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Research Article
Integrated Hybrid Micro Energy Harvester Based on Thermal and Vibration Using Op-amp for Biomedical Devices

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Abstract

Background: Energy harvesting is the process of capturing tiny amounts of energy from one or more innate energy sources, accumulating the collected energy and storing it for future use. Batteries are not really practical because the lifetime of a battery is limited, its replacement and recharging could become major bottlenecks. Therefore, energy harvesting is playing a more and more vital role in the supply of energy to real life applications, such as wireless sensor networks and health care monitoring. **Materials and Methods:** This study presents the design of ultra-low-power hybrid micro-energy harvester (HMEH) circuit with hybrid inputs of thermal and vibration. The main purpose of the hybrid inputs in the system is to support the low input, especially of thermal energy, thereby ensuring that energy continuously flows. Both inputs are simultaneously present and will be combined in parallel at 0.02 and 0.5 V for thermal and vibration inputs, respectively under frequency of 10 Hz. When only thermal energy exists, the system is considered to have the minimum condition, the maximum condition refers to when both inputs exist. **Results:** This HMEH system abled to achieve the output of 4.0 and 3.94 V for simulation and hardware respectively using 1 megaohm (MΩ) load resistance. From the simulation and experimental work, the generated output power of the system is 1.6 and 1.182 mW. **Conclusion:** The proposed HMEH system achieves better performance and functionality when work under the maximum condition. The performance of the HMEH system is compared between the simulation and hardware implementation.

Key words: Hybrid micro-energy harvester, thermal energy, vibration energy, biomedical devices

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INTRODUCTION

Recent applications, such as implantable biomedical sensors and wireless sensor networks, mostly use energy harvesters to obtain energy from the environment. Generally, these energy harvesters are widely used to overcome the battery use as a conventional source for ultra-low power circuits. Batteries become unfavorable because they are bulky, expensive and require regular replacement. The main goal of the energy harvester sources is to achieve the battery-less operation of microelectronic devices. Small electromechanical devices have micro-energy harvesters to collect and convert ambient energy into electrical energy[1]. Typical power ranges of the micro-energy harvester are restricted from nanowatts to milliwatts[2] with the aim to power a wireless sensor network or wearable devices[3]. Normally, energy harvesters can supply an output power of 10-100 µW by limiting the average power for load circuitry operation[4]. Several energy sources can be scavenged from the environment, such as thermal, vibration, solar, Radio Frequency (RF) and wind energy. The power requirements of the specific electronic load and the nature of application will determine the suitability of an energy harvester source[5]. This study will focus on the hybrid input sources of thermal and vibration energy from the human body for biomedical devices.

Thermal energy is one of the most eco-friendly sources, this form of energy is primarily handy for biomedical applications because of its high dependability, compactness, zero emissions, low noise, clean fabrication and zero fuel utilization[6]. Thermal energy can generate a voltage proportional to the temperature difference applied to each side based on the seebeck effect, which was described in the 1820s[7]. In the seebeck effect, heat is directly converted the temperature difference into electrical energy by a thermoelectric generator (TEG) device. The TEG is a solid state device that is commonly composed of semiconductor materials, such as bismuth telluride, silicon germanium and lead telluride. These materials have a high power factor and low thermal conductivity, thereby increasing their cost. Currently, the thermal conductivity of semiconductors can be lowered by nanotechnology without affecting their electrical properties. A typical configuration of a TEG consists of two dissimilar thermoelectric conductors: The p-type and n-type, which are thermally connected in parallel and electrically connected in series. More electricity will be generated when the temperature difference across the module and the efficiency of converting heat energy into electrical energy is increased. The heat source come from human beings will be attached to the skin. For example, a TEG is mounted in a wrist watch for powering a watch with wasted human heat[8].

