20. Simplified and Accurate Photovoltaic Module Parameter Estimation Method Based on Single Diode Model

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Abstract

The aim of this paper is to introduce a simplified and accurate method for the estimation of five electrical model parameters of Photovoltaic (PV) module namely diode ideality factor (a), series resistance (R_s), shunt resistance (R_{sh}), dark saturation current (I_o) and photo-generated current (I_{pv}) under standard test conditions (STC) and to compare the different analytical and iterative methods already popular in technical literature with the proposed method. The parameters extraction approach proposed in this paper exploits a new equation dP/dI=0 at maximum power point for iterative solution rather than $dV/dI=-1/R_p$ or $dV/dI=-1/R_s$. Thus, avoiding the complexity and dependency over series and shunt resistance for five parameters extractions.

Keywords: *parameter estimation method; photovoltaic module; MPP; single diode model.*

1. Introduction

Over the last few years, the exponential increase in energy demand have caused the rapid depletion of fossil fuels like coal, oil, natural gas etc. and also due to emission of greenhouse gases , the world is shifting towards renewable energy sources. Although, renewable energy is relatively expensive [1] but due to inexhaustibility, free availability and environmental friendly nature, renewable energy is becoming more and more popular [2]. Among many renewable energy types solar photovoltaic system is one of the most popularly used one. Photovoltaic system directly converts light into electricity by using phenomenon called photoelectric effect. Photovoltaic module is an arrays or modules formed by either grouping the solar cells in series, parallel or in both. PV systems are never connected directly to the load due to highly non-linear IV-characteristics which results in poor overall efficiency of the system. Therefore, to operate PV system at maximum possible efficiency, many state of the art techniques have been developed worldwide in recent years and are in practice, including MPP tracking, power loss reduction and optimization of algorithms and electronic converters. In order to study and optimize electronic circuits and MPP algorithms, an accurate model of PV module has to be established. Furthermore, mathematical models are developed by researchers to study the effect of temperature, irradiance and other factors on performance of PV modules.

2. Mathematical Modeling

An accurate knowledge of the parameters of solar cell model is necessary for the design, control and process optimization of a solar cell .The selection of mathematical model for the representation of PV module is mainly based on the compromise between the simplicity and accuracy [3]. However, in practice mostly two types of mathematical models are used namely single diode and double diode model. The single-diode model [3] shown in fig 1 requires an extraction of five parameters. The advantages of single diode model include simplicity, accuracy [1] and the possibility of the extraction of all five required parameters from the information provided by the manufacturer’s datasheet [4], [5], [6].

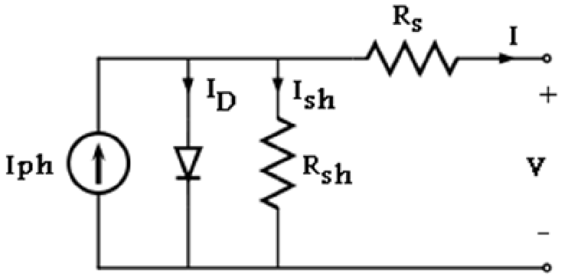

Fig. 1. Equivalent circuit of a PV cell based on single diode model

Applying Kirchhoff's current law, Shockley diode equation and current divider rule on circuit in fig. 1.

$$I = I_{ph} - I_o(e^{\frac{V+IR_S}{aV_t}} - 1) - \frac{V+IR_S}{R_{sh}} \tag{1}$$

