Validation of photovoltaic model for application in a distributed energy source using weather data

Eduardo G Pignaton[1], Danilo P. e Silva[1], Flávio B. B. da Silva[1], José Leandro F. Salles[2], Jussara F. Fardin[2]

[1] *Professional Master's Degree in Control and Automation Engineering, Federal Institute of Espírito Santo*
ES-010 Km-6,5, 29173-087, Manguinhos, Serra - ES, Brasil
edupignaton@gmail.com, danilo.silva@ifes.edu.br, flaviobarcelos@ifes.edu.br

[2] *Department of Electrical Engineering, Federal University of Espírito Santo*
Av. Fernando Ferrari, 514, 29075-910, Goiabeiras, Vitória - ES, Brasil
jleandro@ele.ufes.br, jussara@ele.ufes.br

Abstract. This work presents a photovoltaic model for a simulation of the electric energy production of a distributed energy system. The model will be validated through measured weather data and energy produced by an 88.04 kWp power plant installed on the Federal University of Espírito Santo (UFES) in Vitória. The validation consists of comparing the real power data acquired by the photovoltaic plant and the power data calculated from the model using weather data, specifications of the panels and inverters and the constructive characteristics of the system. The proposed model is based on the paper "Management of an island and grid-connected microgrid using hybrid economic model predictive control with weather data", Applied Energy, v. 278, 2020, https://doi.org/10.1016/j.apenergy.2020.115581. In addition, the model has been improved with the inclusion of new intrinsic parameters of the material, the calculation of losses and the adjustments for different tilt angles and azimuth orientations. Results of this method reveal that the model was able to reproduce the behavior of the real photovoltaic plant, presenting a mean absolute percentage error of 8.8% between real and simulated data.

Keywords: solar photovoltaics generation, photovoltaic model, validation, weather data.

1 Introduction

It is not difficult to notice the great expansion of the use of solar energy almost all over the world. In Brazil, the scenario is the same, since the growth year after year in the use of photovoltaic solar energy is vertiginous. According to ABSOLAR [1], there was a 169% growth in installed capacity in 2020 compared to 2019. In an energy scenario that increasingly demands the use of renewable energy sources, the improvement of this way of generation becomes essential. In this regard, the use of mathematical models that facilitate the handling of photovoltaic solar systems helps in their understanding, operation and maintenance.

This work proposes an improvement of the photovoltaic model proposed by Silva [2] and its validation, applying a case study of an 88.04 kWp photovoltaic system that is an integral part of the largest mini-generation photovoltaic (PV) plant in Espírito Santo, with 4.15 MWp [3]. Modeling and simulation were performed on Matlab platform. Equipment catalogs and PVSyst were used to obtain the losses to be applied.

2 Methodology and simulation steps

2.1 Plant generation and weather datasets acquisition

The dataset was provided by the Institute of Environment and Water Resources (IEMA) referring to the weather station RAMQAr 2 located in Serra-ES, Brazil [4]. The station is located at a distance of around 6.8 km from the plant under study. From the dataset, only global solar radiation incident (W/m²) on horizontal plane and dry-bulb temperature (ºC) were used. The sampling rate is one hour. Weather data were used according to the methodology presented by Pérez [4]. The power generation dataset was obtained through the Sems Portal monitoring system provided by the inverter manufacturer, GoodWe [5].

2.2 Mathematical Modeling

The equations of the one-diode model presented by Humada [6] and Villalva [7] to be used to simulate the operation of photovoltaic cell and photovoltaic current are presented in eq. (1):

$$I = I_{ph} - I_0 \left(e^{\frac{q \cdot V_D}{n \cdot K \cdot T}} - 1 \right) - \frac{V_D}{R_{sh}} \text{ and } I_{ph} = I_{sc} \cdot \lambda_{coll}. \tag{1}$$