Among the energy harvesters, vibration is one of the effective sources in a system because of its natural presence. Mechanical energy is transformed into electrical energy. This mechanical energy refers to the mechanical motion effects from the surroundings. Everything in the universe vibrates at different frequencies as three types of vibration: Electromagnetic, electrostatic and piezoelectric. Human vibration can be categorized in two types: Whole-body vibration and harm-body vibration. According to nanomedicine, the human body can produce voltages between 10-100 mV. This value is very low because some researchers have found that the generated voltages is in the range of 25-60 V for practical processes under a frequency range of 15-30 Hz[9]. In a reality, thermal energy provides low input compare to vibration, which causes the harvest of energy, especially from the human body quite challenging. Therefore, a hybrid energy harvester is applied to combine the inputs into a single system for better functionality[10] other than to increase the overall system reliability[11]. A typical energy harvesting system consists of the energy sources, a transducer to convert energy source to electrical energy, a harvesting circuit to determine the harvesting performance, a storage battery and the load. This study aimed is to attain the output range of 2.0-4.0 V when given a thermal and vibration input of 0.02-0.5 V under a 10 Hz frequency. However, the design of a boost converter circuit with maximum power to transfer to the load is a crucial challenge. The design of convenient components is required for this energy harvesting circuit to achieve better performance. Figure 1 presents block diagram of a hybrid energy harvesting system.

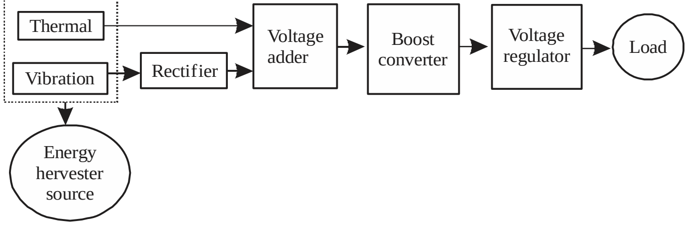

Fig. 1: Block diagram of a hybrid micro-energy harvesting system

MATERIALS AND METHODS

System architecture: A hybrid micro-energy harvester (HMEH) is proposed for harvesting convenient output that can be applied to biomedical devices. When combining input sources to a single system, the HMEH imparts plenty and sufficient power delivery for diverse environmental situations[10]. The main purpose of hybrid input is to ensure that the energy infinitely flows when one of the inputs is very low, which is mainly the thermal input in this case[12]. Previously, researchers utilized an individual inductor to combine inputs ranging from 20 mV to 5 V, the system can always extract maximum power from single harvesters[11]. Most energy harvester loads use DC voltage for their operation, whereas vibration energy harvesters always provide AC voltage. Therefore, a rectification stage is required for vibration input sources.

The full-wave rectification is more competent than half-wave rectification because the polarities of both inputs are converted from AC-DC voltage. The superiority of the full-wave rectifier is that it produces a higher average DC output, the output ripples will be also minimized by the connection of a huge capacitor on the DC side. The full-wave rectifier and voltage doublers are commonly used in a rectifier circuit to achieve greatest output power with a switch-only rectifier because both cycles of input current can be used[13]. However every half-cycle will have a significant value of charge lost in the rectifier during the charging operation. Higher output power can only be acquired if the charge lost is further decreased. Consequently, a bias-flip rectifier with an additional inductor in series is used to solve the switch-only rectifier issue[13]. Fundamentally, the conventional full-wave rectifier uses Scottky diodes and a capacitor to rectify the voltage. In vibration energy harvesting, the diodes cannot be feasibly applied because of the poor efficiency attributed to the forward-bias voltage drop of 0.1 V or higher. An optimal rectifier voltage (V_{rec_opt}) exists to harvest energy with the maximum power:

$$V_{rect\_opt} = \frac{V_{oc}}{2} \tag{1}$$

Equation 1 shows that the optimal rectifier voltage is half of the peak open circuit voltage (V_{oc}) that results from the AC source[14]. To overcome the issues of the forward-voltage drop and power loss, a MOSFET is chosen instead of a diode. The MOSFET has a very inferior constant resistance and can adequately reduce the turn-on resistance while conducting[15]. The basic full-wave rectifier circuit utilizes four MOSFETs for their operation as shown in Fig. 2.

After rectification, vibration input will be combined with thermal input by a voltage adder. The voltage adder is a very flexible circuit based on the standard inverting operational amplifier configuration. This step is performed when more inputs are added to produce an operational amplifier op-amp circuit. The voltage output (V_{out}) is simplified in Eq. 2 by combining both inputs:

$$V_{out} = V_{dc1}+V_{dc2} \tag{2}$$

A schematic of the voltage adder is shown in Fig. 3, with connection of resistor at pin op-amp number 6 as the output.

