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A COMPLETE DESIGN AND DEVELOPMENT OF A MINIATURE BATTERY-LESS POWER MANAGEMENT UNIT FOR POWERING BIOMEDICAL IMPLANT

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Abstract

With the emerging of micro and nanotechnology in energy harvesting system, small size, self-powered, fully integrated on-chip battery-less power management system is preferable. However, a miniature power management system with an ultra-low input voltage as well as low kick- start voltage is the challenging task in the research. For this reason, a single inductor based dynamic closed loop battery-less power management system is proposed by using only 30 mV or 1 °C from the thermoelectric generator to boost up to a minimum of 1.2V. Different topology of miniature boost converters in terms of input voltage, start-up voltage and form factor were reviewed. The focus highlighted on different configurations of CMOS switch inductor boost converter used within energy harvesting circuitry. The design has been developed in 130 nm Silterra CMOS process technology and only occupies an area of 1.00593 mm^2.The measured performance of the proposed system like the simulation result but with slightly lower output voltage due to packaging mismatch. This work shows a complete workflow from design consideration to fabrication and measurement setup of energy harvesting power management unit that has sustainable power and small targeting wearable or biomedical implants.

Keywords: Energy harvesting, Inductor based converter, Power management unit Ultra-low voltage.

1. Introduction

Implantable medical devices and stock tracking devices face a difficulty to do replacement of battery beneath the body as the leakage of mercury of the battery has brought up a health issue. Energy harvesting has been opened great value and possibility in renewable alternatives for a conventional battery. The reason for its broad development is because it can transform into a useful power source from ambient energy which is easy to get, less-tedious replacement compares with battery and the most important is it produces clean, pollution-free energy.

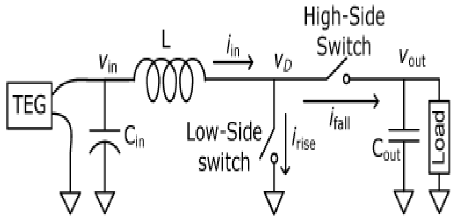
Recently, ultra-low voltage becomes a point of merit in future market demand especially in biomedical implants. Thermoelectric energy harvesting has been given focus as it is able to convert thermal energy from human skin into a small amount of DC electricity. Due to its characteristic of resilient towards environmental change, Thermoelectric Generator (TEG) becomes an attractive solution in the energy harvesting field [1]. There are some examples of good heat sources in our daily application such as the heat from the refrigerator, air conditioner and laptop as they are almost operated continuously [2]. In the future, there is a possibility that Wireless Sensor Node (WSN) or the Body Area Network (BAN) are transmitted or received the data by using the power from the body heat. According to [3], for more efficient operation, to gain a 20 mV, a temperature difference of 4 $°C$ temperature is needed. The researcher carried out this experiment based on the thermal heat from a human arm. This small thermal variation hard to power on the harvester as most of the existing thermal-based energy harvesters required significantly higher than 1 or 2 $°C$ to power on the harvesting circuit. In [4], a 3.5 K of temperature gradient was harvested from a rat and TEH was used to demonstrate a real environment condition.

With the increasing number of wearable electronic devices, biomedical implants and the advent of Internet of Things (IoT), the demand for power supplies has surged. In recent years, Wireless Sensor Node (WSN) has made a great potential in the medical field. Although WSN just need a small battery, frequent charging is required and therefore reducing the wearable compliance. A bulky battery is the size consideration where it is inconvenient to bring or make the application non-wearable. A battery-less power management system through energy harvesting technique thus prolongs the node lifetime. However, there are a lot of challenging part to design a comprehensive power management system. Acceptance of minimum input voltage of the voltage booster is one of the critical parts as if low input voltage can start to operate will reduce the temperature gradient required by the TEG. One of the conventional approaches to implement a voltage booster is a switched-capacitor converter. Since there are many power switches are used in this type of converter, a sophisticated control circuit is required to control power switches which consume much power. Conversion efficiency well depends on the timing on-off of the switches. However, continuous conduction mode of inductor-based converter increases the power losses as it will discharge output capacitor during the switching period when inductor current flows negatively. The start-up mechanism is important to ensure the voltage booster works at the initial stage. Previously, some worked that use batteries or mechanical switches to kick start the CMOS voltage booster. However, for fully battery-free power management unit operation, this way is not preferable.

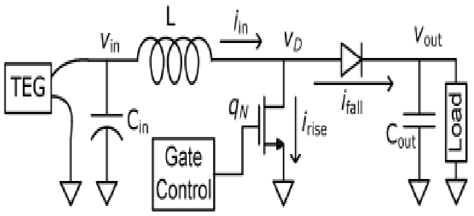
In this work, using the differences of 1 *°C* can produce 30 mV output voltage will be demonstrated. The architecture of switch inductor converter will first be explored. This follows with the proposed method which uses only 1 *°C* to power on the harvester through DC-DC converter and auxiliary supporting circuit. The simulation and the measurement results of the proposed single inductor-based converter will be discussed before the end of the paper.

