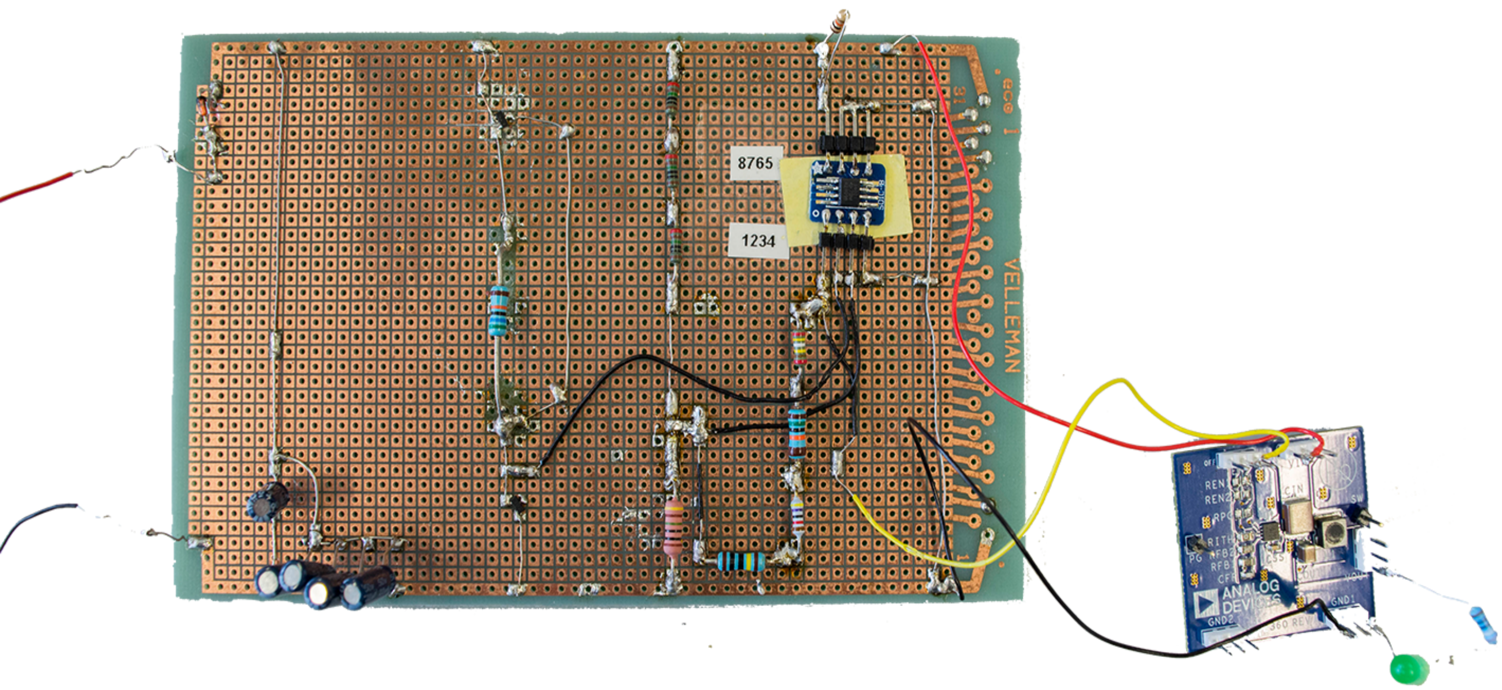
Master of Science Thesis

Energy Harvesting From A Piezoelectric Source To Power A Wireless System

Senthil Kumar Thiruvelselvam



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Energy Harvesting From A Piezoelectric Source To Power A Wireless System

MASTER OF SCIENCE THESIS

For obtaining the degree of Master of Science in Embedded Systems at Delft University of Technology

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Abstract

Batteries are vital sources in many wireless embedded systems applications like the Tire Pressure Monitoring System (TPMS) in the automobile industry. Also, the growth of electric cars will result in an increasing demand for batteries. Although batteries do not directly pollute the environment during their active life, the production phase and decomposition phase will contribute to pollution. The limited lifetime of batteries also emphasizes the need for a change to new technologies. Replacing batteries becomes difficult in applications on desolated places. Energy harvesting can be an attractive alternative solution. Techniques like electrostatic, electromagnetic and piezoelectric energy harvesting can convert the energy in the ambiance to an useful electrical energy. Piezoelectric energy harvesting can be useful as they have been proven vital in converting vibration energy to the required form. This research focuses on powering wireless systems like a TPMS in a car by piezoelectric energy harvesting. It provides the requirements and decisions involved in designing a circuit capable of transferring input energy to output in an efficient manner. The circuit rectifies the output of a piezoelectric material and provides an output of 3.3 V. Result showed that the circuit was able to power an LED for 5.8 s. By adjusting the circuit according to the power requirements, the circuit can be the source to low power wireless embedded systems.

Dedicated to:

My Mom and Dad for supporting throughout my life

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Acknowledgement

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List of Acronyms

CO_2 Carbon dioxide

MJ Mega Joule

LCA Life Cycle Assessment

TPMS Tire Pressure Monitoring System

TREAD Transportation Recall Enhancement, Accountability, and Documentation

NHTSA National Highway Transport Safety Authority

ABS Anti Lock Braking System

CMOS Complementary Metal Oxide Semiconductor

SMPS Switch Mode Power Supplies

AC Alternating Current

DC Direct Current

PWM Pulse Width Modulation

RF Radio Frequency

UVLO Undervoltage-Lockout

U_{TH} Upper Threshold

L_{TH} Lower Threshold

Op Amp Operational Amplifier

JFET Junction Field Effect Transistor

PZT Lead Zirconium Titanate

Chapter 1

Introduction

Technology is an ever growing phenomenon which requires regulations to limit their impact on the environment. This growth is accompanied by the exploitation of natural resources to power the modern day devices. The fossil fuel based sources like petroleum, diesel etc. which are widely used, are the major contributors of Carbon dioxide (CO_2) emissions, which deteriorates the natural environment. This prompted several industries to move towards environment friendly resources.

The automobile industry which is considered to be one of the major contributors of CO_2 emissions has recently developed cars that can be powered by rechargeable batteries. These automobiles are equipped with numerous sensor devices that are mostly powered by batteries based on lithium ion [2], which is a scarce natural resource. Life Cycle Assessment (LCA) is a technique used to study the impact of a product from the beginning of its production till it is decomposed. Figure 1.1 represents the impact of different types of batteries with a capacity per Mega Joule (MJ), during its production phase. This shows

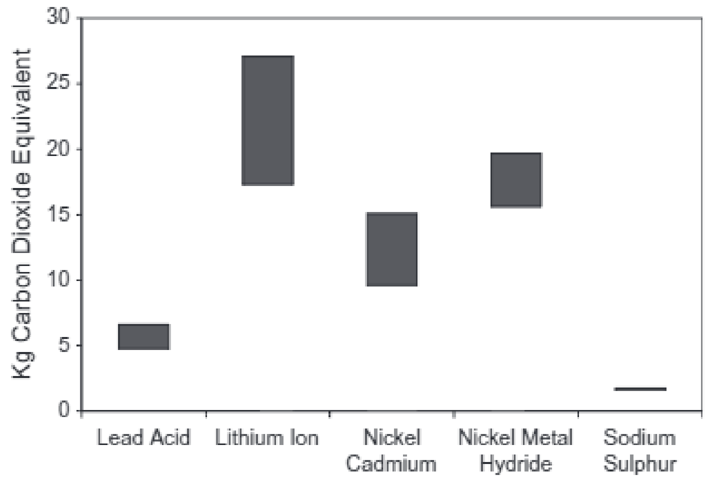


Figure 1.1: CO_2 equivalent per MJ capacity of different types of battery [1]

that moving towards a seemingly less harmful (in terms of CO_2 emission) source like batteries can also have a detrimental impact on the planet. Some of the drawbacks of using a battery are:

- lifetime of a battery which is about 7 to 10 years
- Self discharge of the battery - leakage of charge when no electrodes are connected
- Most batteries are primary cells (i.e they are for one time use) which need to be replaced when they are depleted
- Chemical pollution during recycling

As a consequence, elaborate research is being performed to mitigate the impact of technology on the environment. One such field of research and the main focus of this thesis is Energy harvesting. This is the process of deriving energy from renewable (naturally replenishable) resources. Energy derived from specific renewable sources can be used to power various devices and have been proven to be less harmful to the natural environment. For example, the carbon emission due to solar energy is zero, while that of a natural gas turbine is around 100-230 gC/kWh [3]. This strengthens our motive to use renewable energy sources. One key concern, however, is the size and cost of the energy harvesting device. The Energy Harvesting device must be small and match the low power requirements of the sensor device. It must be unaffected by weather conditions. In this regard, mechanical vibration becomes an attractive option as an energy source for small size electronic devices [4] . Therefore, vibration energy could potentially be used to power several small devices in an automobile which are otherwise powered using batteries.

