PERFORMANCE EVALUATION OF A GRID-CONNECTED PHOTOVOLTAIC SYSTEM BY COMPARING ITS THEORETICAL MODEL TO EXPERIMENTAL DATA

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Abstract

This work evaluates the instantaneous active power supplied by a grid-connected photovoltaic system by means of a comparison between the data acquired in the AC bus via a datalogger system developed by the inverter manufacturer, and the data obtained from a high-precision wattmeter. It also presents the measured energy and the active power estimates at the AC side using a theoretical model. The methodology employed in the analysis of solar irradiance and cell temperature parameters presented results which are consistent with the data available from a solar station in the vicinity of the installation, which are also used as input for the developed theoretical model. It is shown that the theoretical model of the system is in good agreement with the experimental data, making it suitable for application as a complementary tool to monitor operational performance of photovoltaic systems.

Keywords: Grid-connected photovoltaic systems, solar irradiance, temperature of PV cell, electric power, on-grid inverter

1. Introduction

The concept of distributed generation has received widespread attention at all levels of society in the last few years, and the number of such initiatives has been growing rapidly. In this context, solar photovoltaic energy has been gaining prominence as an alternative to commonly used energy sources, such as thermoelectric and hydroelectric power plants, mainly due to its easy implementation and maintenance, as well as the availability of solar resource.

In Brazil, the number of grid-connected photovoltaic system (GCPVS) installations in buildings, in the context of mini and micro-distributed generation, has seen significant growth since the publication of the Normative Resolution 482/2012 by the National Electric Energy Agency (ANEEL), later updated via NR 687/2015 and NR 786/2015. Currently, over 91,720 photovoltaic (PV) plants supply the demand of about 114,741 consumer units (980.59 MW net installed power).

Proper monitoring of GCPVS operation is indispensable not only for performance evaluation of these devices but also to estimate the system's electrical energy production based on theoretical models adjusted to its specific operational conditions and supported by the literature. Such estimates can thus be compared to other means of power production quantification, such as, for example, the one performed by a data acquisition system within the installation or by a bidirectional meter.

The present work is being carried out in the test area of the Group of Studies and Development of Energy Alternatives (Grupo de Estudos e Desenvolvimento de Alternativas Energéticas – GEDAE), located at the main campus of the Federal University of Pará (Universidade Federal do Pará – UFPA), in the city of Belém, Brazil. In a GCPVS therein installed, it was noticed that there was a significant divergence between the AC power data measured by a high-precision wattmeter and the information shown in the display of the inverter in operation. Since the information about the AC power supplied to the grid by the inverter is collected, stored and made available on-line for user consultation through a monitoring system developed by the inverter manufacturer, it was decided to investigate the extent to which such data and the data provided by theoretical modelling differed from the wattmeter measurements.

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2. Methodology

The studied GCPVS is a PV generator with 2.45 kWp nominal power, composed of 10 PV modules in series connection, installed with a 10° inclination and oriented towards the magnetic North (oriented to – 20° from the true North). The PV generator has the following nominal characteristics: 14.6 % module efficiency, $P_{mp} = 2.45$ kW, $V_{mp} = 308$ V, $I_{mp} = 7.96$ A, $V_{oc} = 375$ V, and $I_{sc} = 8.49$ A. The system inverter has a nominal output power (P_{Inv}^{0}) of 3.0 kW and is connected to a 220 V_{rms} / 60 Hz distribution grid. Fig. 1 shows the studied GCPVS and the monitoring system used in the performance evaluation.

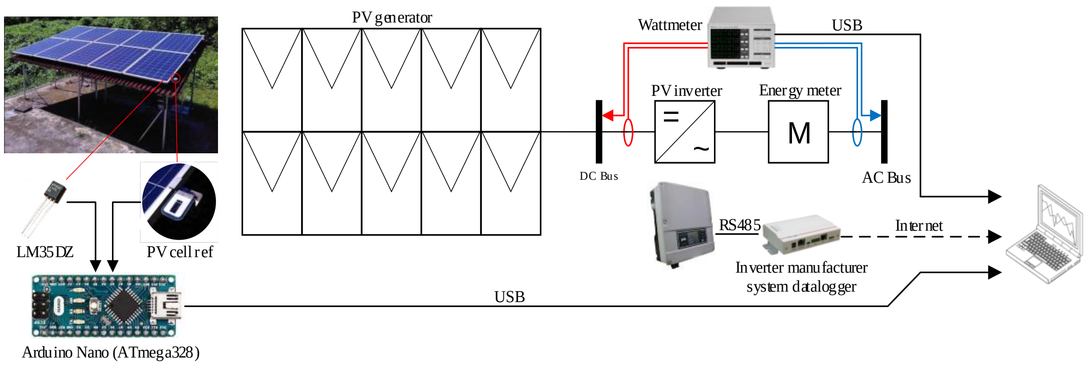

Fig. 1: Single-line diagram of the GCPVS with a monitoring system

In order to obtain estimates of active power supplied by the generator over time, the GCPVS modelling uses Eq. 1, since it takes into account solar irradiance data (G_{avg}) as well as PV cell temperature (T_c), maximum power point tracking efficiency (η_{mppt}), and maximum power temperature coefficient (γ_{mp}). The latter was estimated based on data provided by the modules manufacturer.

