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Acceptance Ratio Analysis in Grid-Connected Photovoltaic System: Is There Any Difference Between DC and AC?

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ABSTRACT

The performance status of a grid-connected photovoltaic (GCPV) system is denoted by performance indices, namely performance ratio, capacity factor, and even through power acceptance ratio (AR), as documented in Malaysia Standard (MS) procedures for acceptance test of GCPV testing and commissioning (TNC). Even though AR analysis can be either on the DC or AC side, the MS TNC procedures implemented analysis on the AC side. Therefore, the question arises whether there is any significant difference when using AC AR analysis compared to DC AR analysis in evaluating the system performance. Thus, this paper evaluates the differences between applying DC AR analysis and AC AR analysis in accessing the performance of the ten kW_p GCPV system in Malaysia. The AR analytical analysis employed the 2019 one-year historical data of solar irradiance, module temperature, DC power, and AC power. The results demonstrated that the monthly AC AR were consistently lower than DC AR with a percentage difference of approximately 3%. The percentage discrepancy was due to the variation of actual inverter efficiencies compared to the declared constant value by the manufacturer used in the AR prediction model. These findings have verified a significant difference between DC AR analysis and AC AR

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analysis. Most importantly, this study has highlighted the significance of AC AR analysis compared to DC AR analysis as a tool to evaluate GCPV system performance because AC AR has taken an additional factor into consideration, which is the inverter efficiency variation.

Keywords: AC acceptance ratio, DC acceptance ratio, grid-connected photovoltaic (GCPV), inverter efficiency, performance

INTRODUCTION

A photovoltaic (PV) energy system is widely used to generate energy by converting sunlight into electrical energy. PV systems can be divided into three types, which are grid-connected (GC), off-grid (OG), and hybrid systems (Appiah et al., 2019; Khatib et al., 2017). Monitoring the output power generated by the PV system is necessary to ensure the shortest return-on-investment (ROI), reduce maintenance costs, and extend the PV system's lifetime. Besides, monitoring PV system's performance is required as the output power generated by a PV system might be reduced due to several factors, such as heat effect, light input, accumulation of dirt, and aging factor (Yusoff et al., 2017). There were also studies conducted on partial shading (Humada et al., 2014) and dirt accumulation due to high pollution in the city center of Krakow, Poland (Jaszczur et al., 2019).

A few performance parameters were introduced in international standard of IEC 61724 for monitoring the PV system, including final yield, performance ratio, efficiency, and capacity factor (OFA, 2010; IEC TS 61724, 2016). Final yield is defined as a ratio of total AC energy output by the PV system during a specific period to the nominal power of the installed PV system; meanwhile, performance ratio represents the overall losses effect on the power output of a PV system (Wittkopf et al., 2012). Unlike the final yield and performance ratio, efficiency represents the net conversion efficiency of a PV module, PV system, and inverter, while capacity factor is the comparison of actual energy to the predicted energy generated by the PV system (Nurdiana et al., 2020).

In Southeast Asia, numerous studies on the performance evaluation of GCPV systems have been reported (Hussin et al., 2013; Nurdiana et al., 2020; Wittkopf et al., 2012). Analytical performance of a 142.5 kW_p rooftop GCPV system using polycrystalline Silicon (p-Si) in Singapore was carried out by (Wittkopf et al., 2012). The performance ratio was about 81%, while the final yield and PV module efficiency were 3.12 kWh/kW_p and 11.8%, respectively. In Serpong, Indonesia, a study conducted by Nurdiana et al. (2020) showed that the performance ratio was 82.42%, with the average value of the final yield, 3.38 kWh/kW_p/d. Meanwhile, the average values of the PV module efficiency, system efficiency, inverter efficiency, and capacity factor were 15.29%, 14.77%, 96.63%, and 14.07%, respectively, during the eight-month monitoring period. Another study on the performance of a GCPV system was reported by Hussin et al. (2013). Three GCPV systems of different PV module technologies (monocrystalline, polycrystalline, and thin-film) installed in Selangor, Malaysia, were used for the analysis. The results showed that the performance ratios for monocrystalline, polycrystalline, and thin-film PV modules were 81.0%, 78.2%, and 94.6% respectively. Besides, the study found that thin-film PV modules exhibit higher energy production, reliability, and conversion efficiency in Malaysia (Hussin et al., 2013).