Several techniques like electrostatic, electromagnetic etc. can be used to harvest energy from renewable sources, but as the size of the device decreases, the amount of energy that can be harvested becomes minimal. In such small scales, vibration energy can be vital. Piezoelectricity is popular for detecting these vibrations and hence is a viable energy scavenging source [5].

This work focuses on exploiting vibration energy using the piezoelectric effect which enables converting vibration force to electricity and subsequently using it to power a tire pressure monitoring system in an automobile.

1.1 Context

This thesis was performed as a joint collaboration with the Novel Aerospace Materials (NovAM) and the Electronic Instrumentation group at Delft University of Technology.

The NovAM group was established in 2003 at TU Delft in the Aerospace faculty. The research group develop space materials and perform extensive research in self- healing materials, metals smart materials and composites and polymers.

The electronic instrumentation lab is part of the micro-electronics group. Their mission is to realize smart sensor systems for data acquisition from different devices.

Since both groups work towards designing a smart system, it was decided to work in collaboration.

1.2 Main Focus

For several years, car tires have been a non active component. Extensive efforts were taken to make the tires an intelligent part of the vehicle to obtain data from the tires which can improve driver safety as well as lead to efficient travel. One such application is the Tire Pressure Monitoring System (TPMS) . These sensors are present in the valve of an automobile tire. They measure the pressure in a tire and communicate it to the driver. This helps the driver to maintain the right pressure in the tire. This system was able to reduce fuel consumption and avoid accidents due to punctures. The TPMS system is powered by a 3V lithium ion battery. The lifetime of these batteries is between 7 to 10 years. As they are attached to the valve stem of the tire, it is difficult to replace the batteries. Manufactures do suggest to replace the complete sensor rather than the batteries.

Piezoelectricity has qualities that suit perfectly to be a power source in an automobile. There is no fixed life time like other sources. It can be combined with any electronic device provided the power requirements match.

The main research question is:

Is it possible to power a wireless system using piezoelectric energy harvesting devices while ensuring optimal power transfer?

The objective is divided into the following questions:

- What are the ways to design an intelligent circuit to handle the energy transfer from source to load?
- What is the amount of energy that can be generated by the circuit with a piezoelectric element as a source?
- What is the efficiency of the circuit to transfer energy from source to load?

1.3 Chapter Overview

In this introductory chapter, the need for replacing the batteries in automobile industries is highlighted. Additionally, a brief overview of energy harvesting is included. The chapter is concluded by introducing the main focus of this work and the research question.

The Second chapter starts with a short history and working of TPMS and piezoelectricity. An overview of existing energy harvesting modules, their working and the components involved in energy harvesting is also provided. Moreover, the existing research in replacing the batteries is mentioned.

In the 3rd chapter, the limitations of the existing modules and components are stated and the decisions involved during the design of the energy harvesting circuit and the setup of the circuit on a dotted circuit board is presented.

The Fourth chapter highlights the results obtained during the experiment with a circuit by using a power supply and a piezoelectric element. It also provides the techniques employed in order for the power supply to mimic a piezoelectric element. The efficiency of the energy transfer is stated and compared with one of the existing modules.

The Fifth chapter concludes the research by revisiting the research question and the result. In the last chapter few suggestions for future research on this topic is mentioned.

Chapter 2

Literature Study

2.1 TPMS - Tyre Pressure Monitoring System

Automobile industry experiences major technological advancement every year. One of the underrated, less focused yet crucial component of a car are the tires. In order to obtain the best performance of a car, the tires should be properly inflated as suggested by the manufacturer. An under inflated tire can cause problems like increased fuel consumption, decreased longevity of the tire, blow out etc. Some of the advantages of having a well inflated tire are:

- the prevention of accidents due to sudden puncture
- the increase of fuel economy
- the increase of tire life
- the reduction of braking distance
- the better handling of the vehicle

These factors proved the necessity to make the tires smart. A smart tire is one which can communicate with the driver about its pressure status, temperature and conditions of the road. The Tire Pressure Monitoring System (TPMS) is one such device that helps in warning the driver about under inflation and over inflation. The first TPMS was installed in the 1980s. It was made mandatory in the United States of America by the Transportation Recall Enhancement, Accountability, and Documentation (TREAD) act and National Highway Transport Safety Authority (NHTSA) in 2006 [6]. The European Union made it mandatory for all passenger cars to be equipped with a TPMS from 2012 [7]. It has now become one of the important safety systems of a car. Many industries developed different versions of TPMS with different capabilities. Depending upon the working of the TPMS, there are two types - Indirect and the Direct systems [8].

2.1.1 Indirect and Direct TPMS

As the name suggests, the indirect TPMS does not involve a direct measurement of pressure i.e. it does not have dedicated sensors. It uses data from other safety systems in the car, for detecting an under inflated tire. For instance, the Anti Lock Braking System (ABS) has data of the number of revolutions of each tire. Indirect TPMS compares the data of each tire with one another or with a reference value as specified by the manufacturer. If there is a discrepancy between the values, it is detected as an abnormality - under or over inflation. This method is cheaper and requires less maintenance when compared to the direct TPMS. However, the indirect TPMS is inaccurate and unreliable [9].

The Direct TPMS has a Complementary Metal Oxide Semiconductor (CMOS) based pressure sensor, a transmitting antenna, a micro controller, and a battery. This system is more reliable and has been employed almost in all vehicle in recent days.

Figure 2.1 shows the block diagram of a TPMS from Infineon.The sensors with the transmitters are attached to the valve of each tire as shown in Figure 2.2b. These sensors are connected to a central receiver via Radio Frequency (RF) as shown in Figure 2.2a.

