Klemen SREDENŠEK, Sebastijan SEME
Faculty of Energy Technology, University of Maribor, Slovenia

doi:10.15199/48.2019.01.42

Parameter determination of a solar cell model using differential evolution algorithm

Abstract. *This paper deals with determination of a double diode model parameters using the differential evolution algorithm. The importance of this method is the implementation of ohmic and shadow losses. Performance of the proposed approach shows high potential as a promising determination method for solar cell parameters.*

Streszczenie. *Przedmiotem artykułu jest określenie parametrów modelu z podwójną diodą przy wykorzystaniu ewolucyjnego algorytmu różniczkowego. Ważność tej metody tkwi w implementacji strat omowych i strat z zacienienia. Działanie zaproponowanego podejścia pokazuje jego duże możliwości w wyznaczaczaniu parametrów modułu fotowoltaicznego. (**Wyznaczanie parametrów modeli modułów solarnych przy wykorzystaniu ewolucyjnego algorytmu różniczkowego**)*

Keywords: double diode model, differential evolution, I-V characteristic, losses, maximum power point
Słowa kluczowe: model dwudiodowy, ewolucja różniczkowa, charakterystyka prądowo-napięciowa I-V, straty, punkt mocy maksymalnejy

Introduction

Research and development of photovoltaic (PV) cells has led to higher efficiencies, significant cost reductions and long operating lifetimes with minimal degradation [1]. The double diode model of the photovoltaic cell/module is fast becoming a viable alternative to the highly popular single diode model for PV simulations [2]. In general, there are two ways to extract the solar cell parameters: (1) analytical and (2) numerical method The analytical technique requires information on several key points of the *I-V* characteristic curve, i.e. the current and voltage of at the maximum power point (MPP), short-circuit current, open-circuit voltage and slopes of the *I-V* characteristic at the axis intersections. It has been noted that the *I-V* is highly non-linear and any wrong selected points may result in significant errors in the computed parameters [3]. While the numerical extraction technique relies on mathematical algorithm to fit all the points in the *I-V* characteristic curve. The results obtained by numerical extraction technique are more accurate, compared to the analytical technique, due to utilization of all points on the *I-V* curve. The following authors present different approaches to extract solar cell parameters.

AlRashidi [4] presents a new technique based on pattern search (PS) optimization for estimating different solar cell parameters. The proposed approach is tested and validated using double diode model, in which the estimated parameters are generated photocurrent, saturation current, series resistance, shunt resistance, and ideality factor. Chin [2] presents the implementation of a hybrid solution, i.e. by incorporating the analytical method with the differential evolution (DE) optimization technique. Three parameters, i.e. generated photocurrent, saturation current of the first diode and shunt resistance are computed analytically, while the remaining ideality factors, saturation current of the second diode and series resistance are optimized using the DE. Chellaswamy [5] presents a new approach based on adaptive differential evolution technique to extract the parameters of the solar cell and compares it with chaos particle swarm optimization (CPSO), genetic algorithm (GA), harmony search algorithm (HSA) and artificial bee swarm optimization (ABSO).

The remnants of this paper is organized in the following way: II. section describes the double diode model and its ohmic and shadow losses; III. section describes the differential evolution and objective function for double diode model; IV. section presents and explains the obtained results; and the conclusion is discussed in section V.

Solar Cell Modeling

Double Diode Model:

The conditions in solar cell are most easily described by the mathematical model of the solar cell. The output current of the solar cell in the double diode model can be calculated by (1):

$$I_L = I_{ph} - I_{D1} - I_{D2} - I_{sh} \quad (1)$$

where I_L is output current, I_{ph} the cell generated photocurrent, I_{sh} the shunt resistor current, I_{D1} and I_{D2} the double diode currents. The double diode currents can be expressed by Shockly equation in (2) and (3), while the shunt resistor current I_{sh} is calculated by (4):

$$I_{D1} = I_{01}\left(\exp\left(\frac{q(V_L + I_L R_s)}{n_1 kT}\right) - 1\right) \quad (2)$$

$$I_{D2} = I_{02}\left(\exp\left(\frac{q(V_L + I_L R_s)}{n_2 kT}\right) - 1\right) \quad (3)$$

$$I_{sh} = \frac{V_L + I_L R_s}{R_{sh}} \quad (4)$$

where I_{01} and I_{02} are the diode dark saturation currents, n_1 and n_2 the ideality factors of the diodes D_1 and D_2, R_s and R_{sh} the series and shunt resistances, V_L is the thermal voltage, k the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), q the electronic charge (1.6×10^{-19} As) and T the cell absolute temperature in Kelvin. By considering (2), (3) and (4) into (1), the output current can be rewritten as shown in (5):

$$I_L = I_{ph} - I_{01}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_1 kT}\right) - 1\right] - I_{02}\left[\exp\left(\frac{q(V_L + I_L R_s)}{n_2 kT}\right) - 1\right] - \left[\frac{(V_L + I_L R_s)}{R_{sh}}\right] \quad (5)$$

