A Novel Wireless Self-powered Microcontroller-based Monitoring Circuit for Photovoltaic Panels in Grid-connected Systems


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Abstract - A monitoring circuit for individual photovoltaic (PV) panels in grid-connected systems is proposed, which exhibits a number of features devised to simplify and reduce cost of diagnostics and maintenance of the PV plant. In particular, the system is provided with an effective energy harvesting supply stage, which eliminates the requirement for external supply or batteries; furthermore, no cables are needed for data transfer due to the adoption of a rugged wireless connectivity.

Index Terms - Energy harvesting, monitoring system, photovoltaic panel, supercapacitor

I. INTRODUCTION

Monitoring of PV plants to quantify the energy yield and detect failures has assumed a relevant role in recent years. Various monitoring solutions have been indeed presented in literature in order to identify the reasons leading to efficiency losses. In [1], some environmental variables and the I–V curves of the PV plant are evaluated; in [2], the energy conversion is maximized by means of a PV panel incorporating a DC-DC converter with an integrated maximum power point tracker (MPPT). However, the proposed circuits are quite complex and often require a cumbersome installation: in [1], additional cables are needed for data transmission and supply distribution over the PV plant; in [2], every panel is provided with a power stage (boost converter) and power line communications (PLC), which reduce the system performance in terms of reliability and working life. Satellite-based monitoring systems have been also developed to identify power outages [3]. However, their application is unavoidably limited to satellite-observed PV plants. Unfortunately, none of the above solutions allow the monitoring of individual panels embedded in grid-connected PV systems, which – accordingly to recent studies [4] – contribute to 15% of the failure cases.

In this paper, a novel system allowing for a single-panel-granularity monitoring is proposed as an attempt to tackle and solve the above shortcomings. The circuit is equipped by a suitable energy harvesting supply stage relying on supercapacitors, which makes the whole system self-powered. For the first time, cabling is avoided by exploiting a rugged wireless communication to transfer the data measured on the individual panel.

II. THE MONITORING CIRCUIT

The proposed monitoring circuit, whose schematic block diagram and PCB prototype are illustrated in Figs. 1 and 2, respectively, can be described as follows.

A. The supply stage

The supply is provided by the monitored panel through an energy harvesting stage, which generates the requested voltages (i.e., 3.3 V for the logic unit and 12 V for the measurement circuit). The supply strategy is based on the adoption of supercapacitors, which are typically preferred to electrochemical batteries in energy harvesting applications (as in e.g., wireless sensors [5], [6]) due to the longer working life [7], [8] (i.e., number of discharge/charge cycles), lower cost and size, higher efficiency, and faster/simpler charging. In the developed prototype, two supercapacitors are employed to operate as back-up energy storage elements (a) during the measurement stage and (b) in low-light hours (i.e., in low solar irradiation conditions). The supply circuit involves two sub-networks, which can be addressed as follows.

The first one is devised to charge the supercapacitors by deriving current from the panel. In previous works [5], [6], [9], this portion is realized through a custom DC-DC converter with a dedicated MPPT to adjust the operating point of the panel accordingly to the energy requirements of the overall circuit. Unfortunately, such a strategy is not suited for energy production applications, in which the operating point must not be affected by the supply circuit. In order to tackle this issue, we conceived and designed an ad hoc charge network, which relies on a “feedback” monitoring action on the voltage drop across the supercapacitors (in particular, such a network automatically starts charging the capacitor as the voltage drop is lower than a threshold value). This strategy – differently from the approach employed in [5], [6], [9] – prevents modifying the operating point of the panel due to the relatively small amount of current derived. In particular, the charge network absorbs 60 mA only during the startup phase (i.e., when the circuit is installed) and, more in general, at each dawn, in order to guarantee a fast circuit switching on, while deriving about 20 mA during the standard behavior. The charge network is fully deactivated by the control logic during the measurement...
stage in order not to affect the accuracy of results.

