Modeling and Simulation of SPVA Characterization under all Conditions

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Abstract—This paper presents an improved model of a solar photovoltaic (SPV) module to represent its behaviour in both forward and reverse bias conditions. An insolation dependent shunt resistance is added in the popular one diode model of the SPV module. It was experimentally found that the value of shunt resistance predominantly depends on insolation variations but its variation with temperature is very low. An empirical relation was established to modify the model by conducting the series of experiments recording the characteristics at different environmental conditions. This model is the better representation of SPV module. A novel technique for fast display and recording of the characteristic of SPV module under forward and reverse biased conditions is presented. Extension of this method to plot the characteristics in all the quadrants is also presented.

Keywords: Improved model, Reverse characteristics, MATLAB, Electronic load, PSPICE

1. INTRODUCTION

The basic building device of the SPV system is SPV cell. Many SPV cells group together in series and parallel fashion to get required voltage and current. The voltage and current available at the terminals of SPV system may directly feed small loads and more sophisticated applications require electronic converter to process the output of SPV system. These converters may be used to regulate the variables at the load side, to control the power flow in grid connected systems, and mainly to track the maximum power available from the source. Whatever the case, one should know the model of SPV system to study the converter and other connected system performances. For this purpose models are required to represent SPV cells/modules. The major task of this paper is to develop a complete simulation model of SPV cell as well as modules to reproduce the characteristics of existing cells/modules in the lab. SOLKAR (Model No.3712/0507) cells and modules are available in the laboratory for practical testing. In order to maintain the conditions of the simulation as realistic as possible, the characteristics of these cells/modules are represented by the less computational equivalent model in MATLAB-M file [28] coding. This paper begins with the modeling and simulation of SPV modules. The non uniform insolation or partial shading occurs very frequently in SPV system. To study the shading effects modeling of SPV module in reverse biased conditions is required. Many models have been reported in literature. Most of the authors neglected the influence of varying shunt resistance or taking as a constant value in the model where the reverse characteristic of the module is greatly influenced by the shunt resistance. The main feature of the proposed model is to include the effect of varying shunt resistance in the model. Experimental determination of voltage-current characteristic of a solar module is required to validate the model. A simple and new method to quickly draw the characteristics and recording the result in both first and second quadrant using an electronic load also has been proposed in this work. The electronic load method is extended to plot the characteristics in all the quadrants has also been presented and results have been obtained using Pspice software.
2. Model of Practical SPVA in First Quadrant

The standard one diode or 5 parameter model is used for modeling the SPV module in I quadrant [1]. It is shown in Fig.1.

From Fig.1, the mathematical equation of the output current of the cell is written by

\[
I_{PV} = I_{ph} - I_D - I_{sh}
\]  

(1)

Different models have been presented in literature to achieve better accuracy and serve for different purposes [2]-[6]. For simplicity, the single diode model of Fig.1 is considered for this work. This model offers a good compromise between simplicity and accuracy [7] and has been used by several authors in previous works, sometimes with simplifications but always with the basic structure composed of a current source and a parallel diode [8]-[10]. The simplicity of the single diode model with the improved equations [11] is utilized here. The equations used to develop a simulation model of a SPV cell are:

\[
I_{PV} = I_{ph} - I_r \left[ \exp \left( \frac{V_{PV} + I_{PV} R_{se}}{V_t} \right) - 1 \right] - \left( \frac{V_{PV} + I_{PV} R_{se}}{R_{sh}} \right) \]  

(2)

Where

\[
I_{ph} = \left( I_{ph, ref} \left[ 1 + \alpha (T - T_{ref}) \right] \right) \frac{G}{G_{ref}}
\]  

(3-a)

\[
I_{ph, ref} = I_{sc, ref} \text{ and } I_{ph, ref} = \frac{R_{sh} + R_{se}}{R_{sh}} \times I_{sc, ref}
\]  

(3-b)

\[
I_r = \frac{I_{sc, ref} + \alpha (T - T_{ref})}{\exp \left( \frac{V_{oc, ref}}{V_t} + \beta (T - T_{ref}) \right) - 1}
\]  

(4-a)

\[
I_{r, ref} = \frac{I_{sc, ref}}{\exp \left( \frac{V_{oc, ref}}{V_t, ref} \right) - 1}
\]  

(4-b)

\[
V_t = V_{tref} \frac{T}{T_{ref}} \text{ and } V_{tref} = \frac{n_{ref} k T_{ref}}{q}
\]  

(5)

\[
R_{sh} = \frac{3.6}{G - 0.086}
\]  

(6)
\[ I_m = I_{mref} \times G \quad \text{and} \quad V_m = V_{mref} + \left\{ \beta \left( T - T_{ref} \right) \right\} \tag{7} \]

\[ R_{se} \frac{G}{G_{ref}} = \frac{V_{terf}}{I_{terf}} \exp \left[ - \frac{V_{mref} + I_{mref} R_{sref}}{V_{terf}} \right] \]

\[ + R_{sref} \frac{G}{G_{ref}} \left( \frac{V_{terf}}{I_{terf}} \exp \left[ - \frac{V_m + I_m R_{se}}{V_t} \right] + R_{se} \right) \tag{8} \]

\[ n = n_{ref} \frac{T}{T_{ref}} \tag{9} \]

