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Comparative performance analysis of grid-connected photovoltaic system by use of existing performance models

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ABSTRACT

Performance analysis of real world efficiency of photovoltaic installations is proven to be a challenging task, as demonstrated by the processing of data from monitoring operation of a photovoltaic park for a period of 3 years. It is important to establish a procedure which evaluates the photovoltaic plant performance based on real world system monitoring data. The role of air mass and clearness index variations in this context is well established and the analysis is conducted with the aid of these factors. The analysis has three main objectives: (i) the evaluation of three existing models, (ii) performance ratio calculation and (iii) the formulation of an evaluation procedure based on normalization to Standard Reporting Conditions. Processing of the monitoring data reveals significant scatter in normalized efficiency. A 10% fluctuation in yearly energy production is observed in the period 2013–2015. It is important to analyze this fluctuation in order to shed light to the reasons behind this fact. Performance ratio analysis, normalization procedure and models comparison, point to a decrease in PV panel's efficiency from the first year of operation. However, this is a small decrease covered by the terms of the manufacturer's warranty. Application of the proposed procedure to the analysis of data from older installations is expected to improve understanding and assessment of aging effects in the PV panels.

1. Introduction and literature review

PV systems' installations in Greece expanded significantly during the last decade, profiting from the favorable feed-in tariff legislation. This includes not only PV park installations (2093 MWp total) but also building-top installations (351 MWp total) [1]. Significant growth rates were observed until the end of 2013, when a correction of the legislated feed-in tariff was initiated. During the last three years, PV market priorities are shifting to net-metering, recently legislated in Greece, as well as to the maintenance and performance monitoring of existing PV parks. Due to the decrease in tariffs, depreciation of the investment cost of a PV park in a sensible period of time requires electricity production with no significant deviations below the nominal production, which determined the initial sizing of the park, based on the expected average irradiance levels for its location. Factors that are able to decrease energy production are described below: Grid faults of grid that most of the times happened because of PPC grid faults. PV panel's degradation (corrosion, discoloration, delamination breakage and cracking cells) [2]. Faults of this category are not readily diagnosed. PID- affected cells is a common problem in cases with transformer-less inverters, that could lead to significant decrease in energy production. Dust effects could be also a problem for particular locations, reported to cause up to 6.5% reduction in urban areas according to a specific study [3]. Power loss due to partial shading and dust accumulation were investigated in a desert environment [4]. These problems can be avoided by optical inspections, monitoring, I-V measurements and IR thermography [5]. The respective standards and guidelines are discussed in [6].

The above facts point to the importance of a monitoring system that would cooperate with a mathematical model to diagnose faults in time, allowing the timely solution of the problems. The system should operate with a grid connected PV park, without loss in energy production. Such a monitoring system is also important in evaluating conformance to the terms of manufacturer's warranty. Most manufacturers' warranties terms allow for a degradation of power output to 90% for the first 10 years and 80% for 25 years. The power output of every PV panel is defined and tested at STC Conditions (1000 W/m^2, 25 °C PV panel temperature, AM1.5 spectrum) and NOCT (800 W/m^2, 20° ambient temperature, 1 m/s wind speed) conditions. Performance at these conditions allows measurement comparisons between different laboratories and different PV modules however it is not representative for outdoor conditions [8]. Thus, manufacturers data do not define the expected energy production of PV panels production under real insolation conditions [9]. The correlation of irradiance and panel temperature effects is feasible because of the existence of many

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Nomenclature

AM	optical path in air [relative air mass]
a	temperature coefficient of P [%/°C]
E	energy production [kWh]
E_t	equation of time
G	measured irradiance [W/m^2]
G_{STC}	irradiance at standard test conditions 1000 W/m^2
G_0	extra-terrestrial solar intensity 1367 [W/m^2]
k	irradiance factor []
K_t	clearness index []
L_{LOC}	geographic longitude
L_{STD}	time-zone of the location
P_{AC}	measured AC power [W]
P_{DC}	computed DC power [W]
P_{STC}	maximum DC power on STC [W]
P_{DC25}	DC power normalized at 25 °C [W]
T_C	module temperature [°C]
T_a	ambient temperature [°C]
A	photovoltaic panel surface area [m^2]
t_{SOL}	solar time
t_{STD}	standard time
WS	wind speed
Y_f	system yield [kWh/kWp]
Y_r	reference system yield [kWh/kWp]
f_{PV}	photovoltaic panel derate factor
f_{DC}	DC power derate factor
f_{AC}	AC interconnection factor
f_{AGE}	age derate factor
f_{EXT}	external derate factor

