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Development of Piezoelectric Energy Harvesting System based on Pressure from Footsteps

Syarifah Nur Afrina Syed Yusof [1], Mohd Noor Abdullah[1]*

[1]Faculty of Electrical and Electronic Engineering,
Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Johor, MALAYSIA

*Corresponding Author Designation

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Abstract: Electricity is essential and becoming more popular in the present era. The primary source of electricity is fossil fuels, and it is depleting and releasing large amounts of carbon dioxide (CO_2) into the atmosphere. Therefore, global energy has shifted from conventional energy to renewable energy sources. The eco-friendly forms of electricity can now be generated by harnessing the energy generated by humans. That energy can be harvested using piezoelectric material. Thus, the primary objective of this project is to design piezoelectric energy harvesting systems based on pressure from footsteps. The mechanism of this system is to convert the mechanical or kinetic energy produced by humans into electrical energy. The system is focused on harvesting low-level energy in the range of microwatts to milliwatts. AC-DC converter circuit is needed in this system to generate DC voltage output because piezoelectric generates AC voltage. This project will use piezoelectric ceramic material with a full-wave bridge rectifier as an AC-DC rectifier circuit. This project is a model for an inexpensive and pollution-free energy harvesting system that uses piezoelectric transducers. The combinations of the full-wave bridge rectifier and DC-DC boost converter effectively increase the output DC voltage. The output voltage generated from the converter is then stored in the rechargeable battery that serves as a storage device. Therefore, the proposed design of the system must be able to generate electricity and able to charge the 12 V lead acid battery. For future recommendations, the number of piezoelectric transducers should be added to result in better performance.

Keywords: Piezoelectric, Energy Harvesting System, Full-Wave Bridge Rectifier, Booster Converter, Voltage Regulator

1. Introduction

Currently, fossil fuels are the primary source of electricity. As a result of the unending demand for power supply and energy by consumers, the supply of fossil fuels is depleting [1]. On the other hand, fossil fuels release large amounts of carbon dioxide (CO_2) into the atmosphere, which is the primary cause of global warming. Therefore, global energy has shifted from conventional energy to renewable

**Corresponding author: mdnoor@uthm.edu.my*

energy sources. By shifting to renewable energy, global carbon emissions are reduced, thereby mitigating global warming, and protecting the atmosphere [2]. There are many sources of ambient energy such as sunlight, wind, water, pressure or vibration and heat. These sources of energy are environmentally friendly [2].

Those types of ambient energy can be collected and stored for future use. The process of collecting usable energy or waste energy from natural and man-made resources is known as ambient energy scavenging or energy harvesting. This captured energy can be used for various applications in several ways [3] that are suitable for low-power electronic devices [1], [2], [4]. Thus, the human body's mechanical energy has been widely studied due to its abundance in daily life [5]. This mechanical energy can be converted to electrical energy by using one of the electromechanical transducers named piezoelectric [4].

Piezoelectric energy harvesting is the term used to describe the process of converting mechanical energy into electrical energy using a piezoelectric transducer. Microwatts to milliwatts of low-level energy are the typical range of energy that piezoelectric energy harvesting focuses on [4], [6]. Because of their inherent electromechanical coupling and high-power density, piezoelectric transducers have been extensively researched for the purpose of producing electricity from mechanical energy sources [4], [5]. Besides that, a piezoelectric harvesting system can provide a permanent, autonomous power source that does not need replacement or maintenance [4].

The piezoelectric effect was discovered in 1880 by Curie brothers, Pierre and Jacques [7]. The Greek word piezen, which means to press or squeeze, is where the term "piezo" comes from. It proved that the direct piezoelectric effect, which is caused when pressure is applied directly to a quartz crystal, results in an electric charge in the crystal. Eventually, it was discovered that the reverse piezoelectric effect occurs when an electric field is given to a crystal, causing the material to deform [8]. An electric potential form on the surface of a piezoelectric crystal when it is subjected to force or mechanical stress. This is due to charge displacement in the crystal [9]. If an electrical voltage is applied, the shape of the crystal will be deformed by changing its dimensions [9]. The piezoelectric effect refers to the process of converting force, pressure, or mechanical stress into electrical energy or vice versa.

Piezoelectric transducers are composed of two components which are a mechanical component that generates electrical energy and an electrical component that contains an electrical circuit that transforms and rectifies the voltage generated by the mechanical component. The basis for a piezoelectric transducer's operation is the discovery that a piezoelectric crystal produces a voltage across all of its faces when a mechanical force is applied to it [10]. Hence, mechanical forces are converted into electrical signals and due to no external power source being required for this transducer to operate, it is an active transducer [10].

2. Materials and Methods

To develop a piezoelectric energy harvesting system, a literature review was conducted in order to acquire data and information related to piezoelectric energy harvesting. This section will explain in detail the algorithm of the piezoelectric energy harvesting system, the components used and the proposed piezoelectric tiles.

