ELectronics EXpress

LETTER

IEICE Electronics Express, Vol.12, No.24, 1–6

High-efficiency high-current drive power converter IC for wearable medical devices

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Abstract: Nowadays multi-functional wearable devices generally require high current drive capability because microcontrollers (MCU) or rechargeable batteries are embedded inside. To achieve both high current and high power efficiency, this article presents a switched-inductor-based AC-DC buck converter that is implemented on a 0.18 µm chip manufacturing process for transcutaneously powered wearable devices. Different from multi-stage AC-DC converters that were widely used for wearable devices, the presented single-stage circuit has concise structure but provides flexible voltage output, high efficiency, and high current drive capability. The maximum output current can go up to 250 mA, and the peak efficiency is measured as 80.1% for 100 mA load current. The chip size is 185 µm × 260 µm.

Keywords: rectifier, AC-DC power converter, PWM rectifier, wearable biomedical devices, wireless power transfer

Classification: Electron devices, circuits, and systems

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DOI: 10.1587/elex.12.20150953
Received November 10, 2015
Accepted November 19, 2015
Publicized December 4, 2015
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1 Introduction

Wireless power transfer (WPT) is an emerging powering technique for medical implants or portable devices. All these devices have the same feature of no wire or physical contact between the device and the power source. Such design can keep devices isolated and avoid frequent battery replacement surgeries.

The general structure of a two-stage WPT system is shown in Fig. 1*a*. The focus of this paper is the power conversion efficiency through the power path. Fig. 1*b* shows AC-DC power conversion in the preceding stage of the power path, which contains half-bridge (HB) or full-bridge (FB) rectifier. The efficiency of such type can be poor with higher conduction loss. In addition, high input AC voltage could cause high dropout voltage and result in lower efficiency on the LDO that is used to regulate output voltage [1, 2]. Other than the diode bridge, Fig. 1*c* presents a comparator-based active rectifier to replace diodes in Fig. 1*b* [3]. This approach adopts excellent comparator-synchronized MOSFET technique and pushes the efficiency of the rectifier to higher level. However, the two-stage structure still exists and the large dropout voltage on LDO could degrade the overall efficiency when input AC amplitude is high.

Two similar methods were proposed afterwards to further enhance the efficiency. In Fig. 1*d*, the rectifier and the regulator circuits are combined together to form an adaptive rectifier or a *recti-gulator* [4, 5]. In [4], the behaviour of the regulating PMOS is similar to that of the LDO, whose PMOS is operating in the linear region. The problem of high dropout voltage in [4] is solved by the adaptive rectifier [5]. In this circuit, the rectifier output is controlled by a feedback loop and can be adjusted to an appropriate level before LDO. However, the maximum load current providing from the adaptive rectifier is limited. If load current requirement is increased to hundreds of milli-amps for the MCU or battery charger, an inductor based switching rectifier is a good candidate to enhance the current output ability. In Fig. 1*e*, one feed-forward AC-DC boost converter is proposed for the wearable biomedical devices [6]. This feed-forward structure allows the control of output voltage by external commands through a wireless link. However, the output voltage

DOI: 10.1587/elex.12.20150953
Received November 10, 2015
Accepted November 19, 2015
Publicized December 4, 2015
Copyedited December 25, 2015

could vary with the load current because there is no feedback from the output. Another similar structure for lower input frequency application (50 Hz) is presented in [7, 8]. Although this design has high efficiency and high current drive capability, its complex control to drive insulated-gate bipolar transistor (IGBT) in the power stage is not suitable for wearable devices.

Inspired from [7], this paper proposes a single-stage structure that could be gainfully applied to the wearable medical devices. Different from the operating case in [8], the proposed power device operates at high input AC frequency to achieve high efficiency in the WPT system. To meet the wearable size requirement, power MOSFETs are manufactured in CMOS process so that the entire circuit can be integrated in one chip. The initial concept of this work was first presented in [9] to show the effectiveness of the prototype. In this paper, a more compact design by reducing one more switch is presented. The associated switch control is also introduced to illustrate the functionality of the proposed device. Demonstration of experimental test follows to show the performance of the proposed circuit.