$$P_{PV} = P_{mp} \frac{G_{avg}}{G_{STC}} \left[1 + \gamma_{mp} \left(T_c - T_{STC} \right) \right] \eta_{mppt} \qquad \text{(Eq. 1)}$$

The determination of the output power (P_{out}) of the inverter considering its self-consumption and system loading losses (k_0, k_1 e k_2) is achieved by solving Eq. 2 (Macêdo, 2007).

$$k_2 P_{out}^2 + \left(1 + k_1 \right) P_{out} + k_0 P_{Inv}^0 - P_{PV} = 0 \qquad \text{(Eq. 2)}$$

Based on this equation, it is possible to estimate the AC power (P_{AC}) injected by the inverter into the grid, also considering the maximum output power of the inverter ($P_{Inv}^{\max}$), by using Eq. 3.

$$P_{AC} = \begin{cases} 0 & \text{, if } P_{PV} < k_0 P_{Inv}^0 \\ P_{out} & \text{, if } k_0 P_{Inv}^0 < P_{out} < P_{Inv}^{\max} \\ P_{Inv}^{\max} & \text{, if } P_{out} \geq P_{Inv}^{\max} \end{cases} \qquad \text{(Eq. 3)}$$

This set of equations led to the development of a MATLAB routine capable of calculating the AC power injected by the inverter into the grid from the electrical parameters of both the PV generator and the inverter, as well as the measured values of G_{avg} and T_c, so as to compare such results with those acquired from the GCPVS AC bus, and with those provided by the inverter manufacturer system.

The G_{avg} and T_c parameters measurement was performed by an Arduino-based datalogger comprised of a Spektron 210 irradiance sensor and a LM35DZ temperature sensor located on the back of one of the PV modules. The GCPVS AC power was also measured with a digital wattmeter, which presents a power measurement error of approximatively ± 0.1% for low-frequency systems (47 Hz to 63 Hz).

3. Results and discussions

Fig. 2 shows the measured G_{avg} and T_c parameters over 10 days of monitoring during the months of July and August 2017. According to INPE (2017), these are among the months with the highest solar radiation incidence in the city of Belém, with average solar irradiation of 5.1 kWh/m^2/day in July and 5.3 kWh/m^2/day on a horizontal surface.

