Simplified modeling techniques for predicting outputs of grid-connected photovoltaic power systems

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Abstract

In any grid-connected photovoltaic (GCPV) system, yield is amongst the most important aspect that the client looks at, as it has direct impact when it involves a Feed-In-Tariff (FiT) scheme. A good technique is needed for this, but, at the same time, should be simple yet precise. Depending on the cost, time and complexity, a balance is needed between simplicity and accuracy. In this work, a simplified modeling technique is proposed to predict the yield and check the optimum power sizing of a GCPV system. These models not only predict reasonably accurate yield, but also detects the optimal matching of PV to inverter power capacities. The user can then examine the GCPV system in a simple and relatively fast, yet reasonably accurate manner. The models used are steady-state equations that take into consideration the major factors affecting yield, such as: array power; irradiation; mismatch; temperature; dirt; cable efficiency; and inverter efficiency. This technique was then tested on two separate GCPV systems installed in Malaysia. One month datasets were used to investigate and validate the models. The results show good agreement between the predicted against the actual values measured. These models not only predict reasonably well results but also enables the user to detect the matching of optimum sizing of the GCPV system. The owner can then examine the system in a simple and relatively fast manner.

Keywords: *Photovoltaic (PV), Grid-connected (GC), System, Yield, Monocystalline, Polycrystalline*

1. Introduction

In several countries in South-East Asia (SEA), the introduction of a buy back scheme from renewable energy (RE) resources, is instrumental in the proliferated use of grid-connected photovoltaic (GCPV) systems. For example, in Malaysia, PV technology is the most popular technology chosen in her Feed-in Tariff (FiT) scheme [1]. In Thailand, the use of PV is seen in the significant numbers and sizes of solar farms and the publication of a solar roadmap [2,3]. Perhaps these examples are an indication of PV's simplicity and elegance.

Regardless of the sizes and capacities, the ultimate goal is to have the highest yields. This will give the fastest Return-On-Investment (ROI), which is every owner's dream. To achieve this, a fundamental effort is to have a good design. Whilst there are plenty of design approaches, all would agree on one common thing, i.e. predicting the yield. This prediction may involve sophisticated tools, mechanisms, or algorithms, designed to give the most accurate and precise results [4,5,6,7]. However, issues like cost, time and complexity may hinder ease and popularity of use. It is here that the issue a simple model to predict the yield from a GCPV system is needed, which ultimately links to power matching between PV array and inverter capacity.

Thus the objective of this paper is to establish a simple mathematical model to predict the yield of a GCPV system and check the optimum sizing of PV array power to the inverter capacity. In this research, two GCPV systems were installed and monitored. The outputs were then modelled and a simplified equation was developed to predict its yield nd check for power ratios. The parameters identified were: array power; irradiation; mismatch; temperature; dirt; cable efficiency; and inverter efficiency.

2. System description

2.1 Physical set-up

The work was carried out at the Green Energy Research Centre (GERC), Universiti Teknologi MARA (UiTM), Shah Alam, Selangor (3˚N, 101˚E). The climate is considered as equatorial rainforest climate and fully humid (Af) [8]. Two GCPV systems were installed with the array azimuth facing due south, tilted at 10 deg from the horizontal. Details of the two systems are listed in Tables 1 and 2.

Table 1 PV module characteristic parameters for system1

Parameter	**Value**
Module	Yingli YL235P Polycrystalline
Pmp_stc	235 W
Imp_stc	7.97 A
Isc_stc	8.54 A
Voc_stc	37.0 V
Temp coeff Voc	-0.37% per deg C
Temp coeff Pmp	-0.45% per deg C
Configuration	2 parallel by 13 series
Inverter	SMA SB5000TL (1-phase)
Array power	6.11 kWp

Table 2 PV module characteristic parameters for system2

Parameter	**Value**
Module	Yingli YL250c-30b (Monocyrstalline)
Pmp_stc	250 W
Imp_stc	8.20 A
Isc_stc	8.71 A
Voc_stc	38.1 V
Temp coeff Voc	-0.33% per deg C
Temp coeff Pmp	-0.41% per deg C
Configuration	2 parallel by 20 series
Inverter	SMA STP8000TL-10 (3-phase)
Array power	10 kWp

The two GCPV systems were installed and placed side-by-side on top of a metal deck that is used as a car porch. The height of the roof is about 4 m from the ground. The monitoring system comprised:

1. Logging of the ambient: solar irradiance; and temperature
2. Logging of the GCPV system: current; voltage; power; energy; and temperature of module.

