total voltage produced from the panel is computed from: $V_{panel} = nV_{cell}$, while the current through all cells is identical. In circuit based-models, the overall PV panel model is also obtained by hardware connection of individual cell to account for the all 36 solar cells.

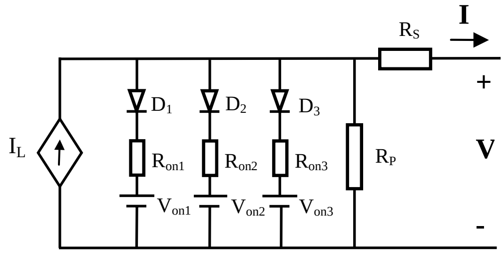

Fig. 5a Proposed PWL Model of PV cell

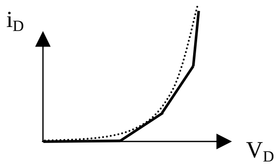

Fig. 5b Proposed diode model

B. *Calculation of Model Parameters*

(1) Bulk PV Model

The proposed model approximates the I-V curve by four line segments as shown in Fig. (5b) taking into consideration the following:

- PV parameters at maximum power point (MPP): V_{max} = 17.3 V, and I_{max} = 2.89 A.
- Vertex points are located at:
  0.9 MPP , MPP , 1.1 MPP.
- The model assumes that: $V_{on1} < V_{on2} < V_{on3}$.

The operation in each segment is explained below:

Segment 1: ($V_D < V_{on1}$)

(V_{on1} = 0.9 MPP = 15.57 V). When the generated voltage is less than V_{on1} , all diodes are OFF, and no current flows through the diodes, thus the light generated current from PV flows through the load and a small portion can flow through the shunt resistance R_{sh} , therefore the current is nearly constant in this segment.

Segment 2: ($V_{on1} \le V_D < V_{on2}$)

Diode D_1 is ON.
Since the PV current fails from 3.17 A to 2.89 A, thus the current through (diode D_1) is 0.28 A.
R_{on1} is computed from the following equation:

$$R_{on1} = \frac{V_{max} - 0.9V_{max}}{I_{D1} - 0} = \frac{17.3 - 15.57}{0.28} \qquad (3)$$

R_{on1} = 6.17 Ω.

Segment 3: ($V_{on2} \le V_D < V_{on3}$)

Diodes D_1 and D_2 are ON.
The current through D_1 is calculated as follows:

$$I_{D1} = \frac{1.1V_{max} - 0.9V_{max}}{R_{on1}} = \frac{3.46}{6.17} = 0.56 \text{ A} \tag{4}$$

Since the PV output current is 2 A, the current through diode D2:

$$I_{D2} = I_{LG} - I_{D1} - I_o = 3.17 - 0.56 - 2 \tag{5}$$

$I_{D2} = 0.61$ A.

R_{on2} is computed from the following equation:

$$R_{on2} = \frac{1.1V_{max} - V_{max}}{I_{D2} - 0} = \frac{19.03 - 17.3}{0.61} \tag{6}$$

$R_{on2} = 2.83\ \Omega$.

Segment 4: $(V_{on3} \le V_D \le V_{OC})$

All Diodes are ON.
The PV load current is zero at open circuit point, the open circuit voltage is 21.8 V.
The current through D_1 is calculated from eqn. (10):

$$I_{D1} = \frac{V_{OC} - 1.1V_{max}}{R_{on1}} = \frac{2.77}{6.17} = 0.44 \text{ A} \tag{7}$$

The current through diode D_2 is computed:

$$I_{D2} = \frac{V_{OC} - 1.1V_{max}}{R_{on2}} = \frac{2.77}{2.83} = 0.97 \text{ A} \tag{8}$$

Since the PV output current is zero, the current through diode D3 is computed from:

$$I_{D3} = I_{LG} - I_{D1} - I_{D2} - I_o \tag{9}$$

$I_{D3} = 3.17 - 0.44 - 0.97 - 0 = 1.76$ A.

R_{on3} is computed from equation (13) :

$$R_{on3} = \frac{V_{OC} - 1.1V_{max}}{I_{D3} - 0} = \frac{21.8 - 19.03}{1.76} \tag{10}$$

$R_{on3} = 1.57\ \Omega$.

(2) Single PV Cell

The same method is used to compute the cell parameters. But, in this case the cell voltage at maximum point is 17.3/36 = 0.48 V. Consequently, V_{on1}, V_{on2} and V_{on3} are scaled to be 0.432 V, 0.48 V, and 0.528 V respectively. The current values are the same because all cells are connected in series. So the same current flows in all cells.

It is important to mention that, vertex points can take other values instead of (0.9MPP, MPP, 1.1MPP) as presented in reference [4]. One of the major advantages of the proposed model, that it is easy to readjust the vertex points and the corresponding model calculations in order to match (fit) the experimental results of a certain PV panel.

IV. Simulation Results

A. Proposed PV Model

The proposed PV model is verified using power System block set under Matlab/Simulink. Within the model, vertex points of (I-V) curve can be adjusted according to previously presented eqns. (6) to (12). V-I curve, and V-P curve of the overall PV bulk model are illustrated in Fig. 6 and Fig. 7 respectively.

