International Journal on Power Engineering and Energy (IJPEE) *Vol. (12) – No. (3)*
ISSN Print (2314 – 7318) and Online (2314 – 730X) *October 2021*

A PV Model Developed to Encompass Solar Irradiation and Ambient Temperature Levels

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Abstract. A PV single diode model with parameters derived from the manufacturer data at STC is developed and results were compared to published ones by the manufacturer. Thereafter the model parameters were extended to include the effect of changes in irradiation level and variation in temperature. Results are confirmed against published ones.

Keywords- PV model assumptions, PV model, parameter identification, maximum power point.

I. INTRODUCTION

Various types of solar photovoltaic (PV) installations require different model configurations and parameter values based on the manufacturing process. As the solar cell is basically a diode junction, its mathematical representation involves nonlinear elements. The difficulty in providing a reliable general model resides in the sensitivity of its parameters to the environmental operating conditions such as variations in solar irradiance, ambient temperature, sun shading effect, junction temperature, module angle of inclination, wind speed, air mass, etc….

Moreover, the data provided by the manufacturer do not directly relate to the adopted model parameters. This ambiguous situation has compelled the analyst to seek various pathways to dig for the identification of model parameters based on the published manufacturer's data given under STC specific operating conditions and also led him to make some assumptions and approximations for the purpose of reaching a manageable but reliable PV model [1].

In this work, the applicability of this model is extended to encompass variations in operating conditions other than STC.

II. THE SINGLE EXPONENTIAL PV MODEL AT STC

In the literature of modeling the PV solar cell, three basic models are encountered, namely the single diode model, the two-diode model and finally the three-diode model [2], [3], [4], [5]. The single-diode model is the most convenient for representing the PV cell [6], [7], [8], and will be adopted here altogether with all relevant assumptions and approximation made in the process of its derivation.

Due to the fact that the data provided by the manufacturer do not specify the values of the parameters of the PV model namely: [I_{ph}, I_o, R_s, R_{sh}, A], it becomes mandatory to adopt means to mathematically deduce the values of these parameters.

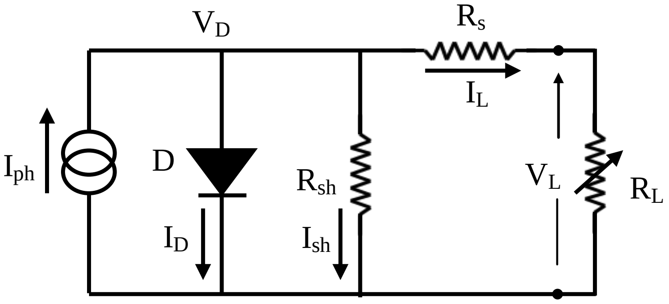


FIGURE (1): Circuit representation of the PV single diode model configuration for a solar cell.

Referring to the PV single-diode circuit model [9], [10] shown in Fig.(1) and applying Kirchhoff's law for current at node V_D yields the following relation:

$$I_L = I_{ph} - I_D - I_{sh} \tag{1}$$

The voltage / current relation in a diode is defined according to the Shockley equation [10]

for a single diode, $I_D = I_o(\exp\frac{V_D q}{AkT_{stc}} - 1)$

for a string of diodes, $I_D = I_o(\exp\frac{V_D}{n_s V_t} - 1)$ (2)

$$where, V_t = \frac{AkT_{stc}}{q} \tag{3}$$

I_D	Denotes the current generated by the diode in Amps.
V_D	Denotes the voltage across the diode in Volts.
I_o	Denotes the diode reverse current or dark current in Amps.
I_{ph}	Denotes the photon current due to solar irradiation in Amps.
V_{oc}	Denotes the open circuit voltage of the PV module in Volts.
V_t	Denotes the cell thermal voltage in Volts.
I_{sh}	Denotes the current flowing in the shunt resistance in Amps.
I_{sc}	Denotes the PV module current when its terminals are short circuited in Amps.