The output from the voltage adder is connected to the boost converter as a part of energy harvesting circuit to increase the low input voltage as shown in Fig. 4. A boost converter is a popular choice among the energy harvesting circuits with low-voltage energy sources, such as when thermal (20-100 mV) and photovoltaic (200-900 mV) cells are used. The NMOS is used as the power switch because it can be classified as fast switching and can operate at a high frequency[16]. The power switch is driven by a pulse-width modulator (PWM) that sets the duty cycle of the switching

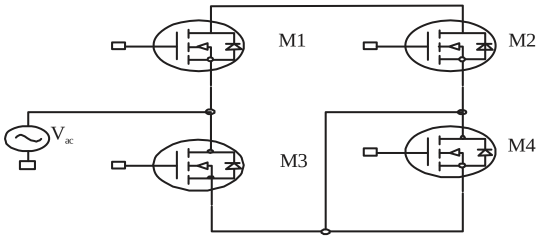

Fig. 2: Basic full-wave rectifier circuit using MOSFETs

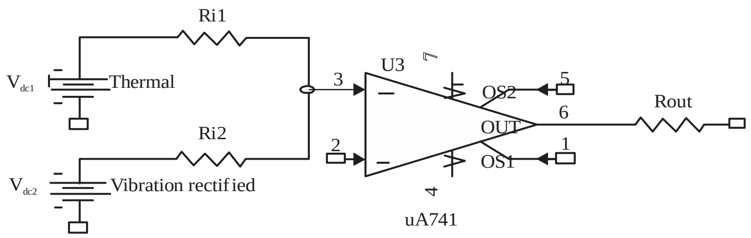

Fig. 3: Voltage adder circuit

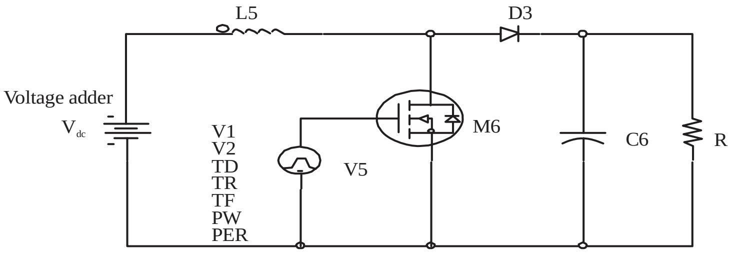

Fig. 4: Boost converter circuit

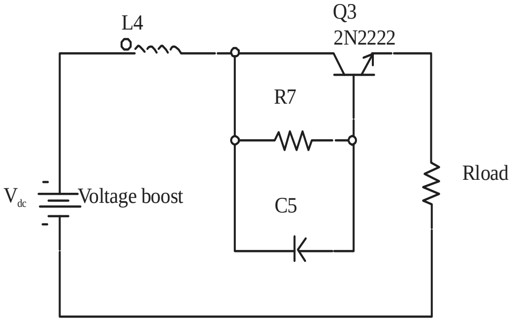

Fig. 5: Voltage regulator circuit

pulses[17]. The PWM parameters, such as the initial value (V1), pulse value (V2), Delay Time (TD), rise time (TR), Fall Time (TF), Pulse Width (PW) and period (PER) are modified to achieve the targeted output. The boost converter also includes a rectifying Schottky diode and an external inductor to avoid a large voltage drop. The converter can be operated in two modes: Continuous Conduction Mode (CCM) and the Discontinuous Conduction Mode (DCM). In CCM, the inductor current from the energy transfer between switching cycles never reaches zero. For DCM, the inductor current falls to zero before the end of the switching cycle; this converter is commonly used as a DC-DC converter.

The last stage for the HMEH circuit is the voltage regulator, as shown in Fig. 5 to regulate the desired output voltage before connecting it to the load. In the voltage regulator, the voltage drop between input and output is controlled by the common 2N222 Bipolar Junction Transistor (BJT). The transistor can operate effectively at moderately high speeds for the low electrical requirements of voltage, current and power. Any variations in the input and load voltage regulator should be minimized. In other study, MOSFET and Op-amp are used to design the voltage regulator, such that it acts as a variable resistor and a sample voltage reference, respectively[18]. Figure 6 demonstrates the proposed whole HMEH circuit that uses the thermal and vibration inputs of the human body. The circuit is performed and simulated with the Pspice software. Then, it is implemented on hardware breadboard to verify its functionality.