2.1 Proposed Algorithm of the Piezoelectric Energy Harvesting System

The electricity generated by the system will be stored in the rechargeable battery. The piezoelectric transducer will generate electricity when the piezoelectric material is pressed, where the mechanical stress will be produced and converted it into AC voltages. The generated voltage is fed to the rectifier circuit to convert the AC voltage to DC voltage. The voltage needs to be rectified due to the need for a constant power supply of voltage. DC voltage generated will pass through the diode to avoid the backflow of the current. Next, the DC voltage will feed to the boost converter and the voltage regulator circuit in order to boost the voltage and regulate the voltage to a certain level respectively. Then, the DC voltage is stored in the rechargeable battery and lastly will supply to the load. Thus, based on Figure

1, the system will be composed of three main parts which is a piezoelectric circuit, a rectifier circuit, and a charging circuit.

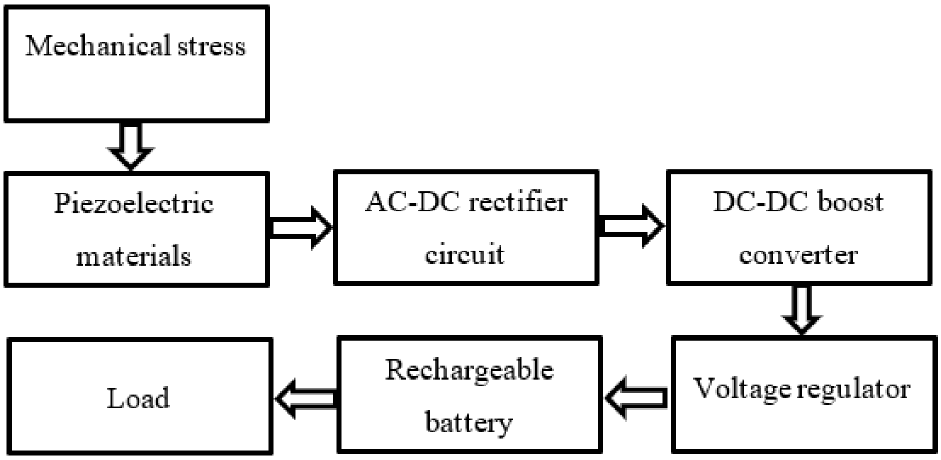


Figure 1: Block diagram of the proposed system for piezoelectric energy harvesting system

2.2 Component Selection for Piezoelectric Energy Harvesting System

The system design will consist of several components such as:

i. Piezoelectric transducer
ii. AC-DC converter
iii. DC-DC boost converter
iv. Voltage regulator and battery charging circuit

2.2.1 Piezoelectric transducer

In this project, 36 pieces of PZT piezoelectric transducer which is based on ceramic material will be used. Based on the literature review, PZT which is the type of piezoelectric ceramic are the preferred choice because it has a greater sensitivity and high operating temperature if compared to other type of piezoelectric transducer. Other than that, PZT has a lower cost and is one of the most commonly used piezoelectric ceramics. Figure 2 shows the PZT piezoelectric transducer.

Figure 2: PZT piezoelectric transducer

2.2.2 AC-DC Converter

The type of AC-DC converter that was used in this project is a full-wave bridge rectifier circuit. Four diodes are used in a bridge rectifier circuit to convert half cycle of the input AC to DC output. The pi filter circuit is used with the voltage multiplier circuit. The model of the circuit will be like a 'π'

symbol. This circuit only consists of capacitors, diodes and inductor. Table 1 shows the list of components used for the full-wave bridge rectifier circuit.

Table 1: List of components for full-wave bridge rectifier with pi filter circuit

Component	Quantity
1N4007 diode	4
470µF capacitor	1
1000µF capacitor	1
10mH inductor	1

2.2.3 DC-DC Boost Converter

In this project, a DC-DC boost converter is used to increase the output voltage from the lower input voltage. It is a type of switch-mode converter that consists of an inductor, MOSFET, diode, capacitor and resistor. The MOSFET used is IRF540 which is an N-channel MOSFET. LM555 timer is used to oscillate a PWM signal to apply at the MOSFET and boost the voltage. Table 2 shows a list of components for the DC-DC boost converter circuit.

Table 2: List of components for dc-dc boost converter

Component	Quantity
1N4007 diode	1
1N479A Zener diode	1
1µF capacitor	1
100nF capacitor	1
3.3mH inductor	1
Power MOSFET IRF540	1
516Ω resistor	1
33Ω resistor	1
IC555 timer	1

