A fully batteryless multiinput single inductor single output energy harvesting architecture

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Abstract: Conventional energy architectures that utilize multiple ambient energy sources are initiated either by an external power supply or through the addition of an extra power source (e.g., battery) to the architecture. However, these interventions compromise the goal of a self-sustainable energy harvesting system. Moreover, conventional architectures are not effective in situations where space is limited (e.g., an artificial heart) or when access to this space is difficult (e.g., human implantable devices), due to their large battery size. Thus, conventional energy combiner circuits that use multiple energy sources are not well suited for supplying power to most applications. This paper presents a fully batteryless energy combiner architecture with a single inductor for the use of multiple ambient energy sources, including a solar cell and a microbial fuel cell. For each energy source, an auxiliary circuit (i.e. a charge pump) is implemented in order to provide a power supply to a digital control circuit, which consecutively connects each ambient energy source to a power converter. This novel architecture is completely self-starting and requires no additional extra power source or battery. This architecture has been designed and verified using a 0.13-μm CMOS process and a peak end-to-end efficiency of 79.33% for two ambient sources is achieved. This proposed system is applicable to numerous loads utilized in energy harvesting systems.

Key words: Energy combiner, energy harvesting, solar cell, microbial fuel cell, single inductor, boost converter, multiple energy sources

1. Introduction

Wireless sensor network (WSN) applications ranging from large scale (e.g., environmental monitoring) to small scale (e.g., implantable medical devices) are omnipresent in this rapid technological era. The current primary energy source for these applications is batteries. However, there are numerous issues surrounding the use of batteries including (1) difficulties during replacement [1], (2) the limited energy capacity [2], (3) large size (i.e. volume issue) [3], and (4) safety concerns related to implantable devices [4]. A promising alternative approach to power these applications is energy harvesters that scavenge energy from biochemicals [1, 3–5], heat [2, 6], light [7, 8], motion [9, 10], radio frequency (RF) [11], and perhaps others not yet identified.

Energy harvesting systems use the surrounding environmental energy sources to attain power for WSN applications via power converters. However, energy flow from these ambient energy sources is irregular and unpredictable due to changing environmental conditions. Thus, driving a WSN application through a power converter via a single energy source (e.g., PV) might not be an effective solution to best exploit the energy

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harvesting. For this reason, efforts to combine and utilize multiple energy sources are gaining popularity among energy harvesting researchers [12–23]. By combining multiple energy sources of the same or different types for flexibility, redundancy, or capacity [24], it is possible to improve system reliability [12, 16–19, 21, 23], achieve robustness against power failures [14, 15], and increase the overall output power [12–24].

Potential implementations of multiple energy sources can be classified into three groups according to whether the battery is used as a primary source (i.e. main source), secondary source (i.e. auxiliary source), or deserted source (i.e. not in use): prebatteryless (PreB), midbatteryless (MidB), and postbatteryless (PostB), respectively. PreB multisources are at an early stage in the development of multiple source energy harvesting systems [23, 25–27]. In PreB systems, the battery is either the main source of power for applications even when ambient energy is available [26], or is only utilized once ambient energy is unavailable[23]. However, ambient energy sources (i.e. energy transducers) are used to either extend the battery's life [26, 27] or lower the burden on the battery [25]. More specifically, the main goal of using PreB as a multiple energy source is to prolong battery life. There are numerous possible applications of PreB-powered technology as the battery is easy to replace and to implement no volume-size constraints required applications, making it an ideal power source for convenience devices.

MidB multiple energy sources are in the second stage of development and are able to drastically reduce battery usage. The main source energy providers shift to predominantly generate energy from the ambient energy source, not the battery. Therefore, in MidBs, batteries are primarily used as auxiliary sources (i.e. secondary sources) to provide power for control energy harvesting circuits during startup [16, 17, 19–22, 28, 29]. Deploying extra power supplies to enable power management functions is undesirable as it compromises the goal of self-sustainability [5]. The ultimate goal for the energy harvesting system is that the whole system including the control circuit, the energy harvesting circuit, and the load are supplied entirely by ambient energy sources. In addition to startup power, the battery is required as an energy source to charge back through energy transducers [22, 28, 29]. This is mainly due to the fact that the load energy demand is less than the generated energy by energy transducers, and so the excess energy is redirected to the battery. Moreover, if the load demands more energy than is generated by energy sources, the battery can then provide a backup supply of energy to the load [22, 28, 29]. The aim of utilizing MidB multiple energy sources is to sustain power to the application to enable almost continuous operation.

Since MidB multiple energy sources allow a time sharing of the inductor (shown in Figure 1a), they are often preferred by researchers and are more commonly studied compared to both PreB and PostB multiple energy sources.

This time sharing achieves savings of (n-1) inductors [17] and reduces the number of capacitors required, allowing smaller architectures to be produced and therefore making MidB technology potentially transferable to size-constrained applications.

Despite this, MidB multiple energy sources are often still too large for some applications due to the size of the battery. However, MidBs have more possible applications to implement than PreBs and are a promising energy harvester requiring further research.

Systems able to completely utilize ambient energy, requiring no extra power source or battery (other than ambient energy transducers), are truly self-sustainable. This can be achieved through the use of PostB multiple energy sources. The main and secondary energy sources in PostBs are energy transducers. For PostBs, all energy sources to the load are combined through n power converters, with n being the number of sources utilized [13, 15, 18], as shown in Figure 1b.

