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A Batteryless low Input Voltage micro-scale Thermoelectric Based Energy Harvesting Interface Circuit with 100mV Start-up Voltage

Abstract*. A Batteryless low input voltage micro-scale thermo electric based energy harvesting interface circuit with 0.1V start-up voltage presents in this paper. The active technique and its components have been chosen such as MOSFET and thyristor to design the proposed DC-DC boost converter with low input voltage (i.e., 0.1V) for energy harvesting interface circuit. The minimum working voltage as low as 0.1V an input the equivalent voltage of thermoelectric transducer has been proposed to design the boost converter. This paper presents techniques for the systematic modeling, analysis, and design of interface circuitry used in the equivalent voltage of the micro-scale thermoelectric energy harvesting systems. In the development of active-based circuits, the DC-DC step-up (boost) converter with thyristor have been designed instead of mainly diode and other components because the forward voltage of diode is (0.7V) higher than the incoming input voltage (0.1V). Finally, the complete proposed energy harvester circuit have been designed and simulated using the PSPICE software. The proposed circuit is capable to step-up regulated DC voltage up to 3.75V. The efficiency of the proposed circuit is greater than 65% following the simulation results. This work has focused on the application of micro-devices Wireless Sensor Network (WSN) device can be operated without battery.*

Streszczenie*. W artykule opisano oszczędnościowe źródło napięcia wykorzystujące jedynie siłę temoelektryczną. Układ elektroniczny startuje już przy napięciu zasilania 0.1V i potrafi wytworzyć wyjściowe napięcie o poziomie blisko 4 V. Jako zastosowanie układu przewiduje się możliwość zasilania czujników bezprzewodowych jedynie z baterii słonecznej. (****Bezbateryjny przekształtnik napięcia termoelektrycznego o poziomie 0.1V na sygnał napięciowy o poziomie kilku woltów****)*

Keywords: Thermoelectric, Energy harvesting, DC-DC converter, Low voltage, WSN.
Słowa kluczowe: przekształtnik DC-DC, siła termoelektryczna, układ bezbateryjny

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Introduction

In the current situation of global energy scarcity, energy harvesting is very important. Although, sufficient amount of energy can be produced to supply to most of the energy needs, this energy is acquired from non-renewable sources [1]. The use of micro-scale thermoelectric generator to harvest energy from ambient thermal has been of great interest to improve the power supply challenge in Ultra Low Power systems (ULP). Fig.1 shows various types of ambient energy sources suitable for energy harvesting [2]. The energy types are thermal energy, radiant energy and mechanical energy. There are many sources of energy that can be scavenged including light, electromagnetic energy, vibrational energy, electrostatic energy and heat [3, 4]. Thermoelectric transducer can be used as a mean of transforming ambient energy into electrical energy that can be stored and used to power other devices. The use of energy harvesting techniques for micro-power applications uses thermal energy can be converted into usable electrical energy by thermoelectric devices, which generate a DC voltage as a function of the temperature gradient between the cold and the hot side of the plates [5]. Temperature difference around surroundings, if efficiently captured can lead to energy harvesting. Thermal energy is a very attractive source of energy with many advantages [6]. There is always unused, waste heat energy produced from home heating, automotive exhaust, and industrial processes [7]. Thermoelectric is the science of conversion of thermal energy into electrical energy and vice versa [8]. This phenomenon was first discovered by Seebeck in 1821 [9]. Seebeck effect, the concept of production of energy utilizing the temperature difference between two surfaces is a big potential field of alternative and pollution free energy source. This concept has been around since last century, recently they have gained much attention [10].

