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# Micro-scale variation-tolerant exponential tracking energy harvesting system for wireless sensor networks ☆

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ABSTRACT

Self-powered stand-alone electronic systems, targeting low power applications, are the future of power management. In wireless sensor networks (WSNs) and implantable devices, battery replacement is expensive and power management of these systems is essential. Energy harvesting is considered one of the main power management methods that scavenge energy from the ambient resources that are available and abundant. They take the advantage of minimizing the maintenance costs as well as saving area (Penella-Lopez and Gasulla-Forner, 2011 [1]). This paper presents a new tracking technique for maximum power harvesting of solar energy using a micro-scale photovoltaic cell. The new design is based on the analytical derivation of the system equations. The power converter used is a tree topology charge pump, the control circuit is a low frequency voltage controlled oscillator (VCO), and the energy storage element is an output super-capacitor. The system is designed using TSMC 65 nm technology node. Typical power efficiency of the proposed circuit reaches 63% where the proposed design is targeting indoors and outdoors light intensities at zero load condition. The maximum power consumption of the harvester reaches 170 μW.



## 1. Introduction

Energy harvesting is a technique used to collect energy from ambient sources. This operation is carried out by means of transducers to transfer the ambient power into electrical power. This power is then managed through power regulating circuits to be suitable for supplying different loads. This process is also called “energy scavenging”. Actually, the idea is old and suits a lot of common applications. For example, it can be used in solar photovoltaic (PV) panels to supply electricity to houses and also in wind turbines, which are considered large-scale systems. In this work, design challenges for powering micro-scale systems, denoted by stand-alone electronic systems, are discussed. The most important application of power harvesters is wireless sensor networks (WSNs). In WSNs, it is very expensive to make the battery replacement frequently and it becomes impossible when the number of WSNs nodes is large. Therefore, integrated harvesters can save time and money for powering WSNs. Other stand-alone applications are traffic, medical and environmental applications, navigation and system controls of buildings.

Solar energy has the highest energy density among the available ambient resources. Table 1 [2] shows a comparison between different ambient energy sources. Solar energy harvesting includes many design challenges especially for the micro-scale systems. First, the size of these tiny systems limits the area of the energy harvester. Thus, the PV cell area should be small. The terminal open circuit voltage of the solar cell ($V_{OC}$) is in the order of 0.75 V. This small voltage cannot directly power an electronic system, especially if there are RF data transceivers that are considered as power hungry modules. Therefore, a voltage multiplier should be added to increase the voltage to a higher value, and this voltage multiplier contains many design issues. Second, the control unit design is critical in terms of power consumption and its tracking approach. Hence, there is a technique called maximum power point tracking (*MPPT*), used to lock the PV cell at the maximum power that corresponds to a certain light intensity. This technique guarantees the delivery of the highest possible power to the load. However the power overhead of this MPPT control circuit should be minimized.

This paper proposes a new circuit technique that has several advantages over the design presented in [3]. The design of the proposed harvester is based on the maximum power locking mechanism that makes use of the exponential relationship between the charge pump frequency and the PV terminal voltage, as discussed in Section 3. The advantages of the proposed design in this paper include (1) the PV cell output power reaches up to 3 mW due to the locking mechanism, whereas the work in [3] produces a maximum PV cell output power up to 0.5 mW, which makes it suitable only for

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**Table 1**
Comparison between different energy transducers [2].

| Sources | | Transduction mechanism | Estimated power density |
|---|---|---|---|
| Light | Solar | Photovoltaic | $< 15$ mW/cm$^2$ |
| | Artificial | (PV) | 10–100 μW/cm$^2$ |
| Motion | | Electrostatic | 50–100 μW/cm$^3$ |
| | | Electromagnetic | $< 1$ μW/cm$^3$ |
| | | Piezoelectric | 50–300 μW/cm$^3$ |
| Δ Temp. (10 °C) | | Seebeck | 5–15 μW/cm$^3$ |

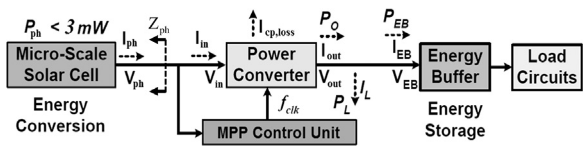


**Fig. 1.** Block diagram of the solar energy harvesting system [3].

indoors applications. Hence, the proposed design has wider locking range that is suitable for indoors and outdoors applications. (2) The power overhead of the tracking system is smaller as extra circuitry for current sensing and decision generation circuits are not needed, it is a plus also in terms of area.