I_L	Denotes the load current in Amps.
V_L	Denotes the load terminal voltage in Volts
A	Denotes the cell ideality factor, for mono-crystalline cell $1 \leq A \leq 2$ [7].
q	Denotes the electron charge in Coulomb, q= $1.602\text{x}10^{-19}$.
k	Denotes the Boltzman's constant k=1.38×10^{-23}.
n_s	Denotes the number of PV series cells in the module
V_{PM}	Denotes the voltage at point of maximum power in Volts
I_{PM}	Denotes the current at maximum power in Amps.
STC	Denotes the standard testing condition at: irradiance G_{STC}=1000W/m^2, ambient temperature T_{STC} =25 °C, air mass AM=1.5, wind speed of 1m/s [9].
T_{STC}	Denotes the temperature at standard testing condition in °K.

III. DERIVING MODEL PARAMETERS FROM MANUFACTURER DATA

To deduce the values of the five unknown parameters corresponding to the PV single-diode model circuit, t*hree remarkable operating points* are applied to equation (1) and two particular system operating conditions will yield the following;

i- PV module terminals are short circuited ie. V_L=0

$$I_{sc} = I_{ph} - I_o(\exp\frac{I_{sc}R_s}{n_sV_t} - 1) - \frac{I_{sc}R_s}{R_{sh}} \qquad (5)$$

ii-PV module terminals are open circuited ie. V_L=0

$$0 = I_{ph} - I_o(\exp\frac{V_{oc}}{n_sV_t} - 1) - \frac{V_{oc}}{R_{sh}} \qquad (4)$$

iii-PV module operating at the point of maximum power, $(V_{LPm},\ I_{LPm})$

$$I_{pm} = I_{ph} - I_o(\exp\frac{V_{pm} + I_{pm}R_s}{n_sV_t} - 1) - \frac{V_{pm} + I_{pm}R_s}{R_{sh}} \qquad (6)$$

iv- at point of maximum power:,

$$\left.\frac{dP}{dV_L}\right|_{P_{\max}} = 0 = I_{pm} +$$

$$V_{pm}\frac{-(\frac{I_{sh}(R_{sh}+R_s)-V_{oc}}{n_sV_tR_{sh}})\exp(\frac{V_{pm}+I_{pm}R_s-V_{oc}}{n_sV_t})-\frac{1}{R_{sh}}}{1+(\frac{I_{sh}(R_{sh}+R_s)-V_{oc}}{n_sV_tR_{sh}})R_s\exp(\frac{V_{pm}+I_{pm}R_s-V_{oc}}{n_sV_t})+\frac{R_s}{R_{sh}}} \qquad (7)$$

v **–** at point of short circuit $\left.\frac{dI}{dV_L}\right|_{I=I_{sc}} = -\frac{1}{R_{sh}}$

$$\frac{-(\frac{I_{sc}(R_{sh}+R_s)-V_{oc}}{n_sV_tR_{sh}})\exp(\frac{I_{sc}R_s-V_{oc}}{n_sV_t})-\frac{1}{R_{sh}}}{1+(\frac{I_{sc}(R_{sh}+R_s)-V_{oc}}{n_sV_tR_{sh}})R_s\exp(\frac{I_{sc}R_s-V_{oc}}{n_sV_t})+\frac{R_s}{R_{sh}}} = -\frac{1}{R_{sh}} \qquad (8)$$

IV. DEDUCING PV MODEL PARAMETERS FROM MANUFACTURER DATA

The Siemens mono-crystalline PV solar module, SM50-H was selected. The detailed manufacturer data at STC are given in [12]. The iterative simultaneous solution of equations (4-8) is performed and yielded the values of the five model parameters, namely [R_s, R_{sh}, I_{ph}, I_o, A] at (STC). Appropriate initial values are to be carefully selected to ensure fast convergence of the iterative process. The flow chart of the computer program is given in appendix A. The computed values of the module parameters are given in table **I;**

Table I- Computed values of the model parameters

R_s	R_{sh}	A	V_t	I_0 in µA	I_{ph}	V_{oc}	I_{sc}
0.36	301.27	1.493	0.042	2.72	3.404	21.4	3.4

The calculated parameter values are to be introduced to the single diode model to finalize the PV representation. The computed maximum power is P_{max}=50.62W, which is conform to the module rating given by the manufacturer.

