Analysis of PV Generation in Honduras by a Mathematical Model in MATLAB / SIMULINK

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Abstract. Today it is common to see how many countries are seeking to reduce their dependence on fossil fuels, so the incorporation of photovoltaic systems has become an alternative to such dependence. In Honduras, it is predicted that by the year 2038, 80% of the energy matrix will be renewable, and approximately 20% of the energy generated is through photovoltaic systems [1]. The objective of this document is to present a procedure for the mathematical modeling of PV modules with a significant volume of data from the different active weather stations distributed throughout the country as input parameters into Matlab/Simulink, and based on this, the electricity generation at the location of these stations is shown according to their solar hours. The model presented is based on equations obtained from an equivalent circuit of a diode that will be able to denote the I-V and P-V output characteristics of a typical 435 W solar module. These characteristics will be determined by the models developed under the meteorological conditions of temperature and solar irradiation that are present in the different departments of the Honduran territory where the weather stations are located. The design of the module is through easy-to-use icons, and a dialog box that the Simulink libraries provide.

1. Introduction
In Honduras, environmental damages have increased during this century and the dependence on fossil fuels has not been significantly reduced, which forces the country to plan an energy model that can satisfy the demands of this society and that does not create a considerable environmental impact to that which is already present in the country.

The use of new solar modules has been shown to be an alternative to the problems that arise today. Photovoltaic systems convert solar energy into electrical energy by taking advantage of the apparently inexhaustible resource of the sun [2], as this is an inexhaustible source, making photovoltaic solar energy a fairly essential means of generating energy. For the use of this technology is relevant the implementation prior to installation of several tools with which it will facilitate the analysis of the behavior of solar modules used [3], evaluate different input parameters such as temperature and radiation that occurs in the area. In this document present the relevance of the tools for the design and analysis of the photovoltaic module modeling is noted. Based on this, a mathematical model will be made in order to design a more efficient model using MATLAB/SIMULINK.
2. Previous studies
The efficiency of solar photovoltaic systems is greatly reduced due to certain non-linear variations found in the output voltage and current. This is due to the behavior of certain variables such as solar radiation and the operating temperature of the solar modules. The latter is one of the most influential, since, based on standard STC condition tests above 25 °C, the 1 °C increase in the surface temperature of the photovoltaic module decreases by 0.5% - 0.65% the efficiency of the same \[^4\]. The behavior of the output voltage when affected by the working temperature of the solar module affects its power output, demonstrating the effect it has on efficiency.

3. Context
Honduras is one of the many countries that are part of various agreements and treaties for the reduction of greenhouse gas pollution. As a result of being part of these treaties, the Honduran energy matrix has been evolving, becoming more diverse by incorporating renewable energy systems. By 2015, the country only had 388 (MW), and by 2019 it already had an increase to 510.8 (MW) of installed nominal power \[^5\].

With the passing of time, technological advances have increased, thus helping the development and implementation of PV technology, providing much more efficient and better performing equipment. It is taken into account that this is a relatively young technology, since around 1995 only approximately 1TWh was produced in the world. Eventually its efficiency increased until it had a percentage of efficiency of 20% at present \[^6\].

4. Methodology

4.1. Mathematical modelling and design of PV cell
A solar photovoltaic module is usually modeled on the equivalent use of a model circuit, which comprises an ideal current source (Iph) connected in parallel to one or two diodes depending on the type of model used (one diode being the present case) and also to a resistance in series (Rs) and another in parallel (Rp) \[^7\]. The equivalent circuit of a diode used in the model presented is shown in Figure 1.

