Evaluating the Effectiveness of Maximum Power Point Tracking Methods in Photovoltaic Power Systems using Array Performance Models

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***Abstract*—Maximum Power Point Tracking methods control the operating voltage of Photovoltaic arrays in order to maximize their power output. This paper presents a method to evaluate the effectiveness of such methods continuously in operating photovoltaic power systems, and hence, under real-world conditions. When operating, the maximum power cannot be measured, and therefore must be estimated. The proposed method relies on additional PV modules to accurately measure the *effective* radiation, and back-of-module sensors for temperature measurements. These measurements are inputs to a model that calculates the maximum power point, which is then compared to the actual operating point of the PV array and inverter.**

INTRODUCTION

Maximum power point tracking (MPPT) is an important control function of power converters in photovoltaic power systems (e.g. inverters, battery chargers): it serves to maintain the photovoltaic array operating voltage at or near a value that maximizes power output. Both the maximum power (P_{max}) and the optimal operating voltage (V_{mpp}) fluctuate in response to the array's operating conditions (irradiance and temperature) therefore the MPPT controller must make frequent adjustments. A variety of control methods have been proposed in the literature and an exhaustive survey is presented in [1].

While other aspects such as complexity play a role in determining which method is most appropriate for a given application or product, the fundamental basis of comparison is the tracking efficiency, η_{mppt}. This is defined as the ratio of energy actually collected over a given period of time vs. the amount of energy that could be collected if the PV array were always exactly at its maximum power point. [2] For the tracking efficiency measured during a simulation or experiment to reflect real-world performance, the test period must include an appropriate range of conditions and dynamic changes to represent a typical year of operation. It can also be helpful to determine efficiency for certain situations, for example clear sky, or overcast, in order to give insight into a method's strengths and weakness. Reported values for η_{mppt} are typically in the range 90-99%.

The real world has periods of stable or gradually evolving conditions as well as periods of rapid change. It is typical in the literature to see illustrations of the MPPT response to step changes in operating conditions to demonstrate both of these aspects. The logic is that if both types of error are minimized in the step response, the real-world MPPT efficiency will be maximized. The magnitude of the tracking error is easy to determine precisely since the ideal step response is known, but evaluating real-world performance from the non-ideal step response is not so easy.

Demonstrations of MPPT methods fall into three general categories: complete software simulations (an example in [3]), PV array simulators coupled to real power converters (an example in [4]), and real PV arrays coupled to real power converters (an example in [5]). Both full and partial simulations can be used to demonstrate the response to artificial conditions, such as step changes, and all three approaches can demonstrate response under realistic conditions with the appropriate inputs. The challenge with the real PV array is to determine the ideal response—something required to calculate η_{mppt}, but not always attempted.

Hohm and Ropp [2] recognized a need for this type of evaluation. They developed a method of estimating the ideal response in a real system, and then implemented and compared several different MPPT methods. The ideal response is obtained from a model of the PV array for which the fixed parameters are determined in separate experiments in advance. The operating conditions, irradiance and temperature, are recorded during the MPPT evaluation and later used with the model to calculate the model maximum power, which is in turn compared to the actual array output power. The authors believe that the absolute error in their measurements of η_{mppt} to be $\leq 4\%$, but they also indicate that the absolute error should affect their results uniformly and therefore not affect the relative results which are the focus of their work. [2] However, this does make it more difficult compare these results with other published results.