Thermoelectric is a revolutionizing field because of its many advantages over the conventional energy harvesting methods even though the efficiency of these devices are very low and they are expensive. No maintenance, high reliability and long lifetime are many of the common questions that are to be addressed, if this technology is to be used. The most attention for obtaining electric energy from the surrounding environment for their ability to directly micro-scale TEG is converted into electrical energy. Thermoelectric generator can be used as a means of transforming ambient heat into electrical energy that can be stored and used to power other devices. Usually, energy harvesting systems based on thermoelectric devices can be summarized to have three core components: thermoelectric generator, power electronic interface and electric energy storage. The energy generated by thermoelectric conversion is extracted from the equivalent TEG using an interface circuitry. The interface circuitry boost converter based mainly consists of a step-up voltage whose operation is efficient for micro-devices operation. The interface circuitry plays a very crucial role in energy harvesting, because it control how much power is being extracted from the TEG.

The ultimate goal of this paper is to design a micro-power module (i.e., Low voltage) energy harvesting circuit for ULP micro-devices application that energy harvester to integrate with WSN node. In this paper, the development of a low voltage energy harvesting circuit (based on simulation) using thermoelectric elements is presented.

Development of Thermoelectric Based Low Voltage Step-up Circuit

This section provides the introductory information on thermo electric energy harvesting system such as energy harvesting block diagram, interface circuits and simulation by Orcad PSPICE. Thermoelectric based energy harvesting interface circuits considering of thermoelectric element, DC-DC converter (step-up) and Temporary storage device. Here, the mentioned characteristics are illustrated through selective block diagram. The proposed block diagram is presented (step-by-step) to design the modeling of the thermoelectric based energy harvesting system, as shown in Fig. 2. To do the development of the energy harvesting system, the active technique and PSPICE software have been utilized on the proposed system. With the recent flow of micro scale devices, thermoelectric power generation can provide a convenient alternative to traditional power sources used to operate certain types of sensors/actuators. Thermoelectric materials can be used as a means of transforming ambient heat into electrical power that can be stored and used to power for WSN and other devices.

Thermoelectric Element

A thermoelectric element converts thermal energy in the form of temperature differences into electrical energy. Many mechanical thermal-based energy harvesting systems use a thermoelectric transducer as a DC power source, whose output voltage must first be step-up before being delivered to a load. Hence thermal energy harvesting is more suitable for low power applications that consume power less than a few *mW* or hundreds of *µ*W.

Development of the DC-DC Boost Converter Circuit

The second block of the energy harvesting interface circuit is the DC-DC step-up converter and its schematic diagram shown in Fig. 3. The corresponding block diagram is shown in Fig. 2 and results shown in section 3. A DC-DC boost converter that is uses capacitors (as energy storage elements) to create either higher or lower voltage power source. The converter needs to be boosted to step-up the voltage. The output of the TEG is very low and this voltage cannot be used in any application without boost up. Therefore, a boost converter needs to be developed based on an active technique to increase the voltage to use the application device. The development of a DC-DC converter provides a boost-up output while the input voltage is too low. The minimum start-up voltage is 3.75V of the development of DC-DC converter outputs while the input voltage ranges at approximately 0.1V DC. Considering the low output voltage of a TEG energy harvester, a switch-mode DC-DC converter is designed for its step-up capability and characterized by a high efficiency, up to 75% of the DC-DC converter.

