Measured and Simulated Performance of a Grid-Connected PV System in a Humid Subtropical Climate

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Abstract

This paper describes research aimed to determine the measured and predicted performance of a photovoltatic grid-connected system in a humid subtropical climate. The performance was modeled and the predicted performance of the systems was compared to the experimentally collected data for the system. In addition, the research allowed for long term simulation analysis of the system under varying conditions and can assist with the optimization of the photovoltaic system.

1. Introduction

As the global population increases along with the advancement of human development and technology, so does the increase in global energy demand. According to the US Energy Information Administration's 2013 report, the world energy consumption was expected to grow by 56% between 2010 and 2040, from 524 quadrillion British thermal units (Btu) to 820 quadrillion Btu [1]. Through these projections, it was estimated that fossil fuels will continue to supply roughly 80% of the world energy through 2040 [1]. Fossil fuels are non-renewable resources with supplies that are drastically being depleted. It was calculated that the depletion time for oil, gas and coal was to be around 35, 37 and 107 years, respectively [2]. Though the accurate timing for fossil fuel depletion is an arguable topic among researchers and scientists, it is an inarguable fact that fossil fuels cannot last forever at the current usage rates. The increase in demand for energy coupled with the knowledge of depleting fossil fuels has led to an increase in demand for research into developing an alternative to using fossil fuels; the most viable alternative being solar energy by means of photovoltaic (PV) modules.

PV production has been doubling every 2 years, increasing by an average of 48% each year since 2002, making it the world's fastest-growing energy technology [3]. PV systems depend on a variety of factors including but not limited to: weather, irradiation levels, temperature, and efficiencies in all components of the system. Various methods have been developed to determine the maximum power output of these photovoltaic systems to improve overall efficiency. This paper aims to determine and analyze the power output of a photovoltaic grid-connected system using the TRNSYS simulation program compared to the recorded performance of the system.

Nomenclature

I	electric current (A)	*Subscripts*	
P	electrical power (W)	*c*	cell (module)
T	temperature (K)	*m*	maximum
Tc	cell/module operating temperature (K)	*mpp*	at maximum power point
V	voltage (V)	*NOCT*	at NOCT conditions
NOCT	normal operating cell temperature (°C)	*oc*	open circuit
		sc	short circuit

2. Description of the System

2.1 System components and characteristics

The University of Texas at Tyler's Texas Allergy, Indoor Environment and Energy (TxAIRE) Institute developed realistic test facilities for the development and demonstration of new technologies related to energy efficiency. The photovoltaic system used for this study was the system supplying the energy for TxAIRE House 2. TxAIRE House 2 is a Net-Zero Energy house as all the power is provided by the ground PV system and it is located in Tyler, Texas which is classified as humid subtropical climate.

The house has a photovoltaic grid-connected system, consisting of thirty-three SolarWorld® SunModule Plus™ polycrystalline 225 Watt solar panels, rated at 7.4 kW. The performance standards under standard test conditions as well as the thermal characteristics as supplied by the manufacturer on the data sheet are shown in Table 1 and Table 2, respectively for the solar modules.

Table 1. Performance under standard test conditions (STC) of 1000 W/m2, 25ºC, AM 1.5.

Characteristic	**Variable**	**SW 225**
Maximum power	P_{max}	225 W
Open circuit voltage	V_{oc}	36.8 V
Maximum power point voltage	V_{mpp}	29.5 V
Short circuit current	I_{sc}	8.17 A
Maximum power point current	I_{mpp}	7.63 A

Table 2. Thermal characteristics of solar panels.

Characteristic	Parameter
NOCT	45ºC
TC I_{sc}	0.034 %K
TC Voc	-0.34 %K
TC P_{mpp}	-0.48 %K
Operating range	-40ºC to 90ºC

The solar panels used for the research are installed in three circuits of eleven modules per circuit for a total of 33 modules. This array converts the solar radiation into DC electricity while an inverter unit is used to convert the DC electricity to AC so that it can be fed into the house's electrical system. The inverter unit in this system was manufactured by SMA Technology model, #SB7000US.

The photovoltaic modules cover an area of 590 ft^2 and are situated on the ground and 25 ft. away from the roofline of the house and are at a 55.8º angle as shown in Table 1 and Table 2.

