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Performance Analysis of Small Grid Connected Photovoltaic Systems

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HIGHLIGHTS

- Set of procedures for performance analysis of small photovoltaic systems
- Analysis of functional and structural aspects
- Study case of 3.5 kWp grid-connected photovoltaic system at UFPR

Abstract: The acceptance and deployment of electric power from sustainable sources, which are less polluting than fossils, have been a consensus throughout society. Specially, the growth of the installed capacity in photovoltaic energy has been considerable in distributed generation. In order to properly take advantage of this growing demand, it is necessary to adopt appropriate measures and procedures to improve the operation and performance of photovoltaic systems. The purpose of this work is to present such measures and procedures, under quantitative and qualitative analysis, using scientific methodologies and tools. In the end, a set of procedures was obtained that analyzes functional and structural aspects of small grid-connected photovoltaic systems. Its validation was carried out in a case study of photovoltaic system of the Department of Electrical Engineering (DELT) of the Federal University of Paraná (UFPR, Brazil).
Keywords: distributed generation, performance, small photovoltaic system.

INTRODUCTION

According to SolarPower Europe [1], the installed photovoltaic (PV) energy global capacity reached 404.5 GW in 2017, an increase of 32% over the previous year. In Brazil, in accord with the Ministry of Mines and Energy [2], installed capacity increased from 84.7 MW, in 2016, to 438.3 MW, in 2017. Similarly, there was significant growth in distributed generation with photovoltaic systems up to 5 MW of installed capacity, from 56.9 MW, in 2016, to 177.1 MW in 2017. This growth in Brazil has been provided mainly from tax incentives, public demand, and the elaboration of standards, such as Aneel's Normative Resolution 482 of 2012, which promotes the use of PV energy.

Despite the accelerated evolution of the solar market, advances in studies related to measures and procedures that would improve the operation and performance of PV systems have not followed at the same rate. Pless, Deru, Torcellini, and Hayter [3], developed a standard method for monitoring the performance of long-term PV systems in buildings. Its methodology consists of performance indicators to carry out comparison with other base systems, regarding economic analysis and system efficiency. Woyte, Richter, Moser, Mau, Reich, and Jahn [4], created a set of good practices and systematic analysis for the monitoring of PV systems, considering performance indicators, as well as temperature, cable, and energy conversion losses. Almeida [5], in addition to using the previously highlighted procedures, deployed aspects related to technical standards. The National Renewable Energy Laboratory (NREL, USA) [6] has developed good practices for operation and maintenance of PV systems involving issues such as system category and type, location, environmental conditions, performance and monitoring.

The majority of the procedures in previous work on performance analysis has been very complex, involving losses, linear and nonlinear factors of PV cells and inverters, harmonics requiring several studies, simulations, and expensive tools; or have been limited only to the installed power and the energy generated. To date, this work has consisted only of analysis of the electrical performance and has not considered structural aspects of the systems. These efforts have also not been directed towards a specific power category of PV systems, meaning that the procedures are too general and superficial. Therefore, it was necessary to create a set of measures and procedures to analyze the functional and structural aspects of small grid-connected PV systems up to 5 MW of installed capacity, involving specific quantitative and qualitative analyzes rarely evaluated in other studies.

Specifically, the goal of the present work was to establish a set of procedures to analyze the operation and performance of small PV systems connected to the electric grid with installed capacity up to 5 MW, using an objective method without the necessity of expensive tools. Among the specific objectives were: (i) to review the literature and standards applicable to PV systems connected to electric grids, (ii) to establish a set of procedures for small grid-connected PV systems, and (iii) to perform a case study to apply and validate this set of procedures.

METHOD

Using national and international technical standards, articles, and academic papers, it was possible to elaborate a set of procedures to analyze the operation and performance (functional and structural) of small grid-connected PV systems. The IDEF0 representation (Integration Definition for Function Modeling) adopted in this work (Figure 1), is a method of modeling decisions, actions, and activities of an organization or manufacturing system in structured graphical form, according to Kim et al. [7]. The IDEF0 model diagram represents the functions (processes, operations, and activities) and the horizontal arrows indicate the inputs and outputs, in this case, representing the evolution of the information (research products) through the process. The controls (arrows down) represent the aspects that construct or conduct the function (methods and tools) and the mechanisms (arrows directed upwards) represent resources (people, software, and databases) that execute the function.