All data were logged at 5 minute intervals using the SMA weblog.

2.2 Mathematical approach

The mathematical relationship developed combines: array power; irradiation; mismatch; temperature; dirt; cable efficiency; and inverter efficiency [9]. The formula for predicting yield was formulated as in equation (1).

$$Y_{expected} = \sum_{t=0}^{23} P_{arraystc} \times H \times k_{mm} \times \left\{ 1 + \left(\frac{\beta_{pmp}}{100\%} \times [T_c - T_{stc}] \right) \right\} \times k_{dirt} \times k_{cable} \times k_{inv} \quad (1)$$

Where

$Y_{expected}$ Expected yield (kWh)

$P_{arraystc}$ Array power (kWp)

H Peak Sun Hour (h)

k_{mm} Module mismatch

β_{pmp} Temp coeff Pmp

T_c Temperature of cell

T_{stc} Temperature at STC

k_{dirt} Dirt factor

k_{cable} Cable loss

k_{inv} Inverter efficiency

β_{pmp} Temperature coefficient (% / deg C)

The formula for predicting power output from the inverter was formulated as equation (2)[10]:

$$P_{expected} = P_{arraystc} \times k_g \times k_{mm} \times \left\{ 1 + \left(\frac{\beta_{pmp}}{100\%} \times [T_c - T_{stc}] \right) \right\} \times k_{dirt} \times k_{cable} \times k_{inv} \quad (2)$$

Where

k_g irradiance (wm^{-2} $\div$ 1,000 wm^{-2})

The two preceding formulations were developed and used as they could predict the yield and instantaneous power, as well as explain what was happening in the system during its operation. This ability would provide the owner to rectify the system, whether caused by uncontrolled natural forces, or coming from the system itself.

3. Results and discussion

3.1 Irradiance and module temperature

For the purpose of this paper, datasets for the month of March 2014 was chosen and analysed, as it typically represents the highest solar irradiation value in the year at the location. Figure 1 shows the profiles.

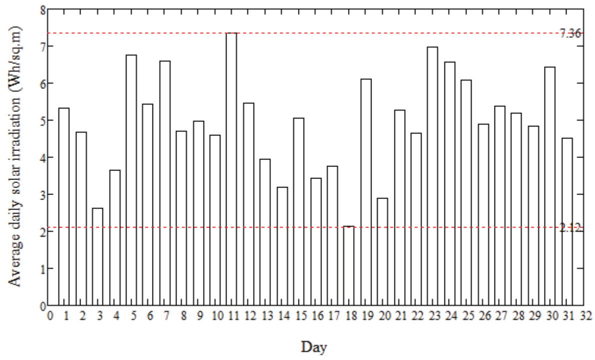
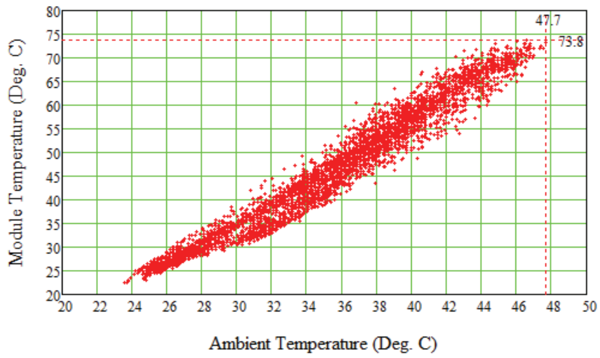
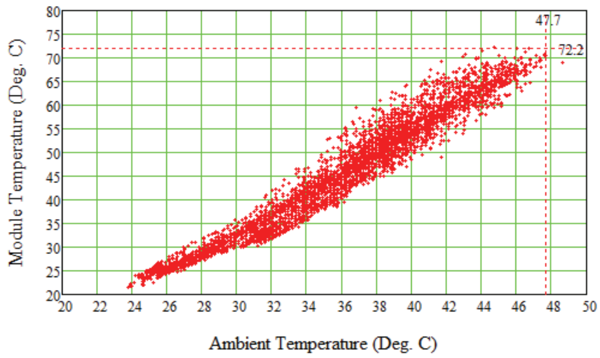


Figure 1. Daily solar irradiation at site for March 2014.

