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Modellingof Organic Photovoltaic Cells Based on an Improved Reverse Double Diode Model

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Abstract

Organic PV cells have gained tremendous attention in recent years for its advantage of having tailored molecular properties and economic manufacturing process. Along with the rigorous and rapid researchesprogressing in the field of organic photovoltaic cells, accurate modelling of organic PV cells has gained extreme importance. Hence in this paper, modelling of organic solar photovoltaic cells based on an improved reverse double diode model is presented. Apart from all other complex mathematical models available in literature, the modelling is performed by introducing simple circuit equations. Furthermore, the model is highly capable of realizing the ideal and non-ideal current-voltage characteristics of an organic PV cell. The eight unknown parameters of the model are extracted using Genetic Algorithm(GA) and the extracted parameters are used to predict the I-V characteristics of a nav-100 organic solar cell. The main aim of this paper is to study the behaviour of organic solar cells and to realize an accurate PV model to replicate the exact I-V characteristics.

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Keywords: Organic Solar PV cell, PV modelling, Genetic Algorithm.

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1. Introduction:

In recent years, the globally increased power demands have initiated the necessity of alternate power generation usingclean and green renewable energy resources. The enormous energy capability and the ease in availability makes sun the most reliable alternative for conventional power resources. Among all the solar energy systems, Photovoltaic systems are most popular for its long lifecycle, less operational cost and environment friendly nature.Compared to the conventional rigid solar cells, organic solar photovoltaic cells manufactured using molecular engineering process possess the advantage of tailoring molecular properties to suite the industrial needs. Even though, the reported efficiencies are low, the highly economic manufacturing process makes organic PV cells an interesting option, to be considered for enhanced researches in the field of photovoltaics.

PV modelling has played an integral part in the researches that have been done for enhancing the reliability of PV systems. The modelling of nonlinear 'S' shaped Current-Voltage curve (I-V curve) of organic PV cells is in fact a highly challenging task. A few methods are available in literature that used the conventional single diode and double diode model to model the organic PV characteristics [1,2]. But all these methods possess significant error while replicating the exact I-V characteristics of the organic cell.An improved single diode model employing a lumped parameter equivalent circuit was the first to replicate nearly accurate I-V characteristics of an organic cell [3].The authors used an explicit form of output voltage equation for analysis. Another improvement was to incorporate an additional diode instead of the parallel resistor in the conventional single diode model. This accounted for the additional upward bend in the curve. However, the explicit mathematical equations are extremely complex and involves many assumptions that may lead to poor convergence.A conventional double diode model based modelling for organic PV cells is presented in [4]. The authors proved that the single diode model is not accurate for organic cell modelling and developed mathematical equations for the double diode model based on the current density and voltage characteristics of the cell. Even though this method lacked accuracy at standard test conditions, the use of double diode model imparted a better accuracy to the model under low irradiance levels.In [5], multiple diodes are connected in parallel with some complex non-linear resistor blocks to replicate the organic PV characteristics. Unfortunately, thismodel failed to replicate the nonlinear regions in the I-V curve. The authors in [5] themselves has modified the double diode model to a Reverse Double Diode model to predict the organic PV characteristics. The modification is to include another diode shunted by a resistor forsimulating a region of the device where the charge accumulation leads to a change in the local electric field and as a consequence,voltage dependent charge injection takes place. This modification accounted for a better curve fit and can be considered as the best method available for organic PV modelling until now. Even though the model is accurate, the mathematical modelling was done using an explicit Lambert W function. This makes the model highly complex with monumental time consumption for convergence. This paper presents a new reverse double diode model which uses simple circuit analysis for formulating the model equations. The model isvalidated for a nav-100 organic PV cell and the performance is analyzed. Genetic Algorithm is used to extract the 8 unknown parameters of the model and the extracted parameters are then used to predict the I-V curve. The obtained curve is in good agreement with the experimental data. Furthermore, the convergence characteristics is also analyzed for a better validation.

