



Hybrid Energy Harvesting for Self-powered Implantable Biomedical Devices

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To cite this article:

Md. Saiful Islam, Md Kamal Hosain, Khalifa Almheiri, Thirein Myo. Hybrid Energy Harvesting for Self-powered Implantable Biomedical Devices. *American Journal of Chemical and Biochemical Engineering*. Vol. 7, No. 1, 2023, pp. 1-6. doi: 10.11648/j.ajcbe.20230701.11

Received: December 26, 2022; **Accepted:** May 26, 2023; **Published:** June 6, 2023

Abstract: Developing implanted devices is vital for the welfare and safety of well-being because they directly affect lives and safety and provides indication for early recovery. In order to realize the high performance of implantable medical devices, powerful energy sources must be judiciously integrated onto conformal platforms. Energy harvesting from environmental sources and human body motion is becoming increasingly relevant for implantable devices. In this paper, we have developed an efficient energy harvesting technique using low-grade ambient energy sources especially, vibration, and temperature difference, which provides the basis of a self-powered system and allows a wide variety of implanted wearable medical devices to be operated. We have experimentally estimated the harvested energy and validated the amount against the requirements of various miniaturized devices such as cardiac pacemaker, cardiac activity sensing, and electrocardiogram amplifier etc. In addition, this paper investigates the output-harvested energy against the temperature gradient (thermal energy harvesting) and vibrational frequency (vibrational energy harvesting). It is observed that the thermal energy harvesting technique provides higher harvested energy compared to the vibrational counterpart and is linearly proportional to the temperature gradient.

Keywords: Energy Harvesting, Thermal Energy, Vibrational Energy, Implantable Medical Devices, Peltier, Vulture

1. Introduction

Powering portable and wearable devices requires clean, sustainable, and renewable energy due to convenience and environmental considerations. Battery power is still the predominant source of power for most wearable devices despite the accelerated growth of these devices [1]. A key challenge with such devices is that batteries need to be replaced regularly, which can be problematic. Up until now, charging or replacing batteries for mobile devices has been accepted as a necessary inconvenience, but energy harvesting technology can dramatically reduce this, potentially removing the need altogether. Energy harvesting technique can be used to power biomedical devices using low-grade ambient energy sources such as infrared light, solar energy, vibration, and temperature difference. These sources can be converted into electrical energy that can be

used to power the implanted wearable medical devices. Therefore, these devices may be useful as replacements for implanted batteries to determine the energy availability for harvester-powered implantable biosensors. Additionally, they promise to be able to power a variety of implantable and wearable medical devices.

Over the last few decades, it has been tremendously increased the importance of energy harvesting which is evident from the rising number of publications and product prototypes. The need for energy harvesting is also prevalently increasing to meet the demand for life-long implanted medical devices [2-4]. The study of human body energy has been ongoing for decades, but research on harvesting this energy is still relatively in its rudimentary [5]. An important requirement for all human body energy harvesting research is

that the harvested energy does not affect the human body's normal activities. As a result, although the human body dissipates a great deal of energy every day, only a small amount of that energy is utilized by the body. Additionally, the current energy harvesting technologies have relatively low conversion efficiencies, resulting in only microwatts of actual conversion power [3].

Due to the increasing demand of implantable medical devices, researchers have paid significant attention to the development of self-powered system which integrates energy harvesting unit, sensing unit and control unit. Jian *et al.* [1] have developed a stretchable and wearable textile-based hybrid super capacitor–biofuel cell system that provides unique architecture and low-cost scalable fabrication. Although it is claimed to be the new garment-based hybrid energy device for smart textiles, it was not best suited for implantable medical devices. Wang's group demonstrated the first hybrid Nano generator in 2009 for harvesting mechanical and solar energy simultaneously [6, 7]. In recent years, this concept has been expanded to include many different types of energy harvesters. Various transducers have been developed extensively since their invention, and several reviews have summarized the advancements in energy harvesting for wearable and implantable medical devices and provided researchers with useful references to their principles and designs [8-12]. However, there is no simultaneously used of energy harvesting for wearable/implantable medical devices.

In this paper, we present a hybrid energy harvesting system using thermal and vibration energy in dual-mode for implantable medical devices. The control circuitry automatically detects the situation of the object (e.g., human, tracking animal) and activates the energy harvesting process accordingly. When the object is in motion, vibrational energy harvesting is activated, otherwise thermal and thermal energy harvesting is activated where the temperature difference between the object's body and surrounding environment is used to harvest thermal energy.

