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Solar energy radiation measurement with a low–power solar energy harvester

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ABSTRACT

Solar energy radiation measurements are essential in precision agriculture and forest monitoring and can be readily performed by attaching commercial pyranometers to autonomous sensor nodes. However this solution significantly increases power consumption up to tens of milliwatts and can cost hundreds of euros. Since many autonomous sensor nodes are supplied from photovoltaic (PV) panels which currents depend on solar irradiance, we propose to double PV panels as solar energy sensors. In this paper, the inherent operation of the low-power solar energy harvester of a sensor node is also used to measure the open circuit voltage and the current at the maximum power point (I_{MPP}), which allows us to determine solar irradiance and compensate for its temperature drift. The power consumption and cost added to the original solar energy harvester are minimal. Experimental results show that the relation between the measured I_{MPP} and solar irradiance is linear for radiation above 50 W/m^2, and the relative uncertainty limit achieved for the slope is ± 2.4% due the light spectra variation. The relative uncertainty limit of daily solar insolation is below ± 3.6% and is hardly affected by the so called cosine error, i.e. the error caused by reflection and absorption of light in PV panel surface.

1. Introduction

Solar energy radiation is essential in plant physiology and pathophysiology hence its knowledge is fundamental for example, to estimate evapotranspiration (Gocić et al., 2015; Petković et al., 2015) and to predict infection risk of some fungus diseases (Katsantonis et al., 2017; Dalla Marta et al., 2008) that are needed to schedule irrigation and fungicide spraying. Solar energy radiation is usually expressed in terms of the energy flux density through a horizontal area (irradiance) and an integrated value over one day (daily solar insolation) fits these applications. For precision agriculture, high accuracy measurements are not required and manufactures recommend the use of photodiode-based pyranometers which are cheaper than thermopile-based pyranometers (Kipp&Zonen, 2018). However, they still cost hundreds of euros and consume some milliwatts hence do not suit low-cost wireless sensor nodes. As an alternative, insolation values in field studies are usually obtained from public weather stations often far away from the crop of interest. This results in errors due to the inhomogeneous solar energy distribution caused by orography, competing vegetation or clouds (Reuter et al., 2005). For extended areas, more reliable in-field data would be better obtained from wireless sensor networks that include solar radiation sensors but this can be thwarted by cost and power consumption constraints (Wang et al., 2006). In order to overcome these constraints, we propose to use the components already integrated into the solar energy harvester of sensor nodes to measure solar radiation too.

During the last decade, small PV panels have been used as low-cost radiation sensors to monitor PV solar plants. Solar irradiance has been deduced from the voltage drop across a resistor biased by a PV panel operating near short-circuit condition (Husain et al., 2011). Short-circuit current is approximately proportional to solar irradiance hence a way to estimate it, but unfortunately the power yield is null at this operating point. Further, the temperature drift of the sensitivity of the PV panel to solar irradiance must be considered. An obvious solution to compensate for temperature drift is to include a temperature sensor (Carrasco et al., 2014; Mancilla-David et al., 2014; Ma et al., 2017) but the sensor and its conditioning circuits add cost. An alternative solution is to measure the open-circuit voltage and the short-circuit current of the PV panel (Ortiz Rivera and Peng, 2006; da Costa et al., 2014). The temperature coefficient of the short-circuit current is positive whereas that of the open-circuit voltage is negative, and both increase with solar irradiance, which leads to a bijective function between them that can be obtained from a physical model for the PV panels. Unfortunately, the calculation is performed by iterative complex algorithms that require DSPs, and current sensors that do not suit low-power solar energy harvesters because of cost and power consumption constraints.

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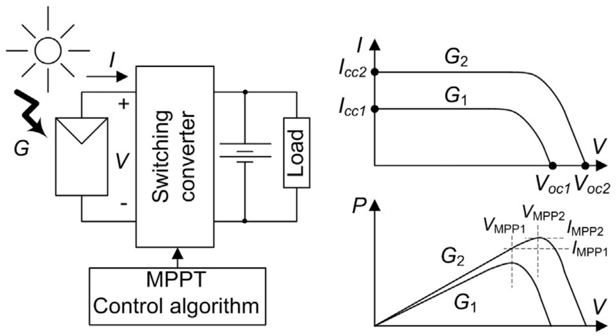

Fig. 1. *I/V* and *P/V* characteristics of a photovoltaic panel and a MPPT.

In order to achieve maximum energy from the sun light, low-power solar energy harvesters bias the PV panels at the maximum power point (MPP) which depends on the solar irradiance on the panel surface (*G*) and temperature (*T*). These circuits are designed as maximum power point trackers (MPPTs) and are formed by an algorithm to find MPP and a switching converter to bias the panel at this point and transfer the energy to a secondary battery and the load. Fig. 1 shows the block diagram of a MPPT and the typical current vs. voltage curve (*I/V*) and power vs. voltage curve (*P/V*) of PV panels. Low-power MPPTs use special control algorithms and switching converters to simplify the implementation and minimize power consumption.

The simplest control algorithm is designed as fractional open circuit voltage (FOCV) and it is based on the empirical relation between the open circuit voltage (V_{oc}) and the voltage at the MPP (V_{MPP}), $V_{MPP} \approx K\,V_{oc}$, where *K* is a constant that depends on PV panel performance but not on environmental operating conditions such as temperature or irradiance (Lopez-Lapena and Penella, 2012; Rawy et al., 2017). FOCV control approximates $V_{MPP}(V_{OC})$ drawn for any temperature and irradiance by a linear regression through the origin. *K* is the slope of this linear regression.