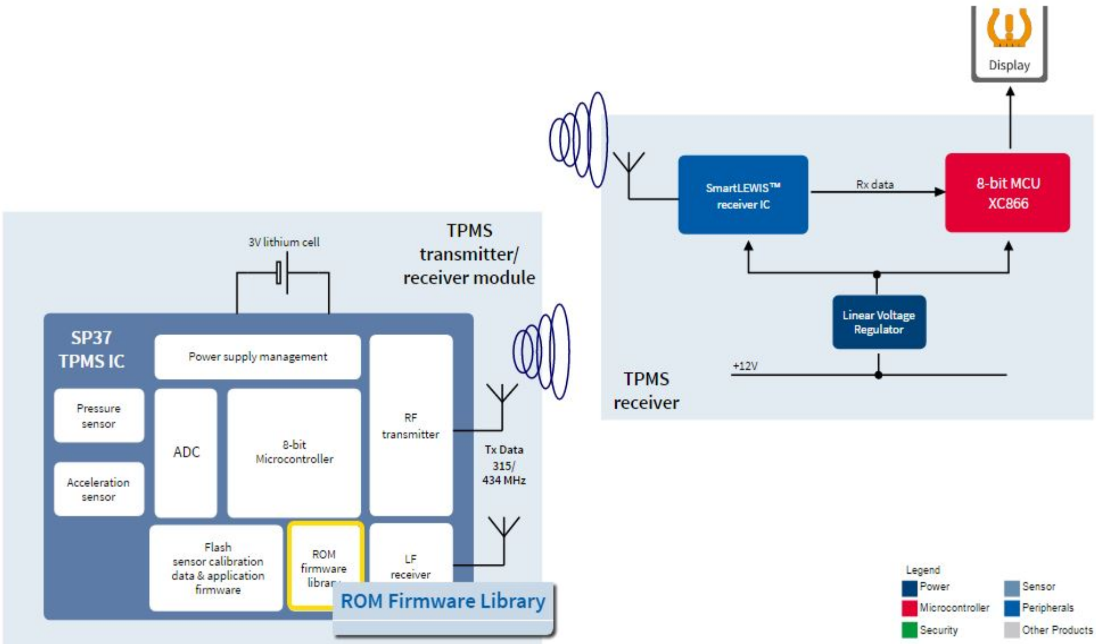


Figure 2.1: TPMS block diagram

Each sensor has a unique ID to distinguish from the sensors of other tires of the same car and nearby cars. The sensors measure the pressure and transmit the data to the receiver. The transmission rate is predetermined by the manufacturer in such a way that the power usage is minimal. Most of the products send the pressure data once in 60 seconds while the car is in motion. This rate increases whenever an abnormality is sensed. When the

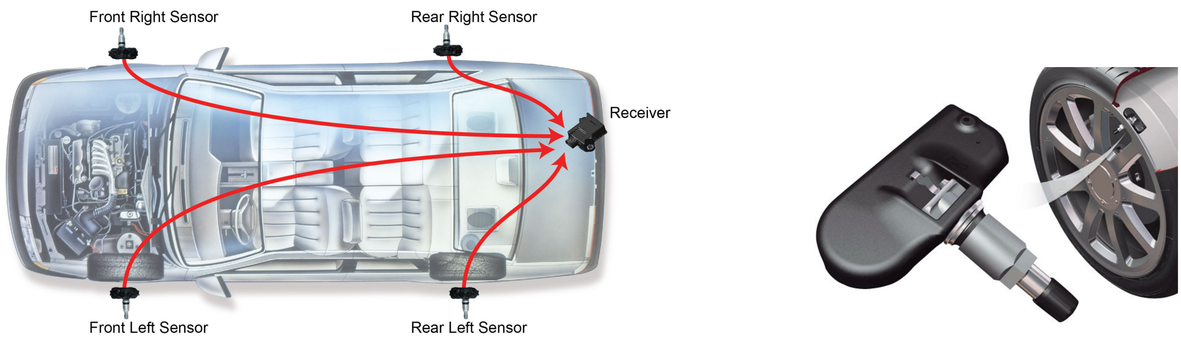
Operating Temperature	-30°C to 120°C
Operating Frequency	433.92MHz
Pressure Monitoring range	0 to 76psi
Battery	3.6V
Sensor Weight	35g

Table 2.1: TPMS sensor Specifications [13]

car is stationary, the sensor transmits in the normal rate for certain period of time say 20 minutes. If the car is at standstill for more than 20 minutes, the modules go into sleep mode. The modules now transmit once for an hour.

This ensures that minimal power is used during standstill. These transmission rates depend entirely on the manufacturer. Most TPMS have an accelerometer. This helps to sense the motion of the vehicle and resume normal transmission. The received data is displayed on the dashboard.

The Direct TPMS warns the driver when the pressure of any or all the tires drops 10psi or 20% below the suggested pressure for the vehicle. The Ideal pressure of a tire is 32 psi [10]. A person can recognize an under inflation only when the pressure is at least below 50% of the sufficient value. This reinstates the importance of TPMS. The specifications of a TPMS is shown in the Table 2.1. A TPMS is powered by a lithium ion button cell. The lifetime of the battery is about 5-7 years. The battery is present inside the module which is placed in the interior of the car; thus it is difficult to replace. It is also advisable to replace all the sensors so that their life time will be similar and it can be synced properly to the receiver. As the module is attached to the valve of the tires, it is absolutely necessary to be air tight i.e no leakage due to the attached sensor. Depending upon the attachment of the module, it is classified into Internal and External TPMS.



(a) TPMS in a Car [11]

(b) TPMS sensor attached to a valve [12]

Figure 2.2: Internal TPMS

2.1.2 Internal and External TPMS

The internal TPMS was the first model of the two to be introduced to the market. Figures 2.2a and 2.2b shows the location of the internal TPMS and how the sensor is attached to the tire. These sensors, as stated earlier, are present inside the tires and attached to the valves of the tires. This ensures the safety of the device from external damage. Consequently, it is difficult to reach the sensors for maintenance or replacement.

Recently many companies have introduced the external TPMS as shown in Figure 2.3. The sensors in Figure 2.3a are attached externally to the valves as shown in Figure 2.3b. Even though this setup eradicates the reachability issue of its predecessor, it makes it prone to external damage due to environmental and human factors. Both types work in a similar fashion. The only difference being the location of the sensor.

As mentioned earlier, the TPMS is powered by a lithium battery with a lifetime of 5-7 years. There is also manual labor in replacing the battery. Hence, there is a need to power these modules by methods that require less maintenance. For these reasons, research was done to power the sensors using energy harvesting techniques.

(a) TPMS sensor and receiver module with display [14]

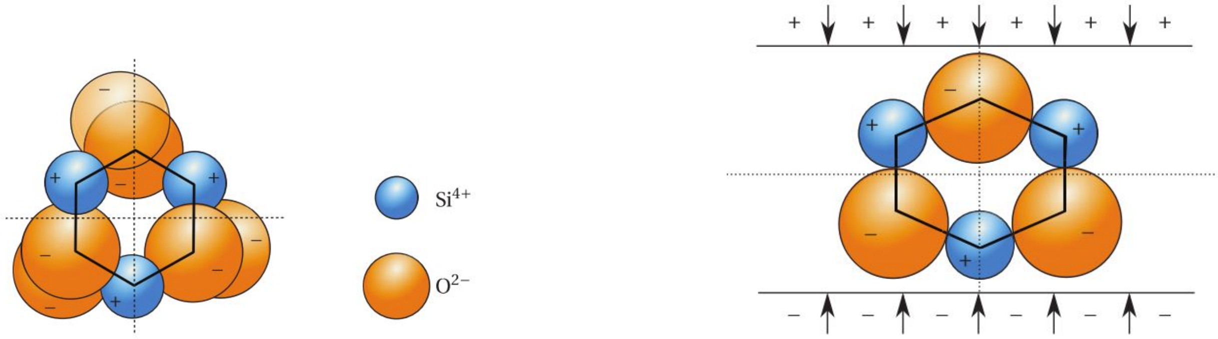
(b) A single sensor attached to the valve externally [15]

Figure 2.3: External TPMS

2.2 Piezoelectricity

Piezoelectricity, discovered in 1880 by Pierre and Jacques in materials such as tourmaline and quartz, has remained a fascinating research topic. There are two types of Piezoelectricity - Direct and Indirect. Direct piezoelectricity is the conversion of mechanical energy into electrical energy and indirect is its converse.

Piezoelectricity exists in materials with dielectric properties i.e. materials that are non conducting. The material should be non centro-symmetric as shown in the Figure 2.4a. When a mechanical force is applied, the ions shift accordingly as shown in Figure 2.4b and dipoles are formed. Dipoles are positive and negative poles separated by a distance. The accumulations of these dipoles along a particular direction results in the accumulation of charges at the two ends of the material. These charges can then be made available to the external world by connecting electrodes to these ends. This is the direct piezoelectric effect. The Figure 2.5 shows the compression and expansion of a piezoelectric material. The compression results in a positive charge and the expansion results in a negative charge. Piezoelectricity does not occur naturally in all types of materials. It occurs only in ma-



(a) Silicon and Oxygen ions in Quatrz **(b)** Displacement of ions

Figure 2.4: Direct Piezoelectric Effect [16]

terials with a particular crystal arrangement as stated previously and with spontaneous polarization. Polarization is the orientation of the dipoles along a particular direction. Thus, the piezoelectric materials are categorized depending upon the arrangement and the manufacturing of these materials, as seen in the next section.