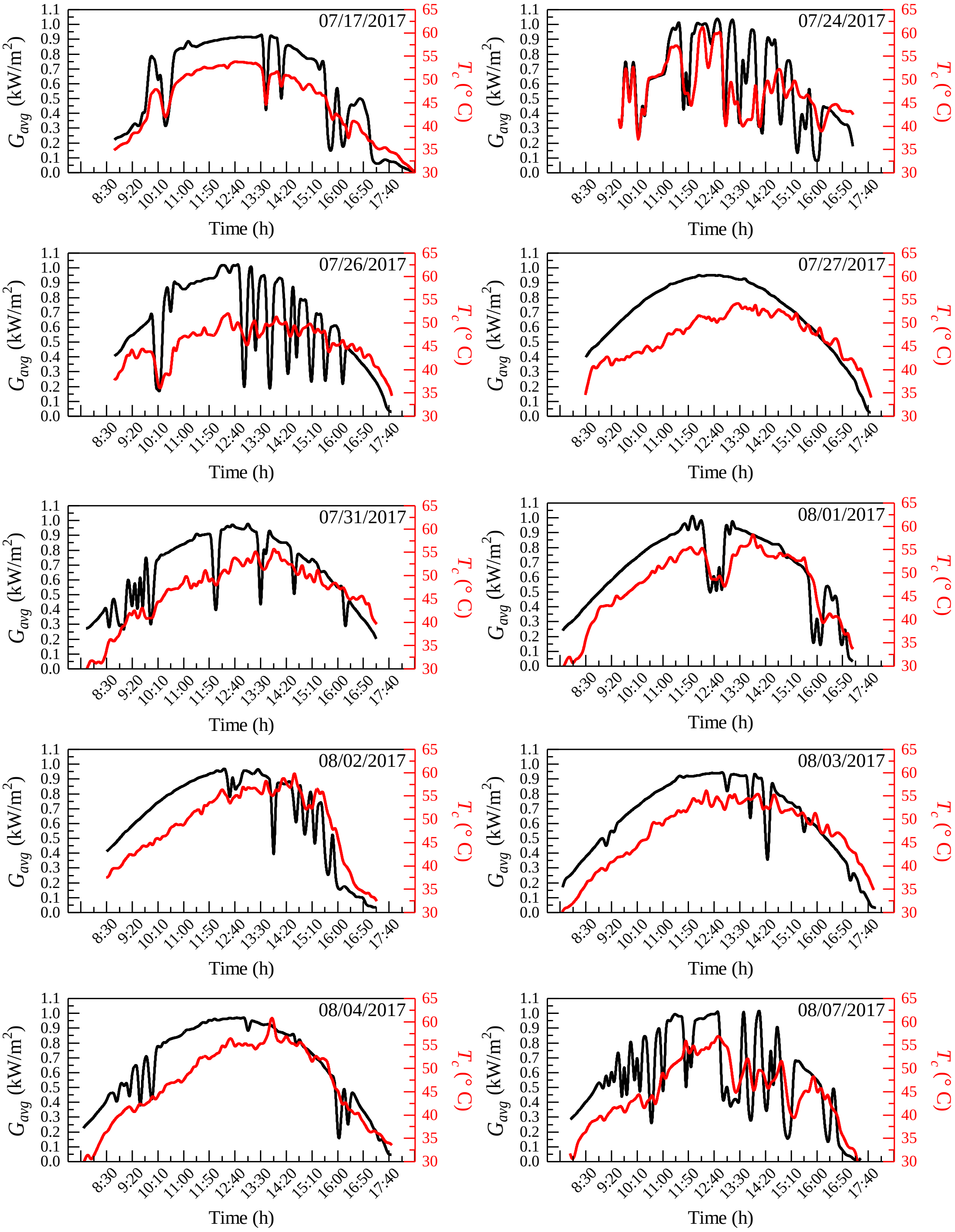

Fig. 2: Measured G_{avg} and T_c

Over the period of monitoring, the average T_c was in the range of 31 °C and 57 °C, and the solar irradiance incident on the PV generator surface peaked at 1.075 kW/m^2 on 08/07/2017 with daily irradiation of

5.37 kWh/m^2, whereas on 07/27/2017 the irradiance peaked at 0.954 kW/m^2, even though daily irradiation reached 6.46 kWh/m^2. As a means of verifying the precision of the measured T_c values, a comparison was made between such data and the estimated PV cell temperature (T_c^*) values obtained from Eq. 4, which provides a good estimate for the PV cell temperature by representing it as a function of ambient temperature (T_a), nominal operation cell temperature ($NOCT = 46$ °C), and G_{avg} incident on the surface of the PV modules.

$$T_c^* = T_a + 0.9 \cdot G_{avg} \left(\frac{NOCT - 20}{800} \right) \quad \text{(Eq. 4)}$$

Data regarding T_a were gathered from a solar station located in the vicinity of the GCPVS installation, whose temperature sensor presents a measurement error of ± 0.21 °C for T_a ranging from 0 °C to 50 °C. Fig. 3 compares T_c and T_c^* values on July 27th and 31st, and August 3rd.