The second one is intended to generate the requested voltages starting from the voltage drop across the supercapacitors and is realized with integrated DC-DC step up converters, which are commonly used in energy harvesting applications [5], [6] due to their high efficiency.

C. The disconnection circuit

This section is devoted to disconnect the panel from the string while concurrently bypassing it not to inhibit the energy production of the whole string during the measurement stage. The circuit is implemented with semiconductor devices, which are preferred to electro-mechanical relays due to higher reliability (i.e., number of on/off operation), smaller size, higher speed, and simpler integration in small electronic PCB.

D. The measurement circuit

This circuit is devised to connect the PV panel to two loads, which lead to open- and short-circuit conditions, respectively, in order to measure Voc and Isc. The impedance matching between the measurement circuit and the MCU ADC is ensured by proper analog conditioning interfaces (buffer stages).

E. The wireless communication

The wireless communication – employed for the first time to allow the monitoring of an individual panel – is based on the Microchip MiWi protocol [10] (IEEE 802.15.4 compliant, 2.4 GHz frequency) and is implemented with a MRF24J40MA transceiver (up to 400 ft range, throughput 250 kbps), which is fully compatible with the adopted MCU and allows low power consumption (typically 19 mA in RX, 23 mA in TX, 2 μA in sleep [11]). The wireless network is configured as a star topology: only one coordinator (i.e., the remote station) starts and organizes the network, while the end devices (i.e., the monitoring circuits) communicate only with it. In the network each monitoring circuit is univocally identified with its own address, which is assigned when the firmware is programmed on MCU: this significantly simplifies the operations of maintenance since the single malfunctioning PV panel is immediately detected also in large solar plant, thereby avoiding the need of an in-situ inspection. The network coordinator stores a data structure called Network Table, which contains the information about the end devices (e.g., address, status, network ID); it also sends requests to the end devices in polling mode and collects the data received from them. Over the network, the data are exchanged through packets referred to as Reports. In our network, we implemented three types of Report: (1) measurement request; (2) measurement results; (3) software reset. When the coordinator sends the Report type (1) to the monitoring circuit, this executes the aforementioned 6 steps (see Section II-B) and then replies with the Report type (2), that contains in its payload the measured (averaged) Voc and Isc. The Report type (3) is useful to remotely reset the monitoring circuit firmware in case of software failures.

F. The MCU firmware

The MCU firmware, which manages all the functions of the monitoring circuit, was developed by exploiting the available power management capabilities in order to minimize the current consumption of the devices, which represents a critical parameter in wireless sensor design [7], [8]. In particular, the sleep mode of MCU and
transceiver is widely adopted; such a functionality allows suitably stopping the clock sources of the related devices, so that only leakage currents are absorbed from supply (down to 100 nA for MCU, depending on the active peripherals). The MCU is periodically awaken from sleep mode by the watch dog timer; during the standard operating behavior, the MCU in turn awakes the transceiver and executes the code until the following sleep mode is activated. Since during the sleep mode the monitoring circuit is not allowed to receive data, the coordinator holds in its output buffer the packets addressed to not-ready devices, and discards them only if a prescribed timeout occurs.

The firmware structure – the schematic flow chart of which is represented in Fig. 3 – can be described as follows: (1) at start up, the MCU initializes the hardware, properly setting the I/O pins connected to the circuit; (2) the wireless protocol stack is initialized; (3) the MCU researches the wireless network and then joins it (it is programmed to make an assigned number of research and join attempts); (4) if the circuit is member of the network, the MCU checks for incoming reports; in case of data request reception, the 6 steps detailed in Section II-B are executed (during this phase, the transceiver is deactivated to minimize power consumption) and then information on measured data is sent to the remote station; MCU and transceiver (5) enter and subsequently (6) exit the sleep mode; then the firmware restarts from (4), checking for pending data.

