Long-Term Monitoring of Photovoltaic Plants

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***Abstract*-**This paper deals with a data-acquisition system that has been specifically developed for a long-term monitoring of ten different photovoltaic plants. The main goals of the system consist in estimating the drift of the plant components, mainly photovoltaic modules and power inverters, and comparing the performance of the ten plants, which are based on different technologies and architectures. Owing to these goals, the traceability-assurance of the obtained measurements is mandatory, hence the data-acquisition system has been designed to be easily calibrated and, if necessary, adjusted to compensate for measuring-chain drifts. In addition, the measurement uncertainty, which has to be suitable to distinguish the behaviour of the different PV plants, has to be stated for each of the estimated parameters. A brief description of the data-acquisition system is provided and its measurement capabilities are highlighted in terms of measured quantities and expected uncertainty. Results that refer to a period of thirty months are also reported.

I. Introduction

Nowadays, at the end of 2012, according to a preliminary document of IEA-PVPS [1], the installed PhotoVoltaic (PV) power around the world is close to the 100 GW_p threshold and the two main markets are the German and Italian ones with about 32 GW_p and 16 GW_p in grid connection, respectively. The corresponding energy productions permit to achieve significant figures of 5.57 % and 5.75 %, respectively, taking into account the different national electricity consumptions (544 TWh/year vs. 335 TWh/year) and solar irradiations (deviations of 20-50%, roughly). In this framework, the accurate assessment of energy performance, day by day, is of great importance in all the possible applications of PV systems in grid connection. In particular, for achieving substantial improvements in production, many options can be employed, such as solar cell technologies with high efficiency and low temperature losses, one axis or dual axis sun-tracking systems, proper cooling techniques for PV modules in building integrated applications (BIPV), power optimizers at dc side, master–slave control for the dc–ac converters [2]. Furthermore, the aging effect in the PV module technologies plays a crucial role in the economic analysis of PV system investments. In the market, most of the manufacturers gives a double power warranty for their products, typically 90% of the initial maximum power after 10 years and 80% of the original maximum power after 25 years. The results in [3]-[4] show that noticeable deviations (positive or negative) from the warranty can occur and the useful lifetime of PV modules can be extended beyond the commonly assumed 25 years.

Our paper investigates the aging effect on monthly basis by means of calibrated instrumentation and presents the 30-month results for different PV technologies, both the crystalline silicon and thin film ones.

II. Experimental set-up

The photovoltaic (PV) plant under monitoring is an assembly of ten independent PV plants that are located in Piemonte (Italy) at a latitude of about 45° N. The investigated PV technologies and the main nameplate specifications of the ten plants are summarized in Table 1, which shows the area (A_{PV}) and the nominal power (P_{nom}) of each array and the efficiency of PV modules (η_{PV}) and power inverters (η_{INV}). Six of the ten plants employ PV modules oriented towards South (azimuth angle $\gamma \approx 0°$) and mounted in a fixed position with tilt angles $\beta = 35°$ (A, B, C, D, E) and $\beta = 0°$ (F). The other four plants employ 2-axis tracking systems; three of them (At, Dt, Et) are based on the same PV modules of the corresponding fixed plants, while the fourth (Gt) uses High Concentration PV (HCPV) modules. After the plants have been installed, their *I-V* characteristics have been experimentally estimated at natural sunlight through the acquisition of the transient charge of a

Table 1. Main specifications of the ten PV plants.

Plant	PV technology	A_{PV} (m^2)	P_{nom} (kW)	P_{act} (kW)	η_{PV} (%)	η_{INV} (%)
A	m-Si	11.2	2.03	1.93	18.1	93
B	p-Si	13.8	1.85	1.80	13.4	95
C	String ribbon Si	17.9	2.28	2.16	12.7	93
D	CIGS	17.5	1.68	1.67	9.6	95
E	CdTe	17.3	1.74	1.61	10.1	95
F	CIGS cylindrical	17.7	1.72	1.69	9.7	92
At	m-Si	11.2	2.03	1.93	18.1	93
Dt	CIGS	17.5	1.68	1.67	9.6	95
Et	CdTe	17.3	1.74	1.61	10.1	95
Gt	HCPV	11.0	1.60	1.55	22.0	92

capacitor [9]-[10] that acts as a load for each PV plant. The actual maximum power (P_{act} in Table 1) at Standard Test Conditions (STC) has been then estimated with an expanded uncertainty (coverage factor $k = 2$) of 2.5%.
The comparison among the performance of the ten PV plants is carried out through the parameter final yield (Y_f), which is obtained as:

$$Y_f = \frac{E_{tot}}{P_{act}} \tag{1}$$

where E_{tot} (kWh) is the total energy produced by a PV plant.