2.2.4 Voltage Regulator and Battery Charging Circuit

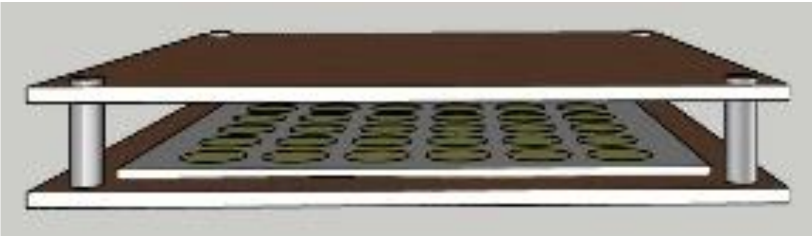
A voltage regulator is an integrated circuit that provides a constant fixed output voltage regardless of a change in the load or input voltage. The boost converter's output voltage is controlled by a voltage regulator. In this project, an LM7812 voltage regulator fixed positive 12 V will be used. It is a voltage regulator that restricts the voltage output to 12 V and draws a 12 V regulated power supply. The rechargeable battery will be protected from overcharging by the voltage regulator. The voltage regulator is connected to the BD139 transistor to amplify the small output current so that it can operate a relay. Table 3 shows the list of components for the voltage regulator and battery charging circuit.

Table 3: List of components for voltage regulator and battery charging circuit

Component	Quantity
0.1uF capacitor	3
ZPD12RL	1
LM7812 voltage regulator	1
BD139 NPN transistor	1
820Ω resistor	1
200Ω resistor	1
12 V relay	1

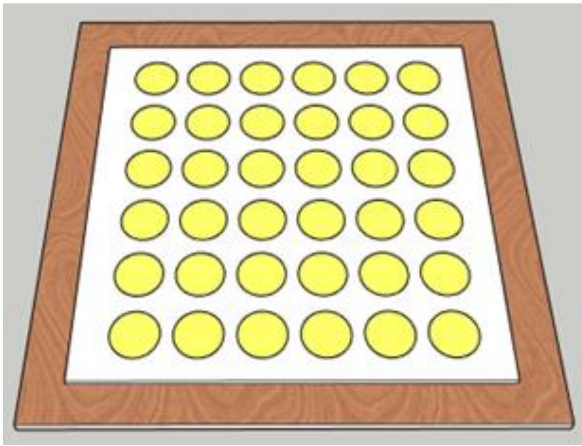
2.3 Proposed Design of Piezoelectric Tiles

Figure 3 shows the proposed design of the piezoelectric tile from front, side and inside view using SketchUp software. The tile can be used for foot press or pumping activities in order to collect the voltage. For the proposed prototype, piezoelectric transducers will be placed between the upper and lower of the piezoelectric tile. The tile is designed in a square shape with a wooden block. The tile is screwed at its edges and combine with the spring to make the upper tile bounce back after the person steps on it. The piezoelectric transducer is placed between the gaps of the two tiles. The subjects are asked to put some pressure on this piezoelectric tile to collect the voltage produced by the piezoelectric transducer. The produced voltage will feed through a rectifier circuit which will convert the AC source to a DC source. Figure 4 shows a schematic representation of the proposed model.



(a)

(b)



(c)

Figure 3: Proposed design of piezoelectric tile with piezoelectric disc (a) side view (b) top view (c) inside view

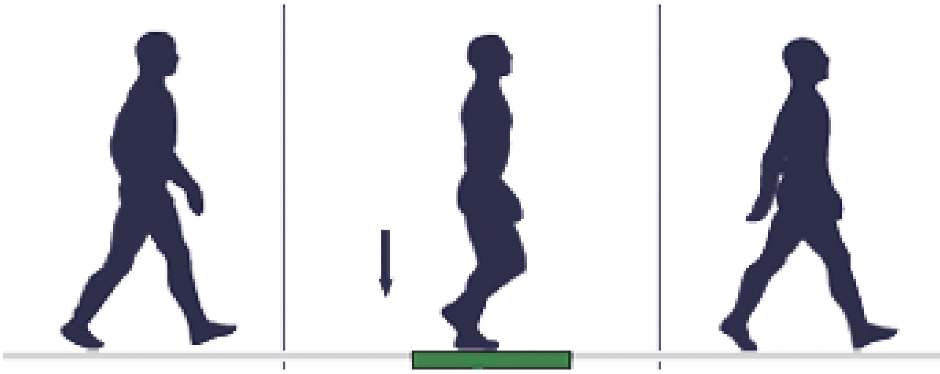


Figure 4: Proposed design of piezoelectric tile with piezoelectric

3. Results and Discussion

The performance of the piezoelectric energy harvesting system was tested in two phases. In the first phase, each schematic circuit of the system was simulated using Proteus Software. While in the second phase is prototype testing. After the circuit simulation using Proteus is a success, the prototype begins to develop. For the prototype testing, a 12 V power transformer is used to represent the AC voltage source, and a 9 V battery is used to represent the DC voltage source in order to test the functionality of the circuit.

3.1 Simulation Result

This section discusses the result of a Proteus Software simulation for the designed circuit. Each of the circuits which is the AC-DC converter circuit, DC-DC boost converter circuit, voltage regulator and the complete circuit is simulated.

