

SIMULATION AND VALIDATION OF THE PERFORMANCE OF A POLYCRYSTALLINE PHOTOVOLTAIC MODULE

*²Abdullahi Usman, ¹Abubakar Muhammad Sani, ¹Shuaibu Alhassan

¹Department of Physics, Kaduna State University, Tafawa Balewa Way, Kaduna, Nigeria

²Department of Physics, Kaduna State College of Education, Gidan-Waya, Kafanchan

*Corresponding Author Email Address: usmabd4@gmail.com

Phone: +23408061573157

ABSTRACT

The performance of a solar module is described by its Current-Voltage (I-V) and Power-Voltage (P-V) curves, it is therefore necessary to generate these curves in order to validate the parameters of the module namely Short Circuit Current, Open Circuit Voltage, Maximum Power, Current and Voltage at Maximum Power Points, Fill Factor, and Efficiency. This study highlights two methods of generating I-V and P-V curves from a 30W sunshine (AP-PM-30) module. The methods include a computer simulation using MATLAB/Simulink software and an experimental procedure at different values of Irradiance and cell temperature. Findings from this study show that an increase in irradiance at constant cell temperature of the solar module results to significant increase in the current produced but slight increase in voltage. Consequently, the power output of the solar module also increases, while increase in cell temperature at constant irradiance decreases the voltage but slightly increases the current produced by the module but power output decreases. Therefore, these explain the influence of irradiance and cell temperature on the performance of a photovoltaic module.

Keywords: Irradiance; Cell Temperature; I-V and P-V characteristic curves; Photovoltaic module; MATLAB/Simulink.

INTRODUCTION

Solar energy from the sun has always been a source of light and heat which the earth depends on. Similarly, terrestrial life need sun to survive and also to achieve their means of livelihood. In recent times the electromagnetic waves from the sun have been discovered not just to provide light and heat but also to generate electricity to meet the energy demands of the people (Maka & Alabid, 2022). The abundance of solar energy has made it the most sought after of all available renewable energy sources such as hydro, wind, geothermal and biomass available for electricity generation.

The transformation of the solar energy from the sun into electricity when its irradiance reaches the earth surface is done using photovoltaic modules (made up of silicon, germanium or other suitable materials) and heliothermic which generates electricity through heating of a fluid and functions similarly as a conventional thermoelectric plant (Reis et al., 2017). Photovoltaic has become the mostly used amongst the two due to its convenience, therefore, photovoltaic modules have become very popular in both rural and urban settlements. As a result of this, the efficiency of the photovoltaic modules is crucial in order to meet the energy demands of the users; the efficiency of the module is the ratio of the useful electrical energy produced by the module to the solar energy incident on it at standard test condition, and this depends on the cell temperatures, energy conversion efficiency and

Maximum Power Point Tracking (Dinçer & Meral, 2010). A single photovoltaic cell is made of two or more thin layers of a semiconductor (absorber) such as silicon, germanium or any other suitable materials. When the cell is exposed to sunlight, the sunlight is absorbed in the absorber part of the cell. If the energy of the photon is equal to the energy band gap of the semiconductor, then electrons get enough energy to break loose from their atoms. This process causes electric potential difference across the cell. Therefore, direct current (DC) begins to flow in the material to terminate the potential difference. But if the energy of the photon is less than the energy band gap of the semiconductor, they do not generate voltage or electric current. Photons with energies greater or equal to the band gap generate electricity. However, only the photons with energies equal to the band gap are used. (Azzouzi & Stork, 2014).

Figure 1 shows the general current-voltage (I-V) and power-voltage (P-V) characteristic curves of a solar cell at a given solar irradiance G and a fixed cell temperature T_c (Pukhrem, 2013). The I-V and P-V characteristic curves describe the behaviour of a solar cell. This study presents an experimental method for generating the curves.

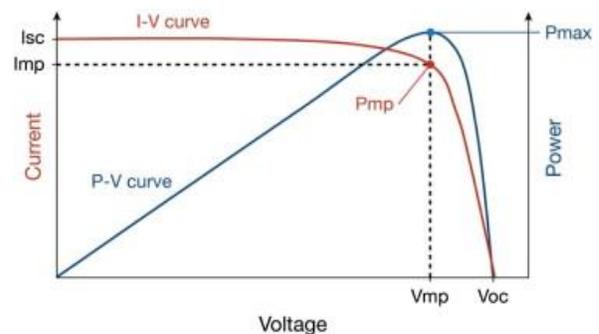


Figure 1: I-V and P-V curves for a Solar Cell

A photovoltaic cell can be characterized by the following basic parameters.

