Operational Analysis of a 34 kWp Grid-connected PV System Considering Local Weather Measurements in Central Brazil

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Abstract

More and more distributed generations systems have been connected to the power system in Brazil, especially PV systems in the range between a few units (residential) to hundreds (power plants) of kW. On that context, this work is related to operational analysis of a new 34 kWp grid-connected PV system based on local weather conditions measured in the city of Goiania, located in Central Brazil. The PV system had been installed by a research and development project approved by ANEEL (Brazilian Electrical Energy Agency) and it was the first rooftop solar plant installed at UFG (Federal University of Goias) and also among other public universities from Central Brazil. After some basics operational tests, that 34 kWp grid-connected PV system started to work continuously on January 2017 after being registered and authorized by local grid utility. Since then an amount of 4.4 MWh has been generated and fed into the power distribution line up to middle of October 2017. Results registered during February 2017 from an existing and active PV plant were chosen to present a possible operational analysis. At the end, the energy and power performance profiles from grid-connected PV system are discussed in terms of weather measurements and conditions. As a fully one operational year from 34 kWp grid-connected PV system has not been concluded yet, authors still working on its performance analysis.

Keywords: PV systems, Weather measurements, Distributed generation, Grid-connected PV system, Renewable energy, Solar inverter.

1. Introduction

Grid-connected photovoltaic (PV) systems have been regulated in Brazil since 2012 (main document had been reviewed in 2015) by the net metering mechanism related to Distribution Generation (DG) systems (Aneel, 2015). After that almost 25 MWp of new grid-connected PV systems have been installed (Aneel, 2017a).

Although there is a clear growing up of installed PV systems, such amount of power does not represent a huge contribution from solar resources considering the fully power generation capacity in Brazil nowadays. According to Tab. 1, renewables resources represent 78.5% of Brazilian power generation capacity up to now (October 2017). This is already known around the world and that is why Brazil has been always cited in renewable global reports or outlooks.

Tab. 1: Official Brazilian power generation capacity up to October 2017 (Aneel, 2017a).

Energy resource	Solar	Nuclear	Foreign	Wind	Biomass	Oil & Fossils	Hydro	Total
Installed power capacity (GW)	0.31 (0.2%)	1.99 (1.2%)	8.17 (5.0%)	11.50 (7.1%)	14.24 (8.8%)	26.89 (16.5%)	99.40 (61.2%)	162.47 (100%)

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However, solar energy (exclusively from PV power plants) represents the lowest contribution (approx. 0.312 GW) of total power capacity in Brazil. It is even lower than the 8.17 GW imported (and paid for) from neighbor countries (Paraguay, Argentina, Uruguay and Venezuela, in descending order). That is obviously an encouraging reason for increasing solar power plants in Brazil over the next years. Considering its geographical localization on Earth, its annual weather conditions and size of its territorial area, Brazil could produce even much more electrical energy from solar resources for sure. Fig. 1 presents an overview of five geopolitical regions of Brazil edited from original file published by (Macedo, 2007) and also its annual global horizontal solar radiation per day estimated by (NREL, 2005). Actually those conclusions are not so new anymore since academics, professionals, foreign and local companies, public agencies, grid utilities and politicians recognize that Brazil still has an unexplored potential for power generation from solar and wind resources.

