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A High-Efficiency Energy Harvesting Interface for Implanted Biofuel Cell and Thermal Harvesters

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Abstract—A dual-source energy harvesting interface that combines energy from implanted glucose biofuel cell and thermoelectric generator is presented. A single-inductor dual-input dual-output boost converter topology is employed to efficiently transfer the extracted power to the output. A dual-input feature enables the simultaneous maximum power extraction from two harvesters, while a dual-output allows a control circuit to perform complex digital functions at nW power levels. The control circuit reconfigures the converter to improve the efficiency and achieve zero-current and zero-voltage switching. The measurement results of the proposed boost converter, implemented in a 0.18 μm CMOS process, show a peak efficiency of 89.5% when both sources provide a combined input power of 66 μW . In the single-source mode, the converter achieves a peak efficiency of 85.2% at 23 μW for the thermoelectric source and 90.4% at 29 μW for the glucose biofuel cell. The converter can operate from minimum input voltages of 10 mV for the thermoelectric source and 30 mV for the glucose biofuel cell.

Index Terms—Energy harvesting, DC-DC power conversion, CMOS integrated circuits, thermoelectric energy conversion, fuel cells.

I. INTRODUCTION

RECENT advances in sensor technologies and ongoing miniaturization of electronics have encouraged the development of implantable devices for many medical applications. Nevertheless, there are still many challenges to overcome in terms of lifetime, size, safety and biocompatibility in order to facilitate the further expansion of implants into numerous pending applications. In this context, energy harvesting plays a key role as an enabling technology for the next generation of fully autonomous, miniature and reliable implants. However, harvesting solutions for implantable biomedical systems are very difficult to implement due to many limitations emerging from a severely constrained size, an extremely low available power and a very high reliability. Potential sources for implantable harvesting include some well-established sources such as thermoelectric [1], but also some emerging ones such as glucose biofuel cells [2] or endocochlear potential [3]. Harvesting energy from multiple sources in parallel can be considered to further improve the system reliability and increase the available power.

Various techniques to tackle numerous challenges related to ultra-low voltage/power energy harvesting technologies have been proposed in the recent literature. For instance, a fully integrated startup technique that cold-starts the system from only 70 mV has been proposed in [4]. In [5], an asynchronous control circuit is employed to achieve high efficiency (>80%) at sub- μW power levels. Finally, [1] has demonstrated the in-vivo

operation of an autonomous energy harvester for implantable biomedical applications. Unfortunately, these solutions rely on a single source to power the system. Due to the unpredictable nature of energy harvesting, any single-source setup raises potential reliability issues which are especially problematic in implantable applications. A multi-source platform that combines power from solar, thermal and vibration sources using a single inductor has been proposed in [6] to improve the overall reliability. A highly efficient (>80%) multi-source power management system is presented in [7]. However, these solutions are efficient at either higher power levels (>1 mW) [6] or higher voltages (>0.5 V) [7] than those available in implantable applications. In this work, a reliable, multi-source energy harvesting interface is proposed to cope with extremely low voltage/power levels generated by implanted biofuel cells and thermoelectric harvesters. A design strategy is proposed and used to optimize the conversion efficiency for varying input voltages of both harvesters simultaneously. A digitally intensive nW control circuit reconfigures the converter to achieve the maximum power extraction, minimize the losses and reduce its own power consumption at the same time. Finally, dynamic frequency scaling reduces the switching losses while the zero-current switching and zero-voltage switching techniques eliminate the synchronization losses of the converter. This paper is organized as follows. Section II discusses the challenges related to self-powered implantable biosensors. Section III introduces the boost converter architecture. Section IV presents the design and control strategy for achieving high efficiency and explains the implementation of critical building blocks. Section V highlights the measurement results. Finally, Section VI concludes the paper.

II. CHALLENGES FOR ENABLING SELF-POWERED IMPLANTABLE BIOSENSORS

The power consumption of an implantable biosensor depends greatly on its application. In general, the required rate of sensing and the amount of transmitted information associated with the specific application define the power demand of a biosensor. Fortunately, most of the underlying biosignals sensed by biosensors change slowly. As a result, the required data rate is relatively low. This allows biosensors to sense, transmit and receive information infrequently. At the same time, the system can tolerate aggressive duty-cycling manifested through long inactive periods (sleep states). Duty-cycling with ultra-low power sleep states can significantly reduce the average power consumption of a biosensor system

Fig. 1. System architecture of the boost converter.

and potentially enable self-powered implantable biosensors, provided that a suitable energy storage mechanism is properly incorporated within the system. Nevertheless, the average harvested power still has to be higher than the average power consumption of the biosensor system [8].

