STC power for 15 MW of PV comparing nameplate, initial power and power after 4 years

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ABSTRACT

To date, the majority of quality controls performed at PV plants are based on the measurement of a small sample of individual modules. Consequently, there is very little representative data on the real Standard Test Conditions (STC) power output values for PV generators. This paper presents the power output values for more than 1300 PV generators having a total installed power capacity of almost 15.3 MW. The values were obtained by the INGEPER-UPNA group, in collaboration with the IES-UPM, through a study to monitor the power output of a number of PV plants from 2006 to 2009. This work has made it possible to determine, amongst other things, the power dispersion that can be expected amongst generators made by different manufacturers, amongst generators made by the same manufacturer but comprising modules of different nameplate ratings and also amongst generators formed by modules with the same characteristics. The work also analyses the STC power output evolution over time in the course of this 4-year study. The values presented here could be considered to be representative of generators with fault-free modules.

KEYWORDS

PV arrays; PV power; power dispersion; degradation; large grid-connected PV plants

1. INTRODUCTION

It is well known that the real power output of the generators in any PV system differs to a greater or lesser extent from the nominal value, understanding the latter to be the sum of the standard test conditions (STC) power nameplate ratings for the modules making up the said generators. A key contributor to this difference is the deviation between the actual power output of the said modules in relation to their nameplate rated value, although other phenomena also intervene, such as soiling, wiring, mismatching or certain undesired problems, such as early degradation, the presence of hot spots, polarisation, and so on [1–4].

Despite the fact that the real STC power output of the PV plant generators plays a decisive role in the final production obtained, the majority of the quality controls made today are based solely on the measurement of the STC power of individual modules, performed prior to installation in the field [5,6]. Such measurements take no account of the aforementioned phenomena (soiling, wiring, mismatching, etc.). For this reason, the literature contains but few representative data on the real values of the STC power output of PV generators. Of the few data available, perhaps the most representative are those published by Martinez *et al.* [7], corresponding to a large number of PV generators (almost 200 MW) installed in Spain during the Spanish PV boom (from 2006 to 2008). The data published in this study show a mean STC power output, for the population analysed, of around 94.3% of the nameplate rated value, with a standard deviation of 4.1%. Account should be taken of the fact that the sample measured in the aforementioned paper corresponded to generators from a number of plants and also to modules of different power ratings and different manufacturers. However, as will be seen in this paper, when an analysis is made of a population of generators formed by modules of the same nominal characteristics and when these modules are free from faults, then the dispersions normally found are considerably smaller.

From 2006 to 2009, the INGEPER-UPNA group, in collaboration with the IES-UPM, conducted a study to monitor the STC power output of the generators at a number of PV plants that the company Acciona Solar has installed in Navarre (Spain). In total, almost 2000 PV generators were analysed, with a total nominal power output of some 20 MW. This work has made it possible to determine, amongst other things, the power dispersion that can be expected amongst generators made by different manufacturers; amongst generators made by the same manufacturer but comprising modules of different name-plate ratings; and also amongst generators formed by modules with the same characteristics. The work also analyses the STC power output evolution over time in the course of this 4-year study.

During the first years in which the study was conducted, a set of PV modules affected by a fabrication defect revealed hot spot problems [8]. The affected generators were located in three of the aforementioned PV plants. Although only some generators were affected and the problem was resolved by the manufacturers by replacing the faulty modules, we have preferred not to include those PV plants in the results given in the present paper in order to ensure that those data are representative of problem-free plants. Once we had excluded those PV plants, the total number of generators studied came to 1346, with a total nominal power output of some 15.3 MW.

2. DESCRIPTION OF THE POPULATION ANALYSED

The more than 1300 generators analysed were distributed amongst a total of four PV plants. It should be mentioned here that 'PV generator' is understood to be the group of modules associated with a single energy meter. Three of the aforementioned PV plants have power outputs ranging from 10.5 to 20.5 MW and are formed mainly by generators with a nominal power output of around 6.5 kW. There are also some PV generators composed of several 6.5 kW units associated with a single energy meter (with power outputs ranging from 13 to 100 kW). All the modules in each plant are from the same manufacturer, although in two of them there are modules of different power classes (different STC nameplate ratings). The other plant has a power output of around 9.5 MW and is formed by generators with different nominal power outputs (ranging from 6.8 to 100 kW) and with modules from different manufacturers. Table I shows a summary of the power output for each plant, the number of generators analysed at each plant, the number of different manufacturers, the power outputs for the various modules installed and the year of installation. All modules are crystalline silicon. In total, there are five different manufacturers (referred to as A, B, C, D and E) and 11 different module models. Modules of the same model are understood to be those pertaining to the same manufacturer and to the same power class (same nominal power). Hereinafter, we shall refer to 'generators of similar characteristics' when formed by modules of the same model and two generators will be referred to as having 'different characteristics' when formed by modules with different models (a different manufacturer or simply a different power class).

