

AN ALTERNATIVE METHOD TO REGRESSION ANALYSIS FOR PV SYSTEM STC RATING

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ABSTRACT

A common method of determining the power rating of a photovoltaic system is through a regression analysis using historical air temperature, wind speed, irradiance and AC production data (1,2,3,4). The derived polynomial, with its system-specific coefficients, describes the system being rated under a range of possible environmental conditions. From this rating method the photovoltaic system AC power output, at standard test conditions (STC), or under any other conditions, can be estimated. This approach often becomes the criterion for assessing contract compliance or the level of subsidy. Through this method the analysis can answer the basic question, “Did the customer or funding agency get the system capacity specified in the contract?” One of the difficulties with this method is that it requires a selectively filtered body of raw data amassed over a significant period—weeks or even months—of time. This paper describes an alternative, single measurement method, to estimate the AC production, and thus the AC STC rating, of a field-installed system, by monitoring its power output in conjunction with the output of a calibrated reference module.

1. INTRODUCTION

The basic dilemma faced by anyone attempting to ascertain the power rating of a grid-paralleled photovoltaic installation is that one cannot simply, as with other nameplate-rated equipment (either generating equipment such as a diesel generator, or utilization equipment such as a motor or a resistive load) take the nameplate rating of the array at face value or easily operate it at its rated power. The

reason for this is that the prime mover, the sun, is moderated by the atmosphere, which is not constant, and the characteristics of the installation not accounted for by the nameplate rating of the PV array can have a significant influence on the final production capacity of the system over time. The specifications for standard test conditions were developed to provide PV module manufacturers with a basis for rating and comparing one module with another. Standard test conditions are a set of environmental characteristics that rarely, if ever, occur simultaneously outside of the laboratory. In the controlled setting of the factory test bed STC represent an essential industry standard, however in the context of field installed PV systems, the STC rating of a collection of modules that make up a photovoltaic array is of limited value, because that unique set of laboratory conditions will rarely occur at the same instant in time in nature.

The question that purchasers of PV systems are most often interested in is, “What is the AC power rating of this system (as installed) and how much energy will it produce for me?” The answer to the first of these questions addresses the unique characteristics and losses of the system. Various approaches have been developed to answer this question ranging from regression analysis to rough approximation¹. The first of these methods is accurate, but time consuming. The second approach is quick, but potentially very

¹ PV USA Test Conditions (PTC), was initially devised as an empirically derived field rating method for PV *systems*, however at present it has become a de facto standard for many funding agencies in the United States and is applied to *modules*. As such, applied to *systems*, it is a rule-of-thumb.

inaccurate. Nonetheless, those who invest in PV systems want to have a measure of what they have purchased, and typically, that measure must reflect what they are able to use, in other words the delivered AC power. In this paper a method will be described that serves as an alternative to commonly used regression analysis rating methods, such as that developed by PVUSA. (The method of using PTC *module* ratings will not be considered as a meaningful approach to rating large-scale PV arrays.)

In the method described here, the manufacturer's STC maximum power ratings (P_{max}) of each of the modules comprising the array are summed and averaged. This average array STC maximum power value is scaled to a calibrated reference module². The balance-of-system (BOS) components of the PV system are modeled as a transfer function to characterize the system losses. The AC output of the system is monitored, while the reference module is installed in the same location and orientation as the array and a curve tracer is used to plot its I-V curve. At the same instant that the I-V curve is taken the AC power output of the PV system is recorded. The DC output that the array should yield, based upon its nameplate rating (STC) is scaled to the reference module's maximum power point at the time of the simultaneous measurements. This simulated instantaneous DC power value of the array is then applied as a forcing function to the system transfer function and an AC power output value is calculated. This value is then compared with the AC power measured at the instant that the reference module was measured, providing us with an effective comparison of the quality of our model. A high degree of agreement between the measured and simulated values indicates that the model (transfer function) accurately characterizes the system. With this knowledge we can apply the average nameplate rating of the array (the STC maximum power value of the array) to the system model as a forcing function to yield the AC STC rating of the system.