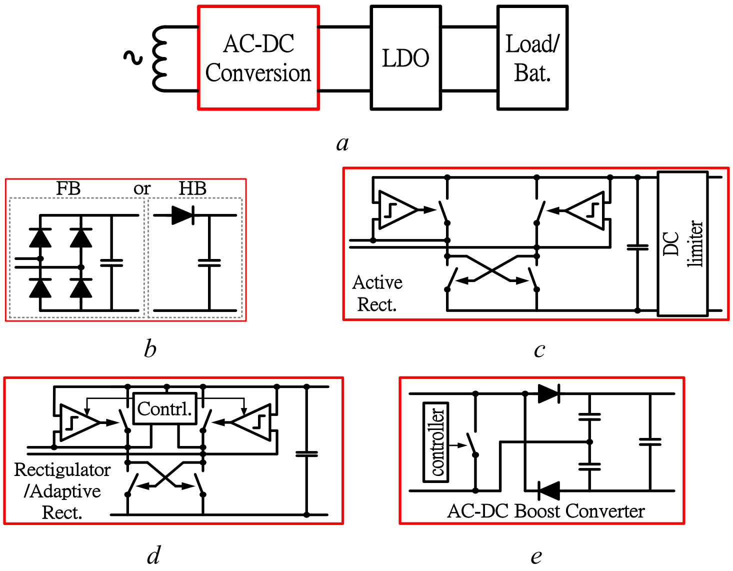

Fig. 1. Evolution of WPT for medical implant devices.
a General structure of WPT system
b Bridge rectifier and LDO [1, 2]
c Active rectifier, with/without DC limiter, and LDO [3]
d Rectigulator or adaptive rectifier and LDO [4, 5]
e Switching rectifier (Boost) and LDO [6]

2 Architecture and circuit operation

The power stage of the proposed circuit is shown in Fig. 2. The four PMOS transistors; MP3, MP4, MP5, and MP6, comprise the biasing circuit for transistors MP1 and MP2 [10]. According to the polarity of the AC voltage, the circuit can be considered as a normal buck converter in either positive or negative voltage cycle. Similar types of the power stage transfer function can be compensated by either a type-II or a type-III compensator [11]. In this case, we use a type-II compensator because there are fewer components in the compensation network than the type-III

DOI: 10.1587/elex.12.20150953
Received November 10, 2015
Accepted November 19, 2015
Publicized December 4, 2015
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compensator. To reduce the system noise, the bandwidth of the loop is selected at 50 kHz, and the phase margin is at 50 degree. There is a trade-off consideration in the inductor selection. The inductor size should be small for wearable device, but the inductance should be high enough to avoid reverse current. By specifying the load current at continuous conduction mode, our solution is employing an 8 µH inductor to fulfill the requirement.

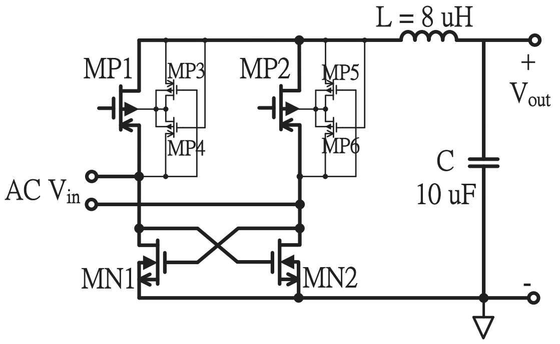

Fig. 2. AC-DC Buck converter with bias circuits for PMOS.

