PIEZOELECTRIC BASED VIBRATION ENERGY HARVESTER

MOHD YUSOF BIN MOHAMMAD

UNIVERSITI SAINS MALAYSIA

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By

MOHD YUSOF BIN MOHAMMAD

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LIST OF ABBREVIATIONS

V	Voltage
AC	Alternating Current
DC	Direct Current
k	Kilo @ 10^3
CEO	Chief Executive Officer
CNN	Cable News Network
PVEH	Piezoelectric Vibration Energy Harvesters
Caux	Auxiliary Capacitor
Vaux	Auxiliary Voltage
mW	Milliwatt
Hz	Hertz

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ABSTRACT

In this project, some of the shortcomings in the existing system have been proposed to be rectified. The advances in technology have allowed numerous ways for power harvesting systems in practical applications in order to meet the power demand. The use of piezoelectric crystal is to generate electric output from surrounding vibrations. Piezoelectric materials have a crystalline structure that can convert mechanical energy into electrical charge and vice-versa. Harvesting mechanical energy from human motion is an attractive approach for obtaining clean and sustainable electric energy to power wearable sensors, which are widely used for health monitoring, activity recognition, gait analysis and so on. This project studies a piezoelectric energy harvester for the parasitic mechanical energy in shoes originated from human motion. The harvester is based on a specially designed sandwich structure with a thin thickness, which makes it readily compatible with a shoe. Besides, consideration is given to both high performance and excellent durability. The different values of frequencies will be taken to indicate the shoe while walking, jogging and running. In order to increase the voltage, the boost converter circuit is used. The use of boost converter is to increase the level of voltage ranges and the charge then will be stored in a supercapacitor. Time duration for the supercapacitor to fully charged will be taken.

PIEZOELEKTRIK BERASASKAN PENUAIAN GETARAN TENAGA

ABSTRAK

Dalam kajian ini, beberapa kelemahan dalam sistem sedia ada telah dicadangkan untuk dibetulkan. Kemajuan teknologi telah membolehkan pelbagai cara untuk sistem penuaian kuasa dalam aplikasi praktikal untuk memenuhi permintaan kuasa. Penggunaan kristal piezoelektrik adalah untuk menjana output elektrik dari getaran sekitar. Piezoelektrik mempunyai struktur kristal yang boleh menukar tenaga mekanikal kepada caj elektrik dan sebaliknya. Penuaian tenaga mekanikal dari pergerakan manusia adalah satu pendekatan yang menarik untuk mendapatkan tenaga elektrik bersih dan mampan untuk memberi kuasa kepada sensor yang dipakai, yang digunakan secara meluas untuk pemantauan kesihatan, pengecaman aktiviti, analisis gaya berjalan dan sebagainya. Dalam kajian ini, penuai tenaga piezoelektrik untuk tenaga mekanikal parasit dalam kasut berasal dari gerakan manusia. Penuai ini adalah berdasarkan kepada struktur sandwich direka khas dengan ketebalan yang nipis, yang menjadikan ia mudah serasi dengan kasut. Selain itu, pertimbangan diberikan kepada kedua-dua prestasi yang tinggi dan ketahanan yang sangat baik. Nilai-nilai frekuensi yang berbeza iaitu ketika berjalan, berjoging dan berlari akan diambil untuk dikaji. Dalam usaha untuk meningkatkan voltan, pengubah litar rangsangan digunakan. Penggunaan pengubah litar rangsangan adalah untuk meningkatkan tahap voltan dan disimpan dalam superkapasitor. Tempoh masa bagi superkapasitor untuk dicas sepenuhnya akan diambil dan dinilai.

CHAPTER 1

INTRODUCTION

Background

Energy is the ability to do work. In physics, energy is the property that must be transferred to an object in order to perform work. Energy can be converted in form but not created or destroyed. Energy can be in many form such as on the form of light, sound, electricity, chemical and heat energy. SI unit of energy is joule. Everything is connected to energy in one form or another. Meanwhile on the other hand, energy harvesting is a process that captures small amounts of energy that would otherwise be lost as heat, light, sound vibration or movement to be usable energy. Energy harvesting also has the potential to replace batteries for small and low power electronic devices. There are numerous researches on the harvester device that have been done to replace the conventional battery. Some of the research works in this area focus on the method of energy harvesting itself [1]–[2] while others on the system architecture of the energy harvester [2] [3] [4]

Energy harvesting development is varied. The most common energy harvesting method is piezoelectric, photovoltaic, pyroelectric and electromagnetic. Energy harvesters can supply energy to small-scale devices by used pressure as source of energy. Advantages of using energy harvesting is that it is a renewable source. The converted energy can be stored in supercapacitor. The stored energy can be used for short or long term. The energy harvester in this project is based on a pressure applied to the piezoelectric sensor.

This project will focus on development of energy harvester circuit by using piezoelectric sensor. This research will ensure that the effectiveness of the energy harvesting on power electronic equipment in the future.

1.1 Problem Statement

Energy cannot be created or destroyed but it can be converted from one form to another. From footfalls to climbing stairs, to opening doors, the cities of the future will look at ways of tapping energy from all the mechanical energy that are spend in our daily lives. When looking at the amount of kinetic energy produced in the average metro station at rush hour, or even on the dance floors of nightclubs, harvesting electricity from human activity makes sense. "People walk up to 150 million footsteps in their lifetime," said Pavegen CEO Laurence Kemball-Cook told CNN. "When I was walking through a busy train station in London I thought what if we can convert the energy from every single person walking at the station into a meaningful amount of power."[5]

As a problem statement, the problem with current wireless system with the battery. Wireless sensors need higher power consumption, thus it will reduce life span on battery. Thus, alternative way to compliment the battery is energy harvesting. To convert the kinetic energy produced and use it for something useful, it is required to have a suitable energy harvesting circuit. The energy harvesting circuit should consist of rectification, boost converter and energy storage.

1.2 Objectives

The objectives of this project are as shown below:

1. To develop piezoelectric based power management energy harvesting circuit.
2. To fabricate and characterize vibration based energy harvesting from footstep.