Although these PostBs are self-sustainable and rely solely on ambient energy sources, they are not good at providing supply power for volume constrained applications (e.g., pacemakers) and hard to reach (e.g., implantable devices) applications. This is because these designs are associated with larger n inductors, requiring a corresponding size increase, which is detrimental to these applications. Thus, conventional PostBs are not well developed for multiple energy sources even though they have some distinct advantages over MidBs and PreBs. However, a more efficient architecture for PostB multiple energy sources is required in order to accommodate especially small scale applications (e.g., pacemakers) without increasing the complexity and battery requirements of the system.

In the present paper, a fully batteryless multiple energy source with a single inductor energy harvesting architecture is presented. This paper exploits a popular energy harvester implementation in MidBs i.e. single inductor scheme, which has distinct advantages over conventional PostBs, requiring no additional power sources other than energy transducers. Figure 1c shows a block diagram of the proposed technique for multiple energy sources. With a fully batteryless multiple energy sources architecture, it is possible to achieve a self-starting operation without increasing the complexity and including a battery, allowing the size of the device to remain small and easily serviceable. A comparison of the three batteryless multiple energy sources is summarized in Table 1.

The rest of the paper is organized as follows. Section 2 discusses previous works and highlights the proposed PostB multienergy source architecture. In Section 3, the proposed fully batteryless multiinput single inductor energy harvesting architecture is presented with a circuit implementation and a control scheme. Section 4 presents the simulation results and conclusions will be drawn in Section 5.
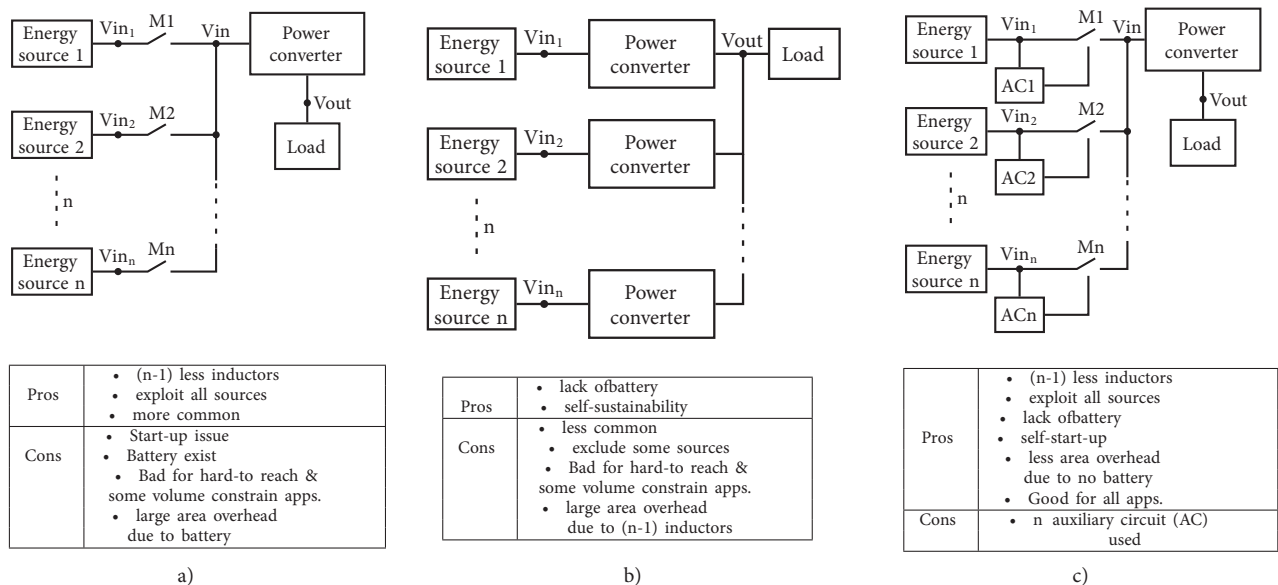

Figure 1: a) Conventional MidB multiinput single inductor (MISI) energy harvesting architecture. b) Conventional PostB multiinput multi inductor (MIMI) energy harvesting architecture. c) Proposed MidB+PostB multiinput single inductor (MISI) energy harvesting architecture.

Table 1: Summary of the three batteryless groups.

	Prebatteryless (PreB)	Midbatteryless (MidB)	Postbatteryless (PostB)	
			Conventional (PostB)	Proposed (PostB)
Main source	Battery	Ambient energy	Ambient energy	Ambient energy
Auxiliary source	Ambient energy	Battery	Ambient energy	Ambient energy
Possible application	Convenience	Convenience Some volume constraint	Convenience Some volume constraint	Convenience Volume constraint Hard to reach
Target	Prolonged battery life	Powered the application	Self-start-up Powered the application	Self-start-up Powered the application
Batteryless	Not	Semi	Fully	Fullyt
Battery replacement cost	Full	Partial	No	No

2. Multisource energy harvesting architectures

2.1. Current architectures

Multiple ambient energy sources are plugged into the load through n power converters shown in Figure 1b, which refers to a conventional PostB architecture. Each ambient energy source generates different voltages at their outputs despite the fact they are designed with the same material, size, and structure.This is because each source is exposed to different environmental conditions. Simply combining all ambient sources to the load through their converters can exclude some source contributions to the load and thus degrade the efficiency. This is mainly due to the fact that the overall efficiency is constrained by the ambient source generating the highest voltage, meaning that other lower voltage ambient sources are not utilized [15]. Additionally, this scheme accommodates variable n inductors. This results in increased complexity in the area overhead. However, a major benefit of this scheme is that it is self-sustainable.