Greek symbols

a_s	solar altitude angle [°]
β	slope of photovoltaic surface [°]
γ	solar azimuth surface [°]
γ_s	solar azimuth of sun [°]
δ	declination angle [°]
η_{INV}	inverter efficiency [%]
η_{PV}	array performance [%]
η_{STC}	PV array performance on STC [%]
η_{DC25}	PV array performance normalized at 25
θ_z	solar zenith angle [°]
φ	latitude
ω	hour angle

Abbreviations

AM	Airmass
AM	1.5 Airmass 1.5 spectrum
AOI	Angle of Incidence
CF	Capacity Factor
IV	Current-Voltage Curve
EN	European Norm
MPP	Maximum Power Point
NOCT	Normal Operating Cell Temperature
PID	Potential Induced Degradation
PPC	Public Power Corporation
PV	Photovoltaic
STC	Standard Test Conditions
PR	Performance Ratio

mathematical models and adequate technical data from manufacturers. Especially, there are several correlations for panel temperature for various applications, so it is important to choose the most suitable for each case [10]. However, checking the third parameter, namely STC conditions performance, is a challenging task, as it involves spectral measurements and information about spectral response of PV panels, something that is not always provided in technical datasheets. Tian et al. discuss the effect of spectral distribution of irradiance, especially in urban areas [11].

There are several models and methods of PV performance analysis in recent literature. The differences between models are related to the kind of input parameters, types of measurement equipment and type of operation, grid-connected or not. There exist three main categories for evaluation and prediction of PV performance: (i) based on real time operation data, (ii) based on off-grid measurements, and (iii) based on simulation.

As far as simulation is concerned, several studies can be found in the literature. Cuce et al. proposed a mathematical model to simulate I-V and P-V curves, to be compared with manufacturers performance [12]. Gupta et al. created a model to simulate PV performance under varying real time climatic conditions: irradiation level, wind speed, temperature, humidity level and dust accumulation [13].

Many researchers studied the performance of PV systems conducting off-grid measurements under outdoor conditions, e.g. I-V curves. Gaglia et al. conducted off-grid measurements in order to compare outdoor operating conditions with laboratory STC conditions. Significant deviations have been found [14]. Bouraiou et al. created an experimental set up and carried out measurements in order to study the effect of climatic conditions on a desert environment and particularly the effect of partial shading and deposition of sand. The evaluation of measurements was based on I-V and P-V characteristics [4]. Guenounou et al. conducted off-grid measurements to compare yearly performance of four different PV modules in a coastal region of Algeria. The experimental data when normalized to STC conditions and results showed significant deviations of STC values from measurements [15].

Further, there exist models based on infrared thermography during on–grid operation. Overheating of PV modules is an important factor that decreases system's efficiency. Aste et al. proposed the use of infrared cameras to identify systems' failure in building integrated systems in Italy [16]. Another study examined failures and PID – affected cells in grid-connected photovoltaic systems [5]. In that context, Kaden et al. proposed a model that assesses power loss based on the IR images of panels [17].

Another analysis approach at outdoor conditions and on grid operation was applied to a PV system in Northern Italy. Micheli et al., proposed a procedure to convert the actual performance of the system to standard conditions, based on the filtering of data with respect to incidence angle and AM values, calculation of temperature coefficients and normalization of the data on STC values [18].

An important performance index for a PV park is the performance ratio (PR), which is the global system efficiency with respect to the nominal installed power. Monitoring of PR of a grid-connected system correct underperforming system and reduces economic losses due to operational problems [19]. PR values are typically reported on a monthly or yearly basis. Aste et al., used PR in order to compare different types of PV technologies and the analysis is conducted in seasonal basis in order to correlate performance with climate conditions [16]. The comparison of yearly PR allows for an indicative assessment of PV park performance, although it does not account for the effect of panel temperatures and the existence of possible periods with the park disconnected from the grid. Nevertheless, PR ratio is useful to identify problems as faults in inverter operation, shading, diode failures and soiling [20]. PR was introduced by the JRC (European Joint Research Center) in order to facilitate comparisons between several PV installations and adopted by many researchers. It is described in the IEC EN 61724 standard [6]. It can be seen as the ratio of parameters Y_f and Y_r