MODELING AND SIMULATION OF A 3 KW PHOTOVOLTAIC SYSTEM FOR AN AUTONOMOUS CONSUMER

Marius - Alexandru DOBREA[1], Mihaela VASLUIANU[2], Giorgian NECULOIU[3], Nicoleta ARGHIRA[4]

The paper aims to model and simulate an assembly composed of 12 photovoltaic panels, each with a nominal power of 250W in order to power a consumer. Starting from the monitoring of the parameters of temperature and solar radiation, a comparison was made during a period of one year, between the simulated power and the real measured one, monitored with a power meter. The paper analyzes the particularities between measured and simulated values in both clear sky and shade conditions. The measured data were compared with a data set used for the simulation which resulted in a correlation coefficient of 93%. The modeling and simulation of this set of photovoltaic panels were performed in the Matlab / Simulink environment.

Keywords: PV, modeling, system, mathematical model, partial shading

1. Introduction

Nowadays, energy is a basic necessity all over the world. Energy use is growing enormously, and, as a result, the population is beginning to worry about the facts involved in this use. Disproportionate greenhouse gas emissions and the consumption of some of the world's available energy resources have become critical issues that have severe effects on climate change [1].

Photovoltaic technologies do not directly emit greenhouse gases and can save more than 30 million tons of carbon on electricity generated compared to a natural gas turbine operating at 45% efficiency [2]. Also, photovoltaic systems are noise-free, flexible in scale, and easy to maintain compared to other renewable technologies. The transformation and use of solar energy into electricity through photovoltaic installations is the most recognized way of using solar energy. Because photovoltaic (PV) solar cells are semiconductors, they have much in

[1] PhD Student, Faculty of Automatic Control and Computer Science, University POLITEHNICA of Bucharest, Romania, e-mail: marius.alexandru.dobrea@gmail.com
[2] Lecturer, Faculty of Hydrotechnics, Technical University of Civil Engineering of Bucharest, Romania, e-mail: mihaelavasluianu89@gmail.com
[3] Lecturer, Faculty of Hydrotechnics, Technical University of Civil Engineering of Bucharest, Romania, e-mail: neculoiu.giorgian@gmail.com
[4] Lecturer, Faculty of Automatic Control and Computer Science, University POLITEHNICA of Bucharest, Romania, e-mail: arghira.nicoleta@gmail.com

common with the processing and production techniques of other semiconductor devices. The sun is the only necessary resource for the operation of photovoltaic systems, and its energy is almost inexhaustible [17]. The primary consumers for an autonomous photovoltaic system can be of many types, both direct current (television, lighting, air conditioning systems) and alternating current (electric motors, heaters, etc.). The most common elements of the power conditioning system are the blocking of diodes, charge regulators, and DC-AC converters [3].

When photovoltaic panels operate under different temperatures and solar radiation, each photovoltaic panel will generate a unique characteristic curve, because the output power of the photovoltaic panel varies depending on the output voltage. Each photovoltaic panel has a unique maximum power point. At the point of maximum power, the corresponding voltage changes as the ambient temperature or solar radiation changes [14].

The authors of [4] consider that an output variable such as the active power obtained from the photovoltaic panel, which is directly influenced by the measurements of solar radiation during a day is an essential variable for creating the model of a photovoltaic panel. In the paper [5], the authors presented the mathematical models of renewable resources used (photovoltaic panels and wind turbines). They performed several operating scenarios that were modeled and tested using a photovoltaic panel and a wind turbine for a hybrid system. In the paper [6], the authors present a hybrid system consisting of eight photovoltaic panels (with 36 cells each) and four wind turbines with a total power of 37,600 W. That system was created to provide energy for a small community. The tests for the entire system were performed using as a period of one day.

The authors of [7] presented the modeling of solar panels using the technical parameters of a photovoltaic panel in catalogs and a mathematical model based on the equivalent circuit of the panel with a single diode. First, modeling and simulation were done in Matlab / Simulink, and then comparisons were made with the values and technical characteristics. The paper [8] presents a method of simulation and modeling of photovoltaic cells in Matlab / Simulink. The technique is used to determine the characteristics of a solar cell in order to model a photovoltaic panel later and to study the influence of different values of temperature and solar radiation on the performance of photovoltaic cells.

