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High efficiency boost converter with variable output voltage using a self-reference comparator

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ABSTRACT

This paper presents a boost converter with variable output voltage and a new maximum power point tracking (MPPT) scheme for biomedical applications. The variable output voltage feature facilitates its usage in a wide range of applications. This is achieved by means of a new low-power self-reference comparator. A new modified MPPT scheme is proposed which improves the efficiency by 10%. Also, to further increase the efficiency, a level converter circuit is used to lower the V_{dd} of the digital section. The low input voltage requirements allow operation from a thermoelectric generator powered by body heat. Using this approach, a thermoelectric energy harvesting circuit has been designed in a 180 nm CMOS technology. According to HSPICE Simulation results, the circuit operates from input voltages as low as 40 mV and generates output voltages ranging from 1 to 3 V. A maximum power of 138 μW can be obtained from the output of the boost converter which means that the maximum end-to-end efficiency is 52%.

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1. Introduction

Small size and low power IC design have been realized due to rapid advances in silicon technology. These small sized ICs are the best choices for biomedical devices and wireless sensors nodes. Recent technological advances in sensors, low-power integrated circuits, and wireless communications have enabled the design of low-cost, miniature, lightweight, and intelligent physiological sensor nodes. These nodes, capable of sensing, processing, and communicating one or more vital signs, can be seamlessly integrated into wireless personal or body networks (WPANs or WBANs) for health monitoring.

One of the main issues related to WBANs is power delivery. These electronics inside the biosensors need power to function properly. Powering of implantable biomedical sensors is a major concern due to various constraints. Typically the leading source of powering involves batteries which can be used inside the human body if placed into a body cavity and are hermetically sealed [1].

One of the main problems in using batteries is their lifetime. As the capacity of the batteries is limited, they limit the lifetime of the sensor nodes. For instance, pacemakers have a lifetime of about 5–10 years. After this period, one should go under a surgical procedure to replace the battery of the pacemaker. Replacing these batteries is cumbersome since it requires surgical procedures. Besides, a battery is not recommended to be placed inside the human body when it may come in contact with blood (such as pH sensor). The main risk of putting batteries in contact with blood is leakage which may lead to poisoning, and even death [1].

There are alternative methods to power up the implantable sensors such as, small thermoelectric generators, individual solar cells, vibration and radio frequency. An overview of these energy transducers can be found in [2]. Harvesting ambient heat energy using thermoelectric generators (TEGs) [3,4] is a convenient means to supply power to body-worn and industrial sensors. Micro-TEG is scalable, reliable and does not require any moving part like vibration energy transducers. As a consequence, it is very appealing in micro-scale energy harvesting systems, such as human body powered biomedical devices [2]. Recently, on-chip TE modules have been used to harvest electrical energy from waste heat [5]. As shown in Fig. 1, thermoelectric generator is a solid state device which converts thermal energy into electrical energy when there is a thermal gradient between its cold and hot surfaces. A TEG can be modeled as a voltage source in series with an internal resistance [6,7]. The open circuit output voltage of the TEG is proportional to the temperature gradient. When implanting a TEG, the best place should be as close as possible to the superficial skin, where a maximum temperature difference between the two junctions of the TEG could be established. This would guarantee a good output of the TEG [8].

Using TEGs for implantable applications limits the output voltage to 50 mV for temperature differences of 1–2 K usually found

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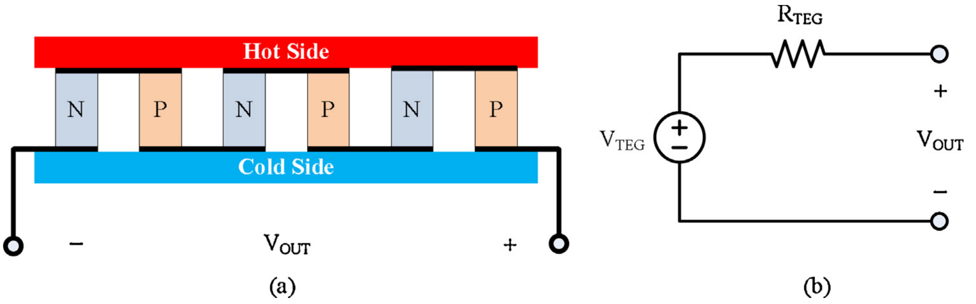

Fig. 1. (a) A typical thermoelectric generator (TEG) and (b) its electrical equivalent circuit.

between the body and ambience. As the environment temperature changes, the temperature difference and as a result the generated power varies. This leads to the need of a power management circuit (PMC). The core functions of the PMC are to provide stable power to the load and also to extract maximum power from the TEG.

As it was mentioned, the output voltage of a TEG is very low. A boost converter is then needed to successfully increase the output voltage to the desired value.