- a. **Short Circuit Current (I_{sc}):** This is the maximum amount of current produced by the solar cell due to the radiation from the sun. It is the current through the solar cell when the cell is short circuited (i.e when voltage is zero) or when the terminals of the cells are externally connected with zero resistance (Honsberg & Bowden, 1999).

$$I \text{ (at } V = 0) = I_{sc} \quad (1)$$

The short circuit current and the photocurrent are the same parameters

$$I_{sc} = I_{ph} \quad (2)$$

- b. **Open Circuit Voltage (V_{oc}):** This is the maximum amount of voltage produced by the solar cell when current is zero. The two terminals of the solar cell are externally disconnected and the resistance $R = \infty$ (Robbins, 2021).

$$V(\text{at } I = 0) = V_{oc} \quad (3)$$

- c. **Maximum Power Point (P_{mp}):** The power of a solar cell is produced from the product of the voltage and current in the circuit (Miller, 2010).

$$P = IV \quad (4)$$

The maximum power point is therefore obtained when the product of the voltage and current are at maximum values due to a wide range of voltages and currents produced from an increasing resistive load using a potentiometer.

$$P_{mp} = I_{mp} V_{mp} \quad (5)$$

The current and voltages at maximum values are known as the Current and Voltage at Maximum Power Points (I_{mp} & V_{mp}).

- d. **Solar Cell Efficiency (η):** The most important parameter of the solar cell is its energy conversion efficiency which is the percentage at which solar energy is converted into usable electricity. It is basically used to compare the performance a solar cell with another. The efficiency of the solar is defined by ratio of the energy output of the solar cell to the input energy from the sun. It depends on the spectrum and irradiance of the sun G and the solar cell temperature T_c . The solar cell efficiency is calculated by the formula in equation 6 (Zekry et al, 2018)

$$\eta = \frac{P_{mp}}{P_{in}} \times 100 = \frac{V_{mp} I_{mp}}{AG} \times 100 \quad (6)$$

Where P_{in} is the incident solar power,
 A =Area of the solar module

G =Solar Irradiance at Standard Test Condition (STC)

- f. **Fill factor (FF):** Fill factor is a measure of the quality of the module. As FF increases, the efficiency of the module also increases. It can be increased by reducing I_s and R_s and increasing R_{sh} . However FF decreases as the cell temperature increases. The fill factor can be obtained by the formula shown in equation 7 (Zekry et al, 2018)

$$FF = \frac{P_{mp}}{P_{Th}} = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}} \quad (7)$$

Where P_{Th} is the theoretical power (product of V_{oc} and I_{sc}).

The irradiance from the sun is an environmental factor that influences the performance of a PV module, its effect on the power output of the PV module is almost linear and can be approximated by the function below as shown in equation 8 (Louwen et al, 2017).

$$P_{mp} = G \frac{P}{1000W/m^2} \quad (8)$$

Where P_{mp} and P are measured and STC rated maximum power output respectively and G is the in-plane irradiance.

The STC for irradiance is $1000W/m^2$ at $25^\circ C$. Most information provided by manufacturers of PV modules is given at STC. However, PV module performance can be obtained under real operating conditions. The irradiance from the sun varies depending on the time and weather of the day. At varying irradiance and fixed temperature, the short circuit current produced by PV module increases significantly with slight increase in the open circuit voltage V_{oc} .

The cell temperature is another environmental factor that influences the performance of the of the PV module. The cell temperature varies due to the change in ambient temperature and also the change in solar radiation. The cell temperature can be estimated using the expression (equation 9) as defined by Masters (2004)

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{800} \right) \cdot G \quad (9)$$

Where T_{cell} is cell temperature ($^\circ C$), T_{amb} is ambient temperature, and G is solar irradiance (W/m^2).

The NOCT in the equation above stands for nominal operating cell temperature which is an indicator provided by manufacturers to help system designers account for changes in cell performance with temperature. This is because only a small fraction of the irradiance on the module is converted to electricity while most of the incident solar energy is absorbed and converted to heat. The NOCT is cell temperature in a module when ambient is $20^\circ C$, solar irradiation is $800 W/m^2$, and windspeed is $1 m/s$. At fixed irradiance and varying temperature, the open circuit voltage V_{oc} of the module drops significantly while short circuit current I_{sc} increases slightly.