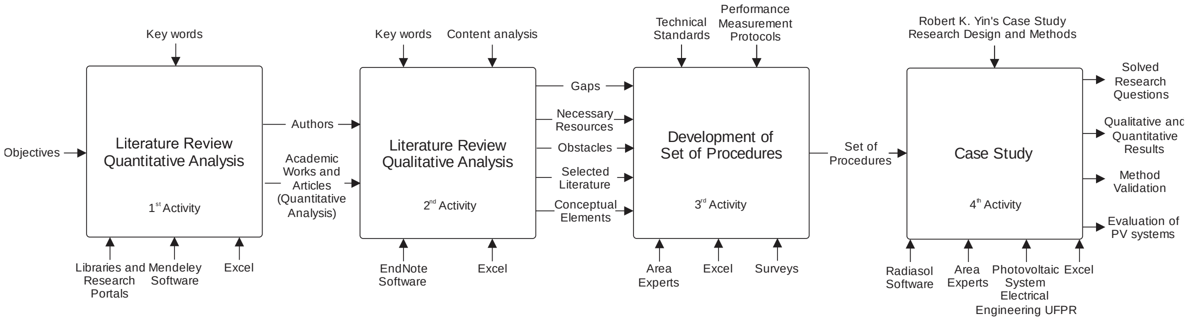

Figure 1. Development of work in the IDEF0 representation.

The methods used in the development of the work involved basic description, as well as quantitative and qualitative analyzes. Validation of the set of procedures was performed in a case study in the Laboratory of Energy Efficiency of the Department of Electrical Engineering of the Federal University of Paraná (UFPR, Brazil), based on the scientific procedures described by Yin [8]. The PV system was grid-connected with 3.5 kWp (peak power) of installed capacity (Figure 2). Additionally, it had a battery bank (2.5 kW) for academic studies. The solar radiation data came from the meteorological station of the National Institute of Meteorology (INMET), located on the polytechnic campus of UFPR.

(a) (**b**)

Figure 2. Photovoltaic system at the Federal University of Paraná
a) Photovoltaic array; b) Inverter, battery charge controller and monitoring system.

Set Of Procedures For Performance Analysis Of Small Grid-Connected Pv Systems

The procedures elaborated were classified in terms of project, installation site, electrical installation, and protection, safety, and maintenance.

Project

First, for project evaluation, the system should utilize documents specified in ABNT NBR 16274 [9], which are essential for verification and maintenance. The PV panels used for visual inspection, should be of the same number and characteristics as the panels specified for the target project. Otherwise, the result may be hotspots or inverter overloads, factors that compromise system performance.

Cables and connections may be subject to rodent degradation and environmental exposure, thus they should be protected and weather resistant to prevent future system shutdowns. Specifically, it is recommended that cables for use in photovoltaic systems should be resistant to UV radiation and saline conditions, and not be halogenated, according to ABNT NBR 16612 [10]. In order to reduce faults and risks to the distribution network, the inverters should be approved by the electric power concessionaires and subjected to several tests determined by the standards ABNT NBR 16150 [11] and NBR IEC 62116 [12]. Similarly, photovoltaic panels should have INMETRO certification and follow IEC 61730 [13]. Those using crystalline silicon technology should follow IEC 61215 [14].

Installation site

The installation site should promote natural ventilation in the photovoltaic array, without the existence of obstacles and architectural elements blocking air circulation through the array. Photovoltaic cells operating at extreme temperatures tend to exhibit reduced efficiency, this being one of the main problems in tropical countries.

The support structure of the photovoltaic array should be resistant to corrosion from acid rain and oxidation, which is one of the requirements presented in ABNT NBR 16274 [9]. It is also true that corrosion of the structure will result in loss of the mechanical strength needed to support the weight of the photovoltaic panels.

The location of the power conditioning equipment (inverter) and battery system should be adequate to provide the degree of international protection (IP) indicated for enclosed equipment. Generally, these should not be exposed to climatic factors and excessive dust.

Correct installation of a photovoltaic array is one that uses the maximum utilization of solar resource available at the installation site. Therefore, installation should consider: (i) the angle of inclination of the photovoltaic array, which must be equal to the latitude of the site; (ii) the orientation of the modules should be to the north, if located in the southern hemisphere, or to the south, if in the northern hemisphere; (iii) the azimuthal deviation (from the relation between the magnetic declination and the magnetic north or south), should be near zero.

