Regression Analysis Program for the Characterization of Photovoltaic Devices

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Abstract

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Characterization of photovoltaic devices is key for understanding of how the devices perform. With a characterized photovoltaic panel, module, or array, one can have an idea of how well that device will produce power under any climatic condition. This program is able to take recorded data and fit it to the Photovoltaic Utility Scale Application (PVUSA) model. The fit will produce coefficients that are then substituted back into the model to give a power rating at the project test conditions. This allows predictions to be made about the performance of the device under varying degrees of weather. It can analyze recorded data and give the power rating of that device under the project pest conditions of air temperature of 20 C, wind speed of 1 m/s, and an irradiance of 1000 W/m^2.

Category (circle one): Engineering

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Introduction

With the cost of oil and other nonrenewable energy sources on the steady increase, more and more people are turning to renewable energy. Imagine going to the store to buy a solar panel or module. If the back panel reads "power rating, 100 watts," as a consumer it would be beneficial if you could depend on this back panel rating as being accurate. If that trust were there, then you could have peace of mind that this device could in fact produce 100 watts of power.

Today the number of companies producing products that convert solar energy to electric energy is growing. These products are called photovoltaic (PV) panels, modules, and arrays. Each product varies depending on the operating conditions and customer need. Arrays are the largest of the PV devices and could be used by a customer with a need for a large amount of power, whereas panels are the smallest devices and have applications like charging car batteries. As manufactures develop new PV technologies, it is important to have standards are set as to what these new technologies claim as capabilities of their new modules. This is important for a myriad of reasons, but probably the most important is customer trust. If consumers are constantly disappointed by false claims of performance, people will stop buying solar panels and this could prevent the PV industry from reaching its full potential.

To characterize or determine the capabilities of a PV device, several parameters must be taken into account for an accurate characterization to be performed. These parameters include, but are not limited to, wind speed and direction, solar angle of incidence, solar spectrum, and operating temperature. For example, a solar panel can be rated as producing 100 watts of power in southern California, but how will this PV device perform in western Oregon where overcast weather is more prevalent? Ideally, there should be a method of testing the potential of a solar cell or module that accomplishes two things. First, and most important, the testing and measurement procedures should be both fair and realistic in stating the solar cell/panel's ability to produce power. In order to accomplish this task there should be some consensus as far as how the PV device's energy-producing potential is measured. Second, the method should use a model or normalization technique that can allow predictions of the PV device's performance under more than one operating condition.

Sandia National Labs and the National Renewable Energy Lab (NREL) have both worked to find reliable ways of testing the efficiency of photovoltaic devices (Kroposki, B., & Marion, W. 1998). Two methods have shown the best results: indoor testing using artificial light to see how the PV panel responds, and outdoor testing using mathematical models to correct for atmospheric fluctuations. Indoor testing has an advantage in that the same reproducible light spectrum can be used, and is therefore, a fair way of contrasting the performance of more than one panel. This is a fair method because all panels are tested under the same operating conditions. There are two major drawbacks to this method of testing. The first one is that it cannot be done on large systems, such as arrays that are too big to fit into a laboratory. The other reason is that artificial light is not the same as sunlight and therefore limits how realistically the measurement can predict the systems performance in actual operating conditions. The drawback to outdoor testing is that having the same testing conditions for a fair comparison of PV systems is virtually impossible because of the chaotic nature of weather.

This project is about creating a program relates real world data taken in the field and translates power production at those conditions to yield information on how well the device will perform under given parameter settings. This way the method is realistic because the outcome of the characterization is dependant on a real world setting and also fair because it translates performance to conditions that are the same regardless of the device used. A group named Photovoltaics for Utility Scale Applications (PVUSA) formulated the regression model used in the program. PVUSA started in 1986 according to Hester & Townsend (1990) with two primary objectives: to asses promising U.S. PV technologies in a side-by-side utility setting, looking toward cost-effective commercialization by the mid-1990s; and to create a program to transfer PV knowledge between government, the PV industry, and U.S. utilities. The PVUSA regression model allows real world data to be used to predict performance with set parameters. These set parameters are called project test conditions (PTC) (Whitaker & Townsend, 1997).

If ways of verifying efficiency are in place, then manufacturers, scientists, and future PV device owners will have the security of knowing that they can trust the performance ratings of PV devices. This project is about creating a program that can characterize PV devices and achieve that trust. This program will allow a prediction to be made about how this device can perform under certain operating conditions. That way a customer can know what the power rating means.