Figure 1. Back view of photovoltaic panels used in study.

Figure 2. Front view of photovoltaic panels used in study.

2.2 Meteorological data collection

The archival data used for comparison in this study is the PV performance and weather data collected from TxAIRE House 2 from August 17th 2012 to December 31st 2014.The variables of interest in terms of PV performance included: solar panel energy (W) and the total solar radiation on the tilted surface (W/m^2). The radiation data was recorded as total radiation. The TRNSYS program requires that the data be input as beam and diffuse radiation, therefore the assumption that beam is approximately 85% of the total and diffuse is 15% of the total recorded radiation was assumed and split into the two prior to being input into the program. Weather data was also collected throughout the same aforementioned time period. The variables of interest in terms of weather data were temperature (°F) and wind speed (mph).

The data for the house was collected using the NI-cRIO-9074 processor; a 400 MHz industrial real-time processor for control, data logging and analysis. PR-T24 thermocouple wires, polyvinyl insulated wires, were also used in retrieving the outside temperature. The data acquisition system (DAQ) was connected by USB to a personal software notebook to retrieve the data.

The weather data was collected from a Davis Vantage Pro 2 weather station situated above TxAIRE House 2 on the roof as shown in Figure 3.

The data was collected every 30 minutes for the time period used for this study for weather and PV performance.

Figure 3. Location of weather station on roof of TxAIRE House 2.

3. System Modeling in TRNSYS

3.1 Overall system

TRNSYS was the software package used to simulate the PV system. This software package uses the one-diode, five parameter model as developed by De Soto [4]. The simulation had the basic outline as shown in

Figure 4 which uses the following components: Type9 (user entered data labeled as Weather Data), Unit Conversion (to convert units to SI), Type 194b PV-Inverter (uses five parameter model as presented by De Soto to solve) and Type65d. The component labeled “Start and Stop Times” was the area in which to input the start and stop time of the simulation. Weather data was input into the Type9 component as a CSV file with temperature, total radiation on the tilted surface and wind speed along with the date and time. These values were then converted into SI units with the unit conversion component and input into the Type 194b PV-Inverter component and output graphically using Type65d. The components labeled Power Output, Voltage, and Current also output those data points for the simulation as a .dat file that could then be opened with Microsoft Excel.

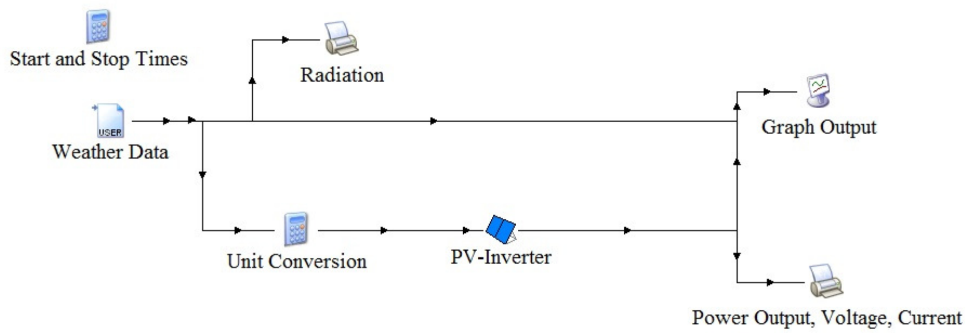

Figure 4. TRNSYS simulation setup.

3.2 Component overview

The first component in the system is the controls (labeled as Start and Stop Times). The start time and stop time are input into this component in terms of hours of the year. For example, if the data file starts on the 145th day of the year at midnight, then the input for start time would be 3480 (24 * 145).

One of the most important components in the simulation is the Type9 component (labeled Weather Data). Type9 is a component that reads data at regular time intervals from a user defined data file. This allows for the user to input data from weather data recorded experimentally rather than taken from the weather database that is included in the TRNSYS package. The component reads the data for the solar radiation, temperature and wind speed and outputs it to the unit converter in terms of W/m^2, Fahrenheit and mph, respectively. The Unit Conversion component then converted the units to SI units (radiation had been converted to kJ/m^2, the temperature to Celsius and the wind speed to m/s) to be input into the Type194b PV-Inverter component.