One of the main issues related to the design of boost converters is maximum power point tracking (MPPT). MPP is a point that maximum power is delivered to the load. MPP of a TEG device alone is different from the MPP of the full system [9]. Designing the TEG and the power converter independently could lead to a sub-optimal system [5]. Choday et al. [5] has shown that the relative values of the contact resistance of TEG and the NMOS switch has a direct impact on the MPP of the whole system. As a result, a kind of algorithm should be used in order to reach the MPP of the whole system.

Several works have been done to lead to the MPP in boost converters. Perturb and Observation (P&O) [10,11] Incremental Conductance (INC) [12,13] and open-circuit voltage [14] are among the methods to manage the circuit in MPP [15]. Open-circuit voltage is frequently used due to its simplicity [16]. Lu et al. [9] has given a methodology for estimating the MPP of a system composed of a TEG and a step-up charge pump. In this paper, with an analytical approach, it is shown that for a system composed of a TEG and a boost converter, MPP is a point at which the input voltage of the converter equals 0.29 × V_{TEG}.

The rest of this paper is organized as follows. In Section 2, the basic concepts of boost converter are reviewed and some analytical approaches regarding MPPT is shown. The proposed technique and its circuit implementations are described in Sections 3 and 4. Simulation results are shown in Section 5. Eventually, Section 6 concludes the paper.

2. The boost converter

Fig. 2 shows a diagram of an ideal boost converter and its related phases. Boost converter operates in two phases. In phase Φ_1, switch S_1 is closed and S_2 is opened. As a result, the energy is stored in inductor L. Next, in phase Φ_2, switch S_1 is opened and at the same time, S_2 is closed. The energy stored in inductor L is then transferred to the capacitor C_{out}.

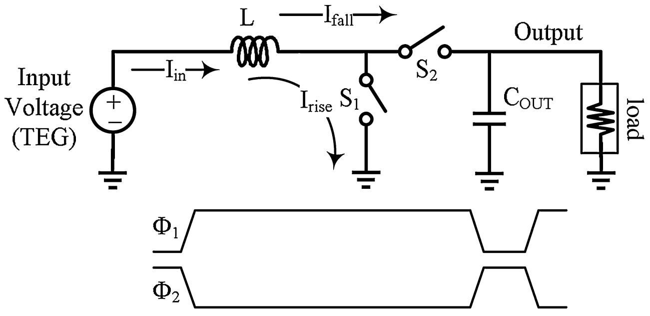

Fig. 2. An ideal boost converter and its phases.

Boost converters typically operate in one of two modes: continuous conduction or discontinuous conduction [17]. The main difference is that, in continuous conduction mode (CCM), the inductor current can flow negative if the load is small enough. In contrast, in the discontinuous conduction mode (DCM), the inductor current is prevented from flowing negative. The DCM is more efficient when the average input current is less than half the ripple current because the CCM will discharge the output capacitor during parts of the switching cycle when the inductor current flows negative, thus increasing switching losses [18]. The voltage–current equations in phase Φ_1 and Φ_2 in DCM mode are given in Eqs. (1) and (2), respectively:

$$\Phi_1: \quad \frac{di_{in}}{dt} = \frac{V_{in}}{L} \tag{1}$$

$$\Phi_2: \quad \frac{di_{in}}{dt} = \frac{V_{in} - V_{out}}{L} \tag{2}$$

Solving these equations calculates V_{out}:

$$V_{out} = V_{in}\frac{1}{1-D} \tag{3}$$

$$D = \frac{T_{rise}}{T_s} = \frac{T_{rise}}{T_{fall} + T_{rise}} \tag{4}$$

where T_{rise} is the rise time of the inductor current, T_{fall} is the fall time of the inductor current and T_s is the period.

Maximum efficiency is achieved when the inductor current never falls below zero (DCM mode).

2.1. Maximum power point tracking

Although in the ideal case of the circuit, the output voltage can be increased to the extent that is required, some non-idealities degrade its performance. One of the main sources of circuit non-idealities is the internal resistance of the input voltage source (V_{TEG}). This resistance limits the input power of the boost converter. According to the maximum available power rule, maximum power that can be delivered to the boost converter is:

$$P_{av,\max} = \frac{V_{TEG}^2}{4 \times R_{TEG}} \tag{5}$$

So, it is important to provide the situation such that one can use this maximum power for the input power of the converter.

Fig. 3 shows the boost converter in the first phase Φ_1 along with the internal resistance of V_{TEG}. As the input power is stored on the inductor directly, the power stored on the inductor should be maximized. The average power (P_{av}) stored on the inductor is as follows:

$$P_{av} = \frac{E_L}{T_{rise}} = \frac{0.5 \times L \times i_{\max}^2}{T_{rise}} \tag{6}$$

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