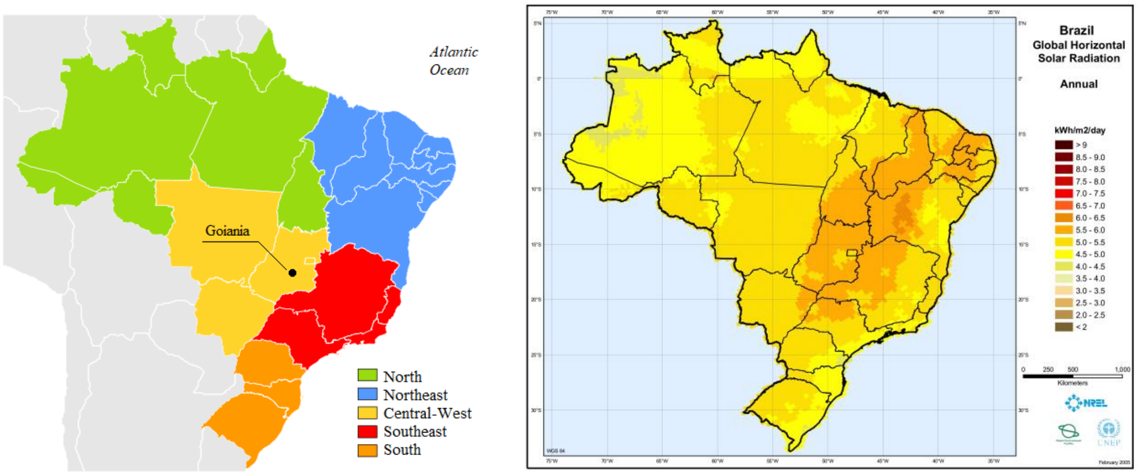

Fig. 1: Brazilian geopolitical regions (left) and its estimated global horizontal solar radiation (right) (Macedo, 2007; NREL, 2005).

Even under an unofficial (but real) political and economic crisis registered during last years that affects new regulations and investments, step by step solar and wind resources have been more and more explored in Brazil. For example, a new record of power generated by wind plants installed in the Northeast of Brazil was stablished during the beginning of September 2017 (approx. 6.8 GW) but it will not last very long since new wind plants are expected to be added to the Brazilian power grid until 2020 (ONS, 2017). In addition, Brazilian agency ANEEL (National Agency of Electrical Energy) officially predicts that new solar (residential and commercial) power plants will also provide plus 3.2 GW to Brazilian power grid among the 2017-2024 years (Aneel, 2017b).

Under that context, this work is related to operational analysis of a new 34 kWp grid-connected PV system based on local weather conditions measured in the city of Goiania, located in Central Brazil. Central Brazil corresponds to entire Central-West and a part of North geopolitical regions presented in Fig. 1. Also from Fig. 1 it can be concluded that city of Goiania has an estimated annual global horizontal solar radiation around 5.0-6.0 kWh/m2 per day. These estimated values suggest a considerable potential for exploring the annual available solar energy source in terms of electrical energy production.

Some results from that 34 kWp grid-connected PV system operation are presented and discussed in terms to propose a possible operational analysis related to such DG systems. Energy and power performance profiles are also discussed in terms of weather measurements and conditions. At the end, some conclusions are presented.

2. Grid-connected PV system description

Fig. 2 shows the basic topology of the DG system covered by this work. It is based on a 34 kWp grid-connected PV system and composed by 145 PV panels (235 W, 60 cells, poly c-Si) connected (in series and parallel associations) with 8 single-phase power inverters. The PV panels and power inverters have been manufactured by SUN EARTH (model TPB 156×156-60-P) and ELTEK (models Theia 2.9 HE-t and 4.4 HE-t), respectively.

That new 34 kWp grid-connected PV system corresponds to a rooftop structure and its installation was provided by a research and development (R&D) project executed by UFG (Federal University of Goias). The R&D project was financially supported by four local power companies: Espora Energetica; Transenergia Sao Paulo;

Transenergia Renovavel; and Caldas Novas Transmissao (Pimentel, 2017). This R&D project was approved by ANEEL and it proudly became the first rooftop solar grid-connected power plant installed at UFG and also among other public universities from Central Brazil.