V. COMPUTING THE I/V CHARACTERISTICS FROM THE DEVELOPED PV MODEL

Solving the single diode model for load values of $0.5 \leq R_L \geq 11{,}330\ \Omega$ will reproduce the I/V characteristics of the photovoltaic module under STC. Program flow chart in use is given in appendix B. The results obtained are presented in fig.(2) and came in good agreement with the ones published by the manufacturer at STC.

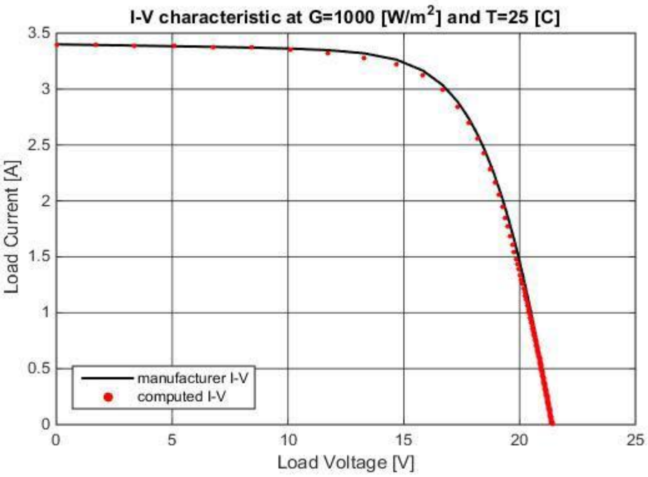


FIGURE (2): Results of computed I/V characteristics against manufacturer published results at STC.

VI. *EXTENDING THE PV MODEL TO CATER FOR ACTUAL CONDITIONS*

a- Implementation of the **assumptions** adopted in the literature of the PV modeling to cater for expected changes in the surrounding operating conditions are given hereafter:

- **i-**The value of the short circuit current is taken to equal to the photon current [13].
- **ii-**The dependence of the dark saturation current I_o on temperature changes is linear and is directly proportional with the irradiation [1].
- **iii-**The assumption that the coefficients of temperature for the current and voltage at maximum power $\alpha_{I_{pm}}$ and $\alpha_{V_{pm}}$ relates to the ones at short circuit current and open circuit voltage by $\alpha_{I_{sc}}$ and $\alpha_{V_{OC}}$ constants k_1 and k_2 respectively such that: $\alpha_{I_{sc}} = k_1\alpha_{I_{pm}}$ and $\alpha_{V_{OC}} = k_2\alpha_{V_{PM}}$, where [1] implies the following: $\alpha_{I_{sc}} \cong 0.8\alpha_{I_{pm}}$ and $\alpha_{V_{OC}} \cong 0.8\alpha_{V_{PM}}$
- **iv-**The assumption of considering the cell series and shunt resistances to be constant over the range of variation in operating conditions [1], thus ignoring the dependency of R_s and R_{sh} on the valuesof irradiation G_{act} and ambient temperature T_{amb}.
- **v-**The effect of the linear superposition of both the diffusion and recombination current effects in the space charge layer is included in a single ideality factor A. Another approach resides in splitting these two effects through modeling them by two Shockley diodes [13], connected in parallel yielding to the double exponential model configuration and resulting in two non-ideality factor A_1 for the diffusion current and the non-ideality factor A_2 for the recombination current representation. This model is sometimes referred to as the seven parameters model. The advantage of this model is that it provides better accuracy at lower irradiating levels [10].
- **vi-**The inclusion of the effect of the grain boundaries and leakage current usually is associated with the representation of the polycrystalline Si- solar cells model [9], which necessitates the presence of a third diode thus yielding to the three-diode PV model.

b- Implementation of the **approximations** adopted in the literature of the PV modules are given hereafter:

i- Regarding the value of the exponential term $(\exp\frac{V_D q}{kT})$ in equation (2) to be much greater than unity[2], thus reducing equation (2) to: $I_D = I_o \exp(\frac{V_D}{n_s V_t})$

ii- Neglecting the value of the exponential term $(\exp\frac{I_{sc}R_s}{n_s V_t})$ compared with the value exponential term $(\exp\frac{V_{oc}}{n_s V_t})$, when reformulating equation (8).