2. PV modeling

A. *Photovoltaic cell operation principle*

The energy produced with the help of photovoltaic (PV) panels is today the most comprehensive solar electric technology in the world. Powered by light, solar cells operate close to ambient temperature, with no moving components and allow generation at any scale: a photovoltaic matrix of 10 square meters (m^2) is theoretically no less efficient than a unit of one kilometer. (km^2). [18]

Photovoltaic panels are installations that convert solar radiation into electricity. Each photovoltaic panel can be composed of solar cells connected in parallel or series. PV efficiency is relatively low, between 8 and 20%, depending on the degree of absorption of solar radiation. [19]

The functionality of photovoltaic panels is based on the absorption of light from a semiconductor, most commonly a PN silicon diode, providing an environment in which incident photons can be converted into energy, usually in the form of heat. Photovoltaic systems do not make noise, there are no moving parts, and they do not emit pollutants into the environment. They produce ten times less carbon dioxide per unit than the energy produced by fossil fuel technologies. [17]

The usual efficiency of photovoltaic solar cells is about 15%, which means that it can convert 1/6 of solar energy into electricity.

The main functions of a solar cell:

• efficiently absorbs sun light;
• creates an electric current and voltage when they are illuminated;
• acts like a battery in sunlight.

Solar panels are built from several photovoltaic cells connected in series and/or parallel. In order to obtain high power, the solar cells must be connected in groups to form a module. When the panels are connected in series, the voltage increases and the current remains the same, and when they are connected in parallel, the voltage remains the same, and the current increases.

Many photovoltaic systems operate autonomously (stand-alone) [12]. Such systems consist of a set of photovoltaic panels, energy storage equipment (e.g, a battery), alternating current and direct current consumers, and elements for electricity conditioning.

The primary consumers for an autonomous photovoltaic system can be of many types, both direct current (television, lighting, air conditioning systems) and alternating current (electric motors, heaters, etc.). [16]

A current source models an ideal PV cell in parallel with a diode. However, no solar cell is ideal, and therefore the shunt (impurities in the cell) and resistors are added to the model, as shown in the photovoltaic cell diagram. R_S is the intrinsic series resistance whose value is very small. R_0 is the equivalent strength of the shunt, which has a very high value. The building element of photovoltaic panels is the solar cell, which is essentially a PN-type junction that directly converts light energy into electricity: the equivalent circuit is described below:

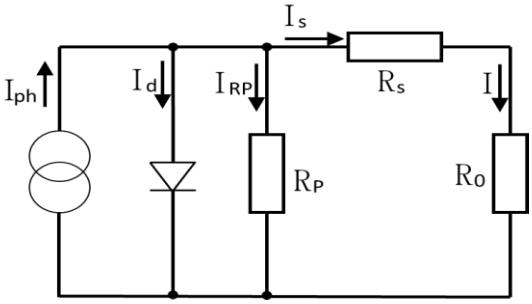

Fig. 2.1. The equivalent circuit of a photovoltaic cell [21]

Iph is the current source and represents the solar induction current; *Rp* represents the intrinsic resistance and has a very high value, and *Rs* is the shunt resistance of the cell with very low value, so it can be neglected to simplify the analysis. Photovoltaic cells are grouped into larger units called photovoltaic modules that are further interconnected in a parallel configuration to form photovoltaic networks or photovoltaic generators. Applying Kirchhoff's law to the node where *Iph*, diode, Rp, and Rs meet, we obtain [13]:

$$I_{ph} = I_d + I_{Rp} + I \quad (1)$$

We obtain the following equation for photovoltaic current:

$$I = I_{ph} - I_{Rpd} - I_d \quad (2)$$

$$I = I_{ph} - I_o \left[exp\left(\frac{q * (V + I * R_S)}{n * K * N_S * T} \right) - 1 \right] - I_{sh} \quad (3)$$

$$I_{sh} = \left(\frac{V + I * R_S}{R_{sh}} \right) \quad (4)$$

Where:
I_{ph} – Current generated due to light or photocurrent;
I –Current generated by the solar cell;
I_0 – Cell saturation of dark current;
V – Voltage generated by the solar cell;
R_s – Series equivalent resistance;
R_p – Shunt equivalent resistance;
V_T – Thermal voltage;
K – Boltzmann's constant;
T – Temperature;
q – Charge of electron.