Methods and Materials

In order for this program to characterize PV devices by assigning a power rating at PTC various factors and issues had to be considered. First, the program needs to read data recorded on different machines from locations. Then it needs to perform regression analysis using the PVUSA model to obtain coefficients, which allow the power rating to be obtained. It should also have a means to selectively choose data points so that outliers and point of non-interest can be eliminated.

Data on meteorological conditions, the physical state of the photovoltaic device and device performance was collected for two different types of PV power producers. PV arrays are tested at the Outdoor Array Field (OAF). The South Pad test bed is primarily used for testing cells, but can accommodate modules with areas up to approximately two and a half square meters. The OAF uses a Campbell scientific data logger to collect the performance data, with the exception of DC current, which was measured using a transducer. The performance data of modules and cells at the South Pad test bed was measured using a Keithley 2420 source measurement unit (K. Emery, personal communication, Aug. 1, 2001). All meteorological data was collected by a group of detectors collectively called the Reference Meteorological Irradiance System (RMIS).

A variety of different parameters were measured to gain a better understanding of the system's spectral response. The main parameters of interest that were measured are the following; temperature of the PV device, open circuit voltage, short circuit current, maximum power for alternating and direct currents, day of the year, pressure-corrected air mass, wind (speed, direction, and temperature), and irradiance (global horizontal, direct normal, and plane of array). The temperature of the PV device was measured using a thermocouple on the back of the PV device. All other parameters were measured by the RMIS. The RMIS is located approximately 13 meters northeast of the south pad test bed. RMIS in addition to measuring meteorological data also measures various kinds of irradiance. Irradiance basically measures how much of the sun's energy is striking a surface. What separates different types of irradiance measurements is how the sun's energy is collected. This global horizontal irradiance is light energy that falls on a horizontal surface from a solid angle of 2π steradians (American Society for Testing and Materials [ASTM], 1998). Direct normal irradiance is the light energy that falls on an aperture pointed directly toward the sun. Plane of array is a small reference panel that measures the solar energy at the same tilt as the panel or other voltaic device.

Analysis of collected data was performed using the graphical programming language LabView. LabView is a graphical programming language using icons and virtual wires to determine data flow and manipulation. LabView is the ideal language for this program because it can run on any platform. Code can be written on an IBM machine, saved on a network drive and be downloaded onto a Macintosh system and ran without any modifications to the code.

This program was written to allow regression analysis to be done on the data using the least squares technique with the single value decomposition algorithm. The single value decomposition algorithm was used because of its versatility for allowing any n by m input array. The equation used to construct the input array was the PVUSA model given in Eq. 1 (Whitaker & Townsend, 1997).

$$1)\quad P = C_1E + C_2E^2 + C_3ET + C_4ES$$

where P is power, E is irradiance, T is air temperature, S is wind speed and $C_1 \ldots C_4$ are the coefficients determined by the regression. The variable T can be either cell temperature or air temperature. Under certain circumstances, the wind speed was not a concern. In those cases the PVUSA model was changed to Eq. 2.

$$2)\quad P = C_1E + C_2E^2 + C_3ET$$

where the last term, including wind speed, is omitted. The program was written so that the irradiance and ambient temperature values could be changed to different settings to see what combination gives the lowest mean-squared error and hence the best fit to the data.

Data filters were utilized so that the data that is of no concern or invalid can be cut out. These filters are used on the following parameters; wind speed, air temperature, time, irradiance and power. This is an important feature because some test locations record data around the clock. It doesn't make sense to analyze data recorded at midnight because there is no power produced. The filters (the irradiance filter in this case) can be used to omit those points. Using the filters helps to cut out "non-sense" data and in turn will give a better fit.

Results

This program gives a power rating to the PV device being tested independent of operating conditions or device type. The program gives coefficients from the least squares fit. If the values of the coefficients are substituted back into Eq. 1, along with the PTC of 20 C air temperature, 1 m/s wind speed and irradiance of 1,000 W/m^2, then the result is the predicted power rating.