As shown in Fig. 3, the operating principle of the whole circuit is decomposed into 4 steps. When the input AC voltage is in positive period, the switches, MP1 and MP2, are synchronized to switch as depicted in Fig. 3*a* and Fig. 3*b*. First, the master switch, MP1, turns on to charge the inductor, and then MP2 turns on to continue providing the current when MP1 turns off. When the input AC voltage is in negative period, MP2 becomes the master switch, and the switches, MP1 and MP2, are synchronized to switch as shown in Fig. 3*c* and Fig. 3*d*.

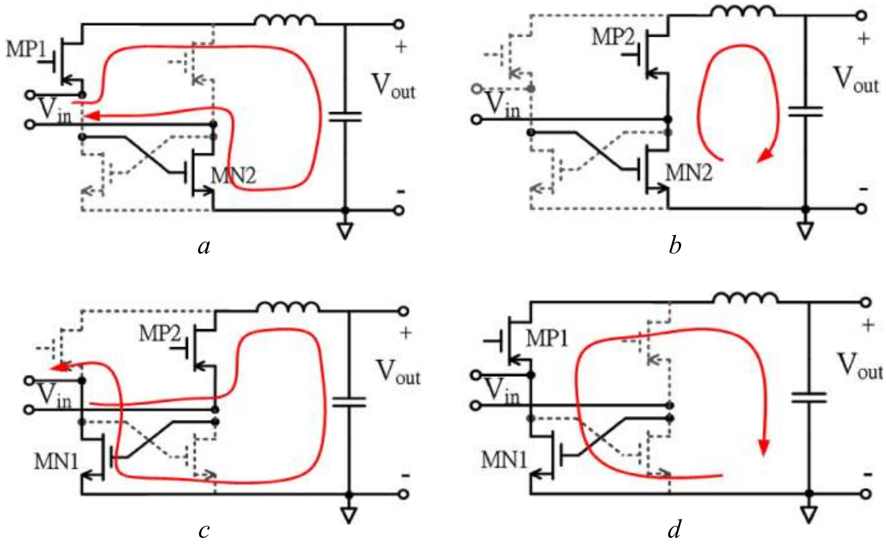

Fig. 3. Equivalent circuits for the proposed structure showing the current flow in positive and negative periods.
a V_{in} in positive period; MP1 master; charge L.
b V_{in} in positive period; MP2 synchronize; discharge L.
c V_{in} in negative period; MP2 master; charge L.
d V_{in} in negative period; MP1 synchronize; discharge L.

DOI: 10.1587/elex.12.20150953
Received November 10, 2015
Accepted November 19, 2015
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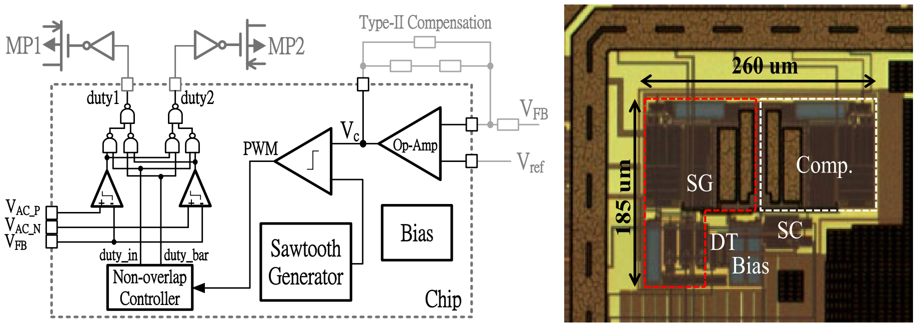
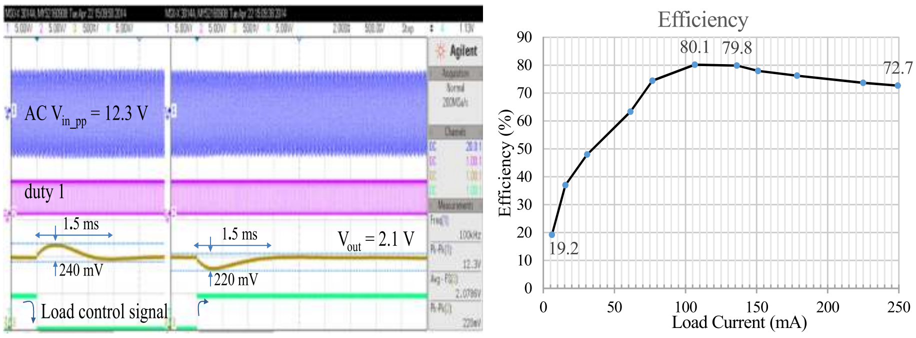
3 Implementation and test results