In operation, the proposed circuit for step-up boost converter was used to design using the following parts: VDC (Voltage source), VPULSH (Voltage source), IRF150 (Switch), R (Resistance), L (Inductance), C (Capacitance), Thyristor (2N1595) / Replace of the diode (DIN4002), GND_SIGNAL/CAPSYM, PARAMETER (For defining variables and their values). In the development of the DC-DC converter, the DC input (V_{in}) = 0.1V used is the output generated by TEG stage. Considering the low output voltage of a TEG energy harvester, a switch-mode DC-DC converter is designed for its step-up capability and high efficiency. When switch control (M1) MOSFET is closed for time t_1, the inductor (L1) current rises, and energy is stored in the inductor and if the switch is opened for time t_2, the energy stored in the inductor is transferred to load through the thyristor (X1) and the inductor current falls. The problems were faced during the design of the DC-DC converter circuit; the low input DC voltage was 0.1V. Thyristor was used in the place of a diode to design this circuit. The values of the (X1) thyristor pulses are, Initial value V1 = 0, Pulsed value V2 = 5V, Delay time TD = 9m, Rise time TR = 0, Fall time TF = 0, Pulse width PW = 0.9m, and Period PER = 1m. This is the new modification in the development of the DC-DC step-up converter. The advantage of this modified DC-DC boost converter, is that it is able to increase the voltage using very low input source. MOSFET (M1) transistor pulses used are, as a switching purpose for open and close. If a large capacitor (C1) is connected across the load as the output voltage is continuous and V_{out} becomes the average value that the voltage across the load can be stepped up by varying the duty cycle and the minimum output voltage is V_{in} when duty cycle = 0. An inductor (L1) was used which is 3.7uH for storing the current, Resistor (R1) is 1kΩ used for a better output, capacitor (C1) is 300uF was used for store voltage and filtering of the output voltage to reduce ripple. Finally, the output voltage V_{out} (3.75V) was achieved after using the DC-DC converter (step-up).

Temporary Storage Device

To design the TEG based energy harvesting system, capacitor plays an important role which is needed to consider for storing energy. The storage devices are such as capacitor, rechargeable batteries and super-capacitors. The rechargeable batteries store electrical energy chemically. The super-capacitors are alternative energy storage devices rather than traditional rechargeable batteries. Few researchers have looked into super-capacitors as energy storage devices in energy harvesting. The storage device voltage is an important factor that influences the efficiency of the thermoelectric energy harvesting system to generate the voltage (Like as a battery) to the load [11]. Therefore, the capacitor (as a storage device) has been considered for this simulation purpose inside the developed completed energy harvesting integrated system in PSPICE platform. The corresponding block diagram is shown in Fig. 2 and its implementation with 300uF capacitor.

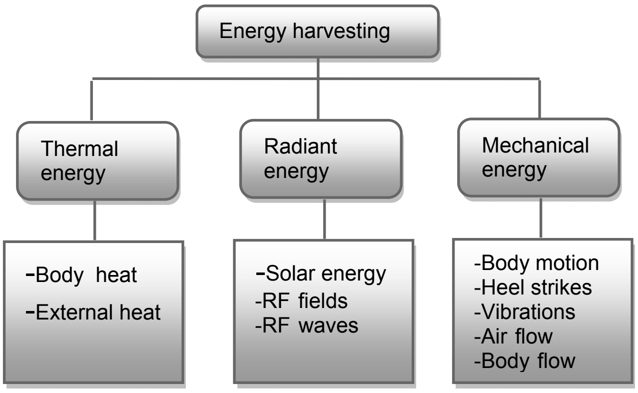

Fig.1.Types of ambient energy sources suitable for energy harvesting

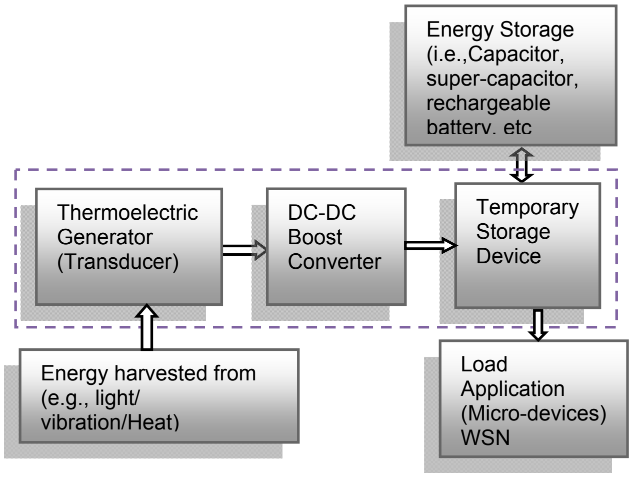

Fig.2. Proposed block diagram of the thermoelectric energy harvesting

Simulation Results in Thermoelectric Transducer PSPICE Software

This thermoelectric generator based transducer produce a very low voltage (i.e., maximum 0.3V) which can be applied to the energy harvesting interface circuit that construct DC voltage. A thermoelectric generator can be modeled as a DC source in parallel with its internal electrode resistor R_p = 1Ω and its results are shown in Fig. 4. It is noted that 0.1V~0.3V was chosen as an input voltage in PSPICE simulation, instead of thermoelectric transducer is equivalent voltage.