RESULTS

Simulation performance of energy harvester system using thermal energy: Although this study focus on maximum condition which is both inputs exist, the simulation system is also tested using a single input. Thermal energy provides an input voltage as low as 0.02 V. Figure 7 shows the simulation result for energy harvester circuit using thermal energy input only. The input of thermal energy has been boosted to 1.6 V. The voltage is stabilized by a voltage regulator circuit that provides output about 1.2 V. This value is considered low to be used in biomedical device applications.

Simulation performance of hybrid micro-energy harvester system: When using hybrid inputs, the most important circuit needed is voltage adder. The combined inputs of the thermal and rectified vibration are dictated by the voltage adder. Vibration input will generate AC voltage. Therefore, this voltage should be rectified to DC voltage first because the desired loads operate in the DC mode. In the simulation, a full-wave rectifier circuit is supported by enhancement mode n-channel MOSFETs and a smoothing capacitor, this circuit is used to convert AC-DC. The simulation is run within the time (t) range of 0-2.0 sec with 1 MΩ load resistance. The vibration input (AC) was rectified as shown in Fig. 8, with the vibration input and rectified output of 0.5 and 0.28 V, respectively. No voltage drop occurs at the input as it has produced exactly 0.5 V. The rectified output increases from t = 0 sec of the simulation, results showed that the DC voltage had more ripples at the early stage. The voltage slowly increased and became constant at t = 1.5 sec.

The next stage is the boost converter, which is used to increase the inputs from the voltage adder. A few parameters, such as the inductor, capacitor, initial values, pulse values, rise times, fall times, pulse width and pulse period are controlled to accomplish the best performance of the boost converter. The boost converter output is regulated by a voltage regulator to obtain a constant voltage. The simulation results of the boost converter and voltage regulator are shown in Fig. 9, which are marked as V_1 and V_2, respectively. From Fig. 9,