The manufacturers of PV modules often provide some of the modules' electrical characteristics namely the short circuit current I_{sc} , open circuit voltage V_{oc} , voltage and current at maximum power point (V_{mp} & I_{mp}) and maximum power output (P_{mp}) of the module.

When exposed to sunlight, the photovoltaic cell which is a simple P-N junction semiconductor absorbs photons and thereby generates charge carriers which are separated by the P-N junction electric field and results to flow of electric current I through the circuit. The current produced varies proportionally to the irradiance incident on module at the point in time (Ma et al, 2013). The PV cell model has been the basis for describing the behaviour of the PV cell, the most widely used is the single diode model shown in figure 2 (Jain & Kapoor, 2003).

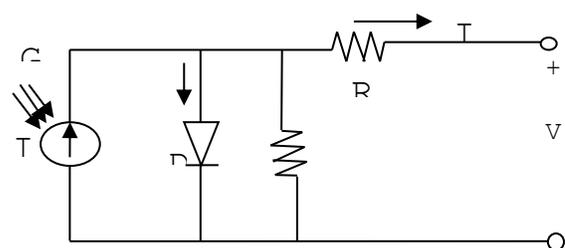


Figure 2: Practical single diode model

The current and voltage outputs of the module's terminal are related by the implicit transcendental equation as follows

$$I = I_{ph} - I_0 \left(\exp \left(\frac{V + IR_s}{nN_s V_t} \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (10)$$

Where $V_t = \frac{kT}{q} = 25.7mV$ at $25^\circ C$

This model has five parameters namely photocurrent I_{ph} , reverse saturation current I_o , ideality diode factor n , shunt and series resistance R_{sh} and R_s respectively (Ibrahim & Anani, 2017; Nguyen & Nguyen, 2015).

MATERIALS AND METHODOLOGY

The materials used to carry out the study are as follows:

1. A 30 Watts sunshine polycrystalline solar module
2. A solar I-V Data capturing device
3. A data logging solar meter
4. A computer system with MATLAB/Simulink and PLX DAQ for Ms Excel

The experimental method was carried out using the materials mentioned above to obtain the I-V and P-V characteristic curves by making observations under the sun with the solar module. The parameters obtained from this method are Photocurrent I_{ph} , Open Circuit Voltage V_{oc} , Current and Voltage at maximum power points (I_{mp} & V_{mp}), Maximum power point P_{mp} , Fill Factor FF and solar cell energy conversion efficiency η .

The software used for the experiment is PLX DAQ in Microsoft Excel which enables data collection and analysis as the experiment is being carried out, while the MATLAB/Simulink was used for simulation.

The image below is the experimental setup carried out in the premises of Kaduna State University, Nigeria.



Figure 3: Experimental setup

Using the above experimental setup as shown in figure 1 the following steps were followed to carry out the experiment.

1. The solar module was connected to the Solar I-V Data Capture device which was connected to the computer using two USB cables (black and blue).
2. The black USB cable was connected to the computer, from the device manager of the computer the com port was taken note of e.g. COM 8 which was used to transmit logging values to excel spread sheet.

3. The blue USB was also connected to the computer to power the digital potentiometer.
4. The solar power was connected to the port on the device
5. The device made 4 beeps when the black cable was connected indicating that the device has booted up.
6. The I-V characteristics curve of the solar module was obtained by varying the potentiometer manually.
7. The excel spread sheet file "Solar-Panel logger" was opened and the "Click to log Data button" on the G1 cell was selected to display data from the solar module.
8. The appropriate com port obtained from device manager was inputted on the PLX DAQ dialog box and the "Connect button" was clicked to start the logging process.
9. The potentiometer of the I-V data capture device was used to vary the resistance each time the system made a beep indicating that a value has been logged or obtained.
10. The input logging delay was set to be 500 milliseconds.
11. The temperature of the solar module was measured using the temperature sensor which was placed behind the module.
12. The disconnect button was clicked to stop the logging process when finished
13. The values were logged automatically on the spread sheet workbook, and the graphs were plotted.

The I-V and P-V curves of the photovoltaic module can be generated using computer software such as MATLAB/Simulink from equation (1) above.