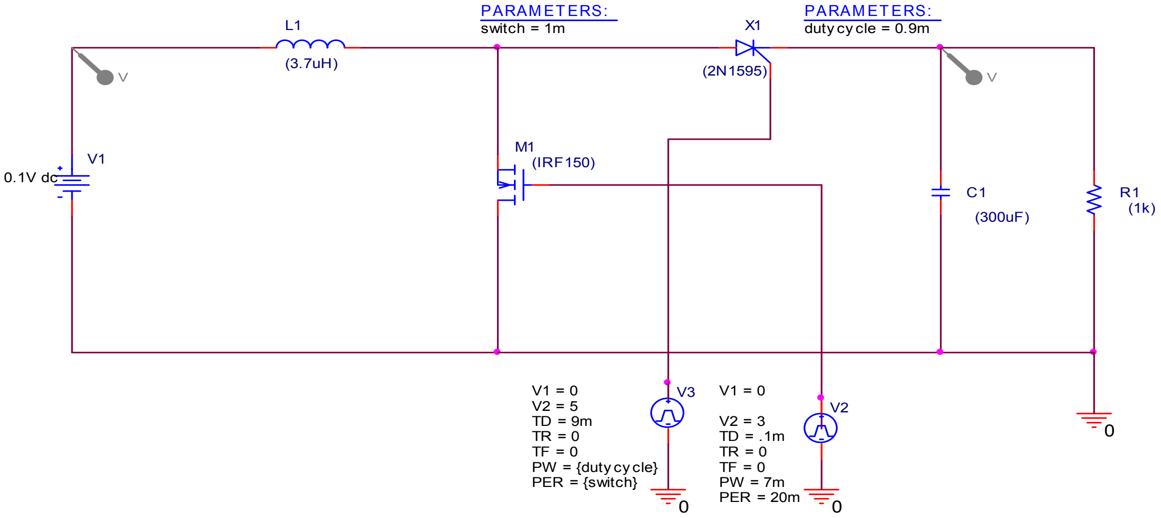

Fig.3. Development of the DC-DC converter circuit (Step-up)

