

# Body Heat Thermoelectric Energy Harvesting for Self-Powered Wearable Electronics

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## ABSTRACT

Over the past several years there has been significant development in low power wearable wireless electronics which can be powered from energy harvesting systems rather than from batteries. In this paper we present a thermoelectric energy harvesting system using human body heat to power wearable electronics. The main focus of this paper is to present a power management system suitable for this application. The voltage produced from the human body is small in quantity (~100mV). Ultra- low voltage boost converters and output voltage regulators have been designed for low power wearable electronics. This work considers the human arm/wrist as a source of heat, placing a thermoelectric generator (TEG) with a heat sink on a wrist using a watch like prototype. The TEG was tested with a body to room temperature difference  $\Delta T=5^{\circ}\text{C}$  producing 1.54 mW. The harvested and regulated power is 0.278 mW sufficient for a wearable wireless sensor (WSN) node [1]. The proposed power management and dc-dc converter circuit operates with an input voltage as low as 30mV. 24% efficiency is achieved from the boost converter stage whilst the dc-dc converter stage gives approximately 75% efficiency. The average end-to-end efficiency is 18%.

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## Keywords

Thermoelectric Energy Harvesting, Wearable Electronics, Thermoelectric Generator.

## 1. INTRODUCTION

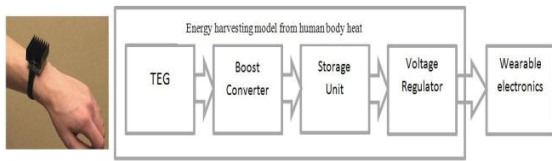
Wireless sensor networks (WSN) have emerged from the research domain to provide commercial solutions for many real-world applications.

Among these recent developments of low power electronics and micro-power energy harvesting it is possible to produce self-powered solutions for wearable health monitoring systems. Some health monitoring system such as pedometer, ECG, blood pressure monitoring systems, EEG devices and their wireless solutions are widely available in the market.

Long-term deployment of these devices with minimized battery maintenance is one of the most desired functionalities in the practical utilization of these wearable systems. Recent studies claim that the global market for wearable electronic may reach 170 million devices for health and fitness application by 2017 [2] [3].

Energy harvesting enabling self-powered wearable electronics has the potential to further increase the market size. In order to operate a given wearable device in an energy autonomous and maintenance free manner the device should use ambient energy where possible [4] [5]. As for wearable devices, three types of energy sources can be utilized for energy harvesting: 1) Photovoltaic energy produced from ambient light, 2) mechanical energy produced from movements of human body (either by itself

or by means of transport) and 3) thermoelectric energy produced from human body when worn. In this work thermoelectric energy is used because of its constant availability whilst solar and mechanical energy are condition dependent.



**Figure 1. Block diagram of Thermal energy harvesting for wearable devices**

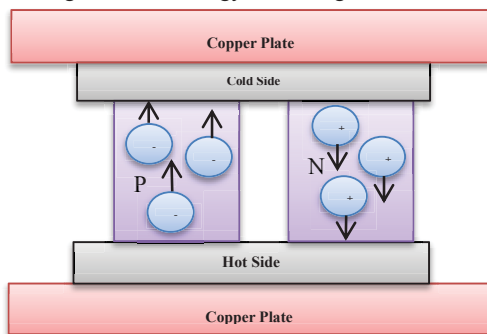
The block diagram in Fig. 1 shows the TEG energy harvesting system. The TEG transducer is used to convert heat energy from the human body into electrical energy. A low voltage boost converter is used in order to increase the voltage from the TEG module. A Super capacitor (10mF) is used as a storage unit. A boost voltage regulator is used to regulate the output voltage for wearable electronics. The TEG working principle and background information will be presented in section 2. Section 3 describes the development and implementation of the power management circuit based on boost converter and voltage regulator circuit. The power management circuit contains the feature of cold start. This section also contains the feature of a super capacitor used as an energy storage unit. The proposed system is tested in a typical office environment and the evaluation results are presented in section 4. Problems encountered during the evaluation, future plans and conclusions are presented in the final section.

## 2. Thermoelectric Generator (TEG)

Thermoelectric energy harvesting is based on the Seebeck effect which directly converts temperature difference into electrical energy. The internal structure of a typical TEG module is shown in Fig. 2. In low temperature conditions, the most commonly used and effective thermoelectric material is  $Bi_2Te_3$  based compound. The compounds are fabricated with P-N doping. When a temperature difference is applied electrons migrate due to electromotive force in the P-N junctions, thus a voltage difference is generated.

$$\Delta V = S \times \Delta T \quad (1)$$

The Voltage generated from the TEG is dependent on two factors, 1) Seebeck coefficient. 2) Temperature difference as expressed in eq. 1. The conversion efficiency of the Seebeck effect is low (<1%) and limited to Carnot cycle efficiency [6]. However, this type of device has the advantage of 1) No moving part and 2) Low temperature gradient for energy harvesting.