The equation (2) represents the practical SPV cell. Here the five parameters are \( I_{ph}, I_v, V_t, R_{se} \) and \( R_{sh} \). It can be shown that the array parameters for series array consists of \( N_S \) cells in series: \( I_{ph,array} = I_{ph}, I_v, V_t, R_{se,array} = N_S R_{se} \) and \( R_{sh,array} = N_S R_{sh} \). For parallel array consists of \( N_P \) cells in parallel: \( I_{ph,array} = N_P I_{ph}, I_v, V_t, R_{se,array} = R_{se}/N_P \) and \( R_{sh,array} = R_{sh}/N_S \).

From equations (3) to (9), the parameters at reference conditions are given by manufacturer data sheet. Some manufacturers provide V-I curve for several irradiation and temperature conditions. These curves make easier the adjustment and the validation of the desired mathematical V-I equation. Basically, this is all the information one can get from datasheets of SPV modules. Usually, \( 1 \leq n_{ref} \leq 1.5 \) and the choice depend on other parameters of the V-I model. Some values for \( n \) are found in based on empirical analyses [12]. The value of \( n \) can be modified as expressed in equation (9) in order to improve the model fitting.

The practical SPV cell has a series resistance \( R_{se} \) whose influence is stronger when the device operates in the voltage source region and a parallel resistance \( R_{sh} \) with stronger influence in the current source region of operation. The value of \( R_{sh} \) is generally high and some authors neglect this resistance to simplify the model [10], [13]-[14]. The value of \( R_{se} \) is very low, and sometimes this parameter is neglected too [13], [15]. The reference value of \( R_{se} \) is found from the V-I characteristics at reference conditions. The equation for variation of \( R_{sh} \) is found experimentally and curve fitting equation is given by equation (6). The simulation results for different cases of parameter considerations are given from Fig.2 to Fig.5. The manufacturer’s datasheet for SOLKAR module is given in Table-1. Table-2 gives the adjusted model parameter values.

![Figure 2. Ideal SPV module characteristics-without considering the effects of Rse and Rsh](image1)

![Figure 3. SOLKAR SPV module characteristics –without Rsh effect](image2)
Figure 4. SOLKAR SPV module characteristics for different values of $R_{se}$ and $R_{sh}$

Figure 5. SOLKAR SPV module adjusted characteristics with $R_{se}$ and $R_{sh}$

<table>
<thead>
<tr>
<th>TABLE I. PARAMETERS OF THE SOLKAR MODULE AT STC</th>
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| 1. Rated Power $(P_{max,e})$ &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &nbsp; &n...
3. Modeling of Reverse Characteristics of SPV Cell

Typically 36 cells are connected in series to get the requisite voltage of SPV module. All the cells are forced to carry the same current called module current in series module. If one or more cells are not receiving the equal illumination or shaded these cells become reverse biased which leads to power dissipation and thus to heating effects. This situation is illustrated in Figure 6 which shows the V-I characteristics of a cell in the whole range.

The forward characteristic extends to the open circuit voltage of approximately 0.6 volts; the reverse biased characteristic is much more extensive and limited by the breakdown voltage. If the cell is shaded, its short circuit current is less than the module current so that it is operated at the reverse characteristic, causing power to be dissipated. Hence it is required to model the reverse characteristics of the SPV cell for the complete representation of it. The breakdown occurs in SPV cell is not taken into account in the five parameter model shown in Fig.1. Therefore the extension of the model based on the model of Bishop [16] is considered for the work. This model includes an extension term which describes the diode breakdown at high negative voltages. The leakage current term \( I_{ph} \), which is a function of voltage and controls the cell reverse characteristic, consists of an ohmic term (current through the shunt resistance) and a non-linear multiplication factor [17]-[19] describing avalanche breakdown [20]:

\[
I_{sh} = \frac{V_{sh}}{R_{sh}} \left[ 1 + a \left( 1 - \frac{V_{sh}}{V_{br}} \right)^{-m} \right] (10)
\]

Where \( V_{sh} \) is the voltage across the junction (V), \( V_{br} \) is the junction break down voltage, \( a \) is the fraction of ohmic current involved in avalanche breakdown and \( m \) is the avalanche break down exponent. Equation (4) is modified as

\[
I_{pv} = I_{ph} - I_{r} \left[ \exp \left( \frac{V_{pv} + I_{pv} R_{se}}{V} \right) - 1 \right] - \frac{(V_{pv} + I_{pv} R_{se})}{R_{sh}} - a \left( \frac{V_{pv} + I_{pv} R_{se}}{V_{br}} \right)^{-m} (11)
\]
The electrical behavior of the solar cell can be described by this equation over the whole voltage range. The unknown parameters are $a$, $V_{br}$ and $m$. These parameters are calculated by extracting parameters in those areas of practical V-I characteristic which are more significant.