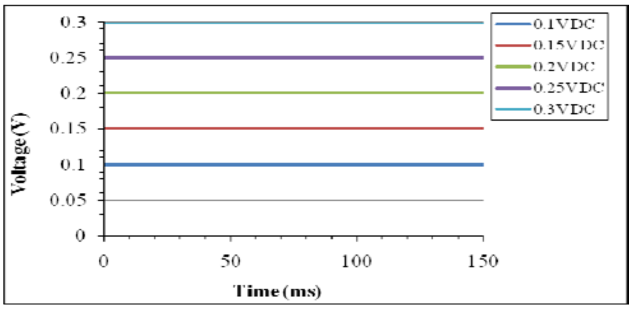

Fig. 4. Input voltage of the thermoelectric transducer

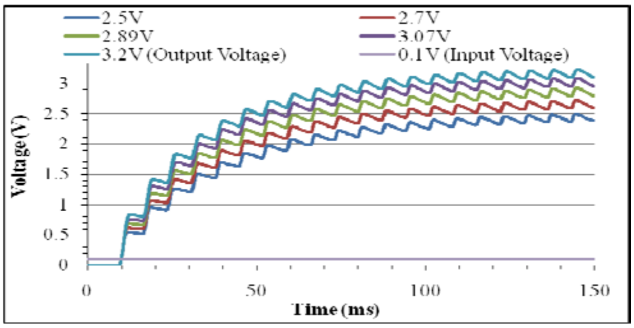

Fig. 5(a). Voltage waveforms of duty cycle with different PW

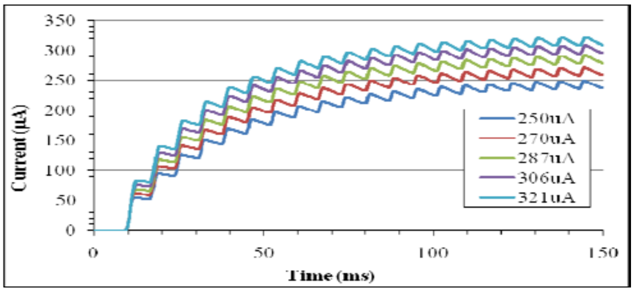

Fig. 5(b). Current waveforms of duty cycle with different PW

Simulation Results of the Developed DC-DC Boost Converter Circuit in PSPICE

The input voltage of thermoelectric transducer equivalent voltage can be increased by the DC-DC converter (step-up). To get output voltage at different Pulse Width (PW), “Parametric sweep” is used from “Simulation parameters settings” and then “duty cycle” is selected as the parameter name. PW values between 0.1 ms to 0.9 ms are considered in which voltage and current are observed. After analysis, a suitable value of target voltage was found for this parameter value. Its start value, end value and increment are specified as shown in Fig. 5(a). From this figure, it can be observed that the voltage increases and decreases with values of the duty cycle. However, beyond 0.9 ms duty cycle, the voltage near exceeds the goal of 3.2V. Therefore, values for the 0.9 ms duty cycle are matched to achieve the expected results. Similarly, corresponding current 321uA can be found as shown in Fig. 5(b). From both these figures, it can be observed that the curve is becoming bent; initially it takes some time to reach the voltage, after 100 ms, it becomes constant. This phenomenon is also clear from these Figures. Similarly, to get output voltage and corresponding current at different periods (PER), “Parametric sweep” is used from “Simulation parameters settings” and then “switch” is selected as the parameter name. PER values duration is considered between 1 ms to 8 ms and voltage and current are observed. After analysis, a suitable value of target voltage was found. Its start value, end value and increment are specified as shown in Fig. 5(c). From this figure, it can be observed that the voltage increases and decreases with values of the switch. However, beyond the 5 ms switch parameter value, the voltage exceeds the goal. Therefore, the values for 5 ms switch are matched to achieve the near expected results of 3.45V. Similarly, corresponding current 3.5uA can be found as shown in Fig. 5(d). From both these figures, it can also be observed that the curve is becoming bent; initially, it takes some time to reach the voltage; after 100 ms, it becomes steady. This phenomenon is also clear from these figures.