The building block of photovoltaic panels is the solar cell, which is essentially a PN junction that directly converts light energy into electricity.

B. The mathematical model of PV panels

Photovoltaic cells are grouped into larger units called photovoltaic modules that are further interconnected in a parallel configuration to form photovoltaic networks or photovoltaic generators.[15]

The equation (5) represents the PV mathematical model used to simplify the PV matrix:

$$I = n_p I_{ph} - n_p I_{rs}\left[exp\left(\frac{qV}{KTAn_s}\right) - 1\right] \tag{5}$$

Where:

I - Current generated by the solar cell;
V – Voltage generated by the solar cell;
n_s – Series number of cells for a PV array;
n_p – Parallel number of cells for a PV array;
q - Charge of electron;
K – Boltzmann's constant;
A – Ideality factor;
T – Solar cell temperature (K);
I_{rs} – Reverse saturation current.

Coefficient A in equation (5) causes the cell to deviate from the ideal characteristics of the PN junction. Coefficient A varies between 1-5, but for our case, we use A = 2.46. The reverse of the saturation current of the Irs solar cell varies with temperature, according to the following equation:

$$I_{rs} = \frac{I_{sc}}{e^{\left(\frac{q*V_{oc}}{n*N_s*K*T}\right)-1}} \tag{6}$$

$$I_0 = I_{rs} * \left(\frac{T}{T_n}\right)^3 * exp\left[\frac{q * E_{go} * (1/T_n - 1/T)}{n * K}\right] \tag{7}$$

Where:

T_n – Reference temperature of the solar cell;
I_0 - Cell saturation of dark current;
E_{g0} – Band gap energy of semiconductor;
V_{oc} – Open circuit voltage;
n – Ideality factor.

Current generated due to light Iph depends on solar radiation and temperature, as can be seen in the following equation:

$$I_{ph} = [I_{sc} + K_i * (T - 298)] * \frac{G}{1000} \tag{8}$$

Where:
I_{sc} - Nominal light generated current;
k_i – Short circuit current;
G – Irradiation level on module surface.

The power of the photovoltaic panel can be calculated using equation (5) as follows:

$$P = I * V = n_p I_{ph} V \left[\left(\frac{qV}{KTAn_s} \right) - 1 \right] \tag{9}$$

Modeling can be done in MATLAB in several ways; standard methods include SIMULINK programming and modeling.

The photovoltaic panel is influenced by temperature, irradiation level, etc. Separate blocks are made for each formula, and, finally, all are combined to obtain the photovoltaic panel [6].

C. *Modeling of photovoltaic panels*

After finding out the mathematical model of a photovoltaic panel, we performed the modeling in the MATLAB / Simulink development environment, as presented in Fig. 2.2.