The Simulink block representation of equation (1) is shown in the figure (2) below; it is done at STC which produces the parameters given by the manufacturer.

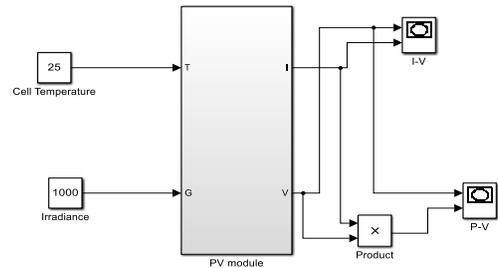


Figure 4: Simulink block representation of the PV module.

RESULTS AND DISCUSSION

The results of the experiments carried out under the sun at different conditions of irradiance and cell temperature are as follows.

Table 1: shows the amount of irradiance and cell temperature measured during the course of the experiments.

Experiments	Measured Irradiance (W/m ²)	Measured Cell Temperature (K)
Experiment 1	153	303
Experiment 2	549	309
Experiment 3	638	313
Experiment 4	712	315

The figures below show the I-V and P-V characteristic curves of the

module obtained from the experiments.

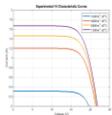
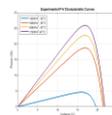


Figure 5: (a) I-V characteristic curves

Figure 5 (a) shows the I-V curves of the four different experiments carried out at different irradiance and cell temperature. The I-V curves show significant increase in the short circuit current I_{sc} and a slight increase in open circuit voltage V_{oc} as irradiance and cell temperature increases. At the knees of the curves are the currents



(b) P-V characteristic curves and voltages at maximum points (I_{mp} & V_{mp}).

Figure 5 (b) shows the P-V curves of these experiments carried out, the curves show a significant increase in maximum power outputs P_{mp} at the peak of the curves as a result of the product of the currents and voltages at maximum points (I_{mp} & V_{mp}).

Table 2: shows the result of the experiments carried out

Experiments	Measured Irradiance (W/m^2)	Measured Temperature (K)	Cell	$V_{oc}(V)$	$I_{sc}(A)$	$P_{mp}(W)$	Fill Factor	Efficiency (%)
Experiment 1	153	303		19.60	0.31	4.61	0.76	15.45
Experiment 2	549	309		21.40	1.25	18.76	0.70	17.51
Experiment 3	638	313		21.60	1.46	22.77	0.72	18.30
Experiment 4	712	315		21.80	1.67	25.91	0.71	19.54

The figures below are the I-V and P-V characteristic curves of the module from the Simulink block representation at STC.

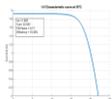
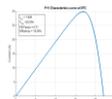


Figure 6: (a) I-V characteristic curve



(b) P-V characteristic curve

Table 3: shows the results from the curves

Parameters	Value
Short Circuit Current I_{sc}	1.92A
Open Circuit Voltage V_{oc}	22.05V
Current at Maximum Power Point I_{mp}	1.71A
Voltage at Maximum Power Point V_{mp}	17.5V
Maximum Power Output	30W

The values of the parameters above have good agreements with the information provided by the manufacturer as shown in Table 4.

Parameters	Value
Short Circuit Current I_{sc}	1.92A
Open Circuit Voltage V_{oc}	22.05V
Current at Maximum Power Point I_{mp}	1.71A
Voltage at Maximum Power Point V_{mp}	17.5V
Maximum Power Output	30W

At different irradiance the I-V and P-V characteristic curves exhibit the behaviours below

a

b

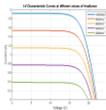
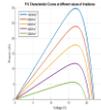


Figure 7: (a) I-V Characteristic Curves



(b) P-V Characteristic Curves

The irradiance is been varied from $200W/m^2$ to $1000W/m^2$ at constant temperature of $25^\circ C$. At different values of cell temperature, the module exhibits the following behaviours.

a

b

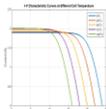
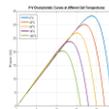


Figure 8: (a) I-V characteristic curves



(b) P-V characteristic curves

The best comparison of the model is done by comparing with the experiment observed. This was done by plotting the difference of the maximum power output ($P_S - P_E$) of the simulation and

experimental results against their Voltages V and also calculating their Root Mean Square Error (RMSE) as shown in figure 9.