3.1.1 AC-DC Converter

The piezoelectric transducer, as previously stated, generates an alternating current voltage. As a result, for application reasons, the piezoelectric output must be converted to DC voltage. The AC-DC converter circuit in this project is designed using a full-wave bridge rectifier circuit. The schematic circuit of the AC-DC converter with a pi-filter circuit is shown in Figure 5. The ripples are excessive in the absence of a filter. As a result, the role of the pi-filter circuit is to eliminate voltage ripple. The pi-filter is the most effective ripple-removing filter circuit because it removes ripples more effectively due to the presence of two capacitors.

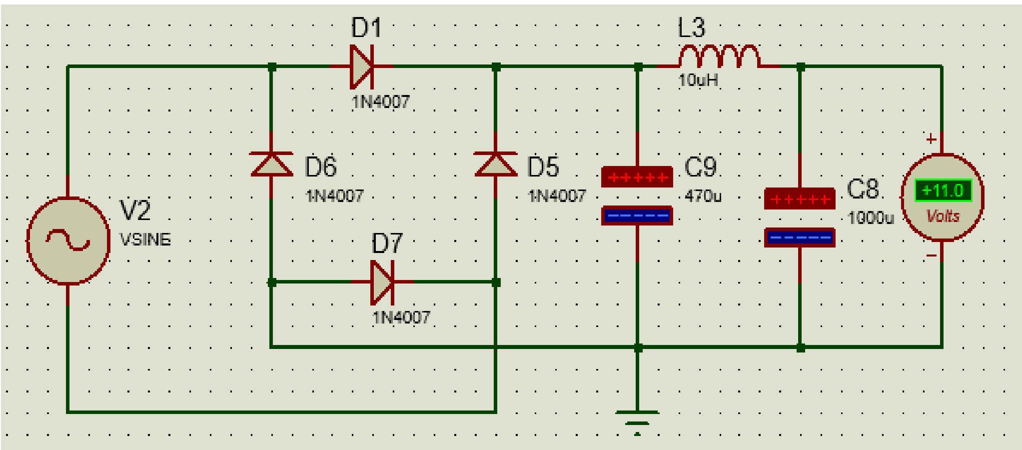


Figure 5: Schematic circuit of ac-dc converter with pi-filter circuit

The input AC voltage is set to 12 V peak-to-peak (AC) and frequency 50 Hz for simulation testing. According to the simulation, the output voltage is converted to DC voltage when it passes through the bridge rectifier circuit and the output voltage is 11 V (DC). Figures 6 and Figure 7 illustrate the graphs of an AC-DC converter generated in the Proteus Software without and with the pi-filter circuit. The effect of the pi-filter circuit may be seen in the simulated graph, where the graph in Figure 6 shows more ripples than the graph in Figure 7.