The long-term drift of PV modules is monitored through their efficiencies at STC:

$$\eta_{PV,STC} = \frac{P_{max,STC}}{G_{STC} \cdot A_{PV}} \tag{2}$$

where $P_{max,STC}$ is estimated by means of the simplified model (3):

$$P_{max,STC} = (I_m + I_{SC} \cdot e_G + \alpha \cdot Dt) \cdot \left[V_m + \beta \cdot Dt - R_S \cdot \left(I_{SC} \cdot e_G + \alpha \cdot Dt\right)\right] \tag{3}$$

where I_m (V_m) is the direct current (voltage) measured at temperature t_m and irradiance G_m, G_{STC} is the solar irradiance at STC (1 kW/m^2), R_S is the series resistance of the PV array, α (A/°C) and β (V/°C) are the absolute current and voltage temperature coefficients respectively, while the short-circuit current I_{SC} and the parameters e_G and Dt are obtained as:

$$I_{SC} = I_{SC,STC} \cdot \frac{G_m}{G_{STC}} \quad ; \quad e_G = \frac{G_{STC}}{G_m} - 1 \quad ; \quad Dt = t_{STC} - t_m \tag{4}$$

A. The monitoring system

The developed data-acquisition system allows the parameters defined in (1)-(4) to be estimated, being able to carry out, for each of the ten plants, the measurement of the quantities: direct voltage V_{dc} and current I_{dc} (upstream the inverter), alternate voltage V_{ac} and current I_{ac} (downstream the inverter), solar irradiance G_m on the plane of the PV modules and temperature t_m of a PV module. A model useful to estimate the main parameters of a photovoltaic panel under real working conditions is proposed in [5]-[6] and the preliminary investigation about accuracy of PV modelling under non-standard test conditions are reported in [7]. Details related to the architecture of the data-acquisition system can be found in [11], while the basics of its metrological management can be found in [12]-[13]. During the calibration of the system, which is performed with a periodicity of almost one year, the maximum admitted error of each measuring chain is verified, then the different chains are adjusted in order to compensate for offset and gain drifts. During the last two calibration sessions, which were carried out in June 2011 and September 2012, the monitoring system was conform to the expanded uncertainties (coverage factor $k = 2$) that are shown in Table 2.

Table 2. Expanded uncertainty of the measured quantities.

Quantity	Range	Expanded uncertainty (k=2)
V_{dc}	(100 ÷ 450) V	0.6 %
V_{ac}	230 V_{rms} @ 50 Hz	0.6 %
I_{dc}	(0.5 ÷ 6) A	0.6 %
I_{ac}	(0.5 ÷ 8) A_{rms}	0.6 %
G_m	(100 ÷ 1500) W/m^2	2.4 %
t_m	(-10 ÷ 80) °C	1.2 °C

III. Experimental results

The final yield Y_f estimated for the plants based on m-Si, CIGS and CdTe modules is shown in figure 1 for a time period of 25 months from December-2010 to December-2012. In the figure, the top left-side chart refers to the modules installed onto tracking systems (At, Dt, Et), while the top right-side chart refers to the same modules in fixed position. For each plant, two lines are depicted that correspond to lower and upper limits of the 95% confidence-level interval; such an interval has been estimated from equation (1) having a relative standard uncertainty of 0.45% for the quantity E_{tot} and of 1.25% for the quantity P_{act}. One should note that the obtained uncertainty allows the performance of different plants to be distinguished. Among the plants that employ fixed modules, the m-Si based plant (A) shows best performance with respect to thin-film based plants (D and E), thanks to its higher efficiency. The situation is different for plants based on tracking systems, since the plants Dt and Et show a higher energy production than the plant At. This is due to the greater temperature of PV modules on tracking systems, being them perpendicularly irradiated, and to the lower power temperature coefficient of thin-film modules with respect to Si modules. In the same figure, an anomalous behaviour of the plant At is

