Technical Paper

Smart Phone Enabled Monitoring of Acoustic Energy Harvesting for Low Power Charging Services

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***Abstract*— This study investigates the capability of Acoustic Energy Harvesters (AEH) in generating electricity to minimize electricity consumption. In AEHs, piezoelectric materials convert mechanical stress into electrical energy. It generates electricity with the application of stimulus such as pressure or sound. This paper reports on the study of a commercial passive piezoelectric transducer effect on an energy harvesting circuit. Based on previous studies, the acoustic energy generated have been mostly used to power up high power devices, such as streetlights and low power devices, such as Wireless Sensor Nodes (WSN)s. Little is known on battery charging services employed using this source of harvested energy. Capitalizing on this potential, AEH could be used in low power charging applications such as mobile electronic gadgets. The methodology employed in this study is via the energy harvesting circuit based on Piezoelectric Acoustic Energy Harvester (PEAEH) technique. The resultant voltage produced by the PEAEH circuit is 3.53 Volts and is found adequate to be used as a battery charger. The battery charging data are consequently transmitted wirelessly via Wi-Fi. Hence, this study advocates the use of a smart phone Android application to monitor the remaining battery-charging capacity with a notification function.**

Keywords—Acoustic Energy Harvesters (AEH); Piezoelectric Acoustic Energy Harvester (PEAEH); piezoelectric; low power battery charging; WiFi; smart phone application

I. Introduction

This project investigates the capability of an energy harvester to minimize electricity consumption. Essentially, the focus is on the Acoustic Energy Harvesters (AEH)s in generating electricity to achieve this objective.

In AEHs, piezoelectric materials convert mechanical stress into electrical energy. It generates electricity with the application of some stimulus such as pressure or sound [1]. Original voltage from a piezoelectric material is very low, i.e. about 200mV to 2V, for an alternating electric signal [2, 3]. To get a reasonable output voltage, amplification and rectification has to be applied.

Although the energy harvesting device discovered from literature had emphasized on the technique of using the piezoelectric technology, little is known on battery-charging services employed using this source of harvested energy. Furthermore, instead of PC-based monitoring, the amount of remaining energy is going to be monitored using smart phones. For wireless monitoring purposes, Wi-Fi technology is highly recommended because it is more cost saving.

The objectives of this study are to investigate the capability of Piezoelectric Acoustic Energy Harvester (PEAEH) technique as a low power charging service; and to design a wireless system to monitor the battery charging. Meanwhile, the scope of this work includes PEAEH circuit design, measurement of maximum voltage produced by the circuit, integration of Wi-Fi module and development of suitable application for smart phone usage. The block diagram of the project is shown in Figure 1.

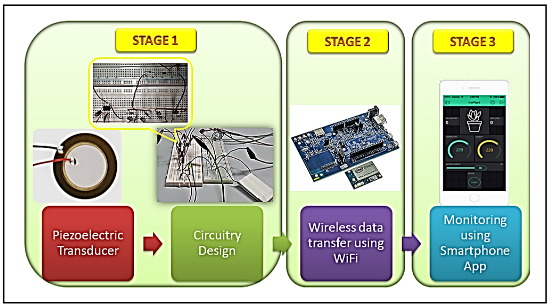

Fig. 1. Project Flow

This project will implement a battery charging system using renewable acoustics energy supply. The system can be used in noisy places for example, industrial areas, train stations, bus terminals or busy roads. The advantage of this project is that it may create a new service for the public to charge their mobile devices conveniently regardless of weather conditions. For example, it will help train commuters or bus passengers to charge their mobile gadgets while waiting for trains and buses without wasting the acoustic energy produced. Finally, it is hoped that the waste energy could be utilized to save and minimize usage of electrical energy.

I. Literature Review

Electricity consumption is ever increasing. One effort to save and minimize usage of electrical energy is via energy harvesting. An energy harvester is a transducer that converts the ambient energy, such as, thermal energy, wind energy, solar energy, hydro energy, kinetic energy, vibrational energy and acoustic energy into electrical energy [1]. Essentially, this paper focuses on Acoustic Energy Harvesters (AEH) in generating electricity.