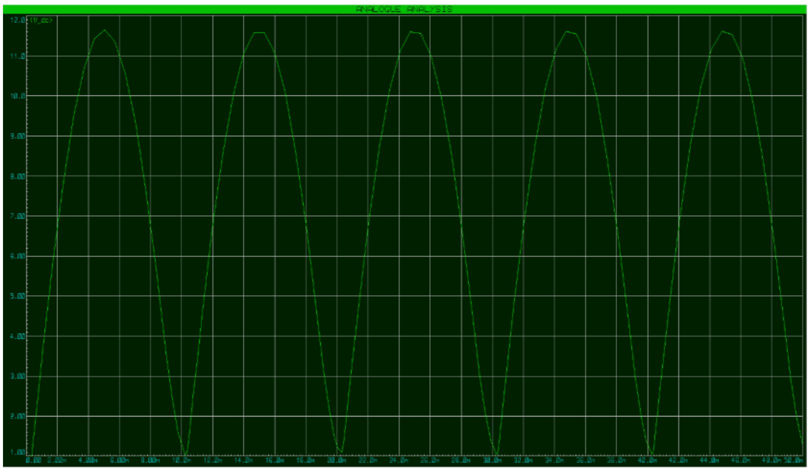


Figure 6: Graph simulation output of ac-dc converter without pi-filter circuit

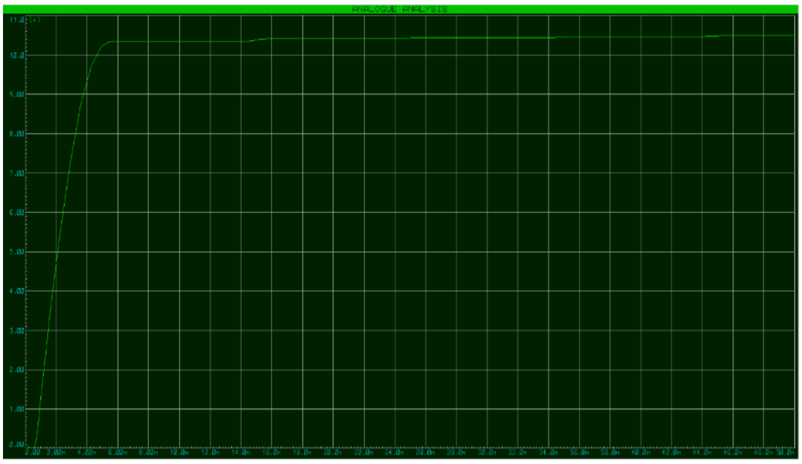


Figure 7: Graph simulation output of ac-dc converter with pi-filter circuit

3.1.2 DC-DC Boost Converter

The piezoelectric transducer has a low output. As a result, a DC-DC booster circuit is necessary to enhance the output of the piezoelectric sensors. A DC-DC booster circuit can provide an output DC voltage that is many times greater than the input AC voltage. Based on simulation results, the DC-DC boost converter can perform from 12 V to 77.7 V. The Proteus Software output for a DC-DC boost converter is shown in Figure 8. The measured output voltage is 77.7 V, and the supplied input voltage is 12 V.

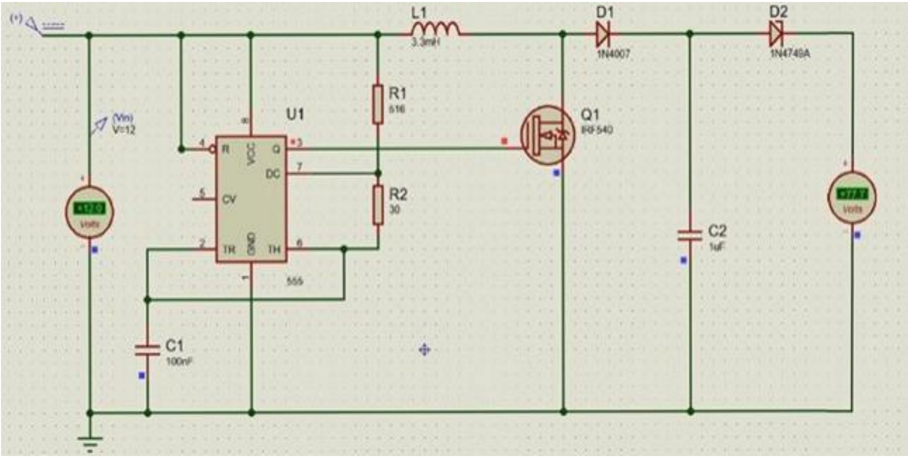


Figure 8: Schematic circuit of dc-dc boost converter

3.1.3 Voltage Regulator and Battery Charging Circuit

A voltage regulator was built into the 12 V rechargeable battery charging circuit to ensure that it received the correct voltage when charging. The Proteus simulation for the voltage regulator and battery charging circuit is shown in Figure 9. In the simulation, 77.7 V which is higher than 12 V voltage was applied to the voltage regulator circuit. Due to the use of the LM7812 voltage regulator, the measured voltage output from the simulation is 12.1 V. The voltage regulator limits the voltage output to 12 V which then will supply to the rechargeable battery.

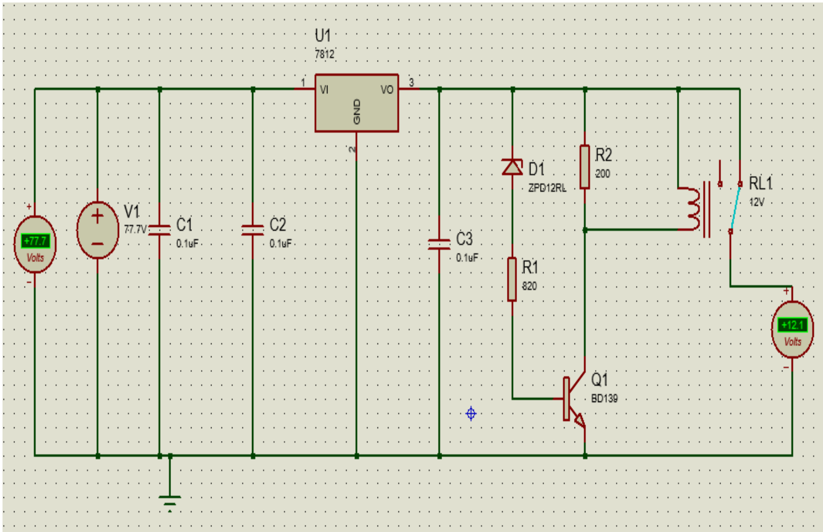


Figure 9: Schematic circuit of voltage regulator and charging circuit

3.1.4 Complete Circuit

This sub-section discusses the complete circuit of the energy harvesting system. Figure 10 shows the complete schematic circuit. From Figure 10, the AC input voltage of 12 V, 50 Hz is supplied to the full-wave bridge rectifier circuit and produces 9.58 V output DC voltage. When the DC-DC boost converter is connected to the voltage regulator and battery charging circuit, the output voltage measure from 9.58 V input is 49.1 V. Then, the circuit is connected to the voltage regulator and battery charging circuit. The voltage output from the voltage regulator is 12 V as shown in Figure 10. This shows that the circuit is able to convert from AC voltage to DC voltage, able to boost the low input voltage to high input voltage and able to regulate the voltage to a constant DC voltage for charging the battery. Table 4 shows the simulation result for the full circuit.