2. PROJECT HISTORY

In the spring of 2004 a nominal 1MW central station photovoltaic plant was brought on line in the city of Cagayan de Oro, in Mindanao in the Philippines, by the local utility, CEPALCO. The contract terms stipulated that, "the Plant is warranted to be capable of generating 950 KW_{ac} measured at the medium voltage (13.8 kV) grid

² The calibration process was conducted in two stages. First, a single, nominal 127 Watt, module was calibrated in the Fraunhofer Institute's PV Calibration Laboratory. This module was then used to calibrate two modules of the type being installed in the array. These two calibrated, Sharp ND-167U1, 167 Watt modules became the references that were used for all of the tests conducted on site.

connection point, where the plant's generated power is directly supplied to CEPALCO's distribution line." And further that, "the test condition shall be Standard Test Conditions (STC)." The funding agency stipulated that CEPALCO meet these conditions, and in turn CEPALCO used this specification as a contract term with its prime contractor.

CEPALCO developed a rating methodology based upon a standard efficiency analysis used for conventional generation technologies. The method calculated the power at multiple locations along the DC collection network and up to the AC interconnection point, by expressing the power at each "node" in the branching network as a product of input power and an efficiency (expressed as a percentage). Each branch of the collection network was characterized by calculating the losses in the conductors, switches and diodes that comprising that portion of the system. The inputs to each node were summed and this value became one of the inputs to the next higher node. The final summed power value was the output of the medium voltage AC switchgear, which served as the interface to the CEPALCO distribution network. This calculated value became the system AC rating.

The module manufacturer, as part of their agreement with the contractor, measured the output of the "Junction Boxes" (each Junction Box contained either three or nine fifteen-modules strings in parallel forming a "subarray") using a Daystar DS-100 curve tracer. There are a total of 432 fifteen-module strings supplying 54 Junction Boxes. A set of six Junction Boxes supplied each of nine "Junction Panels." Each Junction Panel supplies one of nine 110 kW inverters. The AC output of the inverters is then combined in a low voltage switchgear, before being sent to a step up transformer and on to a medium voltage switchgear. The output of the medium voltage switchgear is then connected to the CEPALCO distribution network.



Fig. 1: CEPALCO 1MW PV system.

The I-V curves taken at the Junction Boxes were performed, in very close sequence, with I-V curves taken on a calibrated reference module of the same model as the array modules. The alternative method described here used the reference module I-V curves, in conjunction with AC power measurements from the plant SCADA system.

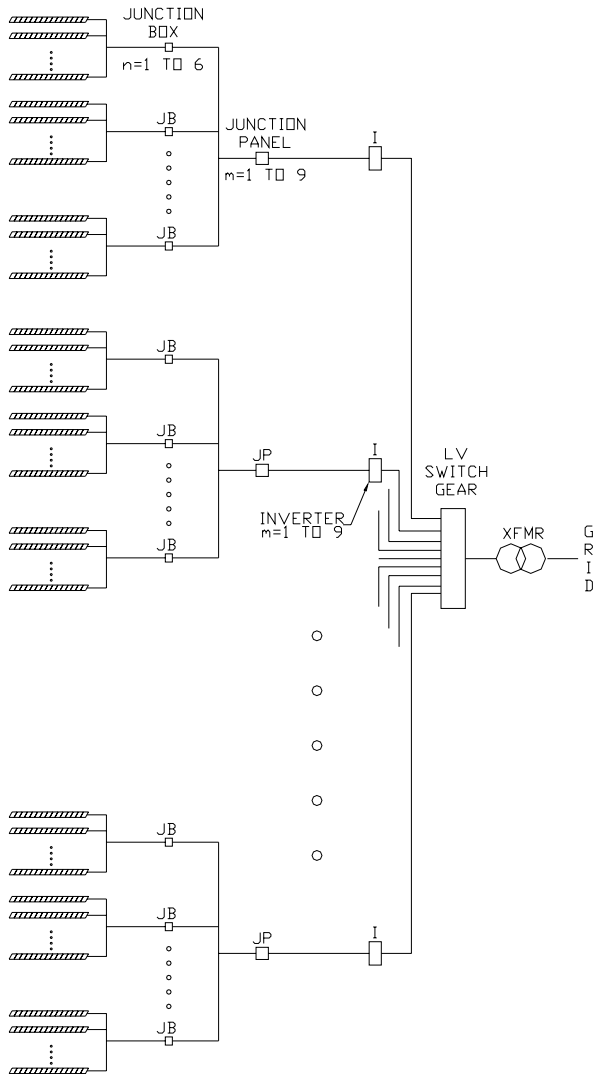


Fig. 2: Array layout showing Junction Boxes, Junctions Panels, and Inverters.