Fig. 2 shows an algorithm implementation wherein a switch (SW) and a sample & hold (S&H) amplifier periodically disconnect the PV panel and measure V_{oc}, which is then used to calculate V_{MPP}. FOCV implementation in a MCU is easy and the resulting CPU (processor core) workload and power consumption are so small that this is currently the most suitable control algorithm for low-power energy harvesters.

The energy available in low-power energy harvesters is so scarce that power losses are usually minimized by replacing the classical PWM (pulse width modulation) technique of the switching converter, wherein transistors are continuously switched ON and OFF, by pulse frequency modulation (PFM) (Lopez-Lapena et al, 2012). Power losses are reduced by keeping the switching converter inactive while the energy coming from the PV panel is accumulated in an input capacitor (C_{in}). Once charged to a limit value, the switch is activated to discharge C_{in} towards the battery at constant current (I_{ds}), while keeping the input voltage within a hysteresis window (Fig. 3). This way, the energy is not transferred to the battery until the energy accumulated in the capacitor is much higher than the energy consumption needed to turn on the switching converter; hence achieving a high power efficiency.

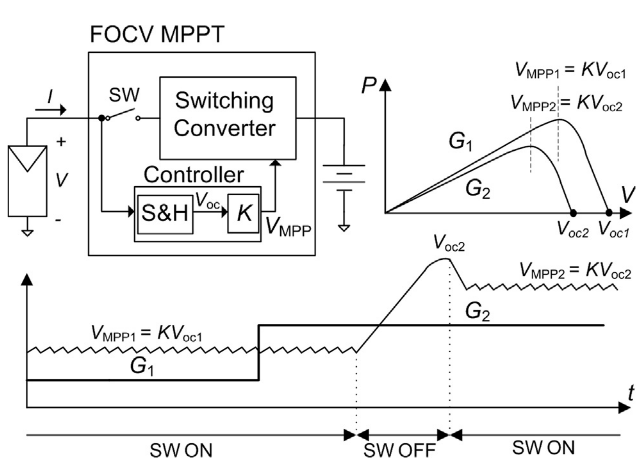

Fig. 2. FOCV control technique.

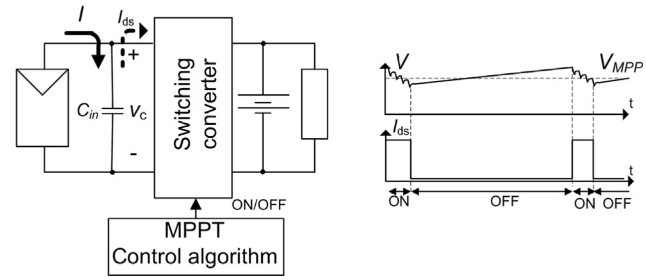

Fig. 3. PFM switching activity.

2. Development of the solar radiation sensor

The proposed solar irradiance sensor relies on a MPPT low-power solar energy harvester based on FOCV algorithm and a PFM switching converter. Solar irradiance and temperature are determined by measuring V_{oc} and the current at MPP (I_{MPP}). V_{oc} measurement is inherent to FOCV operation and I_{MPP} can be easily deduced from the charge duration of the input capacitor C_{in} with PFM.

2.1. Solar energy radiation measurement at constant temperature

The measurement method involves determining the empirical relation between I_{MPP} and *G*. In order to do that, since for constant light spectrum, temperature and moderate resistive losses, the relation between I_{cc} and *G* is quite linear, we can easily infer *G* from I_{cc}. Therefore, we only need to determine the relation between I_{cc} and I_{MPP}. Fig. 4 shows this relation for a SLMD121H04L PV, a 6 cm^2 low-power PV panel, that was illuminated by a high-power LED (BXRA-C1202) with different bias currents (I_{LED}). For I_{MPP} higher than 2 mA, the relation is linear. For lower values, the trace is curved yet includes the point (0,0) which is obtained for zero irradiance resulting in null values for I_{cc} and I_{MPP}.

The nonlinear relation observed in $I_{cc}(I_{MPP})$ around the origin is basically due to the variation of the light-sensitive area of PV panels. This area is defined by the space-charge-region of the PN junctions that constitute the panel. At lower irradiance levels, the resulting I_{MPP} and V_{MPP} are lower and this area is wider, which increases the sensitivity, hence the slope, of $I_{cc}(I_{MPP})$. However, V_{MPP} is almost constant at high irradiance levels by holding a fixed bias voltage of PN junctions and

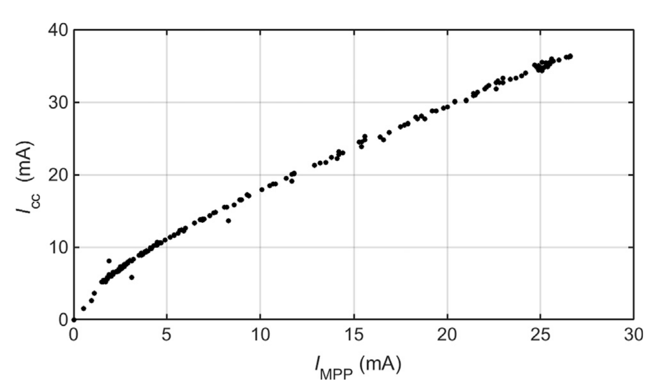

Fig. 4. Measured I_{cc} versus I_{MPP} for a SLMD121H04L PV panel at constant temperature (25 °C).