2. Architecture of Switch Inductor Converter

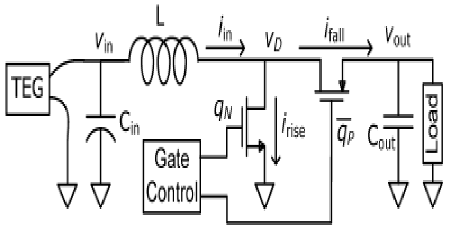
There are few types of switch inductor converter that have been studied in previous research. The examples of switch inductor converter are shown in Fig. 1. Figure 1 shows the inductor-based converter with (a) ideal switches, (b) high side switch replaces with diode and (c) high side switch replace with PMOS [3]. Fig. 1(a) shows the high and low-side switches used to control on and off the charging cycle in the inductor-based converter. However, due to its big size which is not practical to be integrated into a circuit, a diode has been used to replace switches. Nowadays, transistors are used instead of a diode to eliminate the voltage drop [3].



(a) Ideal switches.



(b) Diode replaces high side switch.



(c) Transistor replaces diode.

Fig. 1. Switch inductor converter [3].

2.1. Start-up voltage

Start-up voltage is the critical point in an entire boost converter system. To achieve low start-up voltage, a low threshold voltage of the transistor has to be used. However, low threshold voltage contributes to high transistor off-state leakage loss. The start-up voltage affects the transient response of output voltage to reach at steady state. If the low start-up voltage can be achieved, less time is needed for the boost converter to be triggered. While the time interval for the transient period is known as start-up time.

Jiang et al. [5] used a 70 mV as a start-up voltage by charging a storage capacitor to start the inductive boost converter. This action is known as charge pump storing. The researcher implemented a cross coupled Pelliconi charge pump. The Dickson charge pump is cascaded until 24 stages while the voltage monitoring has been eliminated to reduce the start-up voltage.

Another start-up solution for voltage booster is through a pre-charge load capacitor. This method has been implemented by Carlson et al. [3]. The disadvantage of using a storage element is the converter will be disabled for long periods. The capacitor is used to trigger back the voltage booster when the output voltage reaches a certain level. Although the capacitor has been discharged completely, the switch capacitor circuit is still enough to generate 600 mV to kick start the booster.

Zhang et al. [6] used RF power for a kick start solution for a voltage booster. RF power is provided at -10 dBm for 1 to 2 seconds and rectified through a rectifier. Due to sensitivity matter, a rectifier with 6 stages charge pump is chosen. High RF power is required for the RF rectifier with less stage. RF will start to charge the storage capacitor at a certain level voltage, then the capacitor will kick start the boost converter.

Hernandez and Noije [7] used the start-up technique in the implementation of a pre-start up charge pump and start-up boost converter. The advantage of this start-up technique is the output of TEG is applied to the input of the charge pump. This work starts with the charging of the internal capacitor at the output which makes the voltage capacitor to rise. Comparator is on when the voltage capacitor reaches a certain value and therefore kick start the boost converter.

In the proposed design, RF energy is implemented to kick start voltage booster. The method is referred from the research [8, 9]. The rectifiers from [8, 9] are based on cross-coupled charge pump architecture which is suitable for the initial goal of this research to achieve a fully integrate system. Wong et al. [8] had demonstrate well of its parametric studied in term of the matching circuit, size of transistor and load resistor. Asli and Wong [9] had proposed a rectifier which is able to control the threshold voltage dynamically and reduce the leakage current in the transistors through DTMOS transistor in differential-drive topology. The design does not need a physical load capacitor.

3. Literature Review

The boost converter in [7] is a fully integrated converter design even though the inductor is used. The designer uses an integrated metal-track inductor to replace the external inductor. Therefore, the on-chip inductor design is workable for the application in which the size is extremely small. This inductor converter can boost 300 mV input voltage from a thermoelectric generator to a regulated 1.1 V output voltage.

Rozgi and Markovic [4] stated that the single inductor topology can control the entire energy harvesting system more accurate and trace the output voltage more precious. The integration of Maximum Power Point Tracking (MPPT) which is shown in Fig. 2. has been used efficiently to detect the inductor current zero-crossing and enhance the impedance matching circuit enhance impedance matching between energy harvesting circuit. Instead of using the normal digital control oscillator, the inductive load ring oscillator has been implemented to control the timing and help to control the amplitude exceed the supply rails which allow being operated and triggered with ultra-low voltage. The architecture had achieved a high level of integration and complexity.

