



Procedure for the Quantification of the Degradation Index of Photovoltaic Generators

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Abstract

A procedure is presented for the quantification of the degradation index of Photovoltaic Generators, based on the quantification of the operational losses inherent in the system, which allows maintaining the nominal operating conditions and by the warranty terms of the photovoltaic generator. A photovoltaic generator connected to the network with a nominal power of 7.5 kWp, installed in the Solar Energy Research Center of Santiago de Cuba, is used to evaluate and validate the procedure. The starting point is the mathematical model of the photovoltaic generator, then the operational losses of the photovoltaic generator are quantified and the mathematical model is adjusted to real conditions, through a polynomial adjustment. The results obtained show that the photovoltaic generator presents deviations in terms of the nominal power generation, because the operational losses are 7% with respect to the values given by the manufacturer.

Introduction

Electricity generation has been one of the main challenges that humanity has faced, with the absence of this socio-economic systems would not develop. It is a fact that fossil resources are limited and given the growth of global energy demand, they are expected to run out within a few years. In addition, the increasing and continuous use of primary energies has caused great damage to the environment, problems such as global warming and melting of the poles are consequences of their use.

One of the alternatives of electricity generation, friendly to the environment, are the Renewable Energy Sources (RES), an alternative that in 2008 was very poor in terms of its introduction and use in Cuba, but with the actions that are coming by 2030 electricity generation from SRE is expected to cover 24% of national demand (Gutiérrez et al., 2017; Gutiérrez et al., 2018). see Figure 1.

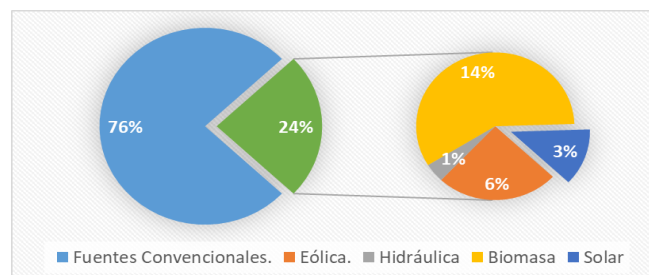


Figure 1. Planning of electricity generation from RES by 2030

Among the alternatives for electricity generation, one of the most widespread currently is Grid-Connected Photovoltaic Systems, hereinafter, (PVGCS). The high and stable potential of solar radiation in the field occupied by the Solar Energy Research Center, Santiago de Cuba (CIES) throughout the year means that this index is around 5 kW-h/m² daily adaptability of technology to local conditions favor its introduction. Currently, one of the objectives pursued by research groups and industry in this sector is to improve the performance of installed Photovoltaic Systems (PVS), i.e. to increase electricity production by reducing losses, that the systems are comply with safety measures (Villegas Berbesi, 2012).

PVGCS are usually supervised according to standards established in each region and measurements can be analyzed annually. These indicators are calculated from data throughout the year to take into account the effect of seasonal variation. Due to the different levels of solar radiation and ambient temperatures, photovoltaic systems operate better at certain times of the year. Annual results can be compared with benchmarks to evaluate system performance.

The ratio of output energy to input energy is nothing more than efficiency, a measure of the PVGCS's ability to convert the solar radiation it receives into alternating energy.

The efficiency of the system provides an evaluation of the process of converting sunlight into alternating energy (Shukla et al., 2016; Chu & Majumdar, 2012) and, as the parameter is largely independent of the size of the PVGCS and the amount of annual solar radiation received, it can be used for all types of systems. However, the efficiency of the system does not take into account the expected performance of the PV system (which depends on the choice of PV modules and the inverter) and therefore does not provide information on whether the system is performing well or poorly.

Developing

The use of the PR (performance ratio) or overall performance is a simple and effective method to evaluate the performance of PVGCS. However, there are theoretical reasons and experimental evidence that show that this parameter varies throughout the year by as much as 10% (Meyer & Van Dyk, 2004) which prevents any value measured over a week from being considered as representative of what happens throughout the year.

The PR is a parameter derived from the efficiency of the system and is the most common method of evaluating the performance of the photovoltaic system, it is widely used as an indicator of quality since, in 1993, it was included in the IEC 61724 standard. This parameter is defined as the relationship between the energy that a photovoltaic system delivers to the grid and that delivered by a hypothetical ideal system, understood as one whose solar cells always work at the reference temperature and which, otherwise, is free from losses.