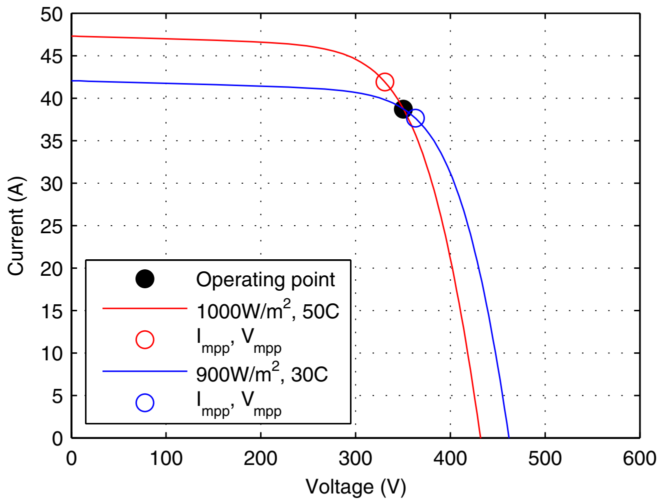


Fig. 1. One operating point, two possible IV curves

Fig. 2. The PV array used for this study

METHOD

The challenge of estimating the maximum available power in an operating PV system is illustrated in Fig. 1. The measured operating point may lie on one of many IV curves, each of which has a different maximum power point. The shape of the curve depends on certain fixed characteristics of the PV array as well as temperature and irradiance. In theory, if all of these items are known there is an excess information, but in practice there is uncertainty associated with each of them.

One of the challenges to the model-based evaluation is to accurately measure the irradiance during the test. The more accurate thermopile pyranometers (such as the Eppley PSP) respond too slowly to be used for this purpose, so a silicon photodiode pyranometer (such as the Li-cor LI-200) is required. Their absolute accuracy is about $\pm 5\%$ but errors can reach $\pm 10\%$. Furthermore their non-uniform spectral response means that they cannot achieve the same level of accuracy under both clear and cloudy conditions. [6]. This last aspect may be helpful or detrimental depending whether the sensor spectral response is similar to the PV array under test or not, and whether the similarity can be quantified.

However, for our purpose the important thing is to accurately determine not the *absolute* irradiance but the *effective* irradiance—that which is actually absorbed by the PV cells. The effective irradiance is proportional to the light-generated current, which is in turn equal to the short-circuit current. Therefore, instead of using a pyranometer, we choose to measure the short-circuit current of a regular PV module of the same type as the array. This eliminates any uncertainty due to spectral content or directionality of the solar radiation and removes a layer of complexity that is present in more advanced PV models [7]. The light-generated current of the array is in fixed proportion to the light-generated current of the shorted module.

The second operating condition, cell temperature, is easy to estimate from measurements on the back surface of a module, but there is some uncertainty there also. [8] If we operate the model at the same effective irradiance and voltage as the actual array, then any significant output current and power discrepancy should be due to incorrect cell temperature. A simple thermal model can relate the back-of-module temperature to the cell temperature and minimize that discrepancy.

Once the entire model is tuned to the array, and reproduces the array current and power at the measured operating voltage, the model maximum power point can be calculated. This represents the true maximum power point of the array. Differences between the two operating points can be examined in terms of voltage, current and power, and η_{mppt} can be calculated.

IMPLEMENTATION

The approach outlined above has been tested using a 20kW grid-connected PV array that is mounted on a south-facing building facade as illustrated in Fig. 2. The array is coupled to a 20kW grid-connected inverter that implements the Perturb and Observe MPPT algorithm. [9] With the default settings this inverter adjusts the operating voltage in one-volt increments at a rate of once per second. Many other details about the system are found in [10].

The array consists of 12 strings of 22 modules each, mounted in 4 rows of 3 strings. Due to the vertical layout of the array, the operating temperature of each of the 4 rows is not identical. Heated air rising along the facade tends to make the upper rows warmer, but wind tends to have a greater cooling effect on the upper rows. Each row has air and panel temperature sensors installed on one module, and in the modeling the three strings at each level are assumed to operate at the temperature measured there.

There are further differences between individual strings: one is producing no current at all; two appear to have developed faulty connections in a module, causing 18 cells to be bypassed by the by-pass diode; and there is measured variation of about 2% in the short-circuit currents. The electrical model accommodates these differences by maintaining a separate set of parameters for each string.

Electrical model

The electrical model of the array is based on the standard 5-parameter, single-diode model [11]:

$$I = I_L - I_o[e^{(\frac{(V+IR_s)}{a})} - 1] - \frac{(V + IR_s)}{R_{sh}} \quad (1)$$

where
I = current flowing through the cell [A]
I_L = light-generated current [A]
I_o = saturation current [A]
V = voltage across the cell [V]
a = curve fitting parameter [V]
T = absolute cell temperature [K]
R_s = series resistance [Ω]
R_{sh} = shunt or leakage resistance [Ω]