2.2.1 Piezoelectric Materials

The piezoelectric materials can be classified as single crystal, piezoceramics, thin film piezoelectrics, composites, and polymers. The spontaneously polarized, naturally occurring materials like quartz and tourmaline that were stated earlier come under single crystals. Piezoceramics are made by heating the powders of desired materials at high temperature in a process called sintering. They are the polycrystalline i.e. a combination of many different orientations of crystals and domains. They are not piezoelectric at a macroscopic scale. This is induced by polarization during a process called poling as shown in Figure 2.6. When observing a piezoceramic material under an electron microscope, many cell like structures can be observed. These single unit cell like structures are called domains. Each domain has a dipole oriented in different direction. During poling, a high electric field is applied and the dipoles orient along the direction of the applied field. These dipoles remain

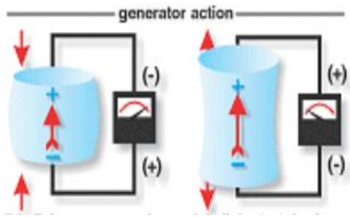


Figure 2.5: Direct Piezoelectric Effect Compression and Expansion of a material [17]

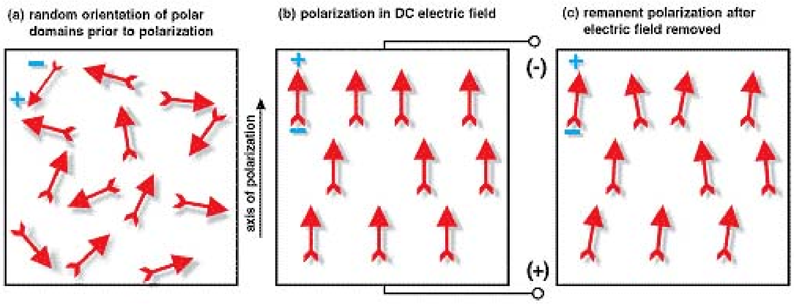


Figure 2.6: Polarization during Poling [18]

in this direction even after the removal of the electric field as shown in Figure 2.6. Now, these materials display piezoelectric properties. The most used piezoceramic is based on Lead Zirconium Titanate (PZT).

The ceramic materials listed above are brittle in nature. In an environment that involves a lot of mechanical stress like in a car, a thinner and flexible material like the thin film piezoelectrics are required. These are thin layers of piezoelectric materials deposited on a substrate. They are also used in inkjet printers and micro scale energy harvesting. Another alternative would be the use of flexible composites consisting of piezoelectric particles inside a polymer matrix on which extensive research is done within the Novam group.

The amount of voltage and current output from these different types of materials depend upon some parameters. These parameters are explained in the next section.

2.2.2 Piezoelectric Parameters

The direct and indirect piezoelectric effect is often represented by a pair of linear constitutive equations as follows:

$$S = s^E T + dE \tag{2.1}$$

$$D = dT + \epsilon^T E \tag{2.2}$$

where,

S : the strain i.e. relative deformation

s^E : compliance, inverse of elasticity, under constant electric field

T : applied stress

d : piezoelectric charge constant

E : applied electric field

D : dielectric displacement

ϵ^T : dielectric constant under constant stress

In the above mentioned parameters, Piezoelectric charge constant is an important parameter.

Piezoelectric Charge Constant

The piezoelectric charge constant (d) is the amount of electric displacement (D) that is induced in the material for the applied mechanical stress (T), under zero electric field (direct piezoelectric effect).

$$D = d \times T \tag{2.3}$$

The piezoelectric charge constant is denoted by two subscripts. The first subscript denotes the direction of the electric displacement or polarization. The second subscript denotes the direction of the applied mechanical stress. The numbers 1,2 and 3 in the subscripts denote x, y and z axis. The z axis is chosen as the poling axis for uniformity. For example, d_{31} denotes that the electric displacement is induced along axis 3 when stress is applied along axis 1. d_{33} is the most widely used configuration. Piezoelectric ceramics are used widely because they have high d_{33} values.

Piezoelectric voltage constant

The piezoelectric voltage constant (g) is the amount of electric field (E) generated per unit of mechanical stress applied (T). Like the charge constant (d), voltage constant is also represented with subscripts. For example, g_{31} denotes the electric field is induced along axis 3 when a stress is applied along axis 1.

$$E = -g \times T \tag{2.4}$$

The piezoelectric charge constant and the voltage constant are related to each other as represented in the below equation:

$$g = \frac{d}{\epsilon} = \frac{d}{\epsilon_r \epsilon_o} \tag{2.5}$$

where, ϵ_0 is the permittivity of free space and ϵ_r is the relative permittivity. Both these constants are temperature dependent. The piezoelectric charge constant increases with increase in temperature while the piezoelectric voltage constant decreases with the increase in temperature.

Coupling coefficient

Coupling coefficient is another important parameter of a piezoelectric material. It gives the relation between the amount of mechanical/electrical energy that is converted into electrical/mechanical energy.

$$k^2 = \frac{\text{Mechanical Energy Converted into Electrical Energy}}{\text{Input Mechanical Energy}} \tag{2.6}$$

The above equation denotes the coupling coefficient for the direct piezoelectric effect. The product of the piezoelectric charge constant(d) and the piezoelectric voltage constant (g) plays a vital role in the energy harvesting application. It denotes the energy density of a piezoelectric material. Energy density is the measure of the amount of energy stored in material per unit volume. A higher value of the product of these two constant denotes that the material has higher energy density [19] .

2.2.3 Piezoelectric materials for energy harvesters

Due to the fact that the piezoelectric materials can generate a electric output when subjected to mechanical stress, it became one of the important branch in energy harvesting applications. Under compression, the piezoelectric material generates a charge, Q. [20]. This charge is stored in the piezoelectric capacitor resulting in a voltage equal to V = Q/C. This voltage is in the poling direction. If the stress is released the material expands and generates a charge in the opposite direction. As a consequence, the piezoelectric material generates an AC output. This AC output is proportional to the applied stress on the material.

The harvested energy is used mostly by an embedded system. These devices require Direct Current (DC) to operate. Thus the Alternating Current (AC) generated from the piezoelectric materials needs to be converted to DC.

2.3 Existing EH modules

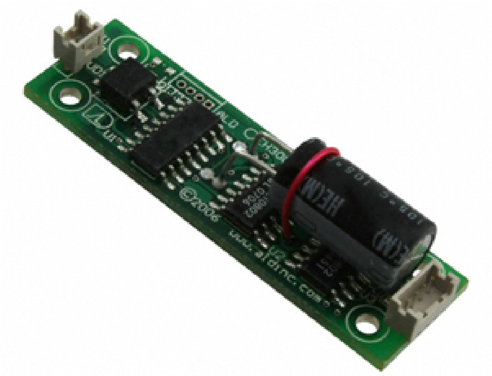
To fulfil the requirement of converting the harvested AC to a DC, there are many commercial modules available on the market. These are ready to use type modules. The piezoelectric material is connected on the input side and the load is connected to the output. The energy produced in the piezoelectric material by constant tapping is transfered to the load by the module. The working of some of these popular modules is provided in this section.

2.3.1 EH300/301

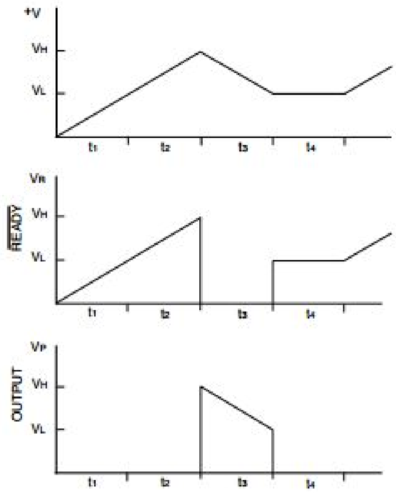
Advanced Linear Devices inc. manufactures some of the popular energy harvesting modules - EH300 and EH301. These modules operate with a variety of sources including vibration, thermal, mechanical, chemical, solar, biological, and human body sources [21]. The EH300 module, shown in Figure 2.7a, operate on very minimum power i.e. most of the energy that is harvested from the source is transfered to the attached load. The module's power management circuitry aids in efficient power transfer. The energy at the input side of the module is converted to a power conventional 3.3V and 5 V.