From Fig. 1, the highest daily solar irradiance is 7.36 $kWhm^{-2}$ and the lowest is 2.12 $kWhm^{-2}$ for this location. The seemingly "high" value is attributable to the experience of a "heat wave" in Malaysia at that time.



(a)



(b)

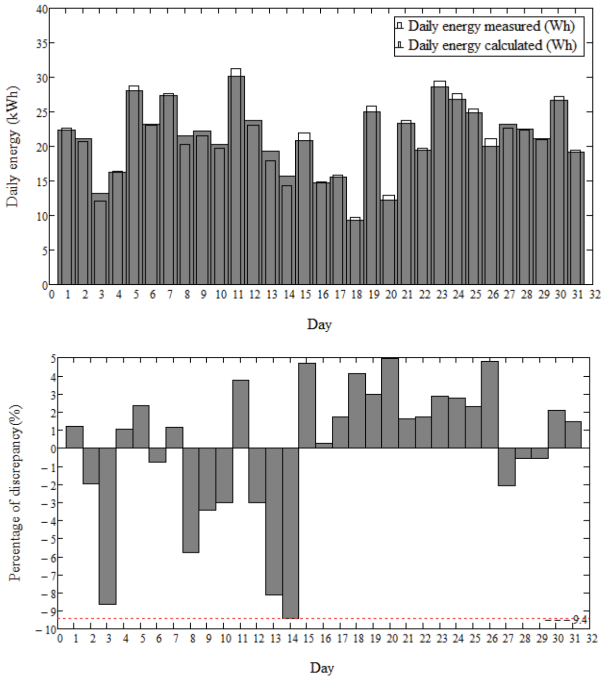
Figure 2. Ambient and module temperatures for: (a) Polycrystalline module (b) Monocrystalline module.

From Fig. 2, the highest ambient temperature is 47.7 deg C and the highest operating temperatures for the polycrystalline and monocrystalline modules are 73.8 deg C and 72.2 deg C respectively. These are also in attributable to the heat wave.

For prediction purposes, these two key parameters, i.e. solar irradiance and module temperature datasets are of fundamental importance required as input data to forecast yield. This is especially true for this location since the wind speed is negligible. Therefore, both inputs will be used to predict the yield and then compared to the measured value.

3.2 Measured versus expected yields

This section presents the results obtained from the measured values in the field and that predicted using the models proposed in this paper.



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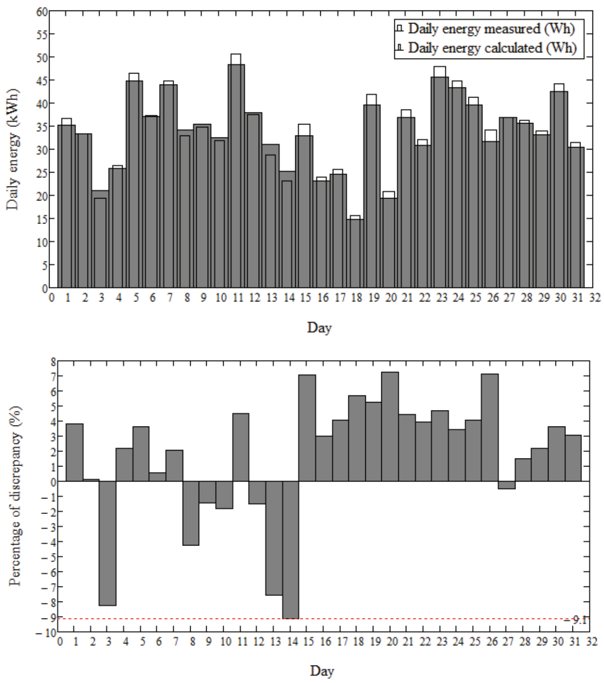


(b)

Figure 3. Daily yield and percentage discrepancy from measured and expected values for: (a) Polycrystalline (b) Monocrystalline PV modules.