Currently, several studies have been performed on AEH to power up high power devices, such as streetlights [5] and low power devices, such as Wireless Sensor Nodes (WSN) [4]. In Malaysia, researches have been done in order to lower power consumption [6] via solar energy technique. This is to address the high electricity utilization which amounts to one third of its overall electricity bill [7]. This effort had helped in reducing the electricity bill for street lighting. However, the unstable weather in Malaysia has negatively influenced the amount of solar energy that could be harvested into the system. Due to this constraint, piezoelectric material has been introduced to supply renewable energy system. Recent development of increasing electrical energy for street lighting is by using piezoelectric materials and solar panel which complement each other [2]. Personal Computer (PC) based monitoring system has also been developed in order to maintain the amount of energy supplied for street lighting purposes.

High power is used in single LED lamps for street lighting i.e. 110 Volts. From reviews, it seems that low power applications are an attractive and promising area for research. This is especially in using piezoelectric materials. This research therefore conducts a preliminary study on a low power charging application using the piezoelectric and AEH concept.

A. *Types of AEH*

There are two types of AEHs; Piezoelectric Acoustic Energy Harvester (PEAEH) and Electromagnetic Acoustic Energy Harvester (EMAEH) [4]. Generally, both types implement a Helmholtz resonator to amplify the acoustic pressure for the transduction mechanism in these energy harvesters.

In PEAEH, the fluctuating pressure in the resonator causes the piezoelectric membrane to oscillate, thereby generating an AC voltage. The generated AC voltage is rectified through the voltage rectification circuit to produce DC voltage which is then supplied directly or can be stored in the storage element for future use. Previous work showed that by changing the piezoelectric material from Polyvinylidenedifluoride (PVDF) beams to Lead Zirconate Titanate (PZT) plates would increase the output power from 2.2 μW to 1.27×10^4 μW [8].

On the other hand, EMAEH comprises of a transduction mechanism composed of a permanent magnet mounted on a clamped flexible membrane and a fixed wound coil [9, 10]. The energy conversion in EMAEH is achieved through the principle of electromagnetic induction. Comparing both types, PEAEH is the preferable technique to be used due to its ease of integration of piezoelectric membrane with the Helmholtz resonator compared to electromagnetic-based mechanism.

B. *PEAEH Hardware Components*

- **Piezoelectric**

  The piezoelectric transducer is mainly composed of a multi-harmonic oscillator, a piezoelectric, an impedance matching device and a casing. The piezoelectric material is made of lead titanate or lead magnesium ceramic material. Due to piezoelectric effect, when the piezoelectric material and the metal sheet are applied at both ends of a voltage, mechanical deformation and sound will be produced [11].

- **Amplifier**

  An amplifier is an electronic device that can increase the power of a signal. Amplifiers can be categorised by the way they amplify the input signal [12].

  - Operational Amplifier (Op-amp)

    An operational amplifier has become very widely used in circuits due to their versatility, gain, bandwidth and other characteristics. It can be controlled by feedback through an external circuit.

  - Audio Power Amplifier

    An audio power amplifier functions to amplify low-power electronic audio signals which are composed of frequencies between 20 - 20 000 Hz to a level that is strong enough and audible to listeners. Example of a power amplifier is LM386N which is a Low Voltage Audio Power Amplifier. The gain is internally set to 20, but the addition of an external resistor and capacitor between pins 1 and 8 will increase the gain to any value from 20 to 200 [13].

- **Voltage Multiplier**

  A voltage multiplier is an electrical circuit that converts AC electrical power from a lower voltage to a higher DC voltage [12]. It typically uses a set of capacitors and diodes. There are several types of voltage multiplier, i.e. half wave voltage doubler, voltage tripler and voltage quadrupler. In this research, voltage quadrupler concept was used and it produced an output of four times the input voltage.