Several of energy harvesting circuit will be studied. The change of frequency, the output voltage and the time for supercapacitor to fully store energy will be taken. An analysis will be conducted to develop a better circuitry for piezoelectric based energy harvesting.

1.3 Project Scope

The scope of the project will focus on:

1. Developing piezoelectric based energy harvesting circuit.
2. Compare the simulation result and practical result.
3. How many steps to be taken for charging the supercapacitor.
4. Power produced by shoe.

1.4 Project Outline

Chapter 1 explain about the idea of the project. The idea was explained in introduction and problem statements. This chapter also explained about objectives of the project and also the project's scope.

Chapter 2 explain about the basic theory about energy harvesting, piezoelectric harvester, rectification, boost converter and energy storage for energy harvesting circuit that has been done. This chapter also explain about supercapacitor.

Chapter 3 is about methodology. In this chapter, step by step method is used for this project is brief. Equipment, measurement and procedure to conduct energy harvesting circuit is discussed.

Chapter 4 is the data that are collected from the simulation and experimental. The simulation data will be discussed first and then experimental result. After that, the calculation for the steps to be taken and power generated also will be shown in this chapter.

Chapter 5 is the conclusion of the project. Not just that, the future work also being discussed in this chapter in order to improve this project.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

Energy and environment, both are the main concern for every researcher all over the words. Energy that otherwise lost as heat, light, sound, vibration or movement are captures by energy harvesting. The process of extracting unused energy from the ambient environment and converting it into a usable form of electrical energy is known as Energy Harvesting. With recent growth in the development of low-power electronic devices such as microelectronics and wireless sensor nodes, as well as the global interest in the concept of "piezoelectric" the topic of energy harvesting has received much attention in the past decade. Piezoelectric materials have received the most attention for obtaining electric energy from the surrounding environment for their ability to directly convert vibrations into electrical energy. Energy harvesting is a technique to provide alternative sources of energy that are environmental friendly and low in cost. Power consumption has decreased opening the field for energy harvesting to become real time solution for providing different sources of electrical power. Energy harvesting is a new technology that is going to make a revolution in the coming decade [5]. The advantages of energy harvesting are, it is environmental friendly, maintenance free and open up for new applications.

There are several sources of energy harvesting. The common sources of energy harvesting are thermal energy, light energy, electromagnetic energy and radio frequency energy. Solar energy being the most interesting one in outdoor deployments due to its relatively high power density [6]. However, they are not suitable for portable devices due to the absence of continuous lighting.

Various conversion mechanisms such as electromagnetic, electrostatic and piezoelectric for harvesting this form of energy have been demonstrated [7]. However, electromagnetic convertors are difficult to integrate due to the number of coil turns and are inefficient at generating strong damping forces in small geometries or at low frequencies. The electrostatic convertors require the use of separate voltage sources and mechanical stops. The piezoelectric convertors are known to overcome these limitations and have proven to produce a higher power output for a fixed device size. Therefore, the development of piezoelectric based vibration energy harvesters (PVEH) is important.

Using of piezoelectric elements from ambient vibrations to harvest energy of great interest over the past few years. One of the most widely used power harvesting techniques for micro-power applications uses piezoelectric materials to convert any type of energy to electrical energy. Figure 2.1 shows a block diagram of ambient energy harvesting system. The choice of the source depends primarily on the specification of the power requirement for an application and design feasibility [8].