3. REAL STC POWER OUTPUT OF THE GENERATORS

An accurate measurement of the STC power output of PV generators requires certain precautions to be taken as far as technical and environmental conditions are concerned. For example, it is advisable to have an irradiance of more than 800 W/m^2 on the module surface to avoid days with wind speeds of more than 5 m/s, to take a number of measurements on the same generator, and so on [7]. All these mean that, for reasons of time, it is not feasible to directly measure the power of all the generators in a large-scale PV plant. In an earlier paper [8], a method was described,

Table I. Summary of the power output for each plant, the number of generators analysed at each plant, the number of different manufacturers, the power outputs for the various modules installed and the year of installation.

Plant	$P_{nominal}$ total (MW)	No. of generators	Manufacturers	Module STC power (W)	Year of installation
1	1.4	130	A	170, 175 180	2005
2	2.6	268	A	180, 185	2006
3	1.8	200	B	159	2005
4	9.5	120	A	180, 185	2006
		17	B	155	2006
		553	C	170	2006
		50	D	205, 210	2006
		8	E	275	2006
Total	15.3	1346	A	170, 175, 180, 185	2005, 2006
			B	159, 155	2005, 2006
			C	170	2006
			D	205, 210	2006
			E	275	2006

which made it possible to obtain, with an acceptable degree of accuracy (error of less than 2%), the STC power output of all the generators in a PV plant on the basis solely of the annual production data of each generator and the direct measurement of the STC power of just a few generators. This is precisely the method used to obtain the STC power of the more than 1300 generators mentioned earlier. The direct measurement of just a few generators in each of the power plants included in the study was performed each year and was based on the use of the capacitive load to obtain the *I–V* curve whilst endeavouring to take the measurements in the same month each year. In order to determine the test radiation conditions, the same calibrated cell was always used, and measurements were always taken with an irradiance of more than 900 W/m^2 on the module surface. The measurements were corrected to avoid the influence of soiling. To do so, one of the modules was measured before and after cleaning, and the corresponding correction factor was applied to all the generators measured. Therefore, the STC power values obtained for generators include wiring and mismatching but not soiling.

Figure 1 shows the histogram with all the STC power outputs for all the generators included in the study 1 year after installation at each of the plants. As can be seen from Table I, the generator population corresponding to manufacturer C is much larger than the rest (up to five times greater). This would have meant that this manufacturer would have had a greater influence on the shape of the aforementioned histogram. For this reason, in order to obtain a histogram with a similar number of generators of each type, the graph shown in Figure 1 only includes a representative sample comprising 100 generators made by manufacturer C. This sample has been selected to ensure that the power distribution is the same as for the 553 generators of this type.

The mean value of the effective power output of the generators is 94.5% of the nominal value, a similar result to the measurements obtained by Martínez *et al.* [7]. However, the power dispersion obtained here is much smaller (the standard deviation is practically half). We would yet again emphasise that the figures shown here solely correspond to problem-free generators (with no hot spots, initial degradation, polarisation, etc.). Therefore, the histogram in Figure 1 is quite a representative distribution of the power values that could be expected today from PV plant generators with problem-free modules. In general, it could be said that most generators offer power outputs of between 94% and 96% of the nominal power and that it is not usual to find generators with outputs of less than 90% of their nominal power.

3.1. STC power rating according to manufacturer and to the module power class

The power distribution shown in Figure 1 could be interpreted as the sum of two superimposed phenomena: the first is the dispersion typical of generators of similar characteristics (formed by modules with the same power class and made by the same manufacturer) and the second is the dispersion existing in the mean power output of generators with different characteristics (formed by modules with a different power class or made by different manufacturers). In fact, if we were to group together the generators with similar characteristics, the resulting power distributions (Figure 2) show a much tighter dispersion than that observed in Figure 1. The dispersions observed in almost all the histograms of Figure 2 are around ±3% or ±4% of the mean value. However, the real difference actually resides in the mean power output values observed for each of the different module models.