The parameters I_o, a, R_s and R_{sh} were determined by fitting the model to a set of measured operating points ranging from short-circuit to open-circuit conditions. The temperature dependence of I_o and a are calculated as in [11] whereas the other two parameters are deemed constant. I_L is dependent on the absorbed or *effective* solar radiation, and also on cell temperature using the coefficient α_{Isc} provided by the manufacturer:

$$I_L = \frac{E}{E_{ref}}[I_{L,ref} + \alpha_{Isc}(T - T_{ref})] \quad (2)$$

where
E = effective solar radiation [W/m^2]
E_{ref} = E at reference conditions [1000 W/m^2]
$I_{L,ref}$ = I_L at reference conditions [A]
T_{ref} = T at reference conditions [298 K]
α_{Isc} = temperature coefficient [A/K]

Under short-circuit conditions $I_L \cong I_{sc}$. For the purpose of this study it was most convenient to short circuit an entire string, so the current I_{sc} on that string is used to calculate E and I_L for the remaining strings.

No dedicated IV-curve tracing equipment was available to characterize the array, but about 100 operating points were gathered for each string over a period of two minutes using a manually varied load. This data indicated a string fill-factor much smaller than the individual module specifications, with an average power translated to standard test conditions (STC) of just over 70W per module rather than the nominal value of 75W. The impact of the series resistance (which is often ignored in simulation) was quite noticeable also, and estimated at 0.25 Ω.

Thermal model

A complete thermal model of the PV array relating cell temperature to ambient temperature should not be required. This is because the back-of-module sensors provide an approximate measurement of the cell temperature, reflecting the thermal mass of the modules, wind speed, ambient temperature and any other factors that influence cell temperature. However during periods of high solar radiation there is a significant heat flux out of the module, causing a small temperature gradient between the cell and sensor. This is gradient is estimated as follows: If a fraction b of the effective radiation E is lost through the back of the module, which has a thermal resistance R, then:

$$b \cdot E = \frac{(T_{cell} - T_{sensor})}{R} \quad (3)$$

$$T_{cell} = T_{sensor} + E(b \cdot R) \quad (4)$$

The constant $(b \cdot R)$ is chosen to minimize the discrepancy between the actual current and the model current, with both operating at the same voltage. Using a value of 0.01, the cell temperatures calculated in this manner are up to 10°C higher than the back-of-module measurements under full sun. This offset would seem high in the context of a single module, but in this case it represents 66 modules operating over some range of temperatures.

Programming

The initial simulations were done using the software TRNSYS [12], assuming a uniform array scaled up from the manufacturers module specifications. TRNSYS uses the above equations, but does not offer the desired flexibility for adjusting various parameters and inputs. The equations were therefore coded in Matlab, and Matlab's numeric solving capabilities are used to calculate the array current and power for the 10 functional strings operating at the same voltage, but with different parameters and operating temperatures.

Two operating points are calculated for the model: the first, at the measured array voltage, is simply referred to as *Model* in the results; and the second, at the maximum power point voltage, is referred to as *Model(MPP)*. To improve the fairness of the comparison, the model is forced to operate at zero current whenever the inverter current is near zero (indicating that it is off).

Data collection

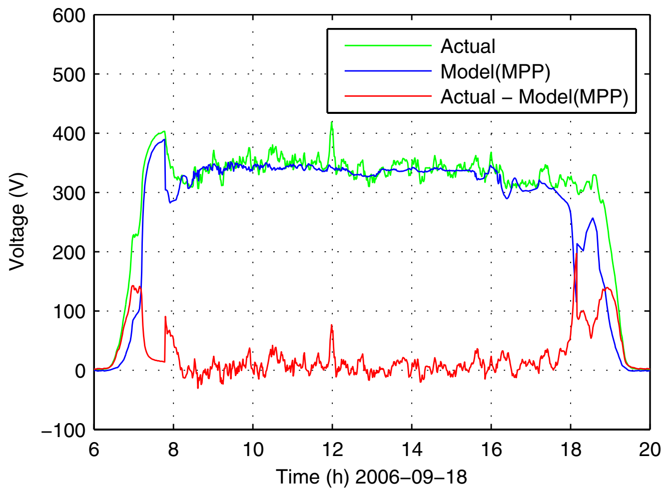
The array has been monitored since it was turned on in July 2003. String number 8, which is located in the middle of the second row down, was short-circuited on August 31, 2006 for the short-circuit current measurements. Unfortunately the array was disconnected from the grid on January 24, 2007, limiting the relevant data set to slightly less than 5 months.