Where, I is the output current, I_{ph} is the photo-generated current, I_0 is the reverse saturation current, q is the elementary electric charge of an electron, V_D is the voltage across the diode, n is the diode quality factor, K is the Boltzmann constant, T is the P-N junction temperature and R_{sh} is the shunt resistance of the model. In the photovoltaic current equation, I_{sc} is the short-circuit current informed by the photovoltaic module manufacturer and λ_{coll} is the incident solar radiation on the collector's plane given as kW/m². Considering the transposition factor (tf) [8] [9], the near shading factor (f_{near}) [10], the soiling factor ($f_{soiling}$) [11] [12] and the incidence angle modifier factor (f_{IAM}) [13], the incident solar radiation on the collectors plane (λ_{coll}) is calculated through eq. (2):

$$\lambda_{coll} = f_{near} \cdot f_{soiling} \cdot f_{IAM} \cdot tf \cdot \lambda, \tag{2}$$

and the voltage V_D is calculated from eq. (3):

$$V_D = V_{pv} + R_s \cdot I. \tag{3}$$

Where V_{pv} is the output terminal voltage and R_s is the series resistance from one-diode model. The parameters R_s and R_{sh}, were extracted from the derivatives of the I-V curve in the standard test conditions (STC) using the technique presented by Humada [6] and have values 0.2414 Ω and 351.39 Ω, respectively. In order to obtain I_0 and n, the four parameters and one-diode model method was used, also presented by Humada [6], and the values found were $1.6005 \cdot 10^{-12}$ A and 1.0313, respectively.

2.3 Generation for each inverter MPPT

The input power for each MPPT (P_{mppt}) is calculated by the multiplication of the number of cells per module by the number of modules per string, by the number of strings per MPPT and by V_{pv} and I. The total power of the plant (P_{arr}) is given by the following equation:

$$P_{arr} = \sum_{l=1}^{j} \sum_{k=1}^{i} P_{mppt(ij)}. \tag{4}$$

This equation sums the powers of the i-th MPPTs of the j-th inverters, being j=1,2,3 and so on. Next, the virtual output power of the inverters (P_{ACvir}) is calculated. It will be a result of the application of a set of losses to the total power of the plant, in addition to the application of the European efficiency of the inverter [14]. Those losses are composed by degradation [15], heating losses [16], partial or complete shading losses [10] [15], module quality factor [15], light induced degradation [15], mismatch between modules and mismatch by voltage difference between strings [15] [17] and Joule losses in DC circuits [15]. This work proposes to include the effect of saturation in the output power of the inverter [18] to obtain the total output power (P_{AC}) through the logic equation below:

$$P_{AC} = \begin{cases} P_{ACvir}, & \text{if } P_{ACvir} \leq \mathrm{P}_{N-INV} \\ \mathrm{P}_{N-INV}, & \text{if } P_{ACvir} > \mathrm{P}_{N-INV} \end{cases}, \tag{5}$$

where $\mathrm{P}_{\mathrm{N-INV}}$ is the nominal power of the inverter informed by the manufacturer.

2.4 Validation

In this section, a comparison is made between the real generation data of the PV plant with the results obtained from the simulation implemented through the evaluated model using the technical specifications of the plant and weather dataset. For comparison purposes, some statistical metrics presented by Kazem [19] were used. Considering the real power of the plant (P_{usina}) and the simulated power output of the plant (P_{sim}), both given in kW, the mean absolute error (MAE) and the mean absolute percentage error (MAPE) are calculated from eq. (6):

$$\text{MAE} = \left|\overline{P_{\text{usina}}} - \overline{P_{\text{sim}}}\right| \text{ and } \text{MAPE} = \frac{\left|\overline{P_{\text{usina}}} - \overline{P_{\text{sim}}}\right|}{\overline{P_{\text{usina}}}} \cdot 100\%. \tag{6}$$