In order to lower the number of components (e.g., inductors) and reduce the effects of redundancy and leakage losses, multiinput energy harvesters have been designed with a single inductor boost converter [16, 17, 19–22]. Figure 1a shows a block diagram of a multiinput single inductor (MISI) energy harvesting architecture. In the upper panel, the circuit consists of a power converter and n switches (M1-Mn). Ambient energy sources can initiate the power converter either sequentially, i.e. one energy source is exploited over one switching cycle [16, 17, 19, 21, 22], or simultaneously, i.e. two energy sources can be utilized over one switching cycle [20] via switches. However, these switches require a supply power to turn on/off to create a bridge between the energy transducers and the converter to power the load.

Due to the relatively low voltages generated at energy transducers' outputs [1, 5, 15, 21, 30], the output of these energy transducers is insufficient to turn switches M1-Mn on/off, as the threshold voltage of the standard CMOS technology is typically higher than the energy transducer output voltage. Therefore, in order to provide

initial operation for a short time, M1-Mn switches in MISI architectures are powered by a battery [16, 17, 20, 21]. Another mechanism to overcome this is the presence of an internal battery that can be used as an energy source to provide power to the control circuit for powering the M1-Mn switches and the load if the existing energy sources do not supply sufficient power [22, 28, 29].

However, these solutions compromise the ultimate goal of a fully self-sustainable energy harvester, i.e. no need for batteries other than energy transducers. To the best of the author's knowledge, there are no existing reports that describe fully batteryless multiple energy sources with a single inductor energy harvesting architecture.

2.2. Proposed fully batteryless multisource energy harvesting architecture

The solution to achieving completely batteryless multiple energy sources with a single inductor has yet to be identified. This is mainly due to the fact that it is difficult to source sufficient voltage levels for the initial M1-Mn switches required for energy harvesting (Figure 1a).

To accomplish fully batteryless operation using multiple energy sources, the present paper develops a more efficient energy harvesting architecture, as shown in Figure 2. For n energy transducers that refer to n input sources, this proposed architecture includes n charge pumps, $2\times n$ switches (M_{ES1} to M_{ESn}, M_{cp1} to M_{cpn}), and a boost converter with a single inductor. Compared to the conventional multiinput single inductor architecture (shown in Figure 1a), this novel architecture has n additional switches (M_{CP1} to M_{CPn}) whose sizes are smaller than M_{ES1} to M_{ESn} switches, and small-sized charge pumps.
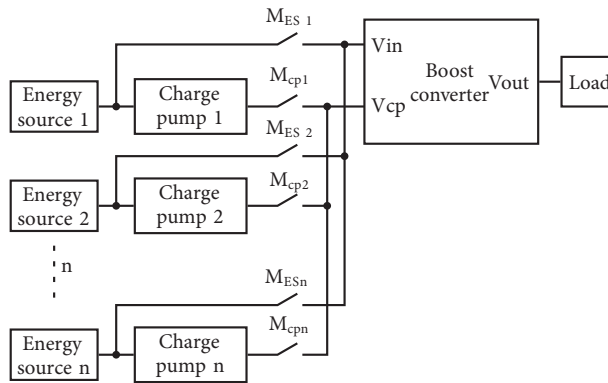

Figure 2: Proposed multiinput single inductor single output (MISISO) energy harvesting architecture.

Generated voltages at outputs of energy sources do not support the operation of the boost converter or on/off status on switches. Thus, an initial startup circuit is required to operate without reliance upon any single external source or battery. The batteryless function (i.e. self-start-up) in the present paper is achieved by deploying n charge pumps, the number of which equals that of the energy sources in the architecture. The pumps increase the low voltage at the outputs of sources to sufficient levels in order to achieve two tasks: (1) to provide supply power to a switch control circuit for M_{ES1}-M_{ESn} switches to sequentially turn on and off and (2) to power a control circuit for the boost converter through M_{CP1}-M_{CPn} switches in order to facilitate the operation of the converter. The detailed circuit implementation of the proposed architecture will be described in the next section.