To illustrate the capabilities of this program it was run using data recorded from the east roof of the (Solar Energy Research Facility) SERF building from 4/1/01 to 5/1/01. The graphics in figure 1, show the front panel of the program. The front panel is where parameters are controlled and outputs are displayed. This is where data is filtered and a time range is selected. The front panel is also where the choices for temperature, formula type, power type and irradiance can be chosen. The center of the front panel shows the main graph contrasting the curve-fitted values against the actual power vs. time plot.

Figure 2 shows two scatter plots, power vs. irradiance and power vs. temperature, along with the fitted values vs. irradiance and temperature. This allows the user to see how the fit values compare to the actual values of power vs. irradiance and temperature and to see what correlation exists between two different sets of data. This feature will allow a researcher to determine how much influence certain parameters have in determining the power output of a PV device. If the two data points on the scatter plots lie on top of each other then there is a strong correlation between them.

Figure 3 shows the error graphs. These error graphs are a way to display visual representation of the fit quality of the three scatter plots in Figures 1 and 2. These graphs take the best-fit values of power produced by the regression and divide them by the corresponding actual power produced. This set of graphs gives a visual display of how well the real world data matches up with the fit data.

Using the data collected on the east roof of the SERF building for the month of April 2001 the power rating at PTC was calculated. Some of the data was filtered by removing low irradiance values that fell below 250 W/m2 and low temperature values were removed as well by omitting values below 10 C. The predicted power output at PTC of this PV system as calculated by this program is 6465.8 watts. The power rating was calculated again without filtering allowing all data point for both irradiance with low values of 6.98 W/m^2 and temperature of –2.54 C. The new power rating with the unfiltered data was 6394.14 watts.

Discussion and Conclusions

The program can be used to see patterns and relationships between parameters, but caution should be exercised when trying to interpret the data. In Figure 1 the plot shows spikes corresponding to daytime sunlight producing power and troughs relating to the morning and afternoon hours where little power is produced. Omitting the lower ten percent of the power output data filtered some of the data out. By doing this along with omitting irradiances below 100 W/m^2, allowed data points corresponding to nighttime to be filtered out. Also in figure 2 there are gaps in the data where no spikes are present. This could represent days where the sky was over cast or some other factor to cause a decrease in power output. If possible a person using this program should supplement the analysis done with notes on factors that might skew the data.

The best way to find data points that are questionable is to use the error ratio graphs shown in figure 4. Most good data points should fall within the range of .9 to 1.1. If a point shows an error of less than .7 or greater than 1.3, then the data point should be checked for authenticity. If the program user has taken notes on the test conditions then points that are outside the boundary conditions on the error plots can be verified as to whether the point is valid or not.

There are also limitations on how well the PVUSA model can work well and give reasonable power rating values (Whitaker, C.M., &Townsend, T.U. 1997). The first is that the data collected should have values above the rating irradiance and be over a range of temperatures and wind speeds. The second issue with the model is that it has bad performance with low irradiance levels. This is why the power rating for the unfiltered data was lower than the filtered data as shown in the previous section. With this in mind data over a period of many days should be collected and the days of low sunlight levels should be noted for future analysis. If these limitations are taken into consideration and corrected for, then the PVUSA model should give a fair and accurate power rating for the PV device at PTC.