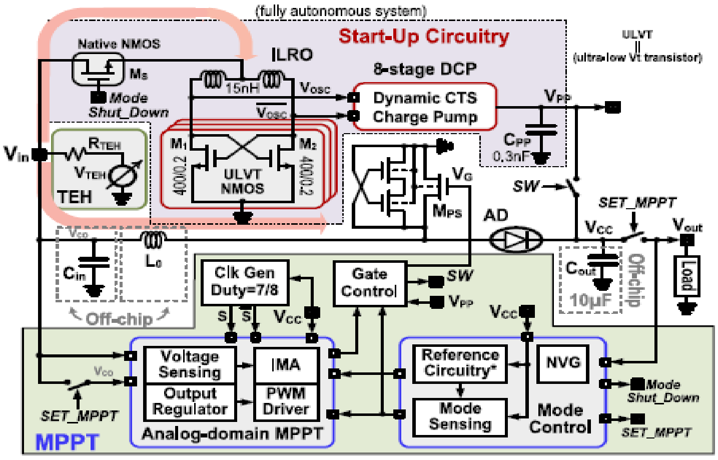


Fig. 2. Inductor based converter with MPPT [4].

The inductor-based converter has a simple structure because it only requires two transistors to act as switches to control the current flow. The benefit of the Discontinuous Conduction Mode (DCM) is where it can control the high side and low side switch is on and off on time to avoid current backflow which leads to leakage. By using an external inductor, a higher inductance can be a choice to store more energy to boost up to high output voltage and current.

Veri et al. [10] used a switch inductor converter together with the feedforward and feedback control circuits. This boost converter is suitable to use for thermoelectric energy harvesting application as it can capture the 40-mV input voltage and step up to 1 V. The advantage of this converter is where it has a feedback network to control the variable of pulse width and the voltage from the booster. This eliminates to have a pre-charged external capacitor in the circuit.

According to Bose et al. [11], the boost converter achieves above 75% efficiency across a matched input voltage range of 15 mV to 100 mV and with a peak efficiency of 82% when input voltage is 50 mV. The architecture of loss-optimized Maximum Power Point Tracking (MPPT) scheme improves the end-to-end power efficiency at low voltages from the TEG and enables the converter to operate at 3.5 mV.

Based on Bose et al. [12], inductor-based converter is used to convert thermal energy into electricity. The key focus of this research is the low start-up voltage which is only requires 57 mV for boost converter. The start-up mechanism enables inductive boost converter to start operates in 135 ms. The integration of inductor-based converter with fully integrated start-up circuit together with oscillator gives a high potential for realizing fully autonomous thermal energy harvesting from the human body heat.

Multi-input single inductor single output architecture is proposed by Umaz [13]. Even though both solar cell and microbial fuel cell energy sources are supplied, only single inductor is used for boost converter in the entire system. By comparing with conventional configuration, this research gives an advantage in term of the amount of inductor used and reduces the complexity as well as the space taken in a chip. The combination of charge pump, boost converter and control circuit enable self-start-up and having an end-to-end peak efficiency of 79.33%.

3.1. Proposed architecture

The proposed single inductor based dynamic closed loop battery-less power management system shown in Fig. 7. consists of a single inductor-based converter, logic gate control and comparator. This unit operates with a minimum 30 mV from the output voltage of TEG and produces a regulated at least 1.2 V output voltage. Figure 3 shows the architecture of single inductor-based converter.

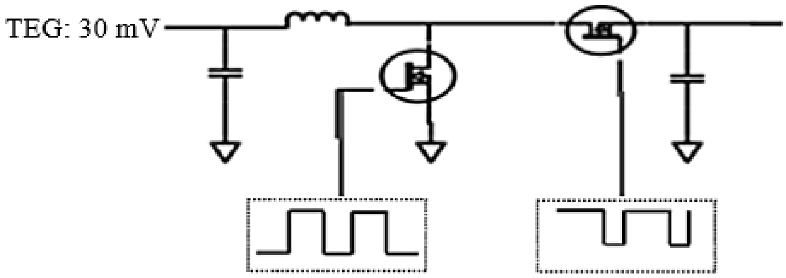


Fig. 3. Single inductor-based converter.

Logic gate control is implemented to replace external pulse generator for switching on the PMOS and NMOS in the boost converter. The logic gate control included of the self-generated ring oscillator, shift register ring oscillator, frequency divider and one-shot block. This logic gate control can operate at approximately 600 mV and produce a DCM pulse as shown in Fig. 4.

In this work, a comparator is implemented to form a closed-loop system which is shown in Fig. 5. It activates the voltage booster when the voltage from the booster is below the reference voltage and deactivates the booster when the output voltage exceeds the reference voltage. Therefore, the voltage from the booster can be regulated.

