EMBARKED PV MODULE'S MATHEMATICAL MODEL: SIMULATION, EXPERIMENT AND VALIDATION

Ovidiu CRISTEA[1], Mihai BĂLĂCEANU[2], Mihai-Octavian POPESCU[3], Aurelian Sorinel CALINCIUC[4]

The paper presents the correlation between the most-known PV cell models and the mathematical models of the ship's movements. The resulted mathematic model is simulated in LabView®. For validating the proposed model of an embarked PV panel, the paper presents a comparative study between simulation and experimental results. The final conclusions offer a good tool for those who are in eco-ships research, or looking for installing PV panels on board ships or within the naval domain.

Keywords: Eco-ship, mathematical, photovoltaic, PV cell model

1. Introduction

The current state of the art comprises a large number of numerical simulations, especially in Simulink, for the mathematical models of an "ideal" PV cell[1]–[8]. The equivalent scheme is realized in a simple way, with only one diode that is connected to the terminals of a photocurrent generating source, or more complex, where both shunt and series resistances are taken into consideration, with two or more diodes included for a better description of the different types of p-n junctions, the base principle being the same. There is a photocurrent source that reacts according to (1), that produces I_{PH}, from which the current I_D, which flows through the forward-biased diode, decreases as can be seen in expression (2). This diode current represents the losses caused by the recombination of the electrons. The reference value of I_{PH} is about 40-43mA/cm^2. Accurate models, which involve a bigger number of diodes, tend to take into consideration the different types of the electron recombination. For example, for the model that contains two diodes, the second one must equalize all the losses

[1] Teaching Assistant, Dept. of Naval Electrical and Electronic Engineering, "Mircea cel Batran" Naval Academy, Romania, e-mail: cristea_ovidiu@yahoo.com
[2] PhD student in EE domain, University POLITEHNICA Of Bucharest, Romania, e-mail: mihai.balaceanu@anmb.ro
[3] Prof., Electrical Engineering Department, University POLITEHNICA Of Bucharest, Romania, email: mihaioctavian.popescu@upb.ro
[4] Expert at ANCOM, Bucharest, Romania, e-mail: aurelian.calinciuc@ancom.org.ro

that are occurring in the p-n junction area of the absorbent materials that are included in the PV cell [9, 10].

$$I_{PH} = [I_{SC} + K_i \cdot (T - T_r)] \cdot \frac{S}{S_R}, \quad (1)$$

where: I_{PH} – photocurrent, I_{SC} – short-circuit current, K_i – short-circuit current temperature coefficient, T – module temperature in Kelvin, T_r - 298°K, S/S_R – normalized irradiation.

$$I = I_{PH} - I_0(e^{\frac{qV}{K_B T}} - 1), \quad (2)$$

where: I_0–reverse-biased diode leakage current, q – elementary charge, V – PV cell voltage, K_B – Boltzmann constant.

Using complex mathematical models, with improved results towards a simple mathematic model, some disadvantages are involved. Besides the increasing number of diodes used in the equivalent electrical scheme, the parameters number is also growing. Some of them are given by the PV module manufacturer, but other must be obtained by approximations, mathematic models or iterative calculation [1, 2, 4, 9, 11, 12]. All these additional determinations hold back the method and the computing time, leading to a hard implementation into the calculation systems of the MPPT`s.

The process of checking the mathematical models is done most of the time with an inspection of three distinct points upon the I-IV characteristics, between the real and simulated values. These points are: (0, I_{SC}), (V_{MPP}, I_{MPP}), (V_{OC}, 0).

