

Design and Analysis of Thermoelectric DC Boost Converter

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Abstract

In today's consumer-oriented market, researchers are increasingly focusing on harvesting energy from ambient and renewable sources to enable sustainable power generation and reduce dependency on conventional energy resources such as batteries and fossil-fuel-based electricity. The rapid growth of portable electronics, wireless sensor networks, and Internet of Things (IoT) devices has created a significant demand for low-power, long-life, and maintenance-free energy solutions. In many practical situations, frequent battery replacement is difficult, costly, and environmentally harmful. Therefore, energy harvesting has emerged as an effective alternative to power such low-energy devices by utilizing naturally available energy in the surrounding environment. Energy harvesting methods offer enormous opportunities to derive power from sources such as mechanical vibrations, human motion, thermal gradients, airflow, and other forms of wasted or unused energy. In general, energy harvesters operate like transducers, where the available ambient energy is extracted and converted into usable electrical power. Among different techniques, triboelectric and thermoelectric harvesting are considered highly promising due to their simplicity, compactness, and suitability for small-scale applications. This research aims to demonstrate the practical implementation and performance validation of thermoelectric energy harvesting (THEH) through developed hardware prototypes and experimental setups. A usable amount of electrical energy is extracted from both harvesters under real-world operating conditions. The generated output is measured, analyzed, and further validated using the developed hardware model to ensure feasibility for real-time applications. The results indicate that ambient energy harvesting using triboelectric and thermoelectric principles can provide an effective solution for powering low-power electronics and self-sustained sensing systems in future smart applications.

Keywords: Thermoelectric generator (TEG), DC-DC boost converter, energy harvesting, Pulse width modulation (PWM), gate switching, low-power electronics

INTRODUCTION

A well-designed electrical circuit can contribute significantly to enhancing the power management of energy available from conventional and non-conventional input sources. Continuous development of energy harvesting circuits has helped scientists generate energy from renewable energy sources. A parallel advancement of circuits alongside power-efficient generators has seen an upward surge with time [1–5]. These electrical circuits can convert the available energy in the environment into usable electrical power. Extensive research has been conducted to prove the practicability of thermal-to-electrical energy conversion using thermoelectric energy generators. This electrical energy has been presented as an alternative solution to operate ultra-low power

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sensors and devices, which are currently dependent on batteries with limited shelf life in the previous chapter [6–10]. Thermocouple material-based thermoelectric generators function as active devices for scavenging ambient and wasted thermal energy into usable electrical power. Due to a simple, non-moving design assembly, endurance, low-cost maintenance, and the absence of any chemical components, scientists worldwide are interested in thermoelectric generators (TEG) and the supporting circuits for highly efficient power generation [11–15]. Already available commercial TEGs have limited usability because of their lower output voltage of the order of a few millivolts. To enhance their serviceability and electrical output parameters, they are often clustered together in series or parallel combinations, which increases the output voltage to an appreciable level [16–20]. The problem with such topologies is the increase in the size of the system, making it bulky. Additionally, the heating and cooling source mechanisms for such systems increase proportionally. The possible combination of electrical circuits with these modules provides a much-improved solution for generating desirable output voltage and power [1–4]. These circuits, which can take in millivolt-level input voltage and provide amplified output voltage in volts, are termed boost converters. We considered a DC–DC boost converter because the output voltage from the thermoelectric harvester is a DC signal. These boost converters work on energy storage elements, and inductors are a general choice for designing them. Inductor-based boost circuits rely heavily on efficient switching mechanisms to transfer power to the load side with minimal losses. This further increases the output power levels. Switching is required to switch ON/OFF the MOSFET deployed as a switch in the circuit [21–25]. To harvest the available low thermal energy from TEGs, a feedback control method for continuous or discontinuous flow of inductor current through an ON/OFF MOSFET switch can be implemented. The switching rate and duty cycle of the switching input for MOSFET operation are critical to the amount of amplification obtained [5–8]. This necessitates a carefully designed circuit for optimum duty cycle ratio selection for optimum switching of the selected MOSFET switch [26–30].