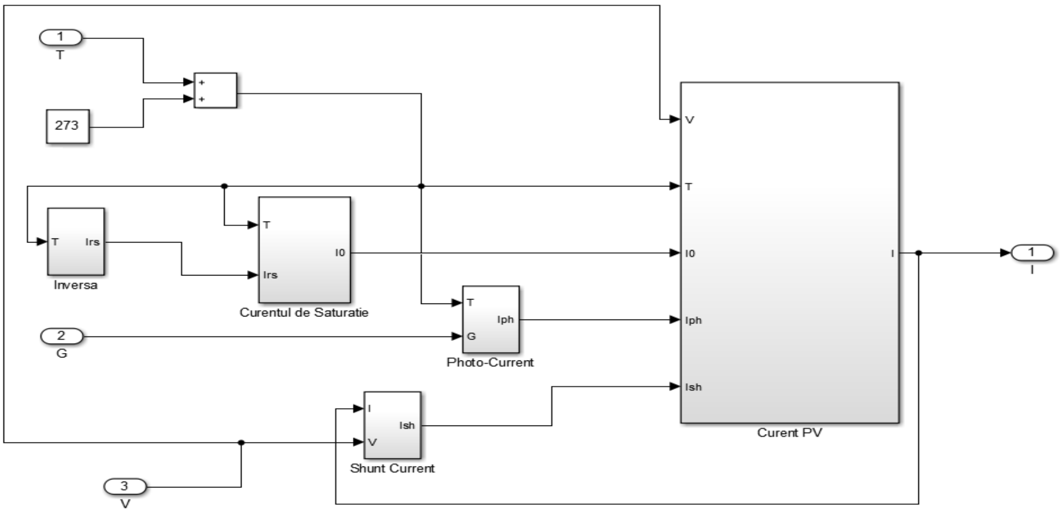

Fig. 2.2. SIMULINK Model Photovoltaic Panel System

The modelled PV panel is tested and validated on a real setup. The entire system is composed of 12 photovoltaic panels of 250 W each, and the simulation is done for a consumer who is in Bucharest, Constantin Brancoveanu area, sector 4, a villa with a total area of 120 m^2 and has a maximum monthly energy consumption of 110 kWh.

Following the modeling of the photovoltaic panel, the next objective is to simulate it for a real case. The generation system, which have 12 panels, is composed of 4 groups with 3 panels each, connected in series, and each group is connected in parallel with the other groups.

We will consider the following constants detailed in Table 1:

Table 1

SOLAR PANEL MODELING CONSTANTS

SYMBOL	PARAMETER	VALUE
k_i	Short-circuit thermal coefficient	0.0032
T_n	The reference temperature of the solar cell	298 K
q	The electric charge of an electron	$1.6*10^{-19}$ C
n	The ideal diode coefficient	1.3
K	Boltzmann's constant	1.38*10-23 J/K
Eg0	band gap of the semiconductor used in the solar cell	1.1
R_s	The sum of the resistors connected in series	0.221 Ω
R_{sh}	Resistance	415.405 Ω

Table 2

TECHNICAL DATA OF THE SOLAR PANEL

CARACTERISTICS	UNIT	VALUE
Nominal power (Pn)	W	250
Deviation power	W	0~5
Maximum allowable power	W	254.99
Open circuit voltage (V_{oc})	V	37.1
short circuit current (I_{sc})	A	8.92
Voltage at maximum power point (V_{mp})	V	30.3
Current at maximum power point (I_{mp})	A	8.28

3. System simulation and modeling

In order to validate the proposed model for the PV system, weather data is necessary for the exact location of the test system. With the help of a telemetry station (ADCON), we took over the measured data for a period of 1 year (March 1, 2019 - March 1, 2020), located in Bucharest, Sector 4, Brancoveanu area.

The parameters used to simulate a photovoltaic panel system were temperature and solar radiation, measured at an interval of 15 minutes. It is located next to the panels for the best possible accuracy. From the measured data set, we made the monthly average at different time intervals to generate a typical day of each month. We implemented the mathematical model based on the measured weather parameters, and by simulating in Matlab / SIMULINK, we computed the generated power of a panel in a day period for the month of March.

Fig. 3.1 represents the evolution in time of the simulated power for a day in March. In the graph, one can see that the maximum power of 1482W was obtained at 12:15 with a panel temperature of 14.2 C and solar radiation of 509 W / m ^{2}.

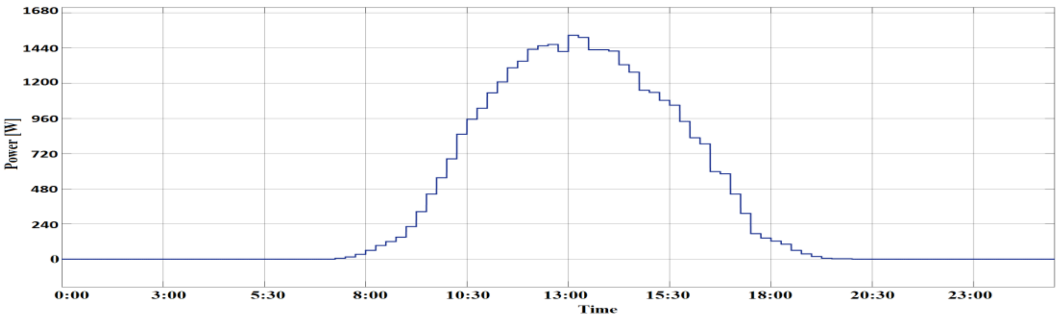

Fig. 3.1: Simulated power for a day in March

The photovoltaic panel system used is a system composed of three panels connected in series, each series being connected in parallel four times, as can be seen in Fig.3.2.