2. Mathematical model of embarked PV module

The simulation purpose of the embarked PV cell operated in a medium with rapid irradiations variations, which more accurately means a variation of the tilt angle with the oscillations of the ship; this is acquired in order to implement the mathematical model of the ship oscillatory movements into a PV cell mathematic model. Because the only parameter that varies at the same time with the tilt angle is the solar irradiation, which is always taken like a freestanding value in most of the mathematic models of the PV modules, we chose to use for the simulation the mathematical model using one diode relation (2). In order to keep the general structure of the numerical simulations on the PVsyst environment, we have chosen the Hay model for the horizontally irradiation. For the sake of simplicity and also because the simulation takes place only once a day with constant irradiation, we considered that the direct irradiation (3) and the diffuse one (4) are constant, and the albedo irradiation(5) varies with the tilt angle of the PV module[13]–[16].

$$Beam_{Inc} = Beam_{Hor} \cdot \sin H_{soli} / H_{sol} \quad (3)$$

$$Diff_{Inc} = Diff_{Hor} \cdot \left[(1 - K_B) \cdot \frac{(1+\cos i)}{2} + K_B \cdot \sin \frac{H_{soli}}{H_{sol}}\right] \quad (4)$$

$$Alb_{Inc} = \rho \cdot Glob_{Hor} \cdot \frac{(1-\cos i)}{2} \quad (5)$$

where: i – the tilt angle, H_{sol} – the Sun high measured from the horizon, H_{soli} – the Sun high measured from the tilt plane (equals with 90°-incidental angle), K_B – the clearness irradiation beam index (6), I_o – the solar constant, ρ – the albedo.

$$K_B = Beam_{Hor}/I_o \cdot \sin H_{sol} \quad (6)$$

In this way, the incident irradiation on the PV module collector plan is equal with the global horizontal irradiation specific to the projection on the surface of the collector plan. As the PV module oscillates at the same time with the ship, the incident solar irradiation will have a reference value for a horizontal orientation and will vary directly proportional with the cosine of the tilt angle of the ship. Combining (1) with (2) and inserting the ship's oscillation mathematical model (7)[17], the embarked PV cell model relations for roll (8) and pitch (9) results:

$$\begin{cases} \varphi = \varphi_A \cos(\omega_\varphi t - \beta_\varphi) \\ \theta = \theta_A \cos(\omega_\theta t - \beta_\theta) \end{cases} \quad (7)$$

where: φ – the roll angle [rad], θ – the pitch angle [rad], φ_A, θ_A – the maximum roll and pitch angle, ω_φ ,ω_θ – the circular frequencies for roll and pitch, β_φ, β_θ – the initial phase of roll and pitch angles.

It should be considered that the expression (7) is applied only for theoretical case of ship's free oscillations (without wave excitations). This mode can be developed for external regular(Airy) and irregular wave excitations[18–20].

$$I = [I_{SC} + K_i \cdot (T - T_r)] \cdot \frac{S \cdot \cos(\varphi_A \cos(\omega_\varphi t - \beta_\varphi))}{S_R} - I_0 \cdot \left(e^{\frac{q \cdot V}{k \cdot T}} - 1\right) \quad (8)$$

$$I = [I_{SC} + K_i \cdot (T - T_r)] \cdot \frac{S \cdot \cos(\theta_A \cos(\omega_\theta t - \beta_\theta))}{S_R} - I_0 \cdot \left(e^{\frac{q \cdot V}{k \cdot T}} - 1\right) \quad (9)$$

The relations (8) and (9) were used in the simulation of the embarked PV cell characterization at fast irradiation variation produced by ship's movements.

3. Simulation results

The most known environment for the simulation of the PV cells and modules is Simulink from Matlab. Because of the fact that the data acquisitions programs, used in experiments with onboard PV panels, were developed in LabView, that will recognize in the future the Matlab-Simulink products, we carried out the simulation of an embarked PV module, in a medium with rapid changes of irradiation, also in this environment.

Fig. 1 presents the LabView application's block diagram of an embarked PV module which functions during rapid changes of irradiation, caused by the oscillatory movements of the ship.