Acknowledgements

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Figures

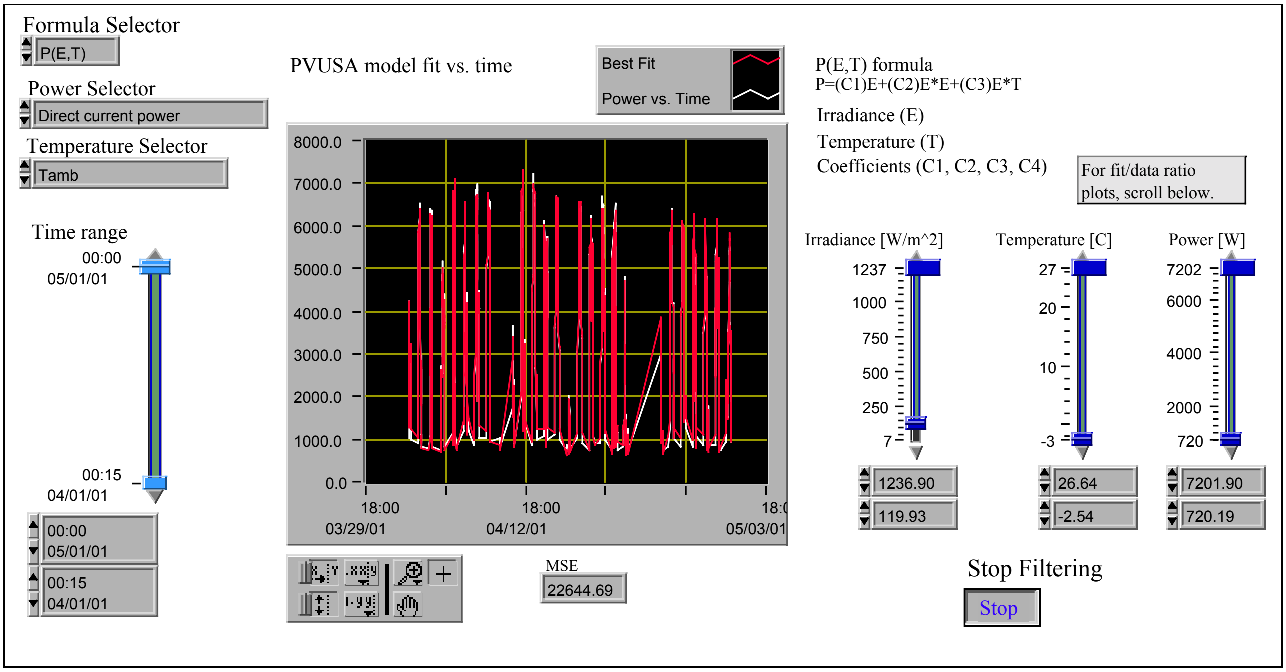

Figure 1

This is the front panel display of the program. The front panel shows the controls such at the time range, irradiance and temperature filtering slider bars. It also shows the selectors that allow the user to choose from various types of regression formulas, power types and temperature locations. The stop filtering button is the mechanism that stops the execution of the program.

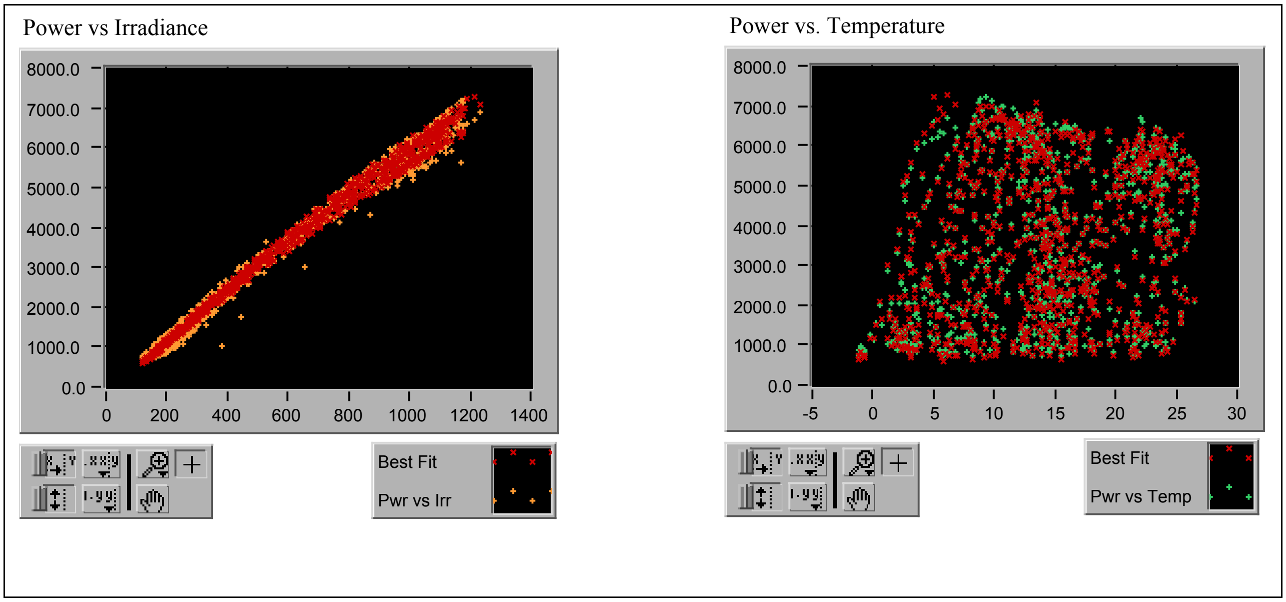

Figure 2

This figure shows the two auxiliary graphs that show the relationship between the real world power output and the best-fit values as functions of irradiance and temperature.