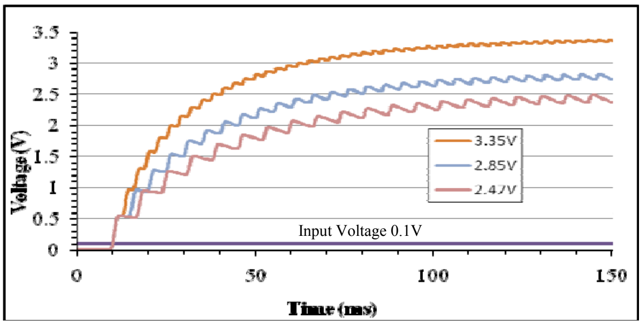

Fig. 5(c). Voltage waveforms of switch with different PER

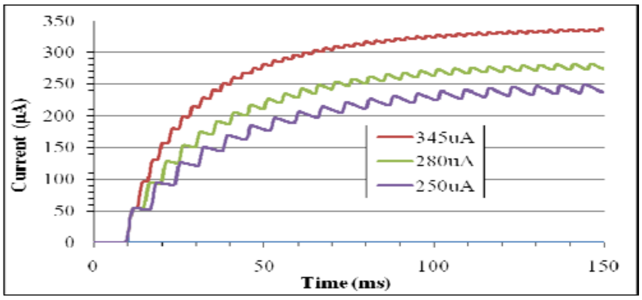

Fig. 5(d). Current waveforms of switch with different PER

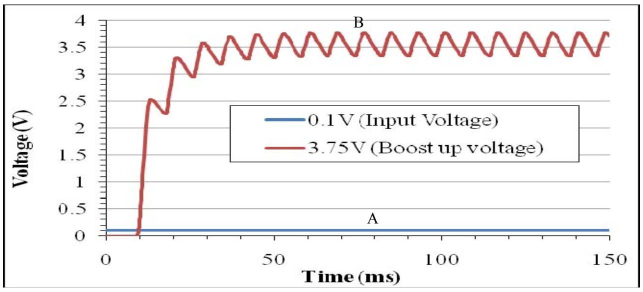

Fig. 5(e). Output of the DC-DC converter (step-up)

Fig. 5(e) shows the final output of the DC-DC boost converter circuit. There are two curves in the figure. Here, curve [A] shows the 0.1V DC as an input voltage in PSPICE simulation, instead of the equivalent voltage of thermoelectric transducer circuit. Curve [B] denotes the final output of the step-up DC-DC converter circuit (3.75V). From this figure, it can be observed that the curve is becoming bent; initially it takes some time to reach the voltage; after 30ms, it becomes steady.

Conclusion

In this paper, the simulation model for a thermoelectric based energy harvesting interface circuit is proposed and analyzed. An active energy harvesting technique is proposed for the system, to simulate the DC-DC boost converter circuit is developed. The benefits of the DC-DC boost-up converter is enable to step-up at 3.75V regulated DC voltage using 0.1V DC thermoelectric based energy harvester equivalent voltage. Based on the results of PSPICE simulation using temporary storage device, it is able to store at 3.75V as enhancement of performance of the WNS. The overall efficiency of the DC-DC boost converter circuit is 65%, as predicted by the simulation.

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REFERENCES

[1] Dresselhaus, M. S. and I. L., Thomas, Alternative energy technologies, *Nature* 414 (2001), 332-337

[2] Roundy, S., D., Steingart, and L., Frechette, Power sources for wireless sensor networks, *Wireless Sensor Networks, First Europeean Workshop, EWSN*, (2004), 13-27

[3] Torres, E. and G., Rincon-Mora, Harvesting Ambient energy will Embedded Devices Autonomous, *Embedded*, (2005), 1-4

[4] Roundy, S., P. K., Wright, and J. Rabaey, A study of low level vibrations as a power source for wireless sensor nodes, *Computer Communications* 26 (2003), 1131-1144

[5] Yara, H., C., Alon, S., Shmuel, and Y., Ben, A High Gain DC-DC Converter for Energy Harvesting of Thermal Waste by Thermoelectric Generators, *IEEE 27th Convention of Electrical and Electronics Engineers in Israel,* (2012), 1-5

[6] Heremans, J. P., Thermoelectric Power of Bismuth Nano-composites, *Physical Review Letters* 88 (2002), 216-220

[7] Snyder, G. J. and E. S. Toberer, Complex thermoelectric materials, *Nat Mater* 7 (2008), 105-114

[8] Goldsmid, H. J., *Introduction to Thermoelectricity*: Springer, (2009)

[9] Seebeck, T. J., Magnetische Polarisation der Metalle und Erze durch Temperatur- Differenz", *Abh. Akad. Wiss. Berlin* 21 (1822), 289–346

[10] Dresselhaus, M. S., New Directions for Low-Dimensional Thermoelectric Materials, *Advanced Materials* 19 (2007), 1043-1053

[11] Rodrigo, G. M., Suitability of capacitors and rechargeable batteries as electrical energy storage in self sufficient sensor nodes powered by energy harvesting. Bachelor thesis, Universitat Politècnica de Catalunya (2010)

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