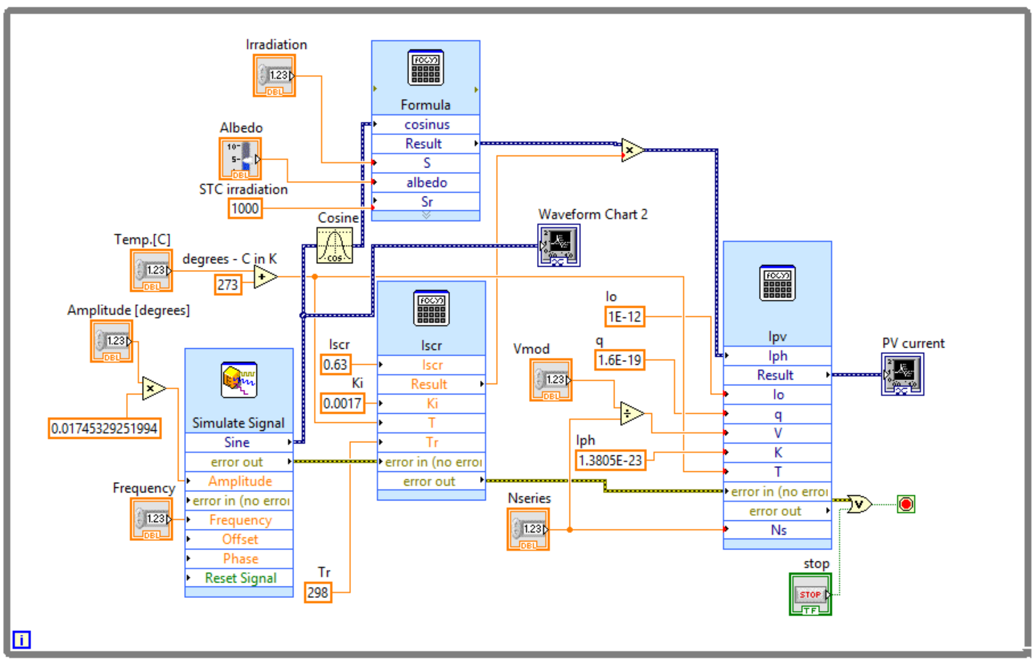

Fig. 1. LabView application's block diagram of an embarked PV module which functions during rapid changes of irradiation

The PV onboard begins with the generation of a sinusoidal signal in order to reproduce the oscillations movements of the ship. This is made with the tool *Simulate Signal* is responsible for this. This way, according to the ship type, the frequency of the oscillations and the maximum amplitude can be set up at the beginning of the simulation, from the LabView application's front panel (Fig. 2).

In the state of the art one can find [18–20] we can find the frequency of the oscillations and the maximum amplitude for a certain type of ship. For this simulation we used an oscillation' frequency of 0,1Hz, zero initial phases of oscillations and only when testing the electrical system purpose, the pitch and roll angles are larger than usual. The equation (7), the maximum tilt angles φ_A and θ_A are given in radians. For a better view of the ship oscillations movements, we decided to use in the simulations the values of the maximum angles in degrees (0°÷30°). The *Simulate Signal* block generates a signal with the tilt angle values in radians. This signal enters a *cosine* block in order to create the cosines tilt angle.

The next stage is the introduction of the ship movement' oscillations into the mathematical model of an ideal PV module. As it is presented above, the incident irradiation of the PV module plan is composed of the direct and indirect irradiation to which is added the irradiation from the albedo. So, the virtual instrument *Formula* computes the expression (5) and then it is added to the cosines of the total horizontal irradiation. Also on this block, the total incident irradiation of the PV module is reported to the reference irradiation value (1000W/m^2).

The input data of this block are the albedo's and the total horizontal irradiation's ones. The block *Iscr* computes the short-circuit current for a PV cell at a certain temperature according to the expression between brackets from (1) relation. The reference temperature T_r is equal with 25°C (298 K) according to STC. The short-circuit temperature coefficient K_i (Kelvin) was settled to 0,0017 A/°C. The short-circuit current I_{scr} has a value of 0,63 A according to the table data of the 10 Wp PV panel, used in the next chapter for validation experiments. The PV temperature must be expressed in °C.

The photovoltaic current I_{ph} is introduced in a new calculus block. Here the current for the PV module is calculated, without taking into account the shunt and series resistances. The data that can be inputted here refers to the open circuit voltage (V_{OC}) and the module's number of PV cells. The I_0 value is 1E-12A, the elementary load q is 1,6E-19C, and the Boltzmann constant k is 1,3805E-23J/K. At the output of the virtual instrument *Ipv*, the current of the onboard PV module results.