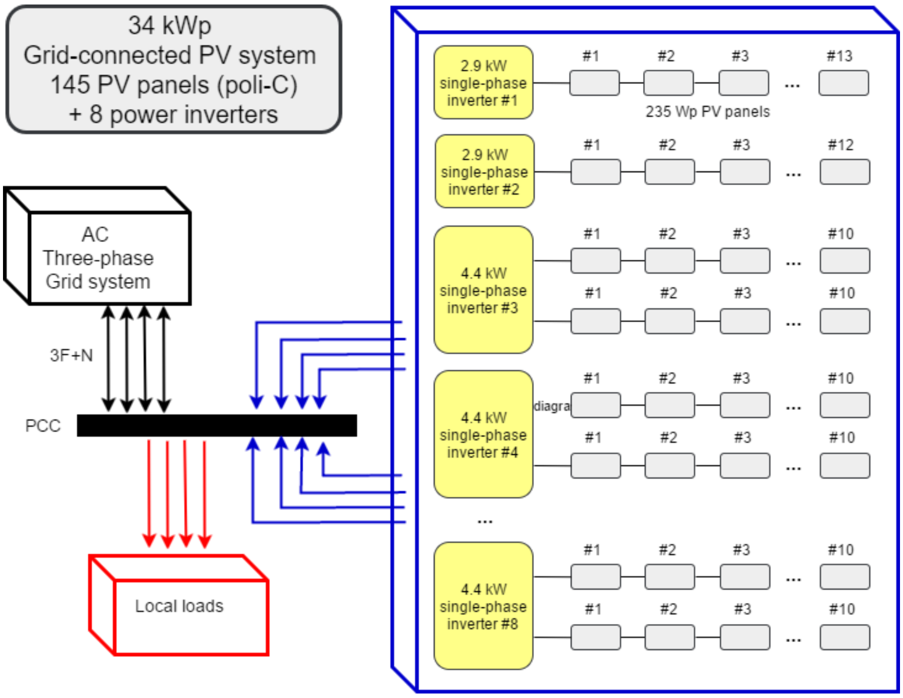

Fig. 2: Basic topology of the 34 kWp PV grid-connected system installed at Goiania (Brazil).

After some basics operational tests during the end of 2016, the 34 kWp grid-connected PV system started to work continuously on January 2017 after being registered and authorized by local grid utility. All the power inverters are connected to the PCC (Point of Common Coupling) which is also connected to the AC three-phase power line based on four wires (more typical situation) and with nominal parameters 220/380 V and 60 Hz. The shunt connection of local loads corresponds to all electrical circuits that feed a three-floor building construction from Electrical, Computer and Mechanical Engineering School (EMC) at UFG.

Fig. 3: A 180° panoramic view from the 34 kWp rooftop PV grid-connected system on April 2017 (autumn).

In addition, Fig. 3 presents a 180° panoramic view from the PV panels related to the 34 kWp rooftop PV grid-connected system during afternoon on April 2017 (autumn). It can be noticed that PV panels had been installed with different orientation and inclination angles. A part of them are faced to North direction (with +15° deviation) with a 10° of inclination (following rooftop's inclination). Others PV panels are faced to South direction with the same deviation and inclination angles. The reason of such different installation procedures is related to R&D objectives and it justifies why nominal power 34 kWp would be never reached all over the year.

3. Power and energy measured performance

It is known that some aspects related to energy production and its performance can be monitored and saved for future numerical analysis. Otherwise other aspects related to local weather conditions can be also involved by that PV system analysis as they could limit overall system performance (Raj, 2016).

This paper discusses the influence of local weather conditions on the operational analysis of an existing 34 kWp PV grid-connected system (presented in Figs. 2 and 3). Its daily operation can be freely accessed by Internet connection through the address (http://200.137.220.91/index.htm) after typing the code 'visitante' into both user name and password fields (from login screen). The web interface (created by power inverters' manufacture) could be describe as a supervisory system and it provides the amount of power and energy produced by power plant or by each of power inverters during a period of time. Fig. 4 presents a print screen from such supervisory system as it appears on October 15th, 2017. It can be noticed the shapes from total PV power output over the last seven days and also a summary of energy and power over the last twelve months.