In the tropical region of Malaysia, the Acceptance Ratio (AR) is one of the parameters used to evaluate the GCPV system under the system acceptance procedure for testing and commissioning (TNC). AR is known as a ratio of actual power to predicted power. According to Malaysian Standard (MS2692:2020), a benchmark range of AR equal to 0.9 up to 1.3 has been documented as the requirement for a GCPV system to be accepted in the TNC procedure (SIRIM, 2020). Notably, the TNC acceptance procedure for designated AR is the AC AR, which utilizes AC power (output power from the inverter) inside the developed mathematical equation instead of DC power.

Several existing studies have shown a relationship between AC AR with failure detection in the GCPV system (Muhammad et al., 2019; Shukor et al., 2021). Firstly, an algorithm comprised of failure detection on AC power by using AR determination (AC AR) has been developed (Muhammad et al., 2019). The analysis was conducted on two GCPV systems of different PV module technologies, polycrystalline and monocrystalline, installed under the tropical climate of Malaysia. The minimum AR threshold of 0.9 introduced in the Malaysian Standard was used as a benchmark in the analysis to identify a fault-free and a failure GCPV system. The result showed that a fault-free GCPV system recorded 31.4% of AR < 0.9; meanwhile, a failure GCPV system demonstrated 93.38% of AR < 0.9. Thus, the study has highlighted the utilization of AR analysis as a significant early fault indicator for PV systems (Muhammad et al., 2019).

Another similar study that used AC AR as an early failure indicator in the GCPV system was reported by Shukor et al. (2021). The analysis was conducted on three GCPV systems installed at different locations in Malaysia. It was found that System 1 under investigation showed an early failure symptom where the cumulative percentage of AR < 0.9 ranges between 34% to 71%, meanwhile System 2 and 3 were identified as fault-free GCPV systems with cumulative percentage AR < 0.9 ranging from 5% until 19% (Shukor et al., 2021). Likewise, a study was also conducted on failure detection at the PV array level, which involved DC AR (Kim et al., 2021). The study proposed that DC AR must range between 0.93 until 1.02 for a normal operating condition. Otherwise, the system will be identified as a failure. In addition, various type of failure was diagnosed from this study, such as series, parallel and total failure. These identified failures were the factors that led to the decrease in the electrical output of the system (Kim et al., 2021).

From the literature on AR, numerous studies have focused on AC power analysis; meanwhile, there were also studies conducted on DC power analysis that would eventually lead to the determination of DC AR and AC AR. However, an issue arises on whether there is any significant difference between these two ratios to evaluate the performance of a GCPV system. Therefore, this study aims to evaluate the percentage discrepancy of DC AR compared to AC AR analysis in evaluating the performance of a GCPV system.

From this point onwards, this study will be elucidated through three sections: methodology, results, discussions, and conclusion. The methodology section contains the information of the selected GCPV system, detailed descriptions of the PV module and inverter used in the studies. A flowchart for DC and AC AR analysis with their explanation is also included in this section. The following section, which is results and discussions, presents the discrepancy in the form of percentage differences between DC and AC AR. Finally, the last section draws out the conclusion for the whole study.

METHODOLOGY

System Descriptions

The study was performed for a ten kW_p GCPV system installed on the rooftop with an inclination angle of 30°. The system was installed and commissioned in December 2015 under the Feed-in-Tariff (FiT) scheme, an initiative introduced by the Government of Malaysia (GoM). The general information of the system is tabulated in Table 1.

Table 1
General information of selected GCPV system

Subjects	Descriptions
Location	Terengganu, Malaysia
Latitude and Longitude	5.2077° N and 103.2049° E
Nominal array power	10 kW_p
Mounting type	Retrofitted (RF)

PV Module and Inverter Descriptions

The GCPV system comprises polycrystalline PV modules connected to an inverter. The related specifications are as described in Table 2.

Table 2
PT-P660250WB module and Blueplanet 9.0 TL3 specification

	Specification
PV technology	Polycrystalline
PV module model	PT-P660250WB
Maximum power, P_{mod_STC}	250 W
Module efficiency, η_{PV}	15.37%
Inverter model	Blueplanet 9.0 TL3
Nominal power, P_{nom}	9000 W
Inverter efficiency, $\eta_{inverter}$	98.30 %

A few other components were connected to the GCPV system, such as a module temperature sensor, ambient temperature sensor, relative humidity sensor, and pyranometer. A data logger (WebBox) was also installed at the inverter to record the system's DC and AC power output and the data coming from the sensors. Each data was recorded in every 5 minutes interval consecutive per day. In addition, historical data of DC and AC power output (P_{DC_actual} and P_{AC_actual}), solar irradiance, and module temperature from 1 January 2019 to 31 December 2019 were collected for further analysis.