Readings are taken approximately once per second by the data acquisition system, but stable voltage and current measurements could be obtained initially only by averaging values over approximately one minute, thereby masking short-term dynamic MPPT behavior. The unstable readings were an aliasing artifact that was substantially reduced by filtering at the end of 2006, providing several weeks of data with better views of the MPPT dynamics.

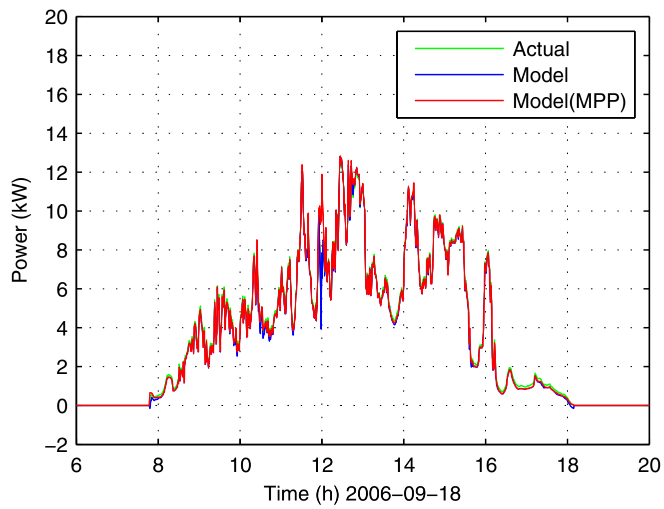
RESULTS

Comparison of model and measurements

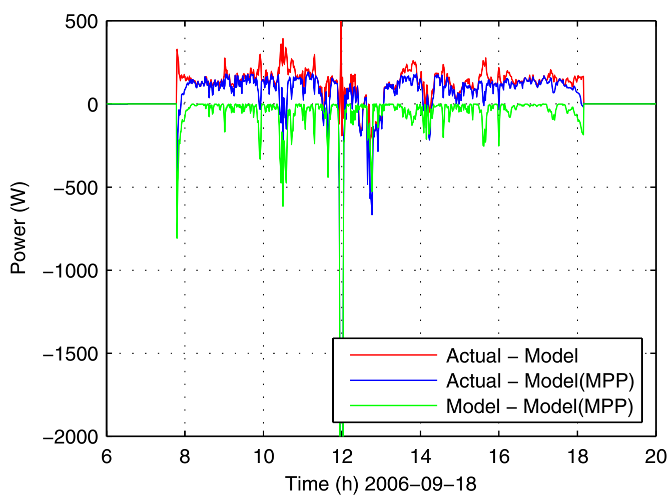
The results produced by applying the above method to our data set are illustrated in a series of graphs comparing voltage, current and power under various conditions. The analysis focuses on 6 days, 3 in early autumn and 3 in winter in order



(a) Actual voltage and V_{mpp} calculated by the model on a cloudy day.

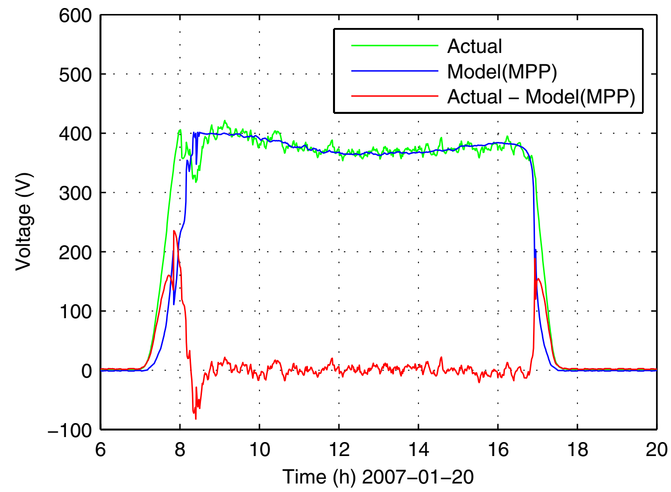


(b) Actual power and power calculated by the model on a cloudy day.