VII. *IMPLEMENTATION OF THE ACTUAL OPERATING CONDITIONS IN THE PV MODEL*

Under any condition other than the STC, rescaling of the manufacturer parameters of the PV module must be effected. The major factors affecting these parameters are the irradiation level (G_{act}) and cell temperature (T_c) and are performed in accordance to the transformations adopted in the literature [14].

i-Short circuit current as function of G_{act} and T, namely $I_{sc}(G_{act},T_c)$

$$I_{sc}(G_{act},T_c) = I_{sc}^0 \frac{G_{act}}{G^0}[1+\alpha_{I_{sc}}(T_c - T_c^0)] \qquad (9)$$

ii-Output current at maximum power as function of G_{act} and T_c , $I_{pm}(G,T_c)$

$$I_{pm}(G_{act},T_c) = I_{pm}^0 \frac{G_{act}}{G^0}[1+\alpha_{I_{pm}}(T_c - T_c^0)] \qquad (10)$$

iii-Open circuit voltage as function of G_{act} and T_c $V_{oc}(G_{act},T_c)$

$$V_{oc}(G_{act},T_c) = V_{oc}^o + \alpha_{V_{oc}}(T_c - T_c^o) + V_t \ln(\frac{G_{act}}{G^o}) \qquad (11)$$

iv-Output voltage at maximum power as function of G_{act} and T_c $V_{pm}(G_{act},T_c)$

$$V_{pm}(G_{act},T_c) = V_{pm}^o + \alpha_{V_{pm}}(T_c - T_c^o) + V_t^o \ln(\frac{G_{act}}{G^o}) \qquad (12)$$

The superscript ^{0} denotes the value of the corresponding variable at STC.

Substituting in equations (4-8) with the modified parameter values of G_{act} and T_{amb} yielding new values of the model parameters $I_{sc}(G_{act},T_c)$, $I_{pm}(G_{act},T_c)$, $V_{oc}(G_{act},T_c)$, $V_{pm}(G_{act},T_c)$. This process must precede the application of the iterative solution to the equations (6, 7, 8, 9 and 10).

The transformation of cell temperature (T_c) from NOCT base to the STC base is given according to the relation [13]

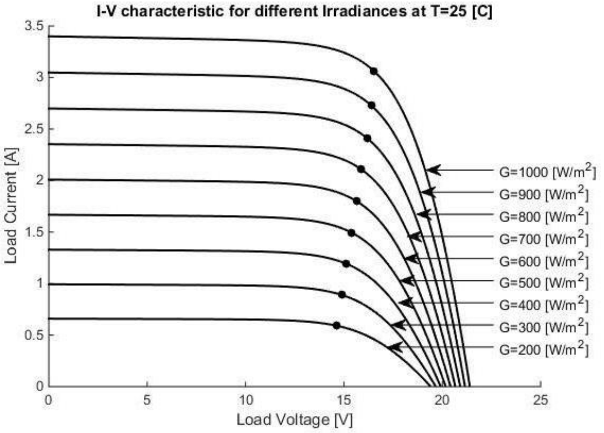
$$T_c = T_{amb} + (NOTC - 20)\frac{G_{act}}{800}$$

where, T_c Denotes the actual cell temperature in °C.