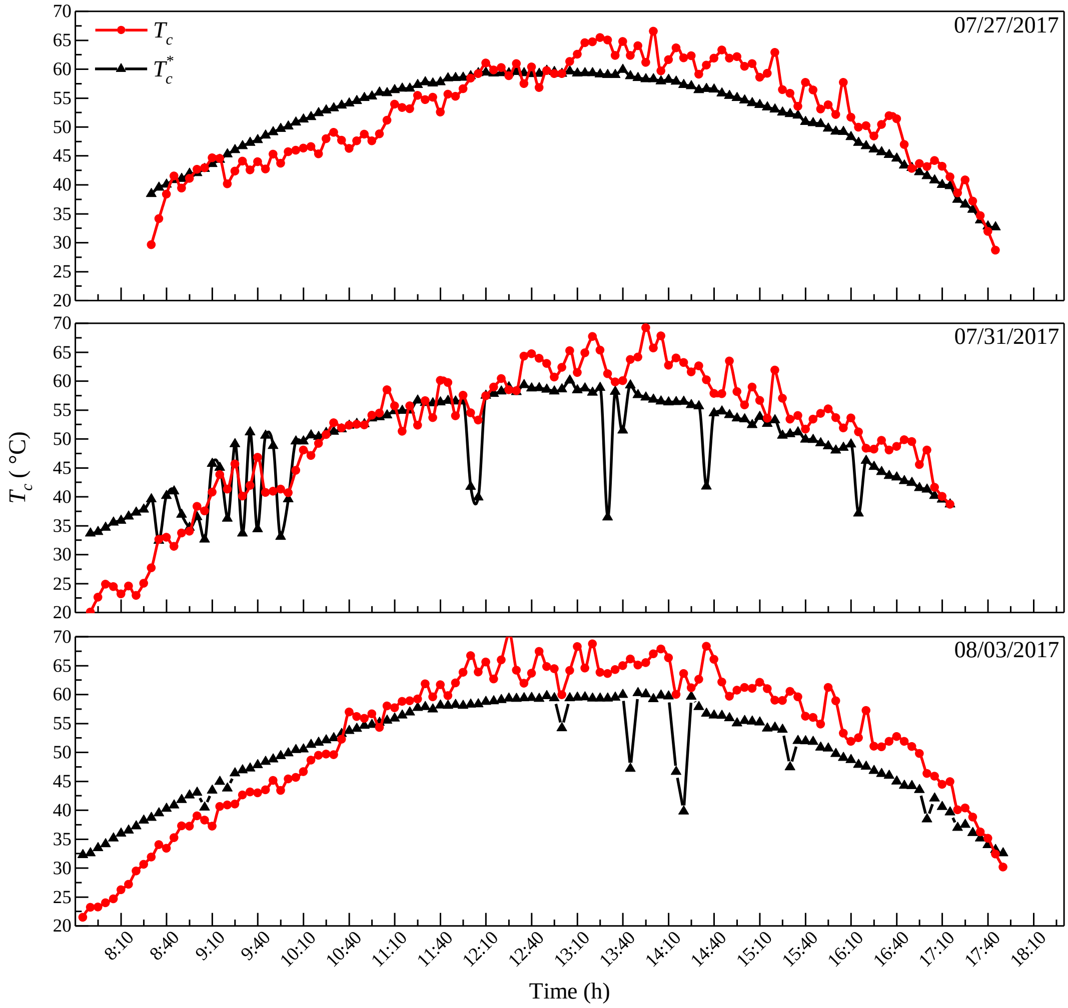

Fig. 3: T_c and T_c^*

It can be observed that the T_c and T_c^* curves are quite similar, exhibiting a coherent pattern as the G_{avg} level on the surface of the PV modules varies. With respect to T_c, the mean squared error of T_c^* is ± 6.09 °C throughout the three measurement days.

The estimated and measured values of P_{AC} are shown in Figs. 4 and 5. $P_{AC,1}$, $P_{AC,2}$ and $P_{AC,3}$ are electrical energy estimates which represent the calculated values from Eq. 3, the wattmeter data, and the inverter manufacturer system data, respectively.

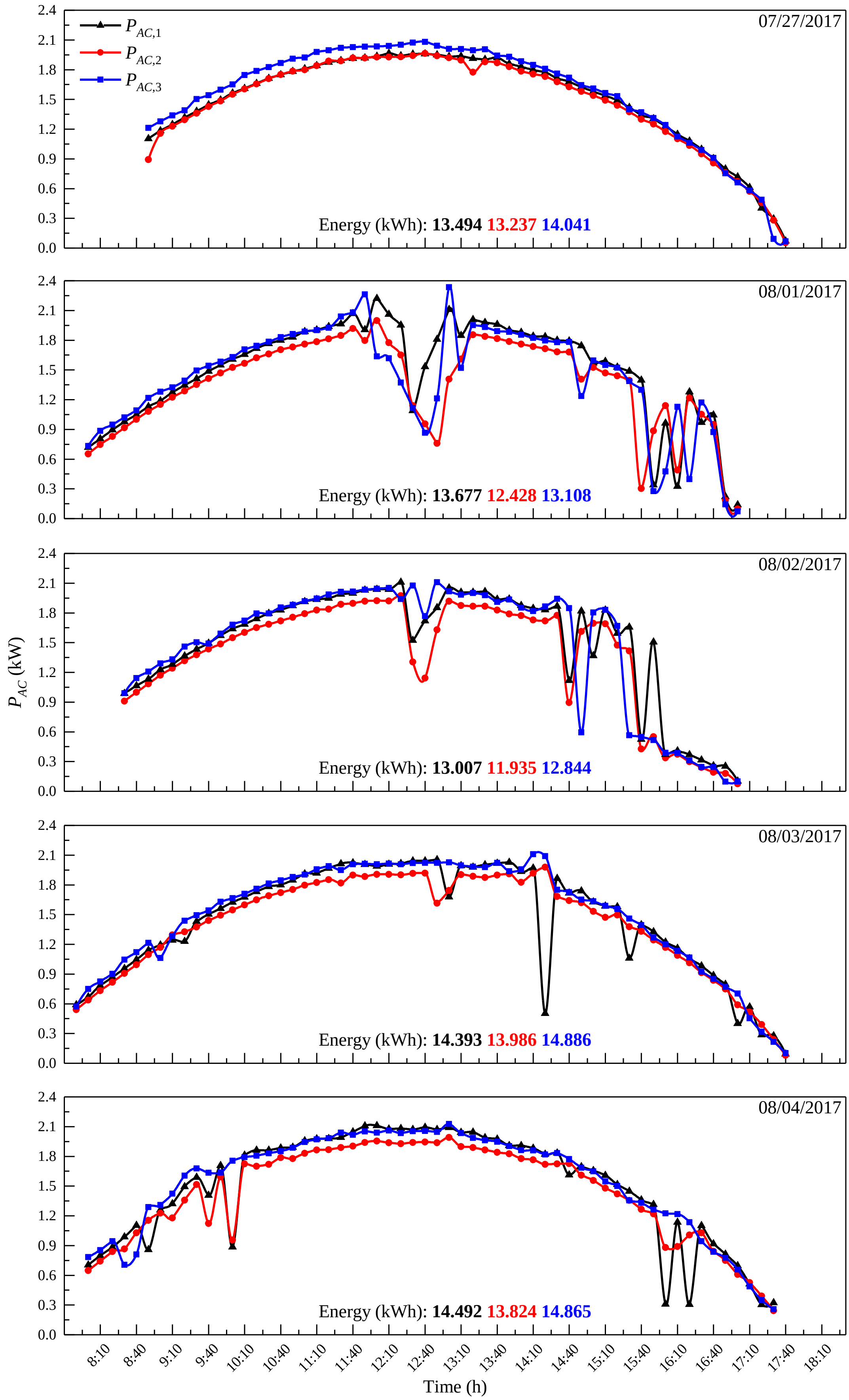

Fig. 4: P_{AC} and electrical energy estimates and measurements for low G_{avg} variability days