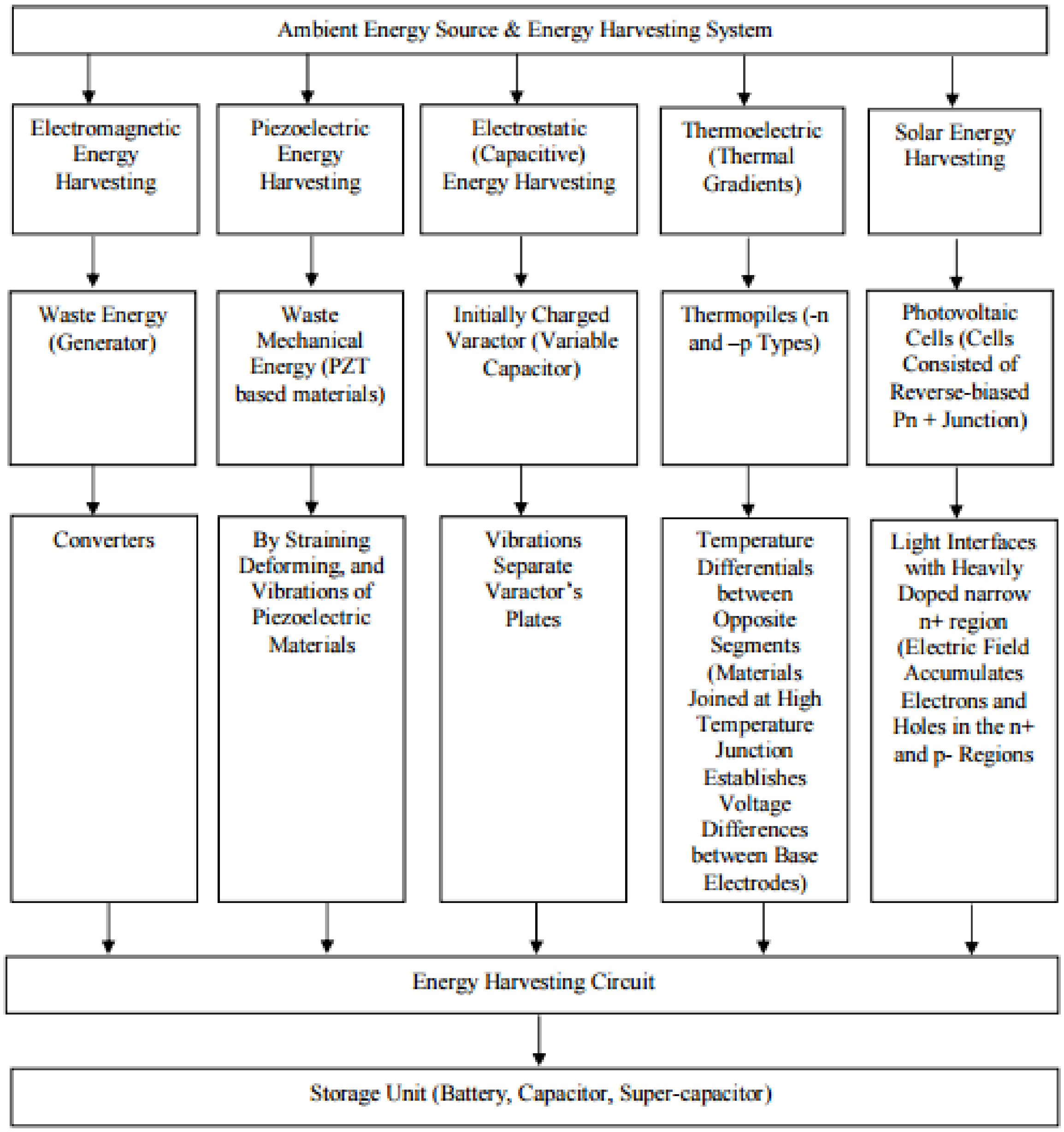


Figure 2.1: Block diagram of ambient energy harvesting system

2.2 Vibration Energy Harvester

Vibration energy is present all around us. the vibration energy from roads, vehicle engine and bridges is typically converted into electrical energy using piezoelectric, electromagnetic or electrostatic transduction mechanism [9]. Piezoelectric transducer will be focus more as it is the generator for this circuit. This section provides the modelling on piezoelectric based energy harvesting system considering of piezoelectric element, AC-DC rectifier, voltage regulator, DC-DC converter (step-up) and temporary storage device. Here mention all these characteristics are illustrated through selective block diagram. A simple produce is step-by-step presented to design the modelling of piezoelectric based energy harvesting system, as shown in Figure 2.1.

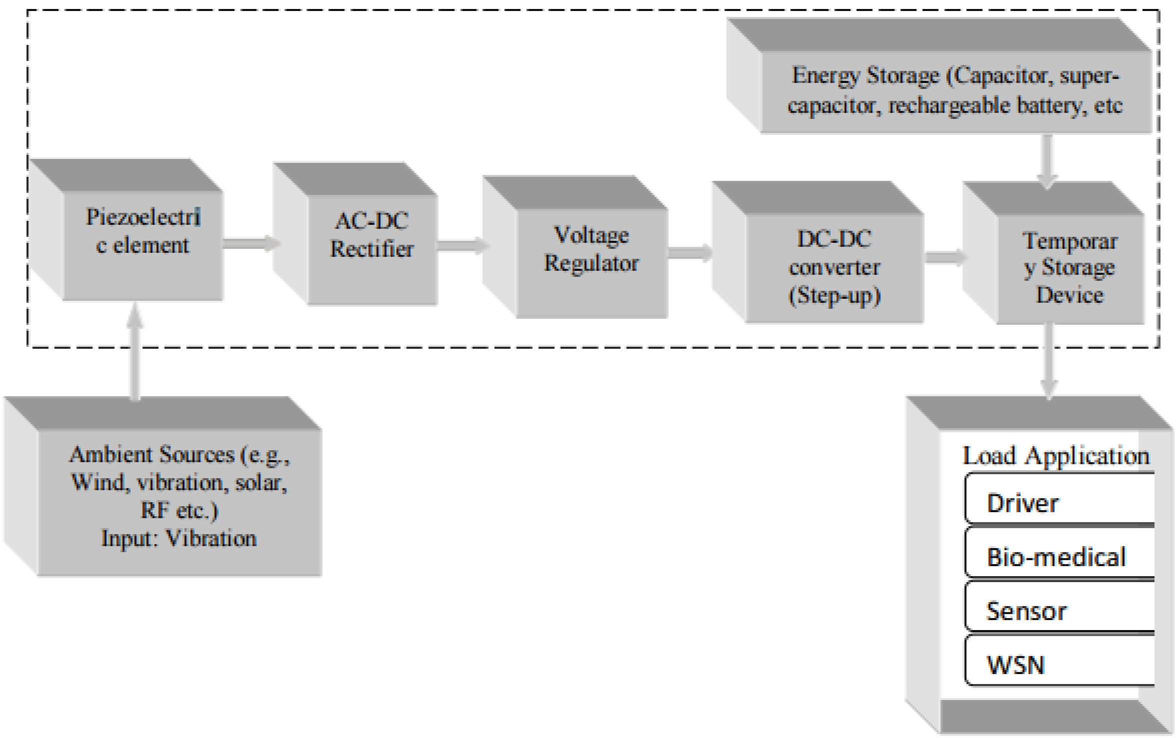


Figure 2.2: Propose Energy harvesting modules (Experimental sub-blocks).

2.3.0 Piezoelectric Transducer

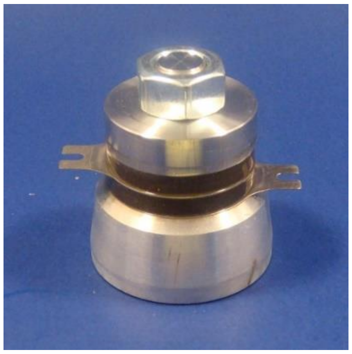


Figure 2.3: Piezoelectric Transducer

Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices. Piezoelectric transducers are a type of electroacoustic transducer that convert the electrical charges produced by some forms of solid materials into energy. The word "piezoelectric" literally means electricity caused by pressure. Piezoelectric transducer is increasingly being used to harvest energy from environmental vibrations in order to power remote sensors or to charge batteries that power the sensors [10]. Piezoelectric materials have received the most attention due to their ability to directly convert applied strain energy into usable electric energy and the ease at which they can be integrated into a system. When strain energy is applied to the material it results in a deformation of the dipole and the formation of a charge that can be removed from the material and used to power various devices. Representative piezoelectric materials can be categorized into piezoceramics and piezopolymers. Piezoceramics have large electro-mechanical coupling constants and provide high energy conversion rate, but they are too brittle to use general shape energy transducer. On the other hand, piezopolymers have smaller electromechanical coupling constant compared to the piezoceramics, but they are very flexible.