The study presented here is based on pulse width modulation (PWM) switching, square wave switching, and simple gate switching of an inductor-based boost converter designed to amplify the output voltage from a TEG. Three inductor-based boost converter configurations with different switching architectures were investigated in this study. The values of the open-circuit output voltages in all three cases were recorded for comparison. TEC1-12706, a commercially available TEG module with a thermal source, was used as the input source for the DC–DC boost converter circuit [31–33].

SYSTEM DESIGN

A boost converter circuit for DC–DC voltage conversion was designed to increase the output voltage generated by a commercially procured TEG module, TEC1-12706. This thermoelectric module comprises many series-connected thermocouples that work on the Seebeck effect to convert the temperature gradient into electrical output power, as discussed briefly. These thermocouples were connected in parallel and in series to increase the output power. A requisite temperature gradient at the junction of these pairs results in the generation of an equally proportional output voltage. Any further change in either temperature junction results in a corresponding change in the output electrical voltage. The actual generated voltage can be calculated using Equation (1) [9].

$$V_{out} = \alpha \cdot \Delta T \quad (1)$$

Where,

α = Seebeck coefficient

ΔT = temperature gradient

The Seebeck coefficient of a thermoelectric module is an intrinsic property of the material used for its fabrication. It is difficult to change this parameter and requires a separate study of the compositional and structural properties. However, the temperature gradient can be varied to achieve the requisite output voltage. As given by the Equation (1), as the temperature gap between the hot and cold sides increases, the output voltage also increases proportionally. This implies that a high-voltage output can be achieved by simply changing the junction temperature.

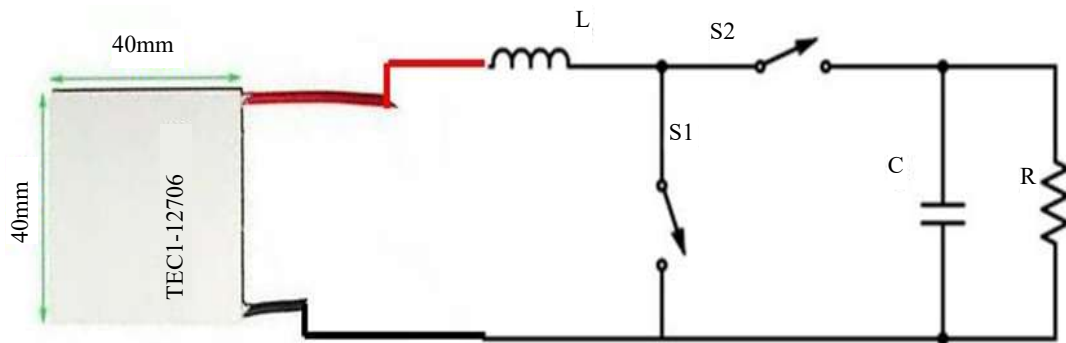


Figure 1. Basic boost converter.

However, for a simpler design structure, this parameter cannot be varied infinitely, as an increase in the hot-side temperature may affect the cooling of the other side, thereby reaching a constant temperature gradient at a certain point. For larger temperature gaps, other modules with better quality semiconductor materials are available, but they are usually very costly. This limitation motivated investigations into the possibility of using a boost converter with such thermoelectric energy generation devices. A DC boost converter is an electrical circuit that can amplify/step up a lower DC voltage level to a higher DC value. Along with amplifying the output voltage, it also regulates the DC voltage to provide a regulated power supply. Figure 1 shows a simple switch-based conventional boost circuit for DC–DC power conversion.

An inductor, two switches, a capacitor, and an output load form the basic components. The amount of power conversion in this circuit is governed by the repetitive closing and opening of the two switches, S1 and S2. The switches involved are semiconductor switches, such as diodes, BJT, IGBT, or MOSFET. The continuous process of alternate switching of S1 and S2 forwards the power from the inductor to charge the capacitor. In the initial cycle, the first S1 is closed while S2 remains open, and the inductor current begins to increase, resulting in energy storage in the inductor. This increase in the current increases the magnetic field of the inductor. This implies that the inductor is now storing energy as a passive device. With the reversal operation, when S1 is opened and S2 is closed, there is a decrease in the current through the inductor. This decreases the magnetic field around the inductor. This, in turn, releases the energy deposited in the inductor. Finally, the inductor current is transferred to the load resistance, thereby charging the capacitor. Continuous conduction mode (CCM) and discontinuous conduction mode (DCM) are the two operating modes for DC–DC boost converters (275). S2 should open if the conductor current approaches zero to achieve maximum efficiency in the boost converters. S1 and S2 switching in the CCM is not based on the inductor current. As shown in Figure 2, at lower load resistances, a reverse current starts to flow from the output to the input, reducing the efficiency of the circuit. In DCM mode, on the other hand, the inductor current approaches zero when S2 is open. This obviously improves the voltage, boosting the efficiency of the circuit by preventing the output current from flowing towards the input side. As discussed, duty cycle variation can affect the output voltage, and the maximum output voltage can be generated with an optimal duty cycle value [10–12]. Various sources can be used to control the switches and change the duty cycle. In this study, different switching sources for generating the maximum output power from a boost converter circuit were investigated. Three sources, namely simple gating pulses, square wave, and PWM input, were employed to control the alternate ON/OFF switching of the MOSFET switch for enhancing the output voltage from the load side.