3. RATING METHODOLOGY

3.1 System Parameters

PPV-mn are array power measurements taken at the Junction Box level, using an I-V curve tracer. These measurements were conducted by the module manufacturer's engineers as part of their performance measurement requirements. The formula that describes the

contract methodology for calculating the AC/STC rating for the Cagayan de Oro PV installation is as follows:

$$\begin{aligned}
 \text{PPV-m} &= \sum(\text{PPV-mn} * \text{Efc-mn}) \\
 \text{PINV-m-i} &= \text{PPV-m} * \text{Efc-20m} \\
 \text{PINV-m-o} &= \text{PINV-m-i} * \text{EEfINV-m} \\
 \text{PLVSG} &= \sum \text{PINV-m-o} * \text{Efc-30m} \\
 \text{PTR} &= \text{PLVSG} * \text{EfTR} \\
 \text{Pw} &= \text{PTR} * \text{Efc-HV}
 \end{aligned}$$

Where:

n = 1 through 6 (corresponding to Junction Boxes, six per Junction Panel)

m = 1 through 9 (corresponding to Junction Panels, one per inverter)

PPV-mn = Junction Box mn output power

PPV-m = Junction Panel m output power

PINV-m-i = Inverter m input power

PINV-m-o = Inverter m output power

PLVSG = low voltage switchgear output power

PTR = Transformer output power

Efc-mn = cable efficiency from Junction Box n to Junction Panel m

Efc-20m = cable efficiency Junction Panel m to Inverter m

EEfINV-m = Inverter m efficiency

Efc-30m = cable efficiency Inverter m to Transformer

EfTR = Transformer efficiency

Efc-HV = cable efficiency Transformer to Grid

Efficiency was calculated at STC, for the DC portions of the systems, as:

$$\text{Ef} = 1 - \text{Vdrop}/\text{V}, \quad \text{Vdrop} = 35.6 * \text{L} * \text{I} / 1000\text{A}$$

Where V = DC voltage (V) measured at the supply
L = Cable length (m)
I = Current (A)
A = Cable cross section (mm²)

The factor 35.6 is the resistivity of copper conductor, expressed in Ohm mm²/km. This value takes into account the round trip path of the positive and negative conductors.

The efficiency of the three phase AC portions of the system is calculated as:

$$E_f = 1 - V_{\text{drop}}/V, \quad V_{\text{drop}} = 30.8 \times L \times I / 1000A$$

Where V = DC voltage (V) measured at the supply
 L = Cable length (m)
 I = Current (A)
 A = Cable cross section (mm²)

The factor 30.8 is the resistivity of copper conductor, expressed in Ohm mm²/km, for a three wire, three-phase system.

The values for inverter and transformer efficiencies were taken from the manufacturer's specifications at rated power.

P_w is the AC "warranted" or contract rated power requirement of the plant, at STC.

3.2 Overall System Transfer Function

All of the preceding expressions can be combined into a single equation expressed in terms of the input, PPV-mn.

$$P_w = (((\sum ((\sum (PPV-mn * E_{fc-mn}) * E_{fc-20m}) * E_{effINV-m}) * E_{fc-30m}) * E_{fTR}) * E_{fc-HV})$$

The input is PPV-mn. The output is P_w . All of the expressions in between are efficiency values that model the system and form a transfer function. This reduces the entire equation to the form of

$$P_w = f(x)$$

Where "x" is the average STC rating of an array module and the function "f" describes the unique characteristics of integrated system.