The most important component in the simulation was the Type194b PV-Inverter component. Type194b determines the electrical performance of a photovoltaic array and may be used with simulations involving electrical storage batteries, direct load coupling or utility grid connections such as the system used in this study. The model determines the current and power of the array at a specified voltage and will also output the current and voltage at the maximum power point. This component uses De Soto's one-diode, five-parameter model to calculate the PV performance. There are other components in TRNSYS to determine the output of PV systems; however this component differs from the others in that it also considers the effects of the inverter and its efficiency. Therefore, this component was chosen to model the PV system because of the added calculation of the inverter efficiency. The inputs of the component come from two sources. One source is the outputs of the Type9 weather data file which are the solar radiation, temperature and wind speed. The other source is from user input of the solar panel parameters mentioned in Table 1 and Table 2.

The last part of the simulation file outputs the data from Type194b into a graph using component Type65d. Type65d is an online graphics component used to display selected variables while the simulation is progressing. The component was used to display solar radiation, temperature, wind speed and PV power against date and time. The power at maximum power point, open circuit voltage and the short circuit voltage were also output into an external data file.

4. Results and Discussion

4.1 TRNSYS Results

Key PV variables and performance parameters were determined using the TRNSYS simulation software using the recorded weather data collected at five-minute intervals as the input variables. To evaluate and validate the performance model against measured data, all data was average over one-hour intervals. The weather data was then converted to TMY3 format. The model outputs are then compared to actual measured data.

As shown, the TRNSYS simulation had a maximum power output of 6770.99 W showing a 9.2% difference from the manufacturer calculated maximum power of 7425 W. To determine the accuracy of the simulation, the power output was compared to the power output as recorded by the NI-cRIO-9074 data logging processor for the years used in this study. Figure 5 shows the correlation between the predicted PV output and the recorded output as a function of radiation.

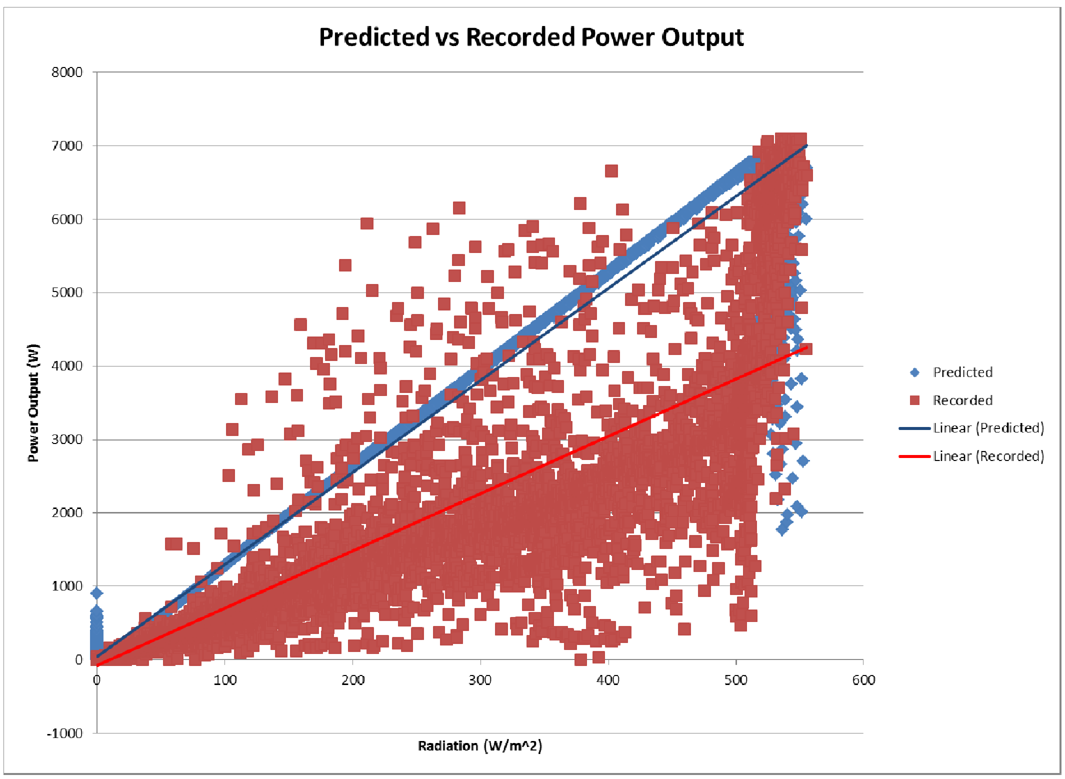

Figure 5. Predicted power versus recorded power output in terms of radiation.