2. Energy Harvesting

In addition to being a source of kinetic energy, human activities also generate thermal energy. Power is produced at different levels by different body activities. As a result of sleeping, approximately 81 milliwatts of power are produced, while sprinting, walking, and moving to generate 1630 milliwatts of power [13-15]. Despite changes in ambient temperature, the human body can retain its temperature. When the surroundings are extremely cold, this property maintains metabolic processes necessary for energy production. It is therefore the purpose of this study to investigate how kinetic and thermal energy can be harvested from the implanted object (human body) and be suitable to power wearable/implantable medical devices. A typical example of thermal energy harvesting and the practical implementation is shown in Figure 1.

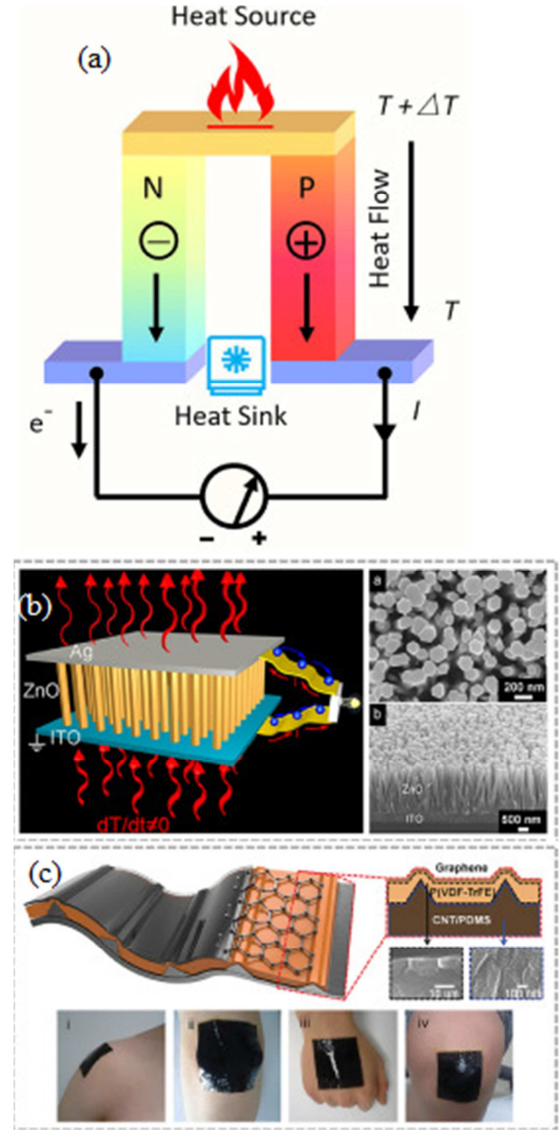


Figure 1. Illustration of energy harvesting: (a) Principle of operation thermal energy harvesting, (b) Piezoelectric energy harvesting.

3. Experimental Setup and Results

3.1. Thermal Energy Harvesting

To conduct the thermal energy harvesting estimation, it requires a number of components including transducer to convert the thermal difference to a corresponding voltage difference, a step-up booster converter and a few more associated components which will be discussed in the subsequent sections. The key component required to initiate this test is the thermoelectric transducer which converts the thermal gradient to the corresponding electrical output. In this experiment, Peltier has selected as a thermoelectric transducer that has various dimensions. The corresponding amount of the electrical output as harvested by this Peltier device depends on the dimension. To generate the electrical output from the Peltier device, one face of the Peltier needs to expose to warm temperature and another face needs to expose to cold temperature. Once, there is a sufficient temperature gradient

(in our case, it is around 2.5°C (ΔT)) produced between the faces of the Peltier, it produces the output voltage. If the faces of the Peltier are exposed in the reverse order (e.g., hot face to cold and cold face to hot), then the Peltier produces negative voltage. However, the Peltier (102-1670-ND) considered in our experiment is auto polarity detection meaning that it always generate the output voltage in one polarity (positive voltage).

To generate different amount of the temperature gradient in the Peltier faces, the following methods are considered

1. Joule heating (applying the voltage to high power resistor to produce the heat).
2. Aluminum plates attached to two different faces of Peltier and then exposed them to two different temperatures.
3. Two different voltages applied to two different faces of the Peltier and then attached it to the examined Peltier device.
4. One face of the Peltier is attached to human body and another face is be exposed to room temperature.