The simulation allows the view of results in real time, displayed as graphic charts and numbers. All the input data for the simulation is settled from the front panel as it is presented in the Fig. 2.

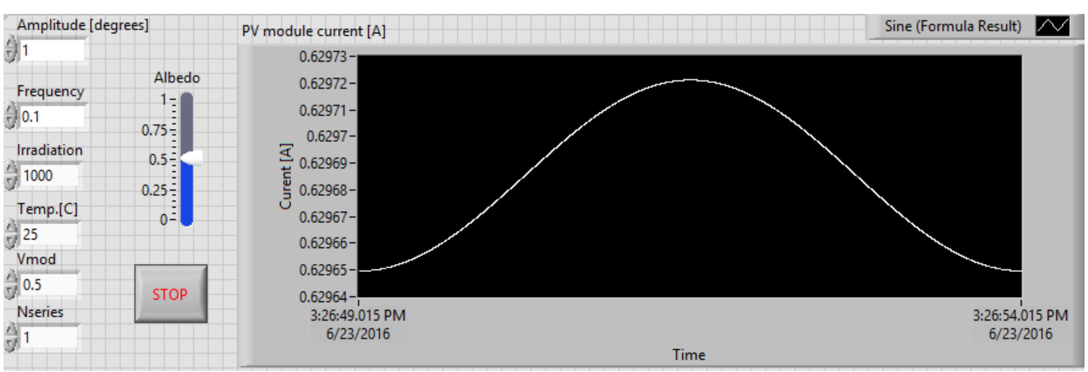

Fig. 2.LabView application's front panel of an embarked PV module which functions during rapid changes of irradiation

For example, for the input data from Fig. 2, the value of the current intensity at the output of the PV module is 0,62972 A, for a horizontal position of the panel, and decreases till 0,629646 A for a tilt of 1 degree with the horizontal, as we can see in the Current-Time representation.

In order to check the mathematical model proposed and implemented in LabView, a simulation has been carried out with data provided by the manufacturer for characteristics provided by the manufacturer for a 10Wp PV panel (Table 1).

Tabel 1

Technical data of a 10Wp PV panel used in simulation and experiments

PV cell number	9
Rated power	10 W
Tension	17,85 V
Current	0,56 A
Free tension	22,18 V
Short-circut current	0.63 A

After the simulation of an embarked 10Wp PV module operated during rapid changes of irradiation, for different maximum amplitude tilt angle and albedo's value, we obtained the results presented in Table 2.

Tabel 2

Simulation results of an embarked 10Wp PV module

Ship tilt [°]	Albedo	Imax [A]	Imin [A]	Difference [A]	Imed [A]	Percent [%]
0	0	0.63	0.63	0	0.63	100
1	0	0.63	0.629905	9.5E-05	0.629953	99.99246032
1	0.25	0.63	0.629915	8.5E-05	0.629958	99.99325397
1	0.5	0.63	0.629928	7.2E-05	0.629964	99.99428571
1	0.75	0.63	0.62994	6E-05	0.62997	99.9952381
1	1	0.63	0.629952	4.8E-05	0.629976	99.99619048
5	0	0.63	0.62752	0.00248	0.62876	99.8031746
5	0.25	0.63	0.62758	0.00242	0.62879	99.80793651
5	0.5	0.63	0.6282	0.0018	0.6291	99.85714286
5	0.75	0.63	0.6285	0.0015	0.62925	99.88095238
5	1	0.63	0.6288	0.0012	0.6294	99.9047619
10	0	0.63	0.6205	0.0095	0.62525	99.24603175
10	0.25	0.63	0.6215	0.0085	0.62575	99.32539683
10	0.5	0.63	0.6228	0.0072	0.6264	99.42857143
10	0.75	0.63	0.624	0.006	0.627	99.52380952
10	1	0.63	0.6252	0.0048	0.6276	99.61904762
20	0	0.63	0.594	0.036	0.612	97.14285714
20	0.25	0.63	0.597	0.033	0.6135	97.38095238
20	0.5	0.63	0.601	0.029	0.6155	97.6984127
20	0.75	0.63	0.6055	0.0245	0.61775	98.05555556
20	1	0.63	0.6095	0.0205	0.61975	98.37301587
30	0	0.63	0.545	0.085	0.5875	93.25396825