3. Proposed fully batteryless multiple sources energy harvesting circuit implementation and digital control circuit

Figure 3 shows the circuit implementation of the proposed fully batteryless multiple sources architecture with $n = 2$ energy transducers. The architecture includes two charge pumps, two source-connected switches (M_{ES1}, M_{ES2}), two pump-connected switches (M_{CP1}, M_{CP2}), one power converter (i.e. boost converter), and a digital control circuit. For each energy source, a three-stage charge pump is deployed to step up from low voltage at the output of each energy source V_{in1-2} to a high voltage level V_{CP1-2}. Source-connected switches (M_{ES1}, M_{ES2}) and pump-connected switches (M_{CP1}, M_{CP2}) are implemented with PMOS transistors. This architecture can be easily extended to any arbitrary number of energy transducers by adding switches and charge pumps to the design.
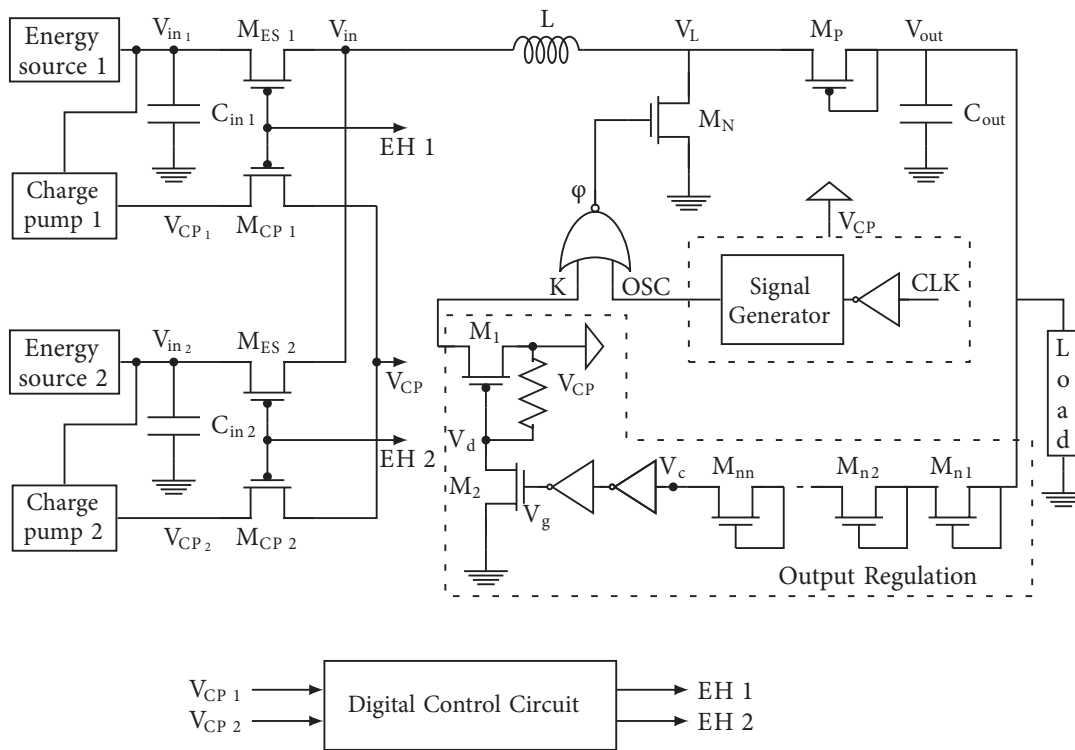

Figure 3: Circuit implementation of the proposed MISISO energy harvesting architecture.

Initially, all switches and the converter are disabled due to not having sufficient voltage levels to operate. Charge pumps start to charge the capacitors at their outputs V_{CP1-2} through energy transducers. Once sufficient voltage is present at the outputs of the pumps, the digital control circuit (DCC) starts to operate. The basic operation and circuit implementation of the DCC will be discussed in detail later in the following subsection of this paper. Once the EH1 signal is activated by the DCC, i.e. the EH1 signal goes low, the first energy source (ES1) and its charge pump (CP1) connect to the boost converter. Thus, stored energy at the capacitor C_{in1} is transferred to the boost converter and therefore the voltage at the output of the charge pump V_{CP1} is available for powering the converter control circuit (e.g., NOR gate and regulating the output of the boost converter). As a result, the boost converter starts operating with the first energy transducer to charge a capacitor C_{out} at the output of the boost converter V_{out}. A load connected to the boost converter draws

power from the capacitor to operate. The time for connecting the first energy transducer to the converter is determined by the DCC.

Once the EH1 signal is deactivated by the DCC, the energy provided to the boost converter by the first energy transducer is cut off. The capacitor C_{in1} starts charging back through the first energy transducer. Secondly, the second energy transducer (ES2) starts to discharge stored voltage at the capacitor C_{in2} to the boost converter since the EH2 signal is activated. The second energy transducer undergoes a similar operation with ES1 to charge the capacitor C_{out}. Once the connected time for the second energy transducer occurs, the DCC enables the EH1 signal again. The same operation process will be consecutively repeated over time. A more detailed explanation of the boost converter used in the present paper is provided elsewhere [31].

3.1. Digital control circuit implementation

Figure 4 shows the circuit implementation of the DCC. It consists of a clock generator, a 4-bit counter, primitive logic gates, a 2-bit serial-in parallel-out shift register, and two buffers. The basic operation of the DCC is described as follows. The clock generator is powered by the first charge pump V_{CP1} in order to generate a clock source CLK. The 4-bit counter is then activated by this clock source and generates four outputs. These outputs feed into primitive logic gates and the 2-bit serial-in parallel-out shift register to generate two signals denoted as $q1s$ and $q2s$. Note that the 4-bit counter, primitive logic gates, and 2-bit serial-in parallel-out shift register are provided with a supply of power by the second charge pump V_{CP2}. The first signal $q1s$ feeds into the first buffer, which is powered by the first charge pump V_{CP1}, which generates the control signal EH1 for the first source-connected switch M_{ES1} and the first pump-connected switch M_{CP1}. The other signal $q2s$ provides the activation signal for the second buffer, whose supply power is obtained from the second charge pump V_{CP2}. Once $q2s$ is activated, the buffer generates the control signal EH2 for the second source-connected switch M_{ES2} and the second pump-connected switch M_{CP2}.
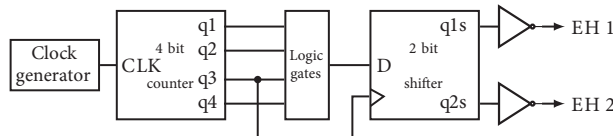

Figure 4: Block diagram of the digital control circuit (DCC) for switches (M_{ES1}, M_{ES1}, M_{CP1}, and M_{CP2}).