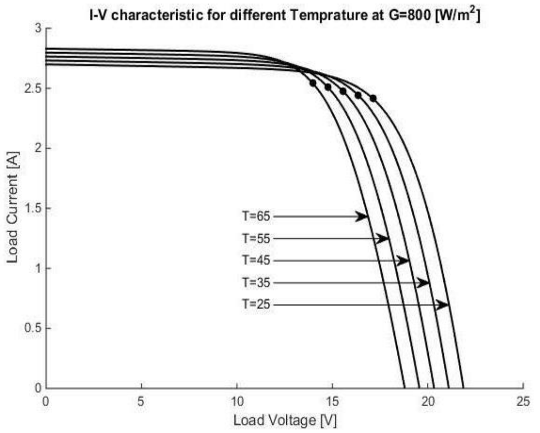
NOCT Denotes the normal operating condition temperature which is taken at an irradiance level of 800W/m^2 and ambient temperature of 20°C.

VIII. RESULTS OF THE EXTENDED PV MODEL

The routine previously adopted in sec(iv) and sec (v) is to be repeated for different values of operating conditions of solar irradiation in the range of 200–1000W/m^2 and ambient temperature levels in the range of 25-65°C .



(a) I/V characteristics at constant temperature

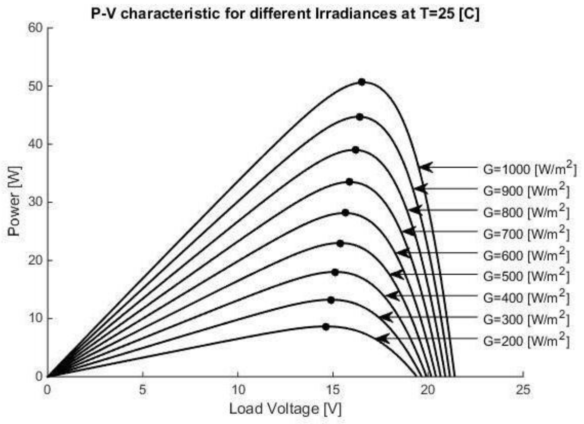


(b) I/V characteristics at constant irradiation

FIGURE4. I/V characteristics computed under various operating conditions

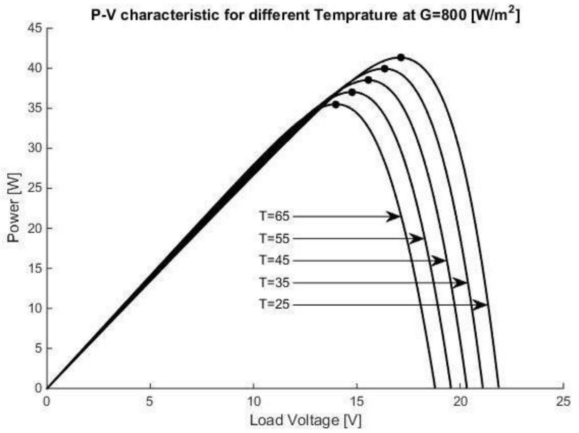
The results displayed in fig(4.a) shows the variation of the PV I/V characteristics due to changes in solar irradiation levels at constant ambient temperature thus confirming the validity of the program. The I/V characteristics shown in fig. (4.b) relates to the changes in the ambient temperature while the solar irradiation is kept constant at 800W/m^2 . In fig. (5.a) and fig. (5.b) the variations in load power versus load voltage under constant temperature and constant irradiation respectively is shown and the points of maximum power is highlighted pointing at the locus of the maximum power point

(d)



(a) P/V characteristics at constant temperature

(c)



(b) P/V characteristics at constant irradiation

FIGURE5. P/V characteristics computed under various operating conditions

IX. CONCLUSION

In this work the single diode model adopted in computing PV , I/V characteristics is developed with parameters derived from the manufacturer data at STC. The results obtained from the analytical study were compared against the manufacturer published ones. These results came in good agreement over most of the variations in I/V characteristics in the zones of constant current and constant voltage, yet some discrepancy appears in the neighborhood of the maximum power operation zone. This observation can primarily be attributed to the pronounced sensitivity of the PV system parameters to the surrounding operating conditions. Although the magnitude of this discrepancy is relatively small, yet it points out to the fact that certain assumptions made are not entirely valid over the expected range of PV module operation.