In the aluminum plate method, two different aluminum plates is attached to each face of the Peltier using a conducting glue. Thereafter, the aluminum plates are immersed in a glass of water with different temperatures (hot and cold water (bag of ice)). On the other hand, since the output of the Peltier is low (few millivolts only), it needs to be boosted using a booster circuit in order to estimate the output power delivered by the thermal energy harvester. In this experimental setup, a 'Demo Board Autopolarity, Ultralow Voltage Step-Up Converter and Power Manager' have been selected to serve this purpose. To estimate the amount of energy harvested from this thermal energy harvester, a known load is connected to the output of the booster circuit. Finding the voltage drop across this load can give an estimation of the amount of current drawing through the load and hence the corresponding harvested energy. Figure 2 shows the experimental setup for this prototype harvesting method. As shown in Figure 2, two faces of the Peltier were attached to two different aluminum plates to apply two different temperatures in these two faces. The differential temperature produces a temperature gradient across the Peltier device. To produce different differential temperature, the heat of the glasses were controlled using hot water and pieces of ices. The output of the Peltier device is typically in the range of few millivolts to few hundred millivolts which is enough to drive a booster circuit. The booster circuit in this case is used to boost the power level as harvested from the transducer. Indeed, the power measured from the load of the booster circuit determines the amount of power harvested from a particular harvesting approach. This is actually a highly integrated DC/DC converter which is employed to provide harvesting surplus energy from exceptionally low input voltage such as Peltier and thermoelectric generator (TEG). This particular DC/DC converter used in this experiment can operate as low voltage as 30 mV only. Since, only a few $^{\circ}\text{C}$ temperature differential can produce 30 mV, therefore this booster circuit was an ideal selection for this experiment.

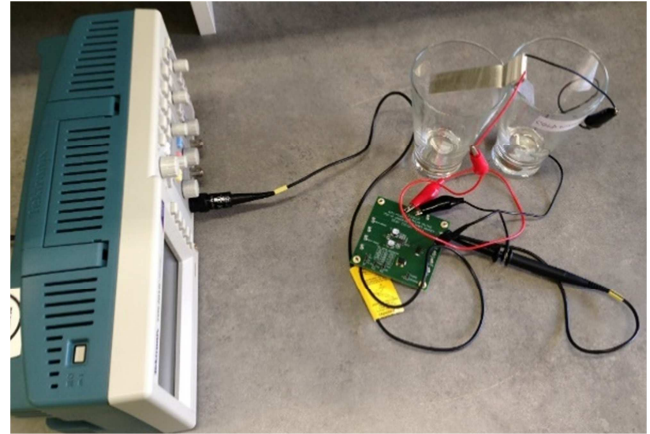


Figure 2. Experimental setup for thermal energy harvesting.

The following Figure 3 shows typical characteristics of the LTC3109 booster for different TEG voltages. This DC/DC convert has a good capability of storing energy which is the main goal of this harvesting approach. For storing purpose, super capacitor and higher power and high efficiency battery were considered for this project [16]. The added advantage of this booster circuit was its variable range of output harvested voltages such as 2.35V, 3.3V, 4.1V or 5V. Therefore, it will restrict its application to a particular area rather can find applications in remote sensing, radio power, predictive maintenance and industrial wireless sensing.

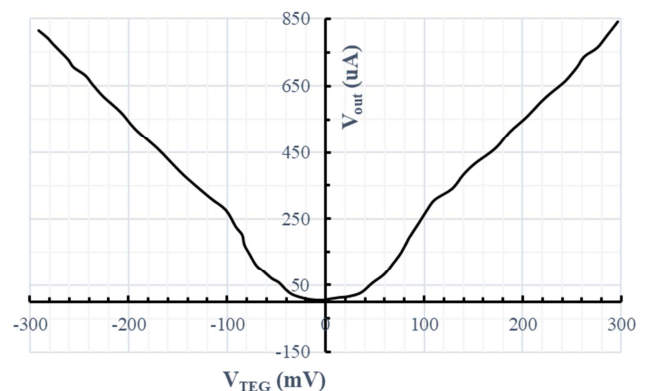


Figure 3. Output voltage versus thermoelectric generator voltage from a LTC3109 booster.

