A Power Conversion Chain by Coil Inductor Sharing in Voltage Converter Structure for Wireless Bio-Implants

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Abstract—**In this paper, a power receiver chain, reusing the power receiver coil to implement the converter is presented. This method reduces the size of the implant significantly and makes it suitable for wireless power transfer via inductive links in bio-implant applications. An active rectifier is employed to enhance the efficiency of the power receiver chain. In addition, four power switches are added to utilize the power receiver coil inductor in the structure of the converter. In the proposed technique, the power receiver chain efficiency becomes almost independent of the coil receiving voltage amplitude. The proposed concept is based on using buck-boost converter in wireless power transfer via inductive links. For the proposed structure, the simulation results are provided. With 10 MHz received signal and amplitude variation within 3~6 V and with the converter switching rate of 200 kHz, the achieved maximum efficiency is 78 %. The proposed regulator can also deliver 10 µA to 4 mA to its load while its output voltage varies from 0.6 V to 2.3 V. Simulations of the proposed converter are performed in Cadence-Spectre using TSMC 0.18 µm CMOS technology.**

Keyword: Buck-boost converters, AC to DC converters, voltage regulators, CMOS full-wave rectifiers, bio-implants, inductive power link.

I. INTRODUCTION

Nowadays, power transmission via inductive links for implantable medical devices (IMDs) becomes more important and pervasive. The reason is that it is an alternative for the battery powered cases and can decrease the total size of the IMD and reduce the probability of infection. A well-known application for IMDs is invasive wireless neural recording [1].

Power consumption and the chip area are two imperative issues that should be addressed in the design of IMDs and in some cases are the bottlenecks of the technology [1, 2]. Fig. 1 shows a typical power conversion chain (PCC) that uses in IMDs. As it can be seen in Fig. 1, the received power is AC and gives a sinusoidal voltage, which should be transformed to DC voltage. After rectification, there should be a regulator to maintain the output voltage at a certain level. So this voltage can be employed as a supply voltage for other parts of the implant. For this to be realized, several solutions have been already reported. The traditional alternative is to employ a linear regulator at the rectifier output. The variation of the regulator input voltage level is the main problem in this method. This may increase the voltage drop over the regulator and, as a result, the efficiency of the regulator is decreased. In inductive links, the regulator input voltage level can be significantly deviated from its specified level due to the variation of the received signal. Nonlinear regulators such as buck-boost converters can also be the solution for the mentioned problem. They can provide wide range of the output currents without the instability concerns. Furthermore, they can have several output voltages with different levels. Despite these superiorities, the frequently used large off-chip inductor in the conventional buck-boost converters can be troublesome. As a clarification, it is worth mentioning that this inductor is usually in the range of µH [2].

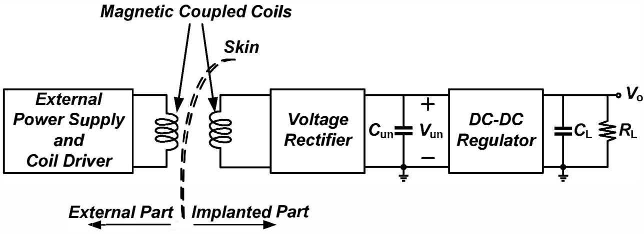

Fig. 1: Power conversion structure in bio-implant systems.

In this paper, a new method is developed in order to take advantages from the buck-boost converter while the need of its inherent large inductor is resolved. As it is known, a large off-chip coil is usually available in the power receiving part of the wireless bio-implants. The proposed idea is to reuse this coil in a different frequency as the inherent inductor in a buck-boost converter. In other words, in the proposed regulator, the power receiving coil is utilized in two different power receiving and regulator switching frequencies. This way, the buck-boost inherent off-chip inductor is avoided. The proposed regulator not only improves the efficiency but also it makes the efficiency to be almost independent of the received power signal amplitude. Furthermore, the proposed regulator is capable of producing DC voltages at levels higher or lower than the received voltage. To increase the total efficiency of the PCC, an active rectifier is employed before the voltage converter.

The rest of the paper is organized as follows. In Sect. 2, the theory and operation of the proposed converter are presented. Several circuit level simulation results of the proposed converter are provided in Sect. 3. Finally, the conclusions are given in Sect. 4.