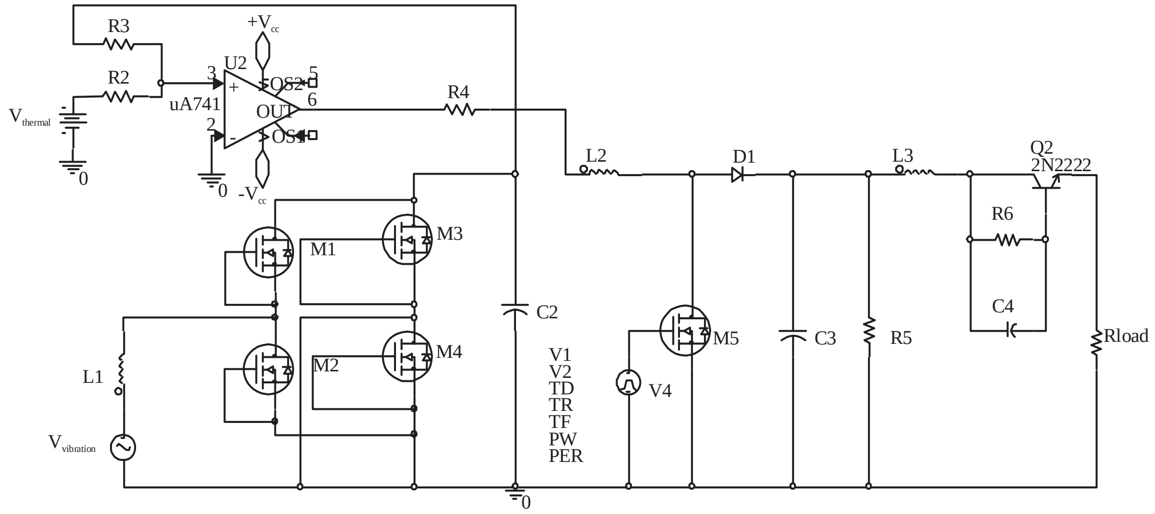

Fig. 6: Proposed HMEH circuit using thermal and vibration inputs of human body

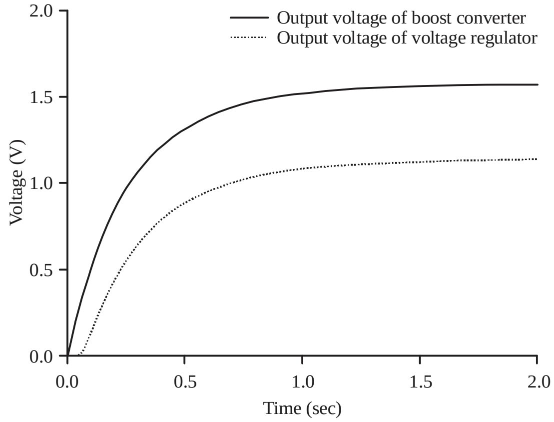

Fig. 7: Simulation performance of energy harvester circuit using thermal energy

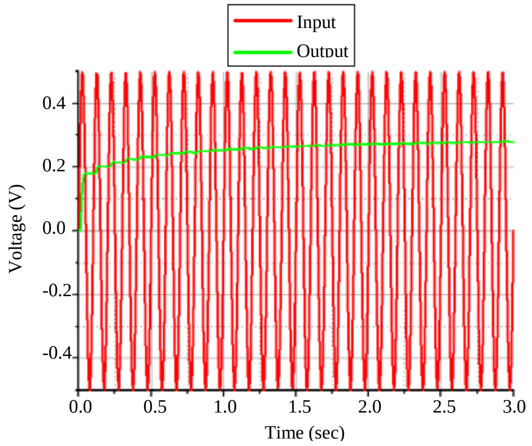

Fig. 8: Vibration input and rectified output voltage

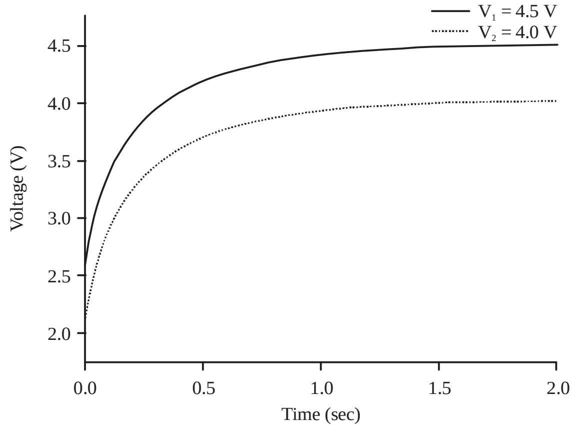

Fig. 9: Output voltage for boost converter and voltage regulator

the voltage increase is directly proportional with time, with slightly different amplitudes for both measurements. The transient response time slowly increased from 0-1.7 sec then became constant. The output voltage, V_1 of approximately 4.5 V was achieved. This voltage then will be the input of voltage regulator with the output generated of 4.0 V (V_2).

In order to calculate the generated output power for the HMEH system, the current probe from Pspice software is marked at the load resistance. Figure 10 shows the graph of output current for the whole HMEH system. The simulation result is increased from 0 sec and achieved constant current of 0.40 mA after 1.2-2.0 sec. Based on the value of the resulting voltage and current, the output power is calculated using Eq. 3 with the output power result of 1.60 mW:

$$P_{out} = V_{out} \times I_{out} \tag{3}$$

Hardware implementation of hybrid micro energy harvester system: The hardware work is implemented to verify the design functionality of the HMEH system as shown in Fig. 11. Inputs are generated from the function generator and DC power supply for the vibration input (0.5 V_{AC}) and thermal input (0.02 V_{DC}), respectively. The project is tested on a breadboard with all the existing components available in the market. The overall output voltage and current from hardware implementation is measured with a multimeter to be 3.94 V and 0.30 mA respectively. The generated output power from hardware implementation also calculated using Eq. 3 with the result of 1.182 mW.

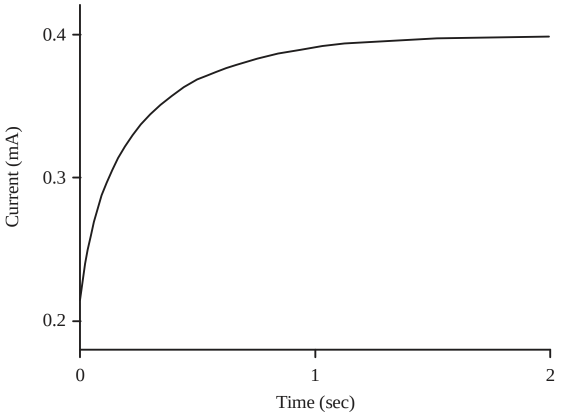

Fig. 10: Output current for hybrid micro-energy harvester system

DISCUSSION

Energy harvester capable to harvest ambient energy from surrounding and convert it into usable energy. It is possible to prolong the battery life for portable devices. Nowadays, the hybrid inputs is extremely demand due to the low voltage issue especially from thermal energy harvester. A hybrid system is performed by combining two or more energy