The schematic block diagram of all three tested circuits is shown in Figure 3(a)–(c). A software simulation was performed for all the switching sources. The desired output electrical parameters, such as the output voltage (open circuit), current, and measured output power, were recorded and compared for maximum power generation for all three configurations.

RESULTS AND DISCUSSION

The aforementioned three DC–DC boost circuit configurations were designed and simulated in power simulation (PSIM). Figure 4(a)–(c) show the PSIM circuit for the gate pulse, square wave, and PWM-controlled boost circuit. When subjected to the appropriate temperature difference, the commercially available TEC1-12706 module produces a 0.2 V output voltage. In the PSIM software, a constant DC source of 0.2 V was used to approximate the symbol representation of the TEG module.

Three different boost converters were designed in PSIM with three different switching sources (Figure 5(a)–(c)). The output open-circuit voltage and corresponding load current were obtained using an output display scope in PSIM. According to the generated results, the gate-controlled configuration generated the highest output voltage for the Figure 4.

Such configurations can amplify the small amount of input voltage available from the TEG for further use. The 0.2 V input voltage was amplified to an appreciable 5.26 V output voltage. The measured output current was also 131 mA. Although the square wave and PWM-controlled boost circuits could amplify the input voltage, they could only do so to 3.5 V and 1.98 V, with 87 mA and 51 mA current, respectively. The output voltage graphs obtained using the PSIM simulations for all three switching configurations are shown in Figure 6.

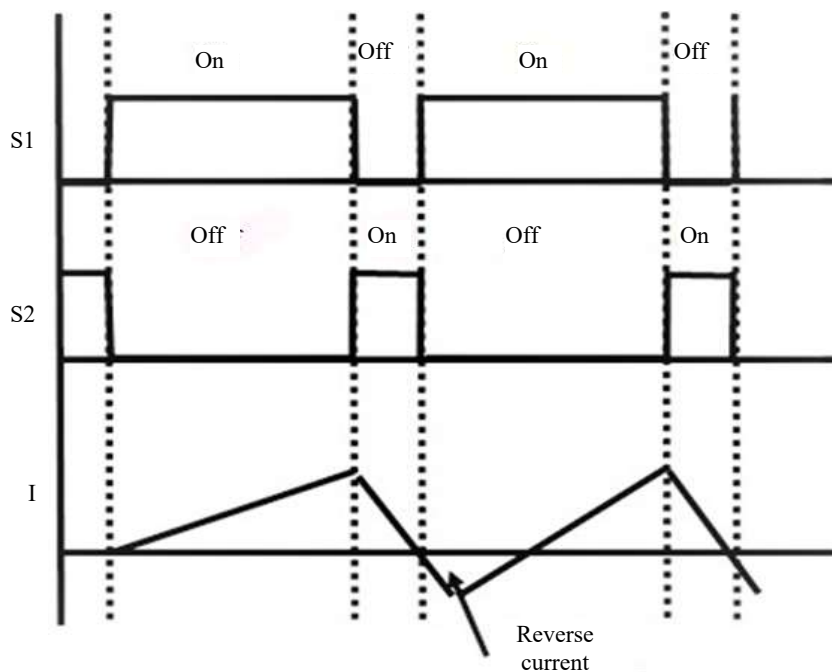


Figure 2. Inductor current in continuous conduction mode (CCM).