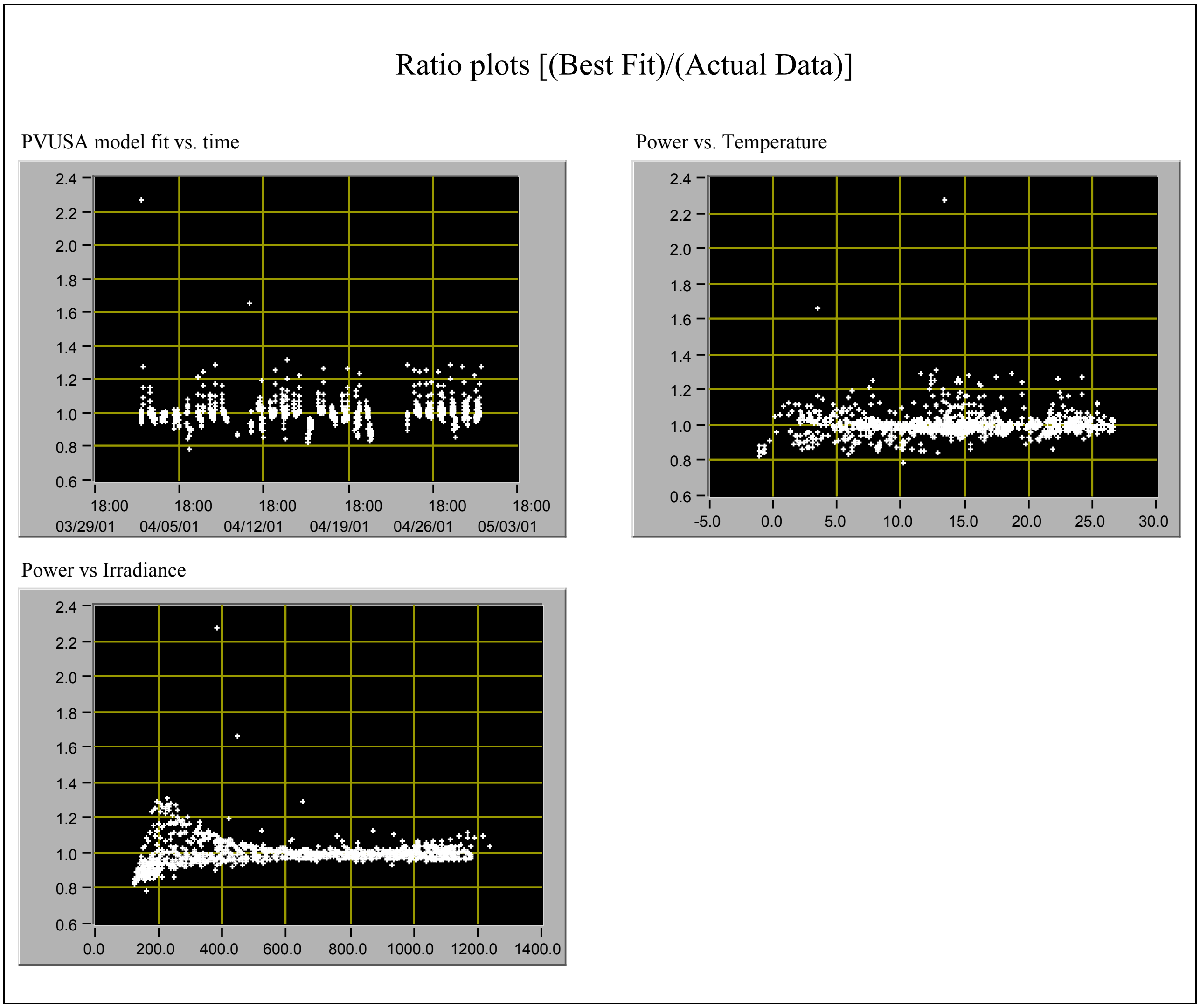

Figure 3

These graphs illustrate how close the fit values are to the real world data. The formula (best fit)/(real world) was used to show the error in the fit. If values deviate far from unity then data points are questionable.