30	0.25	0.63	0.554	0.076	0.592	93.96825397
30	0.5	0.63	0.564	0.066	0.597	94.76190476
30	0.75	0.63	0.5725	0.0575	0.60125	95.43650794
30	1	0.63	0.582	0.048	0.606	96.19047619

We can observe that for small tilt angles of the ship and high values of the albedo, the current variation produced by the PV panel is less than 1%. The maximum current variation took place, as we intuited it, at the maximum tilt angle of the ship and minimum of the albedo. So, for a maximum tilt of 30° and a 0,25 albedo, the minimum current will be 0.066 A less than the maximum current, and an average current equal with 0,592 A that representing 93,968% from the maximum current. It's important to know that that the simulation tests were conducted for a PV cell at rapid irradiation changes and not the ship's oscillations. Hence, only for testing of electrical system purpose, the pitch and roll angles are larger than usual. In practice the pitch angle is less than 5° and the roll angle is less than 20°.

4. Experiment results and simulation validation

In order to verify the simulated results and the proposed mathematical model implemented in LabView, during the period of time from 14:30 to 14:50 on 22.06.2014, we realized an experiment with a 10Wp PV panel. The panel was used in an experimental platform (Fig. 3). The PV panel output voltage was measured with a data acquisition board USB 6008, programmed in LabView from National Instruments, and the tilt angle was measured manually. The experimental platform is based on older versions used by us onboard of ships [21–23].

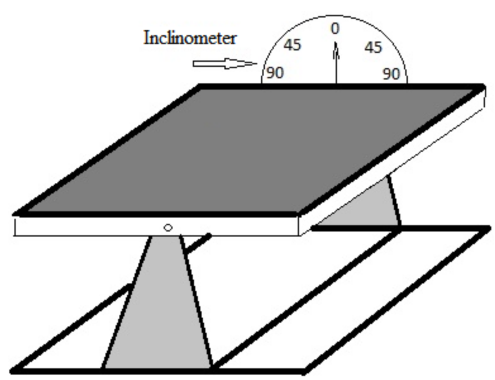

Fig. 3. Experimental platform of an embarked PV module operated during rapid changes of irradiation

The acquisition data is presented in the Fig. 4. In the left side there is the PV module output voltage for roll and in the right side, the one for pitch movements.

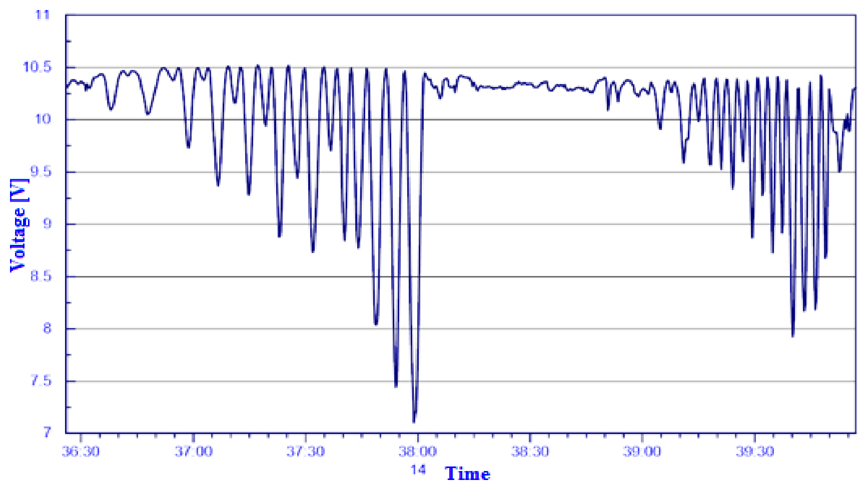

Fig. 4. Experimental results of an embarked PV module which functions during rapid changes of irradiation

The roll and pitch angles are set up using an experimental platform and for the calibration purpose they have values between 0° - 90°. As we mentioned, these values are far bigger than the real ones. The current signal from embarked PV panel is direct proportional with the voltage signal from Fig. 4, because load is a resistor of 17 **Ω**, chosen to obtain maximum power point (MPP) of the PV panel.