3.3 Synthesizing Instantaneous Array Module Power

In the method described here, the array module manufacturer's STC maximum power ratings (P_{max}) of each of the modules comprising the array are summed and averaged.³ This average array STC maximum power value ($P_{\text{max-ave}}$) is scaled to a calibrated reference module's STC maximum power value, ($P_{\text{max-ref}}$) to form a ratio:

$$(P_{\text{max-ave}})/(P_{\text{max-ref}}) = \text{PPV-scaled}$$

³ Sharp provided individually measured maximum power ratings for each of the 6,480 modules in the array.

In order to synthesize the instantaneous power output for the installed PV modules at a particular point in time, ($P_{\text{max-ave}_t}$), we made an I-V curve for the instantaneous maximum power point of the reference module ($P_{\text{max-ref}_t}$). We then solved for $P_{\text{max-ave}_t}$ using the modules power ratio:

$$(P_{\text{max-ave}_t}) = \text{PPV-scaled} * (P_{\text{max-ref}_t})$$

3.4 Simultaneous Measurements

The efficiency values were not measured, but rather were calculated based upon the design characteristics of the system. To test the accuracy of the calculated values, and thus the accuracy of the transfer function that models the system as a whole, when the I-V curve was done for the reference module a measurement was taken at the same time for the AC power output of the inverter who's array was physically closest to the reference module.⁴ When a window in the clouds appeared the engineer initiated the I-V curve, and at the same instant a measurement of the associated inverter AC power output was recorded by the plant SCADA system.

The synthesized instantaneous average module output power for a single module ($P_{\text{max-ave}_t}$) was then calculated. From this value the instantaneous output power of the Junction Boxes is simulated ($PPV-mn_t$). This value is then input to the transfer function and the output for that inverter m is simulated for that instant in time:

$$PINV-m-o_t = ((\sum (PPV-mn_t * E_{fc-mn}) * E_{fc-20m}) * E_{fc-20m}) * E_{effINV-m}$$

The degree of agreement between the simulated inverter output and the value measured by the SCADA system at the same moment in time is an indication of the accuracy of the transfer function model.

4. CAGAYAN DE ORO RESULTS

4.1 Field Measurements

The irradiance conditions during the time of the commissioning tests were very poor. Cloud cover was high and irradiance levels were generally well below 500 W/m². Because of these conditions it was necessary to wait for an opening in the clouds before doing an I-V curve. The varying cloud conditions made it difficult to synchronize the I-V curve with the inverter AC output power data sample. This was because we were initiating the SCADA sample manually and there was an approximate ten second delay in the recording of the AC power data. In some instances the irradiance conditions on the array field were changing so

⁴ The 2-hectare array area, combined with the rapidly changing irradiance conditions, precluded using a single a single I-V curve for all nine inverters.

rapidly that this ten-second latency had a significant impact. The ratios of measured to simulated inverter output for the arrays adjacent to the reference module were:

	Measured kW/Simulated kW		
Inverter 1:	61.50/62.92	=	0.977
Inverter 3:	54.70/63.70	=	0.859
Inverter 4:	65.60/63.18	=	1.038
Inverter 5:	67.20/63.55	=	1.057

4.2 Simulated System STC Rating

The empirical test described above was intended to validate the system model. Once this was done, and a level of confidence was established for the model, the average maximum power value for the 6,480 installed modules (factory STC value) could be applied to the transfer function for the entire system. This calculation would yield a simulated value for the “warranted power,” P_{ws}

$$P_{ws} = ((\sum ((\sum (PPV-mn * Efc-mn) * Efc-20m) * EEfINV-m) * Efc-30m) * EfTR) * Efc-HV)$$

Where each of the values⁵ of $PPV-mn = (Pmax-ave) * 15 * 48$

This alternative method for PV system rating estimated the plant rating to be 997 kW STC. After three months of data collection, subsequent analysis using a regression approach resulted in an STC system rating of the plant of 973 kW.