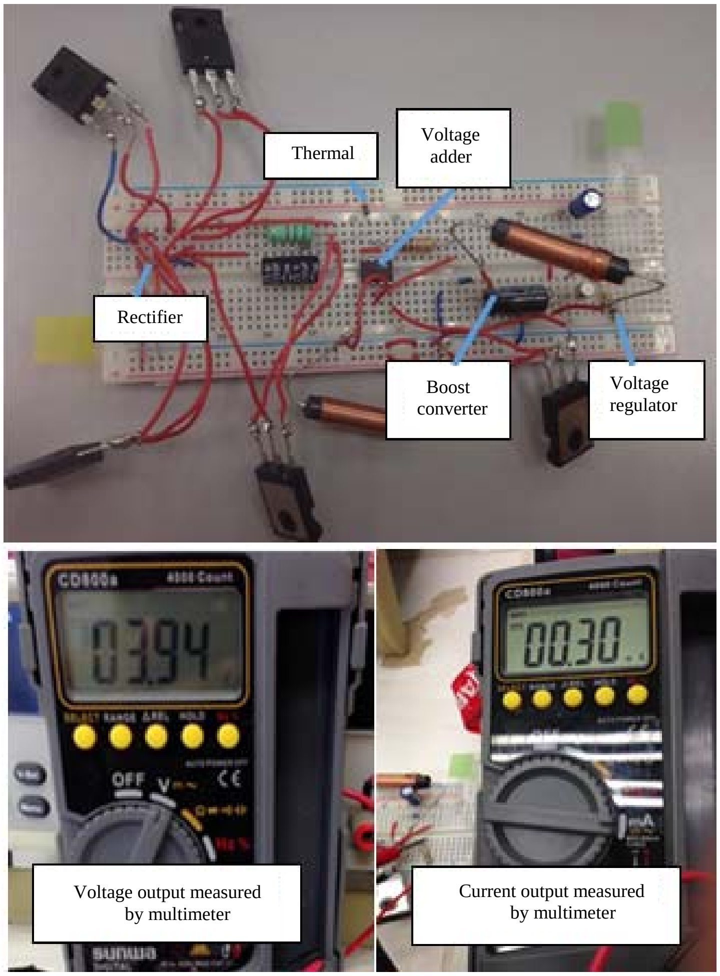

Fig. 11: Hardware implementation for overall hybrid micro-energy harvester system

harvester to a solitary system to overcome the problem of this low ambient input and make sure the energy flow ceaselessly[12,19]. In the previous study, Wischke *et al.*[20] also presented a novel hybrid energy harvester to achieve higher energy density and power output by incorporating both the piezoelectric and the electromagnetic transducer principle. In order to perform the hybrid inputs system, the amount of passive components will be increased[21]. Hence, previous researchers come out with the idea to perform hybrid inputs of ambient thermal and light in one power management circuit to reduce the cost and power losses[22]. Energy harvester from thermal and vibration are universal availability and they have been an attractive topic for powering wearable devices. Hence, for this study, the proposed HMEH is designed with the hybrid input of thermal and vibration for biomedical devices. The thermal and vibration inputs are set to 0.02 and 0.5 V, respectively, under an operating frequency of 10 Hz. When thermal energy only is present, the system is considered to have the minimum input. It consists of thermal energy circuit connected directly to boost converter and voltage regulator. The output voltage is only 1.2 V and this is not enough to supply the load. The maximum input is referred to the hybrid of the thermal and vibration input. However, this HMEH circuit will always operate in maximum conditions to reach preferable operation and functionality. The voltage adder is operated in the positive saturation level and flexible enough to add several individual sources using op-amp 741. This is important part when combining two inputs with the resistances are of equal value R_2 and R_3. The AC form from vibration input need to rectify first before joining with the voltage adder.