4. Results and discussion

In order to evaluate the proposed technique, a multiple ambient energy sources energy harvesting architecture was designed and simulated using a 0.13-μm CMOS process. This design has been tested with two ambient energy sources: a solar cell (PV) and a microbial fuel cell (MFC). MFCs can be modeled as a voltage source in series with an internal resistance, while solar cells can be modeled as a current source in parallel with a diode [30]. Each energy source has different electrical equivalent circuits, but their Thévenin equivalent circuits are the same. Thus, the Thévenin equivalent circuits of all types of energy sources can be modeled as a voltage source in series with a resistor. Thévenin equivalent circuits for solar cells are discussed in a previous study [32], and a more detailed explanation for that is provided in that study. In order to emulate ambient energy sources for simulation results in the present paper, PV was modeled as a voltage of 0.75 V in series with a resistor of 100 Ω and the MFC was designed with a voltage of 0.75 V in series with an internal resistance of 225 Ω. The proposed fully MISISO architecture includes 47-μF input capacitors (C_{in1}, C_{in2}), a 4.7-μF output capacitor C_{out}, and a 20-μH inductor.

The proposed fully MISISO architecture is connected to a load of 1.61 mW in order to evaluate the proposed circuit. Figure 5 shows the voltage waveforms at outputs of PV and MFC (V_{in1}, V_{in2}, respectively), outputs of auxiliary circuits, i.e. charge pumps (V_{CP1}, V_{CP2}, respectively), input V_{in} and output V_{out} of power converter and V_{CP}. Figures 5b and 5c show the zoomed areas in the rectangles A and B of Figure 5a, respectively. Initially, the power converter is disabled and auxiliary circuits (i.e. charge pumps) are charged through energy sources. In other words, voltages at the outputs of pumps V_{CP1}-V_{CP2} ramp from zero to sufficient levels. Once sufficient voltages appear at the outputs of pumps, the DCC starts operating. For each connected source, the voltages at the input of the converter V_{in} and V_{CP} are equal to the voltages at the input of the ambient source (e.g., V_{in1}) and the output of its charge pump (e.g., V_{CP1}), respectively (see Figures 5b and 5c). Stored energy at V_{in1} and V_{in2} is sequentially transferred to the load through the power converter. The converter output V_{out} gradually charges up (see Figure 5b). The output is regulated to 1.52 V. These results verify that the proposed MISISO energy harvesting architecture can effectively connect multiple sources to the load without the need for an external power supply (i.e. battery), and is able to operate using multiple energy sources.

Whenever the load draws more current, voltage degradation at the output is observed. Figure 6 demonstrates the setup of load response in order to monitor voltage ripple at the output of the proposed architecture. In this setup, an external power supply is used to generate the control signal for M_{gd} PMOS transistor to attach the load to the converter and detach it. Figure 7 shows the load response. Initially, the load is attached to the converter (i.e. the load current is 1.06 mA). Once load current is stepped from 1.06 mA to 0 (i.e. the load is detached), a 80 mV drop in voltage at the output V_{outc} is observed. This voltage drop is small and is negligible. This illustrates that the proposed architecture effectively regulates the output.

In order to evaluate the end-to-end efficiency for multiple source energy harvesting architectures, the maximum power available from each ambient source ($P_{max_{MFC}}$, $P_{max_{PV}}$) should be taken into consideration. However, there are no reports prior to the present work that consider all ambient sources in the harvesting to calculate overall end-to-end efficiency. The overall end-to-end efficiency of the architecture is expressed as

$$\eta_{overall_{end-to-end}} = \frac{P_{load}}{P_{max_{MFC}} + P_{max_{PV}}} \tag{1}$$

In the present paper, a peak overall end-to-end efficiency of 79.33% is obtained.