Considering P_{AC} the output power value at instant k and Nh the total number of simulation hours, the following equation for calculating the root mean square error (RMSE) is used:

$$\text{RMSE} = \sqrt{\frac{1}{Nh} \cdot \sum_{\text{k}=1}^{Nh} \left(P_{AC}(\text{k}) - P_{\text{usina}}(\text{k})\right)^2}. \tag{7}$$

2.5 Validation Algorithm

The validation algorithm can be seen in the flowchart in Figure 1. The algorithm is divided into 4 steps. In the 1st stage, the initialization of parameters and reading of meteorological and generation data of an existing plant are carried out. In the 2nd step, the calculation of photovoltaic power by MPPT and by inverter is executed, in the 3rd step of the algorithm, the total power is calculated using the model described in section 2 considering all losses, factors and the inverter saturation logic. In the last step, the simulation results are extracted.

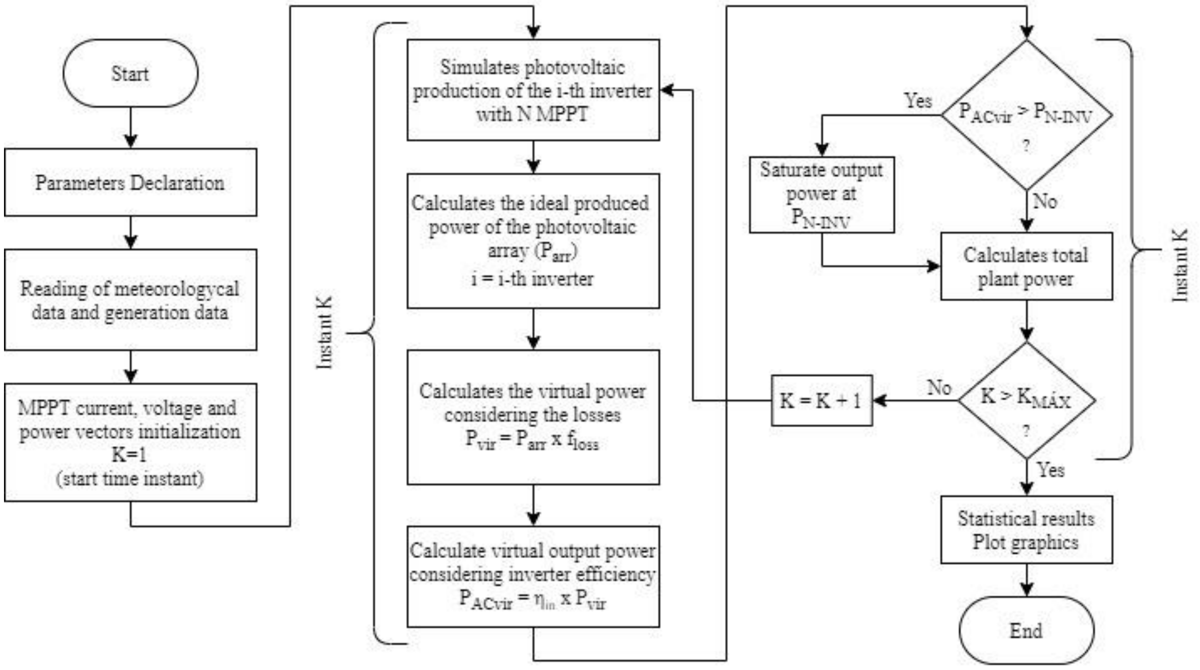

Figure 1. Flowchart - Algorithm

3 Results

The sub-system used to validate the model is part of the university plant and comprises 284 photovoltaic modules of 310 Wp and 2 inverters of 36 kW. Each inverter is installed in a topology of 8 strings (6x18 + 2x17) containing 4 MPPTs per device. The building has a gable roof, one facing 128º southwest and the other facing 52º northeast, both with a tilt of 15º. The modules were installed directly on the roof, divided equally between the two sides. The modules of the 104.1 inverter are installed with 52º northeast azimuth deviation and those from 104.2 in the opposite direction. The short circuit current (I_{sc}) of the modules is 9.91 A, the open circuit voltage (V_{oc}) is 40.3 V and the number of cells (N_{cells}) is 60. The saturation power for each inverter is 36 kW and the European efficiency (η_{in}) is 0.985. The rest of the data related to losses were acquired through the PVSyst software [20].