2. PV Modelling

PV modelling is an essential tool to analyze, compare and simulate PV characteristics. It is an inevitable tool to study and predict I-V and P-V characteristics for different type of solar cells. Once the electrical equivalent circuit is modelled, it can be seamlessly integrated to any other systems such as grid, other renewable sources etc. to analyze the performance using suitable simulation platforms. Apart from the electrical models, some other models are also available in literature [6,7]. However, simulation analysis is not possible with these models. An accurate PV model must be able to replicate the exact characteristics of the cell under all operating conditions.The most commonlyused models in this scenario are the conventional single diode model and the double diode model. The sub sections will help the readers to familiarize the basic concepts of PV modelling.

2.1. Single diode model

The equivalent circuit of a conventional single diode model is depicted in Fig.1. It can be seen that photo currents are generated when the junction exposed to solar irradiation. The electrical equivalent for this phenomenon is a light illuminated current source. The diode 'D_1' is simply the electrical equivalent of the optical and recombination losses at the surface of the semiconductor. 'R_{SH}' represents the leakage losses whereas 'R_S' represents the internal resistance offered by the panel to the flow of electrons.The output current equation for the model can be written as

$$I = I_{irr} - I_0\left[e^{\frac{V+IR_{SH}}{V_T a}} - 1\right] - \frac{V + IR_{SH}}{R_S} \tag{1}$$

Where I_{irr} = Irradiation current or photo generated current

I_0 = Saturation current of the diode

$a =$ Diode ideality factor

V_T = Thermal voltage

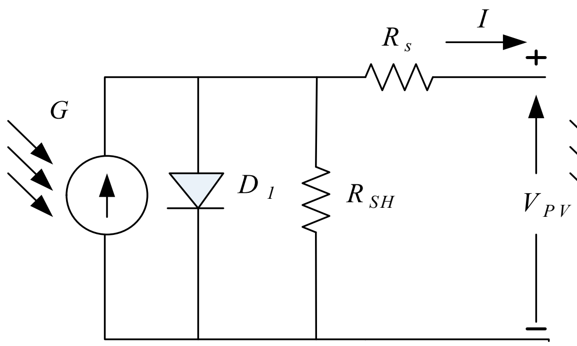


Fig.1. Single diode model

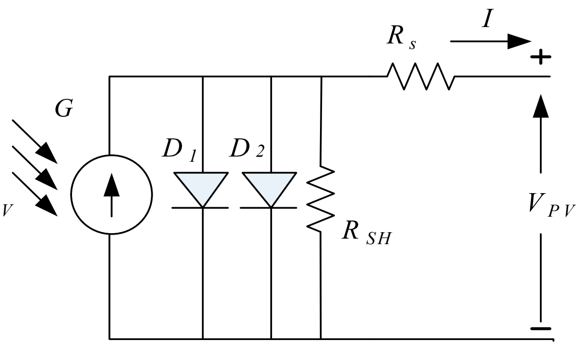


Fig.2. Double diode model

2.2. Double diode model

The only difference in equivalent circuit between single diode and double diode model is the presence of diode, 'D_2' which is connected in parallel with 'D_1' and isillustrated in Fig.2. The presence of diode D_2imparts high accuracy to the model especially under low irradiance conditions. The diode D_2accounts for the recombination losses in the depletion layer. These recombination losses will be significant in low irradiance levels and when the operating temperature of the panel is high. As the model has an inherent capability to compensate for recombination losses, this model is usually preferred over single diode model for sensitive applications even though its slightly complex with 7 parameters. By applying Kirchhoff's Current Law to any of the nodes, the output PV current can be mathematically expressed as

$$I = I_{irr} - I_{01}\left(e^{\frac{V+IR_{SH}}{N_S a_1 V_T}} - 1\right) - I_{02}\left(e^{\frac{V+IR_{SH}}{N_S a_1 V_T}} - 1\right) - \frac{V + IR_{SH}}{R_S} \tag{2}$$

Where I_{01} =Saturation current of D_1

I_{02} =Saturation current of D_2

N_S =No. of cells connected in series.