The angle measurements can be performed using an inclinometer. Additionally, it is recommended that the photovoltaic modules have a slope equal to or greater than 10° to facilitate natural cleaning by rainwater.

The following recommendations are made regarding the region where a system is installed. Arid and semi-arid regions are characterized by low precipitation, which means greater and faster accumulation of dirt on photovoltaic panels. For this reason, frequent cleanings (3 to 4 per year) are required. Moreover, due to the high temperatures in such regions, the power conditioning equipment must be located in a well-ventilated space. Coastal areas make the process of metal corrosion faster due to high humidity (all coasts) and salt in the air (sea coasts). Thus, in coastal regions, the metallic parts of the photovoltaic system should be checked more frequently. Industrial regions, and others with high levels of atmospheric pollution, have present certain oxides in the air that cause acid rain. This causes materials to corrode more rapidly than usual and therefore, those parts of the photovoltaic system exposed to acid rain should be checked frequently.

Electrical installation

A major factor in the good electrical performance of a photovoltaic system is the absence of shading on the panels. Lack of shading is indicated if the day-time energy generation curve obtained by a datalogger is similar to the typical energy generation graph on a sunny day (Figure 3).

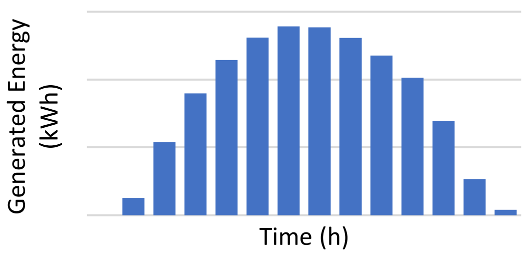

Figure 3. Typical energy generation graph.

Furthermore, a quantitative analysis of a photovoltaic system can be carried out using performance indicators. Thus, the performance rate (PR; Equation 1) normalizes the energy generated using irradiance of 1000 W/m² on the panels. Therefore, this rate should be higher than 75% in Brazil.

$$\mathrm{PR}\ [\%] = \frac{1000 \cdot \mathrm{E}[\mathrm{kWh_{AC}}]}{\mathrm{P_{nom}}[\mathrm{kW}_p] \cdot H[\mathrm{kWh/m^2}]} \tag{1}$$

Where E is the energy generated in the reference month, P_{nom} is the nominal power of the generator block, and H is the solar irradiance on the tilted module surface during the month.

The capacity factor CF expresses the generating capacity of the system in relation to the amount of energy that the system could generate if it operated under nominal conditions 24 hours per day. Therefore, in Brazil, the factor obtained by Equation 2 should be between 13% and 18%.

$$\mathrm{CF}\ [\%] = \frac{\mathrm{E}[\mathrm{kWh_{AC}}]}{24 \cdot (\text{days of the month}) \cdot \mathrm{P_{nom}}[\mathrm{kW}_p]} \tag{2}$$

Protection, safety, and health

Project verification and visual inspection are essential to ascertain the existence of grounding and equipotentialization of the metallic housings of the equipment, the distribution boards, the metallic support structure of the photovoltaic panels, and the power conditioning system. These requirements should comply with ABNT NBR 5410 [15], which establishes that all the masses of the installation located in the same building must be linked to share the same main equipotentialization. If necessary, the installation should have a Lightning Protection System (LPS), according to ABNT NBR 5419 [16].

The system protection and human safety protocol should include the use of a Type 2 Surge Protection Device (SPD) for the DC and AC circuits, a Residual Current Device (RCD), and overcurrent protection devices such as a thermo-magnetic circuit breaker and fuse.

The arrangement of the elements of the system should reflect NR-10 [17] in order to restrict access to only authorized persons. It should be indicated that the site is intended for distributed generation and presents a risk of electric shock. There should be safe and accessible areas for use during operation and maintenance. It is extremely important to have fixed points of anchorage on the roof where the panels are installed, to perform work safely at height, according to NR-35 [18].

In order to reduce the probability of dust accumulation and fungal proliferation due to moisture, which are health-damaging factors, it is necessary that there be adequate (forced or natural) ventilation of the space where the power conditioning equipment and measuring instruments are installed.

Maintenance

Maintenance of a photovoltaic system is important to sustain its operation, as well as to reduce the number of power interruptions due to technical problems. Consequently, frequent pruning of vegetation is important to avoid shading of the photovoltaic panels.