Table 1. Loss / multiplier monthly considered.

Multiplier	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Opt	Nov	Dec
$tf_{52^\circ NE}$	0.96	0.98	1.03	1.04	1.08	1.08	1.08	1.04	1.02	0.99	0.95	0.96
$tf_{128^\circ SW}$	0.99	0.97	0.93	0.92	0.87	0.87	0.87	0.92	0.94	0.96	1.00	0.99
f_{loss}	0.88	0.88	0.88	0.90	0.90	0.91	0.91	0.91	0.90	0.89	0.89	0.88

The values found, respectively, for the near shading factor (f_{near}), the soiling factor ($f_{soiling}$) and the incidence angle modifier factor (f_{IAM}), were 0.996, 0.97 and 0.963. Other losses and factors stratified month by month were presented in Table 1.

Table 2 presents the statistical results that compares the simulated average power (SAP) and simulated average energy (SAE) with the real data measured in the Language Center plant, plant average power (PAP) and plant average energy (PAE). Also presents the statistical data used to validate the method. It is noted that, over a year, the MAPE presents a value of 8.8%. In addition, there is a low RMSE error for every month, which implies a simulated energy graph that follows, or approximates, the average plant energy graph, which is expected in the case of a good energy system simulation.

Table 2. Statistics results

Season	PAP (W)	SAP (W)	PAE (kWh)	SAE (kWh)	MAE (kW)	MAPE (%)	RMSE (kW)
Summer	14630.8	14571.9	2458.0	2448.1	0.6	4.4	0.5
Autumn	10023.8	10448.9	1684.0	1755.4	1.5	15.5	0.4
Winter	12901.8	14398.4	2167.5	2418.9	1.5	11.1	0.5
Spring	14990.5	17368.3	2518.4	2917.9	2.4	15.6	0.6
Total	13136.7	14287.2	26483.6	28803.1	1.15	8.8	0.15

Figure 2 presents a comparison between the simulated and the real daily power curves. The presented data is relative to 42 days distributed over the months of one year. It is possible to notice that the simulated power curve follows the real curve with good precision, which corroborates the information of low RMSE errors presented in Table 2. It is verified that the simulated generation has a maximum value of 72 kW due to the saturation effect of the inverters. Figure 3 presents a comparative graph of the real and simulated energy generated month by month. Note that the simulated energy is predominantly higher throughout the year.

