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Development of a software application to evaluate the performance and energy losses of grid-connected photovoltaic systems

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ABSTRACT

The aim of this paper was to design and develop a software application that enables users to perform an automated analysis of data from the monitoring of grid-connected photovoltaic (PV) systems. This application integrates data from all devices already in operation such as environmental sensors, inverters and meters, which record information on typical PV installations. This required the development of a Relational Database Management System (RDBMS), consisting of a series of linked databases, enabling all PV system information to be stored; and a software, called *S·lar*, which enables all information from the monitoring to be automatically migrated to the database as well as determining some standard magnitudes related to performances and losses of PV installation components at different time scales. A visualization tool, which is both graphical and numerical, makes access to all of the information be a simple task. Moreover, the application enables relationships between parameters and/or magnitudes to be easily established. Furthermore, it can perform a preliminary analysis of the influence of PV installations on the distribution grids where the produced electricity is injected. The operation of such a software application was implemented by performing the analysis of two grid-connected PV installations located in Andalusia, Spain, via data monitoring therein. The monitoring took place from January 2011 to May 2012.

1. Introduction

Within the framework of renewable energy, solar photovoltaic energy (PVE) stands out as having undergone one of the greatest technological developments. Also, it offers the greatest potential for being competitive in the market. In late 2012, 31.1 GW of PVE were installed worldwide, making the worlds cumulative PV capacity greater than 100 GW. Therefore, in terms of installed global capacity, PVE has been consolidated as the third largest source of renewable energy after hydro and wind, even in the current economic and financial crisis. Europe is still the world leader in PVE electricity generation and for the second year running it has been the largest new source of installed generation [1]. In markets outside Europe, such as China, Japan or the USA, the percentage of installed power is still very small compared with their enormous potential. Moreover, there are large parts of Africa, Middle East, Southeast Asia or Latin America where this type of installations are only now beginning to be developed.

The opportunities for improvement in this sector are based not only on the development of installed capacity, but also upon the necessity to meet the challenges of technological improvements that will reduce generation costs. 50% of investments in I + D in this field are aimed at improving the efficiency of the installations [2]. In general terms, research is focused on improving production processes in developing new materials [3,4]; increasing long-term stability of PV cells and modules; constructing new facility configurations [5], or improving the performance and the better use of existing technologies which still function below their expected values [6–9]. If the installed power of these types of installations keeps increasing, a small improvement in performance percentage would lead to a significant net improvement in production. This is turn would reduce the net costs that these facilities need in order to improve their competitiveness with respect to other modes of power generation, this latter being the main priority of the Strategic European Photovoltaic Research Agency [2].

In the literature many authors have analyzed the performance of grid-connected PV systems in different locations and with different characteristics [10–23]. Numerous authors have also verified that, over time, the performance of the facilities decreases due to the degradation of all of their components [11,17,26–28]. Authors like Eltawil and Zhao [24] or Fekete et al. [25] have also analyzed the potential problems arising from the growth in grid-connected photovoltaic systems and the most common failures that occur in this type of facility. Moreover, Strobel et al. [6] showed that characterizing the present margins under which each PV installation operates,

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can facilitate predictive maintenance, resulting in a greater number of operating hours and the consequent increase in profitability. As indicated by Chouder and Silvestre [29], the significant growth of grid-connected PV systems has not been accompanied by the implementation of resources for diagnosis, monitoring and fault detection at the PV facility. These authors indicate that most plants operating today, especially those below 25 kWp power, do so without any supervision mechanism, despite the great importance of having effective failure control.

An exhaustive supervision of the behavior of a PV plant requires, firstly, the presence of a system for monitoring the operating parameters of the various devices that comprise it. In the installations already in operation, most inverters themselves, aided by some additional sensors, can mainly perform this task without posing a significant additional economic cost in investment. However, such a monitoring system would also require an application to process easily and automatically the large volume of data recorded, a task that could not otherwise be addressed by the staff of the small companies engaged in PV plant installation or maintenance. To date, the treatment of all of this information has been carried out primarily in research centers or by large companies. Therefore, and at present, only a very small number of the many facilities currently in service undertake a detailed analysis of the functioning of their components, beyond that of measuring the total energy generated. Furthermore it should be pointed out that most of the above-referenced authors do not make any exclusive reference to how they have treated the data gathered from monitoring the installations studied.