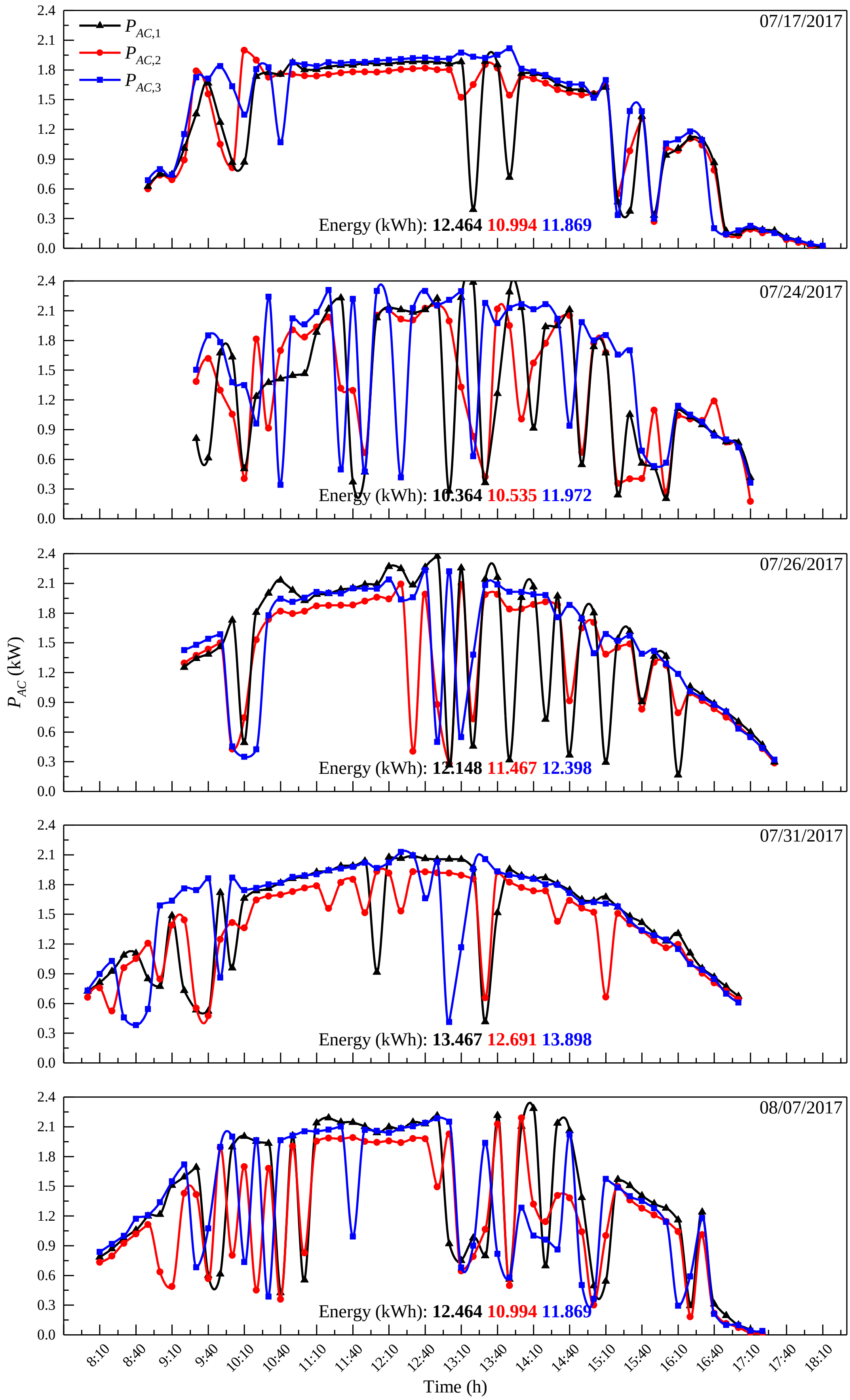

Fig. 5: P_{AC} and electrical energy estimates and measurements for high G_{avg} variability days

Comparing the $P_{AC,3}$ curves, it can be seen that in some situations the data obtained from the inverter datalogger are closer to $P_{AC,1}$ and in others to $P_{AC,2}$, as previously explained. It can also be seen that these discrepancies between data usually happen when the generator operates under high G_{avg} variability. This behavior can be observed for all measurements carried out on July 24th and 26th, and August 7th, for example, which were quite cloudy days. However, it is also noticeable that the differences between $P_{AC,1}$, $P_{AC,2}$, and $P_{AC,3}$ values were practically negligible both at the beginning and at the end of each measurement day, when G_{avg} was low.