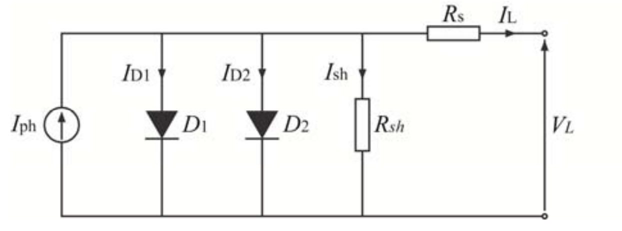

Fig. 1. Double diode model.

The equivalent circuit of a solar cell using two diodes is presented in Fig. 1.

Shadow and Ohmic Losses

In order to describe the losses in the solar cell, Fig. 2 shows a solar cell with tangled bands and fingers, through which the electric charges are collected and discharged into the external circuit. The shadow fractions p_{sb} of tabs and p_{sf} of fingers are given by (6) and (7):

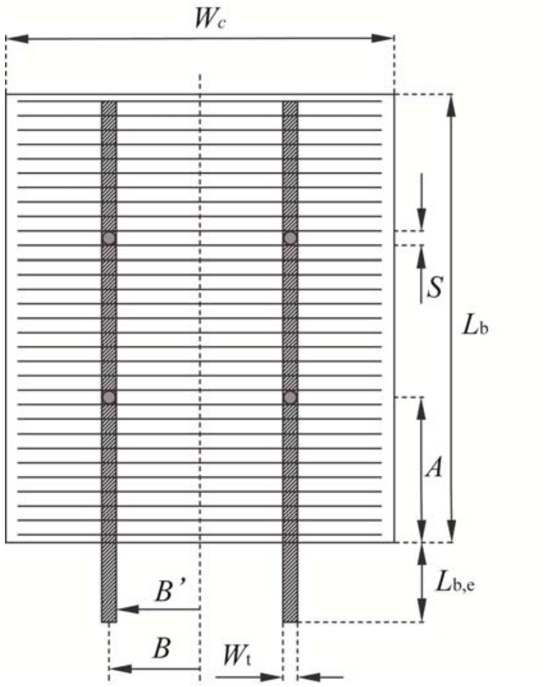

Fig. 2. An H-grid metallization pattern of solar cell.

(6) $$p_{sb} = \frac{n_t\left(1-t_b\right)W_t}{W_c}$$

(7) $$p_{sf} = \frac{\left(1-t_f\right)W_f}{S}$$

where n_t is the number of tabs, W_t the tab width, W_c the cell width, t_b the effective busbar transparency, W_f the finger width, t_f the effective finger transparency and S the finger distance. The total shadow losses are given by (8):

(8) $$p_s = p_{sf} + p_{sb} - p_{sf}\,p_{sb}$$

In addition to shadow losses, the ohmic losses are also taken into account. Ohmic losses are defined as the sum of all ohmic losses of serial resistance $R_{se,pat}$ by (9):

(9) $$R_{se,pat} = R_{te} + R_f + R_e + R_b + R_t + R_c$$

where R_{te} is tab extension loss, R_f the finger resistance loss, R_e emitter resistance loss, R_b the busbar resistance loss, R_t the tab resistance loss and R_c the contact resistance loss. All these losses are defined by (10) – (15):