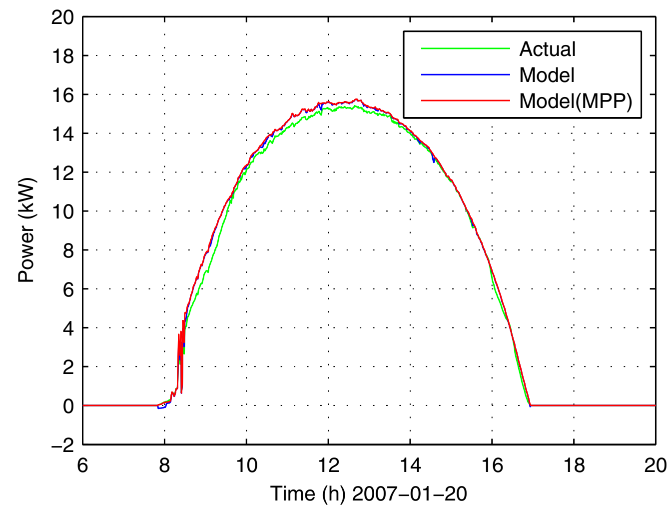


(c) Differences between actual power and power calculated by the model.

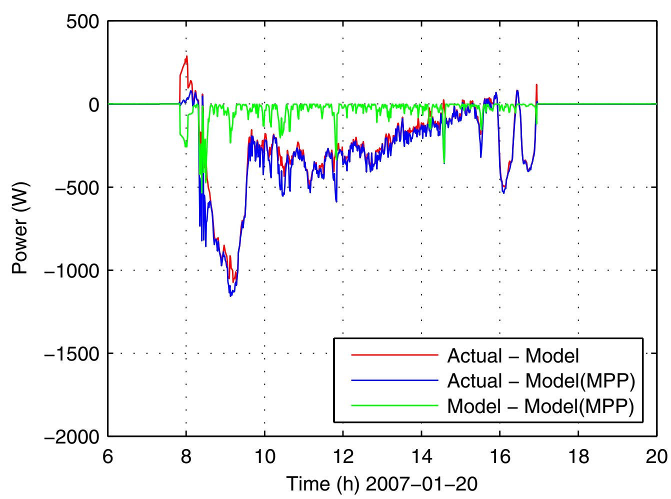
Fig. 3. Observations on a cloudy day



(a) Actual voltage and V_{mpp} calculated by the model on a clear day.



(b) Actual power and power calculated by the model on a clear day.



(c) Differences between actual power and power calculated by the model.

Fig. 4. Observations on a clear day

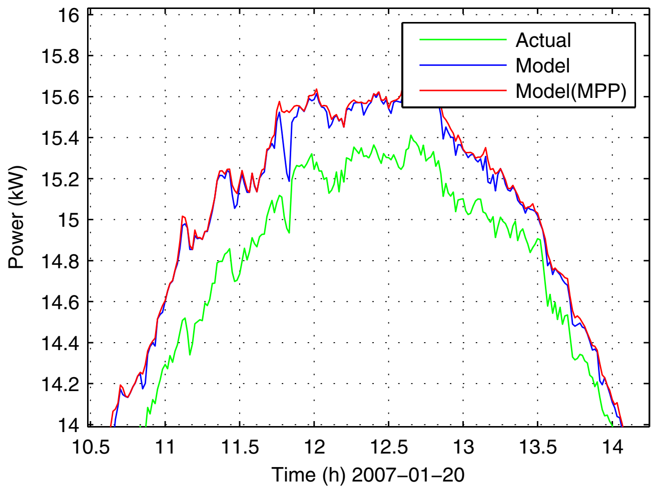


Fig. 5. Close-up fig. 4(b): actual power and power calculated by the model on a clear day.

