Measurement 55 (2014) 641–649

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Uncertainty analysis of degradation parameters estimated in long-term monitoring of photovoltaic plants

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ARTICLE INFO

Article history:
Received 15 November 2013
Received in revised form 8 May 2014
Accepted 10 June 2014
Available online 21 June 2014

Keywords:
Electric variables measurement
Uncertainty
Calibration
Photovoltaic power systems
Data acquisition
Degradation

ABSTRACT

This paper deals with the uncertainty analysis of parameters estimated during long-term monitoring of photovoltaic plants. A specifically developed data-acquisition system is briefly described, which has been conceived to be easily calibrated and, if necessary, adjusted to compensate for measuring-chain drifts, in order to assure the traceability of the estimated parameters. The measurement capabilities of the acquisition system are reported in terms of measured quantities and expected uncertainty. Results that refer to a three-year monitoring of ten photovoltaic plants based on different technologies and architectures are reported. The obtained uncertainty is suitable to distinguish the behavior of the different plants, thus allowing a preliminary comparison to be performed among technologies and architectures. Experimental results highlight an important difference between crystalline silicon devices and thin film technologies in regards to degradation.

1. Introduction

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 energy produced by PV plants in these two countries reached significant figures of 5.57% for Germany with respect to an electricity consumption of 544 TWh/year and 5.75% for Italy with respect to a consumption of 335 TWh/year.

In this scenario, a suitable characterization and modeling of the photovoltaic modules is useful to predict the plant behavior in whatever working condition; several models proposed in literature produce results more or less accurate [2–4] and requires the translation of the electrical performance from standard test to outdoors conditions. In this case, the prediction of the photovoltaic plant behavior is obtained by hardware emulation and software simulations. The first approach is implemented by a power circuit, the second one identifies the mathematical model of the cell and of the module and requires the estimation of the equivalent circuit parameters. For both these methods, an interesting aspect is the capability to correctly simulate photovoltaic cells made with different technologies assuring low uncertainties [5,6]. The basic reason for these studies is to warrant a good investment payback time and a high efficiency of the plant. To this aim, a method for predicting the energy production of existing photovoltaic plants with different PV technologies has been previously proposed and validated by the authors [7].

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

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http://dx.doi.org/10.1016/j.measurement.2014.06.003

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 [8]. 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 [9–12] 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 3-years of results for different PV technologies, both the crystalline silicon and thin film ones.

2. Experimental set-up

2.1. Photovoltaic system under monitoring

The PhotoVoltaic (PV) system 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, the efficiency of PV modules (η_{PV}) and power inverters (η_{INV}), and the number N_{ser} of modules connected in series and the number N_{par} of strings connected in parallel. Six of the ten plants employ PV modules oriented towards South (azimuth angle $\gamma = 0°$) 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. The unique commercial technology not investigated in this work is the amorphous silicon, nevertheless it is well known, in literature, the progressive degradation during the first years of sun exposition [13].

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 capacitor [14–16] 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%.

2.2. Estimated parameters

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} (kW h) is the total energy produced by a PV plant.

The efficiencies of the PV modules at STC is obtained as:

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

where A_{MOD} is the area of each module and $P_{max,STC}$ is estimated by means of the simplified model [17] reported below:

$$P_{max,STC} = \left(\frac{I_{dc}}{N_{par}} + I_{SC,STC} \cdot k_G + \alpha \cdot D_\theta\right) \cdot \left[\frac{V_{dc}}{N_{ser}} + \beta \cdot D_\theta - R_S \cdot (I_{SC,STC} \cdot k_G + \alpha \cdot D_\theta)\right] \tag{3}$$

where I_{dc} (V_{dc}) is the direct current (voltage), which is measured for each PV plant at temperature θ_m and irradiance G_m, G_{STC} and $I_{SC,STC}$ are the solar irradiance and the short-circuit current at STC, R_S is the series resistance of the PV modules, α (A/°C) and β (V/°C) are the absolute current and voltage temperature coefficients respectively, while the parameters k_G and D_θ are obtained as:

$$k_G = 1 - \frac{G_m}{G_{STC}}; \; D_\theta = \theta_{STC} - \theta_m \tag{4}$$

One should note that the model (3) is valid under the assumption of negligible mismatch between the different modules and strings that made up each plant.

2.3. The monitoring system

The developed data-acquisition system allows the parameters defined in (1)–(4) to be estimated, being able

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} (%)	N_{ser}	N_{par}
A	m-Si	11.2	2.03	1.93	18.1	93	9	1
B	p-Si	13.8	1.85	1.80	13.4	95	10	1
C	String ribbon Si	17.9	2.28	2.16	12.7	93	12	1
D	CIGS	17.5	1.68	1.67	9.60	95	12	2
E	CdTe	17.3	1.74	1.61	10.1	95	6	4
F	CIGS cylindrical	17.7	1.72	1.69	9.70	92		
At	m-Si	11.2	2.03	1.95	18.1	93	9	1
Dt	CIGS	17.5	1.68	1.66	9.60	95	12	2
Et	CdTe	17.3	1.74	1.61	10.1	95	6	4
Gt	HCPV	11.0	1.60	1.55	22.0	92		