Analysis of the Power Conversion Modes for Power-Efficient Energy Harvesting Interfaces

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Abstract – **This paper analyzes the power conversion efficiency of conventional buck and buck-boost modes for power-efficient energy harvesting interfaces. In the state-of-the-art energy harvesting interfaces, they transfer harvested power mostly based on the conventional buck-boost mode. Since the power conversion efficiency is one of the most important performance factors for energy harvesting converters, this paper focuses on comparing the conventional power conversion modes based on formulas. In addition, the energy harvesting converter is designed in a 180 nm CMOS process and is simulated to prove that the power can be transferred properly with the analyzed power conversion modes. The converter operates in the discontinuous conduction mode with pulse-skipping modulation and employs the conventional open-circuit voltage method to track the maximum power point of each source. An adaptive on-time controller manages the inductor charging period, and a zero current detector, which is digitally operated, determines the optimum zero current point.**

***Keywords*—DC-DC converter, energy harvesting, Internet of Things**

I. INTRODUCTION

Energy harvesting systems are expected to be candidates for the semi-permanent operation of Internet of Things (IoT) devices. One essential element of IoT technology is the wireless sensor network, which allows us to collect data about real-time conditions of the targeted environment over a long period of time with less manual effort [1].

Small wireless sensors, typically composed of a power management unit, a sensing unit, a microcontroller unit, and an RF transceiver unit, reduce the overall power consumption by applying various energy-efficient operating schemes because of small harvestable input power [2]–[5]. In a similar sense, energy harvesting converters have been studied to increase the harvestable power by using multiple energy harvesting sources [6] and to improve the power density by driving multiple loads [7]. However, owing to the wide voltage range of energy harvesting sources in typical wireless sensor applications, various power conversion modes are available; thus, it is necessary to consider which mode is more power-efficient for each case. Therefore, an analysis between various power conversion modes is required before designing the optimum energy harvesting converter.

This paper introduces an analysis between conventional power conversion modes and shows the simulated results of a designed energy harvesting converter that regulates three input voltages (V_{IN}s) and three output voltages (V_{OUT}s).

This paper is organized as follows. Section II describes the prior-art energy harvesting converter interfaces and analyzes the conventional power conversion modes. Section III explains the designed converter, Section IV shows the simulated results, and Section VI concludes the paper.

II. POWER CONVERSION MODE FOR ENERGY HARVSETING CONVERTER INTERFACE

A. Prior Art

Studies about energy harvesting converters mostly focused on improving the power conversion efficiency because of low-input power conditions. Although the structural advances for improving the overall performance of energy harvesting architectures have been introduced [8], [9], the power stages were implemented mostly based on conventional buck-boost converters. Using buck-boost mode for these multi-input single-inductor multi-output (MISIMO) interfaces may be a reasonable solution during startup operation, but it cannot tell that it is the most power-efficient power conversion mode for improving overall power conversion efficiency.

Figure 1 shows the conventional MISIMO energy harvesting converters and their inductor current (I_L) profiles. The prior work in Fig. 1(a) transfers the power from the V_{IN}s to the multiple loads within a single cycle, which enhances the available output power (P_{OUT}) range and reduces the number of switching operations [8].

However, the converter delivers the power to all outputs during one clock cycle by charging high I_L, which causes a large conduction loss. Furthermore, the power conversion is controlled according to the fixed voltage windows of hysteresis comparators connected to the V_{IN} and V_{OUT} nodes, which may degrade the power conversion efficiency when it is used over a wide V_{IN} range [7].