Piezoelectric transducer can measure pressure in the same way a force or an acceleration can be measured. For low pressure measurement, possible vibration of the amount should be compensated for. The pressure measuring quartz disc stack faces the pressure through a diaphragm and on the other side of this stack, the compensating mass followed by a compensating quartz.

The piezoelectric transducers work on the principle of piezoelectric effect. When mechanical stress or forces are applied to some materials along certain planes, they produce electric voltage. This electric voltage can be measured easily by the voltage measuring instruments, which can be used to measure the stress or force. The physical quantities like stress and force cannot be measured directly. In such cases the material exhibiting piezoelectric transducers can be used. The stress or the force that has to be measured is applied along certain planes to these materials. The voltage output obtained from these materials due to piezoelectric effect is proportional to the applied stress or force. The output voltage can be calibrated against the applied stress or the force so that the measured value of the output voltage directly gives the value of the applied stress or force. In fact, the scale can be marked directly in terms of stress or force to give the values directly [11].

The voltage output obtained from the materials due to piezoelectric effect is very small and it has high impedance. To measure the output some amplifiers, auxiliary circuit and the connecting cables are required.

2.3.1 Piezoelectric Effect

There are certain materials that generate electric potential or voltage when mechanical strain is applied to them or conversely when the voltage is applied to them, they tend to change the dimensions along certain plane. This effect is called as the piezoelectric effect. This effect was discovered in the year 1880 by Pierre and Jacques Curie. Some of the materials that exhibit piezoelectric effect are quartz, Rochelle salt, polarized barium titanate, ammonium dihydrogen, ordinary sugar etc.

The X-Y axis of a piezoelectric crystal and its cutting technique is shown in the figure below. The direction, perpendicular to the largest face, is the cut axis referred to. If an electric stress is applied in the directions of an electric axis (X-axis), a mechanical strain is produced in the direction of the Y-axis, which is perpendicular to the relevant X-axis. Similarly, if a mechanical strain is given along the Y-axis, electrical charges will be produced on the faces of the crystal, perpendicular to the X-axis which is at right angles to the Y-axis. The main advantages of these crystals are that they have high mechanical and thermal state capability, capability of withstanding high order of strain, low leakage, and good frequency response, and so on [12].

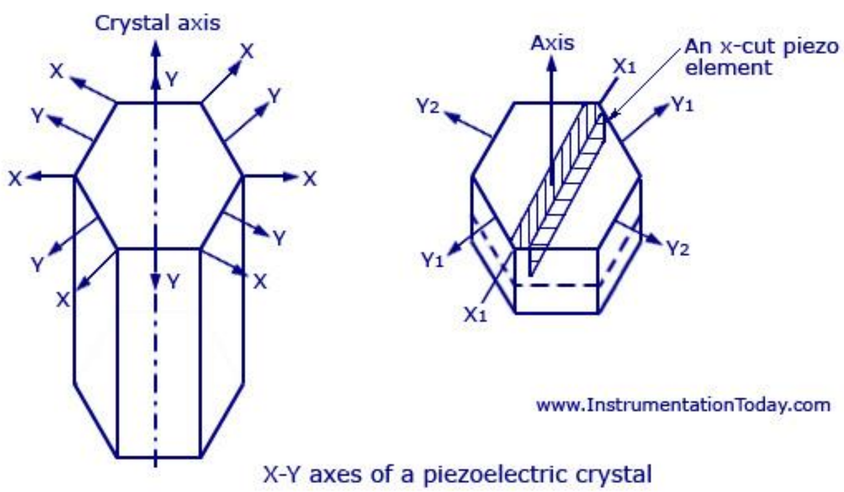


Figure 2.4: X-Y Axes of Piezoelectric Crystal

A piezoelectric transducer may be operated in one of the several modes as shown in the Figure 2.5.

