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Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino™ that complies with IEC standards

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ABSTRACT

A new data logger using the Arduino open-source electronic platform was developed to solve the current problem of monitoring photovoltaic (PV) systems at low-cost, especially in remote areas or regions in developing countries. The data logger meets all of the relevant requirements in terms of accuracy included in the International Electrotechnical Commission (IEC) standards for PV systems, with a resolution of 18-bits, including 8 analogue inputs for measuring up to 8 PV modules and/or weather sensors, 3 inputs for low-cost analogue temperature sensors and virtually unlimited inputs for digital temperature sensors. The new data logger is completely autonomous, and the prototype has achieved an initial cost of only 60 €. It was tested during a 6-month period under the harsh environmental conditions of the summer and winter in Southern Spain. The results using both the sensors and silicon reference cells indicate that the new system is reliable and exhibits comparable performance to commercial systems. This data logger is of special interest for both solar energy research and applications in developing countries, as it is both open-source and flexible. The data logger can be customised for the specific needs of each project at low-cost. The details of the specific design and its implementation are described.

1. Introduction

PV monitoring systems usually require a vast number of parameters to be recorded: temperatures, irradiances, voltages, currents, etc. Such PV monitoring systems are used in research applications that require the monitoring of all cell temperatures of a PV module or in PV installations requiring multiple monitoring systems for an extended network, such as in a number of small solar home systems or medium-size PV plants in developing countries. However, the data collecting devices, commonly known as data loggers, are too expensive, demand special software (with increased cost and requiring additional specific skills), and require a power supply or a PC to be connected all of the time. In addition, typical data loggers do not match the type of sensors to be measured well with regard to accuracy, insufficient number of input channels, or inadequate input channels for the connection of specific sensors, such as in the case of thermocouples or digital sensors. These problems and limitations, both in terms of cost and technological capabilities, led us to design and develop a new data logger capable of monitoring PV systems at low-cost and with a flexible design. The main objective was to develop a data logger with the following characteristics: (a) low-cost, using easily obtained hardware and free software; (b) autonomous operation with low energy consumption and not dependent on a computer or access to a power grid; (c) easy-to-build and handle; (d) high accuracy and meeting International Electrotechnical Commission (IEC) standards (specifically IEC61724 [1] and its normative references); (e) efficient data acquisition; (f) data-file creation capability; (g) robust when used in a harsh environment (i.e., outdoors); and (h) flexibility to be easily adapted to different PV applications by implementing a few changes (for example, allowing the number and type of input channels to be modified).

1.1. Prior work on data loggers for PV monitoring

The fast evolution of renewable energy technologies during the last several years has led to the installation of many systems all over the world. However, most of these technologies have not yet achieved full-development. The costs of renewable energy technologies have not yet

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dropped sufficiently so that grid parity is universally achieved without subsidies. There is still a margin for technology improvement and cost reduction. In the particular case of photovoltaic systems, detailed knowledge of the meteorological data for the location where the system will be installed is desirable, as well as a full monitoring of the PV system performance [2]. On the one hand, it is possible to find reliable meteorological data for a given location due to data collected by National or European institutions [3–5]; this information can be used to obtain general knowledge of the conditions, but this cannot replace the specific data taken on-site. On the other hand, there are many locations where these databases are not available or they are in the process of being collected. A wide range of commercial data loggers for climate monitoring is available, but they are expensive, highly sophisticated and cannot be easily managed. As a result, further development of data-acquisition systems is required to collect and process such meteorological data in addition to monitoring the performance of PV systems under operation, under the premise of obtaining the measured parameters using accurate, easy-to-handle and low-cost systems.