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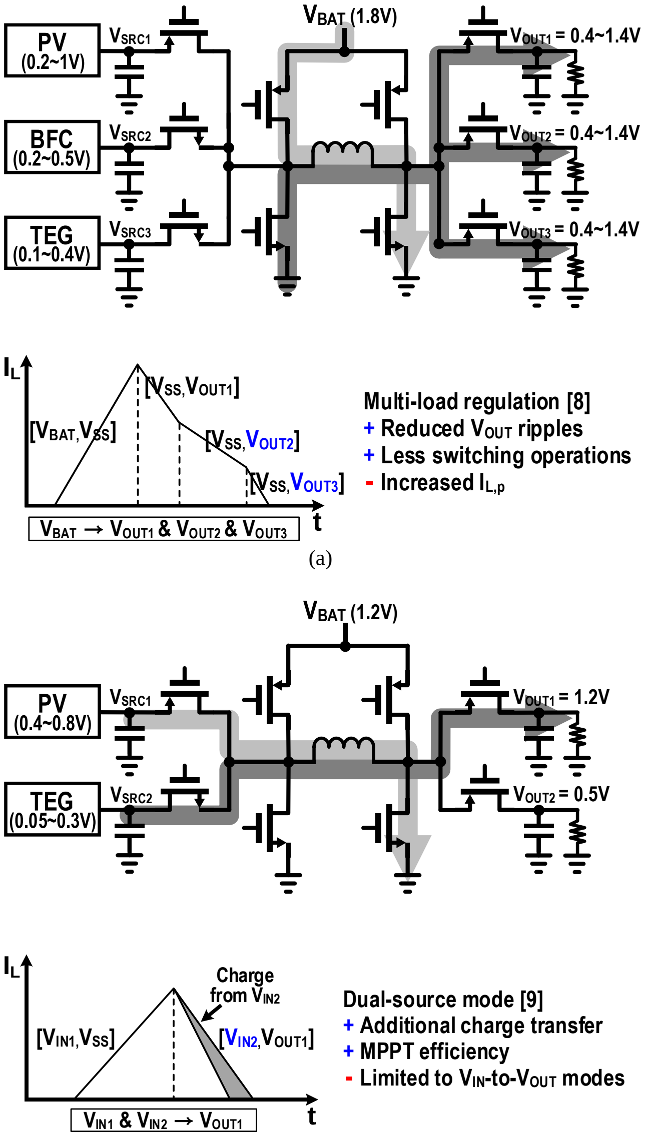


(a)

(b)

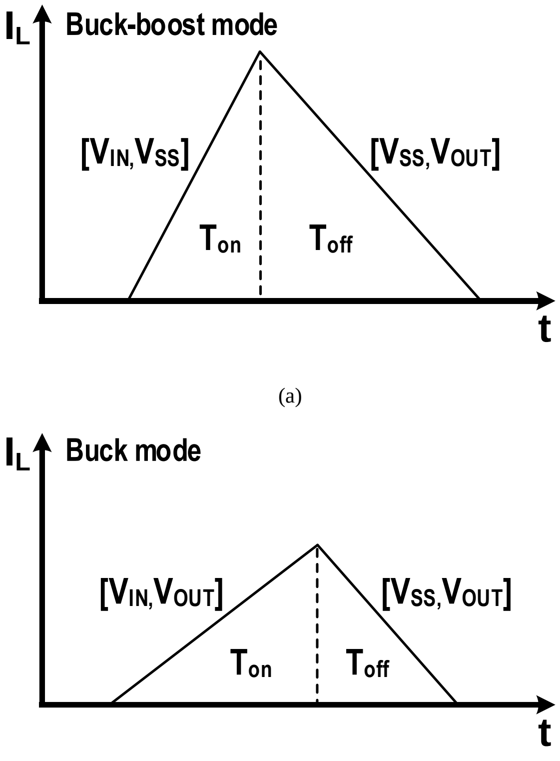
Fig. 1. (a) Multi-load regulation scheme [8]. (b) Dual-source mode [9].

The dual-source mode, as shown in Fig. 1(b), improves both the maximum power point tracking efficiency and the power conversion efficiency by increasing the amount of charge transferred to the V_{OUT} compared with the conventional buck-boost mode [9].

However, it was mainly designed for the case where a high P_{OUT} is supplied from the energy harvesting sources (not from the battery), as the power levels of the sources were sufficient to drive the total P_{OUT} in that study [9]. Furthermore, the dual-source mode conversion is not suitable for a typical battery-to-V_{OUT} power conversion because there should be two available V_{IN}s to conduct the conversion.

B. Comparison between power conversion modes

This paper analyzes which power conversion mode is power-efficient for the higher-V_{IN}-to-lower-V_{OUT} power conversion cases and discusses the overall power conversion modes appropriate for the energy harvesting interfaces.



(a)

(b)

Fig. 2. (a) DCM buck-boost mode. (b) DCM buck mode.

Figure 2 shows the I_L waveforms of conventional buck-boost and buck conversion modes. In conventional discontinuous conduction mode (DCM) buck-boost conversion, V_{IN} and V_{SS} are directly connected to the inductor at on-time (T_{ON}) for accumulating charge in the inductor, and transfer charge to the V_{OUT} at off-time (T_{OFF}), as shown in Fig. 2(a). However, as shown in Fig. 2(b), the conventional DCM buck conversion connects V_{IN} and V_{OUT} at T_{ON} to directly transfer charges, resulting in an increased power conversion efficiency.