It is found from the results that a different temperature gradient as obtained from the two plates of the aluminum produces voltage at the output of the transducer. The output of the transducer is then applied to the input of the booster circuit. It is also noticed from the experiment that the minimum voltage (30 mV) required to operate the booster circuit produces only when there is a temperature gradient of 2°C . Figure 4 and Figure 5 show the transducer output voltage and harvested output power across the load, respectively. In both cases, it is noticed that the harvested power increases with the increase of the temperature gradient. A linear relationship amongst these variables have been established. As shown in Figure 4, the transducer output voltage increases 16.686 mV per 1°C increase of the differential temperature. Similarly, the

output power across the load increases by $165.88 \mu\text{W}$ per 1°C increase of the differential temperature gradient. Theoretically, it is established that the output power is proportional to the square of the temperature difference of the Peltier faces [16] which has been also validated through this experimental result. Therefore, this experimental result ensures the reliability of the expected harvested energy.

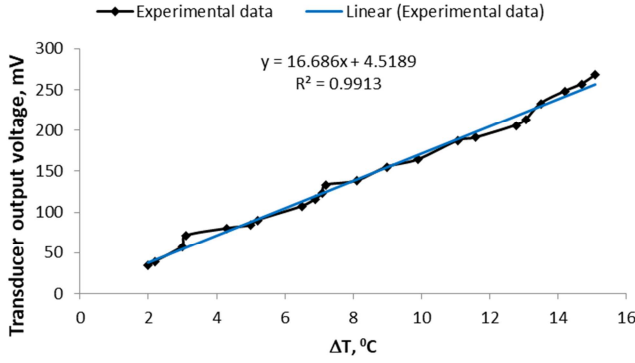


Figure 4. Output of Peltier against different level of temperature difference across the transducer.

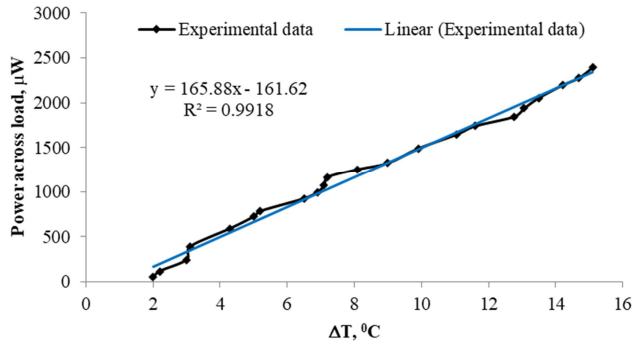


Figure 5. Harvested output power (Booster output) against different level of temperature difference across the transducer.

In another investigation, we have identified that the same temperature difference produced from two different temperature applied to the Peltier produces two different amount of energy harvested. It means that the more the temperature difference at lower temperatures, the more the energy is harvested. As observed from the experimental results that the same 5.2°C was produced at two different temperatures. For example, in this case 5.2°C was produced from 39.2°C and 34°C ($39.2 - 34 = 5.2^\circ\text{C}$). The corresponding harvested output power was found to be $783.45 \mu\text{W}$. In another instance, the same differential temperature of 5.2°C was produced from 35.6°C and 34.4°C which is lower than the aforementioned temperatures. However, the harvested energy in this instance was found to be significantly higher than in the first instance. Therefore, we can conclude from this experimental procedure that the temperature gradient can be generated higher but needs to be at a lower region of temperature.

After estimating the total amount of harvested energy from this thermal energy harvesting, we have then modelled a system on how this harvested energy can be utilized to power

the implanted medical devices. To accomplish this modelling system, we collected different power requirements for various miniaturized devices as shown in Table 1 [17]. It is obvious Figure 5 and Table 1 that the thermal energy harvesting is sufficient to continuously supply the power to these miniaturized devices.

Table 1. The requirement of power to operate different miniaturized devices [17].

Miniaturized Devices	Power Requirements
Cardiac pacemaker	$1 \mu\text{W}$
Cardiac activity sensing	$0.3 \mu\text{W}$
Electrocardiogram amplifier	$2.76 \mu\text{W}$
Electronic-nose sensor system	$250 \mu\text{W}$
Drug pump for ophthalmic use	$400 \mu\text{W}$
Cochlear implant	$100\text{--}2000 \mu\text{W}$
Neural recording	$1\text{--}10 \text{ mW}$
Wireless sensor network	71 nW
Sensor on wristband	0.83 mW
Chest patch	0.96 mW

3.2. Vibrational Energy Harvesting

The activities of the human body offer potential as a source of energy for implantable biomedical devices. For human and environment energy harvesting devices, kinetic energy is a readily available source of power. In order to harvest the energy from the vibration, a vibrational transducer is required which will convert the vibrational energy to the electrical energy. In this experimental, we have used a piezoelectric transducer in particular a Vulture device to harvest the energy from the vibration Figure 6 shows a Vulture piezoelectric transducer for vibrational energy harvesting. Amount of energy harvested by this Vulture device depends on the vibrational frequency, size of the Volute. Since, the output of the Vulture device is AC, a simple bridge wave rectifier is designed to convert the AC to DC. In addition, a Buck converter circuit is designed to boost the voltage level from Vulture.