DC and AC AR Analysis

This section presents the methodology applied for AR analysis between DC and AC. A flow of work is presented in Figure 1.

First, a few parameters, such as solar irradiance, module temperature, DC and AC power output (P_{DC_actual} and P_{AC_actual}), were extracted from the data logger meanwhile $P_{DC\_predict}$ and $P_{AC\_predict}$ were obtained through a mathematical model as shown in Equations 1 and 2 (SEDA, 2016):

$$P_{DC\_predict} = P_{mod\_STC} \times N_T \times f_g \times f_{temp} \times f_{mm} \times f_{age} \times f_{dirt} \times \eta_{cable} \quad (1)$$

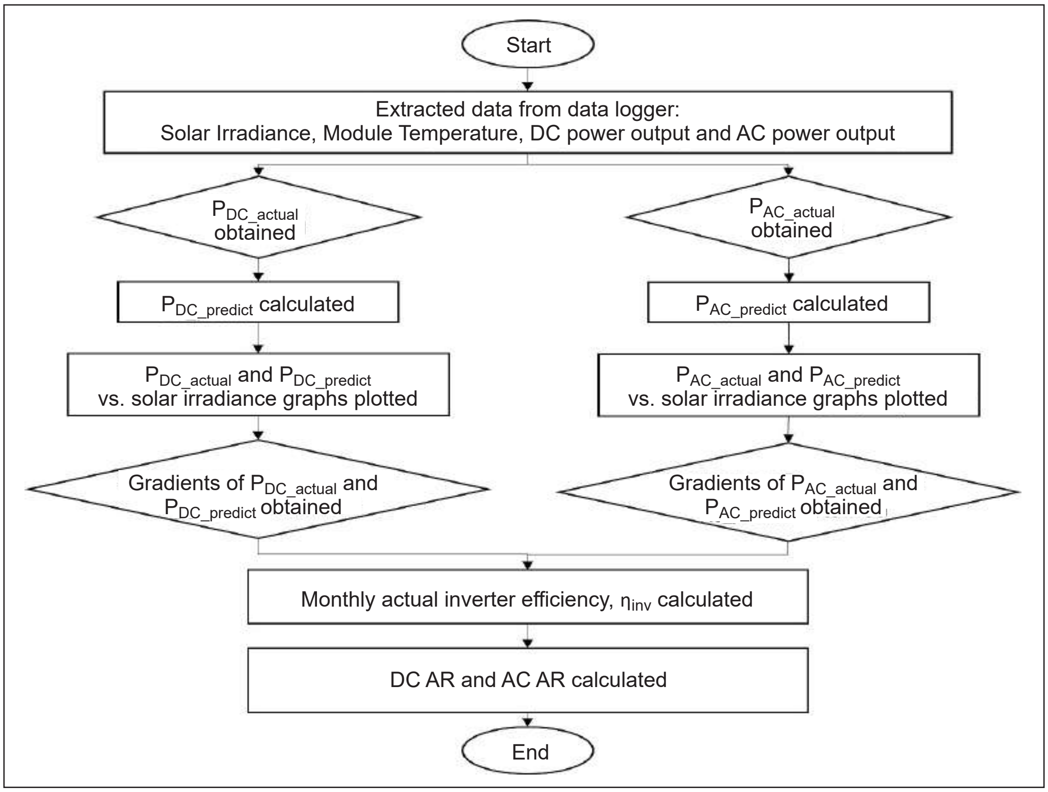


Figure 1. A flowchart of DC AR and AC AR analysis in the GCPV system

For $P_{AC\_predict}$:

$$P_{AC\_predict} = P_{mod\_STC} \times N_T \times f_g \times f_{temp} \times f_{mm} \times f_{age} \times f_{dirt} \times \eta_{cable} \times \eta_{inverter} \quad (2)$$

Where P_{mod_STC} is the maximum power of a PV module at Standard Test Condition, STC (W). N_T is the total amount of PV modules. Next, f_g is the peak sun factor, which can be calculated using Equation 3:

$$f_g = \frac{G}{G_{STC}} \quad (3)$$

Where the solar irradiance at the instant time, G (Wm^{-2}), is divided by the solar irradiance at STC, G_{STC} rated at 1 kWm^{-2}. The value of the temperature coefficient factor for power, f_{temp} , can be determined based on Equation 4.

$$f_{temp} = 1 + \left[\left(\frac{\%\gamma_{pmp}}{100}\right) \times (T_m - 25)\right] \quad (4)$$

Where γ_{pmp} is the temperature coefficient of power (%/°C), and T_m is the temperature of the PV module (°C).