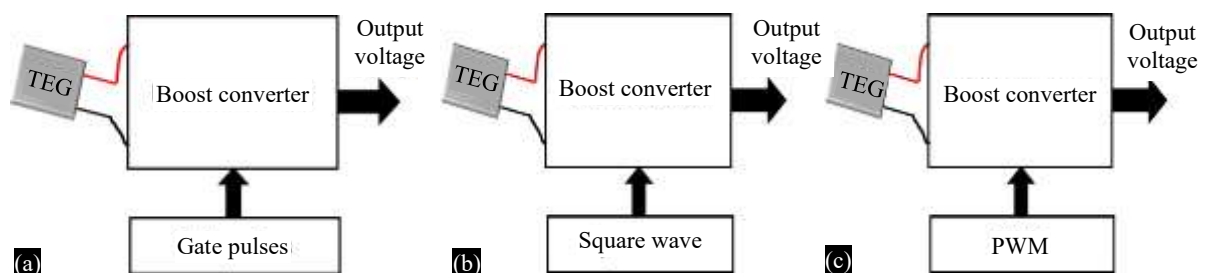


Figure 3. Block diagram of boost circuit with different switching sources: (a) gate switching, (b) square wave switching, and (c) PWM switching.

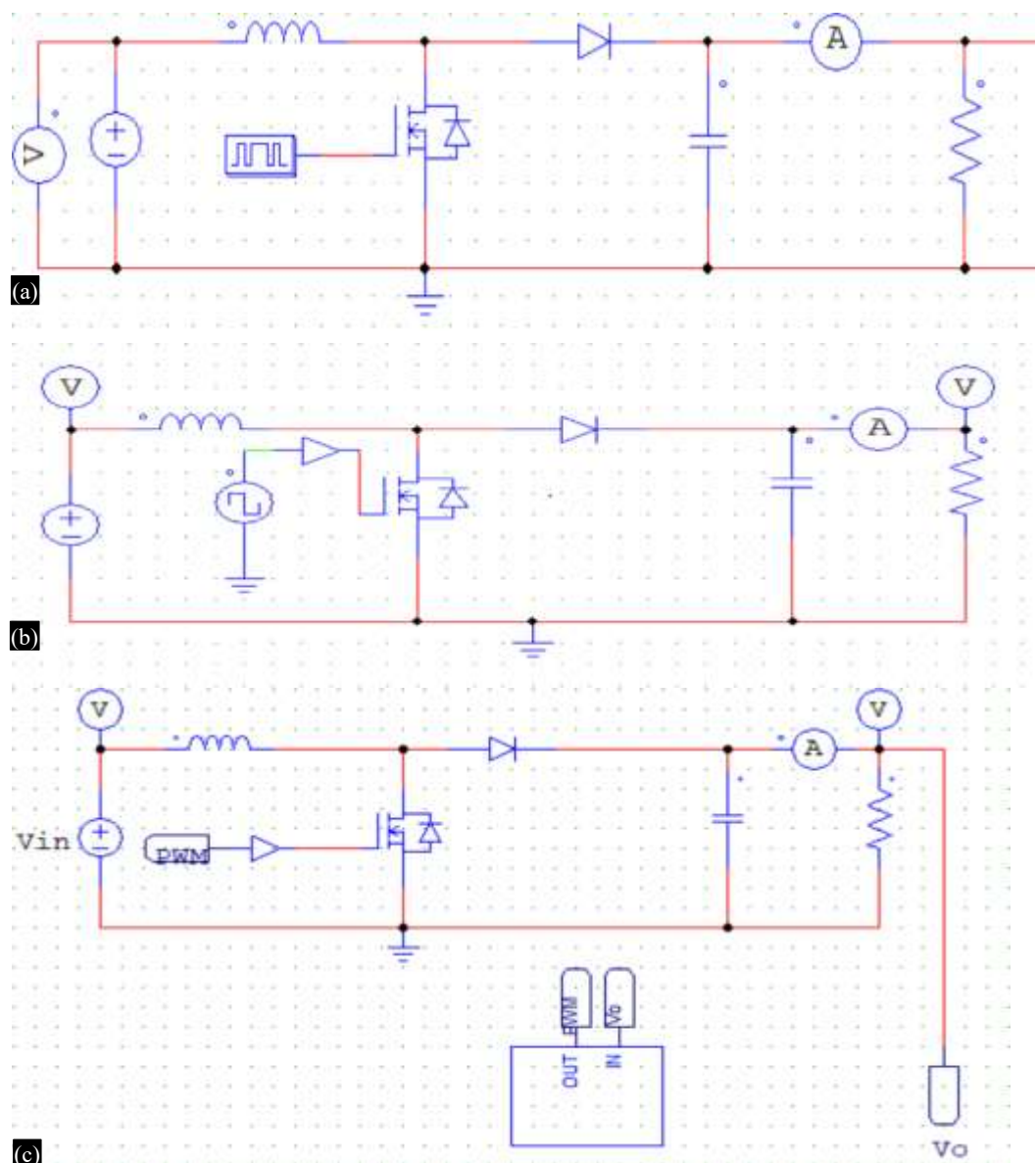
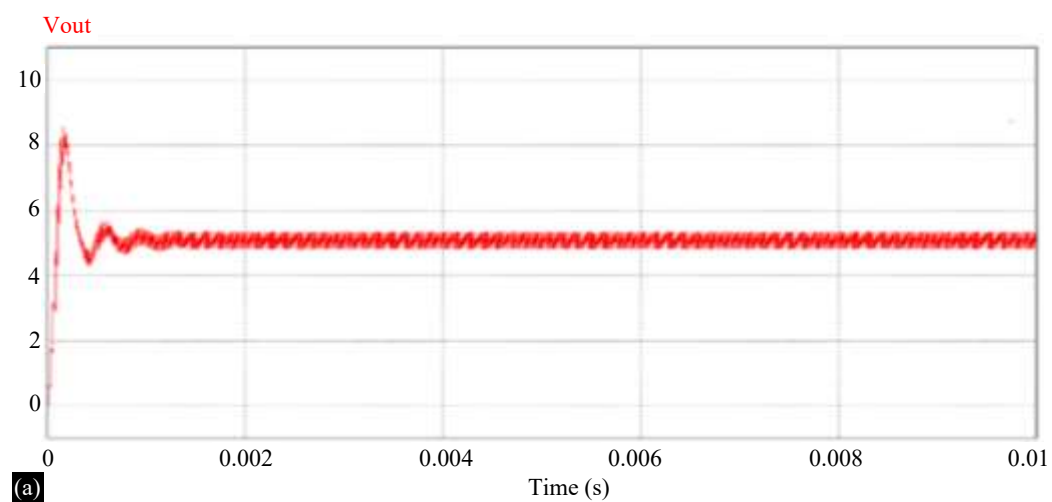