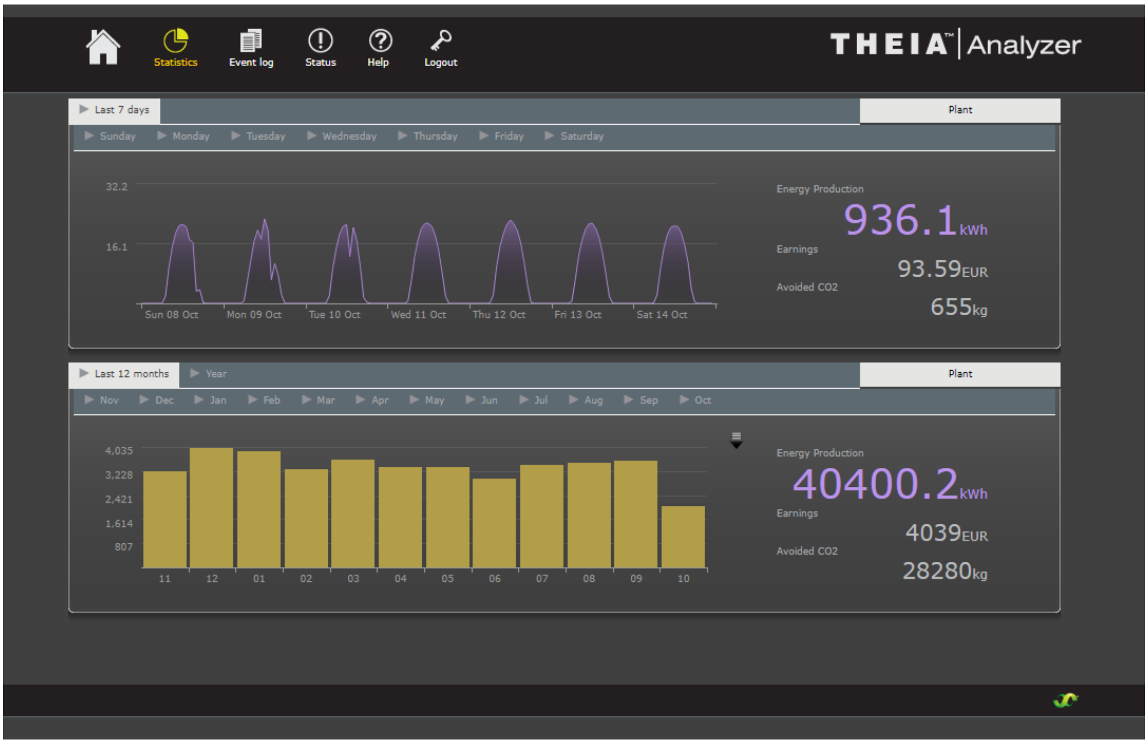

Fig. 4: A screen from supervisory system related to 34 kWp grid-connected PV system as it appears on October 15th, 2017.

An amount of registered data from local weather conditions and PV power performance during February 2017 was considered to support the analysis presented in this work. Then Fig. 5 presents the daily electrical energy provided by the 34 kWp PV system to the PCC (as shown in Fig. 2) during February 2017. The biggest and lowest registered values of energy occurred in days 15 (176.3 kWh) and 16 (71.3 kWh), respectively. However, the AC output peak power from a 34 kW (nominal) PV system had a different behavior with lower variations all over the days. Even so, the biggest output peak power value occurred in day 12 (32,7 kWp) and in the same day with a 'poor' energy production (75,4 kWh).