This is numerically shown in Table II, which gives the mean and the standard deviation for the power distributions plotted in Figure 2. The standard deviations for generators with similar characteristics are all close to 1%, whilst the mean power output varies according to the module model, ranging from 92% to 97% of the nominal power.

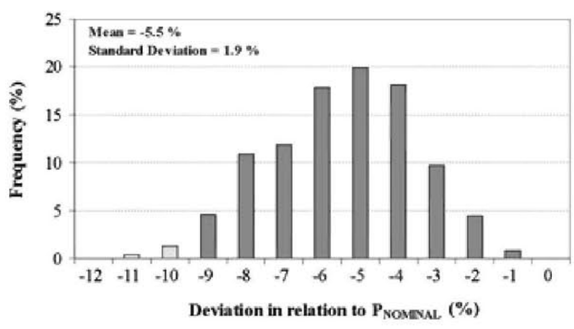

Figure 1. Histogram of STC power outputs for all the generators included in the study. In order to have a similar number of generators of each type, only a representative sample comprising 100 generators made by manufacturer C has been included.

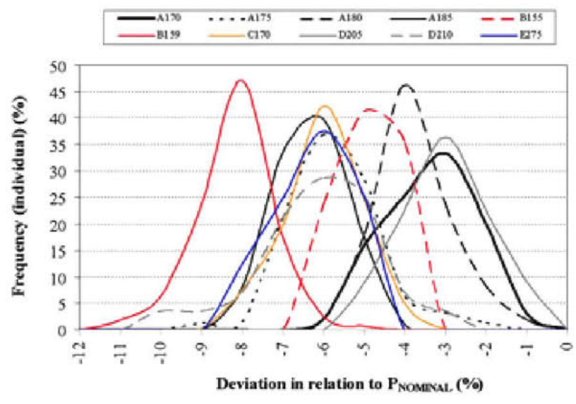

Figure 2. Histograms of STC power outputs of those generators with similar characteristics (formed by modules with the same power class and made by the same manufacturer).

Table II. Mean value and standard deviation for each of the histograms represented in Figure 2.

Model	A170	A175	A180	A185	B155	B159	C170	D205	D210	E275	Mean
Mean	−3.4	−5.7	−3.8	−6.3	−4.9	−8.2	−6	−3	−6.1	−6.3	−5.4
Std deviation	1.1	1.2	1	0.9	0.8	1	1	1.1	1.5	1	1.1

3.2. STC power for generators made by the same manufacturer yet of a different power class

Most manufacturers class their modules into different power classes on the basis of the STC power measurements taken, normally using a flash tester. If this classification were true to reality, then the power distributions for the different module classes ought to have a similar dispersion and show a similar mean deviation in relation to the nominal value. However, it has been observed how generators from the same manufacturer, yet pertaining to different classes, tend also to offer different STC power deviations in relation to the nominal value. This can be seen in Figure 3 showing the power distributions for the generators made by manufacturers A and D, classed on the basis of the power output classes of its modules.

The power deviation in relation to the nominal value for the generators with 175 W modules is around 2.5% higher than that recorded for the generators with 170 W modules (on the right in Figure 3a). This difference is practically the same as the difference existing between their nominal nameplate ratings (175 W ≈ 170 W +2.5%). This all appears to indicate therefore that the power classification made by the manufacturer is unrealistic and that the 170 and 175 W modules have been separated into two power classes when in actual fact their power distributions are practically the same (in other words they ought to be put in the same power class). The same is true for the generators formed by modules from power classes 180 and