The input and output waveform of the module is shown in Figure 2.7b. The topmost waveform denotes the voltage stored, the next one denotes the enable or the ready pin and the last one denotes the output. As it can be seen, the input +V rises gradually from zero to V_H i.e. higher threshold. This is the charging phase of the module. Once it reaches V_H, the module moves to the supply phase i.e. the voltage is supplied to the load. The load uses the stored energy, which results in the decrease of the voltage from V_H to V_L. Now, the module electrically disconnects the load from the storage element. The module is now in storage mode. The module will supply output again only when +V reaches the V_H threshold. This switching ensures that the harvested power is transfered to the load without hindering the charging process.

Figure 2.8 shows the pins of the module and the general connection of the module in an energy harvesting application. This module is widely used in wireless sensor networks, remote circuitries and in other applications that requires long lifetime power sources.

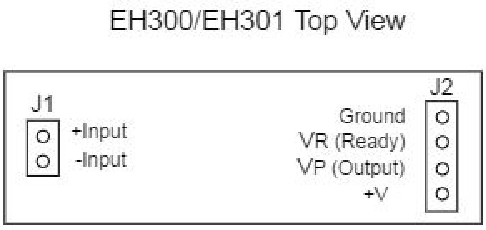


(a) EH300 Energy Harvesting module

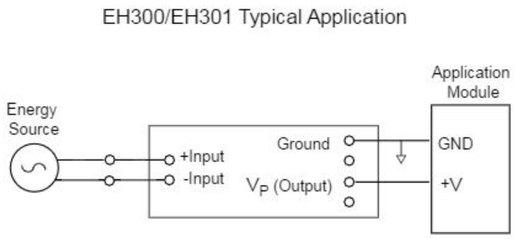


(b) EH300 Waveforms

Figure 2.7: EH300 Module [22]



(a) Top view



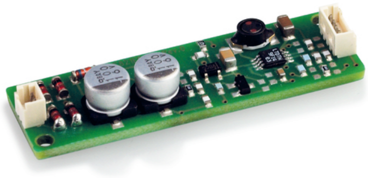
(b) General application

Figure 2.8: EH300 Module pin configuration [23]

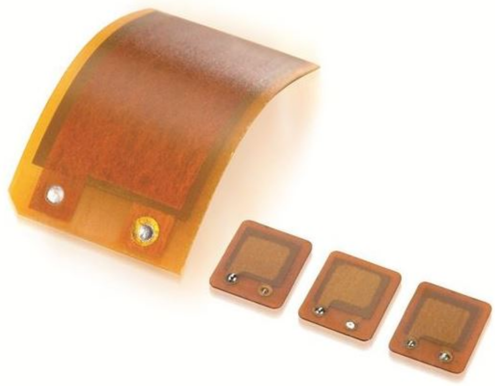
2.3.2 E821 Module for Energy Harvesting

This is an energy harvesting module designed by a German company Physik Instrumente (PI). The E821 evaluation kit is shown in the Figure 2.9. The kit contains the E821 module itself and the P876 Duract transducer. This is a piezoceramic thin film transducer which is bendable and can be used as a source for energy harvesting. Connecting the piezoceramic to the module and exciting it with mechanical force results in the generation of DC voltage proportional to the input energy. The output voltage can be regulated by changing the 0 ohm solder bridge between the pins near the output port.

Like the previous module, it can be used in a wireless sensor network. From Figure 2.10, it can be seen that the working of this module is similar to EH300/301 module. As mentioned earlier, the output voltage is available only when +V is between V_H and V_L.



(a) E821 Module [24]



(b) P876 DurAct Transducer [25]

Figure 2.9: E821 Evaluation kit

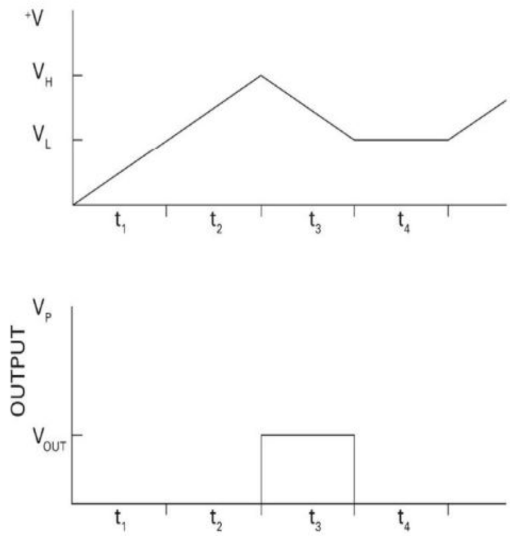
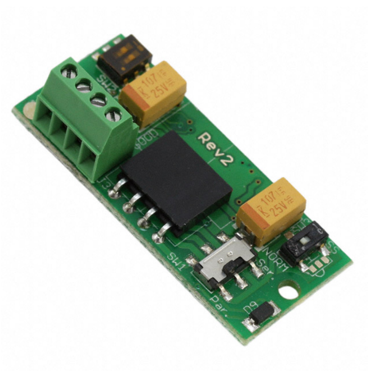


Figure 2.10: E821 output waveform [26]

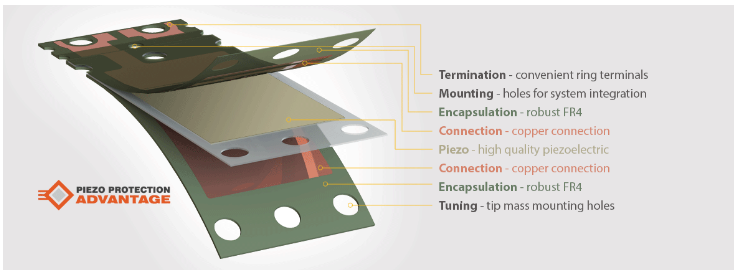
2.3.3 EHE004

The EHE004 module shown in Figure 2.11a is produced by Mide technologies. The module is based on the LTC3588 chip from linear technologies. The working of the chip will be stated further in next section. The module has a rectifier, a charge management circuit, and DC-DC converter [27]. It has a 200μF capacitor and also, the option of adding external capacitors. The module can be configured to provide four different DC voltages - 1.8V, 2.5V, 3.3V and 3.6V. The output can be selected by means of a switch SW2 present on the module. The module operates similar to the other modules by supplying to the load only when the voltage is between the upper and lower thresholds.

The EHE004 energy harvester is compatible with Mide's Volture piezoelectric products like the one shown in Figure 2.11b. These are hermetically sealed(air tight) thin film piezoelectric materials. Two piezoelectric materials are stacked in the form of bimorphs. It can be used in the cantilever or fixed beam configuration. As there are two piezoelectric materials, it can be connected to the module in such a way that the two piezoelectric materials are in series or in parallel. This can be done by adjusting a switch SW1 in the module. The parallel mode is used when higher current is required at a lower voltage and the series mode is used when a higher voltage and lower current is sufficient for the load. The module can also be operated in two different modes - normal and the superseries mode. In the normal mode, the rectifier functions as a full wave rectifier. This ensures maximum power is transfered to the load. When the input energy is minimal, the module can be operated in the super series mode in which the rectifier operates as a half wave rectifier. These functions can be configured by another switch SW3 present on the module.



