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Analysis of yearlong performance of differently tilted photovoltaic systems in Brisbane, Australia

Ruifeng Yan [a], Tapan Kumar Saha [a,*], Paul Meredith [b], Shane Goodwin [a]

[a] School of Information Technology and Electrical Engineering, University of Queensland, Brisbane, QLD 4072, Australia
[b] Center for Organic Photonics and Electronics, University of Queensland, Brisbane, QLD 4072, Australia

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ABSTRACT

Installation of photovoltaic (PV) systems is on a dramatic rise in recent years. This has attracted researchers' attention around the world to examine PV efficiency and integration issues. In the literature, many studies were found on analyzing PV systems in specific regions; however none of them focused on Queensland, Australia. In this paper, PV array performance in Brisbane is investigated by utilizing the yearlong recorded data from the PV systems at the University of Queensland (UQ). The theoretical model has good agreement with the field measurement in terms of per unit representation established in this study. Therefore, this validated theoretical model is applied to estimate PV system performance with different tilt angles and orientations. This study will not only provide invaluable information and tools for Australian PV industries and electricity utilities, but also offer helpful methodologies to PV applications in other countries.

1. Introduction

Photovoltaic (PV) installation has exponentially increased during the last few years in Australia [1]. This is mainly due to government incentives, cheaper PV price and people's awareness of green power. In order to research the impacts of PV on its related industries and to reduce its carbon footprint the University of Queensland (UQ) installed a 1.22 MWp PV system on the rooftops of 3 buildings across its campus in June 2011. The PV panels were set up with different configurations for a comprehensive understanding of PV energy generation. For example, PV modules were tilted to different angles and some of them are connected with energy storage. This real world system offers precious information and analysis of the recorded data will provide an invaluable insight into PV performance not only for researchers but also for the power and energy industry.

In the literature, much effort was put into determining optimal tilt angle and orientation (azimuth) of PV systems in certain areas, such as Japan [2], Taiwan [3], Egypt [4], Italy [5], Romania [6], Greece [7], USA [8], Canada [9], Turkey [10] and many more. Tracking systems were studied against the fixed angle panels [5,6,8], including single-axis and dual-axis trackers. Many important lessons were learnt such as the need for derivation of meaningful performance ratio [5], requirement for non-deterministic orientation program [6] and reliability of PV performance software [8].

Research was conducted by comparing PV power generation between fixed panels with different tilt angles. Various silicon based solar cells were examined and some unique results were summarized in [2]. But due to different directions the panels were facing, it was not easy to have a more uniform conclusion. The results presented in [4,7] were aligned with the rule of thumb – the fixed tilt angle is equal to local latitude facing south in the Northern Hemisphere and north in the Southern Hemisphere with azimuth angle being zero.

Modern techniques such as particle-swarm optimization [3] and neural-network [11] were also introduced to resolve the optimum tilt angle for PV systems. At the same time, some researchers adopted the deterministic approach to this issue [7,10,12], which is based on calculating estimated solar radiation on a PV site. A combination of these methods, which forms a more advanced scheme, can be found in [13,14].

Previously, very few studies used both yearlong power and energy recorded data to validate theoretical estimations and identify dominant factors to PV generation. Moreover, no research has investigated PV performance in Brisbane, Australia. This paper compares theoretical estimations with measured results obtained from the UQ PV system. A per unit representation is established for further verifying the theories. Then these related theories are used to estimate PV performance in the forthcoming years and optimal tilt and orientation angles for PV systems in Brisbane.

* Corresponding author. Address: School of Information Technology and Electrical Engineering, University of Queensland, St. Lucia, QLD 4072, Australia. Tel.: +61 7 33653962; fax: +61 7 33654999.

E-mail addresses: ruifeng@itee.uq.edu.au (R. Yan), saha@itee.uq.edu.au (T.K. Saha), meredith@physics.uq.edu.au (P. Meredith), shane.goodwin@uq.edu.au (S. Goodwin).

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This paper will firstly introduce the UQ PV system studied in this research in Section 2. Then a theoretical model is presented in Section 3, which is then used to estimate annual power and energy generation for two PV systems of interest. A per unit version of the model is developed to avoid difficulties in determining some complicated parameters. Section 4 compares the theoretical estimation with the yearlong recorded data and the reasons for data mismatch are analyzed in Section 5. With good agreement between theory and reality the theoretical model is used to investigate potential optimal tilt angles and orientations of PV systems in Brisbane.

2. Studied photovoltaic systems

The University of Queensland installed a 1.22 MWp PV system, which was in operation since June 2011. It mainly contains Trina polycrystalline PV panels (TSM-PC05, 240 Wp [15]) and 85 × 12.5-kVA (3∅415 V) inverters (AURORA [16]) with several other types of inverters. The data of each inverter on the AC side were recorded in a 15-min time step before 9th December, 2011 and in a 1-min interval after this date.

The whole PV system was installed on the rooftop of three buildings on the St Lucia campus. The systems of interest of this research are the PV arrays on the roof of the UQ Center (Bld. 27A) as shown in Fig. 1 [17]. The system on the left hand side (lower roof part) is called "27A-South" having a total capacity of 129.6 kW (9 × 60 panels). This system was brought online much later than the others so the data from this part of the system is not suitable for performance comparison. As a result it is not included in this study.