Table 3 shows the parameters and references related to the determination of other de-rating factors.

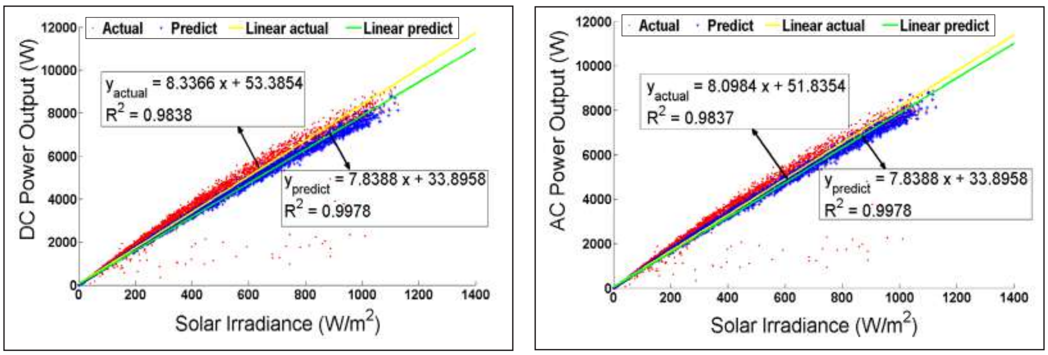
Table 3
Determination of de-rating factors

Parameters	References
Module mismatch, f_{mm}	Module datasheet
Aging factor, f_{age}	Module datasheet / Duration of PV system installation
Dirt factor, f_{dirt}	0.97 (Marion et al., 2005)
Efficiency of cable, η_{cable}	0.97 (Marion et al., 2005)
Efficiency of inverter, η_{inv}	Inverter datasheet (refer Table 2)

Next, monthly DC power graphs (P_{DC_actual} and $P_{DC\_predict}$) and AC power (P_{AC_actual} and $P_{AC\_predict}$) were plotted and analyzed. The linear equation and Pearson correlation coefficient (R^2) were also determined. Finally, the gradients obtained from the linear equations were tabulated. Monthly actual inverter efficiency, DC, and AC AR with their respective percentage differences were also calculated and discussed in the next section.

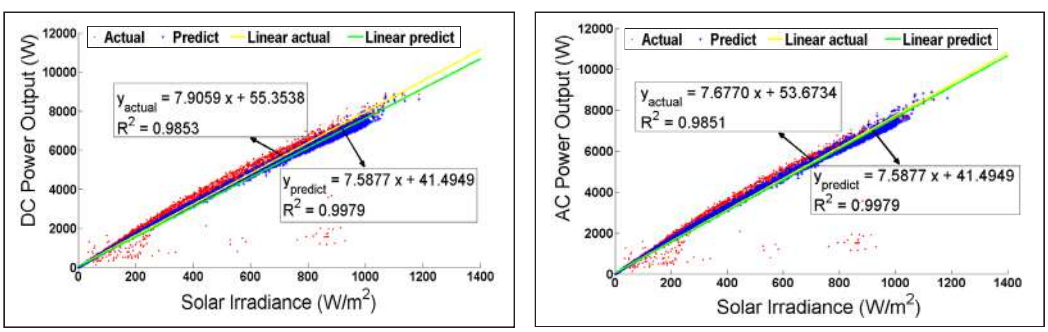
RESULTS AND DISCUSSIONS

For this study, the data of actual DC and AC power output for the system was collected in 2019. It is best to note that the data used were recorded every 5 minutes because a shorter time interval (15 minutes or less) will have minor errors than hourly-averaged data (Hansen et al., 2012). These data were then analyzed by using Excel and Matlab software. Figures 2 until 13 show that the red and blue data markers represent the actual and predicted DC and AC power, respectively. Meanwhile, yellow and green lines refer to the linear regression line for actual and predicted data.