Currently, state-of-the-art harvesting devices have reached useful power densities at miniature sizes, some reaching tens of $\mu\text{W}/\text{cm}^3$ [9], [10]. Among the sources suitable for implantable applications, thermoelectric generators (TEGs) stand out by achieving the highest power densities, more than $100 \mu\text{W}/\text{cm}^3$ [9]. In addition, TEGs are biocompatible, exhibit a long lifetime and have a fixed internal resistance, which simplifies the maximum power extraction (MPE) algorithms. In typical conditions (temperature difference across the plates of around 2 K), TEGs are capable of providing 60 mV voltage and $17 \mu\text{W}$ power to a matched load [1], [9]. At the same time, glucose biofuel cells (GBFCs) emerge as a very promising forthcoming solution. GBFCs have shown remarkable improvement in their performance during the last several years, especially in terms of achievable power density. Besides high power density ($16 \mu\text{W}/\text{cm}^3$), recent non-enzymatic glucose biofuel cell have demonstrated good long-term stability and

biocompatibility [10]. In addition, these GBFCs manifest fixed internal resistance, so their equivalent electrical circuit is similar to the equivalent circuit of TEGs, as it is illustrated in Fig. 1. In typical conditions (glucose concentration of 5 mmol L^{-1}), GBFCs provide voltages around 180 mV and power levels around $16 \mu\text{W}$ to a matched load. Theoretically, both harvesters are able to provide sufficient power for the majority of duty-cycled implantable biosensors. However, an implantable biosensor should not rely on a single-source harvesting which is, by nature, sporadic and unpredictable. Therefore, in this work, a multi-source energy harvesting is considered to circumvent potential reliability issues. The harvested energy from a TEG and a GBFC is combined in a multi-source energy harvesting interface, which is customized to operate efficiently at extremely low input voltage/power levels.

III. MULTI-SOURCE ENERGY HARVESTING INTERFACE

Multi-source energy harvesting can provide substantial improvement over single-source harvesting in terms of overall system reliability and robustness. Depending on the incorporated harvesters, it can also significantly increase the attainable

output power, allowing additional functionality and/or higher activity of the biosensor system. However, these benefits come at the cost of increased interface complexity. Moreover, the physical size of the system may expand due to the need of additional external components to accommodate multiple power paths. Therefore, special design techniques such as inductor sharing are necessary to keep a low number of external components, and maintain a miniature form-factor, which is crucial for implantable applications [6], [7]. Inductor sharing, high reconfigurability and techniques for simultaneous maximum power extraction (MPE) from multiple sources further increase the complexity of the energy harvesting interface. For this reason, a digitally controlled dual-output topology is utilized [11]. This topology allows adding complex digital functionality at a relatively low price in terms of power consumption. Fig. 1 shows the architecture of the proposed single-inductor dual-input dual-output boost converter. It consists of an inductor sharing block, a DC-DC core circuit and a control block.

The converter presents two different equivalent input resistances, R_{IN1} to the GBFC harvester and R_{IN2} to the TEG. In order to achieve MPE for both inputs at the same time, these resistances are matched with the internal resistances of the harvesters, R_{GBFC} and R_{TEG} , respectively. The inductor sharing block grants inductor access to one harvester at the time, alternately. The connected harvester uses the inductor for one or more switching cycles before it is disconnected again. By default, the converter is configured as dual-input, which means that it harvests and combines the energy from both sources at the same time. If needed, the converter can be also reconfigured into a single-input topology by permanently disconnecting (disabling) one of the inputs. In every cycle, the energy extracted from the harvesters is transferred to one of the outputs. The outputs handling is similar to [11]. The digital signal V_{ST_OK} controls the switch which connects the load to the main output when enough energy is accumulated in the storage capacitor, C_{ST} , and disconnects the load when the voltage of the main output, V_{ST} , drops below 1.8 V. The control block is powered from the second output, V_{CTRL} , which is regulated at a lower voltage of around 1 V. The harvested energy is transferred to the second output when V_{CTRL} drops below 1 V. A reduced voltage supply and a relatively low operating frequency restrains the power consumption of the digital control block at nW levels. As a result, it is possible to significantly increase the control complexity by adding additional digital functionality and reconfigurability, while keeping its contribution to the total losses at very low levels.