This work is compared with the state-of-the-art multiple source energy harvesting architectures, as tabulated in Table 2. Two of the MidB architectures [20, 21] have distinct advantages over the PostB architecture [15] in terms of number of inductors and complexity, but they require external supports to start up. Other works [16, 22] utilize batteries to operate. Deploying batteries causes complexity in the system. This limits the operation in some volume constrained applications and the use of these systems in implantable devices impossible. The proposed architecture is truly self-start-up and can be effectively applied to many applications.
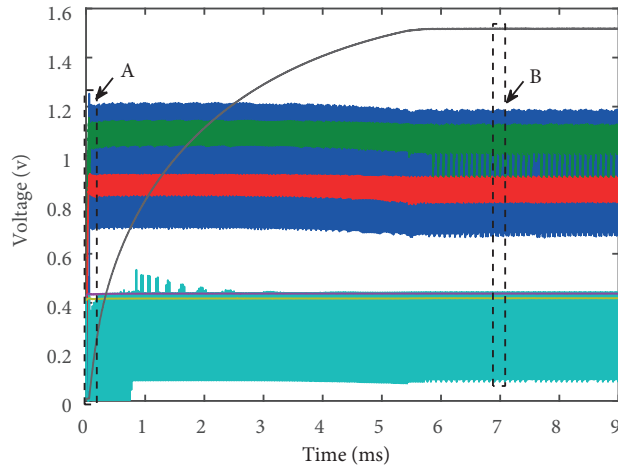
a) Voltage waveforms.
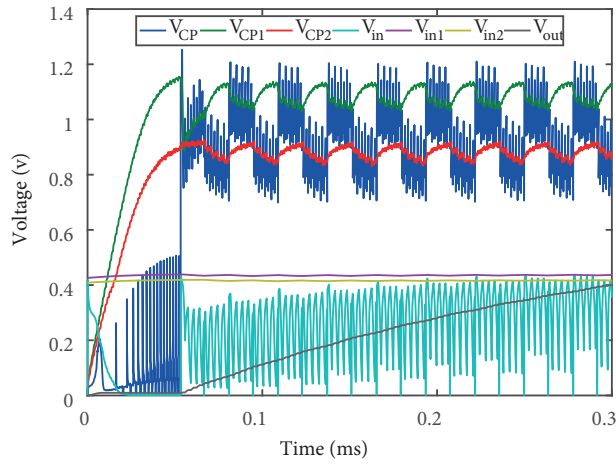
b) Zoom in area shown at the rectangular A of (a).
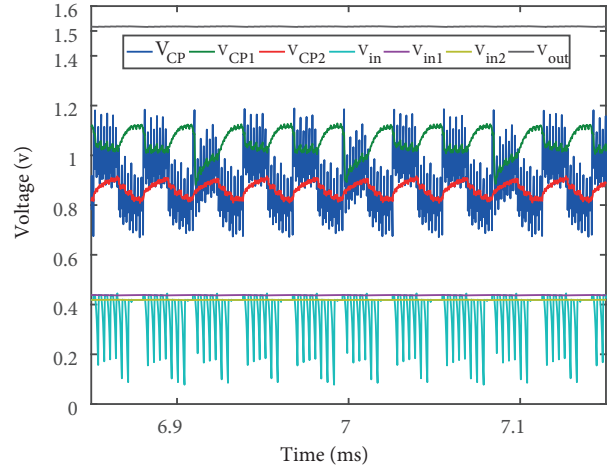
c) Zoom in area shown at the rectangular B of (a).

Figure 5: Voltage waveforms at V_{cp}, V_{cp1}, V_{cp2}, V_{in}, V_{in1}, V_{in2}, and V_{out} in Figure 3.
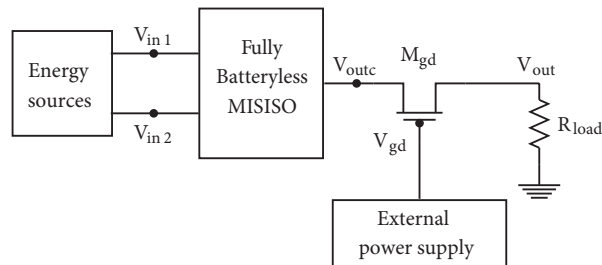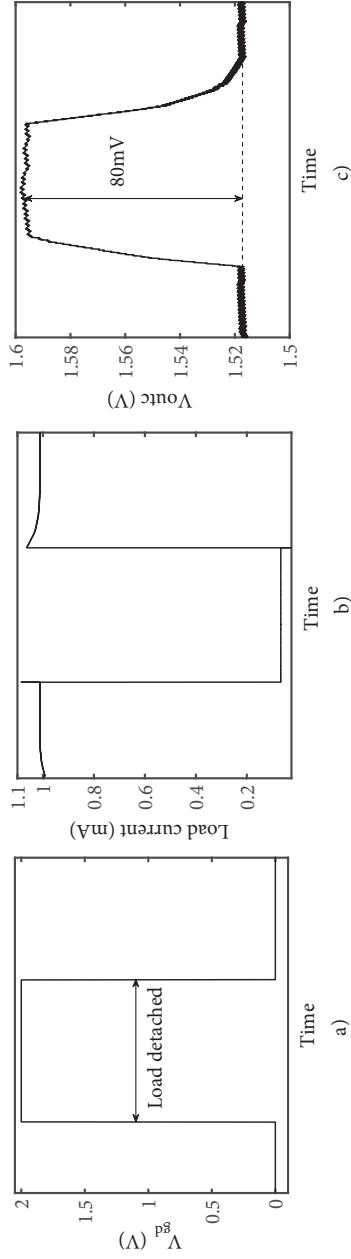

Figure 6: Setup of load response.

Figure 7: Load step response. a) Applied external gate voltage V$_{gd}$. b) Current response from a load to a detached load. c) Load step of 1 mA-0. Voltage ripple is 80 mV.

Table 2: Performance comparison of the proposed fully MISISO architecture with existing solution.