From Fig. 3, it is apparent that the highest and lowest yields were on day 11 and 18 respectively.

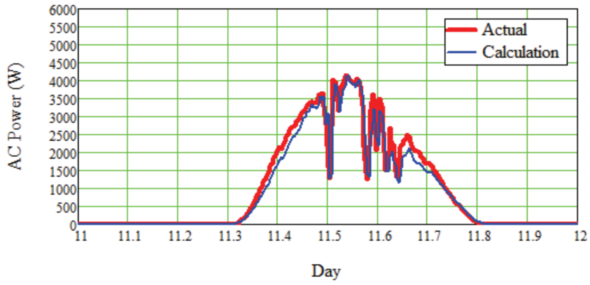
From Fig. 3(a), the measured and expected values are in good agreement. The general pattern matches very closely to each other with the maximum discrepancy being -9.4% which occurred on day 14.

From Fig. 3(b), the measured and expected values are in good agreement. The general pattern matches very closely to each other with the maximum discrepancy being -9.1% which occurred on day 14.

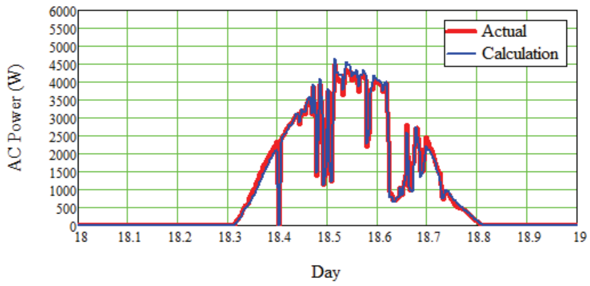
Upon closer scrutiny, it is observed that there are some differences between the measured and expected values for both GCPV systems. However, this is more pronounced for System 2 that uses the monocrystalline modules. The discrepancy is due to fixed parameters used in the model such as dirt as well as accuracy of the solar irradiance and temperature sensors.

3.3 Measured versus expected power

To deeper investigate the cause of the differences between measured and expected values in both systems, the power output at Real Operating Conditions (ROC) was looked into using Eq. (2). The two systems were compared and divided into two types of irradiance conditions, as discussed below.



(a)



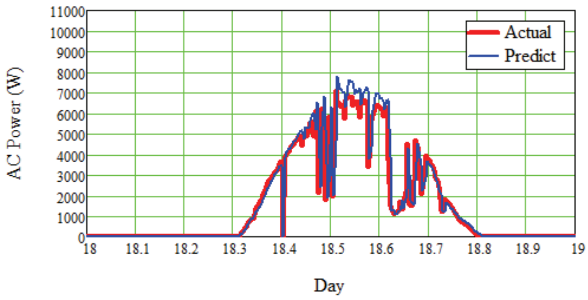
(b)

Figure 4. Comparison of power produced by polycrystalline modules (a) at high solar irradiance (b) at low solar irradiance.

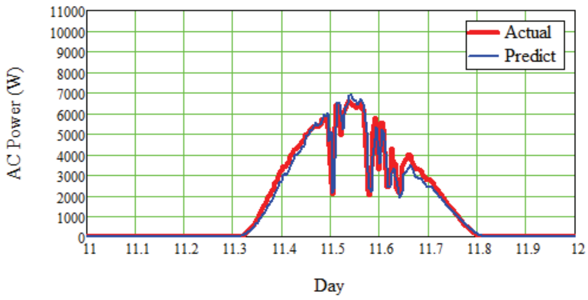
From Fig. 4, a good agreement is seen between the measured and calculated output power from the inverter (AC power) values generally for the polycrystalline modules.

Fig. 4(a) shows the plot for day 11 which quite clearly shows the difference between the actual and expected values differ considerably. Here, the proposed model tends to underpredict the values.