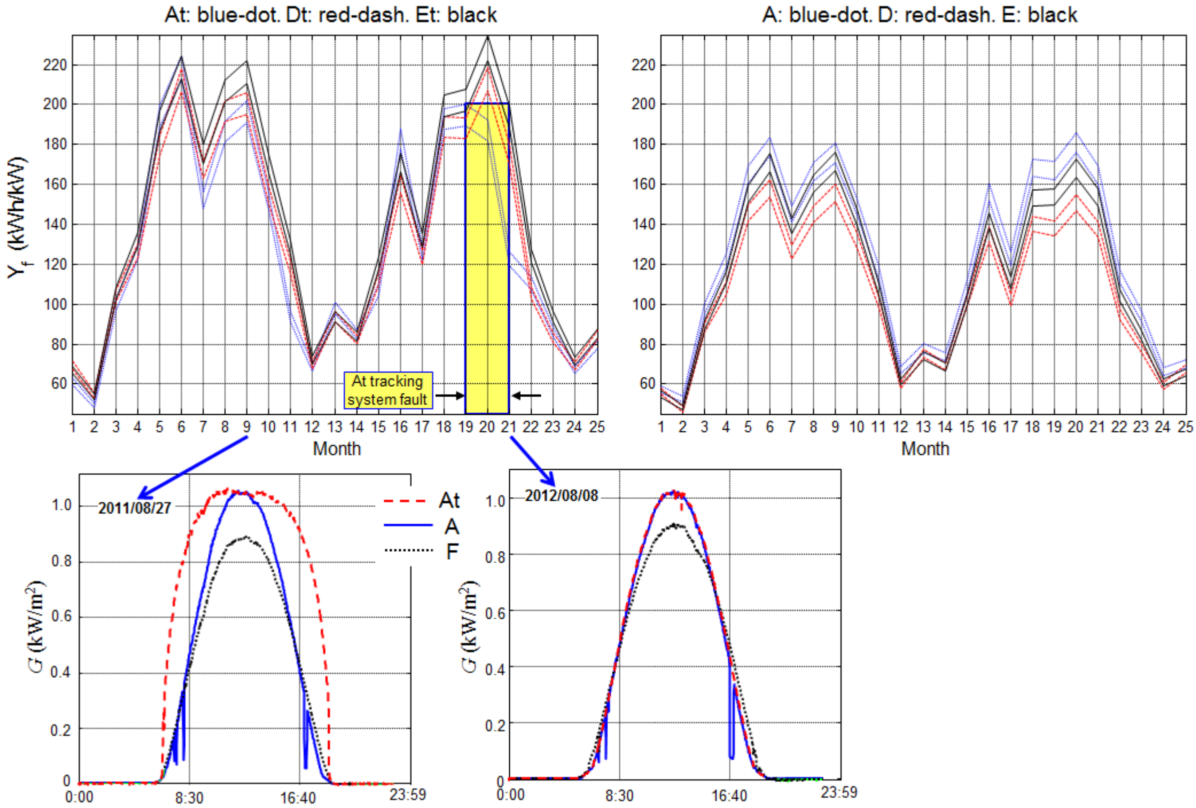

Figure 1. Final yield Y_f of the plants At, Dt ad Et (top left-side), A, D and E (top right-side) in the period from December 2010 to December 2012; the bottom charts show the measured irradiance on the horizontal plane (dot line), the tilted plane (continuous line) and the plane of tracking system (dashed line).

highlighted in the period June-August 2012, during which the energy production of this plant was of about 80% of the energy produced in the same period of the previous year. This was due to a fault of the corresponding tracking system, as shown in the bottom charts that report the irradiance on the PV modules on tracking systems (dashed line), tilted plane (continuous line) and horizontal plane (dot line) during a day when the tracking system was working (27 August 2011) and when the tracking system was positioned to a tilt angle of 35° (8 August 2012) awaiting for mending it. This situation suggests a further use of the developed monitoring system, which could act as an effective automatic diagnosis tool based on the comparison of the results estimated for the different PV plants.