3. Improved Reverse Double Diode Model

As discussed earlier in the introduction, it is worth to be mentioned that the single and double diode models are usually used to simulate the I-V and P-V characteristics of Silicon based rigid solar cells. The results obtained when the same was used to reproduce the characteristics of an organic PV cell was not encouraging. Here lies the importance of PV models that can be used to replicate the characteristics of organic solar cells as well. This paper presents a novel improved reverse double diode model to represent the electrical characteristics of organic PV cells. The simplified reverse double diode model is depicted in Fig.3. The drawback of all conventional models is that they all failed to exactly replicate the upper bend of the 'S' shaped I-V curve of an organic PV cell. Here in the reverse double diode model, a second diode shunted by a resistor is incorporated to precisely replicate the upper bend in the 'S' curve. This exactly simulates the upper bend region, where the charge accumulation leads to a change in the local electric field which in turn leads to voltage dependent charge injection and hence the upper bend in the 'S' curve. [5] utilized the reverse double diode model to precisely replicate the V-I characteristics of an organic solar cell. However, the mathematical modelling was done using an explicit Lambert W function. Even though Lambert W model imparts a better accuracy to the model, the involved computations are extremely complex and time consuming. Furthermore, for accurate simulation, the effect of series resistance, 'R_S'was omitted. This may not be true in the practical scenario where series resistance significantly affects the output current and voltage.Hence, assumption of R_S=0 cannot be trusted under all operating conditions of the cell especially at high temperature and low irradiance levels where the effect of 'R_S' is dominant. However, this paper presents a new methodology which

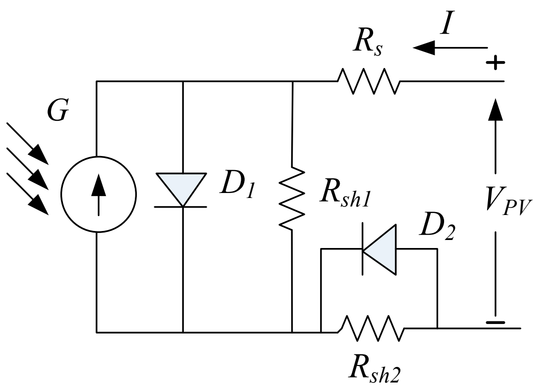


Fig.3. Reverse double diode model

efficiently incorporates the effect of series resistance under all operating conditions of the panel. Moreover, instead of Lambert W function, a simple mathematical modelling procedure is adopted here which utilizes the basic Kirchhoff's equations.By applying Kirchhoff's voltage law(KVL) to Fig.3.

$$V_{D1} = V - IR_S - V_{D2} \tag{3}$$

$$V_{D2} = (I - I_{D2})R_{SH2} \tag{4}$$

$$I_{D2} = I_{02}\left[e^{\frac{V_{D2}}{n_2 V_T}} - 1\right] \tag{5}$$

$$I_{D1} = I_{01}\left[e^{\frac{V - IR_S - V_{D2}}{n_1 V_T}} - 1\right] \tag{6}$$

$$I = \frac{1}{R_S + R_{SH2} + R_{SH1}}\left[-(I_{irr} + I_{D1})R_S + (I_{D2}R_{SH2}) - V\right] \tag{7}$$

Where, V_{D1} = Voltage of diode D_1

I_{01} = Saturation current of D_1
V_{D2} = Voltage of diode D_2
I_{02} = Saturation current of D_2
I_{irr} = Irradiation current or photo generated current

Equation (8) represents the output equation of the improved reverse double diode model which is simple and more realistic. It can be seen that the current values are predicted with respect to the voltage data and it doesn't involve the term which will allow the current to increase further even after getting the 'S' shaped curve. The model can fit experimental data within a range of voltage which is limited. The model however has 8 unknown parameters viz, $I_{irr}, I_{01}, I_{02}, R_{SH1}, R_{SH2}, R_S, n_1$ and n_2 .

4. Extraction of parameters using Genetic Algorithm

From the above discussions, it is clear that there are eight unknown parameters in the Improved Reverse Double Diode model viz $I_{irr}, I_{01}, I_{02}, R_{SH1}, R_{SH2}, R_S, n_1$ and n_2 . Since these parameters are unavailable in the manufacturer's data sheet, these parameters are to be extracted using a suitable parameter extraction technique. There are two methods available for extracting the unknown parameters viz the analytical and the numerical methods. Since the former includes complex mathematical computations and monumental time consumption, the latter is used in this paper. Numerical methods usually treat the dilemma as an optimization problem were an objective function is formulated based on the error difference between the experimental curve and the simulated curve. Any metaheuristic algorithm can be used to optimize the parameters through successive iteration steps. Normally the error function is based on the RMSE (Root Mean Square Error) value which is the most accurate statistic available for measuring the curve fit. Genetic Algorithm is used in this paper to optimize the model parameters of improved reverse double diode model for a nav-100 organic solar cell.