The control block consists of multiple sub-blocks, including a state machine, clock generator, switch control, switch drivers and supporting circuits. The state machine decides which harvester should be used, controls the switching frequency and adjusts the duration of all control signals according to the current state of the system. The clock generator provides clock signals for other sub-blocks within the control circuit. The switch control sub-block generates switches' control signals corresponding to the digital information provided by the state

machine. Supporting circuits provide the biasing current and voltage reference, power the switch drivers and handle the output voltages. A detailed discussion of the control sub-blocks is covered in Section IV.

IV. DESIGN STRATEGY FOR POWER EFFICIENCY

The energy harvesting interface has to extract the maximum possible power from the harvesters and efficiently transfer the harvested energy to the storage capacitors. The proposed design strategy optimizes the efficiency of the interface for varying input voltage/power levels of both harvesters by keeping the total losses and the control power consumption minimum at any moment. It also assures that the MPE is achieved for both sources at any moment. The design strategy is carried out using a highly reconfigurable control circuit.

A. Efficiency Optimization

Efficiency optimization in energy harvesting interfaces implies that the optimal values of certain design parameters (switching frequency, power transistors' widths and inductor value) are determined in order to maximize the conversion efficiency. This technique is introduced in [12] to minimize the total losses within the converter and extended in [11] to include also the power consumption of the control circuitry. In both of these solutions, the optimal parameters are obtained and fixed according to a typical value of the input voltage. If the input voltage departs from the typical value, the optimal values shift and should be readjusted accordingly in order to improve the efficiency. There are three possible methods to perform this improvement. The first method is to adjust the power transistors' widths to track the optimal values [13]. This technique is relatively simple to implement and successfully reduces the total losses of the converter. However, it does not address the power consumption of the control circuit which becomes dominant at very low power levels. The second method is to scale up/down the switching frequency of the converter as the input power changes. This solution is very effective since it reduces the sum of the total losses and the power consumption of the control circuit. On the other hand, it complicates the MPE setting because the input equivalent resistance of the converter changes with the switching frequency. The third method involves jointly adjusting the power transistors' widths and the switching frequency. This solution is the most accurate in tracking the actual optimal values but it is also the most complex. Note that adjusting the value of an external inductor is not considered here since it is highly impractical.

The achievable efficiency improvement of each method can be derived by estimating the sum of losses, similarly as in [12] and [11]. The analysis is performed considering only a single source (GBFC in this particular case) for the sake of simplicity. However, the losses related to the additional switch in the power path (for inductor sharing) are included. This switch contributes with conduction and switching losses whose sum can be expressed as:

$$P_{loss,EN} = \frac{2\sqrt{2}V_{IN}^2 R'_{IN}}{3\sqrt{R_{IN}^3 f_s L}} \frac{1}{W_{EN}} + kC'_{IN} V_{ST}^2 f_h W_{EN}, \quad (1)$$

Fig. 2. Efficiency comparison of the three improvement techniques with the original technique with fixed optimal values.

where f_s is the switching frequency of the converter, f_h is the frequency of connecting different harvesters, k is the power consumption factor of a driver circuit, R'_N is the resistance per unit width, C'_N is the gate capacitance per unit width and W_{EN} is the width of the inductor sharing switch. It is interesting to notice that, if the leakage losses are neglected, the relations between the optimal transistors' widths can be derived [13] as:

$$\frac{W_{EN,opt}}{W_{N,opt}} \approx \sqrt{\frac{f_s}{f_h}}, \quad (2)$$

$$\frac{W_{N,opt}}{W_{P,opt}} \approx \sqrt{\frac{\mu_P V_{ST}}{\mu_N V_{IN}}}, \quad (3)$$