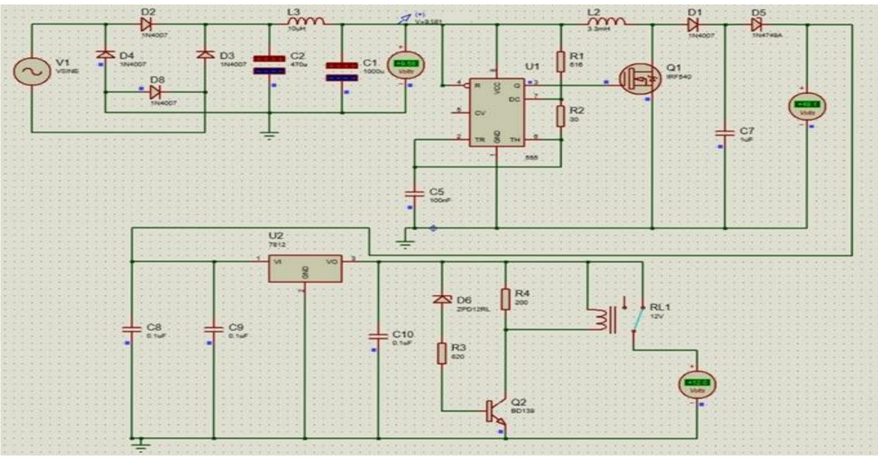


Figure 10: Full schematic circuit

Table 4: Simulation result for the full schematic circuit

Parameter	Voltage	
	Input	Output
AC voltage supply (50 Hz)	12V AC	-
AC-DC converter	12 V AC	9.58 V DC
DC-DC boost converter	9.58 V DC	49.1 V DC
Voltage regulator and battery charging circuit	49.1 V DC	12.0 V DC

3.2 Prototype Result

This section discusses the prototype result for each of the designed circuit. To test the functionality of the circuit, 12 V power transformer is used to represent the AC voltage source and 9 V battery is used to represent the DC voltage source. The complete prototype setup is also shown in this section.

3.2.1 AC-DC Converter

This sub-section shows the result for output DC voltage for the AC-DC converter which is full-wave bridge rectifier with pi-filter circuit. To test the functionality of the circuit, a 12 V power transformer is used to represent the AC voltage source. Figure 11 shows the performance of the full-wave bridge rectifier with pi-filter circuit.

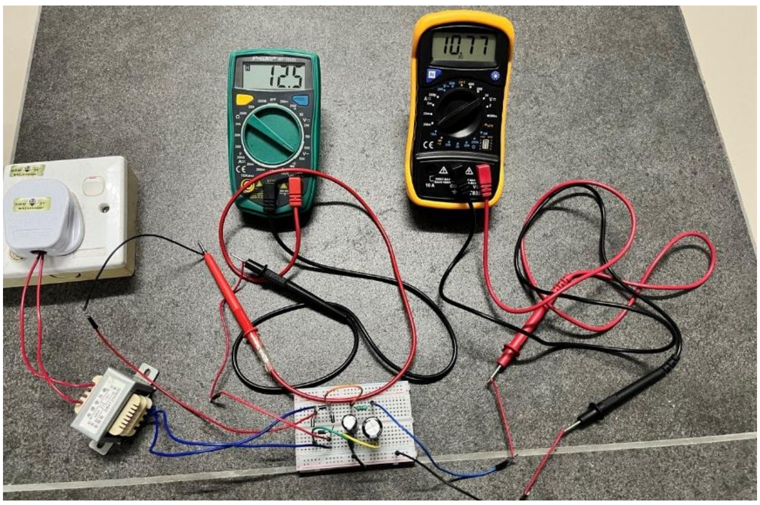


Figure 11: Performance of full-wave bridge rectifier with pi-filter circuit

In order to compare the output voltage, three different weight is used as the parameter which is 60 kg, 70 kg and 96 kg. Each amount of weight is measured in 10 steps. Table 5 shows the measured output DC voltage through a full-wave bridge rectifier with pi-filter circuit. The voltage output comparison of the AC-DC converter for three different weights is shown in Figure 12. Based on the chart in Figure 12, the more the number of steps and the heavier the weight, the higher the output DC voltage.