![Figure 1. Equivalent circuit of one diode](image)

From Figure 1 the output current (I) for a single-diode model is written by applying Kirchhoff’s Current Law (KCL) to the single-diode circuit:

\[
I = I_{ph} - I_d - I_{sh}
\]  (1)

Where:
- \(I\) = Current of the photovoltaic module (A)
- \(I_{ph}\) = Inverse saturation photovoltaic current (A)
- \(I_d\) = Diode current (A)
- \(I_{sh}\) = Shunt current (A)

**Step 1**: Put the values of constant parameters as given following:
- \(Rs = 0.001\) (Ω)
- \(G=\)Solar irradiance per 1000 (W/m\(^2\)) = 1
q = Load of one electron = 1.6e10\(^{-19}\)
n = ideal factor = 1.3
Ns = number of cells in series = 36
Np = number of cells in series = 1
K = Boltzmann’s constant = 1.3805e10\(^{-23}\) (J/K)

**Step 2:** Module saturation current of the diode (\(I_0\)) is designed as Figure 2, depends on working temperature. Can be calculated as (2):

![Modelled circuit for saturation current of the diode](image)

**Figure 2.** Modeled circuit for saturation current of the diode

\[
I_0 = I_{rs} \left( \frac{T_1}{T_0} \right)^3 \exp \left[ \frac{q \cdot E_{g0} \cdot \left( \frac{1}{T_n} - \frac{1}{T} \right)}{(n \cdot K)} \right] \tag{2}
\]

Where:
- \(I_{rs}\) = Inverse saturation current (A)
- \(T_n\) = Reference temperature = 298 (K)
- \(E_{g0}\) = Silicon Band Gap = 1.1 eV

**Step 3:** Module inverse saturation current (\(I_{rs}\)) is designed as Figure 3, and can be calculated as (3):

![Modelled circuit for inverse saturation current](image)

**Figure 3.** Modeled circuit for inverse saturation current

\[
I_{rs} = \frac{I_{sc}}{\exp \left( \frac{q \cdot V_{oc}}{N_s \cdot n \cdot K \cdot T} \right) - 1} \tag{3}
\]

- \(I_{sc}\) = Short circuit current (A)
- \(V_{oc}\) = Open circuit voltage (V)

**Step 4:** Module inverse saturation photocurrent (\(I_{ph}\)) is designed as Figure 4, and can be calculated as (4):

![Modelled circuit for photocurrent](image)
Figure 4. Modeled circuit for inverse saturation photocurrent.

\[ I_{ph} = \frac{I_{sc} + (K_i \times (T - 298)) \times G}{1000} \]  

(4)

Where:
G = Irradiance (W/m²)

Step 5: To conclude with equation (5) the module shunt current or parallel resistance current is designed as Figure 5 and calculated as (5):

\[ I_{sh} = \frac{(V + I \times R_s)}{R_{sh}} \]  

(5)

Where:
R_s = Resistance in parallel (Ω)

Step 6: Integration of each of the modules in the structure of the algorithm through data blocks is designed as Figure 6 provided by libraries of Matlab.

Figure 6. Modeled circuit for I-V

Step 7: PV module designed as Figure 7.
4.2. Reference model
The 435W solar module has been taken as a base module and detailed specifications are given in TABLE 1:

Table 1. Description of solar cell parameter

| Technical parameters                  | MSX 435 W   |
|---------------------------------------|-------------|
| Nominal Max. Power (max)              | 435 (W)     |
| Opt. Operating Voltage (Vmp)          | 39.9 (V)    |
| Opt. Operating Current (Imp)          | 10.91 (A)   |
| Open Circuit Voltage (Voc)            | 48.1 (V)    |
| Short circuit current (Isc)           | 11.47 (A)   |
| Number of cells in series (Ns)        | 36 (-)      |
| Number of cells in parallel (Np)      | 1 (-)       |

5. Results and Analysis

5.1. Simulations
The simulations using the mathematical model of the photovoltaic solar module made in Matlab / Simulink allowed us to calculate the delivery power for each of the data extracted from the meteorological stations in the country, based on the technical specifications of the photovoltaic solar module that was used in this research.

In figure 8 shows an average of the delivery power can be seen with the data taken for the year 2019 from each of the meteorological stations that were analyzed. A global average of 200.93 (W) of delivery power was obtained.
5.1.1. Stations Agua Caliente and La Concepción. Figure 9 shows the months with the highest power output under the climatic conditions of the place where both weather stations are located. The months with the highest power output were March, April and September, delivering approximately 45% of their nominal power. Figure 10 shows the energy generated under such conditions, generating approximately during the year 2,030.26 (Wh), being the months of April-June where most energy was generated.