where μ_N and μ_P are the charge-carrier mobilities of nMOS and pMOS transistors, respectively. From (1) it can be seen that f_h should be as low as possible in order to minimize the switching losses of the enable switch. However, reducing f_h increases the time of charging and discharging the input capacitor, which leads to a higher input ripple, unless the input capacitor is increased. Therefore, to keep the input ripple relatively low and to maintain the input capacitor in the range of μF for a small form-factor, f_h is set to 1 kHz. In calculations, the input resistance is assumed to be equal to 2 k Ω and matched to the internal resistance of the GBFC. The voltages V_{ST} and V_{CTRL} are set to 1.9 V and 1 V, respectively. The parasitic capacitance at node X, C_X , is estimated to 15 pF and the total parasitic series resistance, R_{par} , to 0.3 Ω . The fixed optimal values are $L_{opt} = 100 \mu\text{H}$, $f_{s,opt} = 5 \text{ kHz}$, $W_{P,opt} = 1 \text{ mm}$, $W_{N,opt} = 2 \text{ mm}$ and $W_{EN,opt} = 4 \text{ mm}$. These values are obtained for V_{IN} of 180 mV, which is expected in the typical conditions. The comparison of all three techniques and the original technique with fixed optimal values is shown in Fig. 2. According to this comparison, the second method (frequency adjusting) provides the best performance/complexity trade-off. For this reason, the adaptive frequency is employed in this work.

Fig. 3 illustrates how the optimal switching frequency of the converter changes with the input voltage. In practice, only a

Fig. 3. Calculated and implemented switching frequency.

limited number of switching frequencies can be implemented without substantially increasing the control's complexity and power consumption. In this design, 4 different frequencies (1 kHz, 2 kHz, 4 kHz and 8 kHz, as it is shown in Fig. 3) provide the best trade-off between performance and complexity in terms of maximizing the achievable efficiency. In addition, in this particular case of GBFC/TEG energy harvesting, it is possible to use the same 4 frequencies for both harvesters without notably sacrificing the overall efficiency.

B. Maximum Power Extraction

The converter is operating in the discontinuous conduction mode (DCM), which allows changing the input harvester without disrupting the operation of the converter. At the same time, the converter can present different equivalent input resistances to different inputs [6]. Therefore, the MPE can be achieved for both sources simultaneously if $R_{IN1} = R_{GBFC}$ and $R_{IN2} = R_{TEG}$ at any moment. Assuming that $V_{ST} \gg V_{IN1}$ and $V_{ST} \gg V_{IN2}$, the equivalent input resistances can be expressed as [14]:

$$R_{IN1} \approx \frac{2L}{\tau_{N,GBFC}^2 f_{s,GBFC}}, \quad (4)$$

$$R_{IN2} \approx \frac{2L}{\tau_{N,TEG}^2 f_{s,TEG}}, \quad (5)$$

where $\tau_{N,GBFC}$ and $\tau_{N,TEG}$ are the durations of the nMOS switch ON time when the GBFC and TEG are connected, respectively, and $f_{s,GBFC}$ and $f_{s,TEG}$ are the effective switching frequencies of the converter seen by the GBFC and TEG, respectively. The effective frequency is f_h multiplied by the number of converter's switch cycles during the time that the particular harvester is connected. As it can be seen from (4) and (5), changing the switching frequency of the converter also changes the equivalent input resistances, leading to a disturbed MPE. To mitigate this issue, every time the switching frequencies are changed, the durations of the nMOS switch ON times are changed accordingly so that the input resistances remain constant.

Fig. 5. Switch control sub-block.

Fig. 4. Logic flow chart of the state machine.

C. Control Strategy and Implementation

The control circuit is based on digitally controlled delay elements that set the durations of all relevant pulse signals and delays in order to achieve the MPE and eliminate synchronization losses. All delay elements are controlled by a state machine. The state machine also controls the switching frequencies and inductor sharing. The state machine is based on 4 different counters (1 and 2 for the TEG and 3 and 4 for the GBFC). The output of the 4-bit Counter 1, $s_1(3:0)$, is responsible for fine tuning the duration of the pMOS switch ON time, $\tau_{P,TEG}$, as well as the dead time, $t_{d,TEG}$. The value