The main advantage of the PR is that it is easy to obtain: the grid's energy meter and an incident solar radiation sensor are sufficient. Its main drawback is that it does not allow to differentiate between thermal losses (due to the fact that solar cells normally operate at temperatures above 25° C), which are unavoidable and unrelated to the design and operation of the system, from the rest of losses, which do depend on that is, it does not distinguish between extrinsic (thermal) losses and intrinsic (the rest) losses. Extrinsic losses are influenced by the evolution of environmental conditions (radiation, ambient temperature, wind, etc.). Intrinsic losses depend exclusively on factors linked to the design and quality of the equipment, and its operation.

For this reason, the so-called PR₂₅ has recently been used, defined as the ratio between the energy actually produced by a photovoltaic system and that produced by another hypothetical

one of equal nominal power, which is not affected by any type of losses and whose cells operate at the same temperature as the real system (instead of 25 ° C), as described in equation 1.

$$PR_{25} = \frac{E_{AC, REAL} \cdot G^*}{P_{RG}^* \Delta t \sum_i G_i [1 + \gamma(T_{Cj} - T_C^*)]}$$

where:

$E_{AC, REAL}$, real energy delivered to the grid

$G^* = 1000 \text{ W / m}^2$, irradiance

$T_C^* = 25^\circ \text{ C}$, cell temperature

P_{RG}^* , nominal power of the photovoltaic generator.

Δt , sampling time

i , number of measurements

γ , coefficient of variation of power with temperature, negative value, indicated by the manufacturer.

* Standard Measurement Conditions, **STC**, (1000 W / m², 25° C, AM 1.5)

The PR_{25} (which considers the influence of the operating temperature of the photovoltaic cells), presents difficulties in estimating the maximum output power of the generator photovoltaic (**PVG**), evidence of this is presented in Reise et al. (2020) where, the absolute error resulting from the analysis of one day between the actual measured and the estimated power is 3 times greater than that estimated from the mathematical model of a diode.

This work presents a procedure for the quantification of the degradation index of Photovoltaic Generators, from the relationship between the expected power and the real power for different conditions of temperature and solar radiation.

For this, the PVGCS-CIES was used, which is located on the land occupied by the Solar Energy Research Center, in Santiago de Cuba. It is located at the geographical coordinates: Latitude: 20 ° 00 ' 75 " N and Longitude: 75 ° 77 ' 07 " W. It is made up of 30 photovoltaic modules, with a nominal power of 250 Wp, HELIENE215MA model, grouped in three tables and formed by three chains of 10 photovoltaic modules, each one, with a power of 2.5 kWp, 303 VDC and 8.22 A, which in its entirety has a nominal power of 7.5 kWp.

Results and Discussion

The actions aimed at minimizing operating losses are intended to maintain nominal operating conditions and ensure the guarantee terms of the main elements that make up the PVGCS (Photovoltaic Generator and Grid-Connection Inverter). The actions to correct faults are intended to monitor the behavior of the PVGCS components, and in the event of a fault situation, report it by means of an alarm.

In the case of the PVG, the model describes the system for STC. However, the real operation of the system has operational losses, so its quantification is necessary in order to calibrate the PVG model to the real operating conditions, avoiding false alarms due to a failure.

The simulations were performed using MATLAB 2017b software. From the electrical parameters of the HELIENE HEE215MA68 PV module, shown in Table 1, the mathematical model was parameterized allowing the simulation of the PVG for any environmental condition.

Table1. Electrical Parameters of the HELIENE HEE215MA68 PV Module

Electrical Data STC	
Nominal Power PMPP (W)	250
Tension MPP (V)	30,30
Intensity MPP (A)	8,22
Vacuum tensión (V)	37,40
Short circuit current (A)	8,72

Procedure Description

The analysis carried out considers that the behavior of a PVGCS results from its instantaneous response to variations in two variables: irradiance (S) and cell temperature (Tc). In an ideal system, for the PVG model, the answer is given by the system of equations represented in Figure 2.