Consequently further investigations to the assumptions and approximations adopted are to be carried out in order to minimize this discrepancy as it falls in the zone of great interest to the photovoltaic system efficiency namely the point of maximum power point operation (MPPO) [15].

The model parameters were extended to cope with various operating conditions of solar irradiance and ambient temperature levels. Referring to the results of the study presented in fig. (4) and fig. (5), it can be concluded that the effect of irradiation over the point of maximum power is more pronounced than the that of the ambiant temperature.

X. REFERENCES

1.H. Tian, F. D. Mancilla, K. Ellis, P. Jenkins and E. Muljadi, " *A detailed performance model for photovoltaic systems*'', National Renewable Energy Laboratory NREL/JA-5500-54601, July 2012.
2. Y. Chaibi, M. Salhi, A. El-jouni and A. Essadki, "*A New method to extract the equivalent circuit parameters of a photovoltaic panel*", Solar Energy 163 (2018), pp. 376-386.
3. S. Vergura, "*A complete and simplified datasheet-based model of PV cells in variable environmental conditions for circuit simulation*'', MDPI, Energies 2016, 9, 326, April 2016.
4. A. Ahmad and F. Rahman, "*Modeling and simulation of solar photovoltaic system*'', International Journal of Advance Research in Science and Engineering (IJARSE), vol. 3, issue No. 7, July 2014, pp. 124-135.
5. D. Sera, R. Teodorescu and P. Rodriguez, "*PV panel model based on datasheet values*'', Industrial Electronics, 2007, ISIE 2007. IEEE International, July 2007, DOI: 10.1109/ISIE. 2007.4374981 .
6. T. Ahmad, S. Sobhan and F. Nayan, "*Comparative analysis between single-diode and double-diode model of PV cell: concentrated on different parameters effect on its efficiency*'', Journal of Power and Energy Engineering, 2016, 4, pp. 31-46.
7. N. M. Shannan, N. Z. Yahaya and B. Singh, "*Single-diode model and two-diode model of PV modules: A Comparison*'', IEEE International Conference on Control System, Computing and Engineering,, 29 Nov.-1 Dec 2013, Penang, Malysia, pp. 210-214.
8. J. P. Charles, I. Mekkaoui- Alaouui , G. Bordure and P. Mialhe, "*A critical study of the effectiveness of the single and double exponential models for I-V characterization of solar cells*'', Solid-State Electronics, Vol. 28, No. 8, 1985, pp. 807-820.
9. S. A. Mahmoud, M. M. Alsari and R. M. Alhammadi, "*MATLAB modeling and simulation of photovoltaic modules*", IEEE 55th International Midwest Symposium on Circuits and Systems (MWSCAS), 5-8 Aug. 2012,10.1109/MWSCAS.2012.6292138.
10. N. Aoun, R. Chenni, B. Nahman and K. Bouchouicha, '' *Evaluation and validation of equivalent five- parameter model performance for photovoltaic panels using only reference data*'', Energy and Power Engineering, August 2014, 6, pp. 235-245.
11. S. Kasap, "*pn Junction the Shockley model*'', (S. O. Kasap, 1990-2001), A e Booklet.
12. SIEMENS solar module ,SM50-H, SIEMENS PV. pdf.
13. N.Veissid, "*The I-V silicon solar cell characteristic parameters temperature dependence. An experimental study using the standard deviation method*", 10th European Photovoltaic Solar Energy Conference, April 1991, Lisbon, Portugal, pp. 43-47.
14. S. B. Dongue, D. Njomo and L. Ebngai, "*A new strategy for accurately predicting I-V electrical characteristics of PV modules using a nonlinear five-point model*", Journal of Energy, vol. 2013, article ID 321694.
15. A. Driesse, S. Harrison and P. Jain, *''Evaluating the effectiveness of maximum power point tracking methods in photovoltaic power systems using array performance models''*, IEEE, 2017, pp. 145-150.