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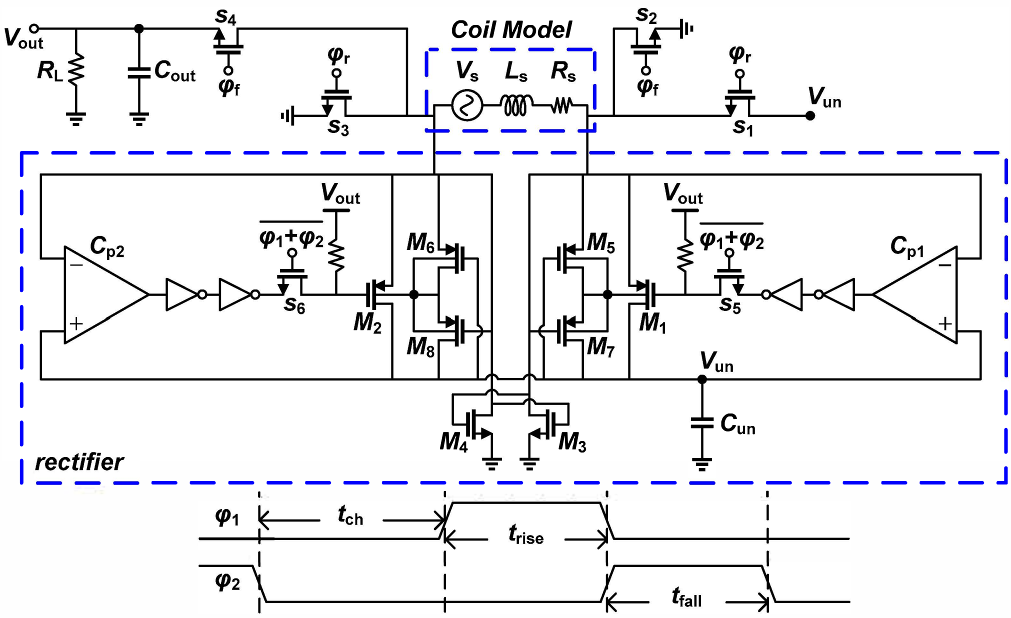


Fig. 2: Proposed inductor-reused buck-boost converter.

II. PROPOSED CONVERTER ARCHITECTURE AND OPERATION

A. Proposed Inductor-Reused Buck-Boost Converter

The proposed inductor-reused buck-boost converter is shown in Fig. 2. Here, the off-chip power-receiving coil is represented by L_s, R_s and V_s according to the simplified model introduced in [3]. In this model, L_s and R_s are self-inductance and series resistance of the IMD's coil and V_s is a sinusoidal voltage source which is induced by an outer coil. The frequency of V_s is considered to be f_1. L_s is a large off-chip inductor. So it can be a proper alternative to be reused in order to realize a buck-boost converter. To reach this goal, the timing in conventional buck-boost converters from two phases, should be changed into three phases. In the first phase, the power from the coil is received and then it is stored in a capacitor located at the output of the rectifier. Two other phases are utilized in the buck-boost operation to convert the initial voltage of the capacitor to a desirable DC voltage level. This way, the coil is reused in two different timing intervals notated as the power receiving phase and buck-boost operation, respectively. The only difference of the proposed buck-boost operation phase with the conventional buck-boost converters is that unlike the DC voltage source, the initial voltage of the capacitor should be applied as the input of the proposed converter.

In Fig. 2, φ_1 and φ_2 are connected to φ_r and φ_f terminals, respectively. In the next section, it will be seen that φ_2 will be the input of the control unit and the output of the control unit will be connected to φ_f terminal. The utilized full-wave active rectifier is comprised of the M_1-M_8 transistors [4]. According to φ_1 and φ_2, the proposed inductor-reused buck-boost converter has three phases of the operation. During the first phase, the level of φ_1 and φ_2 is low and thus S_1-S_4 switches are open. In this phase, the rectifier charges C_{un} to its maximum value, which is equal to V_s amplitude. This voltage will be used as the initial voltage for C_{un} at the start of the next phase. The pulse repetition frequency of φ_1 and φ_2 in Fig. 2 should be much lower than f_1 to give enough time to the capacitor to be charged by V_s. In other words, it takes several periods for V_s to charge C_{un} to its maximum value, depending on the value of C_{un} and amplitude of V_s. So the period of φ_1 and φ_2 should be larger than the period of V_s. In the second phase, only $S_{1,3}$ switches are closed and the energy stored in C_{un} is discharged to L_s. During the last phase, $S_{1,3,5,6}$ switches are open and $S_{2,4}$ switches are closed. Consequently, L_s delivers its energy to C_{out} in order to drive the load.