The literature includes numerous reports of such systems during the last several years. One of the first systems developed for on-site measurements of PV array characteristics and PV monitoring systems, enabling the collection, analysis and presentation of operational data, was conducted by Blaesser [2], where the data acquisition equipment was rather expensive (over 10% of the system cost). Because the prices for data acquisition hardware have decreased more rapidly than the prices of PV systems, analytical monitoring has been gradually applied to small PV installations. One of the first attempts to design low-cost hardware for solar radiation monitoring and then for environmental monitoring was developed by Mukaro et al. [6] and [7]. The system was designed around an 8-bit microcontroller that managed an analogue-digital converter (ADC) and stored data in a serial EEPROM until uploaded to a portable computer. Because of an improvement stage, 4 analogue inputs were available under limited uncertainty. The data were sampled and stored in 10-min intervals; and the power consumption was minimised by keeping the microcontroller in a low-power mode between intervals because the data acquisition system was powered by a rechargeable battery. This system was well suited for monitoring meteorological or environmental parameters at remote stations, particularly in developing countries, and one of its subsequent uses was analysed in Mukaro and Tinarwo [8]. One operator with one laptop is all that was required to collect the acquired data from the systems scattered around an area of interest. Another effort to develop an integrated data-acquisition system for renewable energy sources was reported by Koutroulis and Kalaitzakis [9]. The main disadvantages of this system were the dependence on a PC, the use of commercial software (Labview™), and the requirement of a power grid supply, which increased the price of the system and limited its spread and use. More designs based on microcontrollers can be found in the literature, but some of them use a low resolution ADC attached to an amplifier stage, which defines every input to a specific sensor [10,11], while others depend on a PC [11–14], commercial software [15,16], or do not follow IEC standards to manage accuracy or obtain data, which offset the achievement of low cost, portability and low power consumption, among other advantages [17,18].

With this background and under the current technical development, our approach for a low-cost data logger serves different basic purposes, as mentioned earlier, e.g., because it is supported by free hardware and software, its design is accessible to everybody. This public access facilitates rapid and continuous development. In addition, due to the flexibility of adapting the new data logger design for PV monitoring to each specific case (both research and industrial applications in developed and developing regions), the proposed data logger can enable the PV community to advance faster in some of the research areas that have been in need of full PV monitoring but have been limited by cost and technology issues.

This paper presents the design of the novel low-cost data logger for PV monitoring, discussing first the fundamentals of portable data acquisition in photovoltaic systems and reviewing the main photovoltaic parameters that must be measured, with special emphasis on their accuracy or uncertainties under the IEC61724 standard. The design of the data logger is then presented, including the modular diagram configuration offered by the use of free software and hardware, i.e., a microcontroller unit (MCU) and modules of acquisition, storage, etc., and all of the components used in the manufacturing of the data logger are described thoroughly. Next, the initial characterisation results, including a comparison with the results from a commercial system and the IEC tests, are shown in the electronic Supplementary Materials attached to this manuscript. The testing period performance (over 6 months) under harsh environmental conditions is discussed with different experimental setups, specifically calibrating the PV cells, monitoring a stand-alone PV system, and monitoring a small grid-connected PV system. Finally, a cost analysis and the amount of energy consumption of the data logger are presented.

2. Portable data acquisition requirements in photovoltaic systems

Portable data acquisition applications must meet a number of strict requirements that are not present in traditional laboratory systems. These systems are used in harsh environments that must be considered when selecting this type of equipment, such as extreme temperatures, humidity, dust, shock and vibration. For example, in photovoltaic applications, equipment must withstand temperature ranges that vary between -40 °C and $+85$ °C for PV modules in the worst case [19]. Other concerns include whether this equipment is capable of supporting the mix of the particular sensors that will be used, as well as if there is adequate memory/storage to support the test. Invariably, the accuracy of field measurements is highly dependent upon the sensors being used. For most sensors that have been calibrated in the laboratory and installed in the field, accuracies in the range of 0.01–1% of full scale are typical. Signal conditioning, such as gain and filtering, and the data acquisition sampling speed are other important considerations when determining the accuracy of the system.

Ideally, remote data acquisition systems are typically standalone instruments that, once they are set-up, can measure, record and display data without operator or computer intervention. These systems are able to receive data from multiple inputs, feature built-in signal conditioning and can simultaneously record data from a variety of different sensors. These systems must be compact, light-weight units that can be powered using two different configurations. The first is using a battery pack, and the second is to run an external wire to a DC power supply. To conserve power, users with minimal processing requirements can select a lower range processor and pair it with a high-end storage system to prevent the selection of a processor with capabilities beyond those that are necessary. These systems are left to operate unattended for days or possibly years at a time and can have communication capabilities using telephone connection or wireless systems for downloading data to remote computers, large amounts of built-in storage, and user interfaces for remote setup and control of the device.

These powerful yet compact data acquisition devices play an important role in the verification testing and monitoring of critical systems, and selecting the appropriate device for a given application requires careful consideration. In our case, the design will be