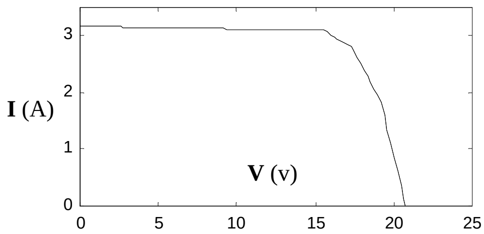

Fig. 6 I-V curve with the proposed model

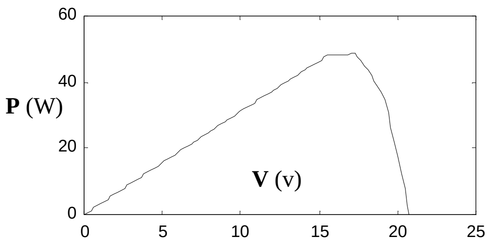

Fig. 7 P-V curve with the proposed model

Fig. 6 presents the I-V curve obtained from the proposed model. The segments of the I-V curve can be observed easily. Fig. 7 illustrates the corresponding P-V curve. The light generated current is 3.2 A. Fig. 8 and Fig. 9 demonstrate the behaviour of the PV under different levels of irradiations. Inside the model, irradiation level can be changed by setting the value of light generated current to the required value. They are selected to be 3.1 A, 2.6 A, and 2 A. The I-V family curves are plotted in Fig. 8, while the P-V family curves are plotted in Fig. 9.

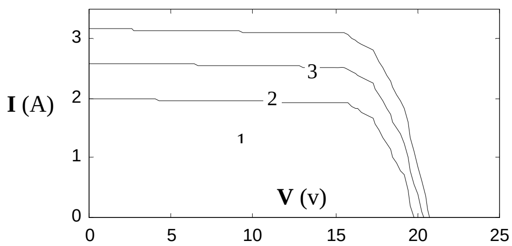

Fig. 8 I-V family curves with proposed model for different irradiation levels

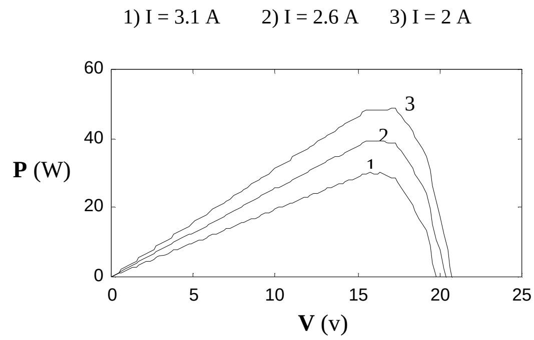

Fig. 9 P-V family curves with proposed model for different irradiation levels

B. Classical PV Model

In addition to the proposed PV model, classical PV model is also carried out for comparison. Simulation results of PV using classical circuit model are presented in Fig. 10 and Fig. 11.

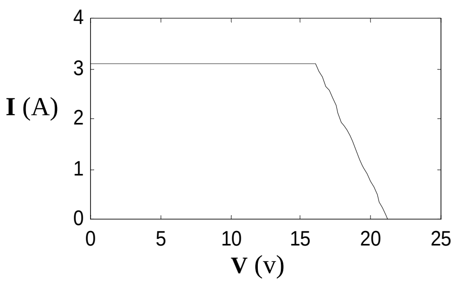

Fig. 10 I-V curve with classical model

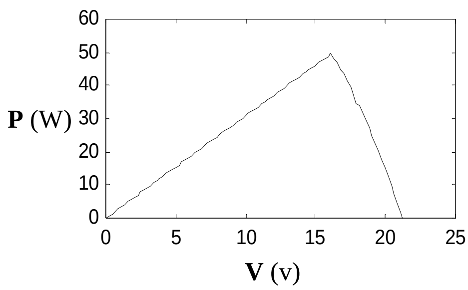

Fig. 11 P-V curve with classical model

According to the obtained results, the proposed model offer better waveforms for I-V and P-V curves. While classical PV model produces abrupt change in the slope of P-V curve and I-V curve observed in Fig. 10 and Fig. 11.

C. Mismatched PV Panels

The proposed PV model is also used to simulate mismatched PV panels when exposed to different solar irradiance. In this section two mismatched PV panels connected in series are simulated. The irradiation levels are adjusted such that the light generated currents are 3 A and 1 A.

The corresponding P-V curve is shown in Fig. 12. It is clear that the curve exhibits two maxima at two different voltage levels which is similar to what happens in real operation.

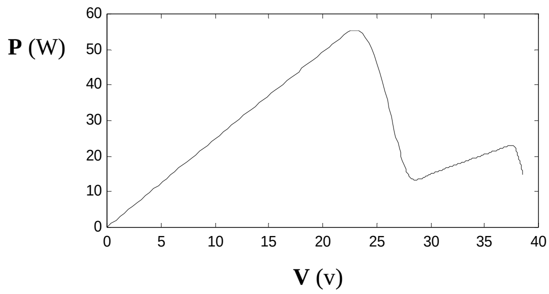

Fig. 12 P-V curve of simulated mismatched PV Panels

V. Conclusion

This paper presents simplified piecewise linear model for PV solar panels suitable for power electronics simulation studies. The proposed circuit model accounts also for the behaviour of mismatched PV panels. The obtained results prove the validity of the proposed model to simulate the PV with considerable accuracy under different operating conditions.

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