4.1. Genetic Algorithm

GA is an iterative population based algorithm inspired by the phenomenon of 'survival of the fittest' [8]. The unknown parameters in the objective function is expressed as decision variables which are then encoded as chromosomes. The quality of each chromosome (solution) is expected to improve through successive iteration steps and is continuously verified. Based on the fitness values, Parent chromosomes are selected in each iteration step and are used to produce off springs. Only fitter chromosomes are selected for the next iteration. The process continues until the termination criterion is met yielding best solutions.Here, an RMSE based objective function is formulated using equation (8) which can be mathematically represented as

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(f_i\left(V,I,X\right)\right)^2} \tag{8}$$

where *N* is the total number of measurements and *X* is the set of model parameters.
The main steps for GA implementation are discussed below [9].

1. Initialization: Setting the population size and defining the control parameters.
2. Crossover: Fitter Chromosomes are selected as parents and are crossed to obtain new off springs.

$$offspring = \begin{Bmatrix} \alpha\,.\,parent1 + (1-\alpha)\,.\,parent2 \\ (1-\alpha)\,.\,parent1 + \alpha\,.\,parent2 \end{Bmatrix} \tag{9}$$

Where α is the crossover rate, *parent1* and *parent2* are the current best solutions.

3. Mutation: A user defined mutation rate, β is used to further improve the quality of the off springs.

$$offspring = \pm\beta.offspring + offspring \tag{10}$$

4. Selection: Fitter chromosomes are selected for next generation and unhealthy chromosomes are rejected.

The flowchart of GA method presented in Fig.4. for a better clarity in understanding. Table 1. illustrates the extracted parameters for the improved reverse diode model for a nav-100 organic solar cell using Genetic Algorithm.

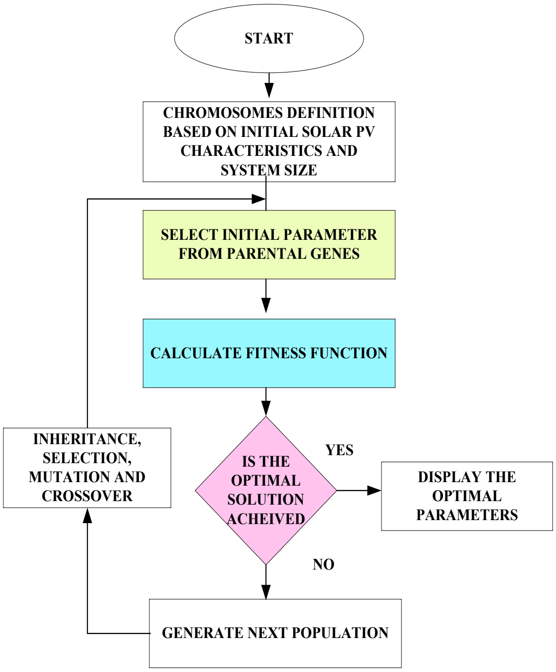
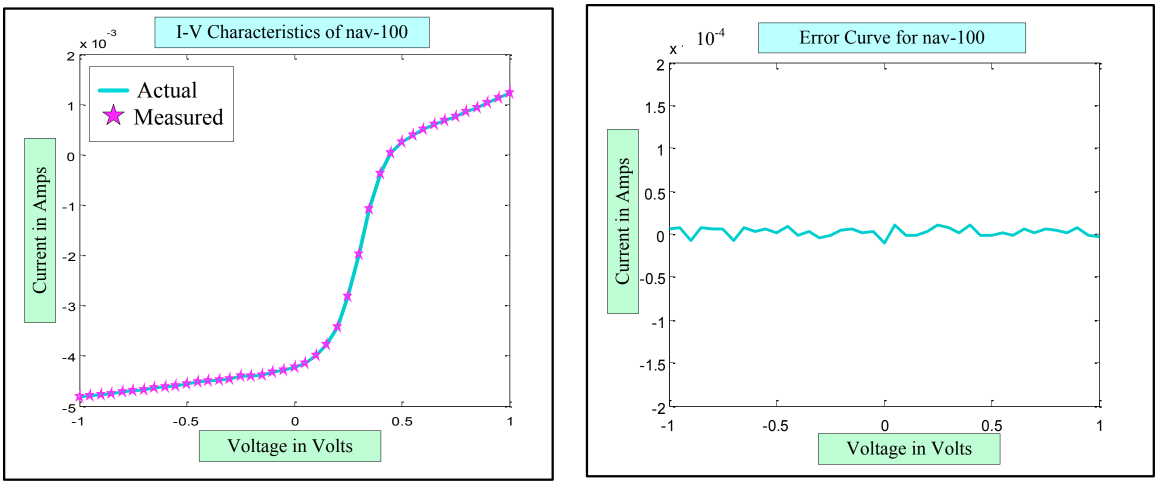