(a) EHE004 [28]



(b) Volture piezoelectric film [29]

Figure 2.11: Mide Products

2.3.4 DC1459B

This is one of the energy harvesting modules of Linear Technologies. Most of the energy harvesting modules from Linear Technologies use the LTC3588 chip. The chip has a full wave rectifier and buck converters, which will be explained in detail in the upcoming sections. It is capable of producing four different types of voltage outputs - 1.8V, 2.5V, 3.3V, 3.6V.

This is the ideal replacement for a battery in many industrial applications. The chip goes into sleep mode with minimal power usage, while the load is not drawing energy. It can convert piezoelectric and solar energy into usable energy. It has an Undervoltage-Lockout (UVLO), that is used to monitor the voltage in the capacitor. As seen in the previous modules, this helps to connect and disconnect the load from the capacitor between upper and lower thresholds respectively. The lower threshold is kept 200mV above the selected output voltage [30]. This is to ensure that the capacitor is not completely drained. If the capacitor is completely drained, the time to recharge the capacitor will increase.

2.3.5 Summary of Energy Harvesting Modules

Different energy harvesting modules (EH300/301, E821, DC1459B, EHE004) were mentioned in the previous sections. Their working is almost similar but still each offer different features. The consumer can choose the module that is best suited to his needs. Table 2.2 shows the comparison of the devices based on various parameters.

Parameter	**EH300**	**EH301**	**E821**	**EHE004**	**DC1459B**
Operating Temperature	-0°C to 70°C	-0°C to 70°C	-0°C to 50°C	-	-
Maximum input voltage/Range		-	11V	18V	4.3V to 18V
Maximum input current/Range	400mA	400mA	20μA to 40mA	-	-
Status	Active	Inactive	-	Inactive	Active
Maximum output current/Range	1A at 3.5Ω	1A at 5Ω	-	100mA	100mA
Choice of Output Voltage	Fixed 1.8V to 3.6V	Fixed 3.1V to 5.2V	Adjustable 1.8 to 5V	Adjustable 1.8V,2.5V, 3.3V, 3.6V	Adjustable 1.8V,2.5V, 3.3V, 3.6V
Based on	-	-	-	LTC3588	LTC3588
Cost	€61,39	€69,96	-	-	€170,73
Manufactured by	Advanced Linear Devices	Advanced Linear Devices	Physik Instrumente	Mide Technologies	Linear Technologies

Table 2.2: Comparison of Energy Harvesting modules

2.4 Components for Energy Harvesting

From the study of the energy harvesting modules in the previous section, it is understood that they have a standard working methodology. They convert the AC from a piezoelectric material to a load friendly DC. These modules can be represented as in Figure 2.12. Most of the energy harvesting circuits contains the following components:

- A rectifying device - AC-DC converter
- Storage device
- A step down converter

The working of the components stated above are explained further.

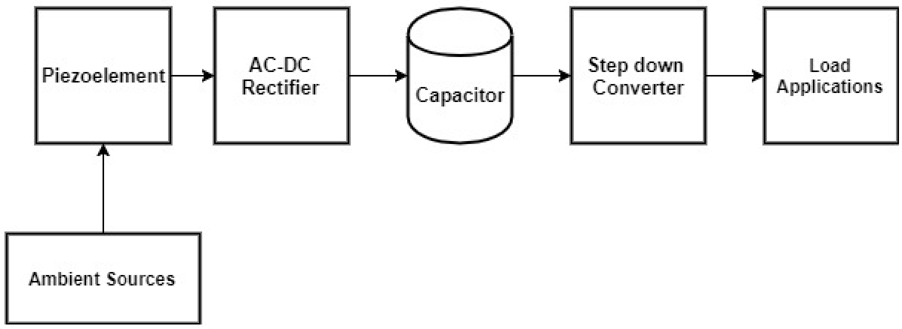


Figure 2.12: Energy Harvesting circuit block diagram

2.4.1 AC-DC rectification

It is now clear that the output from a piezoelectric sensor is an AC and the load needs a DC. Thus, AC is converted to DC by using rectifier circuits. The most commonly used rectifying component is the diode bridge.

Four diodes are arranged in the pattern as shown in Figure 2.13. This pattern or circuit configuration is called the diode bridge or the bridge rectifier. There are two types of bridge rectifiers - half wave and full wave rectifiers. The rectifier under consideration in this report is the full wave rectifier.

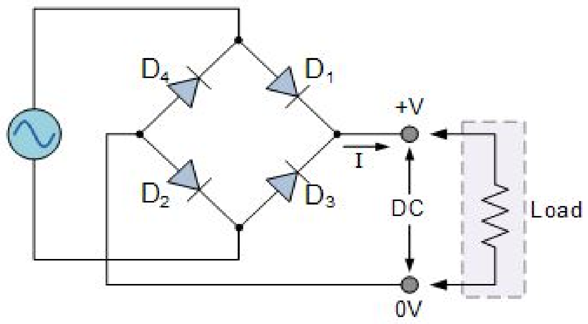
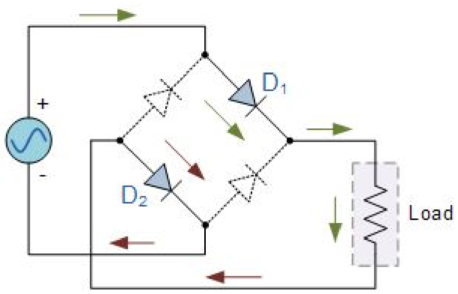
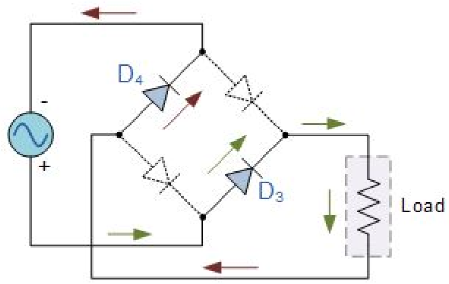


Figure 2.13: Full Wave Rectifier circuit [31]

A full wave rectifier circuit is shown in the image 2.13. It consists of four diodes arranged in such a manner that only two diodes conduct during one half of the cycle. As shown in Figure 2.14a, diodes D1 and D2 conduct during the positive half of the cycle and in Figure 2.14b, didoes D3 and D4 conduct in the negative half of the cycle. This leads to an output at the load as shown in Figure 2.15.



(a) Positive Cycle



(b) Negative Cycle

Figure 2.14: Full wave rectifier conduction [31]

The output shown in the Figure 2.15, has only positive half cycle. This is not a DC signal. We have to smoothen this positive cycle so that we can get a DC signal (a flat signal). Capacitors are used for this purpose.

2.4.2 Capacitors

Capacitors are one of the most commonly used energy storage components. The primary function of a capacitor is to store electric charge. Capacitors are made up of two parallel conducting plates separated by a dielectric, an insulating and charge storage material. For instance, when a voltage is applied between the two plates, the dielectric material is charged. The charges continue to accumulate until the voltage across the capacitor becomes

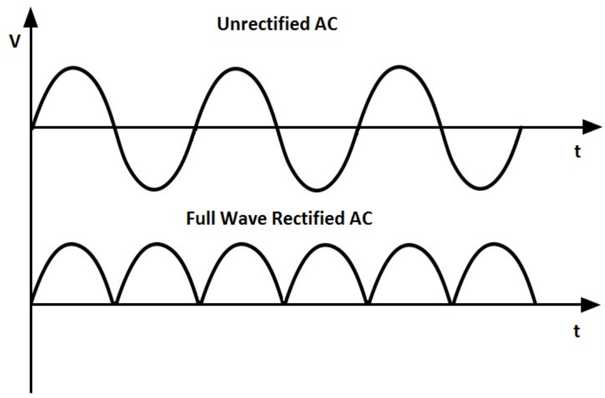


Figure 2.15: AC before and after passing through a full wave rectifier

equal to the applied voltage. This is the charging phase of the capacitor. A capacitor is a passive component i.e. they do not generate energy. When a load is connected to the capacitor, the capacitor becomes discharged and the energy is dissipated by the load.