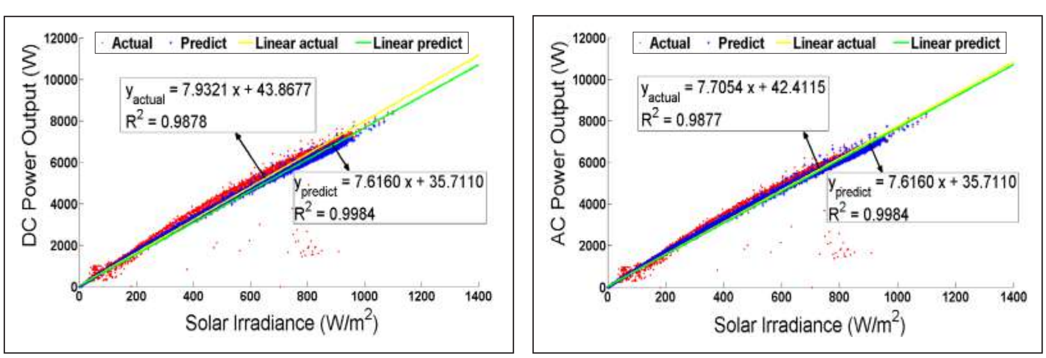
(a) (b)

Figure 2. Power output versus solar irradiance in January 2019 for (a) DC power and (b) AC power



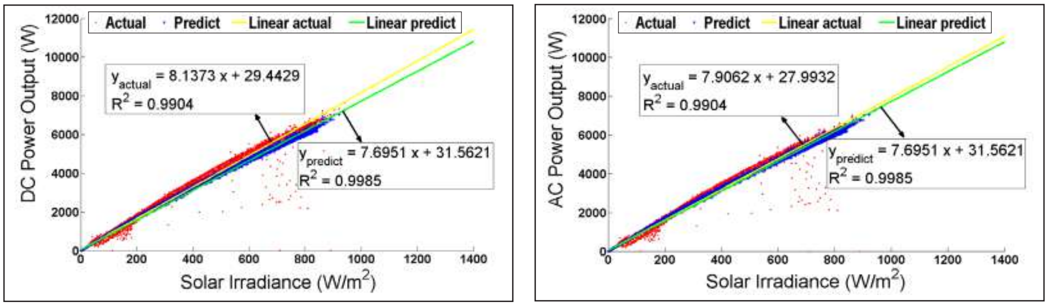
(a) (b)

Figure 3. Power output versus solar irradiance in February 2019 for (a) DC power and (b) AC power



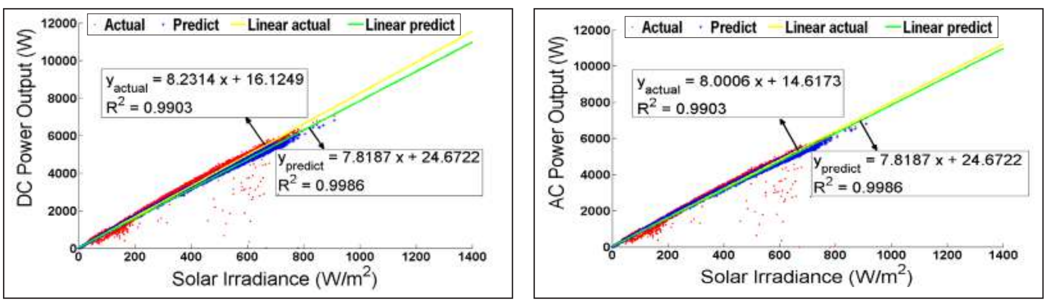
(a) (b)

Figure 4. Power output versus solar irradiance in March 2019 for (a) DC power and (b) AC power



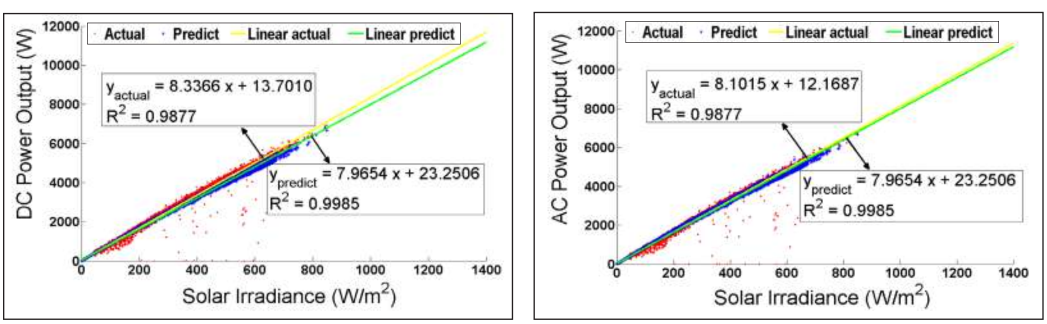
(a) (b)

Figure 5. Power output versus solar irradiance in April 2019 for (a) DC power and (b) AC power