**Figure 2. TEG Block diagram**

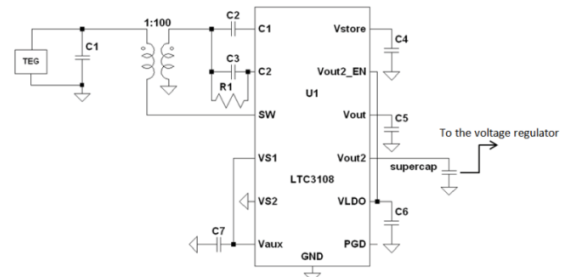
Conventional machined TEGs normally consist of tens to hundreds of thermo-elements. A thin layer of ceramic substrate and a layer of heat-conductive formed carbon thermal pad are applied on each side of the module. A Carbon thermal pad is used to increase the heat transfer from the heat source to the module. In this work, a conventionally machined thermoelectric generator is used. The size of the module is  $6.2\text{cm} \times 6.2\text{cm} \times 0.2\text{cm}$  and with heat sink attached its height increases to 3.5cm. When placed on the arm/wrist, the open circuit voltage it generates is 69.2 mV.

## 3. Power Management Circuit

The small voltage generated from the TEG is not sufficient to power the system directly, so an intermediate circuit is required to fulfill the power management requirements. For this purpose a boost converter, cold start circuit and voltage regulator have been designed.

### 3.1 Boost Converter

A boost converter circuit has been used in order to increase the low voltage from the TEG to charge the super capacitor. A (1:100) turns ratio transformer is used to step up the input voltage and then voltage is feed to a boost converter. The main boost converter is a Linear Technology LTC3108 (1:100) ratio transformer based converter as shown in Fig. 3. This is able to operate input voltages as low as 30mV. This boost converter shows low quiescent current of  $<10 \mu\text{A}$  [7]. However, the ultra-low voltage step-up limits the converter efficiency. This issue is more obvious when the input current is also low (10~20 mA) as in body heat energy harvesting applications. The input impedance of the device is calculated at 2~3 Ohm, similar to the internal resistance (ESR) of the TEG in this configuration. As Dynamic impedance matching is not used in this boost converter it is important to select the TEG module within this internal resistance range in order to maximize output power by matching the input impedance of boost converter and the ESR. Due to the lack of impedance matching the minimum input voltage requirement also depends on the internal DC resistance (ESR) of the supply voltage.



**Figure 3. Boost converter**

This boost converter is extremely suited to systems powered by energy harvesting systems. The boost converter has a cold start function to operate without any external voltage source such a back-up battery. In this proposed system super capacitor type energy storage unit is used. The energy storage unit (ESU) is a key element to enable continuous and long-term operation of the wearable WSN node. The ESU acts as an energy buffer to overcome the sporacity issue related to ambient energy sources, providing a means to avoid power failure when ambient input power is low or not available. A 10 mF super capacitor has been used as the energy storage unit.

### 3.2 Cold Start and Voltage Regulator

Output voltage regulation is necessary from the ESU to resolve the voltage matching issue between ESU and the WSN voltage threshold. In addition it maximizes the useable energy in the ESU (power consumption of microcontrollers and transceivers can be input voltage dependant). The voltage regulator circuit is especially important when capacitive ESU is used, since the voltage fluctuates depending on its state of charge. In the proposed system a Texas Instruments TPS61220 step-up converter is used. The topology of the Cold start and voltage regulator illustrated in the Fig. 4 block diagram.

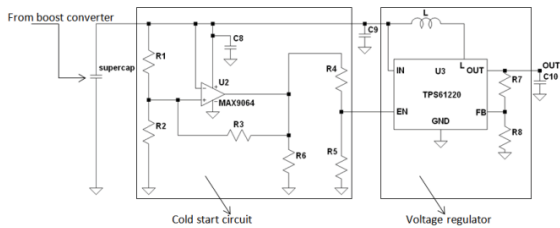


Figure 4. Cold Start circuit and Voltage regulator

This voltage regulator has been selected because of its relatively high conversion efficiency of more than 90%, and relatively low start up voltage threshold 0.7V suitable for the WSN node power levels envisaged. One problem should be addressed here is the cold start of voltage regulator.