The control circuit diagram is shown in Fig. 4*a*. The die photo is shown in Fig. 4*b*. A simple voltage-mode controlled structure is implemented on a chip. Two comparators and several NAND gates are used as the switching controller to ensure the correct switching order of MP1 and MP2. A non-overlap controller inserts a tiny non-overlap zone between the switching signals to avoid MP1 and MP2 turning on at the same time. The switching frequency is 1.2 MHz which is determined by the saw-tooth signal generated from a saw-tooth generator. This design allows different application tests on this device by modifying those external elements outside the die envelope of Fig. 4*a*.



a b

Fig. 4. Control circuit diagram of the proposed device.
a Block diagram of the circuits.
b The die photo of the proposed controller. (SG: sawtooth generator; Comp.: comparator; DT: non-overlap controller; SC: switching controller)



a *b*

Fig. 5. Load transient and efficiency measurement results
a Output voltage response (load step: 1 to 100 mA)
b Measured efficiency versus load current from 1 to 240 mA.

Table I. Specification of the proposed circuit.

Process	V_{in_AC} (V_{pp})	V_{out} (V)	MAX. I_{out}	MAX Efficiency
0.18 µm	5~14	0.1~4.5	250 mA	80.1%
Size (mm^2)	f_{AC_input} (Hz)	f_{sw} (Hz)	Line-to-output gain	
0.0481	*100 k*	*1.2 M*	−48 dB @ *100 kHz*	

DOI: 10.1587/elex.12.20150953
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Accepted November 19, 2015
Publicized December 4, 2015
Copyedited December 25, 2015

The specification of the proposed circuit is listed in Table I. The input rejection ratio is −48 dB at 100 kHz which can be found from the line-to-output gain. The test of load transient is shown in Fig. 5*a*. When the load step is 100 mA up or down, the average overshoot or undershoot on the output voltage is 230 mV with a 1.5 ms recovery time. Fig. 5*b* shows that peak efficiency reaches 80.1% at 100 mA load current. When the load current is low, the switching loss weighs at relatively high percentage in total power consumption causing the efficiency to drop. To reduce this effect, the MOSFETs size needs to be considered carefully. The smaller the size of the MOSFETs, the higher the efficiency at light load. However, the small size results in a high conduction resistance which decreases the efficiency at heavy load. Regarding overall efficiency of AC-DC voltage regulation, the traditional power path generally uses two-stage topology, i.e., one rectifier and one switching converter. The state-of-the-art rectifier's efficiency is around 89% max. The switching converter's efficiency can reach 86% [12]. The combination of these two stages makes the overall maximum efficiency (from the coil to the battery) down to 64%. It is evident that the proposed circuit in this paper has superior efficiency (max at 80%) over that of the traditional topology.

4 Conclusion

A high efficiency fully integrated AC-DC buck converter for WPT is presented in this paper. The proposed structure has high current ability for wearable medical devices or small portable devices that inherit MCUs or wireless battery chargers. The single-stage AC-DC conversion design streamlines the elements of the power line, thus effectively improves the power efficiency of the overall WPT system.

DOI: 10.1587/elex.12.20150953
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Accepted November 19, 2015
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Copyedited December 25, 2015