RF energy has been used as the start-up voltage mechanism in this work as shown in Fig. 6. Therefore, no external battery or capacitors have been used. The rectifier is targeted to capture 2.45 GHz frequency and produce at least 2 V output voltage. The design of RF rectifier has been presented in [8, 9] thus not repeat over here.

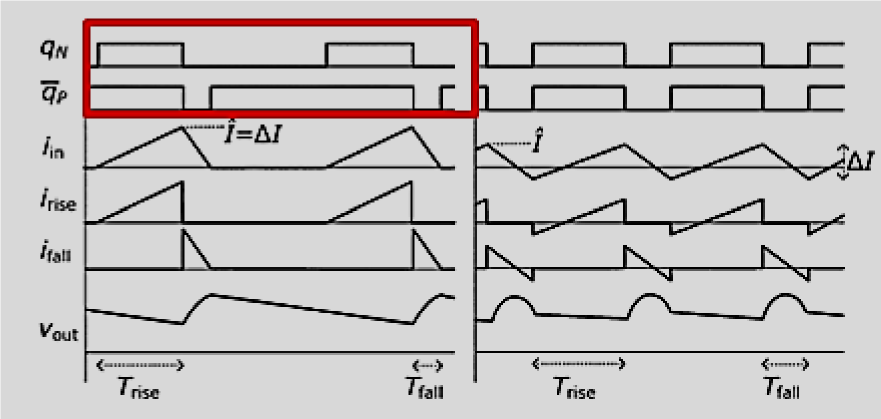


Fig. 4. Comparison between DCM pulse (left side) and CCM pulse (right side) [3].

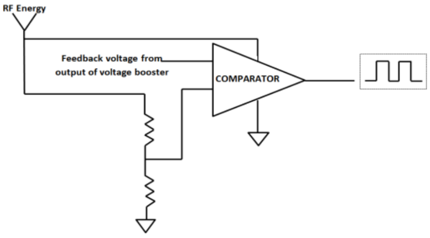


Fig. 5. Block diagram of a comparator.

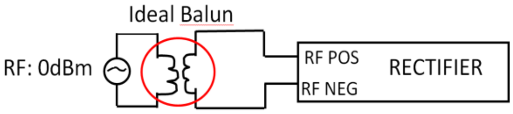


Fig. 6. Block diagram of RF rectifier.

These 4 circuitries are integrated to form a closed-loop power management unit. Figure 7 shows a complete block diagram of the power management unit.

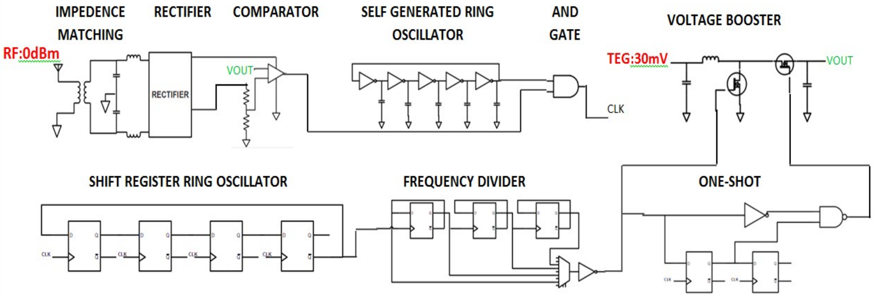
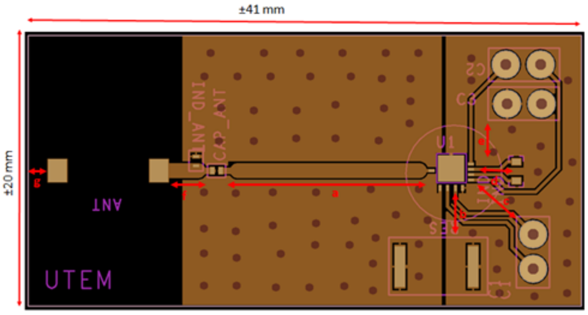


Fig. 7. Block diagram of the power management unit.