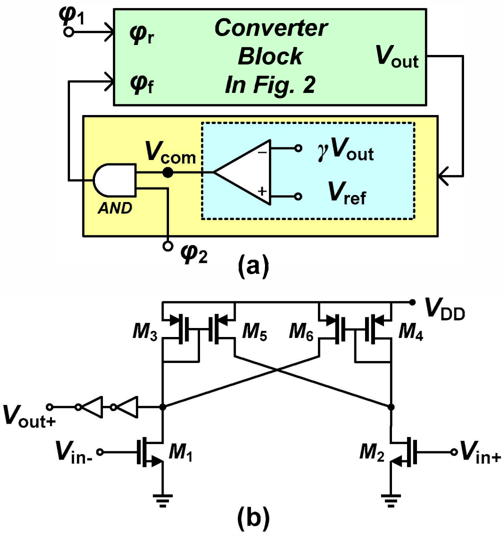
B. Control Unit of the Proposed Converter

The output voltage in Fig. 2 increases up to the maximum value that the converter produces at its output. To regulate the voltage at a certain level, a control unit is needed to limit the output voltage at the desired value. As is shown in Fig. 3(a), this control unit is employed in the feedback branch of the proposed converter. To realize V_{ref}, a CMOS voltage reference generator introduced in [5] is utilized. To regulate V_{out}, the control unit compares a fraction of that notated as γV_{out} with V_{ref} where γ is a resistive ratio of V_{out} that is realized by off-chip resistors. Furthermore, these off-chip resistors can be used to compensate the process variation errors of the reference voltage. In the comparison unit, If $\gamma V_{out} > V_{ref}$, the output of the comparator is low and S_2 and S_4 switches are off. Similarly, if $\gamma V_{out} < V_{ref}$, the output of the comparator is high and in φ_2, S_2 and S_4 switches are closed until the end of this phase. This way, the output is regulated. As it is shown in Fig. 3(b), the utilized comparators are conventional cross-coupled positive feedback amplifier. Here, γV_{out} is connected to V_{in-} and also V_{ref} and V_{com} are connected to V_{in+} and V_{out+}, respectively.

III. SIMULATION RESULTS

To evaluate the functionality of the power conversion chain, a design example of the proposed inductor-reused buck-boost converter and its simulation results is provided in this section. The simulations are performed in Cadence Spectre using TSMC CMOS 0.18 um technology. According to the experimental results, the values of L_s and R_s are considered to be 2 μH and 0.5 Ω, respectively [2]. For near-field in-body power transfer applications, frequencies about 10 MHz have minimum losses when passing through the body [6]. It is assumed $\omega_0 \approx 3\times\alpha$ [7] so it gives C_{un} = 200 nF, where $\omega_0 = 1/\sqrt{L_s C_{un}}$ is the resonance frequency and $\alpha = R_s/2L_s$ is the damping coefficient.

For the circuit shown in Fig. 2, the transient simulations are performed. In the absence of the control unit, the simulated transient current of the inductor in Φ_{rise} and Φ_{fall} is shown in Fig. 4. From equations (8) and (9) in [7], t_{rise} = 0.64 μs and $i_{t,r}(t = 0.64\ \mu s)$ = 330 mA. In power transfer via the inductive link, the received voltage amplitude rarely reaches to 10 V [8]. So, at the worst case, the amplitude of $i_{s,r}(t)$ is less than 80 mA, and therefore from the relation (11) in [7], the minimum value of $i_{L,r}(t)$ at the end of Φ_{rise} is obtained as 250 mA. The simulation result showing the current in Φ_{rise}, follows the equation (11) in [7] where a sinusoidal steady state current is summed with a transient current.



(a)

(b)

Fig. 3: (a) Control unit circuit of the proposed inductor-reused buck-boost converter and (b) Utilized comparator.