The paper is organized as follows: Section 2 gives an overview of the system blocks. Section 3 shows the analytical derivation of the new tracking approach and the hardware implementation. The simulation results of the whole system are monitored in Section 4 capturing the main performance metrics with concentration on some optimization techniques. Section 5 presents the impact of process variations on the system. Section 6 draws the conclusion and future work.

## 2. Microscale energy harvesting system

Efficient design of microscale energy harvesters are discussed in details in [4]. In this section, the system blocks are discussed focusing on the parts used in this work.

### 2.1. PV photovoltaic cell

The energy transducer of the solar energy based harvesters is the photovoltaic cell. Since a typical WSN requires power in the range of microwatt, a micro-scale PV cell is used as shown in Fig. 1. The amount of extracted power reaches up to 3 mW. The PV cell is used to directly convert the light energy into electrical energy through photovoltaic effect and is modelled as a voltage limited current source. Fig. 2 shows the power profile versus the PV voltage at different light intensities. The amount of power extracted from the PV cell varies with the output impedance value ($Z_{ph}$) [5]. For a constant light intensity, there is a corresponding optimum PV voltage that gives the maximum power at this light intensity value. The dotted line represents the locus of the maximum power curve across different light irradiances. The PV model used in the simulations of this study is a compact verilog-A model that is given in [6].

### 2.2. Power converters

Power converters are used in the energy harvesters in order to increase the voltage to a suitable value that is able to drive different loads. There are two types of converters. The first one is the DC–DC buck-boost converter that is used to increase or decrease the input voltage. The main drawback of using these

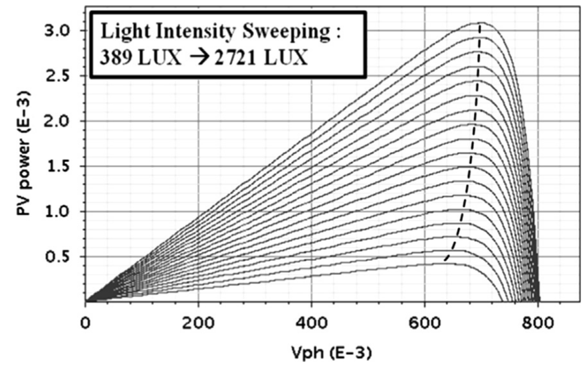


**Fig. 2.** Power profiles for different light intensities versus PV voltage.

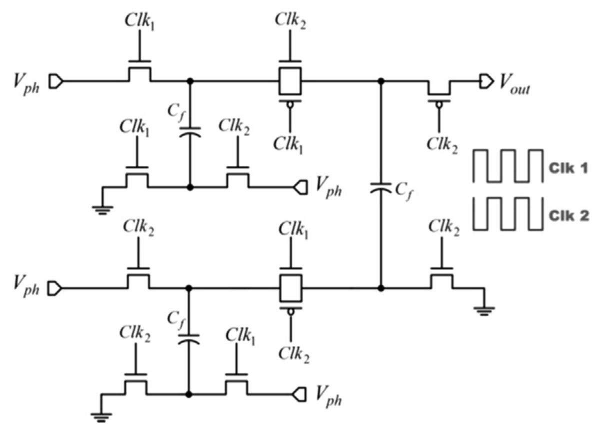


**Fig. 3.** Two stages tree topology charge pump.

converters is the bulky off-chip inductor. This introduces huge electromagnetic interference (EMI) noise as well as occupies large area, that is not suitable for low cost integration due to the die area constraints. The second power converter type is the charge pump power converters, which uses on-chip capacitors and transistors that makes them the perfect match for low cost integration.

Charge pumps have different design metrics such as power conversion efficiency, output ramp up time, and output ripples. The most important metric is the charge sharing capability (the ability of the charge pump to do a complete charge sharing), which is characterized by the knee frequency (the frequency at which the output current of the charge pump reaches $(1/\sqrt{2})$ of the maximum possible current value) of the architecture used [7]. The first published converter is the Dickson charge pump [8], which exhibits a linear characteristics. Linear topologies performance degrades in terms of charge sharing for low input voltage values which is the case for micro-scale harvesters. Several topologies are proposed recently and the most effective architecture proposed is the tree topology [7]. It increases the capability of the charge sharing by decreasing the worst charging time constant, and correspondingly, increases the knee frequency.

Fig. 3 shows a two stages tree charge pump that is used in the proposed design in this work. The number of stages is determined by the input voltage and the output voltage levels. Here, the output voltage is four times the input voltage according to Eq. (1). The charge pump output current depends on the flying capacitance values ($C_f$), frequency of $Clk_1$, $Clk_2$, and the difference between the input voltage and the output voltage [7]. The flying capacitance is chosen to be 500 pF in order to decrease the operating frequency range

$$V_{out} = (N+1)V_{ph} \tag{1}$$