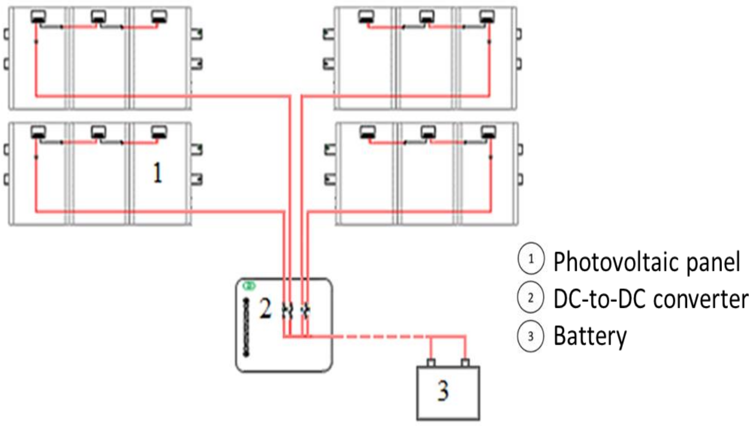

Fig. 3.2: Real power supply system with photovoltaic panels [9]

If the photovoltaic panels are connected in series, then the phenomenon of partial shading can significantly influence their characteristics. [11] The advantage of this model used is the high voltage level (approximately 110 V), but at the time of partial shading, the efficiency of the system decreases significantly.

In the I-V and P-V characteristics of the three panels connected in series, it can be observed the movement of the maximum power point towards a lower value due to the partial shading phenomenon. [10]

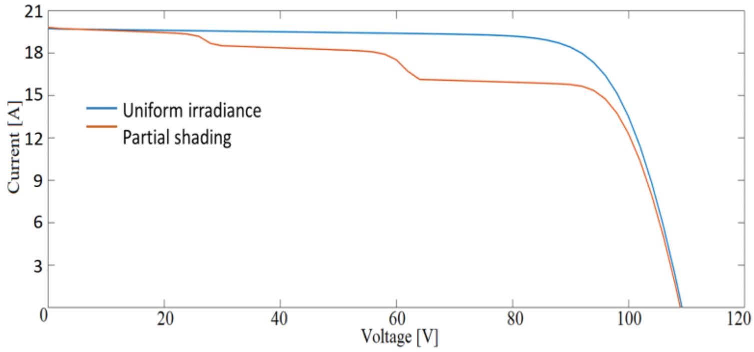

Fig. 3.3: Current-Voltage characteristic at the time of partial shading

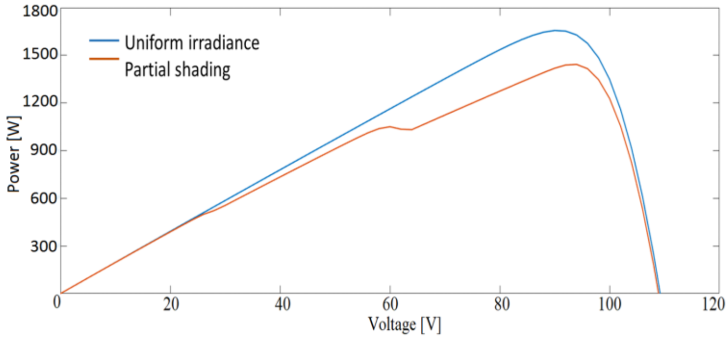

Fig. 3.4: Power-Voltage characteristic at the time of partial shading

With the help of the power meter equipment, we measured during this period, the real power generated by the system at the level of the inverter. This in the figure, you can observe the evolution in time of the simulated power using the mathematical model in comparison with the real power measured by the equipment during a whole year.