Parameters	Ref [15] simulation	Ref [16] measured	Ref [21] measured	Ref [20] measured	Ref [22] measured	This work simulation
Technology	0.13 μm	0.35 μm	0.18 μm	0.18 μm	28 nm	0.13 μm
Architecture	PostB	MidB	MidB	MidB	MidB	MidB+PostB
# of inputs	4+battery	3+battery	2	2	3+battery	2
# of outputs	1+battery	1+battery	1	2	3+battery	1
Ambient energy source	4 MFCs	PV+Piezo+TEG +Battery	GBFC+TEG	TEG+PV	PV+TEG+BFC +Battery	PV+MFC
Min. input voltage	0.35 V	0.2 V (PV), 0.02 V (TEG), 1.5 V (Piezo), 3.3 V (Battery)	0.03 V (GBFC), 0.01 V (TEG)	0.05 V (TEG), 0.4 V (PV)	0.2 V (PV), 0.1 V (TEG), 0.2 V (BFC), 1.8 V (Battery)	0.4 V (PV), 0.35 V (MFC)
Output voltage	1.55 V	1.8 V	1.9 V	0.5–1.2 V	0.4–1.4 V	1.52 V
# of inductors	4	1	1	1	1	1
Start-up	Self	Battery	External	External	Battery	Self

BFC: Biofuel cell; GBFC: Glucose biofuel cell; TEG: Thermoelectric generator; MFC: Microbial Fuel Cell; PV: Solar cell.

5. Conclusions

The present paper presents a fully batteryless energy harvesting system for multiple ambient energy sources including a solar cell and MFC. The fundamental of this work is to combine two popular multiple energy combination schemes (i.e. MidBs and conventional PostB) into a proposed scheme (i.e. proposed PostB). In other words, this work takes advantage of MidBs in using a single inductor and targets the self-sustainable solution from conventional PostBs. The proposed architecture consists of a power converter, two charge pumps, two source-connected switches, two pump-connected switches, and a digital control circuit. A load of 1.61 mW is connected to the proposed architecture in order to evaluate the system. The results show that the proposed architecture achieves truly self-start-up operation with a single inductor for multiple sources. Moreover, a peak end-to-end efficiency of 79.33% for two ambient sources is achieved. This proposed architecture can be applicable to a large number of loads used in energy harvesting systems in multiple devices.

References

[1] Meehan A, Gao H, Lewandowski Z. Energy harvesting with microbial fuel cell and power management system. IEEE Transactions on Power Electronics 2011; 26 (1): 176-181. doi: 10.1109/TPEL.2010.2054114

[2] Ashraf M, Masoumi N. A thermal energy harvesting power supply with an internal startup circuit for pacemakers. IEEE Transactions on Very Large Scale Integration (VLSI) Systems 2016; 24 (1): 26-37. doi: 10.1109/TVLSI.2015.2391442

[3] Yeknami A, Wang X, Jeerapan I, Imani S, Nikoofard A et al. A 0.3-V CMOS biofuel-cell-powered wireless glucose/lactate biosensing system. IEEE Journal of Solid-State Circuits 2018; 53 (11): 3126-3139. doi: 10.1109/JSSC.2018.2869569

[4] Niitsu K, Kobayashi A, Nishio Y, Hayashi K, Ikeda K et al. A self-powered supply-sensing biosensor platform using bio fuel cell and low-voltage, low-cost CMOS supply-controlled ring oscillator with inductive-coupling transmitter for healthcare IOT. IEEE Transactions on Circuits and Systems I: Regular Papers 2018; 65 (9): 2784-2796. doi: 10.1109/TCSI.2018.2791516

[5] Umaz R, Garrett C, Qian F, Li B, Wang L. A power management system for multianode benthic microbial fuel cells. IEEE Transactions on Power Electronics 2017; 32 (5): 3562-3570. doi: 10.1109/TPEL.2016.2585020

[6] Das A, Gao Y, Kim TTH. A 220-mV power-on-reset based self-starter with 2-nW quiescent power for thermoelectric energy harvesting systems. IEEE Transactions on Circuits and Systems I: Regular Papers 2017; 64 (1): 217-226. doi: 10.1109/TCSI.2016.2606122

[7] Chew KWR, Sun Z, Tang H, Siek L. A 400 nW single-inductor dual-input–tri-output DC–DC buck-boost converter with maximum power point tracking for indoor photovoltaic energy harvesting. In: 2011 IEEE International Solid-State Circuits Conference; San Francisco, CA, USA; 2011. pp. 68-69.

[8] Qiu Y, Van Liempd C, het Veld BO, Blanken PG, Van Hoof C. 5μW-to-10mW input power range inductive boost converter for indoor photovoltaic energy harvesting with integrated maximum power point tracking algorithm. In: 2011 IEEE International Solid-State Circuits Conference; San Francisco, CA, USA; 2011. pp. 118-120.

[9] Dini M, Romani A, Filippi M, Tartagni M. A nanocurrent power management IC for low-voltage energy harvesting sources. IEEE Transactions on Power Electronics 2016; 31 (6): 4292-4304. doi: 10.1109/TPEL.2015.2472480

[10] Dell'Anna F, Dong T, Li P, Yumei W, Yang Z et al. State-of-the-art power management circuits for piezoelectric energy harvesters. IEEE Circuits and Systems Magazine 2018; 18 (3): 27-48. doi: 10.1109/MCAS.2018.2849262

[11] Mansano A, Bagga S, Serdijn W. A high efficiency orthogonally switching passive charge pump rectifier for energy harvesters. IEEE Transactions on Circuits and Systems I: Regular Papers 2013; 60 (7): 1959-1966. doi: 10.1109/TCSI.2012.2230499

[12] Carli D, Brunelli D, Benini L, Ruggeri M. An effective multi-source energy harvester for low power applications. In: 2011 Design, Automation Test in Europe; Grenoble, France; 2011. pp. 1-6.