Where I_{ph} is the photon generated current, I_o is reverse saturation current ,R_s is series resistance, R_{sh} is shunt resistance, a is diode ideality factor , V and I are module output voltage and current respectively , V_t is the junction thermal voltage given by the equation

$$V_t = \frac{N_s KT}{q} \tag{2}$$

In above equation q is charge of electron, K is Boltzmann's constant, T is temperature at STC in Kelvin and N_s is number of cells connected in series in photovoltaic module.
In order to model a photovoltaic module it is necessary for design engineer to have value of all unknown parameters [2]. Unfortunately, the manufacturer datasheet provides only the following specifications V_{oc}(open circuit voltage), I_{sc} (short circuit voltage), I_{mp} and V_{mp} i.e. current and voltage at maximum power point , open circuit voltage coefficient(K_v) and short circuit current coefficient(K_i) and Power at maximum power point (P_{mp}) with reference to STC and NOCT. Therefore, unknown parameters must be evaluated. Unlike, electrical sources that either works as current source or voltage source the PV cell has the ability to behave as current source as well as the voltage source based on the operating point region [1]. Furthermore, parameters like I_{ph}, I_o, R_s and R_{sh} not only depend on IV-characteristics of a photocell but also on the external factors such as temperature and irradiance [7]. More sophisticated calculations involves consideration of external parameters like air density, wind speed, different illuminated levels etc. The following equations are present in literature to calculate values of I_{ph}, I_o and V_{oc} at varying temperature and irradiance.

$$Iph = (Iph,n + Ki\Delta T)\frac{G}{Gn} \tag{3}$$

$$Io = \frac{Isc + Ki\Delta T}{e^{(\frac{Voc,n+Kv\Delta T}{aVt})} - 1} \tag{4}$$

$$Voc = Voc,n + Kv\Delta T \tag{5}$$

Where $V_{oc,n}$, $I_{sc,n,}$ are nominal open circuit voltage and short circuit current, ΔT is $T - T_n$ where T and T_n are the actual and nominal temperatures in Kelvin(K) respectively, *G and Gn* are the real and nominal irradiations in watts per meter^2.

3. Literature overview

This section aims to give an overview of the most widely used single diode based PV module parameter estimation methods found in technical literature:

3.1. Villalva Method

3.1.1. Description

Villalva iterative algorithm extracts two parameters R_s and R_{sh} simultaneously keeping diode ideality factor (a) constant relying on the fact that there is only one pair of (R_s, R_{sh}) which satisfies

$P_{mp,model}=P_{mp,curve}=V_{mp}*I_{mp}$ at MPP of IV-curve i.e. to say the maximum power obtained from IV model Eq. (1) should be equal to the maximum power point provided by the manufacturer data sheet IV-curve at MPP. The given method's extracted values greatly depends upon the increment value of Rs and tolerance band [2].

In this method, the author initially assumes the diode ideality factor (a) as constant which later on can be modified to better fit the IV-curve, $R_s=0$ which must be slowly incremented during the iterative process and $I_{ph}=I_{sc}$, but when R_s and R_{sh} converge towards the best model solution the Eq. (5) is used to find I_{ph} value

$$I_{ph} = \frac{R_s+R_{sh}}{R_{sh}} I_{sc} \tag{6}$$

The initial value of R_{sh} is:

$$R_{sh,min} = \frac{V_{mp}}{I_{sc}-I_{mp}} - \frac{V_{oc}-V_{mp}}{I_{mp}} \tag{7}$$

The relation between R_{sh} and R_s is obtained by using relation $P_{mp,model}=P_{mp,curve}$ at MPP which leads to the Eq. (8)

$$R_{sh} = \frac{V_{mp}(V_{mp}+R_s*I_{mp})}{V_{mp}\left[I_{ph}-I_o\left(e^{\frac{V_{mp}+R_s*I_{mp}}{V_t*a}}-1\right)\right]-P_{mp,curve}} \tag{8}$$

The above equation suggests that for any value of R_s there will be only one value of R_{sh} which makes the given electrical model traverse the (I_{mp}, V_{mp}) i.e. MPP provided by the manufacturer datasheet.