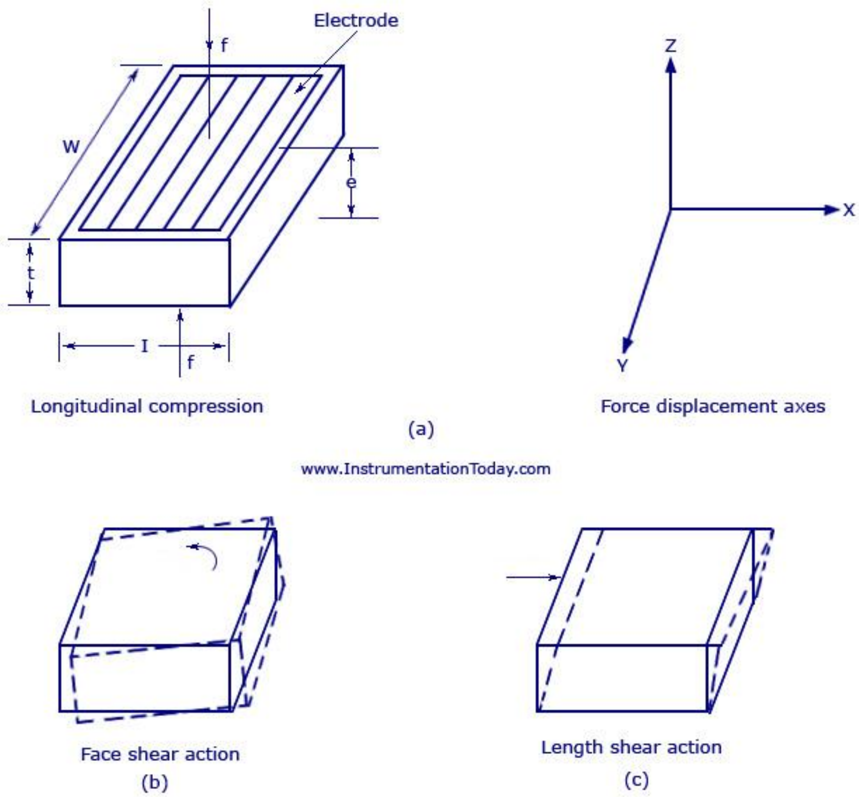


Figure 2.5: Piezoelectric Transducer's Mode

2.3.2 Advantages and Disadvantages

Table 2.1: Advantages and disadvantages of piezoelectric

Advantages	Disadvantages
1. Very high frequency response. 2. Self-generating, so no need of external source. 3. Simple to use as they have small dimensions and large measuring range. 4. Barium titanate and quartz can be made in any desired shape and form. It also has a large dielectric constant. The crystal axis is selectable by orienting the direction of orientation.	1. It is not suitable for measurement in static condition. 2. Since the device operates with the small electric charge, they need high impedance cable for electrical interface. 3. The output may vary according to the temperature variation of the crystal. 4. The relative humidity rises above 85% or falls below 35%, its output will be affected. If so, it has to be coated with wax or polymer material.

2.4 Alternating Current (AC) and Direct Current (DC)

Electric charge (current) that only flows in one direction is called direct current (DC) whereas on the other hand, electric charge (current) of alternating current (AC) changes direction periodically. The changes of current direction cause the voltage in AC circuits also periodically reverses. AC waveform in sine wave as shown in figure below.

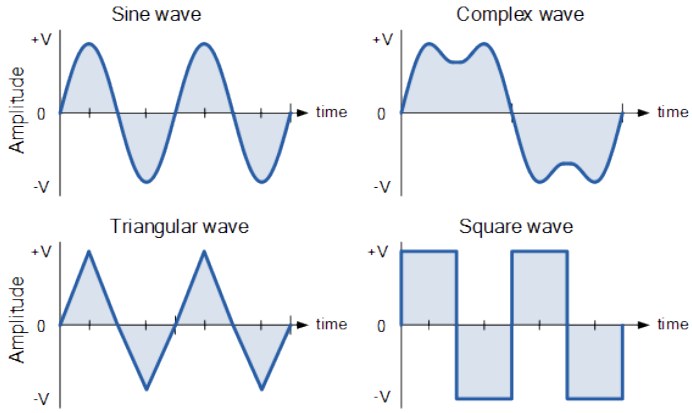


Figure 2.6: AC Waveform

DC is defined as the 'unidirectional' flow of current; current only flows in one direction. Voltage and current can vary over time so long as the direction of flow does not change. Most DC sources provide a constant voltage over time. Example as below.

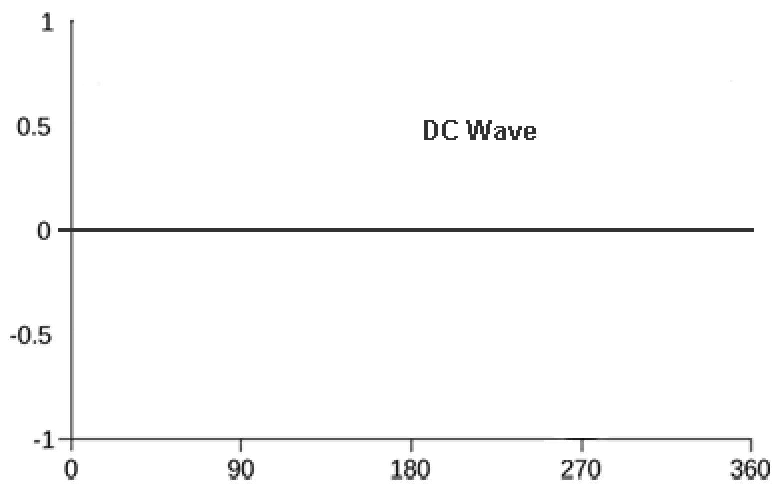


Figure 2.7: DC Waveform

From section 2.3.1, piezoelectric can generate electric potential or voltage when mechanical strain is applied to them, and the output produced from it is in AC signal. Thus, a suitable harvesting circuit is required to ensure the voltage compatibility between the terminal electric load and piezoelectric element. The general requirement for harvesting circuit is rectification, step-up voltage or boost converter, voltage regulator and energy management unit.

2.5 AC to DC converter

The conversion of alternating current (AC) to direct current (DC) is called as rectification. There are several type of rectifier such as full-wave rectifier, full-wave bridge rectifier and voltage multiplier. This project will be focus on full-wave bridge rectifier. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop “bridge” configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below [13].

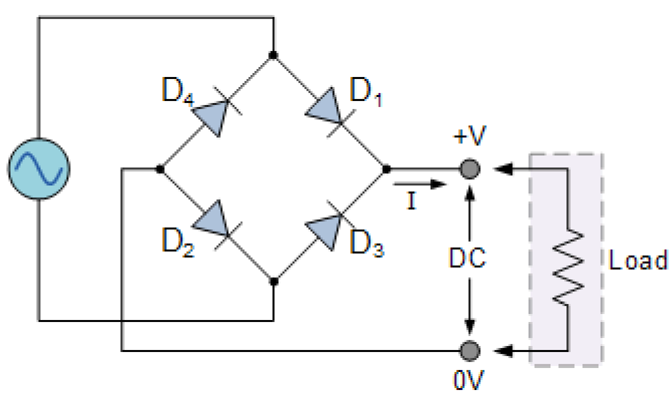


Figure 2.8: Full-Wave Bridge Rectifier [9]

The four diodes labelled D1 to D4 are arranged in “series pairs” with only two diodes conducting current during each half cycle. For this project the AC supply in the above circuit is piezoelectric sensor. There are two stages to the signal process from AC signal to DC signal. For stage one is when the positive half cycle of the supply, diodes D1 and D2 conduct in series while diodes D3 and D4 are reverse biased and the current flows through the load as shown below.