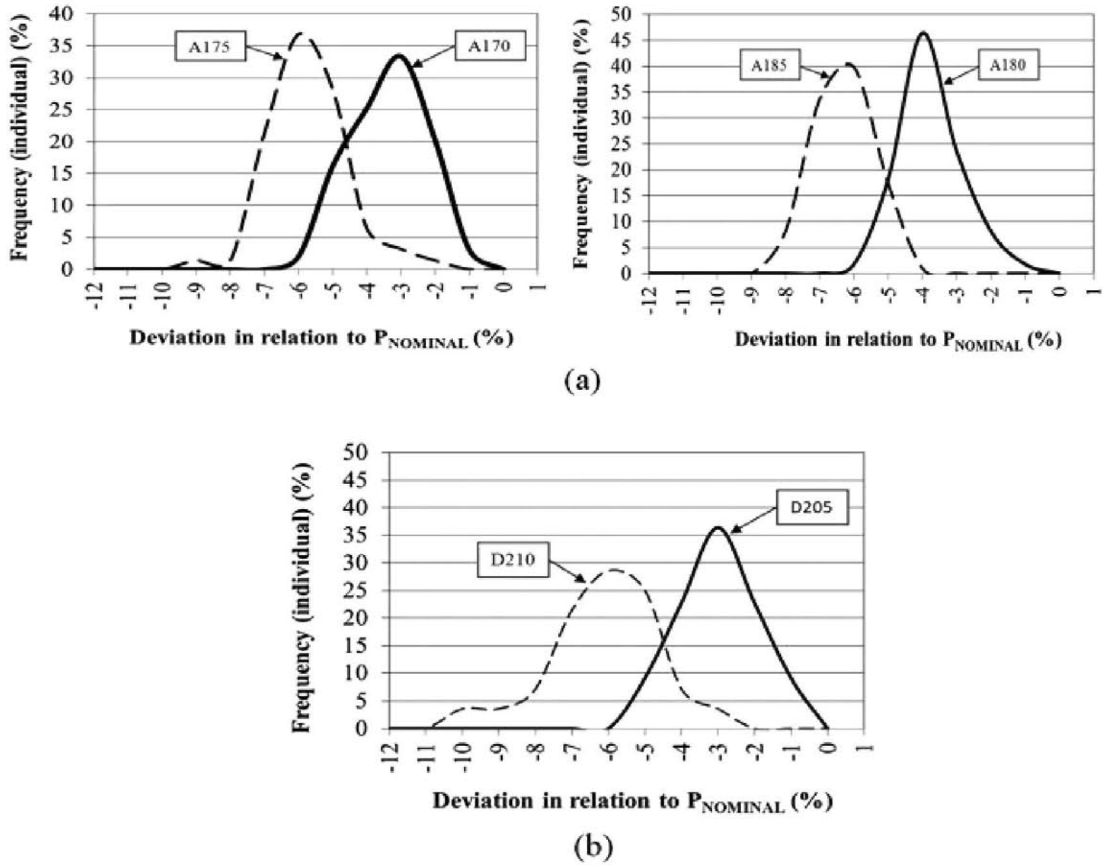

Figure 3. Histograms of STC power outputs of generators made by the same manufacturer. Each histogram corresponds to generators formed by modules of the same power class: (a) manufacturer A (left: modules produced in 2005; right: modules produced in 2006); (b) manufacturer D.

185 W (on the left in Figure 3a). Nevertheless, the latter conclusion could not be applied to the power classes A170 and A180, whose power deviation in relation to the nominal value are very similar.

The latter observations are not a one-off incident that is specific to manufacturer A, given the fact that a similar analysis could be conducted in the case of the generators made by manufacturer D, as shown in Figure 3 (b), reaching a similar conclusion to that put forward for manufacturer A.

The observations made here are not particularly surprising. A number of authors have already warned about the difficulty in calibrating the flash testers and the differences that generally occur between the measurements taken with a flash tester and those made with the sun itself [9–11]. In fact, some authors have demonstrated that there is little sense in classing the modules based on measurements taken with a flash tester when the power output interval between one class and another is less than the measurement error [12]. This is precisely what appears to have occurred with manufacturers A and D.

4. CHANGES OVER TIME IN THE REAL STC POWER OUTPUT OF THE GENERATORS

The typical annual power degradation value for PV plant generators is so small that it is difficult to measure within the space of just a few years. Some authors have estimated the power degradation of crystalline silicon to be around 0.5–0.8% per year [13–17]. However, this is a mean value given the fact that none of these authors has managed to prove that the said degradation is linear. Whatever technique is used to accurately measure the STC power output of a PV generator [11], it is not possible to guarantee an accuracy of less than ±1.5%. For this reason, in a problem-free system, even assuming that the modules have a linear degradation, there should be no significant degradation until quite a few years have elapsed. In fact, in the course of this 4-year study, the INGEPER-UPNA group has not measured any significant degradation in any of the problem-free PV plants studied. For each of these 4 years, the STC power was obtained for all the generators at these plants, following the method described at the beginning of Section 3. By way of example, Figure 4 (a) shows the decrease in the STC power of each of the approximately 280 generators at one of the plants studied from 2006 to 2009. It can be seen that most of the variations are within a range of ±1.5%, and therefore, these variations come within the accuracy of the measuring method. Figure 4(b) shows the STC power output histograms (deviations in relation to the nominal value) for years 2006 to 2009 for the same plant.