(10) $$R_{te} = \frac{\rho_{lt}L_{b,e}}{n_t}$$

(11) $$R_f = \frac{1}{2n_t n_f}\frac{B'}{3}\rho_{lf}$$

(12) $$R_e = \frac{1}{n_t n_f}\frac{\rho_{s,l}\left(S-W_f\right)}{24B'}$$

(13) $$R_b = \frac{1}{2n_t n_f}\frac{A}{3}\rho_{lb}$$

(14) $$R_t = \rho_{lt}\frac{L_b}{3n_t}\left(1+\frac{1}{2n_s^2}\right)$$

(15) $$R_c = \frac{1}{2n_t n_f}\frac{\rho_c}{B'W_f}\frac{\sqrt{\rho_{s,l}/\rho_c}\,W_f/2}{\tanh(\sqrt{\rho_{s,l}/\rho_c}\,W_f/2)}$$

where ρ_c presents the contact resistance, ρ_{lb} the line resistance busbar, ρ_{lf} the line resistance fingers, ρ_{lt} the line resistance tab, $\rho_{s,l}$ the sheet resistance Si, A the half the solder joint distance, B' the connexion distance, L_b the cell length, $L_{b,e}$ the additional tab length, n_f the number of fingers, n_s the number of solder joints/tab, n_t the number of tabs, S the finger distance and W_f the finger width [6].

By considering (8) and (9) into (5), the output current can be rewritten as shown in (16):

(16) $$I_L = \begin{array}{l} I_{ph}\left(1-p_s\right) - I_{01}\left[\exp\left(\frac{q\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{n_1 kT}\right)-1\right] \\ -I_{02}\left[\exp\left(\frac{q\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{n_2 kT}\right)-1\right] \\ -\left[\frac{\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{R_{sh}}\right]\end{array}$$

Differential Evolution

Differential Evolution (DE) is a direct search stochastic algorithm capable of solving global optimization problems, subject to nonlinear constraints [7]. Nowadays, DE has become one of the most frequently used evolutionary algorithms appropriate for solving the global optimization problems, even those dealing with technique and real life problems [8]. However, it has been also shown to be effective on a large range of classic optimization problems. In [9] it was demonstrated that DE performs better than several other optimization methods including four genetic algorithms, simulated annealing and evolutionary programming. The DE operates on a population of candidate solutions and does not require a specific starting point. The population is of constant size *NP*. Within each iteration a new generation of solutions is created and compared to the population members of the previous generation. This process is repeated until the predefined objective function value VTR or the maximum number of generations G_{max} is reached [8].

A nonlinear global optimization problem can be defined as follows: Find the vector of the parameters x = [x_1, x_2, … x_D], x ∈ R^D, which will minimize the function *f*(x). The vector x is the subject of *m* inequality constraints g_j (x) ≤ 0, j = 1, …, *m* and *D* boundary constraints $x_i^{(L)} \le x_i \le x_i^{(U)}$, *i* = 1…, *D*, where $x_i^{(L)}$ and $x_i^{(U)}$ are the lower and upper limits [7].

The population of the G^{th} generation can be written in the form P_G = [$x^j_{1,G}$, $x^j_{2,G}$,…$x_{NP,G}$], *G* = 0,…, G_{max}. Each vector in P_G contains *D* real parameters $x_{i,G}$ = [$x^j_{1,G}$, $x^j_{2,G}$, …,$x^j_{D,G}$], *i* = 1, …, *NP*, *G* = 0, …, G_{max}.

The initial population $P_{G=0}$ is generated using random values within given boundaries, which can be written by (17):

(17) $$x^i_{j,0} = \mathrm{rand}_j[0,1]\left(x_j^{(U)} - x_j^{(L)}\right) + x_j^{(L)}\ i = 1,\ldots,NP,\ j = 1,\ldots,D$$

where rand$_j$ [0,1] is the uniformly distributed random number at the interval [0,1] which is chosen anew for each *j*, whilst (*U*) and (*L*) denote the upper and lower boundaries of the vector parameters. In every generation, the new candidate vectors are created by randomly sampling and combining the vectors from the previous generation, in the following manner described by (18):

(18)

$$i=1,...,NP,\ j=1,...,D,\ G=1,...G_{\max}$$

$$u_{j,G}^{i}=\begin{cases} x_{j,G-1}^{r3}+F\left(x_{j,G-1}^{r1}-x_{j,G-1}^{r2}\right) \text{ if } \mathrm{rand}_{j}[0,1]\le CR \text{ or } j=k \\ x_{j,G-1}^{i} \text{ otherwise} \end{cases}$$

where $F \in [0,2]$ and $CR \in [0,1]$ are the DE control parameters kept constant during optimization, $r1$, $r2$, $r3 \in \{1, …, NP\}$. $r1 \neq r2 \neq r3 \neq i$ are randomly selected vectors from the previous generation, different from each other and different from the current vector with index i. $k \in \{1, …, D\}$ is a randomly chosen index which ensures that at least one $u^{i}_{j,G}$ is different from $x^{i}_{j,G-1}$ [8].