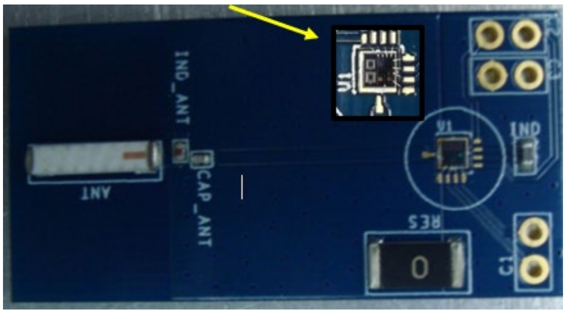
4. Test Set-up and Measurement Results

The inductor-based converter has been sent for fabrication in a 130nm Silterra CMOS process. The entire circuitry occupied 0.826um x 1.2168um which has the chip area layout of 1.00593 mm^2. Figure 8 shows the prototype of the inductor-based boost converter on the PCB. The testing and measurement set-up are shown in Figs. 8 and 9. A 30 mm × 30 mm thermoelectric generator (Peltier Cooler Module) with a model APH-127-10-25-S is used in the experiment to act as the input voltage supply for the voltage booster. A 10uH surface mounted inductor is used for the boost converter and an antenna is moulded on the PCB. The experiment begins by placing the palm on one side of TEG; the other side of TEG is exposed to ambient environment. This action can create a thermal gradient which generates small amount of energy to the inductor-based boost converter. The energy harvester starts with a minimum 30 mV to operate. For these measurements, the start-up voltage is supplied from the function generator which is available in the Digilent Analog Discovery software. The output voltage is monitored when the supply voltage and input voltage are given.

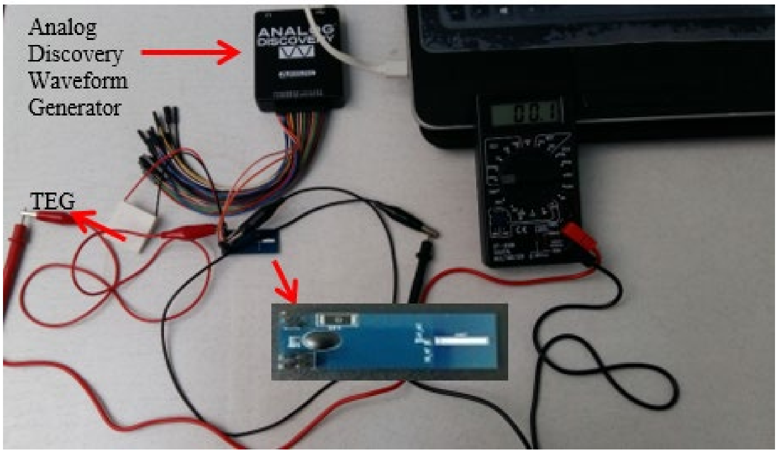
As a result, the power management system can step up a minimum 30 mV. Figure 9 shows the measured output voltage approximate 700 mV from the power management prototype with a start-up voltage of 600 mV. The measurement result is like the simulated result in Fig. 10 but with a slightly lower output voltage level, approximately 700 mV. Various start-up voltages have also been measured with a fixed 30 mV input voltage as shown in Fig. 10. The output voltage increases with the start-up voltage but at a lower rate compared to the simulation result. This is suspected due to process variation in packaging and handling mismatch such as wire bonding.



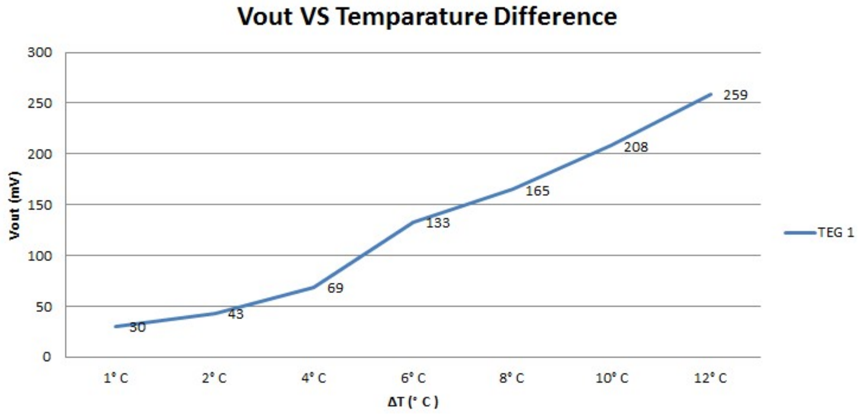
(a) PCB layout of prototype.



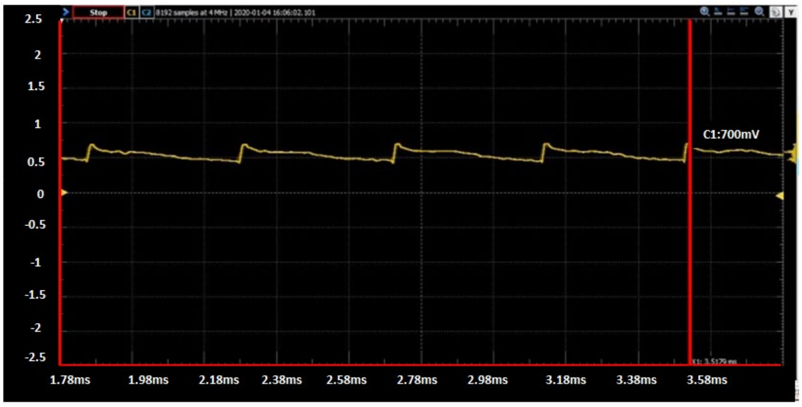
(b) Fabricated chip mounted on the board.
Fig. 8. Prototyping of the proposed energy harvester.