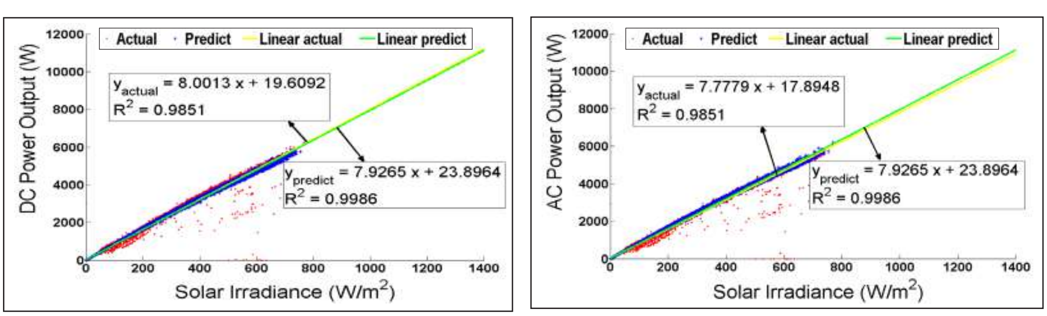
(a) (b)

Figure 6. Power output versus solar irradiance in May 2019 for (a) DC power and (b) AC power



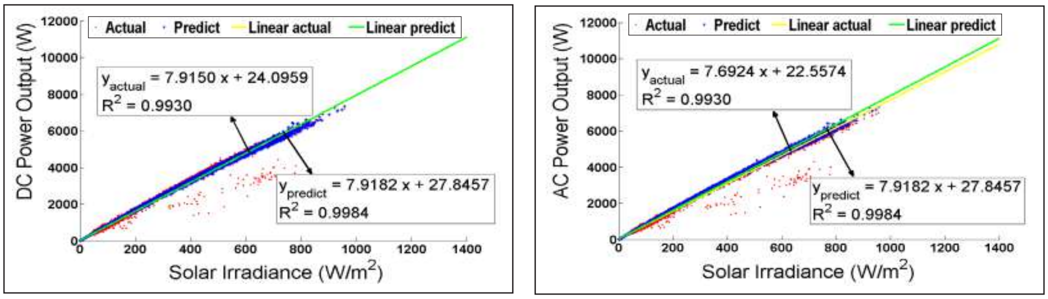
(a) (b)

Figure 7. Power output versus solar irradiance in June 2019 for (a) DC power and (b) AC power



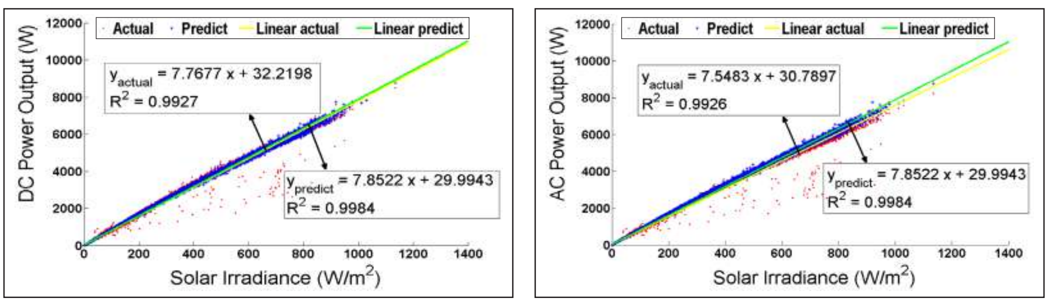
(a) (b)

Figure 8. Power output versus solar irradiance in July 2019 for (a) DC power and (b) AC power



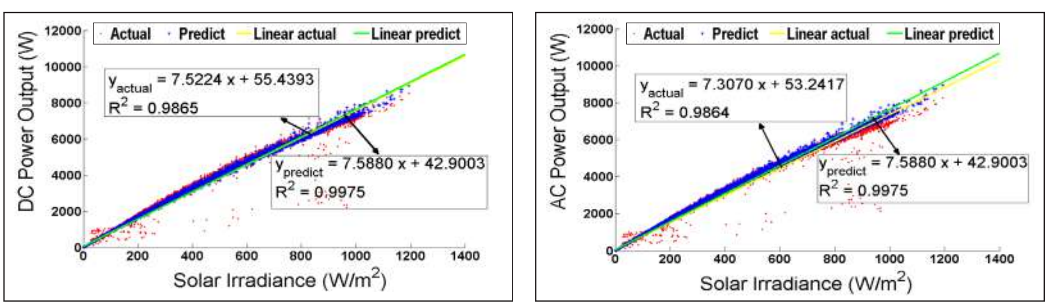
(a) (b)