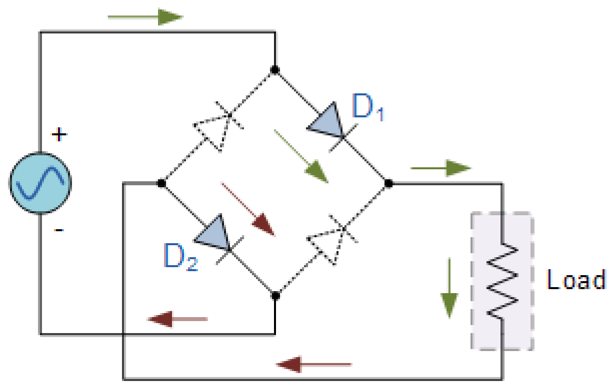


Figure 2.9: Positive Half Cycle of Rectifier

During the negative half cycle of the supply, diodes D3 and D4 conduct in series, but diodes D1 and D2 switch “OFF” as they are now reverse biased. The current flowing through the load is the same direction as before.

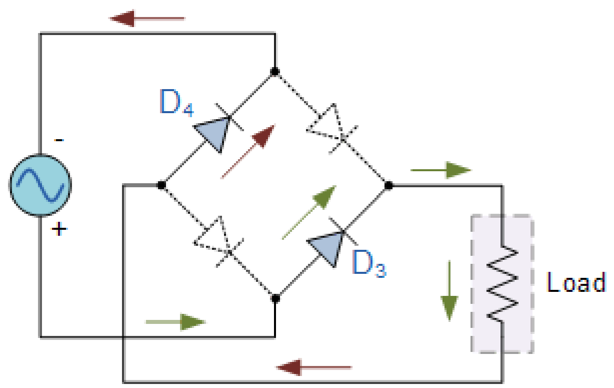


Figure 2.10: Negative Half Cycle of Rectifier

Right now, the output or the waveform will be on positive side only, but the signal will not be smooth because capacitor is not present in the circuit. The capacitor is called as smoothing capacitor. The smoothing capacitor converts the full-wave rippled output of the rectifier into a smooth DC output voltage. Generally, for DC power supply circuits the smoothing capacitor is an Aluminium Electrolytic type that has a capacitance value of 100uF or more with repeated DC voltage pulses from the rectifier charging up the capacitor to peak voltage.

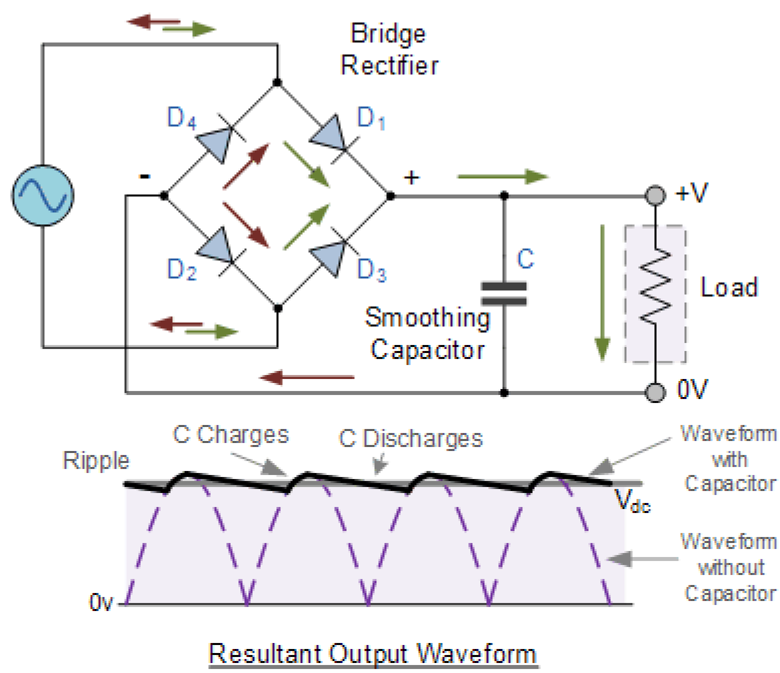


Figure 2.11: Full-Wave Bridge Rectifier with Smoothing Capacitor

However, there are two important parameters to consider when choosing a suitable smoothing capacitor and these are its Working Voltage, which must be higher than the no-load output value of the rectifier and its Capacitance Value, which determines the amount of ripple that will appear superimposed on top of the DC voltage. Too low a capacitance value and the capacitor has little effect on the output waveform. But if the smoothing capacitor is sufficiently large enough (parallel capacitors can be used) and the load current is not too large, the output voltage will be almost as smooth as pure DC.

2.6 Boost Converter (DC-DC Converter)

The power amplitude and the availability of energy harvested from the environment is usually unstable and is depending on the environment conditions. Then some power stage converter is essential to boost up this energy to certain acceptable level to run the device [14]. Various works have utilized different power stage circuit. Some works concentrate only to use one type of converter [15], [16] while some combined individual converter into several converters in either series or parallel architecture [17], [18], [19].

A DC to DC converter is required in order to adapt the low voltage generated by the piezoelectric sensor. There are two kind of DC to DC converters depending on the input and output voltage. For step-up converter or boost converter the output voltage will be higher than the input voltage. For step-down converter or buck converter, the output voltage is lower than the input voltage. So, for this project boost converter will be use. This because the start-up voltage is low and its need to be amplifies for harvesting.

A normal DC-DC boost circuit configuration consists of inductor, diode, load capacitor and switch circuit. The boost converter is a high efficiency step-up DC/DC switching converter. The converter uses a transistor switch, typically a MOSFET, to pulse width modulate the voltage into an inductor. Rectangular pulses of voltage into an inductor result in a triangular current waveform. The boost circuit shown in figure below consist of MEMS switch for switching purposes [20].