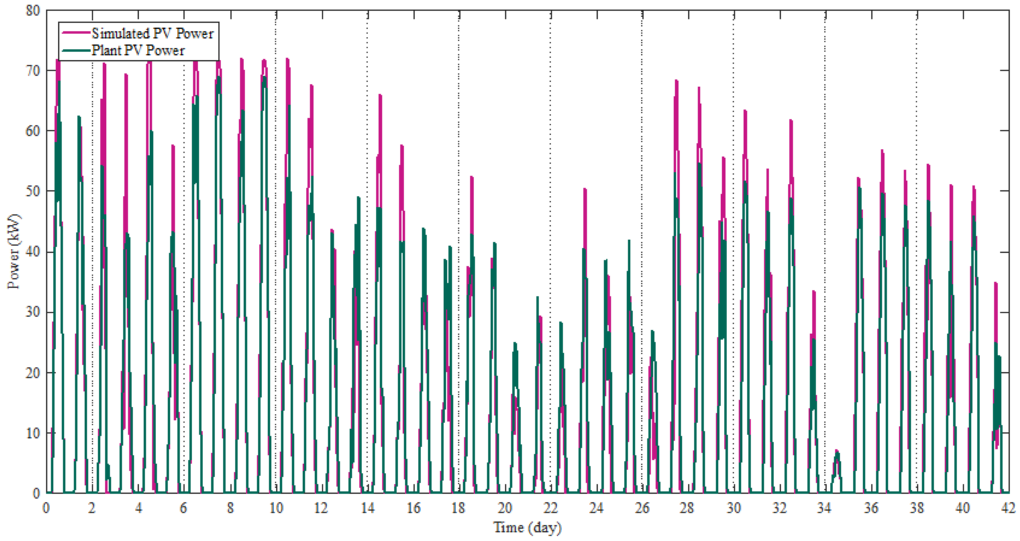

Figure 2. Comparison between the power supplied by the PV plant and the power supplied by the PV model

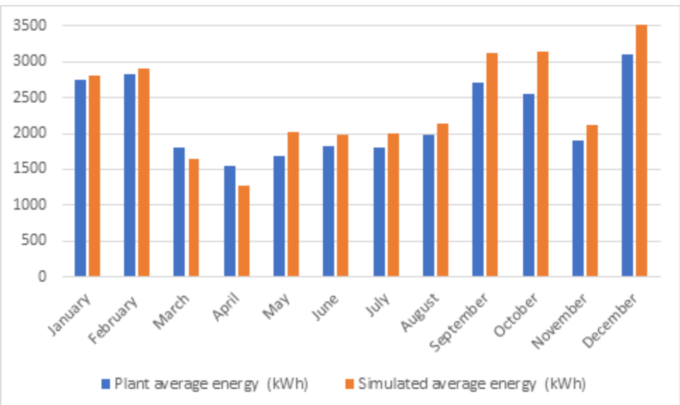

Figure 3. Comparison between the energy generated by the PV plant and the energy simulated by the PV model

4 Conclusions

This article presented the validation of a mathematical modeling methodology for photovoltaic systems using weather data. It was able to validate the proposed mathematical model, since the mean average percentage error found of 8.8% is an acceptable value, and it is close to the percentages presented by Thevenard [21] and Kazem [19]. This model will serve as a useful tool and will be able to help researchers, students and workers in the solar photovoltaic generation field and will collaborate in the assess of photovoltaic plants according to weather data.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] ABSOLAR, "Panorama da solar fotovoltaica no Brasil e no mundo," 2021. https://www.absolar.org.br/mercado/infografico/ (accessed Aug. 10, 2021).

[2] D. P. Silva, J. L. Félix Salles, J. F. Fardin, and M. M. Rocha Pereira, "Management of an island and grid-connected microgrid using hybrid economic model predictive control with weather data," *Appl. Energy*, vol. 278, no. August, p. 115581, Nov. 2020, doi: 10.1016/j.apenergy.2020.115581.

[3] A. N. de E. E. (ANEEL), "Dados abertos." https://www.aneel.gov.br/dados/geracao (accessed Jul. 28, 2021).

[4] A. Agüera-Pérez, J. C. Palomares-Salas, J. J. González de la Rosa, and O. Florencias-Oliveros, "Weather forecasts for microgrid energy management: Review, discussion and recommendations," *Appl. Energy*, vol. 228, pp. 265–278, Oct. 2018, doi: 10.1016/j.apenergy.2018.06.087.

[5] GoodWe, "Datasheet Linha LV MT." https://br.goodwe.com/Public/Uploads/productsbr/pdf/GW_LVMT_Datasheet-PT.pdf (accessed Jul. 30, 2021).

[6] A. M. Humada, M. Hojabri, S. Mekhilef, and H. M. Hamada, "Solar cell parameters extraction based on single and double-diode models: A review," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 494–509, Apr. 2016, doi: 10.1016/j.rser.2015.11.051.

[7] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, May 2009, doi: 10.1109/TPEL.2009.2013862.

[8] J. E. Hay and J. A. Davies, "Calculation of the Solar Radiation Incident on an Inclined Surface.," *Proc. 1st Can. Sol. Radiat. Data Work.*, pp. 59–72, 1980.