The population for the new generation P_G will be assembled from the vectors of the previous generation P_{G-1} and the candidate vectors u^{i}_{G} according to the following selection scheme described by (19):

(19)

$$i=1,...,NP,\ G=1,...G_{\max}$$

$$\mathrm{x}_{G}^{i}=\begin{cases} \mathrm{u}_{G}^{i} \text{ if } f\left(\mathrm{u}_{G}^{i}\right)\le f\left(\mathrm{x}_{G-1}^{i}\right) \\ \mathrm{x}_{G-1}^{i} \text{ otherwise} \end{cases}$$

The process is repeated with the next generation until reaching the predefined objective function value or the maximum number of generations.

Objective Function

The determination of the solar cell parameters is an optimization process, which minimizes the difference between real and estimated values [5]. In this paper the root mean square error (RMSE) is used as the objective function, which is described by (20):

(20)
$$RMSE=\sqrt{\frac{1}{M}\sum_{i=1}^{M} f\left(V_L, I_L, x\right)^2}$$

where M is the number of real *I-V* data and the output of *RMSE* guide the optimization search for the better value of the vector x [5]. The homogeneous equation for the corresponding equation (16) is given by (21):

(21)

$$f(I_L,V_L,x)=I_L-I_{ph}(1-p_s)-I_{01}\left[\exp\left(\frac{q\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{n_1kT}\right)-1\right] -I_{02}\left[\exp\left(\frac{q\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{n_2kT}\right)-1\right] -\left[\frac{\left(V_L+I_L\left(R_s+R_{se,pat}\right)\right)}{R_{sh}}\right]$$

Vector $x=\left\lfloor I_{ph}, I_{01}, I_{02}, R_{te}, R_f, R_e, R_b, R_t, R_c\right\rfloor$ consists of nine parameters of double diode model that needs to be determined. The main aim of optimization process is to minimize *RMSE* with respect to x. The most ideal value of *RMSE* is zero.

Results

The solar cell parameter determination using the selected DE is correlated with the technical parameters of the selected solar module (current I_{MPP} and voltage V_{MPP} of at the maximum power point, short-circuit current I_{SC} and open-circuit voltage V_{OC}). In order for successful implementation, the DE control parameters must be set correctly [2]. The optimal values of population size (NP), mutation factor (F) and crossover rate (CR) are set to be 90, 0.7 and 0.5 respectively. Maximum number of iterations/generations is set to be 100.000. The selected DE strategy is the DE/rand-to-best/1/bin, while [2] and [3] have chosen DE/best/1/bin strategy. Table I. presents the values of optimized solar cell parameters. Fig. 3 and 4 presents *I-V* and *P-V* characteristics of solar cell obtained from DE for various irradiance.

TABLE I. Values of Optimized Solar Cell Parameters

Parameter	***Value***
I_{ph} – cell generated photocurrent	6.3391 A
I_{01} – first diode dark saturation current	$1.6179\cdot10^{-10}$ A
I_{02} – second diode dark saturation current	$1.6462\cdot10^{-05}$ A
R_{te} - tab extension loss	0 Ω
R_f - finger resistance loss	0.0022 Ω
R_e - emitter resistance loss	$4.9242\cdot10^{-04}$ Ω
R_b - busbar resistance loss	$7.3455\cdot10^{-05}$ Ω
R_t - tab resistance loss	$8.5821\cdot10^{-04}$ Ω
R_c - contact resistance loss	$5.6666\cdot10^{-04}$ Ω

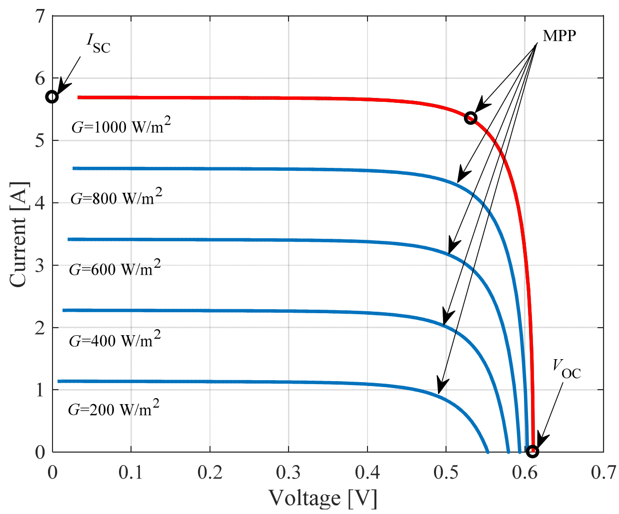

Fig. 3. The *I-V* characteristics at varying irradiance.