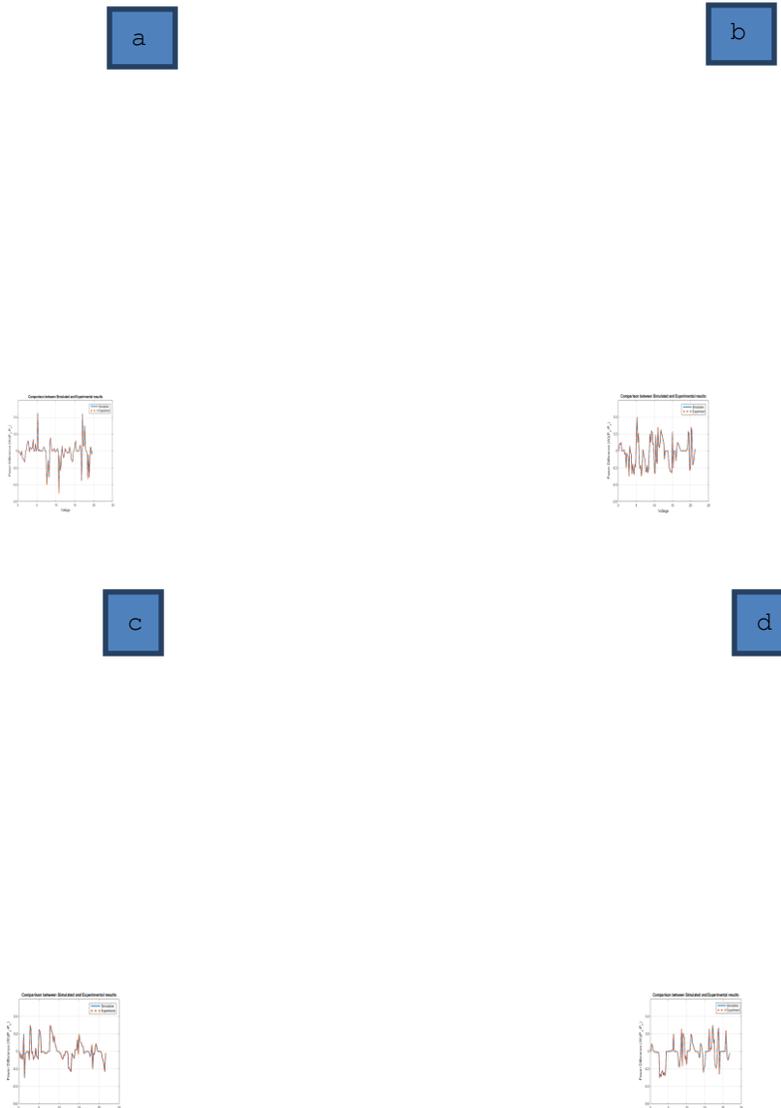


Figure 9: (a)-(d) Comparison between the simulation and experimental results

Conclusion

The graphs shown above depict excellent agreement between the model and the experimental observations. The average Root Mean Square Error (RMSE) of all experiments is 0.13 which is known as the measure of uncertainty.

Solar energy has a great potential across the globe and Nigeria in particular, harnessing this potential will contribute to solving the energy problems. Abundant sunlight and the non-pollutant nature of the solar module is what makes it a better choice of alternative source of energy worldwide.

The short current circuit I_{sc} produced by the different experiments are 0.31A, 1.25A, 1.46A and 1.67A respectively, while the open circuit voltage V_{oc} are 19.60V, 21.40V, 21.60V and 21.80V the fourth experiment has the maximum current and voltage and consequently has the maximum power output as a result of the product between the current and voltage outputs of the module.

The power outputs for the experiment are 4.61W, 18.76W, 22.77W and 25.91W respectively. The fill factor for the module is approximately 0.7 and the solar cell energy conversion efficiencies for each experiment carried out are 15.45%, 17.51%, 18.30% and 19.54%. The fourth experiment has the maximum solar cell efficiency.

Results from the experiments is due to the irradiance and cell temperature of the module which are the two main factors influencing the behaviour of a solar module, it was found that an increase in irradiance and cell temperature increases the current produced by the module significantly and the voltage slightly. The experiment 1 with the lowest irradiance and cell temperature has the lowest short circuit current I_{sc} , the lowest open circuit voltage V_{oc} and consequently has the lowest power output P_{mp} while experiment 4 with the highest irradiance and cell temperature has the highest short circuit current I_{sc} , open circuit voltage V_{oc} and

consequently with the highest power output P_{mp} . Therefore, current generated from this module can be used to solve some energy problems. The amount of sunlight in Nigeria can be used to generate electricity that will meet the needs of the populace for their work, businesses and leisure etc.