[9] R. Perez, P. Ineichen, R. Seals, J. Michalsky, and R. Stewart, "Modeling daylight availability and irradiance components from direct and global irradiance," *Sol. Energy*, vol. 44, no. 5, pp. 271–289, 1990, doi: 10.1016/0038-092X(90)90055-H.

[10] D. Bernadette, M. Twizerimana, A. Bakundukize, B. J. Pierre, and N. Theoneste, "Analysis of Shading Effects in Solar PV System Email address : To cite this article :," *Int. J. Sustain. Green Energy*, vol. 10, no. 2, pp. 47–62, 2021.

[11] A. Comerio, P. R. Muniz, M. Rampinelli, and J. F. Fardin, "A review on impacts from dust deposition on photovoltaic modules," *2018 13th IEEE Int. Conf. Ind. Appl. INDUSCON 2018 - Proc.*, pp. 502–508, 2019, doi: 10.1109/INDUSCON.2018.8627241.

[12] A. Kimber, L. Mitchell, S. Nogradi, and H. Wenger, "The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest Region of the United States," *Conf. Rec. 2006 IEEE 4th World Conf. Photovolt. Energy Conversion, WCPEC-4*, vol. 2, pp. 2391–2395, 2006, doi: 10.1109/WCPEC.2006.279690.

[13] K. Meisenzahl *et al.*, "Measuring the incidence angle modifier of optically uncoupled glass for PV application," in *36th European Photovoltaic Solar Energy Conference and Exhibition*, 2019, no. October, pp. 1252–1256, doi: 10.4229/EUPVSEC20192019-4AV.2.57.

[14] M. Valentini, A. Raducu, D. Sera, and R. Teodorescu, "PV inverter test setup for European efficiency, static and dynamic MPPT efficiency evaluation," in *2008 11th International Conference on Optimization of Electrical and Electronic Equipment*, May 2008, pp. 433–438, doi: 10.1109/OPTIM.2008.4602445.

[15] J. J. Roberts, A. Cassula Marotta, J. C. Freire Junior, and P. O. Prado, "Simulation and Validation of Photovoltaic System Performance Models," *B. Abstr. Proc. 11th Latin-American Congr. Electr. Gener. Transm. CLAGTEE 2015*, no. November 2018, p. 82, 2015, doi: 978-85-61065-02-7.

[16] A. D. Dhassa, E. Natarajana, and P. Lakshmi, "An investigation of temperature effects on solar photovoltaic cells and modules," *Int. J. Eng. Trans. B Appl.*, vol. 27, no. 11, pp. 1713–1722, 2014, doi: 10.5829/idosi.ije.2014.27.11b.09.

[17] N. D. Kaushika and A. K. Rai, "An investigation of mismatch losses in solar photovoltaic cell networks," *Energy*, vol. 32, no. 5, pp. 755–759, 2007, doi: 10.1016/j.energy.2006.06.017.

[18] E. Martins Deschamps and R. Rüther, "Optimization of inverter loading ratio for grid connected photovoltaic systems," *Sol. Energy*, vol. 179, no. December 2018, pp. 106–118, Feb. 2019, doi: 10.1016/j.solener.2018.12.051.

[19] H. A. Kazem and J. H. Yousif, "Comparison of prediction methods of photovoltaic power system production using a measured dataset," *Energy Convers. Manag.*, vol. 148, pp. 1070–1081, 2017, doi: 10.1016/j.enconman.2017.06.058.

[20] PVsyst, "PVSYST PDF TUTORIALS." https://www.pvsyst.com/pdf-tutorials/ (accessed Aug. 10, 2021).

[21] D. Thevenard and S. Pelland, "Estimating the uncertainty in long-term photovoltaic yield predictions," *Sol. Energy*, vol. 91, pp. 432–445, May 2013, doi: 10.1016/j.solener.2011.05.006.