Figure 4. PSIM models of boost converter: (a) gate pulse control, (b) square wave control, and (c) PWM control boost circuit.



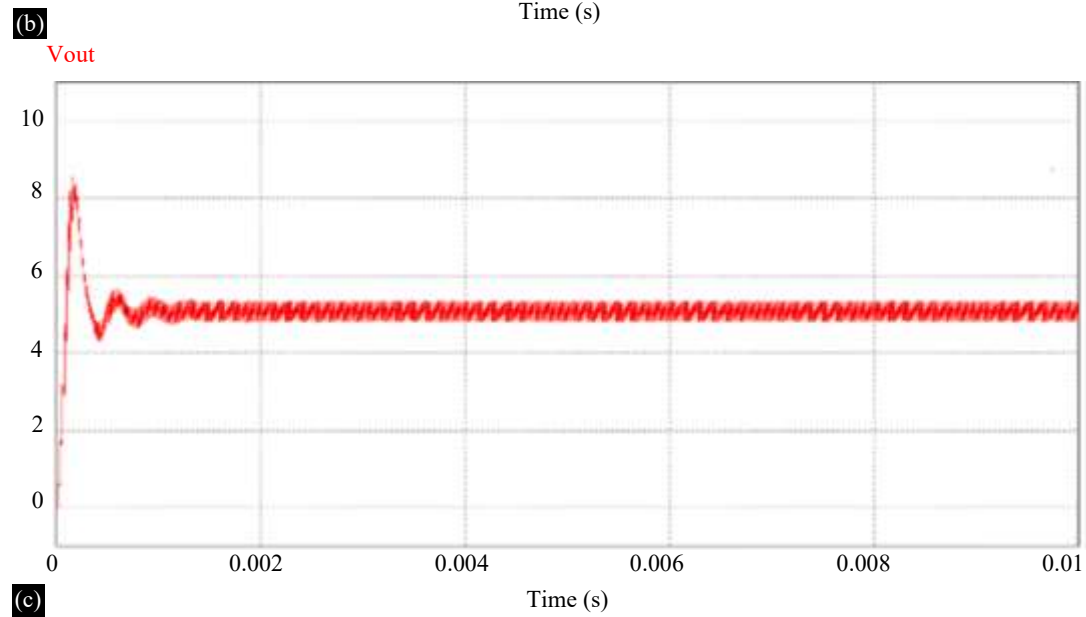
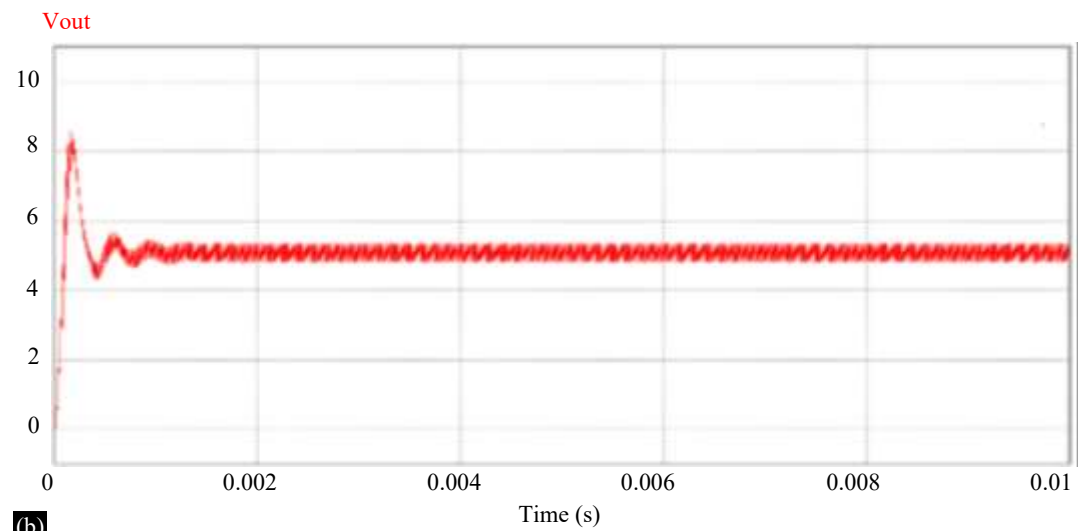
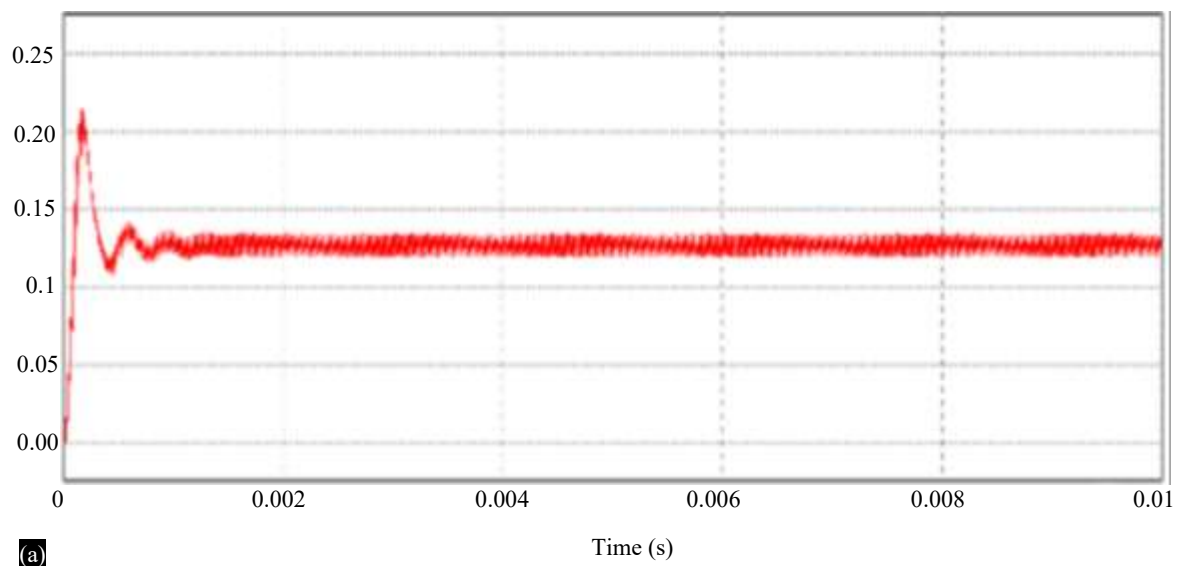