XI. APPENDICES

Appendix A

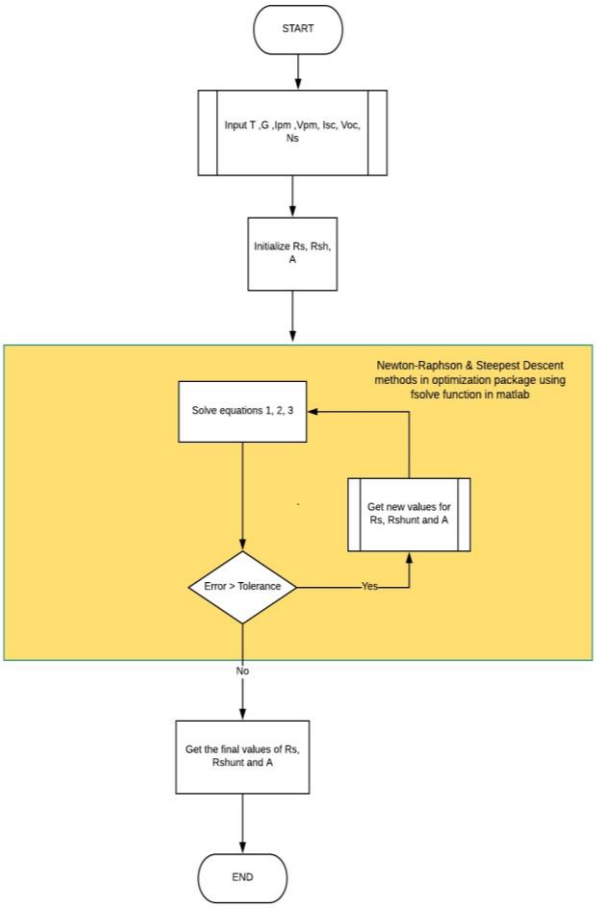


Fig. (a) Flow chart for computing model parameters

Appendix B

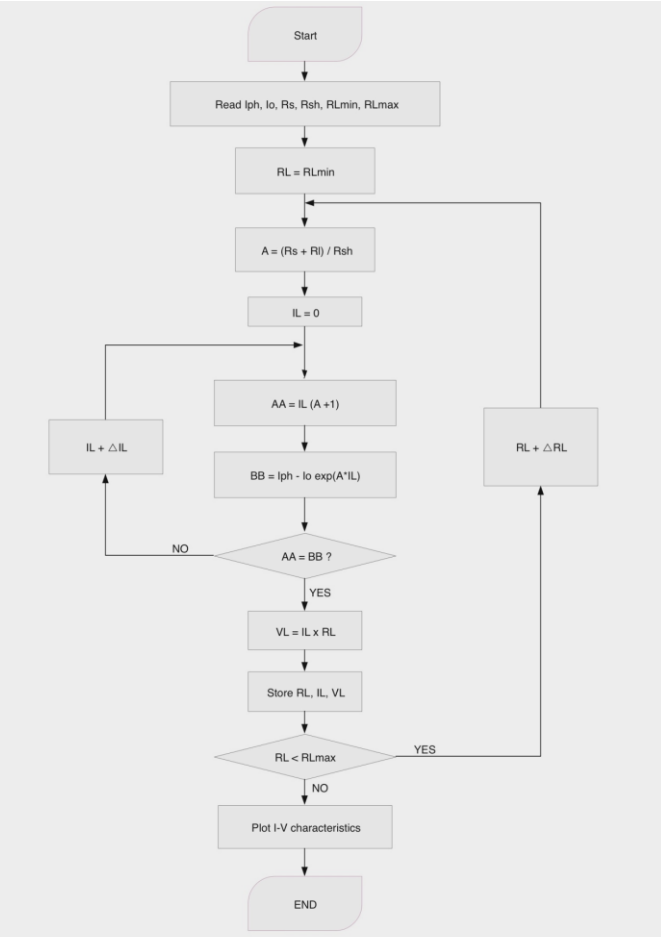


Fig. (b) Flow chart for computing PV I/V characteristics