The average value for recorded power was calculated to be 783 W with a maximum of 7095 W. The average value for predicted power calculated by TRNSYS was 1052 W with a maximum of 6771 W. The percent difference between both the averages was -29% and maximums was -5%. The data shows that the TRNSYS model tends to under predict the maximum solar power obtained from the solar panels, yet over predict the recorded data on average.

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4.2 Statistical Analysis

A statistical analysis was conducted using Microsoft Excel as Analysis of Variance (ANOVA). The maximum daily values of power output of the recorded data were compared to the maximum daily values of power output supplied by TRNSYS. ANOVA determines if there is a statistical difference in the data by analyzing the significant effects of the parameters using the frequency test (F-test). The analysis was carried out for a level of significance of 5% (for 95% level of confidence). Table 3 shows the result of the ANOVA analysis for three scenarios: 1) using the complete data sets (August 2012 – December 2014), 2) using only the summer months (June – September) and 3) using only the winter months (December – March). The "percent" contribution (*p*) of each factor as the total variation is shown in the last column and is an indication its influence on the result.

Using the data set for the complete time, the resulting *p* value was 6.97E-27, which indicates a difference between the two data sets. The average of the maximums for the recorded data was 5157 W with the average of the maximums for the TRNSYS data being 6002 W. The TRNSYS analysis was over predicting the power output. The next analysis was ran using only data from the summer months. This resulted in a *p* value of 1.65E-74, again showing a difference between the two data sets and a larger difference than using the entire data set. The average of the recorded data was 4070 W and the average of the TRNSYS output was 6616 W. The last analysis used only data from the winter months. The resulting *p* value was 0.204 meaning that there is not a difference in the data. The average of the recorded data was 5176 W and the average of the TRNSYS data was 5493 W.

Table 3. ANOVA Results of the analysis of variance of recorded vs. TRNSYS maximum daily power output values

	Number of Data Points	F-test	F-crit	Contribution (p, %)
Complete period	859	119.23	3.85	6.97E-27
Summer months	122	720.58	3.88	1.65091E-74
Winter months	121	1.62	3.88	0.204

The analysis showed that there is a difference in the data set, evident in the summer months, while the winter months show no difference between the data. TRNSYS over predicts during the summer months but accurately predicts in the winter months. Although there was a difference in measured versus recorded values, the trend between the measured and simulated results is similar. The difference might have come from errors within the TRNSYS component or measurement errors.

Root mean square error (RMSE), mean absolute deviation (MAD), absolute percentage error (MAPE) and model efficiency (EF) were also used to compare the recorded data to the simulated data. The RMSE is given by Eq. (1).

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(H_t - F_t)^2} \quad (1)$$

where H_t is the recorded value, F_t is the simulated value and n is the number of values in the data set. RMSE is used to measure the differences between data set values and the results should be as close to zero as possible.

The mean absolute deviation is used to calculate the average distance from each data point to the mean of the recorded data. MAD is given by the following Eq. (2).

$$MAD = \frac{1}{n}\sum_{t=1}^{n}|(H_t - F_t| \tag{2}$$

Absolute percentage error is another measure of accuracy between the recorded and simulated data points defined by Eq. (3).

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{(H_t - F_t)}{H_t}\right| \times 100\% \tag{3}$$

The last method to determine accuracies between the data points used Eq. (4) shown below for model efficiency, where z is the average value of the recorded data.

$$EF = \frac{\sum_{t=1}^{n}(H_t - z)^2 - \sum_{t=1}^{n}(F_t - H_t)^2}{\sum_{t=1}^{n}(H_t - z)^2} \tag{4}$$

The TRNSYS model accuracy results are shown in Table 4. The values for RMSE and MAD are higher than desired, indicating a difference between the recorded and modeled data. This is in line with the ANOVA analysis of the model accuracy. All of the statistics point to a difference between the recorded and modeled data, particularly at higher radiation levels.