III. EXPERIMENTAL RESULTS

The measurements were carried out by employing the experimental set-up depicted in Fig. 4. The monitoring circuit was applied to one 50-Wp PV module of a 10-panel string mounted on the rooftop of the DIBET in Naples. The remote station is represented by a PC equipped with (1) a Matlab code that allows acquiring, storing for subsequent analysis, and displaying the measured data; (2) a Microchip PICDEM Z demo-board, connected to the PC via USB to serial adapter, which acts as network coordinator and guarantees the wireless communication through a properly developed firmware that sends a Report of type 1 to the monitoring circuit every 5 minutes. Lastly, a LeCroy WaveRunner 64Xi oscilloscope – remotely driven by the aforementioned code – is exploited to measure the voltages of interest in the energy harvesting supply network, thereby acting as a useful diagnostic tool for the validation of results obtained by the monitoring circuit. Figs. 5a and 5b illustrate the behavior of Voc and Isc of the monitored panel within the time range 5 AM – 7 PM, as measured over two days. It is shown that Isc reaches the highest values at maximum solar irradiation (i.e., 11:00 AM – 12:00 PM); the temporary shadowing conditions (i.e., due to clouds) are recognizable from the “irregular” behavior (see e.g., the period between 10:00 AM and 12:00 PM in Fig. 5a). As concerns the open-circuit voltage Voc, a slight initial lowering (just after 8:00 AM) can be plainly spotted, which is due to architectural shadowing. In order to deepen the comprehension of the monitored Voc and Isc evolutions, it is to be remarked that Voc is less sensitive to the lower irradiation conditions compared to Isc [12]. Fig. 6 details the behavior of the key voltages of the supply network, namely, the voltage drop across the supercapacitors Vsc, and the DC voltages amounting to 3.3 and 12 V that supply the monitoring circuit, as well as the open-circuit voltage Voc, as measured by the oscilloscope; the data refer to the day corresponding to Fig. 5a. It is evidenced that, after the supercapacitors charging phase at dawn, the supply stage provides the expected (and constant) values for the DC voltages that feed the logic unit and measurement circuit. Fig. 7 describes the behavior of voltage Voc, as measured by both the monitoring circuit and the oscilloscope; an admirable agreement is found (a huge number of analyses allowed evidencing a maximum discrepancy lower than 1%) except for the dawn period, wherein the circuit is still inactive. The ruggedness of the wireless communication between the circuit and the network communicator was tested and verified during the Voc/Isc evaluation by using the Microchip wireless network analyzer ZENA to sniff the packets: it was found that no packets were lost during a whole measurement day.
Figs. 8a and 8b show the experimental evolutions of current and voltage of the monitored module, as well as of the current conducted by the overall 10-panel string, during the measurement stage. First, the panel is disconnected from the string via an active low logic signal provided by the MCU and operates under open-circuit conditions. Consequently, the voltage reaches the Voc value and the output current vanishes. Afterward, the panel is connected to the measurement circuit (see Section II-D) that sequentially forces the open- and short-circuit conditions in order to detect Voc and Isc, respectively. At the same time, the panel is bypassed in order to keep the overall string current unaltered, as plainly illustrated in Fig. 8a. An inspection of the graphs reveals that the whole monitoring duration (covering all the steps addressed in Section II-B) amounts to 2.2 ms, whereas the mere measurement stage (involving steps 3 and 4) requires 1.8 ms.

IV. CONCLUSIONS

A novel monitoring circuit for individual PV panels embedded in grid-connected systems has been designed and realized, which relies on an energy harvesting stage involving supercapacitors, whereby external supplies and batteries can be avoided. The circuit absorbs only 20 mA during the standard operating mode and exploits a rugged wireless communication – never adopted before for the monitoring of a single panel – to provide measured data to a remote station. An extensive comparison with results obtained by performing direct oscilloscope-based measurements evidences the noticeable accuracy of the proposed strategy: a discrepancy limited to less than 1% was indeed determined. As a result, the proposed circuit represents a useful means to accurately quantify both energy yield and reliability of the whole solar plant with a single-panel resolution, and can be employed to evaluate the performance of PV systems.
REFERENCES