Table 5: DC output voltage under three different weights

Number of Steps	Output Voltage (DC)		
	60 kg	70 kg	96 kg
1	1.31	1.52	2.23
2	2.26	2.39	2.94
3	3.15	3.27	3.72
4	3.54	4.16	4.51
5	4.09	4.91	5.18
6	4.72	5.63	6.34
7	5.12	6.38	7.29
8	5.90	7.02	8.47
9	6.67	7.52	9.16
10	7.34	8.17	10.04

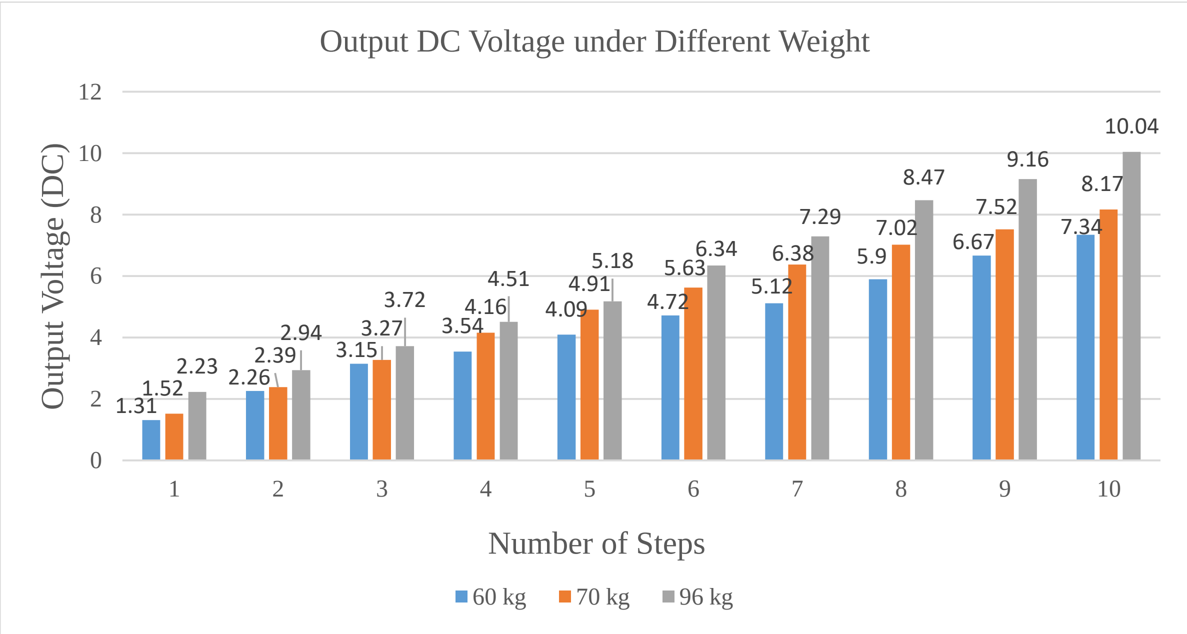


Figure 12: Graph of output DC voltage under three different weights

3.2.2 DC-DC Boost Converter

Figure 13 shows the performance of a DC-DC boost converter circuit. For testing purposes, the input voltage is set to 8.4 V by using a 9 V battery to represent the DC voltage source and the measured output voltage of the booster circuit is 76.9 V. In this circuit, the power MOSFET used is an IRF540 N-channel MOSFET, where the maximum voltage that can be placed between the drain and source while the gate and source are short-circuited (V_{DS}) is 100V. The IC 555 timer will generate a PWM signal, which will be applied to the MOSFET to increase voltage. Because there is no feedback at the output load, the output voltage is not set to the desired voltage and can change if the input voltage is changed.

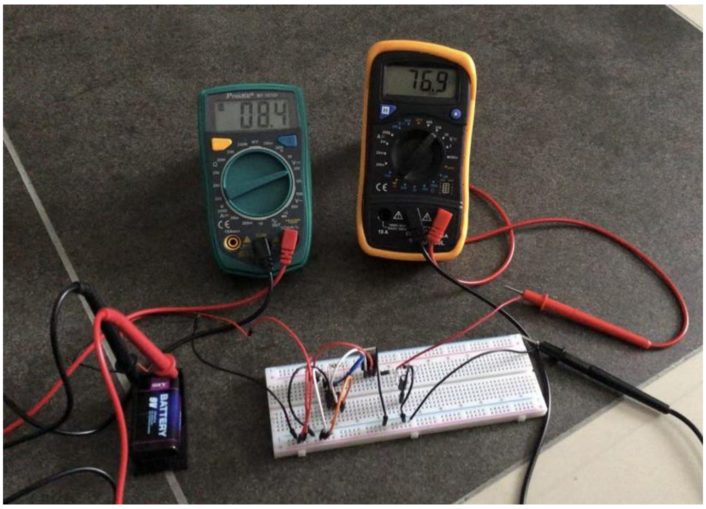


Figure 13: Performance of dc-dc boost converter circuit

3.2.3 Voltage Regulator and Battery Charging Circuit

Figure 14 shows the performance of voltage regulator circuit. In this circuit, LM7812 voltage regulator is used to limits the voltage output to 12 V which then will supply to the rechargeable battery. In the battery charging circuit, a BD139 transistor is used to boost the small output current so that it can drive a relay. The input voltage to the circuit is set to 17.37 V from 2 pieces of 9 V battery that connected in series to represent the DC voltage source and the measured output voltage is 12.1V. Because 12 V rechargeable batteries are used to store harvested energy, and output fluctuations that jump from ±2 V can potentially harm charging devices, therefore, the voltage must be regulated to 12 V.

