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Abstract. There has been a growing interest in using energy harvesting techniques for powering wireless sensor networks. The reason for utilizing this technology can be explained by the sensors limited amount of operation time which results from the finite capacity of batteries and the need for having a stable power supply in some applications. Energy can be harvested from the sun, wind, vibration, heat, etc. It is reasonable to develop multisource energy harvesting platforms for increasing the amount of harvesting energy and to mitigate the issue concerning the intermittent nature of ambient sources. In the context of solar energy harvesting, it is possible to develop algorithms for finding the optimal operation point of solar panels at which maximum power is generated. These algorithms are known as maximum power point tracking techniques. In this article, we review the concept of maximum power point tracking and provide an overview of the research conducted in this area for wireless sensor networks applications.

1. Introduction

There has been a growing interest in using energy harvesting techniques for powering wireless sensor networks [1-6]. Wireless sensor nodes are usually powered by batteries [7-8]. Therefore, the operation time of wireless sensors is usually limited by the finite capacity of onboard batteries which can be a crucial factor in those applications requiring the use of stable power supplies. It is necessary to note that battery replacement in some networks can become a complicated procedure due to the large number of sensors deployed [9] or the harsh environment where the monitoring network is located [10]. Energy can be harvested from the sun, wind, vibration, heat, etc. Ambient source selection can be carried out based on the availability of energy sources as well as the type of application considered. As ambient energy sources have an intermittent nature, it is reasonable to develop multisource energy harvesting platforms [4,11]. Moreover, energy harvesting process can be optimized. In the context of solar energy harvesting, it is possible to develop algorithms for finding the optimal operation point of solar panels at which maximum power is generated. These algorithms are known as maximum power point tracking techniques [12,13] and for instance, can be used to increase the efficiency of the storage medium charging process [14]. The structure of this paper is as follows. In Section II, we overview three common methods for maximum power point tracking and in Section III the results of some research in this area is presented. In Section IV, a conclusion is made based on our survey.

2. Maximum power point tracking methods

Maximum power point tracking has been widely used in solar energy harvesting systems [12,13,15]. Solar panels generate the maximum amount of power at an optimal point which is a function of solar irradiance and temperature. An MPPT device can be realized by utilizing several techniques. In order for the MPPT circuit to be used for wireless sensor networks applications, it is necessary that the energy consumption of the MPPT circuit be as low as possible.

Fractional open circuit voltage (FOCV) is one of the methods used for MPPT techniques according to which the maximum power point is a constant fraction of the solar panel open circuit voltage [16]. Based on this method, there is a linear relationship between the maximum power point voltage V_{mpp} and the open circuit voltage V_{oc}. The relationship is mathematically expressed as $V_{mpp} = K_1 V_{oc}$. The open circuit voltage is measured periodically. Maximum power point can be also tracked by using the fractional short circuit current (FSCC) method in which case the solar cell maximum power point current I_{mpp} changes linearly with respect to the short circuit current I_{sc} [17] and in terms of equations is described as $I_{mpp} = K_2 I_{sc}$. The constants K_1 and K_2 are used to calculate the values of maximum power point voltage and current from open circuit voltage and short circuit current respectively.

Another method called perturb, and observation (P&O) involves "perturbing" the solar panel operating point periodically by changing its voltage in order to find the maximum power point (MPP).The solar panel power is controlled before and after each perturbation. An increase in the amount of power after a voltage perturbation means that the solar panel operating point has moved closer to the MPP, and the perturbation should be held in the same direction. A decrease in the amount of power after a voltage perturbation means that the solar panel operating point has moved away from the MPP and the perturbation needs to be reversed. The implementation of this method requires a more complex circuit with respect to the fractional open circuit approach [18,19].

3. Related work

The authors in [20] developed an MPPT algorithm for wireless sensor networks applications which searches for the optimal point by perturbing the solar panel operating point. If an optimal point is reached the control algorithm evaluates the power gradient in the neighborhood of the working point as the changes in weather conditions may alter the maximum power point. The platform performance was compared with the one which used a diode. The maximum power point tracking algorithm generated more power with respect to the system based on the diode. The MPPT system delivered power as low as 1 mW while the other system could not extract power at levels below 10 mW.

The research presented in [21-23] apply the FOCV method for tracking the maximum power point. According to reference [21], the authors use a pilot cell for measuring the open circuit voltage which allows for performing continuous maximum power point tracking.

