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A design approach of the solar harvesting control system for wireless sensor node

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ABSTRACT

In the last recent years the implementation of PV (PhotoVoltaic) solar harvesting maximum power point tracking (MPPT) systems has been widely investigated to achieve self-powered and fully autonomous wireless sensor networks (WSNs). In this context, this paper mainly aims to design an efficient and long-lived solar harvesting control system for sensor nodes. Specifically, a design approach of the overall solar harvesting control system, that is composed of PV source, controller, converter, and UltraCapacitor (UC), is provided in order to obtain the desired performance in terms of autonomy and efficiency. The methodology is based on the analytical derivation of system efficiency and takes into account design requirements. The approach is applied to the design of an harvesting control system supplying an off-the-shelf Texas Instruments $eZ430-RF4500$ mote. The prototype is realized and used to experimentally validate the approach by mean of out-door four days test. The experimental results show the effectiveness of the methodology to assess the required performance in terms of efficiency (about 0.86) and autonomy (four days).

1. Introduction

The recent development of low cost smart sensors and microcontrollers supporting network connectivity (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002) is promoting the implementation of distributed monitoring and control algorithms in many industrial and civilian applications (e.g. environment monitoring, home automation, military and automotive industry) through architectures (Heinzelman, Chandrakasan, & Balakrishnan, 2002; Manfredi et al., 2013; Neumann et al., 2007) composed of *Wireless Sensor nodes* (WSns). Wireless data communication networks aim to reduce costs in both management and maintenance. One of the main challenges in the WSns design is the energy autonomy, because nodes are usually deployed in remote area, where the access points to the electrical grid are absent. WSn load current profiles are typically impulsive. Their power absorption ranges from some μW in the sleep mode to tens of *m*W during communication mode (Frezzetti, Manfredi, & Suardi, 2014; Jiang, Polastre, & Culler, 2005; Moravek & Komosny, 2011; Wang & Yang, 2007). Stand-alone WSn are usually equipped with renewable photovoltaic (PV) cell and storage device, that allow a perpetual solar energy supplying. In this case, a Maximum Power Point (MPP) tracking method has to be implemented in order to guarantee the maximum power production. It has been noted that WSn can be efficiently supplied by UltraCapacitors (UCs) storage device, because this technology shows higher power density, lower Equivalent Series Resistance (ESR), lower leakage current (Kim, No, & Chou, 2011; Rafika, Gualous, Gallay, Crausaz, & Berthon, 2007) and slower degradation effects than the typical rechargeable batteries. A typical PV-based harvesting system scheme considered in the literature (e.g. Ahmad & Kim, 2009; Brunelli, Moser, Thiele, & Benini, 2009; Dondi, Bertacchini, Brunelli, Larcher, & Benini, 2008; Lopez-Lapena, Penella, & Gasulla, 2010, 2012) is depicted in Fig. 1. It consists of the PV cell, a power converter stage, the storage device (e.g. UC) and a solar harvesting system controller. While the power converter interfaces the PV source with the storage buffer, the controller tracks the actual MPP value and dynamically modulates the operating point of the PV cell through the converter.

Many studies investigate the efficiency of power conversion system pointing out the relation of system losses and tracking reliability with the overall system efficiency. In order to increase the tracking reliability, Brunelli et al. (2009) and Weddell, Merrett, and Al-Haschimi (2011) propose to use two PV cells aimed (1) to harvest energy and (2) to instantaneously track the voltage of MPP, namely V_{MPP} value. In this setup, however, the system consumption due to the presence of two cells is neglected. Most part of schemes presented in the literature (e.g. Ahmad & Kim, 2009; Simjee &

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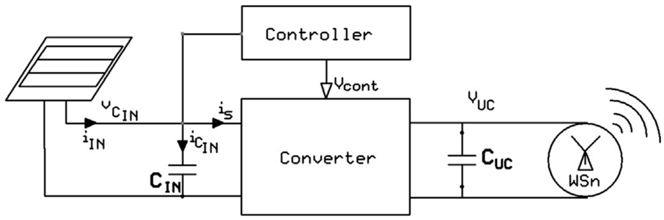

Fig. 1. General solar harvesting control system scheme for a WSn.

Chou, 2008a) includes a single cell and a low power timer that periodically disables the harvesting process and estimates the V_{MPP} voltage value. In this case, when the irradiation variability is slow in time, the use of just a single PV cell allows to assess a good MPP tracking capability. Finally, with reference to Fig. 1, it is equally assessed in the literature the use of buck or boost power converters (Lopez-Lapena et al., 2010, 2012), due to their low losses and high efficiency in power conversion.