(a) Measurement setup.



(b) Voltage generated by TEG.



(c) Output voltage from the converter.

Fig. 9. Measurement of the fabricated battery-less power management unit.

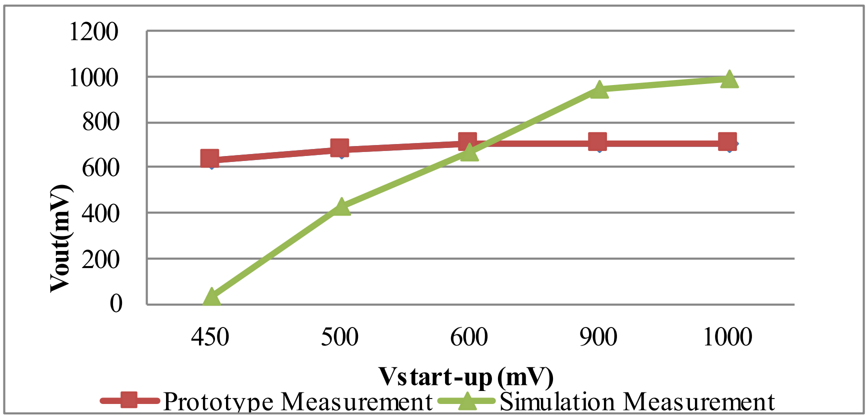


Fig. 10. Start-up voltage versus output voltage of power management system.

5. Simulation Result

An inductor-based converter had been designed in 0.13 um Silterra technology. The schematic and layout designed are done by using Cadence software. Figure 3 shows the proposed structure of the inductor-based converter. Table 1 shows the design parameters of the proposed inductor-based converter. Since the target is utilizing low input voltage, which is from the TEG, the proposed inductor-based converter is designed based on low input requirement.

The proposed inductor-based voltage booster is successfully operating with a minimum 30 mV from the output voltage of TEG with the operation of Discontinuous Conduction Mode (DCM) signal which is shown in Fig. 11. The DCM is more efficient than the CCM as the PMOS turns off before the current flow negative. The voltage booster can boost 30 mV to 1.2715 V with current drawn 2.1193 uA under 600 kΩ load condition which is shown in Figs. 12 and 13. The switching frequency is 1.136 MHz to drive the gate of PMOS and NMOS in inductor-based converter. Figure 14 shows the final output voltage produce from the battery-less power management system. The system manages to produce a regulated 1.2 V at 105 us.

Table 1. Design parameter of inductor-based converter.

Parameter	Value
Length of NMOS	130 nm
Width of NMOS	99 µm
Length of PMOS	11 um
Width of PMOS	150 nm
Input ripple capacitor	9 pF
Output ripple capacitor	100 pF
Inductor	10 uH
Load resistor, RL	600 kΩ

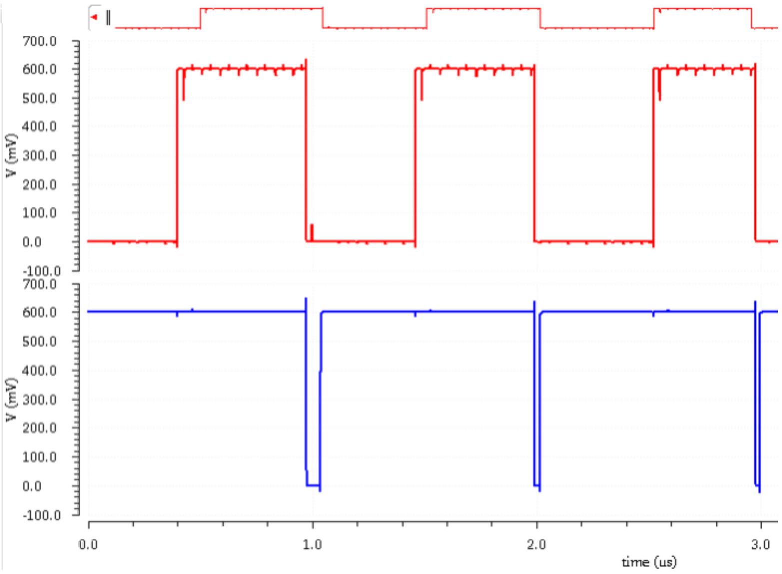


Fig. 11. DCM pulse signal.