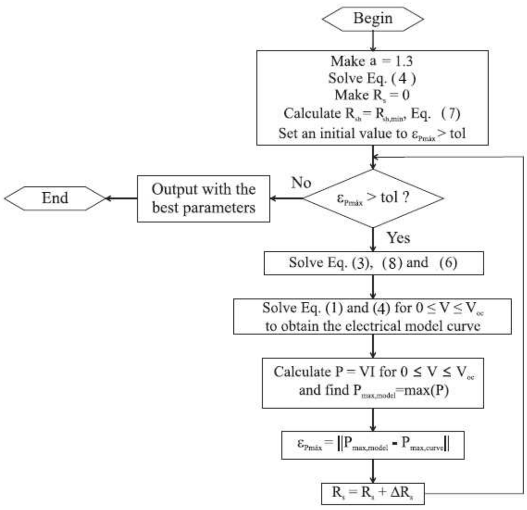

Fig. 2. Flowchart of Villalva's Method

3.1.2. Limitations

Villalva method is accurate near MPP but it can be inaccurate in other regions [3] because all values are evaluated at MPP and *a* is treated constant.

3.1.3. Algorithm

The flow chart of Villalva method is given in fig 2.

3.2. Non-linear Least Square Method

3.2.1. Description

The least square method is the most widely used curve fitting method which extracts the required parameters by minimizing the squared error between the estimated target variables and experimental data [2].

To estimate the five parameters (a, R_s, R_{sh}, I_{ph}, I_o) of PV module, the non-linear least square method uses five objective functions

$$f_1(x) = 0 = I_{ph} - I_o\left[e^{\left(\frac{I_{sc}R_s}{aV_t}\right)} - 1\right] - \frac{I_{sc}R_s}{R_{sh}} - I_{sc} \quad (16)$$

$$f_2(x) = 0 = I_o\left[e^{\left(\frac{V_{oc}}{aV_t}\right)} - 1\right] + \frac{V_{oc}}{R_{sh}} - I_{ph} \quad (17)$$

$$f_3(x) = 0 = I_{ph} - I_o\left[e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} - 1\right] - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} - I_{mp} \quad (18)$$

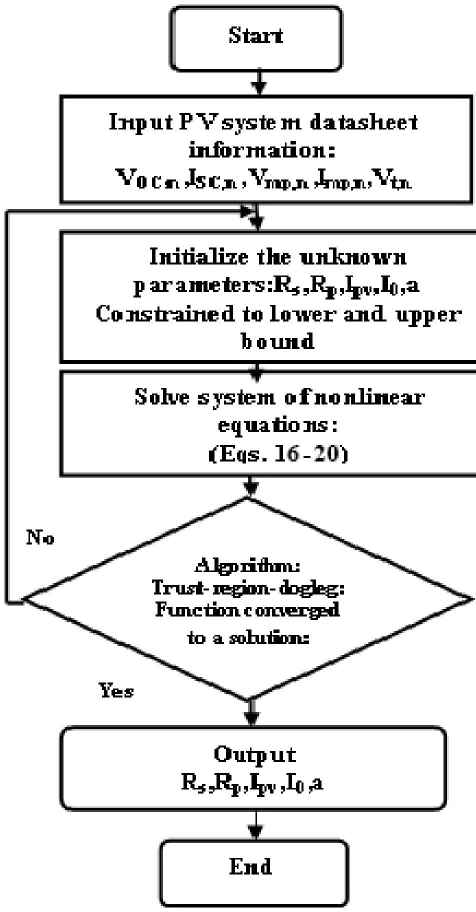

Fig. 3. Flowchart of NLS Method

$$f_4(x) = 0 = V_{mp}\left[\frac{\frac{I_o}{aV_t}e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} + \frac{1}{R_p}}{1 + \frac{R_s I_o}{aV_t}e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} + \frac{R_s}{R_{sh}}}\right] - I_{mp} \quad (19)$$

$$f_5(x) = 0 = \left[\frac{\frac{I_o}{aV_t}e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} + \frac{1}{R_{sh}}}{1 + \frac{R_s I_o}{aV_t}e^{\left(\frac{V_{mp}+I_{mp}R_s}{aV_t}\right)} + \frac{R_s}{R_{sh}}}\right] - \frac{1}{R_{sh}} \quad (20)$$

The above five objective functions are based on the system of non-linear equations corresponding to the short circuit, open circuit and MPP condition of photovoltaic module and other two equations. The minimization of objective function is obtained by fsolve command in MATLAB [3]. Trust region dogleg algorithm is used for the minimization. Lower and upper bound constrains are used to avoid anomalous results.