Parts and screws that cannot be loosened, or that are loose on the structures and fittings, are usually the consequence of the application of improper torque or difficult access to the tightening tool, respectively. Parts and screws should show no signs of oxidation.

Infiltration of water past the enclosure covers and through cable glands on the distribution boards can cause short circuits and consequently damage the system. This also increases the susceptibility of metal components to oxidation. Therefore, it is recommended to check that sealing gaskets are hydrated, and no cracks exist in any equipment housing.

Discoloration of the inverter housing, usually plastic, indicates its exposure to the Sun. If so, the inverter may be operating at temperatures high enough to reduce its efficiency. In such cases, it is recommended that the designer reinstall it in a safe, shaded, dry, and well-ventilated area. The forced ventilation of the inverter should leave it free of dust accumulation to assure correct operation of the cooling system.

The PV panels should be clean and free of surface particles blocking the solar rays from reaching the photovoltaic cells. Therefore, two cleanings per year are recommended. If there are cracks in the panel glass (from thermal shock or mechanical impact), or even discoloration of the photovoltaic cells as a result of the panel being near the end of its life, panel replacement is required.

Finally, when panels have solar trackers it is essential to lubricate the motors and gears annually to reduce friction, wear of metal parts, and to protect them from oxidation.

CASE STUDY

The system procedures used during the case-study project were adequate for the most part. This is known because all the project documentation was found. The cables of the photovoltaic system had thermoplastic anti-flame compound insulation and with gutters that protected against external influences and rodent action. The number and characteristics of installed equipment conformed to information about the project. The SMA Sunny Boy 3600TL-21 inverter had international certification, but certification from the National Institute of Metrology, Quality, and Technology (Inmetro) was not found.

The installation site allowed natural ventilation within the photovoltaic array, good accessibility, and effective connectivity to the inverter datalogger. The metal support structure of the panels showed no sign of material deterioration, such as corrosion. Moreover, the photovoltaic array was correctly installed, considering the orientation of the panels (to the north because the system is located in the southern hemisphere) and at an azimuthal deviation of 20° to the East (the best condition allowed by the roof). In an ideal situation (maximum use of the available solar resource), the angle of inclination of the modules should be equal to the latitude and the azimuthal deviation should equal 0° in relation to true North. However, given the limitations imposed during installation of a real facility, no unacceptable errors were found that significantly impacted system performance.

The photovoltaic system was not located in an arid, semi-arid, coastal, or industrial area. Although the Industrial City is on the outskirts of Curitiba, the pollution generated there is not carried by the wind to the region where the photovoltaic system was installed. According to INMET data, the direction of the wind is from 32° or ENE (east-northeast).

Based on analyses of the energy generation graphs (Figure 4), no patterns indicating a shading effect were detected for the photovoltaic panels.

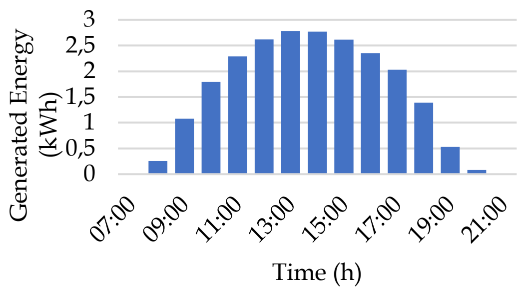

Figure 4. Energy Generation on January 13, 2017.

From the data for the energy generated and monthly solar radiation in the horizontal plane for 2015 and 2016, it was possible to calculate the PR (Figure 5). This considered the generated energy and solar irradiance on the tilted surface in the same period (Table 1). The value of this indicator was mostly greater than 75%. In Figure 6, the CF showed appreciable results, close to 13%.

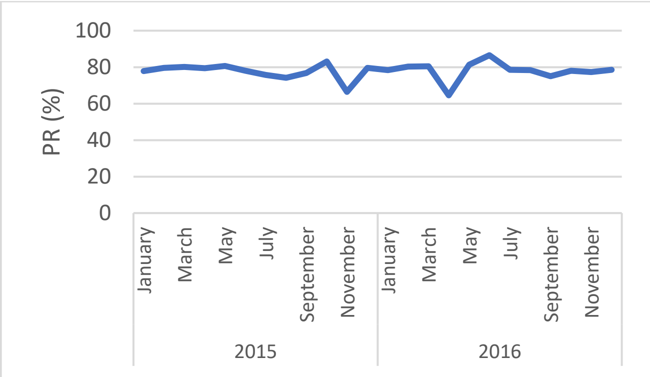

Figure 5. Performance rate (PR) in 2015 and 2016.