REFERENCES

- Azzouzi, M., & Stork, M., (2014). *Modeling and Simulation of a photovoltaic cell considering single diode model* International Journal of Research in Engineering & Technology (IMPACT:IJRET) ISSN(E):2321-8843; ISSN(P):2347-4599. Vol. 2, Issue 11, Nov 2014, 19-28 ©Impact Journals
- Dinçer, F., Meral E. M. (2010). *Critical Factors that Affecting Efficiency of Solar Cells Smart Grid and Renewable Energy*, 2010, 1, 47-50 doi:10.4236/sgre.2010.11007 Published Online May 2010 (<http://www.SciRP.org/journal/sgre>) Copyright © 2010 SciRes. SGRE University of Yuzuncu Yil, Department of Electrical and Electronics Engineering, Van, Turkey.
- Honsberg, C., & Bowden, S. (1999). *Photovoltaics : [devices, systems & applications]. Part 1, Photovoltaic devices* Published by [S.I.] : The University of New South Wales Photovoltaics Centre, cop. 1999.
- Ibrahim, H., Anani, N. (2017). *Variations of PV module parameters with irradiance and temperature*. 9th International Conference on Sustainability in Energy and Buildings, SEB-17, 5-7 July 2017, Chania, Crete, Greece
- Jain, A., Kapoor, A. (2003). *Exact analytical solutions of the parameters of real solar cells using Lambert W-function*. Solar Energy Materials & Solar Cells 81 (2004) 269–277. Available online at www.sciencedirect.com.
- Louwen, A., de Waal, A. C., Schropp, R. E. I., Faaij A. P. C., and van Sark, W. G. J. H. M.,(2017) *Comprehensive characterisation and analysis of PV module performance under real operating conditions*. Progress In Photovoltaics: Research And Applications Prog. Photovolt:Res.Appl. 2017; 25:218–232 Published online 8 December 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2848
- Ma, J., Man, K. L., Ting, T. O., Zhang, N., Guan, S-U., and Wong, P. W. H. (2013). *Approximate Single-Diode Photovoltaic Model for Efficient I-V Characteristics Estimation*. Hindawi Publishing Corporation The Scientific World Journal Volume 2013, Article ID 230471, 7 pages <http://dx.doi.org/10.1155/2013/230471>
- Maka A. O.M., & Alabid J. M., (2022) *Solar Energy Technology And Its Roles In Sustainable Development* Clean Energy, 2022, 6, 476–483 <https://doi.org/10.1093/ce/zkac023> Advance access publication 11 June 2022 Perspective
- Masters G. M., (2004) *Renewable and Efficient Electric Power Systems* pp 476 Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
- Nguyen. X. H., and Nguyen, M. P., (2015) *Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink*. Environmental System Research a spring open journal. (2015) 4:24 DOI 10.1186/s40068-015-0047-9
- Miller, M (2010) *Maximum Power from a Solar Panel* Undergraduate Journal of Mathematical Modeling : One + Two doi - 10.5038/2326-3652.3.1.22
- Pukhrem, S. (2013). *A Photovoltaic Panel Model in MATLAB/Simulink Program* Renewable Energy System Wroclaw University of Technology, 27 Wybrzeże Wyspiańskiego St., 50-370 Wroclaw, Poland doi 10.13140/rg.2.1.2628.4645
- Reis, L. R. D., Camacho, J. R., Novacki D. F. (2017). *The Newton Raphson Method in the Extraction of Parameters of PV Modules* International Conference on Renewable Energies and Power Quality (ICREPQ'17) Malaga (Spain), 4th to 6th April, 2017 Renewable Energy and Power Quality Journal (RE&PQJ) ISSN 2172-038 X, No.15 April 2017
- Robbins, M. (2021) *Ultimate Electronics: Practical Circuit Design and Analysis* ultimateelectronicsbook.com.
- Zekry, A., Shaker, A., & Salem, M. (2018) *Solar Cells and Arrays: Principles, Analysis and Design* pp25 available online at: <https://www.researchgate.net/publication/323309527>