Figure 5. Output voltage for switching modes: (a) gate pulse, (b) square wave, and (c) PWM input.



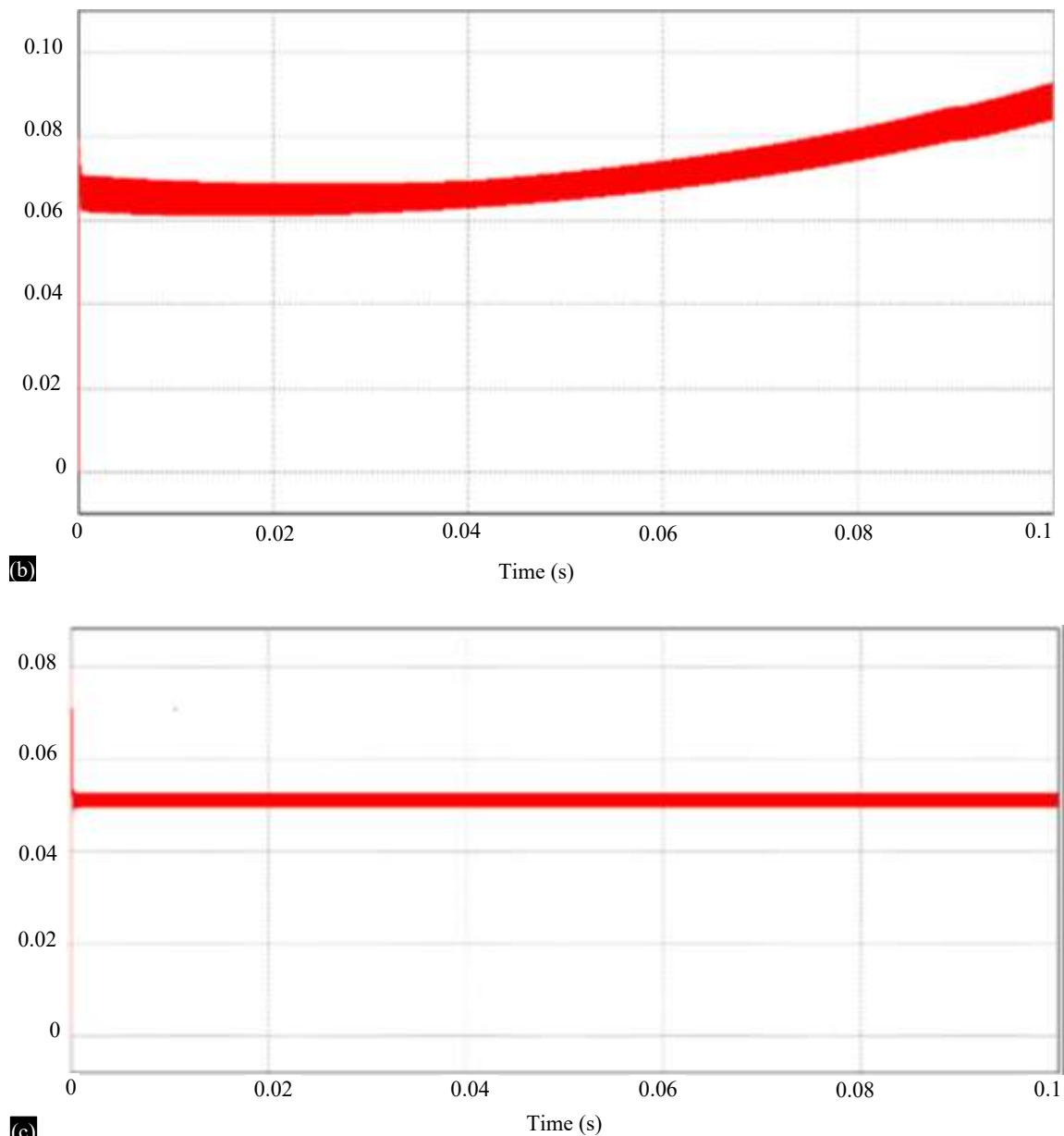


Figure 6. Output current for switching modes: (a) gate pulse, (b) square wave, and (c) PWM input.