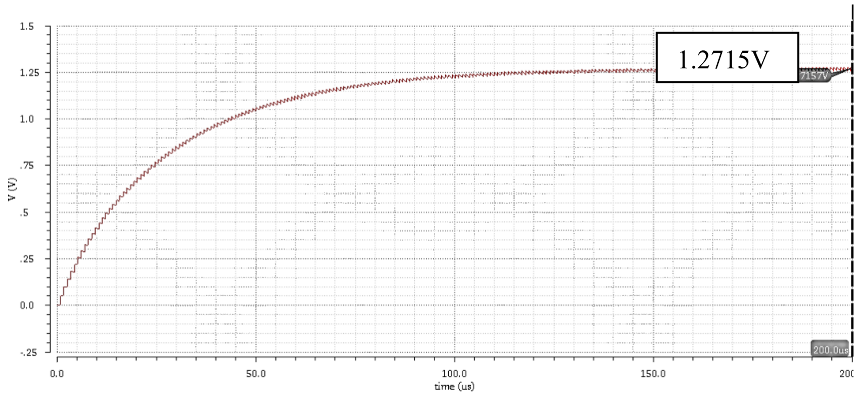


Fig. 12. Output voltage of inductor-based converter.

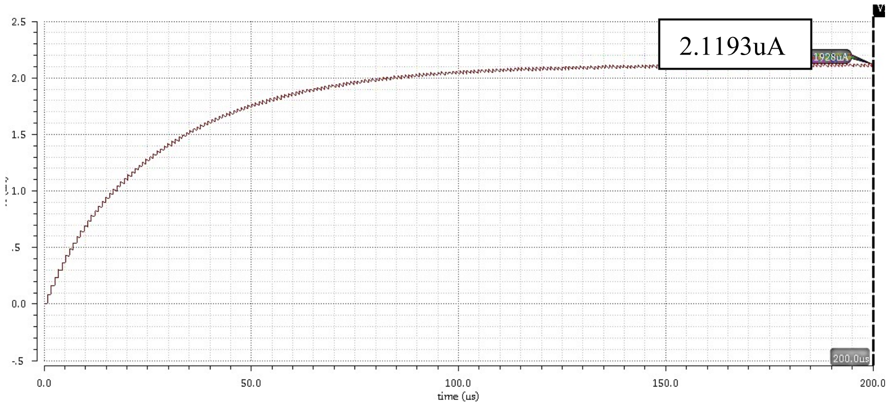


Fig. 13. Output current of inductor-based converter.

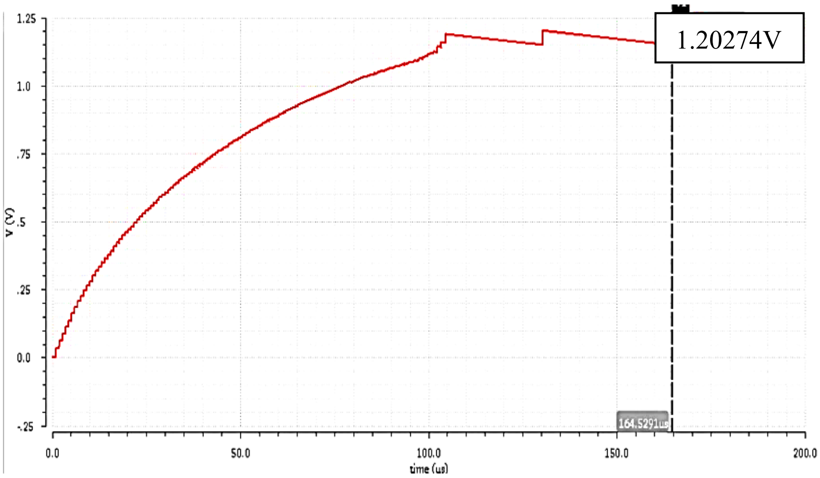


Fig. 14. A regulated output voltage from the battery-less power management system.

Figure 15 shows the response from the dynamic closed loop power management. Figure 15 also indicates the red colour line shows that the output voltage of CMOS voltage booster starts to reach constantly at 100 us. This is because the scaled-down output voltage (blue colour line) of CMOS voltage booster meets with the reference voltage (yellow colour line). Once the CMOS voltage booster reaches 1.2 V, the comparator (pink colour line) transits to low which causes the pulse from digitally control oscillator (purple colour and orange colour line) to off. The clock generator (light blue colour line) is enabled and disabled based on the trigger from the comparator. Therefore, the CMOS voltage booster will not keep boosting up the input voltage but regulated at 1.2 V.