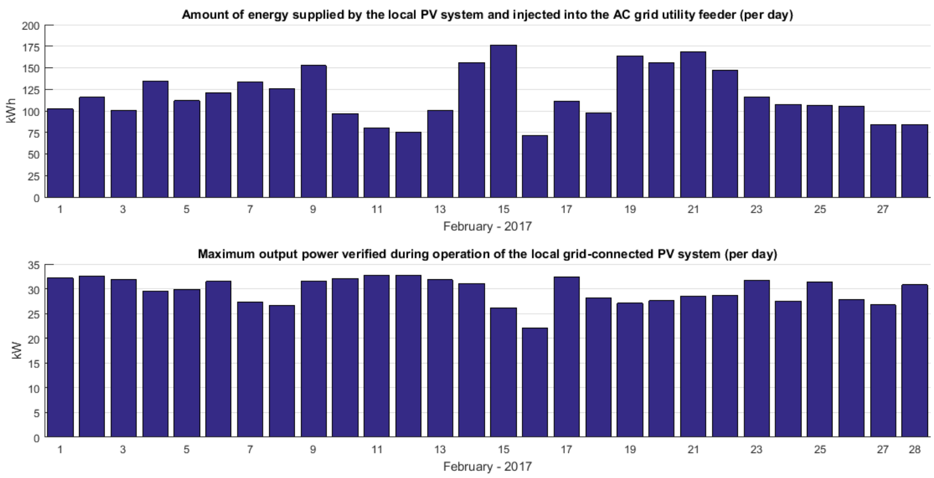

Fig. 5: Daily energy production and output power peak from a 34 kWp PV grid-connected system on February 2017.

Those conclusions suggest that both energy production and maximum power may be used to describe some PV system performance. However, they are not directly dependent just because they are determined by different local weather variables and/or power inverter capability. These issues are described during the next section.

4. Influence of registered local weather conditions

It is well known the direct relationship between power or energy performance from any PV system and the available weather conditions during a period of time. As this particular 34 kWp grid-connected PV system was related to a R&D project, an autonomous local weather station had been also purchased and installed alongside with its PV panels. Fig. 6 presents a general view from local weather station installed closed to the PV panels.

Fig. 6: Local weather station installed alongside the 34 kWp grid-connected PV system at UFG (Goiania, Brazil).

The weather station showed in Fig. 6 automatically collects values from seven different weather sensors during an interval of 10 seconds and registers an average of those captured values over one minute. Each average value from all seven weather variable is then added to a table that could be accessed by user through a serial or IP port. Besides time, the weather measured variables are: wind speed; wind direction; air temperature; relative humidity; precipitation; global solar horizontal irradiance; and atmospheric pressure.

All variable values registered by local weather station since July 2015 are available to visualization (and for free downloading) from an Internet portal through the address: https://sites.google.com/site/sfvemcufg/weather-station. Updates involving data registered by local weather station and its sharing are weekly made by authors of this work. Some of these data had been considered by authors to analyze the operation points from the 34 kWp grid-connected PV system power plant and are presented below.

Fig. 7 presents the horizontal global solar irradiance and air temperature exactly at the 34 kWp grid-connected PV system power plant during February 2017. It can be noticed that from February 12th to February 17th, both local weather variables have distinct behaviors than other days. For that reason, this period of six consecutive days from entire month had been chosen for a more detailed analysis.