Transient simulations for the complete converter that is shown in Fig. 3(a) are performed assuming that the received voltage level and switching frequency are equal to 4 V and 200 kHz, respectively. Also, the output voltage of the circuit is considered to be 1 V. The simulated output in different process and temperature corner cases are illustrated in Fig. 5. It can be seen that for the worst case the maximum output voltage error is less than 20 mV. In addition, simulation results show that the maximum voltage ripple is 0.5 mV at a 1 mA load current.

According to the measurement results in [8], here, it is assumed that the voltage amplitude of the received AC signal across the coil varies in the range of 3~6 V. By using the nonlinear regulator introduced here for IMD applications, the variation of the efficiency is less than 8 % for this range of input voltage while its maximum efficiency is 78 %.

It should be noted that, the utilized rectifier in the proposed converter is taken from [4] and its efficiency is not included in the calculations. This is because in this paper, only the DC to DC converter is studied. As in the other similar works, only the converter results are reported.

The performance summary of the proposed buck-boost converter in comparison with several other works is given in Table 1. It should be mentioned that in the comparison table, the effect of the rectifier circuit is excluded in all of the referred works and also in our proposed converter. Although the proposed inductor reused buck-boost converter has the smallest inductor, its maximum power efficiency is comparable with other works.

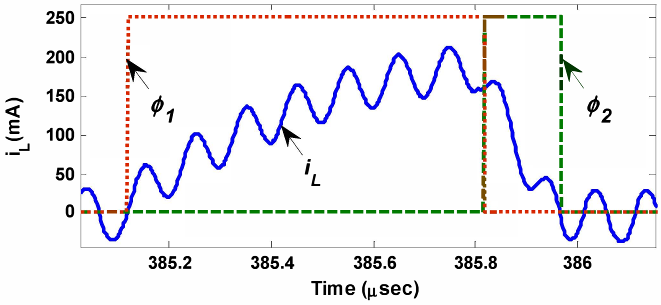


Fig. 4: Inductor current of the proposed converter in Fig. 2 in φ_1 and φ_2.

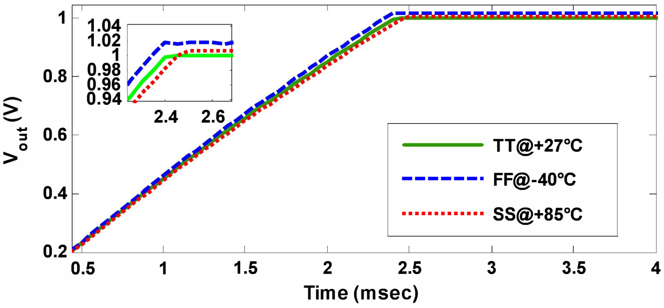


Fig. 5: Output voltage of the circuit in Fig. 3(a) in different process corner cases for V_{out} = 1 V.

Table 1: Performance summary and comparison.

Parameter	JSSC'15 [9]	TPE'13 [10]	NORCAS'15 [11]	This work***
CMOS process	0.18 um	0.35 um	0.18 um	0.18 um
Architecture	Buck-Boost	Buck-Boost	Buck-Boost	Buck-Boost
Input DC voltage*	3 V	2.5 V ~ 5 V	0.9 V ~ 2.2 V	1.5 V ~ 3.5 V
Output DC voltage	1 V, 1.8 V, 3 V	3.3 V	0.9 V ~ 2.2 V	0.6 V ~ 2.3 V
Output current	1 mW ~ 10 mW**	300 mA	200 mA	10 uA ~ 4 mA
Inductor	10 µH	18 µH	4.7 µH	2 µH
Output capacitor	10 µF	47 µF	10 µF	10 µF
Switching frequency	312.5 Hz	500 kHz	0.7 MHz ~ 1.3 MHz	200 kHz
Maximum efficiency	83 %	65 %	75.6 %	78 %
Line regulation	-	-	0.05 V/V	0.048 V/V
Load regulation	-	-	-	0.027 V/V
Maximum ripple	-	-	±5 mV	±0.5 mV

* After rectification if required.
** The output power is reported.
***Simulation results.