Analyzing Fig. 4, it can be seen that the $P_{AC,3}$ values are closer to those of $P_{AC,1}$ at times when the PV generator is not subjected to shading. At other times, the $P_{AC,3}$ values collected by the inverter manufacturer's system were very different from the rest, as on July 31st, and August 2nd and 3rd.

Considering all analyses, the maximum relative errors of 61.79 % and 32.69 % were verified for $P_{AC,3}$ and $P_{AC,1}$, respectively, when compared to $P_{AC,2}$ on July 24th, and minimum relative errors of 7.91 % and 3.3 % on July 27th, as summarized in Fig. 6. This happens mainly because of the G_{avg} variability throughout the measurements, as well as inaccuracies inherent to the acquisition process of G_{avg} and T_c for the theoretical model.

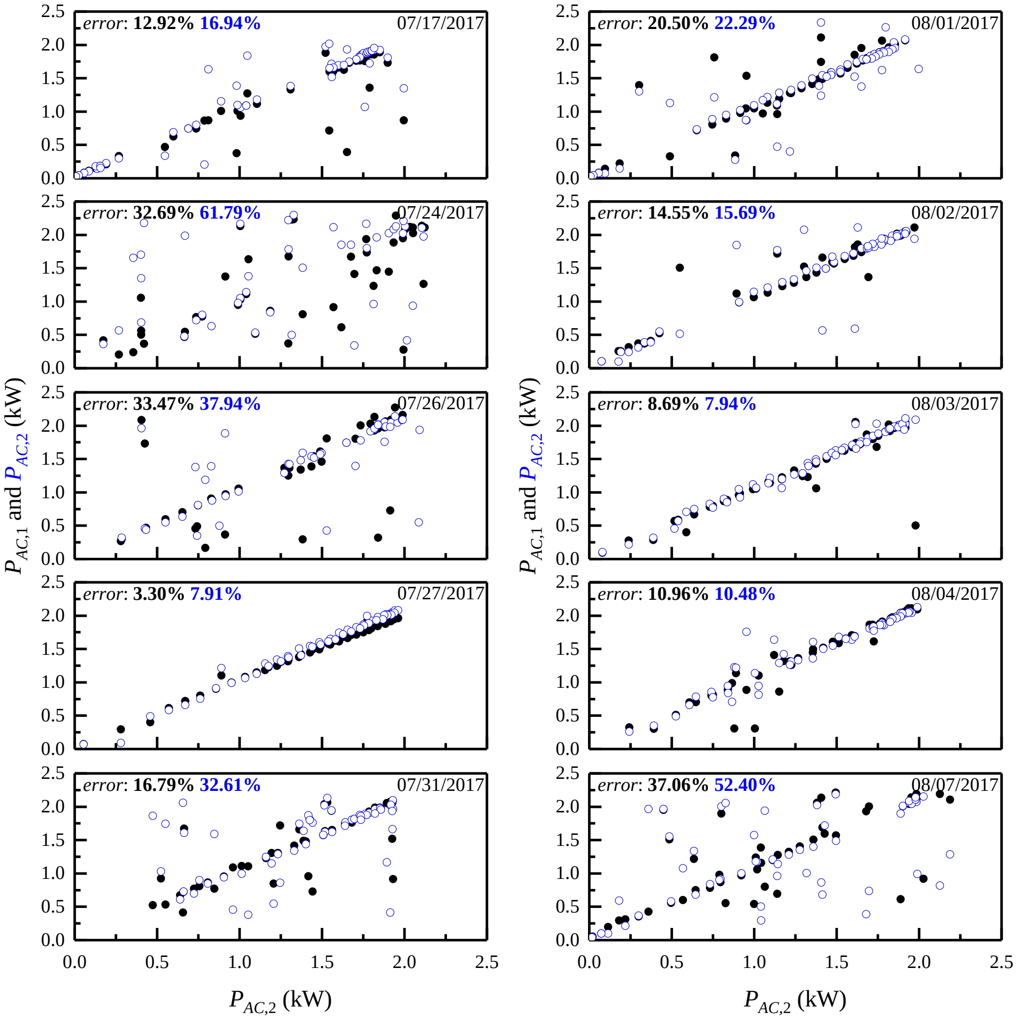

Fig. 6: Dispersion of $P_{AC,1}$ and $P_{AC,3}$ values with respect to $P_{AC,2}$

On the other hand, since one does not have access to the $P_{AC,3}$ acquisition process carried out by the manufacturer's system (hardware information, data sampling rate, etc.), it is not possible to precisely pinpoint the reasons for the divergence between these values and the others.