The comparative studies between simulated and experimental results are presented in Table 3 and 4. Please take in consideration that only for testing the electrical system capabilities the pitch and roll angles are bigger than the real ones.

Tabel 3

Comparative study between simulated and experimental results for ship's roll

Roll angle [°]	**Imax simulated[A]**	**Imax real[A]**	**Imin simulated[A]**	**Imin real[A]**	**Imed simulated[A]**	**Imed real[A]**	**Percent error Imed**
0	0.63	0,631	0.63	0,631	0.63	0,631	-0.2
10	0.63	0,631	0.6205	0,562	0.6253	0,612	2,1
20	0.63	0,631	0.594	0,557	0.612	0,607	0,8
30	0.63	0,631	0.545	0,533	0.5875	0,594	-1,1

Tabel 4

Comparative study between simulated and experimental results for ship's pitch

Pitch angle [°]	**Imax simulated[A]**	**Imax real[A]**	**Imin simulated[A]**	**Imin real[A]**	**Imed simulated[A]**	**Imed real[A]**	**Percent error Imed**
0	0.63	0,625	0.63	0.625	0.63	0.625	0.8
10	0.63	0,624	0.6205	0,574	0.6253	0,607	2,9
20	0.63	0,624	0.594	0,560	0.612	0,600	2,0
30	0.63	0,623	0.545	0,532	0.5875	0,593	-0,9

The calculation of the acquired data, from 0°-30° angles, revealed that the values for the roll movements are from 0,631 to 0,426 A, with an average value of 0,587 A, and the values for the pitch are from 0,625 to 0,476 A, with an average value of 0,587 A.

The small error percent between simulated and real result, less than 3%, indicate that the proposed mathematical model of an embarked PV panel, at fast variation of irradiation, is valid.

5. Conclusions

The paper presents a proposed mathematical model for an embarked PV panel during the fast variation of solar irradiation. The mathematical model is implemented in a LabView simulation. The real experiment values validate the mathematical model and the simulation environment.

Even the fact that the real results between roll and pitch angles are not the same, after processing the acquisitioned data in DIAdem it results that the average current values produced by the PV panel are the same.

Further research should be made on real onboard conditions and using more complex mathematical models for PV cells and ships' oscillations.

A very important conclusion is that a horizontal PV panel embarked onboard a ship with an average maximum amplitude tilt angle of 10° will have losses in effective energy production of 14,6kWh/m^2/year.

The conclusions of the study presented in this paper show that the implementation of renewable energy in this field should be made with a rigorous documentation and research, in order to obtain the best solution and effectiveness.

Acknowledgment

The work has been funded by the Sectoral Operational Program Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/134398

R E F E R E N C E S

[1] *K. Ishaque, Z. Salam, and Syafaruddin*, "A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model," Sol. Energy, vol. 85, no. 9, pp. 2217–2227, 2011.

[2] *C. Qi and Z. Ming*, "Photovoltaic Module Simulink Model for a Stand-alone PV System," Phys. Procedia, vol. 24, pp. 94–100, 2012.

[3] *Z. Erdem and M. B. Erdem*, "A Proposed Model of Photovoltaic Module in Matlab/SimulinkTM for Distance Education," Procedia - Soc. Behav. Sci., vol. 103, pp. 55–62, 2013.

[4] *C. Qi and Z. Ming*, "Photovoltaic Module Simulink Model for a Stand-alone PV System,"

Phys. Procedia, vol. 24, pp. 94–100, 2012.