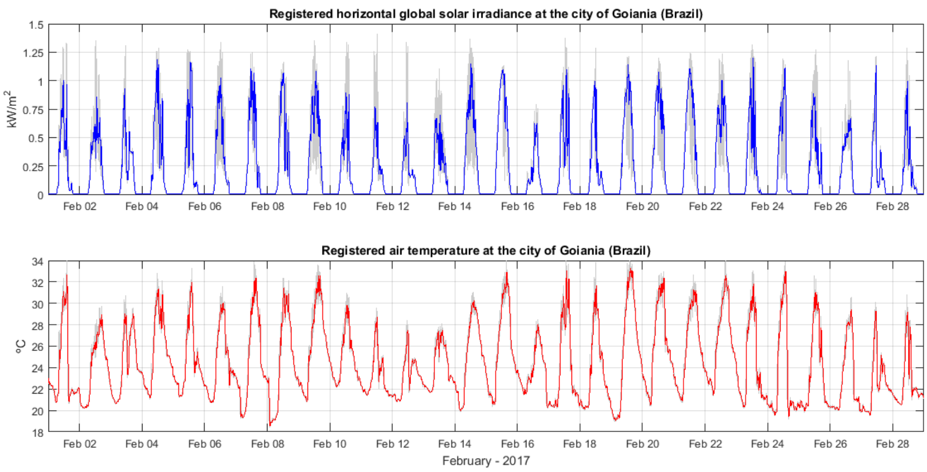

Fig. 7: Local horizontal global solar irradiance (top) and air temperature (bottom) at Goiania (Brazil) during February 2017.

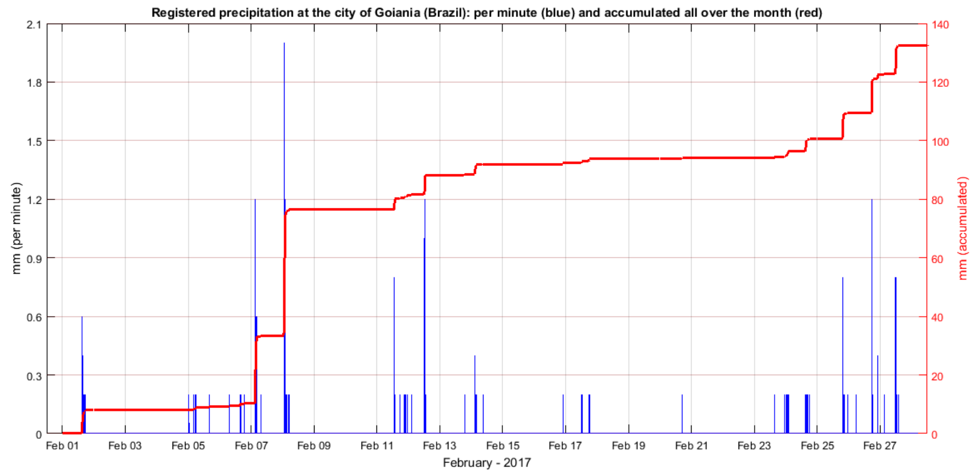

Fig. 8: Amount of local precipitation per minute (blue) and accumulated (red) at Goiania (Brazil) during February 2017.

During the entire month of February 2017, a cyclic oscillation had been verified on air temperature in Fig. 7 (bottom). It suggests that power inverters operation probably had been not limited by temperature. Those peaks verified on horizontal global solar irradiance (not the average blue curve) could explain a possible power saturation on power inverters. It can be noticed that highest values verified in Fig. 5 (bottom) occurred on the same days which global solar horizontal irradiance reached 1.1 kW/m2 (or higher) in Fig. 7 (top).

As February corresponds to a summer season in the city of Goiania and it means a lot of raining days (at least on that of Earth), the oscillations on energy production verified in Fig. 5 (top) can be compared with the local precipitation presented in Fig. 8. And it can be also noticed that significate rains were scattered along the month and have not influenced those energy production oscillations. Even for that period from Feb-12 to Feb-17 that reflects a distinct behavior from the rest of the month, the accumulated precipitation had just a slightly transition over the days 12 and 13.

However, Fig. 8 shows only the precipitation measurements over the month and not how many cloudy were those days (or that distinct period). Fig. 9 exhibits the correspondent part of Fig. 7 related to period from Feb-12 to Feb-17 and Tab. 2 describes this period in terms of energy and weather conditions.

It can be concluded from Fig. 9 that ‘low’ solar irradiance and ‘low’ air temperatures were verified on days 12, 13 and 16. Then, they were probably cloudy days and affected the energy production presented in Fig. 5 (top). In addition, the constant behavior of output power in Fig. 5 (bottom) could be determined by the MPPT capability from power inverters (Hosseini, 2016; Killinger, 2016).