The final yield (95% confidence-level interval) of all the monitored plants in the same 25-month period is shown in Table 3 in descending order. These results confirm that the plants that exhibit the best behaviour are Et among those mounted onto a tracking system and A among those with a fixed tilt angle, while the plant based on high concentration PV modules (Gt) is the worst because it is operative only in the presence of direct light. In addition, the plant Gt has shown a low availability due to frequent faults. Among the other plants, CIGS and m-Si modules onto tracking systems (Dt and At) seem to exhibit similar performance, since their intervals overlap and also considering the reduced production of the plant At due to the fault of its tracking system, as highlighted in Figure 1. String ribbon Si (C) and CdTe (E) fixed plants are almost equivalent but better than CIGS (D), p-Si (B) and CIGS cylindrical (F) modules.

The available data has been also used to estimate the long-term drift of PV-module efficiency in a 30-month period from October 2010 to April 2013. For this purpose, the efficiency $\eta_{PV,STC}$ of the first five plants (A, B, C, D, E) at STC has been estimated by means of equations (2) and (3), selecting a clear day per month and looking for the point (I_m, V_m) that corresponds to the maximum DC power P_{max}. This choice makes the error related to the use of the simplified model (2)-(3) negligible, since for almost all the months in a year the selected point corresponds to a measured irradiance G_m very similar to G_{STC}. In addition, the analysis of the uncertainty contributions related to the measured quantities I_m, V_m, G_m and t_m shows that the uncertainty of the estimated quantity $\eta_{PV,STC}$ is minimized when $G_m \approx G_{STC}$, i.e. when $e_G \approx 0$. The obtained results are summarized in Figure

Table 3. Y_f of the ten plants in the period from December 2010 to December 2012.

Plant	Y_f (h) 95% confidence level
Et	3308 ÷ 3492
Dt	3111 ÷ 3284
At	3012 ÷ 3180
A	2851 ÷ 3009
C	2708 ÷ 2858
E	2671 ÷ 2819
D	2491 ÷ 2630
B	2223 ÷ 2346
F	1615 ÷ 1704
Gt	683 ÷ 721

Table 4. Estimated drift of the efficiency of Si-based modules and CIGS thin-film modules.

Plant	η_{PV} drift	
	Absolute	Relative
A	-0.016/year	-0.09 %/year
B	-0.01/year	-0.08 %/year
C	-0.044/year	-0.37 %/year
D	-0.24/year	-2.6 %/year

2, where the thickness of the lines represent the 95% confidence interval of the STC efficiency of the first five plants. For Si-based modules (plants A, B and C), the initial estimated intervals include the nameplate efficiencies, while the plants based on CIGS thin-film modules (D) and CdTe thin-film modules (E) have never reached theirs nameplate efficiencies. On the other hand, the plant E does not exhibit a significant drift during the investigated 30-month period as the other plants do.

An estimation of the long-term drift of the efficiency of the PV modules A, B, C and D has been obtained by fitting the experimental data with a straight line using a least square algorithm. Figure 3 shows the obtained results: in each chart, the dots are the experimental efficiencies estimated every two months during the investigated period, the thick trace is the nameplate efficiency of each plant, the thin trace is the fitted straight line. The estimated drifts per year of the module efficiency, expressed as absolute values and as percentages of the initial efficiency, are reported in Table 4. The modules based on m-Si and p-Si technologies show the lower drifts (-0.09 %/year and -0.08 %/year respectively), that are almost a fourth of the drift of the modules based on string-ribbon Si technology (-0.37 %/year). A high drift has been instead obtained for CIGS thin-film modules (-2.6 %/year) that, if confirmed during next years, largely affects the expected producibility of this plant.