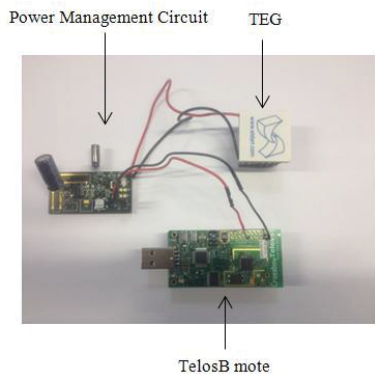


Figure 5. Power Management board with TEG

A hysteresis control circuit has been set up based on a nano-power comparator in order to overcome the cold start problem. The hysteresis band has been set up between 1.1V and 1.67V. When the charge on the super capacitor crosses 1.67V the comparator switches on to enable the output regulator and its connection to the load.

### 4. Experimental Result and Analysis

The proposed prototype system has been tested in various experimental configurations. The Super capacitor voltage level has been monitored with the help of an Agilent N6705B power analyzer. Furthermore, several tests have been conducted in order to verify the cold start problem. The proposed energy harvesting system is used to evaluate the efficient energy usage in order to monitor the environment temperature in the lab area with the application running on a TelosB mote [8]. The super capacitor is charged with the input voltage produced by the TEG module. Fig.

6 shows the input voltage, voltage level on super capacitor and the output of voltage regulator. A human hand is applied on one end of the TEG module whilst the other end is naturally cooled by a heat sink at room temperature. As the voltage level on super capacitor crosses 1.67 V the cold start circuit turns on the output voltage regulator. TPS61220 has been programmed for 3.3 V at the output as shown in Fig. 6. In this test a 10mF super capacitor is used which takes 48 seconds to charge up to 1.67 V from human body heat only.

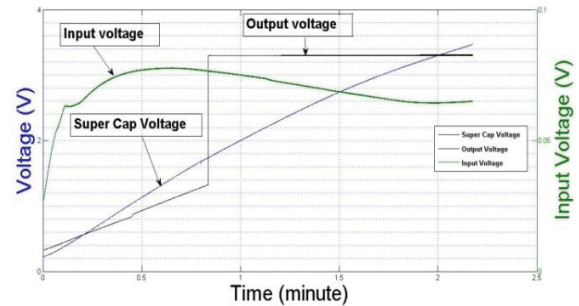


Figure 6. Evaluation of Energy harvester model

In this body heat energy harvesting experiment the efficiency of different system stages have been measured. The power produced and efficiency of each stage is shown in fig. 7. The power produced from the TEG is 1.54 mW. The conversion efficiency of the LTC3108 based boost converter is 24% from the harvested energy of the TEG.

In this calculation leakage from the super capacitor is also taken into consideration which is 9.12  $\mu$ W based on a 1 hour leakage (i.e. self-discharge) experiment. The TPS61220 based voltage regulator can achieve approximately 75% efficiency from a charged super capacitor. Overall the proposed system can produce 0.278 mW by applying body heat on the TEG module in a 20°C room temperature environment.

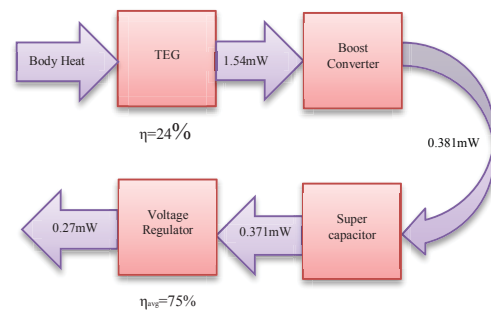


Figure 7. Power and efficiency evaluation at different stages of model

The results above demonstrate that the proposed energy harvesting system can power the mote autonomously by applying body heat as a source of energy. But the placement of system on the body part is critical, it is suggested that the proposed module should be worn as bracelet like prototype due to its need for exposure to ambient temperature. The proposed design has the potential to achieve system lifetime up to 10~20 years.

## 5. Conclusion and Future Work

In this paper an autonomously operated body heat energy harvesting system is presented. A complete energy harvesting system is presented with the features of ultra-low voltage boost and voltage regulation. The proposed system can operate at an input voltage as low as 30mV. A low voltage boost converter, super capacitor and voltage regulator have been used with multi-stage circuitry in order to achieve good efficiency whilst boosting 100mV to 3.3V. With an optimized thermal energy harvester and TelosB operating in low power mode, continuous mote operation is achieved. For future work, a suitable miniature prototype should be developed for the optimum placement. There is also a need to find a method for the reduction of leakage current from the super capacitor in order to increase the system life time.

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