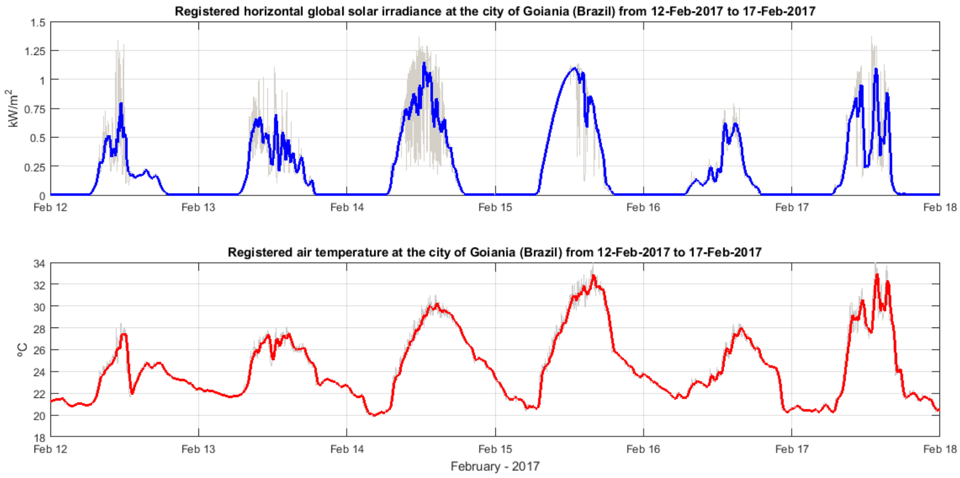

Fig. 9: Particular distinct behaviors verified on local horizontal global solar irradiance (top) and air temperature (bottom) during a period of six consecutive days of February 2017 at the city of Goiania (Brazil).

Tab. 2: Power performance and weather conditions measurements registered during operation of the 34 kWp PV grid-connected system from 12-Feb-2017 to 17-Feb-2017.

Day	Energy from PV system	Output power from PV plant	Daily air temp. range	Effective rain duration	Solar irrad. (average peak)
12-Feb-2017	075.4 kWh	32.7 kW	~ 21-28 °C	~ 1 h (at 1 pm)	~ 0.8 kW/m²
13-Feb-2017	100.6 kWh	31.8 kW	~ 22-27 °C	< 1 h (at 7 pm)	~ 0.7 kW/m²
14-Feb-2017	155.9 kWh	31.1 kW	~ 20-30 °C	~ 1 h (at 3 am)	~ 1.2 kW/m²
15-Feb-2017	176.3 kWh	26.2 kW	~ 21-34 °C	-	~ 1.1 kW/m²
16-Feb-2017	071.3 kWh	22.1 kW	~ 22-28 °C	< 1 h (at 10 pm)	~ 0.6 kW/m²
17-Feb-2017	111.6 kWh	32.4 kW	~ 20-34 °C	~ 1 h (at 6 pm)	~ 1.1 kW/m²

In addition, Tab. 3 presents some values obtained by performance parameters related to PV systems during February 2017. The daily (and monthly) amounts of energy produced by PV power plant, its capacity factor (CF) and the verified performance ratio (or productivity) are presented.

Tab. 3: Daily (specific) and monthly performance parameters registered by 34 kWp grid-connected PV system on February 2017.

Period of time	AC electrical energy produced (kWh)	PV power plant capacity factor (CF)	PV plant performance ratio (kWh/kWp or h)
Feb 12th	75.40	9.24%	2.22
Feb 13th	100.60	12.33%	2.96
Feb 14th	155.90	19.11%	4.59
Feb 15th	176.30	21.61%	5.19
Feb 16th	71.30	8.74%	2.10
Feb 17th	111.60	13.68%	3.28
All month	3302.60	14.45%	97.14

Considering the selected distinct period of six days from Feb-12 to Feb-17, the effects of daily variations on weather conditions can be cleared verified. A capacity factor of 15.0% (average) and a performance ratio around

5 h (average) have been obtained. Such values are typical on good PV systems and they were expected since PV panels and power inverters have been recently manufactured. Among specific days presented in Tab. 3, Feb-15 can be selected as most representative day from a PV system in the city of Goiania during a summer. High solar irradiance and clear sky (no clouds) over a long period of time have been observed during that day. The amounts of CF and performance ratio achieved on Feb-15 are also in accordance with the expected values from Fig. 1 (right) considering the localization of 34 kWp grid-connected PV system.