![Figure 9. Output P-V plot from Agua Caliente and La Concepción.](image)

![Figure 10. Generated energy from Agua Caliente and La Concepción.](image)

5.1.2. Station Ermita. The weather station is located in Francisco Morazán. The figure 11, denotes that the months of greater delivery of power are from February to April with a 52.44% with respect to its nominal power, nevertheless, the figure 12 shows that the months where I present/display more generation are the months of March, April and June with an approximated one of 2,893.8 (Wh).

![Figure 11. Output P-V plot from La Ermita](image)

![Figure 12. Generated energy in La Ermita](image)

5.1.3. Station Coyolar. In the previous weather station, the months of greatest energy delivery are between February and March at the El Coyolar station. However, at the location of this station the module performance is more efficient, with 61% efficiency compared to 52.4% at La Ermita weather station. Figure 13 shows the power delivered throughout the year, and figure 14 shows the months of greatest generation are from February to April, with a generated energy of approximately 3,003 (Wh).

![Figure 13. Output P-V plot from Coyolar.](image)

![Figure 14. Generated energy from Coyolar.](image)
5.1.4. Station Guayabillas. Figure 15 shows the performance of the model used for this research under the meteorological conditions of Las Guayabillas station. The months that presented the greatest power delivery were March, August and September, showing an efficiency of 51.04% compared to standard test condition. Figure 16 denotes the generation in the different months of the year for this weather station.

![Figure 15. Output P-V plot from Guayabillas.](image)

![Figure 16. Generated energy from Guayabillas.](image)

5.1.5. Station La Entrada. La Entrada station, located in the west of the country, has 8.16% less irradiation per square meter compared to the Ermita, however, its monthly temperature is relatively lower, 30.7 (°C) of the 31 (°C) that are concentrated in the Ermita, even receiving less irradiation. In figure 17 it is shown as “The entrance” presents 1.93% more power delivery than the Hermitage, due to its temperature. Figure 18 shows the generation of the proposed module throughout the year, generating approximately 2,854.71 (Wh) in the months of March, April and June, being the months of highest generation.

![Figure 17. Output P-V plot from La Entrada.](image)

![Figure 18. Generated energy from La Entrada.](image)

5.1.6. Station Playitas. Figures 19 and 20 show a significantly high efficiency of 65.34% of its annual energy supply, 4.34% more than El Coyolar station. The estimated monthly temperature in this sector is 31.70 (°C), which is not a high temperature compared to the 5,080 (W/m²) it receives in the sector.

![Figure 19. Output P-V plot from La Playitas.](image)

![Figure 20. Generated energy from La Playitas.](image)
5.1.7. Station Quimistan. Figure 21 shows the performance of the module used under the climatic conditions of Quimistan, Santa Barbara. The P-V curve shows how the module managed to deliver 52.53% of its nominal power in that sector. Figure 22 shows the energy generated throughout the year, with an average annual generation of 2,497 (Wh).

![Figure 21. Output P-V plot from Quimistan.](image1)

![Figure 22. Generated energy from Quimistan.](image2)

5.1.8. Station Victoria. Figure 23 shows that the month of highest output power delivery at La Victoria station is September with an efficiency of 62.01%. Figure 24 denotes that a year-round yield of 59.82% is maintained, under climatic conditions of 31.25 (°C) and 4462.75 (Wh/m²), with an approximate generation throughout the year of 2,725(W).h.

![Figure 23. Output P-V plot from Victoria.](image3)

![Figure 24. Output P-V plot from Victoria.](image4)

6. Conclusions
In this document it was possible to make a mathematical model capable of predicting the power of input parameters determined by the different weather stations, and based on the simulations developed, conclusions are reached:
1. The temperature has a considerable degree of effect on the P-V output characteristics of the model used in this research.
2. As the output power is affected by the heating of the solar cells, these also directly affect the I-V output characteristics of the module.
3. The energy generated under certain weather conditions denotes that temperature has a greater impact on its efficiency than radiation.
4. With regard to the output powers obtained from the model used, it was determined that the months of greatest use in terms of PV energy generation at the weather stations are the months of March, April and September, maintaining 52.90% efficiency throughout the year.

7. References
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