IV. CONCLUSIONS

In this paper, realization of a power receiver chain for power transferring through the inductive links, especially for the bio-implant applications, is introduced. By reusing the inherent inductor of the coil, the large off-chip inductor of the conventional buck-boost converter is eliminated. In addition, by employing an active rectifier the efficiency of PCC is enhanced, significantly. According to the simulation results, the performance of this PCC is comparable with other works. The efficiency of the proposed PCC is almost independent of the received voltage amplitude. So, it can be regarded as a suitable alternative for PCCs with linear regulators utilized in power receiving inductive links. The main superiority of the proposed PCC is that it utilizes only four power switches and a low power control unit to implement the converter. This way, a voltage converter with a lower complexity is achieved. The simulation results confirm that it can be a proper choice for low-power bio-implant applications.

REFERENCES

[1] D. A. Schwarz, M. A. Lebedev, T. L. Hanson, D. F. Dimitrov, G. Lehew, J. Meloy, et al., "Chronic, wireless recordings of large-scale brain activity in freely moving rhesus monkeys," *Nature methods*, vol. 11, no. 6, pp. 670-676, Jun. 2014.

[2] M. Kiani, M. Ghovanloo, "A 13.56-Mbps Pulse Delay Modulation Based Transceiver for Simultaneous Near-Field Data and Power Transmission," *IEEE Trans. Biomed. Circuits Syst.*, vol. 9, no. 1, pp. 1–11, Feb. 2015.

[3] C.-J. Chen , T.-H. Chu , C.-L. Lin and Z.-C. Jou , "A study of loosely coupled coils for wireless power transfer" , *IEEE Trans Circuits Syst. II, Exp. Briefs*, vol. 57, no. 7, pp. 536 -540, Jul. 2010.

[4] H. Lee, M. Ghovanloo, "An integrated power-efficient active rectifier with offset-controlled high speed comparators for inductively-powered applications", *IEEE Trans. Circuits Syst. I Reg. Papers*, vol. 58, no. 8, pp. 1749-1760, Aug. 2011.

[5] L. E. Toledo, P. Petrashin, W. Lancioni, F. Dualibe, and L. Canali, "A low voltage CMOS voltage reference based on partial compensation of MOSFET threshold voltage and mobility using current subtraction," *IEEE Symp. Circuits Syst.*(*LASCAS*), pp. 1-4, Feb. 2013.

[6] Thotahewa, Kasun MS, Ahmed I. Al-Kalbani, Jean-Michel Redouté, and Mehmet Rasit Yuce, "Electromagnetic Effects of Wireless Transmission for Neural Implants," *In Neural Computation, Neural Devices, and Neural Prosthesis* (Z. Yang, ed.) pp. 1-22, Springer New York, 2014.

[7] M. Barati and M. Yavari "A power efficient buck-boost converter by reusing the coil inductor for wireless bio-implants," *International Journal of Circuit Theory and Applications*, DOI: 10.1002/cta.2320, Jan. 2017.

[8] R. R. Harrison , P. T. Watkins , R. J. Kier , R. O. Lovejoy , D. J. Black , B. Greger and F. Solzbacher, "A low-power integrated circuit for a wireless 100-Electrode neural recording system," *IEEE J. Solid-State Circuits*, vol. 42, no. 1, pp. 123 -133, Jan. 2007.

[9] G. Yu, K. W. R. Chew, Z. C. Sun, H. Tang, and L. Siek, "A 400 nW Single-Inductor Dual-Input-Tri-Output DC-DC Buck-Boost Converter With Maximum Power Point Tracking for Indoor Photovoltaic Energy Harvesting," *IEEE J. Solid-State Circuits*, vol. 50, no. 11, pp. 2758-2772, Nov. 2015.

[10] J. J. Chen, P. N. Shen, and Y. S. Hwang, "A High-Efficiency Positive Buck-Boost Converter With Mode-Select Circuit and Feed-Forward Techniques," *IEEE Trans. Power Electronics*, vol. 28, no. 9, pp. 4240-4247, Sept. 2013.

[11] J. S. Kim, J. Y. Lee, and B. D. Choi, "High-efficiency peak-current-control non-inverting buck-boost converter using mode selection for single Ni-MH cell battery operation," *Nordic Circuits and Syst. Conf.* (*NORCAS*), pp. 1-4, Oct. 2015.