VALIDATION OF PHOTOVOLTAIC MODEL FOR APPLICATION IN A DISTRIBUTED ENERGY SOURCE USING WEATHER DATA

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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.


RESUMO: Este trabalho apresenta um modelo fotovoltaico para simulação da produção de energia elétrica de um sistema de energia distribuída. O modelo será validado por meio de dados meteorológicos medidos e da energia produzida por uma usina de 88,04 kWp instalada na Universidade Federal do Espírito Santo (UFES), em Vitória. A validação consiste em comparar os dados reais de energia adquiridos pela usina fotovoltaica e os dados de energia calculados a partir do modelo usando dados meteorológicos, especificações dos painéis e inversores e as características construtivas do sistema. O modelo proposto é baseado no artigo "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. Além disso, o modelo foi aprimorado com a inclusão de novos parâmetros intrínsecos do material, o cálculo de perdas e os ajustes para diferentes ângulos de inclinação e orientações de azimute. Os resultados desse método revelam que o modelo foi capaz de reproduzir o comportamento da usina fotovoltaica real, apresentando um erro percentual absoluto médio de 8,8% entre os dados reais e os simulados.
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 (°C) 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. Erro! Fonte de referência não encontrada.: 

\[ I = I_{ph} - I_0 \left( \frac{qV_D}{e^nK \cdot T} - 1 \right) - \frac{V_D}{R_{sh}} \quad \text{and} \quad I_{ph} = I_{sc} \cdot \lambda_{coll}. \] (1)

Where, I is the output current, Iph is the photo-generated current, I0 is the reverse saturation current, q is the elementary electric charge of an electron, VD 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 Rsh is the shunt resistance of the model. In the photovoltaic current equation, Isc is the short-circuit current informed by the photovoltaic module manufacturer and \( \lambda_{coll} \) 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 (fnear) [10], the soiling factor (fsoiling) [11] [12] and the incidence angle modifier factor (fIAM) [13], the incident solar radiation on the
collectors plane (\( \lambda_{coll} \)) is calculated through eq. Erro! Fonte de referência não encontrada.: 

\[
\lambda_{coll} = f_{near} \cdot f_{soiling} \cdot f_{LAM} \cdot tf \cdot \lambda,
\]

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

\[
V_D = V_{pv} + R_s \cdot I.
\]

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 \( \Omega \) and 351.39 \( \Omega \), 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 1.6005·10-12 A and 1.0313, respectively.

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:

\[
P_{arr} = \sum_{j=1}^{3} \sum_{i=1}^{i} P_{mppt(ij)}.\]

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 (\( P_{A_{vir}} \)) 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 (PAC) through the logic equation below:

$$P_{AC} = \begin{cases} P_{AC\text{vir}}, & \text{if } P_{AC\text{vir}} \leq P_{N-INV} \\ P_{N-INV}, & \text{if } P_{AC\text{vir}} > P_{N-INV} \end{cases}$$

where PN-INV is the nominal power of the inverter informed by the manufacturer.

2.3 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 (Pusina) and the simulated power output of the plant (Psim), both given in kW, the mean absolute error (MAE) and the mean absolute percentage error (MAPE) are calculated from eq. Erro! Fonte de referência não encontrada.:  

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

(6)
Considering PAC 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:

\[
RMSE = \sqrt{\frac{1}{Nh} \sum_{k=1}^{Nh} (P_{AC}(k) - P_{usina}(k))^2}.
\]  

(7)

2.4 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 a 52º northeast azimuth deviation and those from 104.2 in the opposite direction. The short circuit current (Isc) of the modules is 9.91 A, the open circuit voltage (Voc) is 40.3 V and the number of cells (Ncells) is 60. The saturation power for each inverter is 36 kW and the European efficiency (ηin) is 0.985. The rest of the data related to losses were acquired through the PVSyst software [20].
Table 1. Loss / multiplier monthly considered.

<table>
<thead>
<tr>
<th>Multiplier</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{PNE}} )</td>
<td>0.96</td>
<td>0.98</td>
<td>1.03</td>
<td>1.04</td>
<td>1.08</td>
<td>1.08</td>
<td>1.04</td>
<td>1.02</td>
<td>0.99</td>
<td>0.95</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>( f_{\text{LSW}} )</td>
<td>0.99</td>
<td>0.97</td>
<td>0.93</td>
<td>0.92</td>
<td>0.87</td>
<td>0.87</td>
<td>0.92</td>
<td>0.94</td>
<td>0.96</td>
<td>1.00</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>( f_{\text{IAM}} )</td>
<td>0.88</td>
<td>0.88</td>
<td>0.88</td>
<td>0.90</td>
<td>0.90</td>
<td>0.91</td>
<td>0.91</td>
<td>0.90</td>
<td>0.89</td>
<td>0.89</td>
<td>0.88</td>
<td></td>
</tr>
</tbody>
</table>

The values found, respectively, for the near shading factor (f\(_{\text{near}}\)), the soiling factor (f\(_{\text{soiling}}\)) and the incidence angle modifier factor (f\(_{\text{IAM}}\)), 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>
<thead>
<tr>
<th>Season</th>
<th>PAP (W)</th>
<th>SAP (W)</th>
<th>PAE (kWh)</th>
<th>SAE (kWh)</th>
<th>MAE (kW)</th>
<th>MAPE (%)</th>
<th>RMSE (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>14630.8</td>
<td>14571.9</td>
<td>2458.0</td>
<td>2448.1</td>
<td>0.6</td>
<td>4.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Autumn</td>
<td>10023.8</td>
<td>10448.9</td>
<td>1684.0</td>
<td>1755.4</td>
<td>1.5</td>
<td>15.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Winter</td>
<td>12901.8</td>
<td>14398.4</td>
<td>2167.5</td>
<td>2418.9</td>
<td>1.5</td>
<td>11.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Spring</td>
<td>14990.5</td>
<td>17368.3</td>
<td>2518.4</td>
<td>2917.9</td>
<td>2.4</td>
<td>15.6</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>13136.7</td>
<td>14287.2</td>
<td>26483.6</td>
<td>28803.1</td>
<td>1.15</td>
<td>8.8</td>
<td>0.15</td>
</tr>
</tbody>
</table>

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.

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References