Fig. 7 shows the estimated ($\eta_{Inv,1}$) and measured ($\eta_{Inv,2}$) efficiencies for the inverter's DC/AC conversion process. It is noticeable that $\eta_{Inv,1}$ and $\eta_{Inv,2}$ hardly varied over the course of the measurements, with the exception of July 24th and 26th and August 7th. On average, $\eta_{Inv,1}$ was roughly 97.5 %, whereas $\eta_{Inv,2}$ was in the region of 95 % during the measuring period. The overall mean squared error between $\eta_{Inv,1}$ and $\eta_{Inv,2}$ was 4 %.

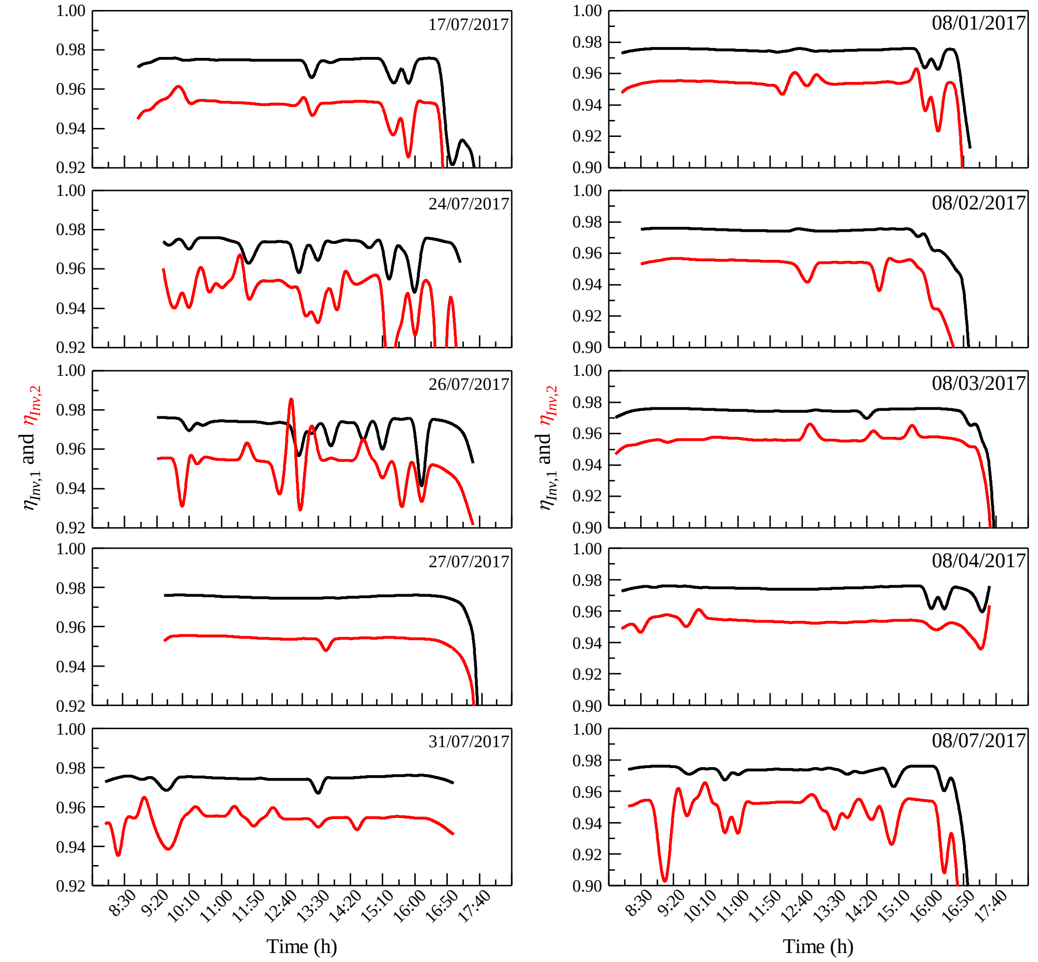

Fig. 7: Estimated and measured DC/AC conversion efficiencies

Fig. 8 shows the inverter loading parameters $p_{AC,1}$ and $p_{AC,2}$ ($P_{AC,1}$ and $P_{AC,2}$ normalized with respect to P^0_{Inv}, respectively) of the conducted experiments. Their respective average values were approximately 47.4 % and 45.2 % of the inverter's nominal output power, with standard deviations of 20.1 % and 18.2 %. Maximum loading was estimated at 87.7 % and measured at 72.9 %.