The PCE formulas of the buck-boost and buck modes are compared to verify that the buck mode is more power-efficient than the buck-boost mode. The conduction loss of the buck-boost mode ($E_{cond,b\text{-}b}$) is derived as follows [11]:

$$E_{cond,b\text{-}b} = \frac{{I_{L,p,b\text{-}b}}^3 L}{3V_{IN}} R_{on,b\text{-}b} + \frac{{I_{L,p,b\text{-}b}}^3 L}{3V_{OUT}} R_{off,b\text{-}b}, \qquad (1)$$

where $R_{on,b\text{-}b}$ and $R_{off,b\text{-}b}$ represent the equivalent series resistances from V_{IN} to the V_{OUT} during the T_{on} and T_{off} of the buck-boost conversion, respectively, and $I_{L,p,b\text{-}b}$ represents the inductor peak current of the buck-boost conversion. The exponential terms of I_L are ignored in this study, for simplicity. Similarly, the conduction loss of the buck mode ($E_{cond,b}$) can be expressed as,

$$E_{cond,b} = \frac{{I_{L,p,b}}^3 L}{3(V_{IN} - V_{OUT})} R_{on,b} + \frac{{I_{L,p,b}}^3 L}{3V_{OUT}} R_{off,b}. \qquad (2)$$

Terms that have the same meaning as in the buck-boost mode but different values in the buck mode are distinguished by changing “b-b” to “b”. Additionally, the transferred energy from the V_{IN} to charge the inductor with the buck-boost and buck modes ($E_{IN,chrg,b\text{-}b}$, $E_{IN,chrg,b}$) can be expressed as follows:

$$E_{IN,chrg,b\text{-}b} = \frac{{I_{L,p,b\text{-}b}}^2 L}{2}, \tag{3}$$

$$E_{IN,chrg,b} = \frac{{I_{L,p,b}}^2 L V_{IN}}{2(V_{IN} - V_{OUT})}. \tag{4}$$

Assuming the same amount of the energy is transferred to charge the inductor from the V_{IN}, (3) and (4) give,

$$I_{L,p,b} = \sqrt{\frac{V_{IN} - V_{OUT}}{V_{IN}}} \cdot I_{L,p,b\text{-}b}. \tag{5}$$

This indicates that the $I_{L,p,b}$ is lower than the $I_{L,p,b\text{-}b}$. Regarding the battery supplies the switch control power, the power conversion efficiency during a single power conversion can be expressed as,

$$\text{Power conversion eff.} = \frac{E_{in} - E_{cond}}{E_{in} + (C_{gate} + C_{par}){V_{DD}}^2}, \tag{6}$$

where E_{in} represents the input energy to the converter; C_{gate} and C_{par} represent the total gate and parasitic capacitances of the operated power switches, respectively; and E_{cond} represents the conduction loss. Using (1), (2), and (5), it can be proven that E_{cond} is smaller in the buck mode, and lesser switching operations of the buck mode also reduce C_{gate} and C_{par}. Thus, the power conversion efficiency of buck mode is typically higher than that of the buck-boost mode, which means that energy harvesting converters should be designed with the buck conversion mode rather than with the buck-boost mode.

For the lower-V_{IN}-to-higher-V_{OUT} power conversion case, the conventional boost mode transfers more charge with the same switching operation than that of the conventional buck-boost mode. With the same switching conditions, a more transferred charge enhances the power conversion efficiency, which means the increased power conversion efficiency [12]. Therefore, the power conversion modes of the energy harvesting converters should be designed with the boost mode rather than with the buck-boost mode.

III. CIRCUIT IMPLEMENTATIONS

Figure 3 shows the top diagram of the designed MISIMO energy harvesting converter to show that the energy harvesting converter can be designed based on the above analysis. The converter operates in the DCM for low-P_{OUT} power conversion efficiency. After each clock cycle, the digital mode selector decides the operating mode and skips the power conversion if such signals are not triggered (pulse-skipping modulation).

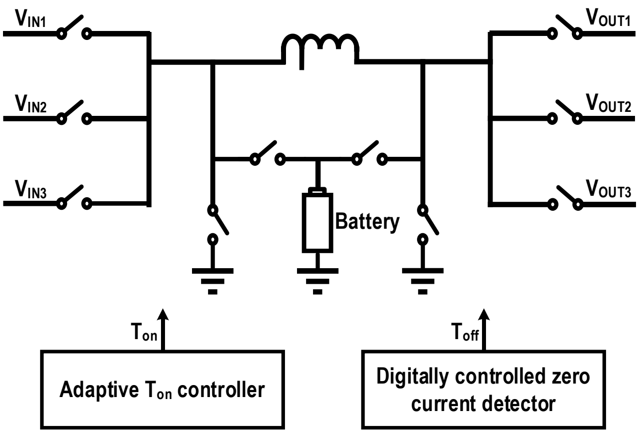


Fig. 3. Top diagram of the designed converter.

The conventional open-circuit voltage method [13] is employed to track the maximum power point of each V_{IN}. The frequency of the system clock is 125 kHz at a light-load condition.