With the reference of the system in Fig. 1, the following efficiency definitions are usually adopted in the literature and will be used hereafter: (1) MPP tracking efficiency, (2) input system efficiency and (3) converter stage efficiency. The *MPP tracking efficiency* is related to ability of the tracking algorithm to correctly estimate the real MPP. The *input system efficiency* refers to the ability of the MPPT system to dynamically seek the estimated MPP. Finally, the *converter stage efficiency* is the amount of harvested energy divided by the energy at the input of the converter and it gives indications of actual power delivered to the output as it takes into account the system power losses.

1.1. Paper contribution

In this context, this paper derives an analytical formulation of the overall efficiency of a solar harvesting control system in Fig. 1. On the base of previous analysis, a design methodology is carried out to both select the PV cell and UC and design the converter and controller parameters in order to cope with the desired performance in terms of system efficiency and autonomy. As a representative example, the proposed approach is used to design a low cost representative solar harvesting control system to supply an off-the shelf mote.

In the literature, only few works propose a study to design the efficiency of a PV-based harvesting system. In Dondi et al. (2008) authors derive the theoretical converter stage efficiency and the formulation is experimentally validated for different set of parameters. Based on the modelled efficiency, authors provide a series of guidelines to design the system parameters in order to achieve only the maximization of the converter stage efficiency. Lopez-Lapena et al. (2010, 2012) provide a more accurate overall system efficiency formulation than in Dondi et al. (2008), taking into account also the MPP tracking efficiency and the input system efficiency. An example of system design is provided and a prototype is implemented in order to validate the effectiveness of the proposed formulation. Other works propose embedded and low consumption harvesting schemes with high efficiency (e.g. Alberola, Pelegril, Lajaral, & Perez, 2008; Alippi & Galperti, 2008). Most of the above implementations are characterized by an external battery that supports the system autonomy.

In this scenario, the paper contribution are the following:

1. In the analytical formulation, the input system efficiency is taken into account in addition to the converter stage efficiency. Moreover, differently from many formulations given in the literature, herein we explicitly consider power losses related to the switch and parasitic elements. Finally, we approximate the PV cell characteristic around the MPPT point with a complete second-order Taylor polynomial, resulting in a more accurate derivation of the input system efficiency and therefore of the overall system efficiency as well.
2. Differently than existing approaches, herein is presented a systematic procedure to design the harvesting control system in order to cope with the desired performance in terms of system efficiency and autonomy. We give simple and low computationally demanding design conditions based on the above analytical derivation that considers in an unified framework the overall system efficiency, autonomy, system reliability requirements and components constraints.
3. The above procedure is used and validated to design a low cost harvesting control system prototype to supply a representative off-the-shelf Texas Instruments mote. This makes the procedure potentially applicable to the design of harvesting control system for a wide range of off-the-shelf devices.
4. Finally, the technological implementation of the developed prototype is notable that our system is completely supplied by the UC and this characteristic distinguishes our implementation from the most part of implementations found in the literature.

The outline of the paper is given. In Section 2, the general solar harvesting control system considered in the paper is briefly introduced. In Section 3, a theoretical analysis of the PV-based harvesting system efficiency is formulated and the system of inequalities is provided. As a representative example, the proposed approach is used to design a PV-based harvesting system (Section 5) with assigned WSn load, autonomy constraints and fixed overall efficiency. Finally in Section 6, a prototype of the designed harvesting system has been implemented and the effectiveness of the design procedure has been experimentally validated with four days of experimental test.

2. Solar harvesting control system scheme

In this section, the PV-based harvesting system scheme depicted in Fig. 1 will be briefly introduced. Herein, we describe the physical function of each system component in Fig. 1 and we also formulate the MPP controller law.

2.1. PV and C_{IN}

The PV and C_{IN} devices convert the environmental solar light in the electric power and deliver it to the converter.

2.2. Controller and converter blocks

A wide variety of MPPT controller schemes have been studied and implemented in the literature. The general principle behind these works considers an ON–OFF control over the PV cell voltage $v_{C_{IN}}(t)$ with a fixed hysteresis V_H according to

$$V_{cont} = \begin{cases} ON & \text{if } v_{C_{IN}}(t) > V_{MPP} + \dfrac{V_H}{2} \\ OFF & \text{if } v_{C_{IN}}(t) < V_{MPP} - \dfrac{V_H}{2} \end{cases} \tag{1}$$

where V_{MPP} is the desired voltage value, i.e. the MPP voltage of the cell. V_{MPP} can be estimated by one of the well known methods proposed in the literature (Dondi et al., 2008; Kim et al., 2013; Simjee & Chou, 2008b).

The converter transfers energy from C_{IN} input capacitor to the UC. Moreover, the voltage level on C_{IN} swings around the estimated V_{MPP} voltage. An analysis on mean voltage values is carried