Figure 9. Power output versus solar irradiance in August 2019 for (a) DC power and (b) AC power



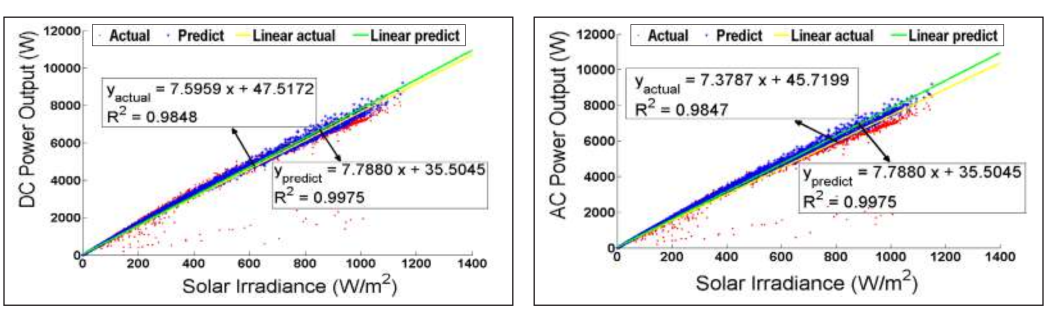
(a) (b)

Figure 10. Power output versus solar irradiance in September 2019 for (a) DC power and (b) AC power



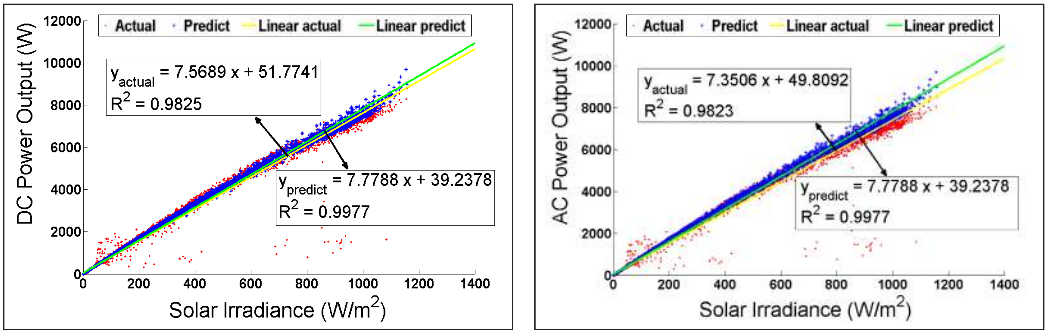
(a) (b)

Figure 11. Power output versus solar irradiance in October 2019 for (a) DC power and (b) AC power



(a) (b)

Figure 12. Power output versus solar irradiance in November 2019 for (a) DC power and (b) AC power



(a) (b)

Figure 13. Power output versus solar irradiance in December 2019 for (a) DC power and (b) AC power

For DC power analysis, it can be observed that the predicted DC power ($P_{DC\_predict}$) is slightly lower than the actual DC power (P_{DC_actual}) in the month January until June 2019, as shown in Figures 2 (a), 3(a), 4(a), 5(a), 6(a), and 7(a). It is proposed that some of the de-rating factors for output power were underpredicted, causing slightly lower predictions. It is also interesting to observe that the P_{DC_actual} and $P_{DC\_predict}$ graphs have a good agreement as to the solar irradiance increases from July to December, as shown in Figures 8(a), 9(a), 10(a), 11(a), 12(a), and 13(a). It is suggested that based on the data, the system is working properly. However, several of the P_{DC_actual} and P_{AC_actual} were observed to be abnormally low despite relatively high solar irradiance (in each month of the year 2019), and they fluctuated from the prediction. Lower power production at high solar irradiance might be due to recorded data inside cloud server storing not being synchronized with the actual measurement generated by the inverter (Platon et al., 2015).

For AC power analysis, the predicted AC power ($P_{AC\_predict}$) was observed to be slightly lower than the actual AC power (P_{AC_actual}) in January 2019, as illustrated in Figure 2(b). It is found that some of the de-rating factors were underpredicted, same as for DC power. Starting from February until August, the graphs of AC power ($P_{AC\_predict}$ and P_{AC_actual}) are quite aligned, as shown in Figures 3(b), 4(b), 5(b), 6(b), 7(b), 8(b), and 9(b). On the contrary, P_{AC_actual} were underpredicted from September until December 2019, as depicted by Figures 10(b), 11(b), 12(b), and 13(b).