Table 4. Model accuracy analysis results using RSME, MAD, MAPE and EF.

RMSE	**MAD**	**MAPE (%)**	**EF (%)**
1468	-884	34.88%	33.85%

4.3 Effects of radiation, temperature and wind speed review

To further develop the simulation model, radiation, temperature and wind speed data was purchased for 10 years from 2004 to 2014 for the Tyler, Texas area from Meteonorm and used in the TRNSYS simulation model. The differences in data between the recorded and the purchased showed a 1.3% difference between the temperature data, 41.5% difference in the wind speed data and a 30.8% difference in the radiation data. The wind speed data was not used in the simulation and the results ended with an 88% difference of the TRNSYS results with the purchased data and the recorded data.

Due to the differences in the data results, during the analysis of the TRNSYS simulation power output compared to the recorded power output, the effects of the variables of radiation, temperature and wind speed were reviewed and are discussed. The results showed that radiation is the leading factor in determining the power output as compared to temperature and wind speed. According to Khatib et al. [5] the power produced by PV systems is proportional to the amount of solar radiation it collects. Standard test conditions assume 1000 W/m^2; Khatib et al. [5] explain that if only half of STC conditions are available then the PV output will also only produce about half of the power. As ambient temperature increases, the cell temperature also increases. With each 1°C increase of cell temperature, PV module's power decreases by 0.5-0.6%. Bhattacharya et al. [6] show a value of correlation coefficient (R) between ambient temperature and PV performance to be 0.9642 suggesting a strong positive correlation between the two. The value of coefficient of determination (R^2) was determined to be 0.9297 meaning a 92.97% correlation between the variables indicating a direct proportionality. According to Bhattacharya et al. [6], the value of correlation coefficient (R) between wind speed and PV performance is 0.6857 with a coefficient of determination (R^2) of 0.4702. This means that 52.68% of the total variation in the PV performance variable is unexplained.

5. Conclusion

The results of this project have shown that in determining the performance of a PV grid connected system the following should be taken into account:

- The weather data has the most significant effect on the prediction performance, with the most effect coming from the radiation data followed by temperature and lastly wind speed. Therefore carefully selecting the correct weather data set is crucial; particularly the radiation data.
- The TRNSYS simulation was able to accurately predict the max power output within 5% difference; however, the average prediction had a 45% difference with most of the difference coming from calculations during the summer months.

Though accuracy can be increased with the addition of the losses due to shading, dirt, differences with the nominal power, mismatch and temperature as well as additional data for radiation, the model using TRNSYS was determined to provide an accurate model of power performance. This model is simple but accurate and can help to design future PV systems in the East Texas area as well as help to improve current PV systems

References

[1] U.S Energy Information Administration (2013). 2013 World Energy Consumption. Retrieved September 2014 from: http://www.eia.gov/todayinenergy/detail.cfm?id=12251.

[2] Shahriar, S., & Topal, E. (2009). When will fossil fuels reserves be diminished? *Energy Policy*, *37*, 181-189.

[3] Kropp, R. (2009). Solar Expected to Maintain its Status as the World's Fastest-Growing Energy Technology. SRI World Group, Inc. Retrieved September 2014 from: http://www.socialfunds.com/news/article.cgi/2639.html.

[4] De Soto, W., Klein, S.A., & Beckman, W.A. (2006). Improvement and validation of a model for photovoltaic array performance. *Solar Energy*, *80*, 78-88.

[5] Khatib, T., Mohamed, A., Mahmoud, M., & Sopain, K. (2012). A new approach for meteorological variables prediction at Kuala Lumpur, Malaysia, using artificial neural

networks: application for sizing and maintaining photovoltaic systems. *Journal of Solar Energy Engineering*, *134(2)*, 021005-1 - 021005-10.

[6] Bhattacharya, T., Chakraborty, A. K., & Pal, K. (2014). Effects of ambient temperature and wind speed on performance of monocrystalline solar photovoltaic module in Tripura, India. *Journal of Solar Energy*, *Article ID 817078*, (5 pages).

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