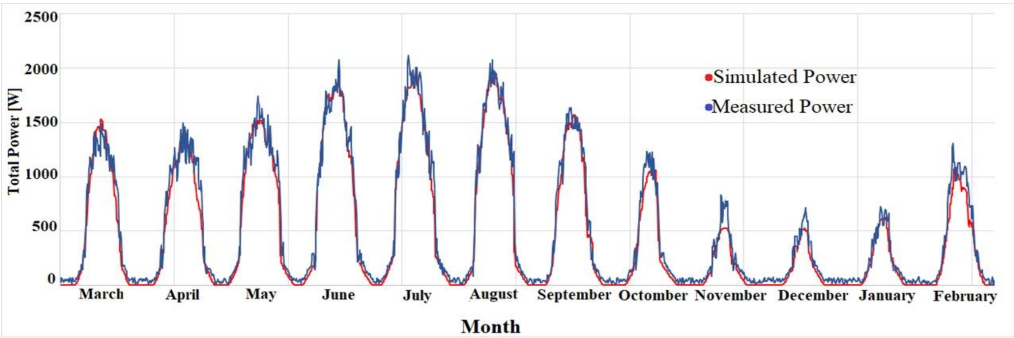

Fig. 3.5: Comparison of simulated and measured powers for each month

To determine the degree of accuracy we applied the correlation coefficient formula:

$$Correl(X,Y) = \frac{\Sigma(x-\bar{x})(y-\bar{y})}{\sqrt{\Sigma(x-\bar{x})^2\,\Sigma(y-\bar{y})^2}}$$

where, $\bar{x}$ is the average simulated data and $\bar{y}$ is the average measured data.

The simulated data compared to the measured ones have a correlation coefficient of 93%, so we can deduce that the implemented mathematical model satisfies the necessary conditions. From the analysis of the two power curves, we identified a set of particular cases. During the night, even if the pyranometric sensor did not record solar radiation values, the photovoltaic panel system generated power with negligible values. This power was influenced by street lighting. The influence of the partial shading phenomenon led to a lower real power than that resulting from the mathematical model, as can be seen obviously in March. Due to the lack of maintenance, in September and October, the parameters recorded by the telemetry station have low values, which disrupts the output power of the panel in the case of the simulated model.

4. Conclusions and future work

The paper aimed to simulate and model a set of 12 photovoltaic panels for a house with an area of 120 m2 located in Bucharest. Each photovoltaic panel has a nominal power of 250W, and they are connected three in series and each group in parallel four times. Starting from the monitoring of the parameters of temperature and solar radiation, a comparison was made, for one year, between the simulated power and the real one, monitored with a power meter. The modeling and simulation of this set of photovoltaic panels were performed in the Matlab / Simulink environment.

The simulated data compared to the real ones have a correlation coefficient of 93%, so we can say that the implemented mathematical model satisfies the necessary conditions and that it can be an approved model for subsequent implementations. Due to the partial shading the correlation coefficient is not 100%. This type of energy could cause serious economic problems, given the high cost of investments in photovoltaic panels. Shading effects are another serious problem for the distributed photovoltaic panel generation system, especially for the large-scale installation of photovoltaic panels. In general, the overall conversion efficiency of photovoltaic generations will be reduced due to partial shading.

Future work involves modelling and simulation for a lead-acid battery, specially used for autonomous consumers. The solution will consider a model of the battery that can be discharged until the voltage drops below 30% of the nominal value, whereby operating the necessary switches, the battery can only receive energy. The goal is to create an autonomous system with generation from both PV panels and several batteries connected, either in series or in parallel, able to meet the energy need of the consumer.

R E F E R E N C E S

[1] *Sara Gallardo Saavedra* - Analysis and simulation of shading effects on photovoltaic cells, June 2016

[2] *S. H. Kim, C. M. Cracken and J. Edmonds*, “Solar Energy Technologies and Stabilizing Atmospheric CO2 Concentrations”, Progress in photovoltaics: research and applications, vol. 2000, no. 8, pp. 3-15, 2000.

[3] *Marius Dobrea, George Suciu, Cristian Beceanu, C.M. Balaceanu, M. Anwar,* Weather Monitoring for Predicting Thermal Comfort and Energy Efficiency, 2018 SIITME 978-1-5386-5577-1/18 ©2018 IEEE

[4] *M. Puianu, R.-O. Flangea, N. Arghira, S. S. Iliescu*, “PV panel -wind turbine hybrid system modelling”, IEEE 21st Control Systems and Computer Science Conference, in press, 2017

[5] *Mihaela Puianu, Ramona-Oana Flangea, Nicoleta Arghira, S.S. Iliescu,* Microgrid Control Simulation and Testing, University Politehnica of Bucharest Scientific Bulletin Series C-Electrical Engineering and Computer Science, Volumul: 2, pg: 57-68, ISSN: 2286-3540, 2018