CONCLUSIONS

1. A low-cost, robust triboelectric pair material-based sensor was fabricated and tested for harvesting triboelectricity. When frictional contact was applied to a sensor strip made of thin sheets of polytetrafluoroethylene (PTFE) and aluminum, an output voltage was generated. A generic counting system for counting the occurrences of certain events can be developed using triboelectric material-based sensors. This low-cost triboelectric sensor strip does not require any input power and is efficient for long-term use owing to its robustness.
2. An experimental investigation was conducted to analyze the output performance of a TEG. To maximize heat absorption for generating thermoelectricity, thermally conducting materials such as Al, Fe, and matte-finish metal paint can be applied to a thermoelectric module. This TEG assembly can be used to generate an output voltage using heat absorbed by different heat-absorbing materials. A comparative study of various materials showed that it was the best available material for heat absorption. A series of three thermoelectric modules can generate an adequate amount of energy to power low- and ultra-low power systems and sensor nodes.

3. A triboelectric sensor for a traffic monitoring system was developed to calculate the speed of moving vehicles and estimate their weights. This system has numerous advantages, including low cost, quick response, automated measurements, and ease of deployment and maintenance. A robust low-cost triboelectric sensor was fabricated and tested for accurate speed measurement and corresponding weight estimation of passenger vehicles in motion. A number of road tests conducted on this system revealed more than 95% accuracy potential for such systems with a 3% mean absolute percentage error.
4. A candle-soot-coated thermoelectric module for harnessing thermal energy from sunlight is a promising technique for generating a significant amount of output voltage. A substantial temperature gradient, created across two dissimilar surfaces of a thermoelectric module by concentrating sunlight and flowing water, can generate an appreciable amount of energy. Soot coating with different thicknesses obtained by direct exposure to candle flame delivered 1.5 V of maximum open-circuit voltage with 14 mA peak current.
5. A carbon-soot-coated thermoelectric module (TEC1-12706) can utilize solar heat for thermoelectric energy harvesting when exposed to direct sunlight. The TEG module was coated with candle soot of different thicknesses using a candle flame, and the crystal morphology was examined using Raman spectroscopy. When coated with the fourth consecutive candle soot (CS) layer, a maximum open-circuit voltage of 1.46 V and a peak current of 14.2 mA were obtained. Further, if solar radiation and continuous water flow can maintain the required temperature difference, the output voltage can be further elevated using an electrical circuit like a DC–DC boost converter. Such an arrangement can charge a rechargeable battery (e.g., 2.1 V VARTA NI-MH used here).
6. Different DC–DC boost converter circuit configurations can generate different output voltages. In this study, three such arrangements were designed, and simulations were performed. It was observed that gate pulse switching in the boost converter generated the highest output voltage. Apart from efficient energy harvesters, improvements in DC–DC boost converters and other related electrical circuits can further enhance the output voltage.

Future Scope of Present Research

This study demonstrates energy generation mechanisms using triboelectricity and thermoelectricity. Although the energy generated from the designed systems was able to demonstrate the potential of using these technologies for efficient power generation, there exist some areas that can be explored for further improvements. To assist researchers in future work, the following topics are suggested for further investigation:

1. The integration of two or more independent renewable sources for developing a multi-input source system can be investigated to enhance resource utilization. In our generators, we used a single ambient source for primary energy generation. An integrated system can guarantee energy generation from at least one source in the absence of other sources. This can significantly increase the usability and reliability of the system to a great extent.
2. The electrical circuits used for voltage amplification can be further investigated. We have focused our research only on boost converter circuits. Other topologies, such as charge pumps and other circuits for voltage enhancement, can be designed and tested for maximum power optimization.
3. The effect of the maximum power point tracking (MPPT) system on the designed energy harvesters can be investigated for possible performance enhancement.

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