of the 2-bit Counter 2, $s_2(1:0)$, sets $f_{s,TEG}$ and $\tau_{N,TEG}$, and provides the coarse tuning of $\tau_{P,TEG}$ and $t_{d,TEG}$. Similarly, the 4-bit Counter 3 and the 2-bit Counter 4 are responsible for setting the signals related to the GBFC. The logic flow chart of the state machine is illustrated in Fig. 4. The state machine first decides which harvester to use based on clk_H signal provided by the clock generator. For instance, $clk_H = 0$ means that the TEG is connected during that half period. Afterwards, according to the 2-bit digital signal, b_1b_0 , the state machine updates the value of the Counter 1 or stops both counters. The signal b_1b_0 is obtained from sensing the voltage at node X, V_X , and provides the information whether $\tau_{P,TEG}$ is long ($b_1b_0 = 00$), short ($b_1b_0 = 11$) or accurate ($b_1b_0 = 10$). The reading $b_1b_0 = 01$ is not used. The counters are stopped when $\tau_{P,TEG}$ reaches the accurate value. When the Counter 1 reaches the limits of the range, the next up/down command resets/sets the Counter 1 and updates the value of the Counter 2. Then the state machine repeats the cycle. Lets assume that temperature gradient around the TEG drops. Consequently, V_{TEG} and V_{IN2} are reduced, $\tau_{P,TEG}$ becomes longer than accurate, sensing of V_X returns $b_1b_0 = 00$ and, finally, the Counter 1 value is decreased. This process may be repeated a few times until the accurate $\tau_{P,TEG}$ is reached again. If the value of the Counter 1 was already 0, it is then set to 15 and the value of the Counter 2 is decreased. As a result, the switching frequency is scaled down and $\tau_{N,TEG}$, $\tau_{P,TEG}$ and $t_{d,TEG}$ are adjusted accordingly. Note that for $clk_H = 1$, the state machine enters the other branch of the flow chart, which is not shown in the figure for the sake of simplicity. The other branch is equivalent to the shown one, except that the counters in the other branch (3 and 4) are setting the parameters and signals related to the GBFC. The counters in charge of the GBFC are independent of the counters that are in charge of the TEG. Therefore, they produce separate switching frequencies, durations and delays. Nevertheless, they share the circuits for generating the output controlling signals by using multiplexers. Accordingly, the output signals of the state machine $set_{(3:0)}$ and $sel_{(1:0)}$ take the value of the counters in

Fig. 6. Clock generator.

Fig. 7. Die photo of the test chip.

one of the branches depending on which input is used at the moment.

The implementation of the proposed switch control sub-block is shown in Fig. 5. The delay elements of the nMOS pulse generator are implemented as loaded current starved buffers. The delay is digitally programmable to provide 8 different durations (4 for each harvester). The durations are set so that the input resistances given by (4) and (5) remain constant when the effective frequencies are changed. This guarantees that the MPE for both harvesters is achieved. The digitally controlled pulse of the pMOS one-shot generator exhibits 64 different durations. The pulse duration is controlled by 2 bits that perform coarse and 4 bits that perform fine tuning. The durations of the pMOS switch ON times are considered accurate when zero-current switching (ZCS) is obtained. Finally, the dead time generator presents 8 different durations which are controlled through the nonlinear decoder using 6 bits in total. The dead times are set in order to obtain zero-voltage switching (ZVS).

The proposed implementation of the clock generator is shown in Fig. 6. The outputs of the current starved ring oscillator are processed through the frequency dividers and multiplexed to obtain 4 clock signals clk_H , clk_N , clk_D and clk_C that are delayed with respect to each other. The clock for selecting the harvester, clk_H , operates at a fixed frequency of 1 kHz, while the remaining 3 clocks can be controlled to

work at one of 4 different frequencies of 1 kHz, 2 kHz, 4 kHz and 8 kHz depending on the signal $sel_{(1:0)}$.

The switch drivers modify the high level of the digital signals and drive the gates of the switches using levels shifters and tapered buffers. The supporting circuits (current and voltage reference, voltage divider, voltage monitor and supply multiplexer) are similar to [11].