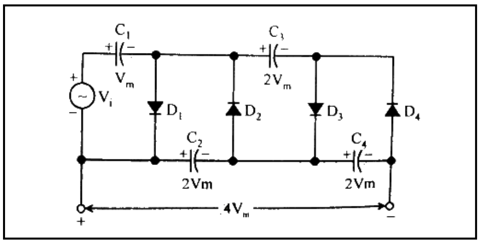

Fig. 1. Voltage Quadrupler

C. Wireless Data Transmission

Wi-Fi (IEEE 802.11) is a medium range wireless communication. Wi-Fi was chosen to transfer the data wirelessly because of the propagation distance of 100 meters and convenience as many public places nowadays have Wi-Fi connectivity. It operates in 2.4 GHz and 5 GHz frequencies, higher than cell phone frequencies. Higher frequencies allow for signal to carry more data. The Intel® Edison is one of the module that provides WiFi interface.

- **Intel Edison module**

The Intel® Edison is an open source hardware and software development environment. It is a System on Chip (SoC) that includes a 22nm dual - core, dual – threaded 500MHz Intel® Atom™ CPU and a 100MHz Intel® Quark™ microcontroller. There is 1GB LPDDR3 memory and 4GB eMMC flash storage on board. It can connect to the Internet through Wi-Fi interface that supports IEEE 802.11 a/b/g/n standards [14]. Since Wi-Fi capability is required for data transmission, the Intel Edison module was chosen.

In this project, the Arduino breakout board was used with Intel Edison to give the ability to interface with Arduino shields.

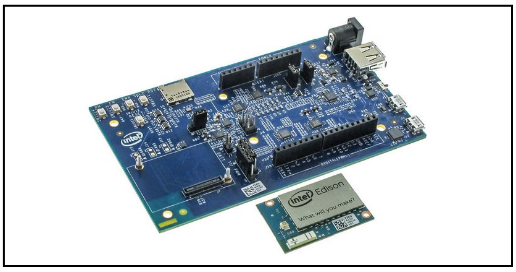

Fig. 2. Intel Edison and Arduino Breakout Board

- **Arduino IDE Software**

The Arduino Integrated Development Environment (IDE) software was used as the programming software for the microprocessor, which is open-source [15]. An IDE normally consists of a source code editor, build automation tools and a debugger. The Arduino IDE originated from the IDE for the languages Processing and Wiring. It was created for people with little knowledge of electronics for ease of use.

D. Smart Phone Application

Various smartphone applications are used today for general productivity and information retrieval. In this project, a smart phone app will be implemented as a monitoring system, which can display data in real time. The technique was chosen because of high cell phone usage nowadays where user gets connected compared to web based monitoring. Blynk app was chosen to be developed as it allows controlling of a variety of microcontrollers and can be used by both Android and iOS devices.

- **Blynk App**

Blynk was designed for the Internet of Things. It can display sensor data, control hardware remotely, store and visualize data and others [16].

There are three major components in a Blynk platform:

i. Blynk App - allows creating interfaces for projects using various widgets provided.

ii. Blynk Server - responsible for all the communications between the smart phone and hardware. It is either using the Blynk Cloud or run private Blynk server locally. It is open-source and could easily handle thousands of devices.

iii. Blynk Libraries - enable communication with the server and process all the incoming and outgoing commands.

II. METHODOLOGY

A. Energy Harvesting Circuit Based on Piezoelectric Acoustic Energy Harvester (PEAEH) technique.

Basically, this energy harvesting system consists of three main components:

i. Energy source, in the form of sound vibration with an output current that is insufficient to use as a direct power supply. Therefore, harvesting is required.

ii. Amplifier to increase output voltages for low voltage input from the piezoelectric.

iii. Voltage Multiplier to create DC voltage suitable for energy storage.