3.2.2. Limitations

NLS method may confine to local minima during minimization iterations and does not represent the actual parameters [3]. Furthermore, the appropriate choice of initial values is inevitable because rate of convergence and accuracy of algorithm depends on initialization [2].

3.2.3. Algorithm

Flowchart of Trust region dogleg algorithm based NLS's method is given in fig 3.

3.3. Lambert W-function based explicit solution

3.3.1. Description

The method presented in [7], [8] utilizes the symbolic expressions for solving R_s and R_{sh} of electrical model. Unlike iterative method, which uses mutually dependent non-linear equations for parameter extraction this method uses the two separate independent equations to approximate R_s and R_{sh} .Starting values of I_{ph} , a and I_o are given in Eq. (9-11)

$$I_{ph} = I_{sc} \tag{9}$$

$$a = \frac{K_v - \frac{V_{oc}}{T}}{V_t \cdot \left(\frac{K_i}{I_{ph}} - \frac{3}{T} - \frac{E_{gap}}{KT^2}\right)} \tag{10}$$

$$I_o = I_{ph} \cdot e^{\left(-\frac{V_{oc}}{aV_t}\right)} \tag{11}$$

Based on the change of variable

$$x = \frac{V_{mp} + R_s \cdot I_{mp}}{aV_t} \tag{12}$$

The above equation allows to write series and shunt resistance as

$$R_s = \frac{xaV_t - V_{mp}}{I_{mp}} \tag{13}$$

$$R_{sh} = \frac{V_{mp} + I_{mp}R_s}{I_{ph} - I_{mp} - I_o\left(e^{\frac{V_{mp} + I_{mp} \cdot R_s}{a \cdot V_t}} - 1\right)} \tag{14}$$

After few substitutions and approximations

$$x = W\left[\frac{V_{mp}(2I_{mp} - I_{ph})e^{\frac{V_{mp}(V_{mp} - 2V_t)}{a^2 V_t^2}}}{aV_t I_o}\right] + 2\frac{V_{mp}}{aV_t} - \frac{V_{mp}^2}{a^2 V_t^2} \tag{15}$$

Where W is the Lambert W-function whose value is computed by the algorithm proposed in the [9] which uses Halley's method and series approximations as initializations.
The value of x obtained from Eq. (15) is substituted in Eq. (12) and Eq. (13) to get values of series and shunt resistance.

3.3.2. Limitations

According to comparison presented in [7] it can be in inferred that the explicit solution based on lambert W-function is not accurate. Although the transcendental nature of Eq. 1 can be converted into explicit analytical expression by the use of lambert W-function but it increases the complexity e.g. : the use of CC function by Ortiz-Conde et al make the curve fitting multi-dimensional[10]

4. Proposed Method

The proposed method uses the same initialization procedure as adopted by Villalva. However, unlike Villalva's method which adjusts R_s and R_{sh} to match the $P_{mp,model}$=$P_{mp,curve}$ at MPP keeping diode ideality factor(a) constant [1], the proposed method adjusts R_{sh}, R_s and n simultaneously at MPP using two different differential Eq. (19) and Eq. (20) thus, providing more accurate results.