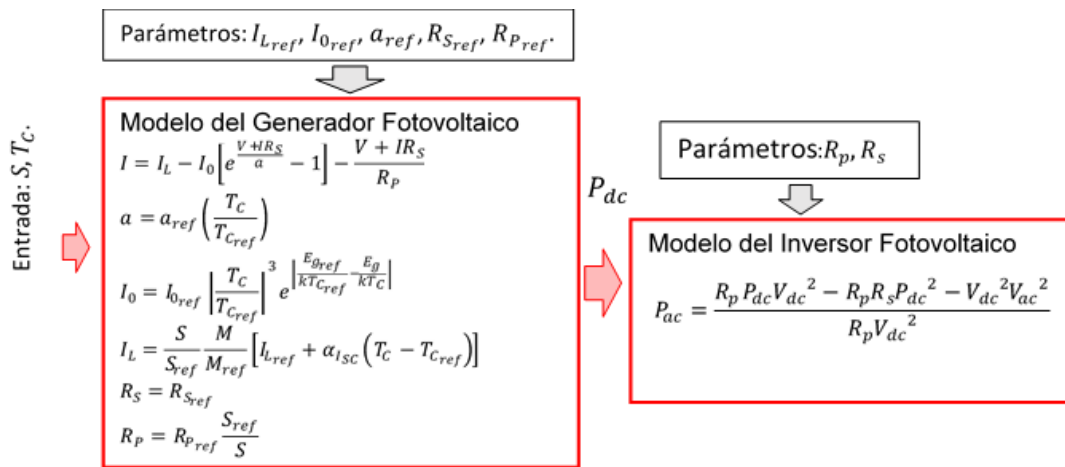


Figure 2. System of Equations that Define the PVG

Once the prevailing climate and the nominal parameters of the photovoltaic system have been characterized, it is possible to predict the behavior of the system and calculate the deviation between the ideal and real response (Lorenzo et al., 2007). The procedure for quantifying operational losses consists of: Obtain the output power of the photovoltaic generator (P_{DC} , EXP) under the irradiance and operating temperature conditions of the PV module for a sufficient time to sweep the entire spectrum of operating conditions.

Simulate the PV generator output power (P_{DC} , SIM) for the same irradiance and operating temperature values that were presented during step 1, (Lorenzo et al., 2007).

Determine the coefficients a, b and c for the polynomials of equations 2, 3 and 4 starting from a polynomial fit.

$$P_{dc,EXP} = (a_{Pdc} + b_{Pdc}(T_C - 25^\circ C) + c_{Pdc}S)P_{dc,SIM} \quad (2)$$

$$V_{dc,EXP} = (a_{Vdc} + b_{Vdc}(T_C - 25^\circ C))V_{dc,SIM} \quad (3)$$

$$I_{dc,EXP} = (a_{Idc} + b_{Idc}(T_C - 25^\circ C))I_{dc,SIM} \quad (4)$$

where:

- a_{Pdc} defined by the line $P_{dc,EXP} = (a_{Pdc})P_{dc,SIM}$

- $a_{V_{dc}}$ defined by the line $V_{dc,EXP}=(a_{V_{dc}})V_{dc,SIM}$
- $a_{I_{dc}}$ defined by the line $I_{dc,EXP}=(a_{I_{dc}})I_{dc,SIM}$

S , is Irradiance, expressed in $\frac{W}{m^2}$.

T_C , is the operating temperature of the PV module, expressed in [$^{\circ}C$].

$P_{dc,EXP}$, $P_{dc,SIM}$ is the output power of the PVG measured and simulated respectively, expressed in [W].

$V_{dc,EXP}$, $V_{dc,SIM}$ is the output voltage of the PVG measured and simulated respectively, expressed in [V].

$I_{dc,EXP}$, $I_{dc,SIM}$ is the output current of the PVG measured and simulated respectively, expressed in [A].

Quantification of Operational losses

The test was carried out in the 7.5 kWp PVGCS-CIES, throughout the month of June 2019. 6340 $P_{DC, EXP}$ (S , T_c) points were obtained experimentally and their corresponding $P_{AC, SIM}$ (S , T_c) were calculated, as shown in Figure 3.