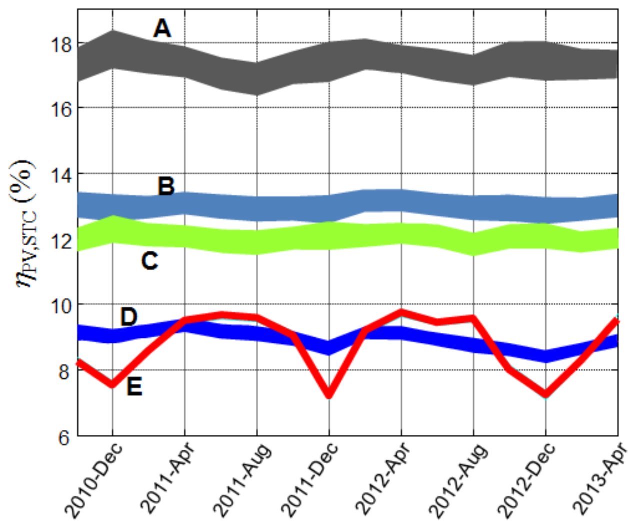

Figure 2. Efficiencies at STC of the PV plants A, B, C, D and E in the period from October 2010 to April 2013.

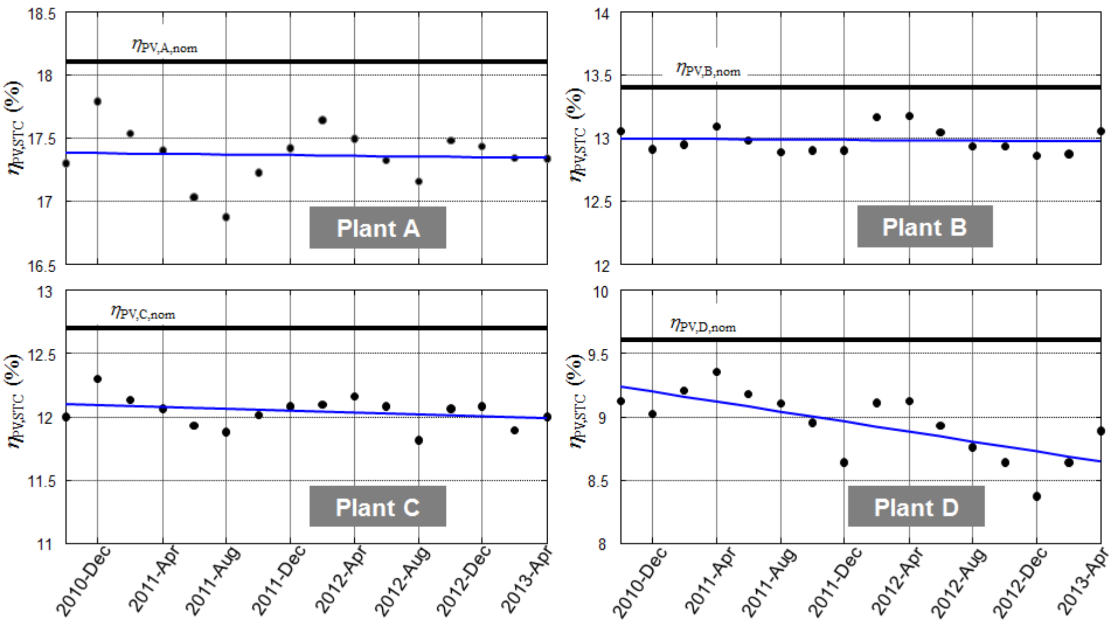

Figure 3. Efficiency drift of the PV plants A, B, C, and D in the period from October 2010 to April 2013.

IV. Conclusions

The developed data acquisition system allows the real-time monitoring of PV plants to be performed for both diagnosis and measuring purposes. The peculiarity of such a system with respect to commercial devices and other systems described in the literature is its metrological management, which assures the traceability of the obtained measurements and allows the uncertainty estimated for each measured quantity to be periodically verified. In addition, thanks to the periodical adjustment of the different measuring chains, offset and gain drifts are compensated, thus ensuring a suitable behaviour of the system along the long time-interval (more than ten years) during which the PV plants have to be monitored.

The obtained results, that refer to a period of thirty months, have given very useful information related to the in-field behaviour of different PV technologies and different plant architectures, which can be used in the design of a PV plant. Another valuable result is that related to the estimation of the efficiency drift of PV modules, which, according to authors' knowledge, is not available in the scientific literature. The obtained drifts, which will be consolidated during next years, are key factors in the estimation of the expected energy production of a PV plant, which mainly affects the estimation of the pay-back period.

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