The Everlast platform [14] is another example which used the FOCV method for tracking the maximum power point of a solar panel. One of the reasons for choosing this method reason was based on measuring the values of K_1 and K_2. K_1 was chosen due to its narrower range of change (which was between 0.8 and 0.68) in comparison with the short circuit current method (varying between 0.25 and 0.68). The authors developed a sample and hold circuit for realizing the MPPT method. The circuit is illustrated in Figure 1. The timer 555 was used to signal the circuit to sample the solar panel voltage and turns the pulse frequency modulation regulator on and off. The voltage from the solar panel is divided since V_{mpp} is a fraction of V_{oc}.

The research demonstrated in [24] analyzed the design issues concerning indoor light energy harvesting for powering wireless sensors nodes. The authors simulated the performance of a solar panel under a 500 lux illuminance. The simulated operation voltage of the solar panel and its power without using an MPPT circuit were 3.14 V and 129 μW. The solar panel yielded its maximum power point at 151.59 μW. An attempt was made to apply a microcontroller based MPPT circuit. According to the results of their analysis, the mentioned MPPT method was not considered to be effective since the power gain of the MPPT circuit was 22.6 μW which was less than the power consumption of the

MPPT microcontroller having a value of 300 μW. As the authors have mentioned, even the use of four solar cells cannot compensate for the microcontroller power consumption. The paper also addressed the use of the FOCV method. The authors considered a circuit consisting of an ultra-low power comparator, MOSFET switch and a low drop regulator implementing the MPPT method which according to their calculations could result in a 30 μW power consumption.
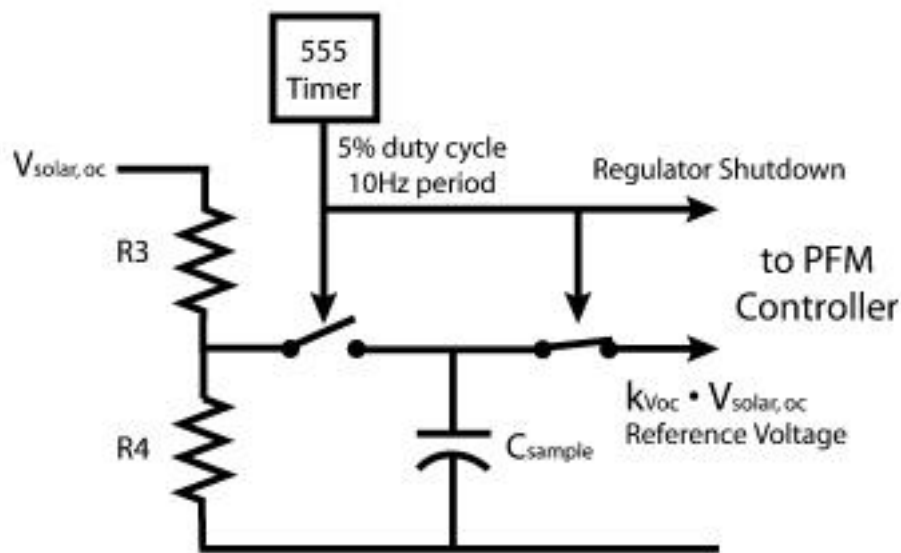

Figure 1. The sample and hold circuit developed in [14]

The measured values for MPP voltage and power for an illuminance of 500 lux were 2.59 V and 139.2 μW which indicate a power gain of 10.2 μW. As the authors have stated, if four solar cells have been used the power gain of the MPPT controller is equal to 40.8 μW and by subtracting the mentioned value from the power consumption of the MPPT circuit, the power gain applied to the load is almost 10.8 μW. The authors proposed to use a directly coupled system with a diode to prevent the reverse current flow to the solar panel. Based on their method, the average V_{mpp} for an irradiance range 100-1000 lux was calculated and, the values of capacitance and the equivalent series resistance of the capacitor were determined such that V_{mpp} could be achieved.

Reference [25] presented an MPPT platform designed to operate in indoor environments. The platform is based on utilizing the FOCV principle for tracking the MPPT. A sample and hold circuit is developed in order to realize the MPPT method. The authors estimated the power loss which can occur during the sampling process. Sampling efficiency was evaluated for a time interval 0 to 7200 seconds. As a result of the experiment, the maximum efficiency can be achieved at the time interval 60 to 300 seconds. A period of 60 seconds was chosen as the duration of the sampling process which according to the authors of the paper is considered appropriate taking into account the rapid changes in the light level. The method developed in [18] finds the MPP by nulling the difference of the solar panel average power for two consecutive subintervals of the charging time.

4. Conclusion
We have overviewed the FOCV, FSCC and P&O methods which are considered as three common MPPT techniques. Also, a survey concerning the application of MPPT for wireless sensor networks was presented. Regardless of the type of the MPPT method, it is necessary that the power consumption of the MPPT circuits be as low as possible, an issue which has been addressed in the current research trend to broaden the perspectives of using these circuits for wireless sensor networks applications.

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