A PEAEH circuit was proposed using a commercial piezoelectric transducer as the sensor to capture sound energy. A piezoelectric element consists of two conductors made of metal and piezoelectric material. The piezoelectric has the tendency to vibrate at the resonant frequency and maximum energy is produced at resonant frequency. The energy generated is dependent on mechanical deflection of the piezo element at the specific frequency.

Fig. 3. Piezoelectric Transducers

A low cost commercial circular piezoelectric transducers of 28mm diameter were used to convert sound into electrical energy as shown in Figure 5. A sinusoidal wave of 10.0 Vpp was applied using the function generator and the frequency was varied. The output voltage level was measured using digital oscilloscope.

B. *Amplification Technique utilizing Operational Amplifier (Op-amp)*

This circuit combined an inverting operational amplifier using LM324N Op-amp and a Quadrupler Voltage Multiplier to increase the output voltage to 4 times higher as shown in Figure 6. 4.7µF (16V) capacitors and 1N4001 diodes have been used in the circuit. A 10kΩ resistor was used as the feedback resistor. 5V DC power supply was applied to the op-amp. The resultant voltage at the output of the Quadrupler circuit, Vout was used to charge a Li-ion battery.

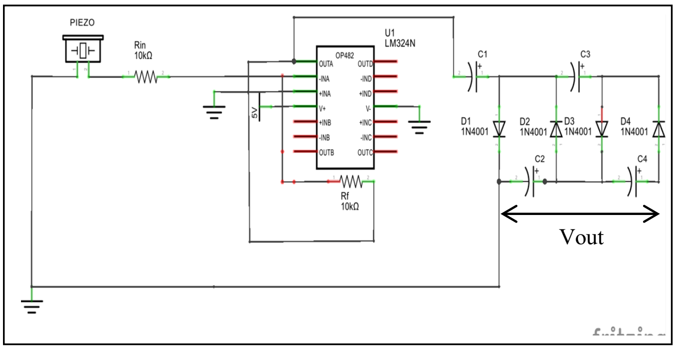

Fig. 4. PEAEH Circuit Diagram with Operational Amplifier

C. *Amplification Technique utilizing Audio Power Amplifier*

Another alternative circuit as shown in Figure 7 was implemented that combined the Low Voltage Audio Power Amplifier circuit using LM 386N and a Quadrupler Voltage Multiplier. Similarly, this circuit used 4.7µF (16V) capacitors and 1N4001 diodes. 5V DC power supply was applied to the power amplifier. Output voltage, Vout from the Quadrupler circuit was used to charge the Li-ion battery.

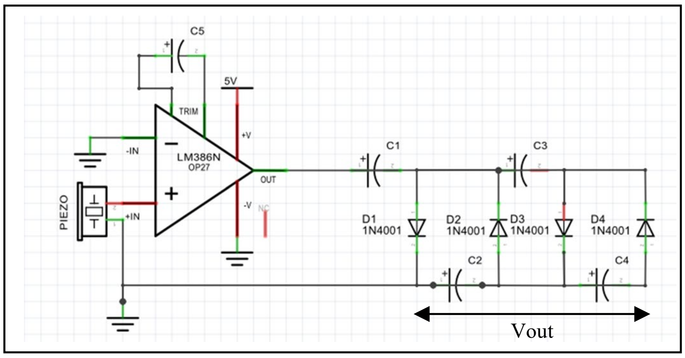

Fig. 5. PEAEH Circuit Diagram with Audio Power Amplifier

D. *Battery Charging*

The Nikon EN-EL5 battery was used as the rechargable battery for the experiment. It is a 3.7 Volt Li-ion, 1100 mAh battery that is used for a digital camera. Before battery charging, it was drained to 0.1Volt. A 1kΩ resistor was connected in series between the quadrupler output and the battery to limit the current and to drop the charger voltage to battery level. A diode was used to prevent discharging of the battery when there was not enough sound source. Output of the voltage quadrupler circuit was used to charge the Li-ion battery as shown in Figure 8, which later produced charged voltage that was measured using digital multimeter.