The amount of charge a capacitor can store depends upon its capacitance. The capacitance of a parallel plate capacitor is given by the following equation:

$$C = \frac{\epsilon_0 \epsilon_r A}{d}$$

where C is the capacitance in Farads, ϵ_0 is the permittivity of air, ϵ_r is the permittivity of the dielectric material, A is the area of the conducting plate and d is the distance separating the two planes. From the equation, it can be seen that the capacitance can be increased by increasing the area of the plates and/or decreasing the distance between the plates. The amount of charge a capacitor can store is given by the equation:

$$Q = C \times V$$

which means that the charge accumulated or stored in a capacitor is equal to the capacitance, C, of the capacitor multiplied by the voltage, V, of the applied power supply . The current in a capacitor is given by

$$i = C \times \frac{d(V(t))}{dt}$$

This indicates that the current in a capacitor depends upon the rate of change of the voltage applied to it. The above equation shows that the current in a capacitor varies with time, when the voltage varies with time.

There are different type of capacitors depending upon the materials used to manufacture them. Some of the commonly used capacitors are listed in the Table 2.3.

Type	Capacitance	Pros	Cons
Ceramic	<100μF	Small in size, less expensive, less leakage	Small capacitance, large size and relatively expensive
Film Capacitors	33pF to 1000μF	Can withstand high temperatures, lower leakage compared to electrolytic type	Large, flammable at overload condition, high ripple current
Electrolytic	1μF - 1mF	small in size, large capacitance and cheap	applying over voltage will damage the device
Super capacitors	Farads	Store very high energy. Releases the energy quickly. High lifespan	Voltage ratings is usually low.

Table 2.3: Types of Capacitors

A capacitor in a AC circuit displays Capacitive Reactance X_C. Capacitive Reactance is the opposition of a capacitor to the current flowing through it. The reactance is given by the following equation:

$$X_C = \frac{1}{2\pi f C}$$

where, f is the frequency in Hertz of the applied voltage and C is the capacitance in farads. So higher the frequency, lesser the reactance and hence more current flows. In an AC circuit, the capacitor is charged and discharged depending upon the frequency of the applied AC supply.Whenever the voltage reaches the maximum (rate of change is zero) the current will be zero and when the voltage is undergoing a maximum negative change, the current will be at its negative maximum as in the Figure 2.16.

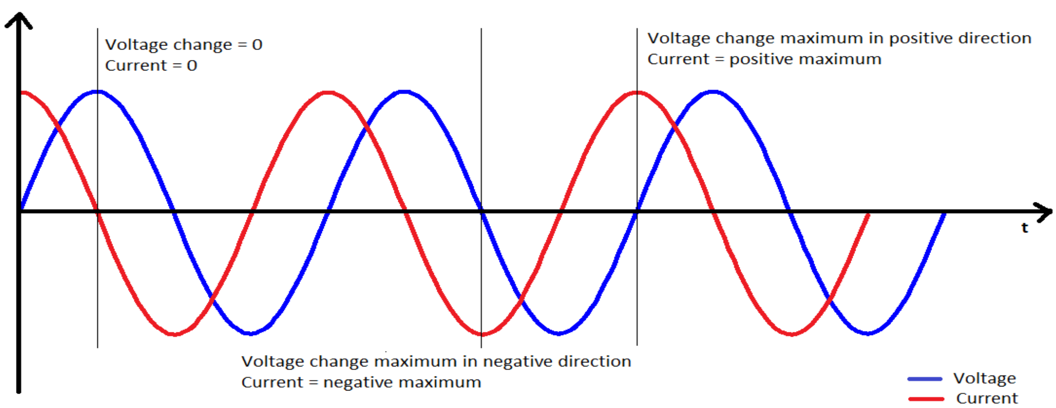


Figure 2.16: Voltage and Current of a Capacitor in AC circuit

Figure 2.17 shows the charging effect of a capacitor. The signal from the half wave rectifier has only positive cycles. These positive cycles charge and discharge the capacitor. The charging and discharging time depends upon the frequency of the signal and the capacitance of the capacitor. As shown in Figure 2.17, when the capacitor is in discharge phase, the next voltage pulse is applied and thus starts to charge. The output will thus be a ripple. The frequency of the ripple depends upon the frequency of the AC input signal. If the capacitance is large, the ripple will be small. At the same time, increasing a capacitance increases the time to charge the capacitor. So there is a trade-off in choosing the capacitor.

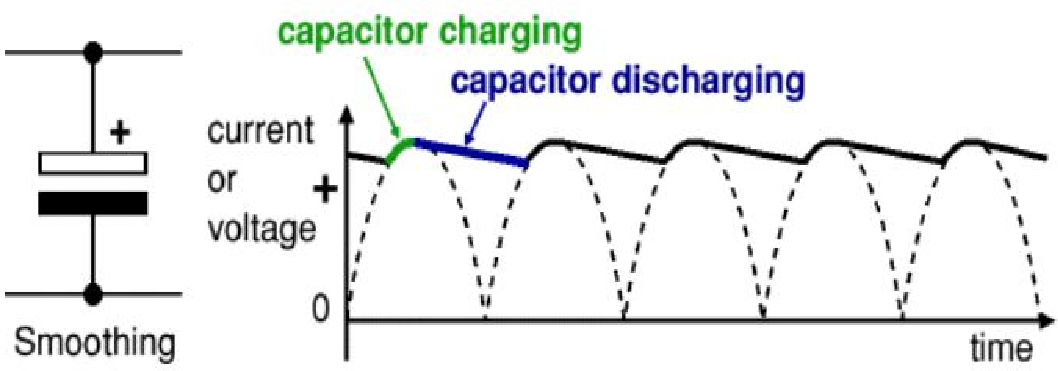


Figure 2.17: Charging Effect of a Capacitor

The storing of charge in the capacitor and the supply of that charge to the load should take place at different time periods. This ensures that our storage device - capacitor is used efficiently. In order to achieve this, a voltage comparator is necessary in these modules.

2.4.3 Voltage Comparator

Operational Amplifiers popularly known as Op Amps are widely used as voltage comparators and differential amplifiers. These are 3 terminal devices as shown in the Figure 2.18. Depending upon the configuration in which it is used, there are a wide variety of applications.

The output of an operational amplifier is given by the below equation:

$$V_o = A(V_+ - V_-) \tag{2.7}$$

where A is the gain or the open loop gain (without feedbacks) of the amplifier. As the main application is to amplify a signal, the gain of an amplifier is very high. This gain can be adjusted according to the need by connecting a resistive load as feedback from the output.

An ideal Operational Amplifier (Op Amp) has the following properties:

- Infinite input impedance (Z_{in}) - This means that no current flows into the input terminal of an ideal Op Amp.

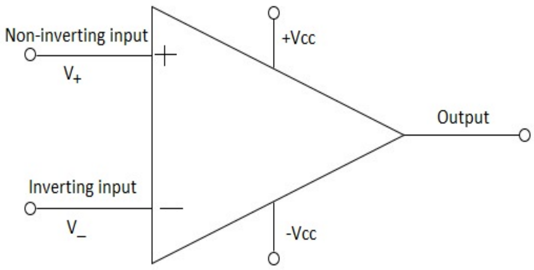


Figure 2.18: Operational amplifier inputs and output

- Zero output impedance(Z_{out}) - current flow does not affect the output voltage.
- Has infinite loop gain. So, the differential input voltage will be zero. Tt is assumed to be virtually short for simplification in the calculation of resistors.

Based on the input pins to which the feedback is connected, an Op Amp can be Inverting or Non-inverting amplifier.