V. MEASUREMENT RESULTS

The proposed single-inductor dual-input dual-output boost converter was implemented in a $0.18 \mu\text{m}$ CMOS process. The chip die photo (total area of 2.3 mm^2) is shown in Fig. 7. A quad-flat no-lead package (QFN), $5 \text{ mm} \times 5 \text{ mm}$, is used to minimize the losses from parasitics. The off-chip components include a $100 \mu\text{H}$ inductor L ($4.8 \text{ mm} \times 4.8 \text{ mm} \times 2.8 \text{ mm}$, number 744043101 [15]), a $4.7 \mu\text{F}$ input capacitor C_{IN1} , a $10 \mu\text{F}$ input capacitor C_{IN2} , a 100 nF storage capacitor C_{ST} and a 30 nF control supply capacitor C_{CTRL} . An external load switch (TPS22860 [16]) is used to connect the resistive load to the storage capacitor in order to model a duty cycled biosensor. This switch is turned ON/OFF by the V_{ST_OK} signal from the chip. The capacitor C_{CTRL} was precharged to 1 V to start-up the converter. The equivalent circuits of the GBFC and TEG were used to characterize the converter, as it is shown in Fig. 1. The parameters of the equivalent circuits correspond to the devices presented in [10] for the GBFC ($R_{GBFC} = 2 \text{ k}\Omega$) and in [9] for the TEG ($R_{TEG} = 210 \Omega$). The chip has 3 different modes of operation. It can operate as the single-source TEG interface, a single-source GBFC interface or a multi-source TEG and GBFC interface. In the single-source mode, one of the inductor sharing switches (M_{GBFC} or M_{TEG}) is always ON while the other is always OFF to reduce their switching losses. In addition, the driving signals related to the unused input are also disabled to save the power in the control circuitry. The mode is set externally using 2-bit digital signal $mode_{(1:0)}$ (in Fig. 1).

The converter was initially set to multi-source mode of operation and the voltages of the equivalent circuits, V_{GBFC} and V_{TEG} , were fixed to their typical values of 360 mV and 120 mV, respectively. The measured input voltages of the converter, V_{IN1} and V_{IN2} , are shown in Fig. 8a. Harvesters are connected to the converter alternately for a half period of clk_H (approximately $500 \mu\text{s}$). When GBFC is connected (switch M_{GBFC} is ON), the converter transfers the harvested energy from the input capacitor C_{IN1} to the output for 8 switching cycles. During this period, the TEG is disconnected (switch M_{TEG} is OFF), so its generated energy is accumulated in the input capacitor C_{IN2} . Similarly, when TEG is connected, C_{IN2} is charged while C_{IN1} is discharged. The average values of the input voltages, V_{IN1} and V_{IN2} , are relatively close to $V_{GBFC}/2$ and $V_{TEG}/2$, respectively, so the MPE is achieved for both harvesters. The measured output voltages, V_{ST} and V_{CTRL} , and the load voltage, V_L , are shown in Fig. 8b. The harvested energy is transferred to C_{CTRL} only when V_{CTRL} drops below 1 V. Otherwise, the energy is accumulated in C_{ST} . The load (a $47 \text{ k}\Omega$ resistor) is connected when V_{ST}

Fig. 8. Measured waveforms: (a) input voltages of the converter, (b) output voltages and the voltage across the load.

Fig. 9. Measured voltage at node X for 4 different combinations of input voltages: (a) $V_{IN1} = 180 \text{ mV}$, $V_{IN2} = 40 \text{ mV}$, (b) $V_{IN1} = 160 \text{ mV}$, $V_{IN2} = 20 \text{ mV}$, (c) $V_{IN1} = 140 \text{ mV}$, $V_{IN2} = 70 \text{ mV}$, and (d) $V_{IN1} = 40 \text{ mV}$, $V_{IN2} = 90 \text{ mV}$.

reaches 1.98 V and disconnected when V_{ST} drops to 1.74 V. Fig. 9 shows the measured voltage V_X for a few different combinations of input voltages. For instance, in Fig. 9a V_{IN1} is 180 mV, so when the GBFC is connected, the converter switches 8 times during the half period of clk_H . As a result, the effective frequency for GBFC is $8 \cdot f_h = 8 \text{ kHz}$. On the other hand, V_{IN2} is 40 mV, so during the half period for the TEG converter switches 2 times and the effective frequency is $2 \cdot f_h = 2 \text{ kHz}$. Note that τ_N is also changing according to the effective frequency to maintain the MPE.

The conversion efficiency is evaluated for all three modes of operation. Fig. 10a shows the theoretical and measured conversion efficiency versus input voltage V_{IN1} when only GBFC is connected. The input voltage V_{IN1} is varied from 30 mV to 250 mV. The efficiency is higher than 80% for the input voltages above 110 mV and it starts to drop more abruptly when the input voltage drops below 90 mV, which corresponds to the input power of $4 \mu\text{W}$. The converter shuts