Considering a higher period of time, Fig. 10 presents some daily CF values observed from April 2017 to October 2017 on the same 34 kWp grid-connected PV system. As it was previously concluded, an average CF value around 15.0% still being observed on 34 kWp grid-connected PV system. Even so, some low FC values have been also noticed from May to August, a period of year related to dry season (no raining) in the city of Goiania. Such reduction can be explained by two typical weather conditions related to that dry season: higher amount of accumulated impurities on the PV panels; and lower solar irradiance over the days (winter). Future measurements from FC values may present the expected efficiency degradation from PV panels over the years.

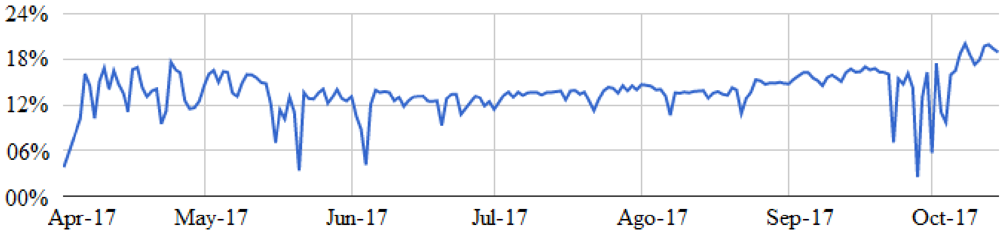

Fig. 10: Curve of daily capacity factor values observed on 34 kWp grid-connected PV system from April to October 2017.

5. Conclusions

Some operational results from a 34 kWp grid-connected PV system installed in the city of Goiania (Central Brazil) have been presented and discussed.

As the number of installed grid-connected PV systems in Brazil has been increasing over that last five years, this paper described a new 34 kWp grid-connected PV system installed in the city of Goiania (Central Brazil).

After some basics operational tests, that 34 kWp grid-connected PV system started to work continuously on January 2017 after being registered and authorized by local grid utility. Since then an amount of 4.4 MWh has been generated and fed into the power distribution line up to middle of October 2017.

Some operational results observed on this solar power plant during February 2017 have been presented and discussed. For the same 34 kWp grid-connected PV system, a method for validating operational results from PV systems based on weather measurements has been also proposed and discussed.

From presented results, it can be concluded that days with low solar irradiance and low air temperatures cannot be related to raining days only. Some cloudy days may have same aspects and they can also affect seriously the power production from PV panels. Over the next months, the authors concluded that the clearness factor verified during daylight actually has more impact on the efficiency of PV panels than the presence of raining. This conclusion is valid in the city of Goiania since its average temperature does not significantly varies over a year.

Besides, the constant behavior of output power from 34 kWp grid-connected PV system over an intermittent solar month as observed during February 2017 can validate the MPPT capability from power inverters and its efficiency considering the accomplish of DC input voltage range specified by manufacturer.

Some performance parameters related to PV systems have been also calculated. A capacity factor of 15.0% (average) and a performance ratio around 5 h (average) have been obtained. Such values are typical on good PV systems and they were expected since PV panels and power inverters have been recently manufactured.

As a fully one operational year from 34 kWp grid-connected PV system has not been concluded yet, authors still working on its power inverters and weather conditions monitoring, on energy performance parameters analysis and on reliability of solar power plants.

6. Acknowledgments

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