As a consequence, the objective of this work was to develop and implement a software application, called *S·lar*, that enables an automated data analysis of grid-connected PV systems which could be performed, while also integrating data from all of the devices that record information in the installation. This includes such devices as environmental sensors, inverters and meters. The application is intended to be sufficiently flexible in order to analyze installations with different characteristics, configurations and components (modules and inverters), from different manufacturers and with different technical specifications.

Tsankov [30], Fernández-Pacheco et al. [31] and Gagliarducci et al. [32] have already developed software applications to analyze parameters from PV installations. Moreover, several companies already commercialize such software [33]. What differentiates the application developed in this paper, however, is that it provides a greater amount of information when analyzing PV plants. In addition to determining the total power or energy generated by the PV installation, or its PR value, *S·lar* software enables a more comprehensive and detailed study of the operation of the plant to be performed, determining the value of different performance and loss rates corresponding to systeḿs components, for different time scales, with the aim of facilitating its management and maintenance. The application also makes easier to undertake a preliminary analysis of the installation's influence on the distribution grids – one of the current areas of study in this field [34]. The objective was for *S·lar* to be used by small companies with installations already in operation, taking advantage of their existing equipment. Moreover, it can also support the work of scientific research, thanks to its versatility in obtaining relationships between parameters and magnitudes. The operation of *S·lar* was implemented analyzing two grid-connected PV systems located in Andalusia, Spain.

2. Characterization of grid-connected photovoltaic systems

2.1. Technical specifications of photovoltaic system components

In a grid-connected PV system the electricity produced during the sunlight hours is directly injected, online, into the conventional low (LV) or medium voltage (MV) distribution grids [35]. The main components of these types of installations are the PV modules, connected in strings; the inverters, in charge of transforming the DC power produced by the PV modules to power grid characteristics; and the power meter, installed by the electricity supply company, which measures the energy injected into the grid.

Each PV plant will be equipped with different PV modules with distinct specifications, e.g., material, area, performance, tolerance, temperature coefficient, nominal operating cell temperature (NOCT), nominal power, open circuit voltage, short circuit current, voltage and current for maximum power. In each PV installation, modules will be connected with different architectures (schemes), so that each inverter will receive the power generated from a different number of PV panels. Inverters may be of different models or manufacturers, so they may have distinct input and output characteristics, such as nominal power, maximum power, efficiency or Maximum Power Point (MPP).

A key aspect is that before undertaking the study of a particular PV system, its configuration and equipment must be perfectly characterized. All of this information must be available to the computer application which will be used to analyze its behavior.

2.2. Monitoring a grid-connected PV system

Monitoring PV installations is regulated by European standard UNE-EN 61724:1998, "Monitoring of photovoltaic systems – Guidelines for measurement, data exchange and analysis" [36], which requires them to know the behavior of all their components, indicating which basic parameters must be monitored and under what conditions. Previous to this standard there were some documents prepared by the JRC (Ispra, Italy) called "Guidelines for the Assessment of Photovoltaic Plants", separated into two documents, Document A, "Photovoltaic System Monitoring" (EUR 16338 EN) [37] and Document B, "Analysis Presentation of Monitoring Data" (EUR 16339 EN) [38].

As already noted, in much of the grid-connected PV installations already in operation, monitoring is carried out via their inverter equipment. The parameters which they usually monitor are shown in Table 1. However, in practice not all inverter models monitor all of these parameters, and obviously each manufacturer or, indeed, each model can use a different notation for each of the parameters – even to the point of using different measurement units for the same magnitude.

Table 1
Magnitudes generally measured by inverters.

Magnitude	Notation
DC current from PV modules	I_{DC}
Current from each string	I_{strg}
Inverter input DC voltage from PV modules	V_{DC}
Inverter input DC power from generator	P_{DC}
Inverter output AC power	P_{AC}
Inverter output total energy	E_{AC}
AC current injected into the grid	I_{AC}
Grid current	I_{grid}
Grid AC phase voltage	V_{AC}
Grid frequency	f_{grid}
Grid impedance	Z_{grid}
Inverter operating status	Status
Error code (where appropriate)	Error
Number of times that the inverter finds the MPP	n_{MPP}
Inverter working total hours	h_{on}
Grid injecting total hours	h_{on_grid}
Total connections to the grid	n_{on_grid}
Installation boot-up number	n_b
Boot-up time	h_b
Inverter operating temperature	T_{inv}
Isolation resistance	R_{isol}