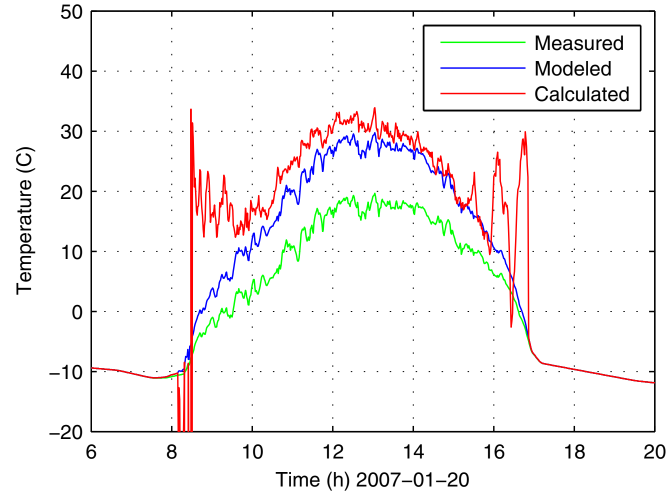


Fig. 6. Cell temperature measured at the back of the module, predicted by the simple thermal model, and calculated to match the actual array current.

to capture a full range of conditions. Several of these graphs are presented here, as well as tables to summarize the main indicators. Note that in graphs showing a full day, particularly in January, shading causes major discrepancies early and late in the day.

Figures 4(a) and 3(a) compare the *Actual* array voltage as controlled by the inverter with V_{mpp} predicted by the *Model* on a clear and cloudy day respectively. The inverter follows the general trend of the model, but shows considerable variation or searching even on the clear day. However as Fig. 4(b) shows for the same clear day, this does not affect the power levels much since dp/dv is small around the maximum power point.

Figures 4(c) and 3(c) provide the three differences between the three power curves on an expanded scale. The difference between the *Actual* and *Model* power should be zero since both are operating at the same voltage, but this is not the case. Rapid fluctuations are evident in individual graphs and comparisons between all 6 days suggest that systematic errors are also present, which may be a function of seasonal and/or a radiation intensity variations.

The rapid fluctuations in the power curves are not completely random nor unexpected. They look quite similar in both the *Actual* and *Model* power curves because these are both influenced by the measured voltage variations of the inverter, and therefore represent the MPPT tracking error. This is apparent in Fig. 5, which is a close-up of Fig. 4(b). However, the unexplained errors overshadow the MPPT tracking errors and *Actual* power sometimes even exceeds *Model(MPP)*, therefore the difference between *Actual* and *Model(MPP)* cannot be used as intended to calculate the tracking efficiency. Either the model is too simple, or the system too complex.

Alternate cell temperature calculation

The simple thermal model described above has a single parameter with which to determine cell temperature and minimize the modeling error. An alternate approach for determining the unknown cell temperature is to calculate it from the other known variables at each timestep. This can be done by searching for T_c such that $I_{Actual} - I_{Model} = 0$.

The resulting cell temperatures for a clear day are shown in Fig. 6, and Fig. 7 shows the resulting power differences. Now the *Actual* power always equals *Model* power and the difference between *Actual* and *Model(MPP)* can be integrated to evaluate the tracking efficiency.

The drawback of this method is that it discards the existing knowledge of cell temperature and depends on the accuracy of the remaining known parameters and measurements. This can lead to mistakes. For example, early and late in the day the calculated temperatures tries to compensate for partial shading, and the resulting values are unrealistic.

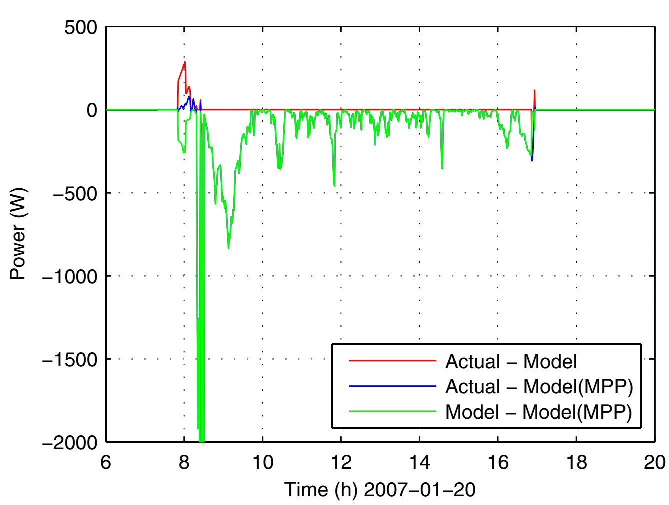


Fig. 7. Differences between actual power and power calculated by the model when cell temperature is calculated at each time step.