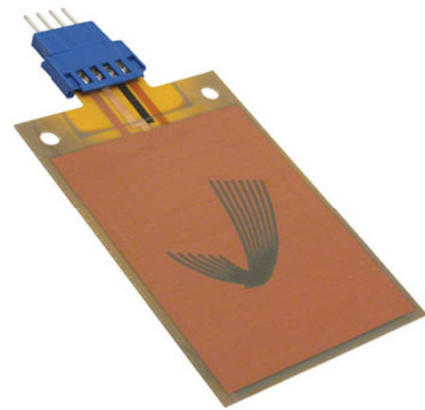


Figure 6. A Vulture piezoelectric transducer for vibrational energy harvesting.

In experiment, a prototype of the vibration energy harvesting is designed using a piezoelectric transducer (Vulture), a buck converter (booster), a bridge rectifier and a servo motor. Initially, a manual vibration is generated using

the servo motor which is then applied to the piezoelectric transducer (V22B). The frequency of the generated vibration is controlled by attaching the tip mass to the piezoelectric transducer. The rectified DC voltage is fed into the buck converter. A load resistance is connected across the output of the buck converter (LTC3588-2) to estimate the amount of the generated output power harvested from the piezoelectric transducer.

As shown in Figure 7 that the output power varies with the

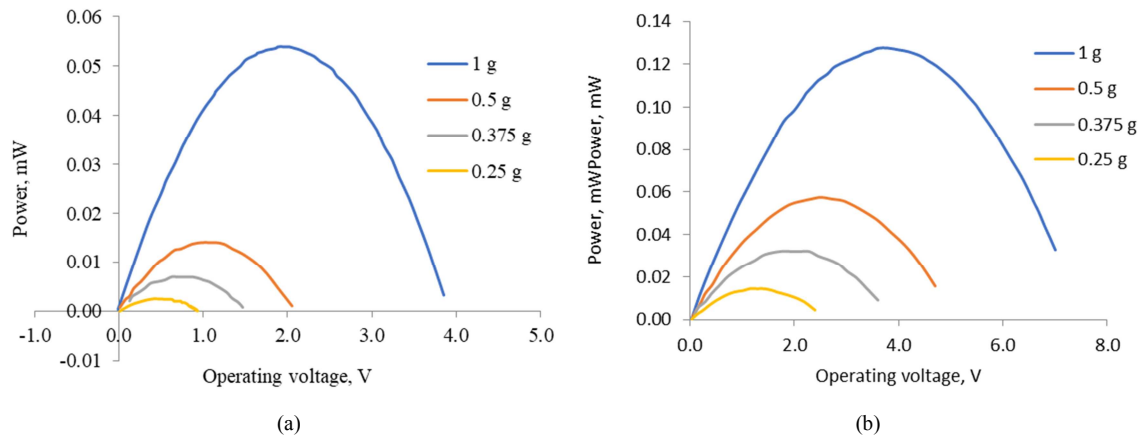


Figure 7. Variation of power against the operating voltage for various tip mass attached into the piezoelectric transducer: (a) tuned at 240 Hz and (b) tuned at 125 Hz.

4. Conclusion

The ever-rising demand for energy with the diminishing supply of high grade fossil fuels has opens new avenue for finding alternating energy sources. There are many sources of energy available in unlimited quantities. Solar and wind energies are such sources which are worth considering for harvesting energy from them. Although energy harvesting from these available energy sources has been introduced over a number of decades however harvesting of energy in implantable medical devices is fully explored in an integrated form. This paper presents energy harvesting in wearing/implantable medical devices by considering the thermal and vibrational energy sources. The harvested energy is modelled against the power requirements of different miniaturized devices and ensured the applicability of the available harvested energy. This hybrid and dual energy system could successfully produce and store the energy in practical exercise, providing a major advancement in the development of wearable self-powered implantable medical devices.

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