Some P_{DC_actual} and P_{AC_actual} values were recorded as zero from March until July 2019 (Figures 4 until 8). Based on the anomaly observed, we proposed that the anomaly resulted from a system technical problem. Thus, an in-depth investigation needs to be done in the future to understand the root cause of the anomaly.

Table 4 shows the monthly values for actual inverter efficiency, DC, and AC AR with their percentage differences from January until December 2019 of the installed GCPV system. From Table 4, the monthly inverter efficiency can be determined by calculating the ratio of actual measurements between P_{AC_actual} (output power from the inverter) to P_{DC_actual} (input power to the inverter), expressed by the following Equation 5:

$$\eta_{inv} = \frac{P_{AC\_actual}}{P_{DC\_actual}} \approx \frac{gradient\ of\ P_{AC\_actual}}{gradient\ of\ P_{DC\_actual}} \tag{5}$$

From the calculation, the maximum and minimum η_{inv} were recorded as 97.21% and 97.10%, respectively (Table 4). Therefore, the average monthly actual inverter efficiency of the system, η_{inv}, was 97.16% compared to 98.30%, which is the maximum η_{inv} declared by the manufacturer. These findings prove that the inverter is not working at a constant maximum of 98.30% efficiency, but the actual efficiency varies and is slightly lower than 98.30% on average during the operation.

Table 4
Average monthly inverter efficiency with DC AR and AC AR

Month	Gradient, m				Monthly actual inverter efficiency, η_{inv} (%)	AR		Percentage differences of AR (%)
	$P_{DC\_predict}$	P_{DC_actual}	$P_{AC\_predict}$	P_{AC_actual}		DC	AC	
Jan	7.8388	8.3366	7.8388	8.0984	97.14	1.06	1.03	2.90
Feb	7.5877	7.9059	7.5877	7.6770	97.10	1.04	1.01	2.94
Mar	7.6160	7.9321	7.6160	7.7054	97.14	1.04	1.01	2.90
Apr	7.6951	8.1373	7.6951	7.9062	97.16	1.06	1.03	2.88
May	7.8187	8.2314	7.8187	8.0006	97.20	1.05	1.02	2.84
Jun	7.9654	8.3366	7.9654	8.1015	97.18	1.05	1.02	2.86
Jul	7.9265	8.0013	7.9265	7.7779	97.21	1.01	0.98	2.83
Aug	7.9182	7.9150	7.9182	7.6924	97.19	1.00	0.97	2.85
Sep	7.8522	7.7677	7.8522	7.5483	97.18	0.99	0.96	2.86
Oct	7.5880	7.5224	7.5880	7.3070	97.14	0.99	0.96	2.91
Nov	7.7880	7.5959	7.7880	7.3787	97.14	0.98	0.95	2.90
Dec	7.7788	7.5689	7.7788	7.3506	97.12	0.97	0.94	2.93

Since the study aims to evaluate whether there is any significant difference using DC AR compared to AC AR, the AR analysis was conducted. AR is just the ratio of measured power to the predicted power as calculated by the following Equation 6:

$$AR = \frac{actual\ power}{predicted\ power} \approx \frac{gradient\ of\ actual\ power}{gradient\ of\ predicted\ power} \tag{6}$$

The AR on the DC side was calculated, followed by the AR on the AC side. Finally, a comparison was made between DC AR and AC AR. The results presented in Table 4 shows that the AC AR were consistently lower than DC AR for the whole 12 months with a percentage difference of approximately 3%. These findings were as expected based on the understanding that AC AR has included one additional variable, which is η_{inv} that was declared a constant in the prediction calculation as 98.30%.

In summary, the results and analysis above have proven a significant difference between DC AR and AC AR. More than that, it is found that AC AR is more reliable to access GCPV system performance because it takes into consideration the inverter efficiency performance.

CONCLUSION

The study has succeeded in achieving the aim by proving that DC AR significantly differs compared to AC AR by 3% when analyzed based on one-year historical data for a GCPV system located in tropical Malaysia. The discrepancy was due to the additional factor in AC AR analysis compared to DC AR analysis, which refers to the inverter efficiency that varies during actual operation compared to constant manufacturer declared inverter efficiency used in the AC AR prediction. Thus, an in-depth investigation should be conducted to delve into the typical yet anomaly behaviors of the daily operating inverter efficiency compared to the constant declared inverter efficiency by the manufacturer.

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