TABLE I
SUMMARY OF DAILY ENERGY PRODUCTION AND η_{mppt} WITH MODEL CELL TEMPERATURE DETERMINED BY THE SIMPLE THERMAL MODEL

Date	Weather	Actual		Model		Model MPP
		kWh	% of MPP	kWh	% of MPP	kWh
18-09-2006	cloudy	36.1	99.8%	35.5	98.2%	36.1
27-09-2006	mixed	46.4	98.4%	46.6	98.9%	47.1
06-10-2006	clear	61.0	98.1%	62.1	99.8%	62.2
01-01-2007	cloudy	7.8	104.8%	7.2	96.8%	7.5
10-01-2007	mixed	65.3	98.0%	66.2	99.3%	66.7
20-01-2007	clear	71.1	98.1%	72.3	99.8%	72.5

TABLE II
SUMMARY OF DAILY ENERGY PRODUCTION AND η_{mppt} WITH MODEL CELL TEMPERATURE CALCULATED AT EACH TIME STEP

Date	Weather	Actual		Model		Model MPP
		kWh	% of MPP	kWh	% of MPP	kWh
18-09-2006	cloudy	36.1	98.4%	36.1	98.4%	36.6
27-09-2006	mixed	46.4	98.8%	46.4	98.8%	47.0
06-10-2006	clear	61.0	99.7%	61.0	99.7%	61.2
01-01-2007	cloudy	7.8	101.4%	7.4	96.2%	7.7
10-01-2007	mixed	65.3	99.0%	65.3	99.0%	66.0
20-01-2007	clear	71.1	99.6%	71.1	99.6%	71.4

Tracking efficiency

This section summarizes the tracking efficiency calculations for all 6 days that were analyzed. In order to avoid the periods of partial shading the time range 10 am to 3 pm is considered rather than the full days shown in the graphs. Table I lists the results obtained using the simple thermal model, and II lists those obtained with the calculated cell temperatures.

In each table the two columns under the heading *Actual* are the measured energy output, and the column *Model MPP* is the estimated maximum energy output to which the former is compared. The two columns under the heading *Model* represent the energy the model would produce if operated at the measured array voltage. In Table I the *Model* column emphasizes that the model is not sufficiently accurate, whereas in Table II it confirms the modeling accuracy. The only exception is on 01-01-2007, a very cloudy day where at certain times no cell temperature could be found to satisfy the matching criterion.

The η_{mppt} values listed in Table II are slightly higher than those reported by [2] for the Perturb and Observe algortihm. This is probably due to the fact that short-term dynamics were removed by averaging. Despite this, the differences between clear and cloudy days are comparable.

A final observation about the *Model* columns in these two tables is that the η_{mppt} values are nearly identical for the same days, and there are no "impossible" values. This observation raises the possibility that *Model/Model(MPP)* could be used as a proxy for *Actual/Model(MPP)* with reduced sensitivity to the modeling accuracy.

DISCUSSION AND CONCLUSIONS

The modeling approach proposed in this paper was not adequate to reproduce the operation of the array under under investigation, and could not achieve the level of accuracy required for evaluating the inverter's MPPT performance. This is not a fundamental flaw of the method, but rather evidence of its limitations. Both the size of the array, and the fact that it is mounted on a building facade lead to important complexities in the system that are difficult to model, in particular:

- The incident radiation, and therefore also the effective radiation, is not uniformly distributed. There is shading early and late in the day, and the higher strings (particularly the top row) receive more diffuse radiation that the lower ones.
- The facade mounting results in uneven temperature distributions. The overall vertical variation is measured by one column of sensors, but there is likely also some horizontal variation near the ends of the building and differences between the upper and lower cells within modules.
- Due to the building mass and limited ventilation behind the panels the ratio of front-to-back heat loss will vary.
- The large area of the array means that rapid transitions on partly cloudy days do not occur simultaneously for each string. This becomes be a problem when the time step is reduced (as it should be) to capture more of the MPPT dynamics.

Incorporating more of these complexities into the array model would be challenging, and since the purpose of the method is to evaluate the inverter rather than the array it is preferable to apply this method with simpler, smaller, more uniform installations.

A variation on the proposed method is to continually adjusts the model cell temperature to match the model and actual array currents. If the array parameters and effective irradiance are measured with sufficient accuracy and cell temperature is the only unknown, then this approach may provide better results.

ACKNOWLEDGMENT

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