down completely when the input voltage drops below 30 mV ($0.5 \mu\text{W}$). The theoretical and measured conversion efficiency versus input voltage V_{IN2} is shown in Fig. 10b. In this case when only TEG is connected, the voltage V_{IN2} is varied from 15 mV to 90 mV. The efficiency is higher than 80% for input voltages above 40 mV ($7.6 \mu\text{W}$). The converter is operating until the input voltage drops below 10 mV ($0.5 \mu\text{W}$). Fig. 10c shows the efficiency of the converter in the multi-source mode versus the total input power. The total input power represents the combined power from the GBFC and TEG. The individual input power of the harvesters are set to be approximately equal for every measurement point in the plot by properly choosing their input voltages. For instance, when the total input power is $30 \mu\text{W}$, the input power of the GBFC as well as of the TEG is approximately $15 \mu\text{W}$, and the input voltages are $V_{IN1} \approx 173 \text{ mV}$ and $V_{IN2} \approx 56 \text{ mV}$. This was the most intuitive way to characterize the efficiency in the multi-source mode, since one total input power point can be obtained by infinite combinations of individual ones. The measured efficiency of the converter in the multi-source mode is higher than 80% for the total input power above $9 \mu\text{W}$ and achieves a peak efficiency of 89.5% at the total input power of around $66 \mu\text{W}$.

This work is compared with the state-of-the-art multi-source [6], [7] as well as single-source energy harvesting interfaces [5], [11], [17], [18] in Table I. The proposed single-inductor dual-input dual-output boost converter provides the highest efficiency when the energy from multiple sources is combined. In addition, to the best of the authors' knowledge this paper presents the first reported highly efficient GBFC interface for implantable applications.

VI. CONCLUSION

This paper has presented a micropower energy harvesting interface for implantable glucose biofuel cell and thermoelectric harvesters. The dual-input topology has enabled extracting the maximum power from both harvesters simultaneously by using a single inductor. The dual-output feature has allowed adding intensive digital functionality in the control circuit for a relatively small power headroom. The nW control circuit reconfigures the converter to improve the efficiency

Fig. 10. Efficiency of the converter in the different modes of operation: (a) single-source only GBFC, (b) single-source only TEG and (c) multi-source GBFC and TEG.

TABLE I
COMPARISON OF THE CONVERTER WITH STATE-OF-THE-ART WORK.

	[5]	[11]	[17]	[18]	[6]	[7]	This Work
Year	2015	2016	2016	2015	2012	2016	2017
Process	0.18- μm	0.18- μm	0.32- μm	0.18- μm	0.35- μm	0.18- μm	0.18- μm
Sources	Single: PV	Single: TEG	Single: Any DC	Single: Microbial Fuel Cell	Multi: PV, Piezo and TEG	Multi: PV, Piezo and RF	Multi: GBFC and TEG
Output Voltage	2.9-4.1 V	1.9 V	1.8-3.3 V	0.9-1.2 V	1.9 V	1-2 V	1.9 V
Min. Input Voltage	14 mV	15 mV	74 mV	200 mV	20 mV	50 mV	10 mV
Peak Efficiency	85% @ 1 μW	86.6% @ 30 μW	77.1% @ 400 μW	85% @ 10 μW	83% PV @ 1 mW 79% Piezo @ 220 μW 58% TEG @ 2 mW	85% PV @ 12 μW 87% Piezo @ 18 μW 80% RF @ 22 μW 80% Combined @ 30 μW	85.2% TEG @ 23 μW 90.4% GBFC @ 29 μW 89.5% Combined @ 66 μW

and achieve MPE, ZCS and ZVS. In the multi source mode, the converter achieves a peak efficiency of 89.5% at 66 μW and maintains a high efficiency of more than 80% for input powers above 9 μW . In the single source modes, the converter achieves peak efficiencies of 85.2% and 90.4% for TEG and GBFC, respectively. The converter operates properly with input voltages higher than 10 mV for TEG and 30 mV for GBFC, which corresponds to the input power of only 500 nW. Such performance makes this interface a strong candidate for enabling reliable self-powered implantable biosensors.