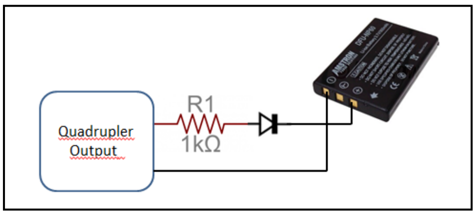

Fig. 6. Battery Charging Circuit

E. *Data Transfer via WiFi*

Output from the battery charging circuit was connected directly to the analog input port, A0 of the Intel Edison board as shown in Figure 8. Values of the analog voltage produced were sent in real time to the Intel Edison development board. IDE programming was used to connect the board to Wi-Fi. Figure 9 shows the algorithm flowchart.

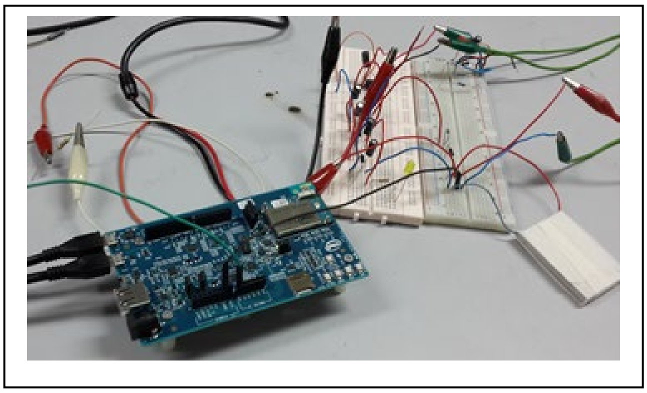

Fig. 7. Circuit Setup of Whole System Hardware

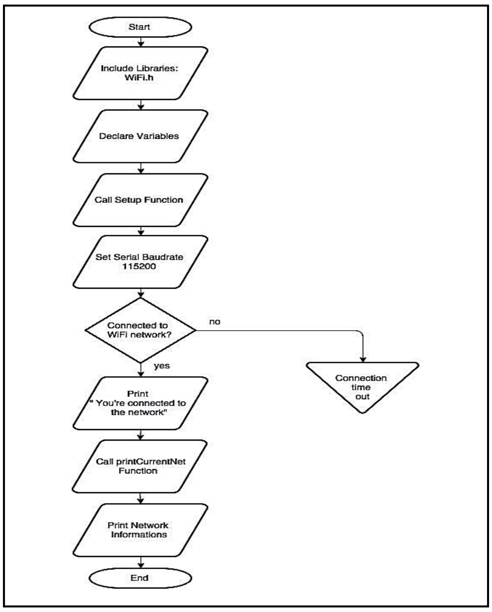

Fig. 8. Board Connect to WiFi Flow Chart

F. Display to Blynk App

The battery charging values that were transferred via Wi-Fi was displayed in the Blynk app. The development of a new function is by a set of Widgets and assignment of virtual pins. The flowchart for display at Blynk app is as shown in Figure 10 and 11.