[5] *N. A. Rahim, H. W. Ping, and J. Selvaraj*, "Photovoltaic Module Modeling using Simulink/Matlab," Procedia Environ. Sci., vol. 17, pp. 537–546, 2013.

[6] *P. Sudeepika and G. G. Khan,* "Analysis Of Mathematical Model Of PV Cell Module in Matlab / Simulink Environment," pp. 7823–7829, 2014.

[7] *T. Salmi, M. Bouzguenda, A. Gastli, and A. Masmoudi*, "MATLAB / Simulink Based Modelling of Solar Photovoltaic Cell," vol. 2, no. 2, 2012.

[8] *K. Ding, J. Zhang, X. Bian, and J. Xu*, "A simplified model for photovoltaic modules based on improved translation equations," Sol. Energy, vol. 101, pp. 40–52, 2014.

[9] *K. Ishaque, Z. Salam, and H. Taheri,* "Simple, fast and accurate two-diode model for photovoltaic modules," Sol. Energy Mater. Sol. Cells, vol. 95, no. 2, pp. 586–594, 2011.

[10] *A. V. Pavan Kumar, A. M. Parimi, and K. Uma Rao*, "Performance Analysis of a Two-Diode model of PV cell for PV based generation in MATLAB," in 2014 IEEE International Conference on Advanced Communications, Control and Computing Technologies, 2014, pp. 68–72.

[11] *M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia*, "Characterization of PV panel and global optimization of its model parameters using genetic algorithm," Energy Convers. Manag., vol. 73, pp. 10–25, 2013.

[12] *A. H. Besheer, A. M. Kassem, and A. Y. Abdelaziz*, "Single-diode Model Based Photovoltaic Module: Analysis and Comparison Approach," Electr. Power Components Syst., vol. 42, no. 12, pp. 1289–1300, Jul. 2014.

[13] *Y. Tham, T. Muneer, and B. Davison*, "Estimation of hourly averaged solar irradiation□: evaluation of models," Build. Serv. Eng. Res. Technol, vol. 1, no. 31, pp. 9–25, 2010.

[14] *D. Yang, Z. Dong, A. Nobre, Y. S. Khoo, P. Jirutitijaroen, and W. M. Walsh*, "Evaluation of transposition and decomposition models for converting global solar irradiance from tilted surface to horizontal in tropical regions," Sol. Energy, vol. 97, pp. 369–387, Nov. 2013.

[15] *D. Yang, Z. Ye, A. M. Nobre, H. Du, W. M. Walsh, L. I. Lim, and T. Reindl*, "Bidirectional irradiance transposition based on the Perez model," Sol. Energy, vol. 110, pp. 768–780, Dec. 2014.

[16] *C. K. Pandey and A. K. Katiyar*, "A comparative study of solar irradiation models on various inclined surfaces for India," Appl. Energy, vol. 88, no. 4, pp. 1455–1459, Apr. 2011.

[17] *M. Viorel*, Mecanica si constructia navei (The mechanics and building of a ship - in Romanian), Vol. II. Bucuresti: Editura tehnica, 1987.

[18] *V. Bertram*, Practical Ship Hydrodynamics. Oxford: Butterworth Heinemann, 2000.

[19] *E. M. Lewandowski*, The Dynamics of Marine Craft. New Jersey: World Scientific, 2004.

[20] *K. J. Rawson and E. C. Tupper*, Basic Ship Theory. Oxford: Butterworth Heinemann, 2001.

[21] *O. Cristea*, "Testing of PV module efficiency in naval conditions," in 2013 8TH INTERNATIONAL SYMPOSIUM ON ADVANCED TOPICS IN ELECTRICAL ENGINEERING (ATEE), 2013, pp. 1–4.

[22] *O. Cristea and N. Badar*a, "Advanced data acquisition system for testing PV efficiency on naval domain," in Maritime Scientific Forum, 2013, no. 16–17 May, Varna.

[23] *O. Cristea, M.-O. Popescu, and A. S. Calinciuc*, "A correlation between simulated and real PV system in naval conditions," in 2014 International Symposium on Fundamentals of Electrical Engineering (ISFEE), 2014, pp. 1–6.