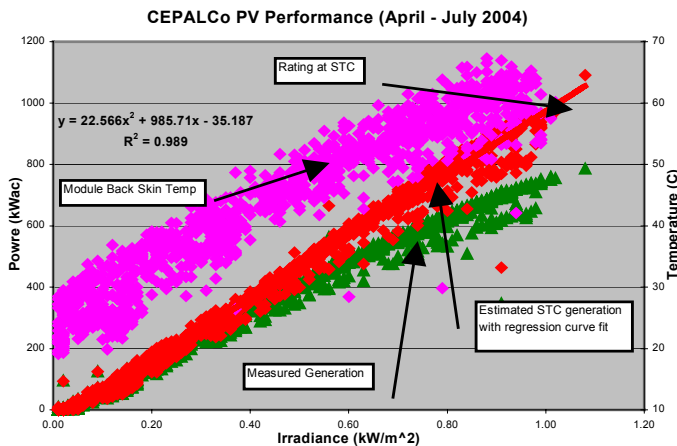


Fig 3: Initial Performance of CEPALCO PV system

The CEPALCO system was rated for commercial terms based on a regression analysis using irradiance, measured module back skin temperature, and the manufacturer’s stated coefficient for the variation of maximum power point voltage with cell temperature. The temperature rise between the back skin and the cell was taken to vary linearly, with a 10 C rise at 1 kW/m². Fig 3 shows the hourly power

⁵ 15 modules per string; 48 strings per Junction Box.

generation of the system, and module back surface temperature versus irradiance. The theoretical performance at 25 C cell temperature is computed and displayed for each hour. Finally a quadratic curve fit is applied to the theoretical performance. At 1 kW/ m² irradiance this analysis rates the system at 973 kW.

4.3 Limitations, Assumptions, and Dominant Factors

There are several factors that make this study somewhat unique and are worth noting. Point measurement of the reference module may not take into account all of the characteristics of all parts of an array that is spread out over a large area such as this one. Because of the size of this system the verification of the model had to be conducted by comparing the simulated inverter output to the measured output of the closest inverters in the array field. If the irradiance conditions on the day of the test had been more uniform, or for a smaller system, this simulation could have been done for the entire array.

The efficiency calculation for the cable I²R losses were made at V_{mp} at STC. This value would not be linear over the operating range where we were conducting I-V curve tests, however this did not present a problem because the dominant factors in the efficiency calculations, by a large margin, were the inverter efficiency and the transformer losses.

All of the conductor lengths and the factory measured P_{max} value for each of the modules were known. Because this level of information was readily available we used it. This same method could be applied almost as well with fewer precisely calculated values.

We assumed that the ratio of $(P_{max-ave}) / (P_{max-ref})$ to $(P_{max-ave}_i) / (P_{max-ref}_i)$ was roughly constant over the range of irradiance values we were measuring.

There are three major requirements for the use of this method. The first is that it requires a calibrated module to use as a reference. The second is that it requires the use of an I-V curve tracer. And the third is that it requires a means of measuring PV system AC output.

5. CONCLUSIONS

Despite extremely poor test conditions, the method described here provided a reasonably accurate estimate of system STC AC rating using very few field measurements. Under more uniform irradiance conditions this method should perform extremely well. Also this method assigns losses throughout the system and has the ability to aid in the identification of any unanticipated losses, thereby improving the design. Regression analysis, be comparison, simply characterizes the entire system, irrespective of the contributions of constituent parts.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. "PVUSA Model Technical Specification For a Turnkey Photovoltaic Power System" Prepared by Robert N. Dows, E. James Gough Bechtel Corporation, and PVUSA Project Team, Project Manager: Brian K. Farmer, November 1995
http://www.osti.gov/bridge/product.biblio.jsp?osti_id=172103&query_id=0
2. "Residential PV Systems Cost Report Cost Analysis for TEAM-UP Residential PV Installations" Prepared by the Solar Electric Power Association, Washington, D.C. December 2001
<http://www.resourcesaver.com/file/toolmanager/O63F22750.pdf>
3. "PV Performance Data Report: Results determined from the performance monitoring of over 100 TEAM-UP PV installations" Prepared by the Solar Electric Power Association, Washington, D.C., December 2001
<http://www.resourcesaver.com/file/toolmanager/O63F22751.pdf>
4. M. Russell, "Predicted and Measured Performance for 10 Similar PV Systems In Wisconsin", Solar Technologies Systems Symposium, October 2003.
<http://www.sandia.gov/pv/docs/PDF/Symposium2003/Russell.pdf>