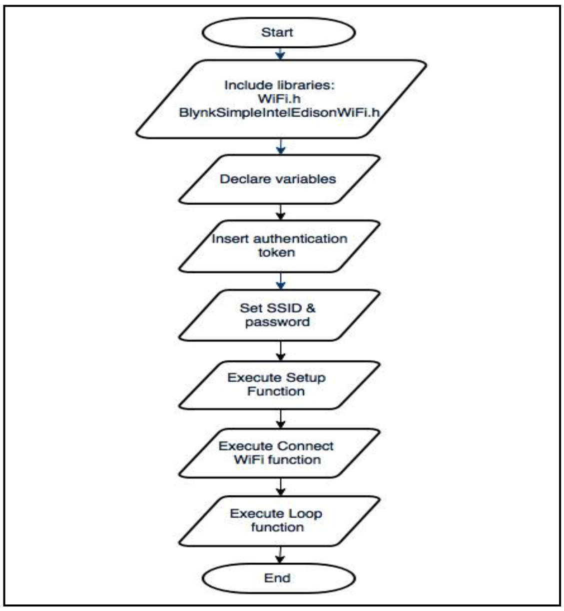

Fig. 9. Display Data Flow Chart

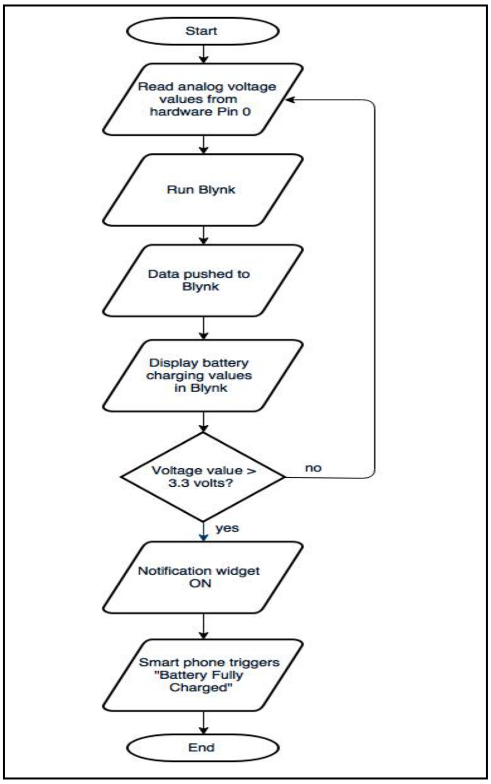

Fig. 10. Loop Function Flow Chart

III. Results & Discussion

A. Resonant Frequency of the Piezoelectric Transducer

To achieve maximum output voltage, experiments were conducted to obtain the resonant frequency of the piezoelectric transducer. Sinusoidal wave was applied and the output showed that the maximum frequency was 2.78 KHz at 10Vpp. The output voltage level was very low and varied from 80mVpp to 9.68Vpp. Figure 12 shows the resonant frequency and frequency range of the piezoelectric transducer.

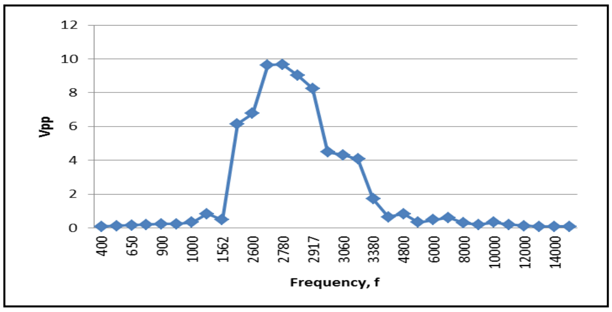

Fig. 11. Piezoelectric Output Voltage vs Frequency Range

B. Output Voltage at Resonant Frequency

From the resonant frequency and maximum voltage output of the piezoelectric transducer, measurement was performed to see the values in output voltage, Vout of the circuit. Initially, Vout of PEAEH with Operational Amplifier circuit (Circuit I) was measured using digital multimeter. The values were observed to be quite low i.e. 7.19VDC. This caused another circuit to be developed i.e. PEAEH with Audio Power Amplifier circuit (Circuit II). Basically, Circuit II produced higher Vout of 22.7VDC compared to Circuit I. The values measured are shown in Table I below.

TABLE I. OUTPUT VOLTAGE AT RESONANT FREQUENCY

Output Voltage Measurement versus Time				
Frequency (Hz)	*Vin(VAC)*	*Power Supply (V)*	*Amplifier Type*	*Vout (VDC)*
2780	9.68	5.0	Op-amp LM324N	7.19
			Power amp LM386N	22.7

Generally, different amplifiers used produced different output voltages. This is mainly due to the characteristics of the amplifier that have different gains.