[13] Tan YK, Panda SK. Energy harvesting from hybrid indoor ambient light and thermal energy sources for enhanced performance of wireless sensor nodes. IEEE Transactions on Industrial Electronics 2011; 58 (9): 4424-4435. doi: 10.1109/TIE.2010.2102321

[14] Colomer-Farrarons J, Miribel-Catala P, Saiz-Vela A, Samitier J. A multiharvested self-powered system in a low-voltage low-power technology. IEEE Transactions on Industrial Electronics 2011; 58 (9): 4250-4263. doi: 10.1109/TIE.2010.2095395

[15] Umaz R, Wang L. An energy combiner design for multiple microbial energy harvesting sources. In: 2017 the ACM Great Lakes Symposium on VLSI; Banff, Alberta, Canada; 2017. pp. 443-446.

[16] Bandyopadhyay S, Chandrakasan AP. Platform architecture for solar, thermal, and vibration energy combining with MPPT and single inductor. IEEE Journal of Solid-State Circuits 2012; 47 (9): 2199-2215. doi: 10.1109/JSSC.2012.2197239

[17] Shi C, Miller B, Mayaram K, Fiez T. A multiple-input boost converter for low-power energy harvesting. IEEE Transactions on Circuits and Systems II: Express Briefs 2011; 58 (12):827-831. doi: 10.1109/TCSII.2011.2173974

[18] Kang T, Kim S, Hyoung C, Kang S, Park K. An energy combiner for a multi-input energy-harvesting system. IEEE Transactions on Circuits and Systems II: Express Briefs Sept 2015; 62 (9):911-915. doi: 10.1109/TCSII.2015.2435231

[19] Dini M, Romani A, Filippi M, Bottarel V, Ricotti G et al. A nanocurrent power management IC for multiple heterogeneous energy harvesting sources. IEEE Transactions on Power Electronics 2015; 30 (10): 5665-5680. doi: 10.1109/TPEL.2014.2379622

[20] Liu C, Lee H, Liao P, Chen Y, Chung M et al. Dual-source energy-harvesting interface with cycle-by-cycle source tracking and adaptive peak-inductor-current control. IEEE Journal of Solid-State Circuits 2018; 53 (10): 2741–2750. doi: 10.1109/JSSC.2018.2844358

[21] Katic J, Rodriguez S, Rusu A. A high-efficiency energy harvesting interface for implanted biofuel cell and thermal harvesters. IEEE Transactions on Power Electronics 2018; 33 (5): 4125-4134. doi: 10.1109/TPEL.2017.2712668

[22] Amin SS, Mercier PP. MISIMO: a multi-input single-inductor multi-output energy harvesting platform in 28-nm FDSOI for powering net-zero-energy systems. IEEE Journal of Solid-State Circuits 2018; 53 (12): 3407-3419. doi: 10.1109/JSSC.2018.2865467

[23] Park C, Chou PH. Ambimax: autonomous energy harvesting platform for multi-supply wireless sensor nodes. In: 2006 3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks; Reston, VA, USA; 2006. pp. 168-177.

[24] Patoka M. Fundamentals of power system ORing. Power Management Design Lines EE Times, March 2007.

[25] Park C, Chou PH. Power utility maximization for multiple-supply systems by a load-matching switch. In: 2004 International Symposium on Low Power Electronics and Design; New York, NY, USA; 2004. pp. 168-173.

[26] Raghunathan V, Kansal A, Hsu J, Friedman J, Srivastava M. Design considerations for solar energy harvesting wireless embedded systems. In: Fourth International Symposium on Information Processing in Sensor Networks; Los Angeles, CA, USA; 2005. pp. 457-462.

[27] Jiang X, Polastre J, Culler D. Perpetual environmentally powered sensor networks. In: Fourth International Symposium on Information Processing in Sensor Networks; Los Angeles, CA, USA; 2005. pp. 463-468.

[28] Yu G, Chew KWR, Sun ZC, Tang H, Siek L. 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 Journal of Solid-State Circuits 2015; 50 (11): 2758-2772. doi: 10.1109/JSSC.2015.2476379

[29] Kim S, Rincon-Mora GA. 23.4 dual-source single-inductor 0.18 μm CMOS charger-supply with nested hysteretic and adaptive on-time PWM control. In: 2014 IEEE International Solid-State Circuits Conference; San Francisco, CA, USA; 2014. pp. 400-401.

[30] Umaz R, Wang L. Design of an inductorless power converter with maximizing power extraction for energy harvesting. International Journal of High Speed Electronics and Systems 2018; 27 (01n02): 1840007.

[31] Umaz R. Power management systems for biomass-based energy harvesting. PhD, University of Connecticut, Storrs, CT, USA, 2018.

[32] Chatterjee A, Keyhani A. Thevenin's equivalent of photovoltaic source models for MPPT and power grid studies. In: 2011 IEEE Power and Energy Society General Meeting; Detroit, MI, USA; 2011. pp. 1-7.