[6] *Mihaela Vasluianu, Oana Carmen Niculescu Faida, Ramona–Oana Flangea, Neculoiu Giorgian, Mariana Marinescu*, “Microgrid System for a Residential Ensemble”, 2019 22nd International Conference on Control Systems and Computer Science (CSCS), IEEE

[7] *Lucian Mihet – Popa, Octavian Cornea, Voicu Groza*, “PV System Simulation Models Developed for a Distribued Network and Validated by Experiments”, World Energy System Conference – WESC, Buletinul AGIR nr. 3/2012, iunie-august

[8] *Ioan – Viorel Banu, Marcel Istrate*, “Modeling and Simulation of Photovoltaic Arrays”, World Energy System Conference – WESC, Buletinul AGIR nr. 3/2012, iunie-august

[9] *George Suciu, Mari-Anais Sachian, Marius Dobrea, Cristiana-Ioana Istrate, Ana Lavinia Petrache, Alexandru Vulpe, Marius Vochin*, Securing the Smart Grid: A Blockchain-based Secure Smart Energy System, Proc. 54th Int. Univ. Power Eng. Conf. (UPEC), Sep. 2019, pp. 1–5

[10] *D. Sera, T. Kerekes, R. Teodorescu, F. Blaabjerg*, "Improved MPPT Algorithms for Rapidly Changing Environmental Conditions," in Proc. 12th International Conference on Power Electronics and Motion Control, 2006, pp. 1614-1619.

[11] *P. A. Lynn*, Electricity from Sunlight: An Introduction to Photovoltaics, John Wiley & Sons, 2010, p. 238.

[12] *S. Jain, and V. Agarwal*, “A New Algorithm for Rapid Tracking of Approximaten Maximum Power Point in Photovoltaic Systems”, IEE Power Electronics letter, Vol. 2, No 1, March 2004.

[13] *Wafaa ABD EL – BASIT, Ashraf Mosleh ABD EL – MAKSOOD and Fouad Abd EL – MONIEM Saad SOLIMAN*, “Mathematical Model for Photovoltaic Cells”, Leonardo Journal of Sciences, Issue 23, July – December 2013, p. 13-28, ISSN 1583 – 0233.

[14] *R. Messenger and J. Ventre*, Photovoltaic Systems Engineering, 2nd ed. Boca Raton, FL: CRC Press, 2004.

[15] *Jasim Abdulateef,* Simulation of Solar Off- Grid Photovoltaic System for Residential Unit. International Journal of Sustainable and Green Energy. Special Issue: Engineering Solution for High Performance of Solar Energy System. Vol. 4, No. 3-1, 2014, pp. 29-33.

[16] *Mihaela Puianu, Ramona-Oana Flangea, Mariana Marinescu, Viorel Marinescu*, "Cloud Computing for a Hybrid System", 2017 16th RoEduNet Conference: Networking in Education and Research (RoEduNet), Targu Mures, Romania, ISSN: 2247-5443

[17] *A. Cotar, A. Filcic, D. Jardas*, "Photovoltaic Systems", IRENA – Istrian regional energu agency, Rijeka, January 2012

[18] *Reja Amaya, Filile Breshett, Andrew Campanella, Jill Macko, Andrea Maurano, James McNerney, Timothy Osedach, Pablo Rodilla, Amy Rose, Apurba Sakti, Edward Sreinfeld, Jessika Trancik, Harry Tuller*, "The Future of Solar Energy", Energy Initiative Massachusetts Institute of Technology, 2015, ISBN 978-0-928008-9-8

[19] *Camacho E.F., Berenguel M., Rubio F.R., Martinez D*., "Control of Solar Energy Systems", Editura Springer, ianuarie 2012;

[20] *F. Dragomir, O.E. Dragomir, N. Arghira, V. Calofir,* Evaluation of PV Systems Degradation Performances, Proceeedings of 14th International Multidisciplinary Scientific Geoconference, ISBN:978-619-7105-15-5, ISSN: 1314-2704, pp 221-228, Albena, 2014

[21] *Gabriel Cibira*, Relations among photovoltaic cell electrical parameters, Applied Surface Science (2018), doi: https://doi.org/10.1016/j.apsusc.2018.05.194