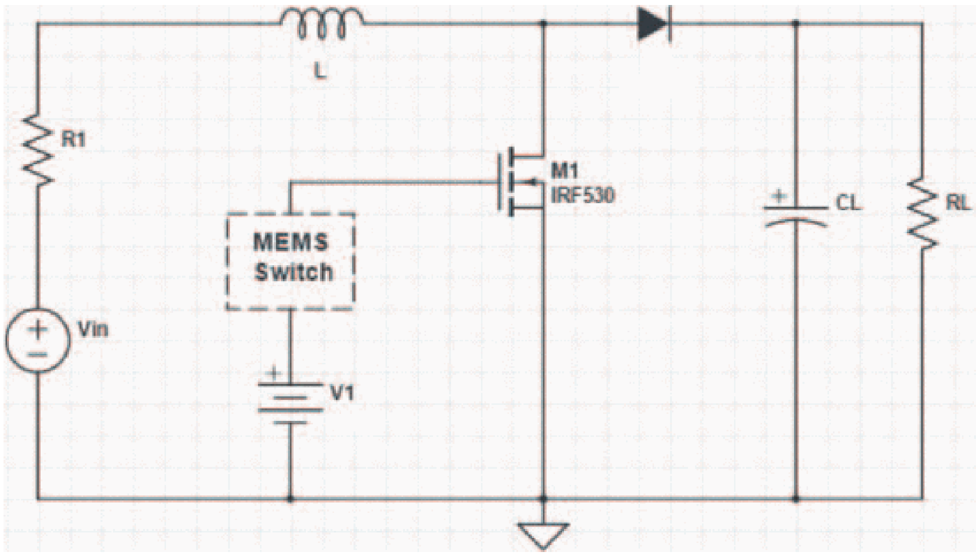


Figure 2.12: Normal DC-DC Boost Converter [16]

The equation of the output of the boost converter is,

$$V_{out} = \frac{V_{in}}{1 - D}$$

So, it is clear that the output voltage is related directly to the duty cycle of the pulses.

2.7 Supercapacitor

Supercapacitor are one of the potential type of energy storage (ESE) [21]. Supercapacitors, or electric double-layer capacitors, have lower energy density than batteries by an order of magnitude but much higher power density, which enables their use in applications that require short-term high power draw, such as electric vehicles and medical equipment [22], [23]. Despite the lower energy density, their very long life cycles make them suitable for use as ESE for energy harvesting system. Such a system usually consists of the following four components: the energy transducers (e.g., solar, wind, vibration etc.), energy-harvesting circuitry, energy storage subsystem, and target load. Figure 2.13 shows the energy harvesting system as mentioned before.

Although supercapacitors are an excellent form of ESE for sustainable operation of the harvesters, they are far from being drop-in replacements for batteries. This is due to their very different characteristics. Unlike batteries, the stored energy of a capacitor is proportional to V^2, which means two voltage conversions are usually required. First of it is one from the energy transducer for charging the supercapacitor, and another is from the supercapacitor for driving the load. For battery charging, chargers based on buck/boost regulators are commonly used for converting the input voltage to the target voltage. For supercapacitor charging, charge pumps have been shown to be more efficient by raising the voltage without having to target a specific output voltage. In either case, such converters may be 80–90% efficient [21].

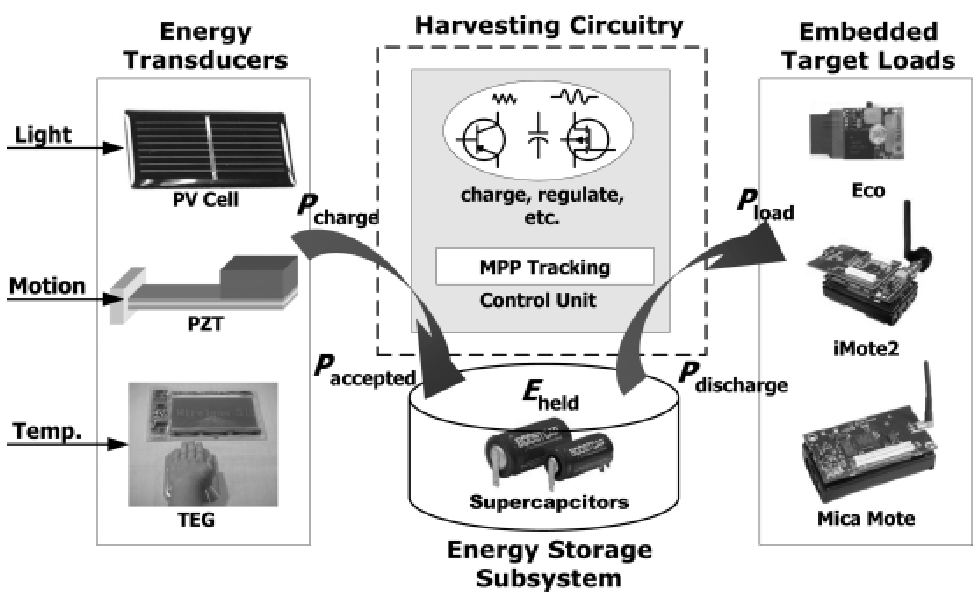


Figure 2.13: Energy Harvesting System [17]

2.8 Chapter Summary

This chapter discussed about all the theory of the project and the component used. The energy harvester has four sub component starting with the piezoelectric and its effect, rectifier, boost converter and lastly supercapacitor.