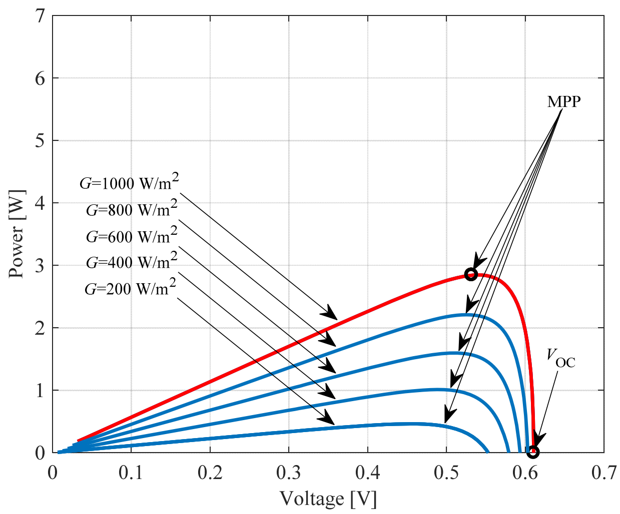

Fig. 4. The *P-V* characteristics at varying irradiance.

Figure 3 and 4 shows that *I-V* and *P-V* characteristic curves are precisely defined, as they fully fit the technical data of the selected solar cell (I_{SC}, V_{OC}). The technical data of one solar cell under standard test conditions (STC: G = 1000 W/m^2, T_m = 25°, AM = 1.5) are as follows: I_{SC} = 5.69 A, I_{MPP} = 5.35 A, V_{OC} = 0.6105 V and V_{MPP} = 0.5319 V.

Conclusion

This paper presents the parameter determination of a solar cell using differential evolution algorithm. The *I-V and P-V* characteristics of the solar cell are approximated by the corresponding function. The parameters of the objective function are determined by optimization, based on the technical data of the solar cell and the corresponding double diode model. The outcomes signify a great potential of DE algorithm as a tool for parameter determination of a solar cell.

Authors: *Klemen Sredenšek, klemen.sredensek@um.si, Sebastijan Seme, sebastijan.seme@um.si, Faculty of Energy Technology*
University of Maribor, Krško, Slovenia

REFERENCES

[1] P.G. McCormick and H. Suehrcke, "The effect of intermittent solar radiation on the performance of PV systems," Solar Energy, vol. 171, pp. 667-674, 2018.
[2] V. J. Chin, Z. Salam and K. Ishaque, "An accurate modelling of the two-diode model of PV module using a hybrid solution based on differential evolution," Energy Conversion and Management, vol. 124, pp. 42-50, 2016.
[3] K. Ishaque, Z. Salam, S. Mekhilef and A. Shamsudin, "Parameter extraction of solar photovoltaic modules using penalty-based differential evolution," Applied Energy, vol. 99, pp. 297-308, 2012.
[4] M. R. AlRashidi, K. M. El-Naggar and M. F. AlHajri, "Parameters estimation of double diode solar cell model," International journal of electrical, robotics, elektronics and communications engineering, vol. 7 (2), pp. 93-96, 2013.
[5] C. Chellaswamy and R. Ramesh, "Parameter extraction of solar cell models based on adaptive differential evolution algorithm," Renewable energy, vol. 97, pp. 823-837, 2016.
[6] A. R. Burgers, "New metallisation patterns and analysis of light trapping for silicon solar cells," PhD Thesis Utrecht University 2005.
[7] G. Štumberger, D. Žarko, A. Tokić and D. Dolinar, "Magnetically nonlinear iron core characteristics of transformers determined by differential evolution", ISEF 2009 – XIV International Symposium on Electromagnetic Fields in Mechatronics, Electrical and Electronic Engineering, 2009.
[8] S. Seme and G. Štumberger, "A novel prediction algorithm for solar angles using solar radiation and Differential Evolution for dual-axis sun tracking purposes," Solar Energy, vol. 85, Issue 11, pp. 2757-2770, 2011.
[9] K. V. Price, R. M. Storn and J. A. Lampinen, "Differential Evolution: A Practical Approach to Gloabal Optimization (Natural Computing Series)," Springer, 2005.