The measured V-I characteristics under reverse biased conditions for dark condition is shown in Fig.7. The characteristics are smoothened by curve fitting. Breakdown voltage is calculated by linear regression of the straight line of voltage against the inverse of current near breakdown region from the dark characteristics [17]. The breakdown voltage $V_{br}$ is found to be 13.5 V. The other two parameters are found by tuning them in model by trial and error method so as to match with the experimental characteristics. The values of ‘a’ and ‘m’ is found to be 0.10 and -3.70 respectively. The modelled and experimental curves of reverse biased measurements for dark and illuminated conditions are shown in Fig.8.

The single SPV cell model in the reverse biased condition is extended to simulate SPV module consists of 36 cells in series by making $V_{br}$ multiplied by $36(N_s)$ and the modifications in ‘m’ and ‘a’. The complete simulated curve of the solar module in both forward and reverse biased modes for a particular illumination is shown in Fig. 9.
4. VALIDATING THE MODEL

As Tables I and II and Fig.5 have shown, the developed model and the experimental data are exactly matched at the reference remarkable points of the V-I curve, and the experimental and mathematical maximum peak powers coincide. The objective of adjusting the mathematical V-I curve at the three remarkable points was successfully achieved. In order to test the validity of the model, a comparison with other experimental data (different of the reference remarkable points) is very useful. Due to randomly changing field conditions, it is difficult to use voltmeter-ammeter method to draw the characteristics of a SPV module. Several systems for measuring the V-I characteristic of solar modules have been proposed. Most of them can characterize them only in the first and fourth quadrants. They use adjustable resistance [21], programmable electronic load [22], active load [23] or capacitors for variable load [24]. It is required to develop a simple, inexpensive and automatic V-I characteristic measurement system in both the quadrants. A simple method to quickly draw the characteristics of a SPV module in I and II quadrants under field conditions is proposed in this work. The schematic of the proposed work is shown in Figure.10. A linear MOSFET (IRF 150/IRF 460) is used as a load resistance [25]-[26].

The proposed circuit is simulated in Pspice [29]. The Pspice schematic and the simulation results are shown in Fig.11 to Fig.14. In Fig.11 the module current is given to the inverting terminal. Hence this schematic is known as the circuit to produce I quadrant using current source. To get II quadrant using current source variable RPS is included between module and the MOSFET shown in Fig.13. The simulated characteristics using the above circuits are shown in Fig.12 and Fig.14 respectively. The hardware set up of electronic load
with a sample snap shot of the CRO screen shows V-I characteristics of the module is shown in Fig.15. GWINSTEK GDS-1022 Digital Storage Oscilloscope (DSO) is used to trace the practical characteristics. It is calibrated using Fluke 5500A Multi-Product Calibrator. For different insolation and temperature the practical characteristics are easily traced out using electronic load method and the relevant data traced by DSO are stored in Excel spreadsheet for comparison of model parameters.

Figure 11. Pspice schematic to produce I quadrant characteristics using current source

Figure 12. Simulated characteristics using current source in first quadrant
Figure 13. Pspice schematic to produce I and II quadrant characteristics using current source

Figure 14. Simulated characteristics using current source in I and II quadrants

Figure 15. Hardware set up of an Electronic load and Sample snap shot of DSO screen for I and II quadrant plots
The first quadrant characteristics can also be obtained by giving the module voltage to the inverting terminal. This schematic is known as the circuit to produce I quadrant using voltage source. For this case the P channel MOSFET IRF9140 has to be used as shown in Fig.16.

Figure 16. Pspice schematic to produce I quadrant characteristics using voltage source

The concept of the proposed electronic load method (Fig 13) is extended to plot the characteristic in all the necessary quadrants as shown in Fig. 17. The simulated characteristic is shown in Fig.18. To implement practically this circuit, Op-amp with high current capability is required.

Figure 17. Simulated characteristics using current source in I and II quadrants
5. CONCLUSION
In this paper a modified method to model the SPV module to represent the complete characteristics has been discussed. The straightforward method has been proposed to fit the mathematical V-I curve to the remarkable points without the need to guess or to estimate any parameters. The proposed method has given a closed solution for the problem of finding the parameters of the five parameter model equation of a practical SPV module. In order to represent the complete characteristics, model has been extended in the reverse biased conditions. To measure the practical characteristics in both forward and reverse biased conditions, a simple method to quickly draw the same using MOSFET as the load has been presented. The concept has been extended to plot the SPV module characteristics in all the necessary quadrants. The proposed system is not only inexpensive but also characterizes V-I in all the quadrants. This tracing system is automated and rapid.

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REFERENCES


[28] www.mathworks.com

[29] www.cadence.com