C. Charged Voltage

Li-Ion battery charging was performed using two different amplification techniques, i.e. PEAEH with Operational Amplifier circuit (Circuit I) and PEAEH with Audio Power Amplifier circuit (Circuit II). The results were then compared with Nikon MH-61 Lithium Ion battery charger to compare the characteristics.

For both circuits, simulated signal was applied to the piezo source and the battery charging process was executed. For

Circuit I, the charged battery was observed to peak 3.05 Volts in 5 minutes and increased to 3.11 Volts after 23 minutes. After 2 hours, the charged voltage was 3.17 Volts. On the other hand, for Circuit II, the charged battery peaked to 3.39 Volts in 1 minute and increased to 3.44 Volts after 30 minutes. After 2 hours, the charged value was noticed to be 3.53 Volts. It was observed that after the initial abrupt charging, the charged voltage values kept on increasing consistently as shown in Figure 13 and Figure 14.

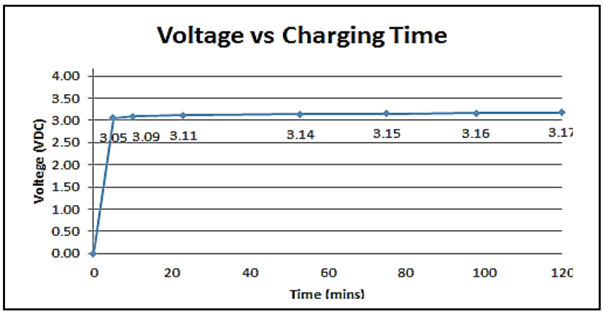

Fig. 12. Voltage vs Charging Time PEAEH with Operational Amplifier circuit (Circuit I)

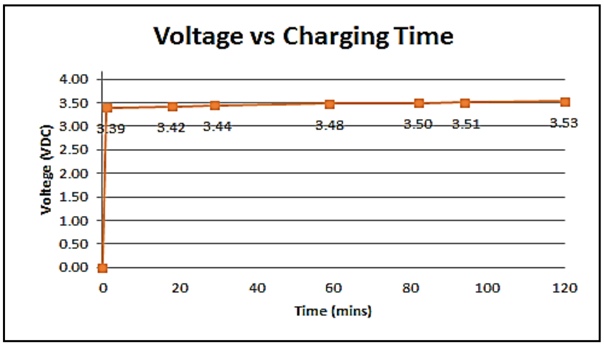

Fig. 13. Voltage vs Charging Time PEAEH with Audio Power Amplifier circuit (Circuit II)

By using the original battery charger, it was found that the battery was fully charged within 2 hours with voltage value of 4.17 Volts as shown in Figure 15.

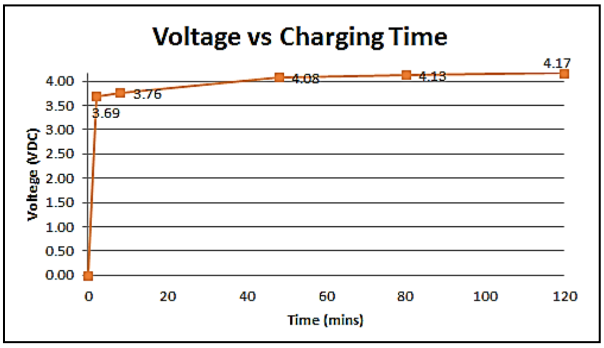

Fig. 14. Voltage vs Charging Time Using Nikon MH-61 Lithium Ion battery charger

Based on the experiment results, the voltage charged using Circuit II had produced higher voltage that is 3.53 Volts as compared to using the designated battery charger that is 4.17 Volts. The value obtained was quite high and is viable to be used as a charger for the digital camera although the battery was not fully charged.

By comparing with other works, results showed that the performance of the piezoelectric transducer depends on the material used and the harvester volume. Higher volume and usage of modified crystal material produced more power as shown in Table II.