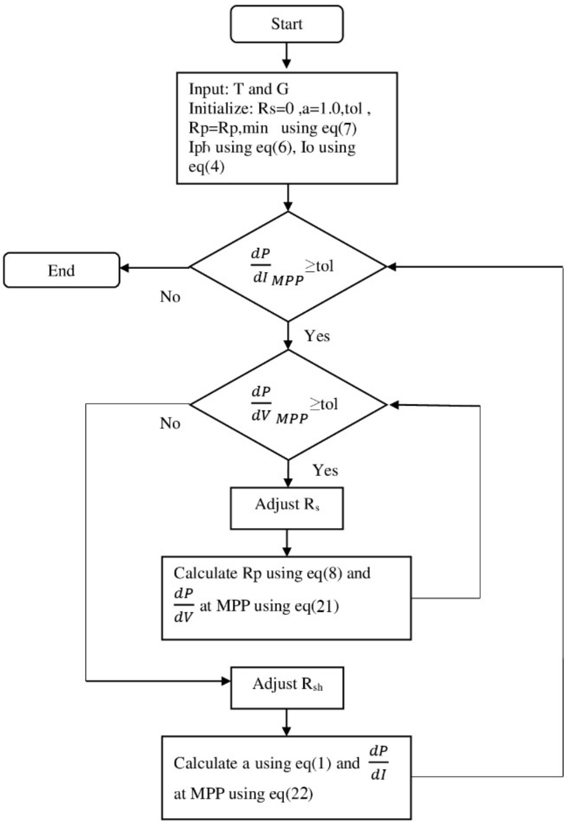

Fig. 4. Flowchart of Proposed Method

$$\frac{dP}{dV}_{MPP} = I_{mp} + V_{mp}\frac{dI}{dV} = 0 \quad (21)$$

$$\frac{dP}{dI}_{MPP} = V_{mp} + I_{mp}\frac{dV}{dI} = 0 \quad (22)$$

The Eq. (21) represents derivative of power with respect to voltage at MPP which is equal to zero. Similarly, another Eq. (22) is obtained by taking derivative of power with respect to current at MPP. It should be noted that according to the best knowledge of author, Eq. (22) does not occur in previous literature for any kind of iterative solution. The Eq. (22) replaces the equation usually used by researchers that is $\left[\left(\frac{dI}{dV}\right)_{Isc} = -1/(R_{sh})\right]$ .The Eq. (20) not only eliminates the dependency over shunt resistance for an iterative solution but also ease the technical complexity, excessive model parameters adjustment[11] which in turn increases the computational time and accuracy. Since the proposed method tends to adjust R_{sh}, R_s and n efficiently and simultaneously, it minimizes the error previously present in iterative and numerical methods. The flow chart of proposed method is given in Fig. 4.

5. Case Study

For case study KC200GT Panel is selected [12].The manufacturer provided parameters are provided in table I. A case study is conducted to compute five parameters of PV panel KC200GT from Kyocera solar using datasheet values at STC (parameters can also be evaluated under varying conditions by using open circuit and short circuit current coefficients listed in datasheet). The five parameters are extracted by each discussed method separately and are given in table 2.

Table 1. PARAMETERS OF THE KC200GT SOLAR ARRAY AT AIR MASS AM1.5, IRRADIANCE 1000W/m2, CELL TEMPERATURE 25 ◦C

I_{mp}	7.61A
V_{mp}	26.3V
$P_{mp,curve}$	200.143W
I_{sc}	8.21A
V_{oc}	32.9V
K_v	-0.1230V/K
K_i	0.0032V/K
N_s	54

Table 2. COMPARISON AMONG THE DIFFERENT ESTIMATION METHODS FOR MODULE KC200GT AT STC

Methods	Villalva Method	NLS Method	Lambert-W method	Proposed Method
Ideality Factor a	1.3	1.241	1.079	1.3029
Rs(m Ω)	138.7	198.4	236.8	229.0
Rsh(Ω)	466.0	599.9	204.0	587.01
Iph(A)	8.193	8.193	8.193	8.2133
Io(nA)	85.2	35.8	2.0	98.25
Percentage Error (%)	6.983e-04	2.729e-5	1.51e-2	4.79e-10

6. Conclusion

This paper have discussed the different popular methods present in literature and then compare the proposed methods with them. Unlike, other methods the proposed method does not require any guess value (such as *n* [1]).The proposed method is found more accurate than discussed method as comparison shown in table II. In addition to being accurate the proposed method is very simple and does not require any complex calculations. Furthermore, the proposed method uses a new differential equations based approach for numerically determining five parameters of a PV cell.

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