Table 1. Generated energy and solar irradiance on the tilted surfaces in 2015 and 2016.

Month	Generated energy (kWh)		Solar irradiance on the tilted surfaces (kWh/m²)	
	2015	2016	2015	2016
January	498.14	453.40	129.58	165.23
February	375.79	378.54	119.10	134.56
March	363.34	399.20	95.17	141.67
April	331.05	336.18	99.90	148.80
May	268.94	253.34	96.72	88.97
June	272.86	266.24	145.70	87.90
July	256.66	314.63	129.60	114.39
August	377.88	328.13	118.11	119.66
September	348.21	419.08	107.10	159.60
October	343.38	356.15	138.88	130.51
November	249.17	411.11	129.58	151.80
December	387.23	405.07	119.10	147.25

In the case of equipment protection, the metal support structure of the panels was ungrounded, but all the expected protection devices were found.

The physical location where the power conditioning equipment and measuring instruments were installed, was also used for storage of materials, which is prohibited by NR-10 [17]. There also was no warning sign with an access restriction message or warning of a risk of electric shock. In addition, the roof (6 meters above the ground) did not contain fixed anchorage points to assist in performing work at height, as according to NR-35 [18].

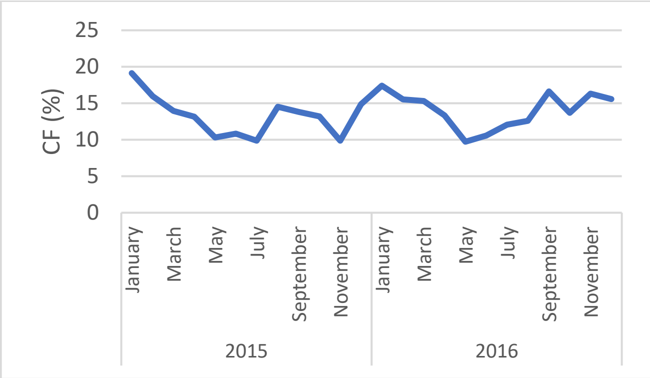

Figure 6. Capacity Factor between 2015 e 2016.

All the maintenance procedures were in compliance. In particular, there was no shading of the photovoltaic panels from vegetation and there were no loose parts or screws on the support structure of the modules and sensor fittings. The metallic components of the entire photovoltaic system did not show oxidation; nor did the equipment housings, distribution boards, and cable entries have water infiltration. The inverter housing was not discolored or cracked and its forced ventilation system was clean. The photovoltaic panels were also clean and with no evidence of cracking and discoloration of the photovoltaic cells.

CONCLUSIONS

A set of procedures was elaborated, and these were classified into those pertinent to the project, installation site, electrical installation, protection and safety, and maintenance. First, the photovoltaic system project was evaluated, considering the documentation, equipment, accessories, and cables used. At the installation site, the conditions of the photovoltaic system installation (for example, location and ventilation) that directly influence the performance of the system, and the accessibility of the individuals responsible for the system, were evaluated. Verification of an effective electrical installation was determined from the efficiency, amount generated, and performance indicators obtained using data from the photovoltaic system, such as performance rate and capacity factor.

Regarding safety and health issues, a set of measures and procedures were established for electrical installations, and for services involving electricity, in order to guarantee the safety and health of the individual responsible for the system. The items classified were based on technical and regulatory standards. Finally, maintenance is essential to sustain or improve system performance, as well as to minimize the number of power interruptions due to technical problems. The maintenance analysis included reviews of shading of the photovoltaic panels, loosening and oxidation of parts, water infiltration, and lubrication of moving parts.

Therefore, the set of procedures proposed in this work present functional and structural aspects that contribute to improved operation and performance of small grid-connected photovoltaic systems. Quantitative and qualitative analyses were performed according to a methodical procedures and the set of procedures was validated in a case study of an experimental photovoltaic system at UFPR.

There were limits to this work regarding the literature review and the case study. The bibliographic portfolio is composed of academic work and articles published in journals and magazines, of which the databases are constantly being updated. For a more comprehensive, concrete, and generalized validation, it would be necessary to carry out case studies including other small grid-connected photovoltaic systems. An analysis of the systems before and after application of the set of procedures, in addition to comparisons of the operation and performance of such systems, is proposed for future work.

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