Fig.4.Flowchart for Genetic Algorithm

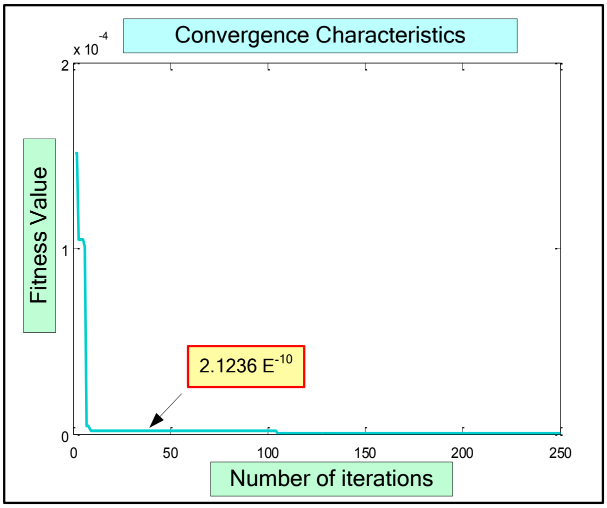
Table 1. Extracted parameters for a nav-100 organic solar cell

Extracted Parameters	
$R_{SH1}(\Omega)$	1200.01
$R_{SH2}(\Omega)$	262.1211
$I_{01}(\mathrm{A})$	0.000006
$I_{02}(\mathrm{A})$	0.000247
n_1	0.080046
n_2	0.022348
$I_{irr}(\mathrm{A})$	0.003680
$R_S(\Omega)$	2.19729

5. Validations and Results



(a) (b)



(c)

Fig.5. (a), (b) and (c) Simulated Curves for nav-100 Solar cell

Fig.5. shows the results obtained for a nav-100 organic solar cell using the improved reverse double diode model. It can be clearly seen in Fig.5. (a) that the simulated I-V curve exactly replicates the experimental curve. The conventional issue of the in accurate upper bend in the 'S' curve has been eliminated. Furthermore, it can be interpreted from Fig.5. (b) that the individual error values obtained for the output currentat each instant is significantly low. It is to be noted that unlike the Lambert W based reverse double diode model, all the eight unknown parameters are extracted and used to realize the model. The introduction of series resistance will remarkably increase the accuracy of the model under varying irradiance and temperature levels. Moreover, the extraction of parameters using Genetic Algorithm shows excellent convergence characteristics and is depicted in Fig. 5. (c). Genetic Algorithm has converged to an optimum fitness value of 2.123E^{-}10 with in 50 iterations indicating the significance of simple mathematical computations used.

6. Conclusion

In this paper, an in-depth analysis of the characteristics of organic PV cells have been carried out to realize an accurate PV model which can exactly replicate the 'S' shaped I-V characteristics of the organic solar cells. The paper proposed an improved reverse double diode model which can exactly reproduce the 'S' shaped curve. The proposed model has due provisions to accurately replicate the upper bend in the 'S' curve. Apart from the other models available, this model efficiently incorporates the effect of series resistance which will increase the accuracy at all operating conditions. The conventionalGenetic Algorithm was used to extract the 8 unknown parameters of the model. The mathematical formulations for the model were based on simple circuit theory. This enhanced the convergence speed while extracting the unknown parameters. The results obtained was validated for a nav-100 organic solar cell and the simulated curve obtained was in good agreement with the experimental curve. Furthermore, the method shows significant reduction in the individual relative error of the output current.

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