TABLE II. DESIGN COMPARISON OF PEAEH WORKS

Previous Research Works	***Harvester Fabrication Material***	***Harvester Volume (cm^3)***	***Resonant Frequency (kHz)***	***Power (µW)***
B. Li, et. al	PZT plates, polycarbonate panels	8.4×10^2	0.199	1.27×10^4
F.Liu, et al.	Modified PZT (APC850)	2.47	2.64	1.21×10^4
L.Y. Wu, et al.	PVDF	47.15	4.2	4×10^{-2}
This Work	**PZT**	**2.46**	**2.78**	**3.53**

D. Data Transfer via WiFi

The serial monitor was observed and a message was displayed when the board was connected succesfully to WiFi. Network information was also displayed for monitoring purposes.

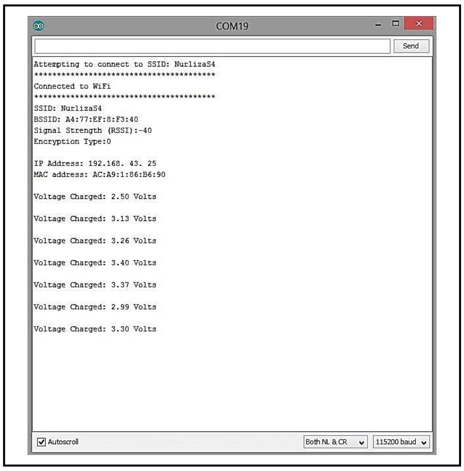

Fig. 15. Serial Monitor Display

E. *Blynk App*

Blynk was used in the development for the smart phone application to monitor the charged energy to the Li-Ion battery as shown in Figure 17. A widget for notification was added to alert users that the battery has been fully charged.

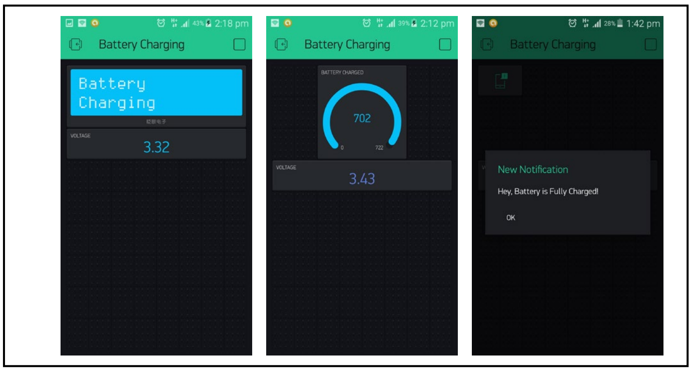

Fig. 16. Display on Blynk App

The limitation of the app is that basic free functions are limited. To enable more features to be unlocked, it has to be purchased.

IV. Conclusion & Recommendation

This study had shown that Acoustic Energy Harvesting is capable of producing sufficient source of voltage for low power device application using Piezoelectric Acoustic Energy Harvester (PEAEH) technique. A wireless system has also been successfully developed using Blynk app for the battery charging monitoring.

Further studies can be conducted to look into how the output voltage could be boosted up, for instance by adding more piezoelectric transducers as the sound source. Choosing different material for the piezoelectric could also be considered to enhance the transducer performance since this project had only used a general use low-cost commercial piezoelectric. For example, utilizing more durable and specially designed Lead Zirconate Titanate (PZT) materials for energy harvesting purposes normally produced more power than Polyvinylidene Fluoride (PVDF). Other than that, piezoelectric volume could also be increased to enhance the output power.

Random sound energy from the environment is treated as a source of electric power after conversion through suitable transducer. Through this project, it is hoped that the waste energy could be utilised to save and minimise usage of electrical energy, hence reduce the overall electric consumption and save on electric bills.

Acknowledgment

The author would like to thank the Research Management Institute (RMI), UiTM 600-RMI/DANA 5/3/LESTARI (45/2015) for the financial support of this research.

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