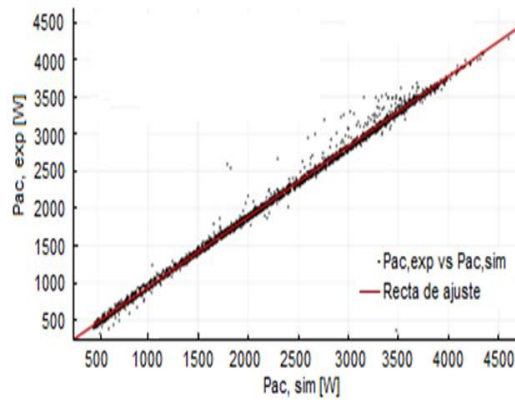


Figure 3. Result of the Analysis of the Operating Data. Straight Adjustment

The value of $a = 0.93$ with a coefficient $R^2 = 0.996$, indicates that the operational losses of the system, $P_{ope} = (1 - 0.93) = 0.07$ is 7%. The adjustment values of the parameters of the polynomials of the PVG mathematical model are shown in Table 2.

Table 2. Indices of the Fit Polynomial

Polynomial	Parameters
Adjustment polynomial P_{dc}	$a_{P_{dc}}=0.9411$ $b_{P_{dc}}=0.0772 \text{ \%}/^{\circ}C$ $c_{P_{dc}} = -2.959 \cdot 10^{-03} \text{ \%}/\frac{W}{m^2}$
Adjustment polynomial V_{dc}	$a_{V_{dc}}=0.9941$ $b_{V_{dc}}=-0.000278 \text{ \%}/^{\circ}C$
Adjustment polynomial I_{dc}	$a_{I_{dc}}=0.9475$ $b_{I_{dc}}=-3.47 \cdot 10^{-03} \text{ \%}/^{\circ}C$

Figures 4 and 5 show the plane defined by the mathematical model of the PVG and the polynomial described above with respect to the experimental values.

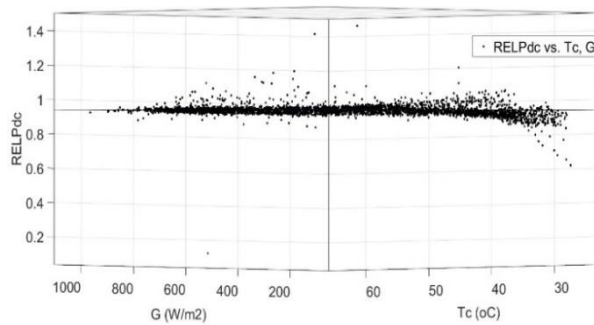


Figure 4. Theoretical Plane of the Maximum Power Point of the PVG with Respect to the Experimental Data, Front View

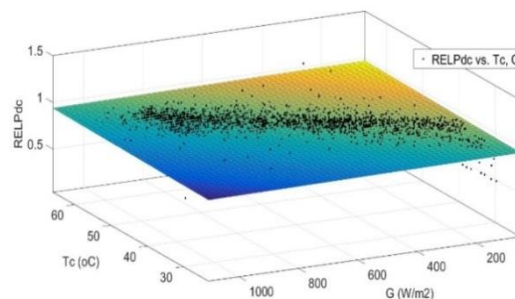


Figure 5. Theoretical Plane of the Maximum Power Point of the PVG With Respect to the Experimental Data, Diagonal View

Using the adjustment value a , it is possible to determine that the degradation rate estimated by the solar generator algorithm is 7%, that is, the power delivered is around 7% less than the nominal power given by the manufacturer. This result is similar to the average degradation that was obtained with the I-V400 instrument (6.73%), with less than 1% difference, so the procedure gives satisfactory results.

Conclusion

The procedure for the quantification of the degradation index of the PVGCS has been presented, which allows characterizing its operation and taking maintenance actions if required. This indicator, unlike the PR, does not depend on environmental conditions and is more rigorous in calculating the power estimated by the PVG model. The results obtained as part of the implementation of the procedure show that the PVGCS-CIES subjected to evaluation presents 7% operational losses, with respect to the values given by the manufacturer. This result is similar to the average degradation that was obtained with the commercial model curve tracer instrument, I-V400, (6.73%), with less than 1% difference. Therefore, the procedure gives satisfactory results.

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