Moreover, for covering the wide V_{IN} range of each energy harvesting source, the adaptive on-time controller, which is designed based on [9], determines the on-time of each power conversion of V_{IN}, and the digitally controlled zero current detector, which is designed based on [14], determines the off-time of each power conversion.

IV. SIMULATION RESULTS

The top layout of the designed converter is shown in Fig. 4. The total active area is approximately 2.58 mm^2. The power switches are located at the corners of the chip to reduce the series resistance between on-chip and off-chip power-lines, and the controller is located in the middle of the chip to operate the power switches of the converter at the same time as possible.

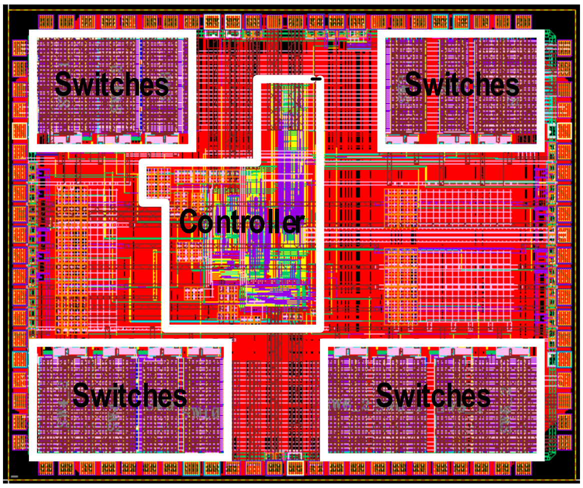
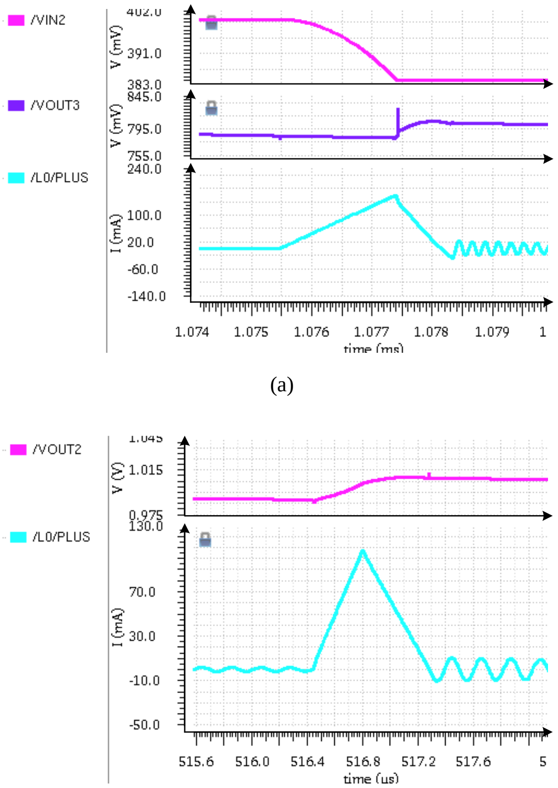


Fig. 4. Overall layout of the chip.

TABLE I.
Specifications of the simulated MISIMO energy harvesting converter

Parameter	Value
Process	180 nm
# of V_{IN}s	3
# of V_{OUT}s	3
Inductor	4.7 µH
Input capacitor	10 µF
Output capacitor	2.2 µF
Switching frequency	> 125 kHz

Table I presents the summarized specifications of the simulated MISIMO energy harvesting converter. As shown, the converter is designed comparable specifications to the state-of-the-art MISIMO converters [8], [9]. The converter was designed using TSMC 180 nm technology, however, only 5 V MOSFETs were used. The converter employs one 4.7 µH off-chip inductor, three off-chip 10 µF capacitors at V_{IN}s, and three off-chip 2.2 µF capacitors at V_{OUT}s.



(a)

(b)

Fig. 5. (a) Buck-boost conversion. (b) Buck mode conversion.

Figure 5 shows the simulated waveforms of the designed converter. Fig. 5(a) indicates that the converter operates in buck-boost conversion mode with V_{IN2} and V_{OUT3} nodes, and Fig. 5(b) indicates that the converter uses the battery to regulate V_{OUT2} with buck conversion mode. Also, I_L waveforms show that the designed on-time and off-time controllers functioned properly. Therefore, the simulation proves that designing the energy harvesting converter based on the above analysis is a feasible approach.

V. CONCLUSION

An analysis for designing a power-efficient energy harvesting interface was introduced. Through formula analysis, the buck conversion mode is proven to be more power-efficient than the buck-boost conversion mode. Additionally, the MISIMO energy harvesting DC-DC converter is designed to show that designing power conversion modes based on the above analysis is feasible.

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