Fig. 4(b) shows the plot for day 18 which quite clearly shows the difference between the actual and expected values differ much less. The model predicts quite well for this regime.



(a)



(b)

Figure 5. Comparison of power produced by monocrystalline modules (a) at high solar irradiance (b) at low solar irradiance.

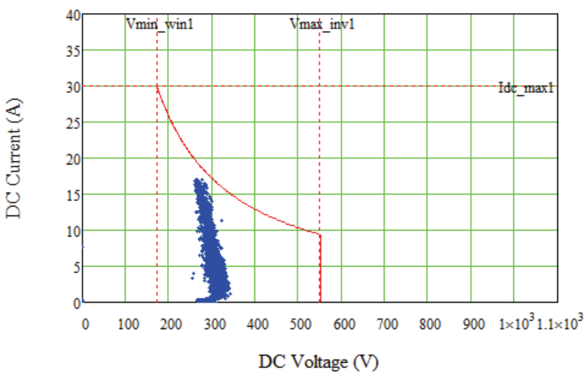
From Fig. 5, a good agreement is seen between the measured and calculated output power from the inverter (AC power) values generally for the polycrystalline modules.

Fig. 5(a) shows the plot for day 11 which quite clearly shows the difference between the actual and expected values differ considerably. Here, the proposed model is very accurate, execpt at the very peak regions where it tends to overpredict the values.

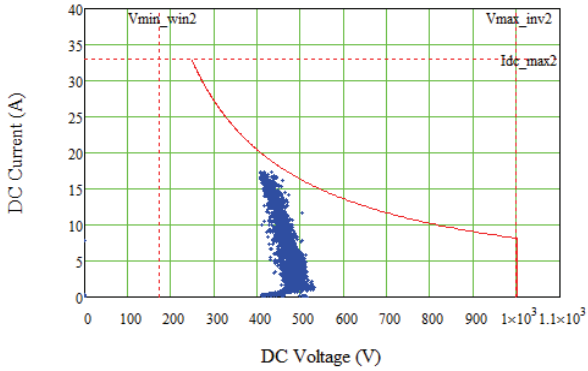
Fig. 5(b) shows the plot for day 18 which quite clearly shows the difference between the actual and expected values differ much less. The model predicts quite well for this regime, except at the very low levels which tends to underpredict.

In summary, it appears that for both systems: polycrystalline and monocrystalline PV modules, the measured and expected values are generally in good agreement. There are still some residual discrepancies at the peak irradiance for both the polycrystalline and monocrystalline modules and at low irradiance for the monocrystalline modules.

A deeper study reveals results as shown in the following figure.



(a)



(b)

Figure 6. IV curve versus SOA on inverter (a) Polycrystalline module (b) Monocrystalline module.

Fig. 6 shows the plot of current versus voltage (IV curve) and the power curve on the same graph. This plot shows the Safe Operating Area (SOA) of the inverter with respect to the PV array power input. From both figures, it is clear that the inverter from both systems operate in the SOA.

Fig. 6(a) shows that the input voltage was about 300 V DC and reached a current of about 17 A DC. Since the dataplots did not touch the SOA curve, one can conclude that the PV array and inverter power is well matched for this system.

Fig. 6(b) shows that the input voltage ranged from 400 to 500 V DC and reached a current of about 17 A DC. Since the dataplots did not touch the SOA curve, one can conclude that the PV array and inverter power is well matched for this system.

Some other issues that need to be looked into are: spectral distribution; aging; and Light Induced Degradation (LID) phenomenon that generally appears in thin film PV technology. Some of these should also be taken into consideration in high irradiation regions, with plenty of clouds, like low latitude areas [10-12].

4. Conclusion

In this paper, a simplified modeling technique for grid-connected power systems has been introduced. The models employ steady state conditions considers several key parameters, such as: array power; irradiation; mismatch; temperature; dirt; cable efficiency; and inverter efficiency. There are two models developed in this work: yield prediction; and power prediction. These have been tested and proved to be in good agreement generally with field results in Malaysia.

These models not only predict reasonably well results but also enables the user to detect the matching of optimum sizing of the GCPV system. The owner can then examine the system in a simple and relatively fast manner.

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