The system investigated is situated on the right hand side of Fig. 1 named "27A-North", containing a 303.84 kWp array with 17 sets of 56 panels tilted 5.5° to the North (5.5°N), 4 sets of 60 panels tilted 2.5° to the South (2.5°S), 1 set of 52 panels 5.5°N and 1 set of 22 panels 5.5°N. All PV panels in the UQ Center are exactly the same type – Trina TSM-PC05. The 27A-North system is orientated 16° East of North (16°EoN) and all panels are fixed on the roof without any tracking systems. Currently, in Australia most PV systems have fixed tilt angles and orientations. This is the main reason for this paper to analyze PV performance with different systems of fixed tilt and azimuth angles.

3. Theoretical estimation of PV generation

In this research, a yearlong recorded data is examined to reveal the PV performance from July 1st 2011 to June 30th 2012. There are 17 sets of 56 panels tilted 5.5° to the North and 4 sets of 60 panels tilted 2.5° to the South with each set attached to an inverter of the same type. Because in each of these two configurations, the same number of PV panels was installed in each set of arrays, only one set from each tilted configuration is investigated. For example, one set with 56 panels tilted 5.5° to the North (5.5°N) and one set with 60 panels tilted 2.5° to the South (2.5°S) are studied in this paper. They are denoted as 5.5°N/56 and 2.5°S/60 for a simpler representation of the systems in the rest of this paper.

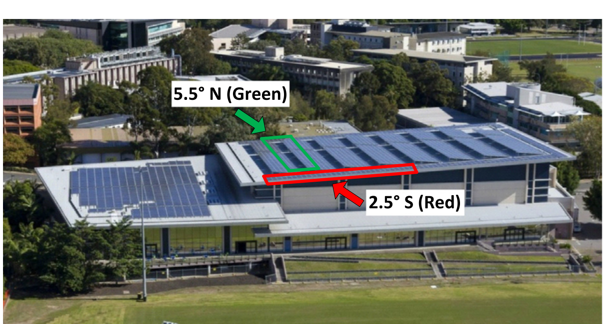

Fig. 1. UQ center rooftop PV systems with the studied sets of PV panels circled [17].

3.1. System assumptions

The energy generation of a PV system depends on many factors, such as sunlight intensity, power conversion efficiency, system location, panel tilt/azimuth angles, weather conditions and so on. Fortunately, the 5.5°N/56 and 2.5°S/60 systems were installed side by side with the same type of panels, so most factors are approximately the same – e.g. global irradiance, ambient temperature and air density. However, due to differences in shadings, reflections and air flow between these two systems, weather conditions may not affect the systems in exactly the same way. Small errors are inevitable.

The most significant influence on PV output should be solar irradiance including direct, diffuse and reflected beams. Among them, direct irradiance dominates the power generation [18]. Therefore, only direct beam is considered in theoretical calculations as in Eq. (1). The annual energy generation (E) is a function of power efficiency (η), sunlight intensity (G_a, W/m^2), incident angle (θ), the number of PV panels (n) and area of each module (A, m^2).

$$E = \sum_{1}^{365} \sum_{\theta\text{sunrise}}^{\theta\text{sunset}} (\eta \times G_a \times \cos\theta \times n \times A) \tag{1}$$

However, power conversion efficiency and sun irradiance change throughout the year, so it is hard to precisely determine these parameters. But they can be represented as equivalent values as in the following equation:

$$E = \eta_{\text{equi}} \times G_{\text{a\_equi}} \times n \times A \times \sum_{1}^{365} \sum_{\theta\text{sunrise}}^{\theta\text{sunset}} (\cos\theta) \tag{2}$$

As mentioned previously, due to the closeness and configuration of the 5.5°N/56 and 2.5°S/60 systems, these equivalent values are almost the same. Because all PV panels are in a very close proximity, the equivalent sun irradiance should be almost identical. Moreover, all PV modules are in the same type – Trina TSM-PC05, the module efficiency will be very similar. However, there will be a small difference of 0–3% between the individual modules as stated in the manufacture datasheet of Trina TSM-PC05 [15]. But this study did not compare one module to another single module. Instead, analysis is conducted between two systems of more than 50 PV panels with different tilted angles. Statistically, the individual difference will be averaged out, so the individual module efficiency should have negligible effects on the results. Therefore, by taking the 2.5°S/60 system as a baseline, energy generation of the 5.5°N/56 system can be expressed in a per unit form as in Eq (3). Following the same principle instantaneous PV power output can be formulated as in the following equation:

$$E_{56} = n_{56}/n_{60} \times \sum_{1}^{365} \sum_{\theta\text{sunrise}}^{\theta\text{sunset}} (\cos\theta_{\text{PV}-5.5^\circ\text{N}}) \Bigg/ \sum_{1}^{365} \sum_{\theta\text{sunrise}}^{\theta\text{sunset}} (\cos\theta_{\text{PV}-2.5^\circ\text{S}}) \tag{3}$$

$$P_{56} = n_{56}/n_{60} \times (\cos\theta_{\text{PV-5.5}^\circ\text{N}})/(\cos\theta_{\text{PV-2.5}^\circ\text{S}}) \tag{4}$$

By using this per unit representation, the calculation of some unknown equivalent parameters can be avoided which will make the comparison to recorded data much easier later in this study.

Some assumptions should be adopted to make Eqs. (3) and (4) valid, such as domination of direct beam and similar weather con-