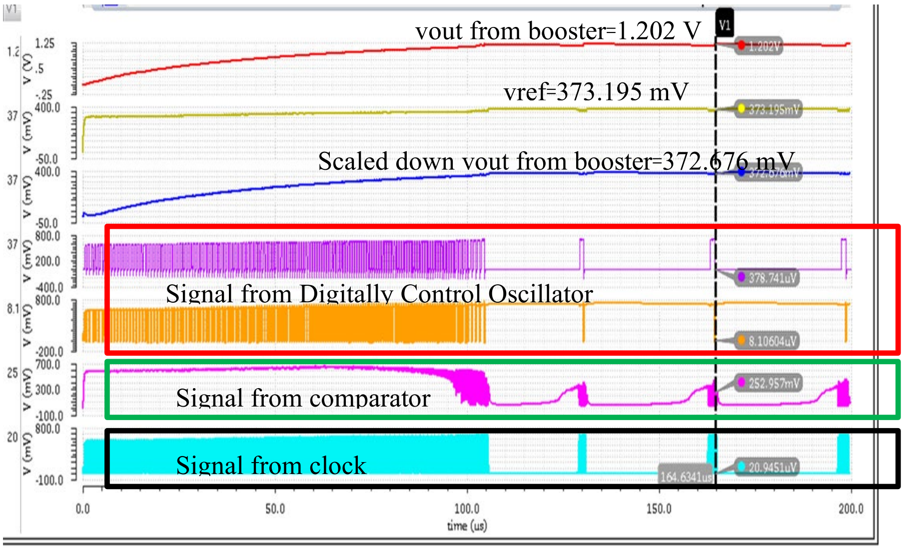


Fig. 15. Transient response of single inductor based dynamic closed loop battery-less power management.

The inductor-based converter requires one external inductor, 10 uH, therefore this needs to be eliminated in the future work to achieve a fully integrated on-chip system. The inductor-based converter is recommended for the application required higher output power and lower frequency. Table 2 shows the benchmarking of the boost converter architecture and the proposed work.

Table 2. Comparison with latest techniques for boosting inductor-based converter.

	Topology	Input Voltage	start-up	Output voltage	Process Technology
[3]	Inductor based converter	20 mV	600 mV	1 V	130 nm
[4]	Inductor based converter	65 mV	65 mV	1.8 V	65 nm
[7]	Inductor based converter	300 mV	750 mV	1.1 V	180 nm
[10]	Inductor based converter	40 mV to 400 mV	40 mV	1 V	65 nm
[11]	Inductor based converter	3.5 mV	50 mV	1.2 V	180 nm
[12]	Inductor based converter	40 mV	57 mV	1.8 V	180 nm
[13]	Inductor based converter	350 mV/ 400 mV	-	1.52 V	130 nm
Single Inductor based converter	Inductor based converter	30 mV	600 mV	1.27 V	130 nm

6. Result Analysis

In summary, the proposed single inductor based dynamic closed loop battery-less power management system can boost 30 mV input voltage to at least 1.2 V output voltage based on the post-layout simulation result. However, the measurement from the prototype is only managed to achieve approximately 700 mV by using ideal start-up voltage.

The low output voltage obtained by the test-setup measurement might be due to the process variation, parasitic resistance on the PCB board, wire bonding resistance etc. By comparing with previous research study in Table 2, the input voltage is considered low by comparing with [7, 10]. While in research [11], it is capable to sustain input voltage at 3.5 mV. However, a huge inductor is used which is 100 uH.

In research [12], the acceptance of input voltage is only 40 mV and the cold start-up voltage is only 57 mV but it required 220 uH inductor and produced unregulated 1.8 V output voltage which is not a preference for a miniature biomedical device. Research [3] can accept minimum 20 mV input voltage but achieved lower output voltage.

The proposed work can achieve high output voltage which is 1.27 V with 30 mV by using single inductor. The contribution of this work is where the power management unit can operate at low input voltage which is only 30 mV and boost up to 700 mV in a real condition by having 1 °C gradient between thermal body heat and ambient energy. Furthermore, the power management unit produces a regulated output voltage which can reduce the risk of damaging low power devices.

7. Conclusions

This paper has presented an inductor-based boost converter as a harvester for a battery-less power management system. The prototype of the inductor-based boost converter shows that a 1 mm^2 miniature power management system can boost an ultra-low voltage 30 mV to approximate 700 mV. This work demonstrates a miniature thermoelectric energy harvesting power management has been developed by using 30 mV which equivalent to 1 °C harvested from the ambient environment, making it feasible for bio implant or wearable devices application.

Acknowledgements

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Abbreviations

BAN	Body area network
CCM	Continuous conduction mode
CMOS	Complementary metal-oxide semiconductor
DC	Direct current
DCM	Discontinuous conduction mode
IoT	Internet of things
NMOS	N-type metal-oxide-semiconductor
PCB	Printed circuit board
PMOS	P-type metal-oxide-semiconductor
RF	Radio frequency
TEG	Thermoelectric generator
TEH	Thermal energy harvester
WSN	Wireless sensor network

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