REFERENCES

- [1] D. Rozgic and D. Markovic, "A 0.78 mW/cm² Autonomous Thermoelectric Energy-Harvester for Biomedical Sensors," in *IEEE Symp. VLSI Dig. of Tech. Papers (VLSI)*, 2015, pp. 278–279.
- [2] B. I. Rapoport, J. T. Kedzierski, and R. Sarpeshkar, "A glucose fuel cell for implantable brain-machine interfaces," *PLoS ONE*, vol. 7, no. 6, pp. 1–15, Jun. 2012.
- [3] P. P. Mercier, A. C. Lysaght, S. Bandyopadhyay, A. P. Chandrakasan, and K. M. Stankovic, "Energy extraction from the biologic battery in the inner ear," *Nature Biotechnol.*, vol. 30, no. 12, pp. 1240–1243, Dec. 2012.
- [4] J. Goepfert and Y. Manoli, "Fully integrated start-up at 70 mV of boost converters for thermoelectric energy harvesting," *IEEE J. Solid-State Circuits*, vol. 51, no. 7, pp. 1716–1726, Jul. 2016.
- [5] D. El-Damak and A. P. Chandrakasan, "A 10 nW–1 μW Power Management IC With Integrated Battery Management and Self-Startup for Energy Harvesting Applications," *IEEE J. of Solid-State Circuits*, vol. 51, no. 4, pp. 1–12, Apr. 2016.
- [6] S. Bandyopadhyay and A. P. Chandrakasan, "Platform architecture for solar, thermal and vibration energy combining with MPPT and single inductor," *IEEE J. Solid-State Circuits*, vol. 47, no. 9, pp. 2199–2215, Sep. 2012.
- [7] G. Chowdary, A. Singh, S. Chatterjee, and S. Member, "An 18 nA, 87% Efficient Solar, Vibration and RF Energy-Harvesting Power Management System With a Single Shared Inductor," *IEEE J. Solid-State Circuits*, vol. 51, no. 10, pp. 2501–2513, Oct. 2016.
- [8] B. H. Calhoun, S. Khanna, Y. Zhang, J. Ryan, and B. Otis, "System design principles combining sub-threshold circuit and architectures with energy scavenging mechanisms," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, 2010, pp. 269–272.
- [9] Micropelt GmbH, "TGP-651 Thin Film Thermogenerator inside standard package," 2015. [Online]. Available: <http://www.micropelt.com/>
- [10] V. Oncescu and D. Erickson, "High volumetric power density, non-enzymatic, glucose fuel cells," *Nature Scientific Reports*, vol. 3, no. 1226, pp. 1–6, Mar. 2013.
- [11] J. Katic, S. Rodriguez, and A. Rusu, "A Dual-Output Thermoelectric Energy Harvesting Interface with 86.6% Peak Efficiency at 30 μW and Total Control Power of 160 nW," *IEEE J. Solid-State Circuits*, vol. 51, no. 8, pp. 1928–1937, Aug. 2016.
- [12] S. Bandyopadhyay, P. P. Mercier, A. C. Lysaght, K. M. Stankovic, and A. P. Chandrakasan, "A 1.1 nW energy-harvesting system with 544 pW quiescent power for next-generation implants," *IEEE J. Solid-State Circuits*, vol. 49, no. 12, pp. 2812–2824, Dec. 2014.

- [13] J. Katic, S. Rodriguez, and A. Rusu, "An Adaptive FET Sizing Technique for High Efficiency Thermoelectric Harvesters," in *Proc. IEEE Int. Conf. on Electronics, Circuits, and Systems (ICECS)*, 2016, pp. 1–4.
- [14] Y. K. Ramadass and A. P. Chandrakasan, "A battery-less thermoelectric energy harvesting interface circuit with 35 mV startup voltage," *IEEE J. Solid-State Circuits*, vol. 46, no. 1, pp. 333–341, Jan. 2011.
- [15] Würth Electronics, "WE-TPC SMD Shielded Tiny Power Inductor," 2014. [Online]. Available: <http://katalog.we-online.de/>
- [16] Texas Instruments, "TPS22860 Ultra-Low Leakage Load Switch," 2015. [Online]. Available: <http://www.ti.com/product/TPS22860>
- [17] M. Dini, A. Romani, M. Filippi, and M. Tartagni, "A Nanocurrent Power Management IC for Low-Voltage Energy Harvesting Sources," *IEEE Trans. Power Electronics*, vol. 31, no. 6, pp. 4292–4304, Jun. 2016.
- [18] X. Zhang, H. Ren, S. Pyo, J.-I. Lee, J. Kim, and J. Chae, "A High-Efficiency DC-DC Boost Converter for a Miniaturized Microbial Fuel Cell," *IEEE Trans. Power Electronics*, vol. 30, no. 4, pp. 2041–2049, Apr. 2015.