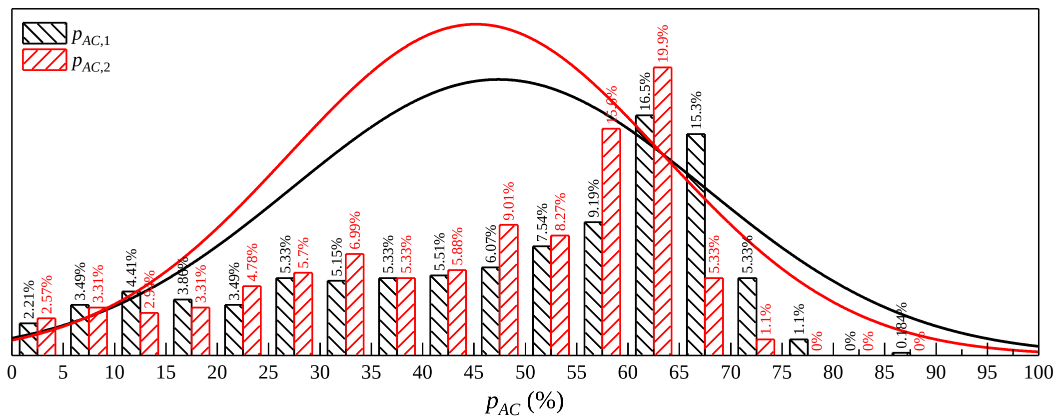

Fig. 8: Estimated and measured loading parameters during inverter operation

Considering that, according to the inverter manufacturer, a loading parameter of 50 % corresponds to a DC/AC conversion efficiency of 97.5 %, it is possible to state that 95 % denotes satisfactory inverter performance under operational conditions quite unlike those of the manufacturer's efficiency tests. However, another possible explanation for such difference relates to the error associated with the losses coefficients k_0, k_1 and k_2.

As experimentally demonstrated by Teles (2017), the losses associated solely with the inverter's self-consumption (k_0), seen in Fig. 9, amounted to 18.94 W. Wattmeter measurements were used to estimate losses as a function of the inverter loading parameter p_{AC}. On the other hand, by applying the theoretical model to estimate $P_{AC,1}$, it was observed that these same losses would amount to roughly 12.44 W.

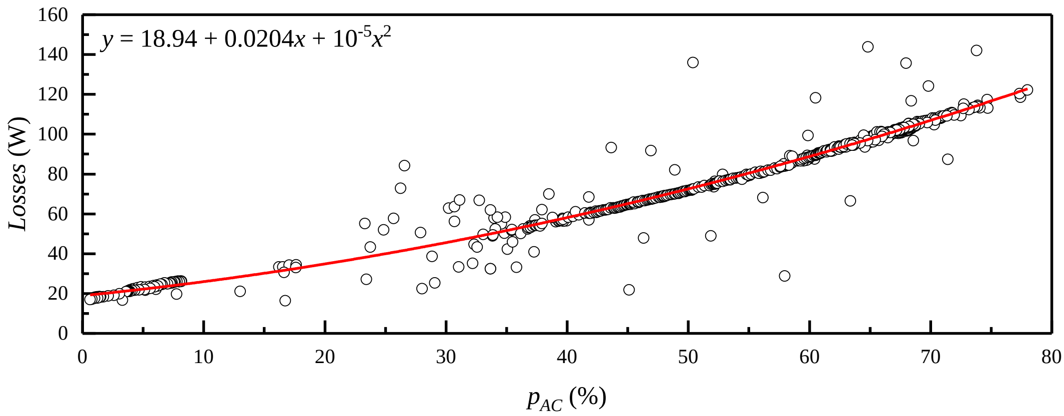

Fig. 9: Electrical losses *versus* inverter loading

Conversely, since neither the P_{PV} values nor the DC current and voltage parameters are made available by the inverter manufacturer's data acquisition system, it was not possible to assess the inverter's DC/AC conversion efficiency based on $P_{AC,2}$ measurements.

4. Conclusions

This work's starting point consisted in evaluating AC instantaneous active power supplied to the grid by a GCPVS through comparison of mathematical estimates, high-precision wattmeter measurements, and data acquired by the inverter manufacturer's datalogger system, which are available on-line for user consultation.

Solar irradiance and PV cell temperature data obtained from the Arduino-based datalogger developed for this work led to coherent results. Similarly, the theoretical model estimates of PV and AC power data were also quite coherent when compared to wattmeter measurements, with the exception of very cloudy days in which abrupt variations in the measured power data were observed due to accuracy-decreasing issues of the irradiance and PV cell temperature sensors.

Comparing the AC power results obtained from the theoretical model to those measured via the inverter manufacturer's datalogger and via wattmeter, it was noticeable that the datalogger's measurements were closer to the mathematical estimates than to the wattmeter data under certain operational conditions. However, circumstances such as high irradiance variability days could make those measurements to greatly differ from the other two.

The divergences observed arise not only from the sensors' measurement inaccuracies, a consequence of high irradiance variability, but also from the data acquisition algorithm embedded in the manufacturer's datalogger. The monitoring system might also have been affected by irradiance level variations as well as by low inverter loading, since this device operated under 50 % loading during all measurement days.

Finally, it was found that the inverter's DC/AC conversion efficiency was below its nominal value as informed by the equipment's nameplate, even considering the mean squared error of up to 4 % that was obtained during measurements. Nevertheless, it is worth pointing out that the manufacturer's data information were acquired under specific testing conditions, which are different from real operational conditions, as well as under low inverter loading. Such reasons might explain the visible difference between the estimated and the measured efficiency values. In spite of that, the inverter carries out the DC/AC conversion process with good performance, even with operational loading below its nominal power during the monitoring period.

5. Acknowledgments

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