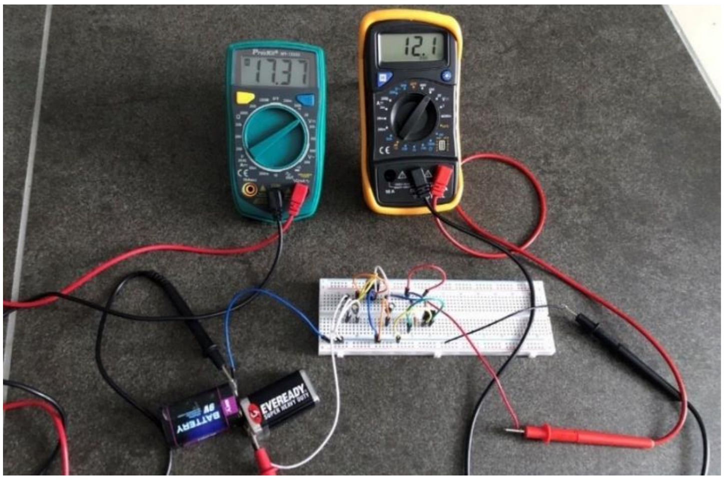


Figure 14: Performance of voltage regulator and battery charging circuit

3.2.4 Prototype Arrangement

Figure 15 shows the prototype arrangement of the energy harvesting system. This prototype was built using 36 piezoelectric transducer which is connected in a series-parallel connection. The piezoelectric circuit is placed under the wooden tile. When pressure is given onto the piezoelectric transducer, electrical energy is produced through the AC-DC converter circuit which is a full-wave bridge rectifier circuit with the pi-filter circuit. The DC voltage produced from the AC-DC converter is then connected to the DC-DC boost converter circuit and lastly connected to the voltage regulator circuit. From Figure 14, the 12 V AC is supplied from the piezoelectric transducer and the measured output voltage for the AC-DC converter is 10.04 V. When the DC-DC boost converter is connected to the voltage regulator circuit and battery charging circuit, the voltage measured from the 10.04 V input is 56.6 V and the voltage measure at the voltage regulator circuit is 12.23 V. Table 6 shows the result from the prototype testing in tabulated form.

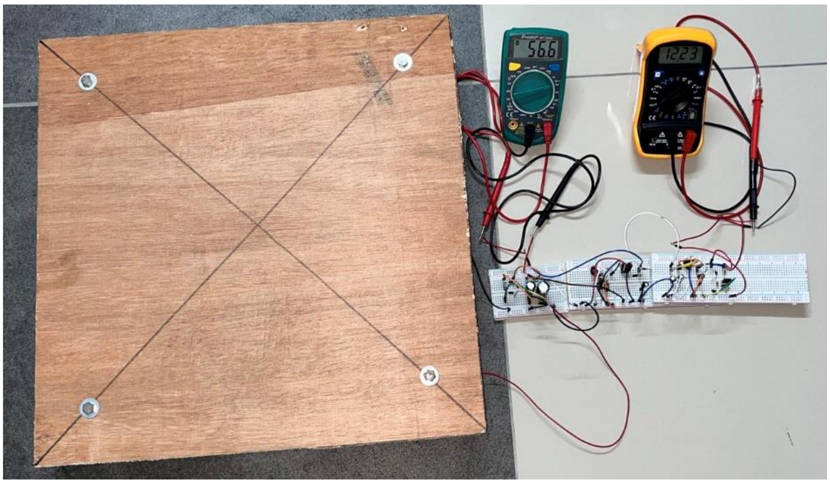


Figure 15: Prototype arrangement of the energy harvesting system

Table 6: Result from the prototype testing

Parameter	Voltage	
	Input	Output
Piezoelectric transducer	12.00 V AC	-
AC-DC converter	12. V AC	10.04 V DC
DC-DC boost converter	10.04 V DC	56.60 V DC
Voltage regulator and battery charging circuit	56.60 V DC	12.23 V DC

4. Conclusion

In conclusion, the piezoelectric energy harvesting system based on pressure from footsteps is successfully developed according to the proposed design and system. An electrical circuit known as a full-wave bridge rectifier can convert an AC voltage into DC voltage. Since the output voltage from the rectifier circuit is too low, the DC-DC boost converter circuit are used to boost the voltage resulted in higher DC voltage. In order to ensure that the voltage supply to the battery is constant when charging, the voltage regulator circuit must be used because excessive fluctuation will destroy the battery. Thus, it can conclude that the piezoelectric transducer is able to harvest energy based on pressure, but it is only available or recommended for applications in low voltage electronic systems. There is a limitation in this system which is the voltage produced is too low. Therefore, the number of piezoelectric transducers should be added to result for better performance in the future research.

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