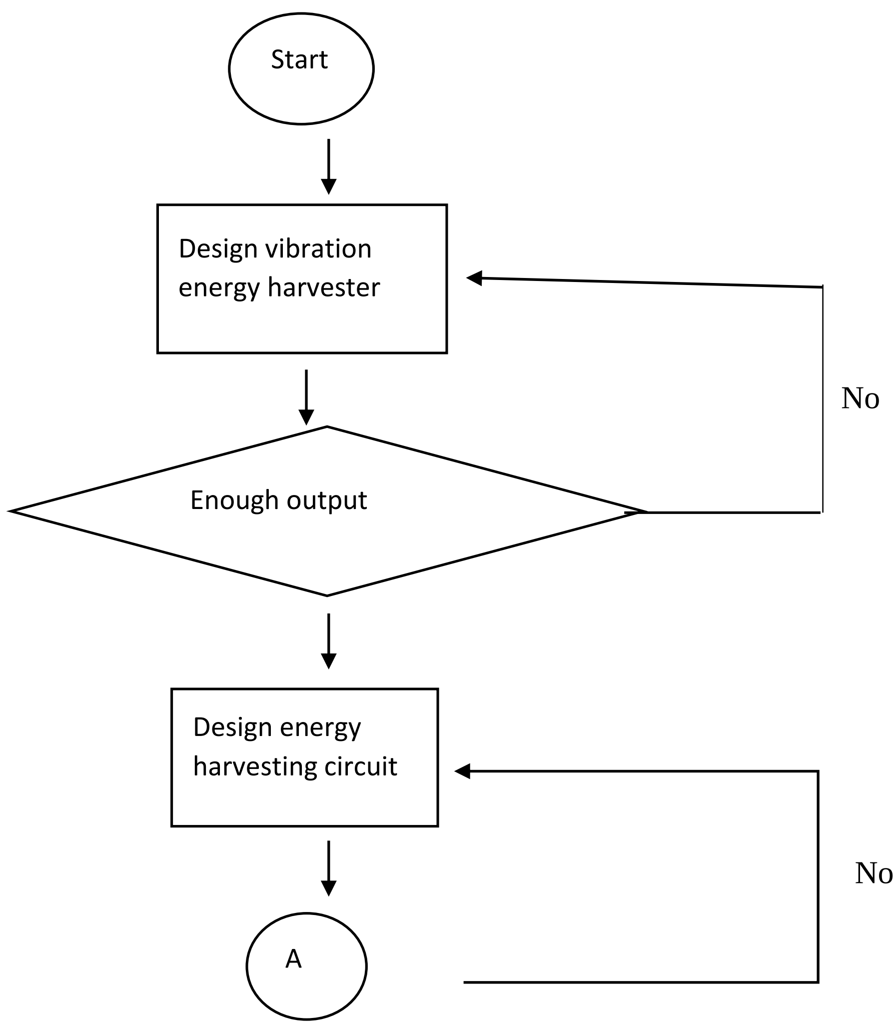
CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter explain about the methods used to ensure the success of this project which is piezoelectric based vibration energy harvester. Not just that, this chapter also explain about the flow of the project from the beginning till end.

3.2 Project Implementation Flow



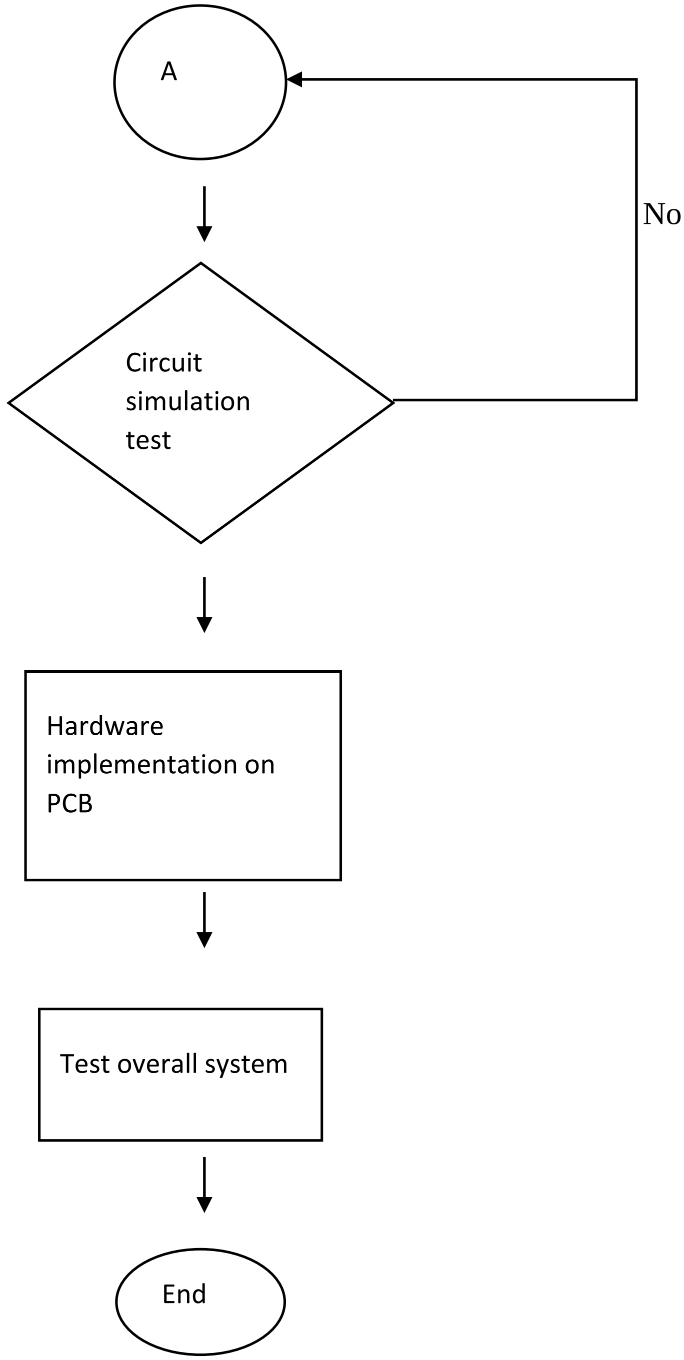


Figure 3.1: Overall Project Flowchart

3.3 Equipment and Materials

First of all, the components and equipment used for the project need to be list down before the experiment is conducted. Table 3.1 shows the components that are used throughout this project.

Table 3.1: Components and Equipment

Component / Equipment	Quantity
Piezoelectric sensor	4
Rectifier module W04M	1
Capacitor 1000uF	1
Capacitor 1.5F	1
Germanium Diode 1N34A	1
Boost Converter MT3608 module	1
CY8C29466 – 24PXI	1
LED	1
Switch	1
Shoe	1
Personal Computer	1