In rectifier circuit, MOSFETs are applied for the good efficiency as no forward-voltage drop happen in input side. An optimal rectifier in Eq. 1 is applied for conventional rectifier circuit using Schottky diodes due to this voltage drop[14]. The expected result is very poor which is below of the half voltage input value. Compare with rectifier using MOSFET, the result is achieved 0.28 V and this value is very close to half of the peak open circuit voltage (V_{oc}) in conventional part. Hence, n-channel MOSFETs with the behavior of fast switching speed and ruggedized device design is used. When the voltage source polarity is positive and negative at the top and bottom respectively, this state is considered the first half-cycle. Only MOSFETs M1 and M4 conduct at the positive half-cycle by producing the sine waveform. In the negative half-cycle, the MOSFETs M2 and M3 will function as the current flows through the reverse voltage polarity. The capacitor is used as a filter to reduce ripples of the output voltage.

Implementation of boost converter circuit is really needed to step up the low input for better efficiency. It is become heart of the energy harvesting circuits because most of the energy sources are extremely low to directly run the system. Most of the low power applications work in discontinuous conduction mode to limit the value of the inductance with the power range from microwatts to megawatts[23]. A switched mode boost converter is efficient to step-up the lowest input voltages of 20 mV to 1 V[24]. In this study, the performance of the voltage from boost converter circuit is controlled by the duty cycle of pulse width modulation parameter. It is able to boost up the small voltage efficiently. It is achieved the output voltage of 4.5 V and work in continuous conduction mode as the output voltage never reach zero point. This value is slightly higher for the load, hence need voltage regulator to stabilize and control the output voltage to a constant value[25]. The value of the voltage across the load is determined by the bipolar junction transistor base emitter and performed as an emitter follower with the output voltage of 4.0 V and the output current of 0.40 mA. In hardware work on the breadboard part, the output voltage and current of HMEH system is achieved 3.94 V and 0.30 mA, respectively, these values are expected for real implementation due to the power losses occur.

The harvested power from the HMEH system is about 1.60 and 1.182 mW for simulation and hardware work respectively. This generated power is higher than what is harvested by the single source energy harvester system either from thermal energy source of 223 μW[22] and vibration source of 0.25 mW[26]. Therefore, hybrid input proves the significance of the proposed HMEH system. Table 1 is shown the comparison performance between this study and previous studies using hybrid two inputs. The previous researchers has used hybrid ambient from indoor light and heat energy[22] while other researcher has used hybrid of solar and thermal energy[27]. The power generated is depend on the sources, too many sources will increase the output power of the system. Based on the Table 1, the power generated from this study is higher than previous studies, hence make it is more effective to power up the system.

Table 1: Comparison performance between this study and previous study

Researchers (Years)	Sources	Input voltage (V)	Output voltage (V)	Output power (mW)
Tan and Panda[22]	Light, heat	~3.6	~5.5 (hardware)	0.621
Wang *et al.*[27]	Solar, TEG	1.42	1.417 (CMOS technology)	0.1
Present study	Thermal, vibration	0.02-0.5	4.0 (simulation) 3.94 (hardware)	1.6 (simulation) 1.182 (hardware)

CONCLUSION

This study mainly focused on the design of the architecture of ultra-low power HMEH with a hybrid input of thermal and vibration energy based on the human body for biomedical devices. Thermal and vibration inputs are represented by voltages of 0.02 and 0.5 V, respectively, while operating at 10 Hz. The goal of HMEH is to combine both inputs into a single system such that the inputs simultaneously operate because the thermal input is very low. The minimum and maximum input refer to the thermal source and the combination of both inputs (thermal and vibration), respectively. The HMEH circuit consists of thermal and vibration elements as input, a full-wave rectifier to convert AC voltage to DC, a voltage adder to combine both inputs with an op amp 741 boost converter to increase the smallest input and a voltage regulator to control and limit the voltage. The HMEH system able to achieve the output voltage of 4.0 and 3.94 V for simulation and hardware part respectively with the generated output power of 1.6 and 1.182 mW.

SIGNIFICANT STATEMENTS

Energy is harvested from the environment surrounding to be used in many real life application to power up the system. However, the energy harvester is often provides in small quantities that is not enough to supply adequate power to the load. Thermal energy provides very low input (0.02 V) and not sufficient to run the system. Hence, the combination of two or more inputs is really needed to achieve the best output voltage performance and efficiency. Thermal energy is combined with vibration input (0.5 V) to perform hybrid micro-energy harvester (HMEH) for biomedical devices. This system will always operating only in maximum condition when both of the inputs exist to achieve the better performance.

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