It can be seen how the four power histograms maintain practically the same dispersion (standard deviation), thus indicating a uniform degradation throughout the plant. Furthermore, the mean power values for the four histograms

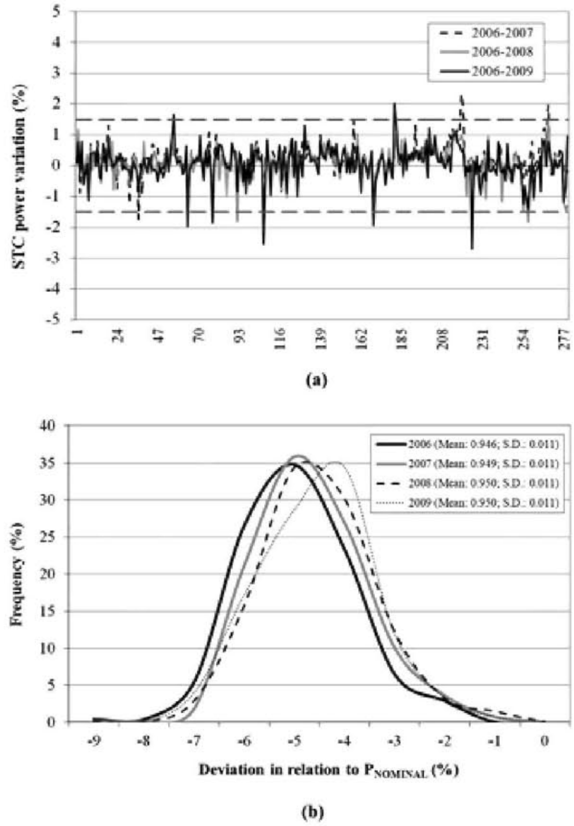

Figure 4. (a) Decrease in the STC power of each of the 279 generators at the Castejón PV plant from 2006 to 2009; (b) STC power output histograms (deviations in relation to the nominal value) for years 2006 to 2009 for the same plant.

are very similar, with maximum differences of under 0.4%. As has already been mentioned, these differences are more likely due to the actual error in the calculation of the STC power than to the degradation of the different generators. This has also been observed in the other plants studied.

Everything appears to indicate that if significant degradation is observed in the PV plant generator power output during the initial operating years, this is more than likely due to some kind of problem [4].

5. CONCLUSIONS

This paper has presented the results obtained by the INGEPER-UPNA group when monitoring the STC power outputs of the generators at various PV plants. Of the more than 1300 PV generators studied, those generators free from any type of problem were selected. The generator modules pertained to different manufacturers and to different power classes; however, all the modules were crystalline silicon.

The mean STC power output of the generators studied was 5.5% lower than the nominal value, with a standard deviation of nearly 2%. These power deviations in relation to the nominal value can be regarded as representative of the current state of the art for PV generators.

It was also found that the dispersion between generators of similar characteristics was somewhat tighter than the dispersion for the group of generators taken as a whole. The standard dispersion for a population of problem-free generators of similar characteristics is around 1%. The mean STC power deviation in relation to the nominal value for each population varies considerably depending on the manufacturer and the power class of the modules in that population (the mean is around 5.5%). For some manufacturers, it has been shown how the classification of modules in power classes is not consistent with the values obtained in field measurements. As a result, generators formed by modules made by the same manufacturer but with different power classes practically have the same mean STC power (in other words, these modules ought to be in the same class).

Likewise, it has been shown that, in a problem-free system, there should be no significant degradation of the crystalline silicon modules until a number of years have elapsed. Therefore, if significant degradation of the generator power is observed at a PV plant during the initial years of operation, then it is highly likely that there is some kind of problem.

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