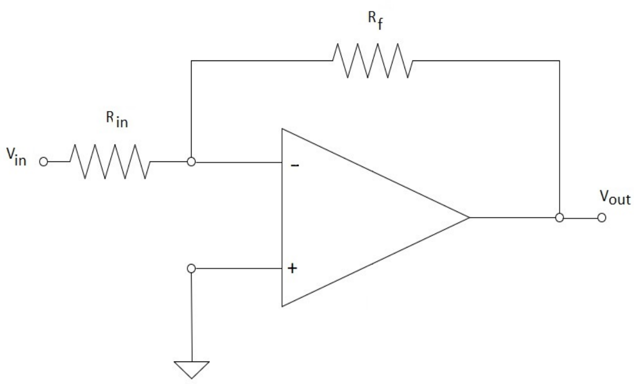


Figure 2.19: Inverting operational amplifier

In this configuration as shown in Figure 2.19, the feedback is attached to the negative terminal or the inverting terminal of the Op Amp. The feedback path has a feedback resistance R_f. The feedback helps in controlling the overall gain of the amplifier. The input signal is also applied to the inverting input through an input resistance R_{in}. The non inverting terminal is connected to the ground in this configuration.

A feedback means that a part of the output signal is applied to the input of the device. The output of this configuration is given by the following relation:

$$v_{out} = -v_{in} \times \frac{R_f}{R_{in}} \tag{2.8}$$

The negative sign indicates that the output is 180° out of phase with respect to the input. From the equation, it is clear that the output of the inverting amplifier can be controlled easily by choosing the appropriate resistors R_{in} and R_f. The inverting amplifier can be used as a summing amplifier to add many signals.

A non inverting amplifier configuration is shown in Figure 2.20. As shown in the image, the input signal is applied to the non inverting terminal of the Op Amp. The feedback from the output is connected to the inverting terminal through a resistor R_F. With the help of this feedback resistance, the gain of the amplifier can be controlled.

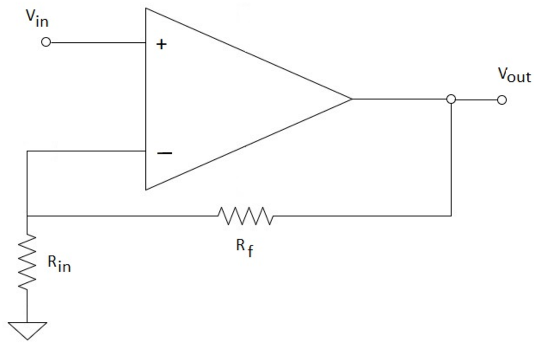


Figure 2.20: Non Inverting operational amplifier

The output of a non inverting amplifier is given by the following equation:

$$v_{out} = v_{in} \times A \tag{2.9}$$

where,

$$A = (1 + \frac{R_f}{R_{in}}) \tag{2.10}$$

The input is applied to the non inverting terminal. So the gain of the amplifier is positive and the output is in phase with the applied input. The amplifier in this closed loop configuration has high input impedance and low output impedance. The gain of the non inverting amplifier is given in equation 2.10. From the equation, it is clear that the gain is always greater than unity and it can be controlled by varying the resistances R_{in} and R_f.

2.4.4 Regulators

The voltage at the capacitor is not a proper DC. It has positive ripples as shown in the Figure 2.17. Due to these ripples, the voltage is not steady because of the varying input voltage. Normally, the load requires a fixed level DC to function properly. Hence, a regulator is used to suppress these ripples and realize a neat stabilized DC signal.

There are two different types of Regulators - Linear Regulator and Switching Regulator.

Linear voltage regulators are three pin devices that are used to reduce the incoming voltage to a defined and steady output voltage. It is a cheap and easy method to reduce the voltage. It has the ability to reduce a higher voltage to a lower voltage. The difference between the input voltage and the output voltage is dissipated entirely as heat. Therefore, they are most often used with a heat sink set up.

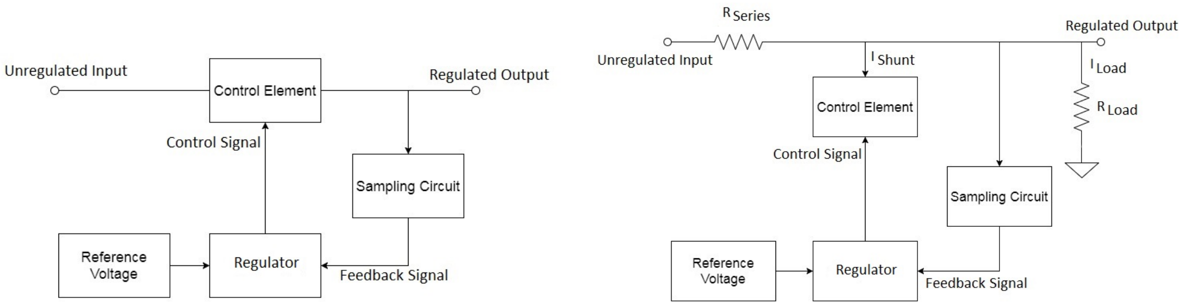
A 7805 regulator can convert 7V to 12V input voltage to a stable 5V output. The dropout of this regulator is 2V which means that the input must be at least 2V greater than the desired output (input must be at least 7V to get an output of 5V). This is a fixed voltage regulator i.e. the output is always 5V for the input voltage between 7V to 12V.

There are two basic types of linear regulator - the series and shunt regulator. As shown in Figure 2.21a, the control element is in series with the load in a series regulator. The comparator and the control element are the important components of the regulator. The output voltage supplied to the load is fed back to the comparator. The comparator compares the output voltage with a preset reference voltage. When the output voltage is more than the reference voltage, the comparator signals the control element to reduce the voltage passing through it. This helps in maintaining the output voltage at the required level.

A shunt linear regulator is shown in Figure 2.21b. Now, the control element is in parallel with the load. This regulator maintains the output voltage by shunting the current i.e. it removes part of the current flowing to the load. This will affect the output voltage. Like in the previous case, the output voltage is compared with a reference voltage by a regulator. When the output voltage increases, the regulator signals the control element to increase the magnitude of the current to be shunted thus maintaining the output voltage in a linear way.

The switching regulators are popularly known as Switch Mode Power Supplies (SMPS). It is found in most of the day to day electrical appliances. As the name suggests, a switching device is used. The switch loads an inductor for temporary energy storage and then transfers the stored energy into a capacitor. If the switch, inductor, and capacitor have no resistive parasitic elements, they do not exhibit energy loss and hence the circuit has high efficiency. It has a complex circuitry when compared to the linear regulator and costs more. A switching regulator can both step up and step down the input voltage efficiently. It is used to convert AC into DC and to step up or step down DC.

The general block diagram of a SMPS is shown in Figure 2.22. The switching regulator first regulates the input AC into DC using the input rectifier and a filter capacitor. The output



(a) Series **(b)** Shunt

Figure 2.21: Linear Regulators

from the rectifier passes through a switching circuit. The switching circuit is controlled by a Pulse Width Modulation (PWM) modulator. The switch converts the DC into high frequency AC. The high frequency AC is transfered through the transformer. On the secondary side of the transformer, the AC is converted into DC by the output rectifier and filter circuit. A feedback signal is used to monitor the output voltage. The feedback is compared with a reference voltage by a comparator. The output from the comparator is applied to the PWM modulator to adjust the frequency of the switching operation. If the output voltage is high, the switching frequency is decreased. This decreases the output voltage. Similarly, the switching frequency is increased if the output voltage is lower than the reference voltage. The same mechanism can be done by modulating the pulse width while keeping the switcher frequency constant.

As stated, SMPS is used mainly in high power circuits like in computers, smart-phones etc. With the recent advancements, the switching regulators are designed with simple components in much smaller scale. They can be called as Switch Mode Nano Power supplies. More importantly these devices do not dissipate heat compared to the former. Thus being an ideal choice for energy harvesting applications.

2.5 Existing research

A popular research by Pirelli tires called the Apollo project investigated the information obtained from different types of sensors placed on automobile tires [32]. The objective of the project was to make the tire a smart component in the automobile. Three different types of sensors - acceleration sensor, an optical sensor, piezoelectric sensors were used to observe the interactions of an automobile tire with the road. The data obtained was used to compare the usefulness of the information from each sensor in tracking the interactions. It was observed that the optical sensor had more information than the other sensors. The piezoelectric sensor performed better than the acceleration sensor. They also found that

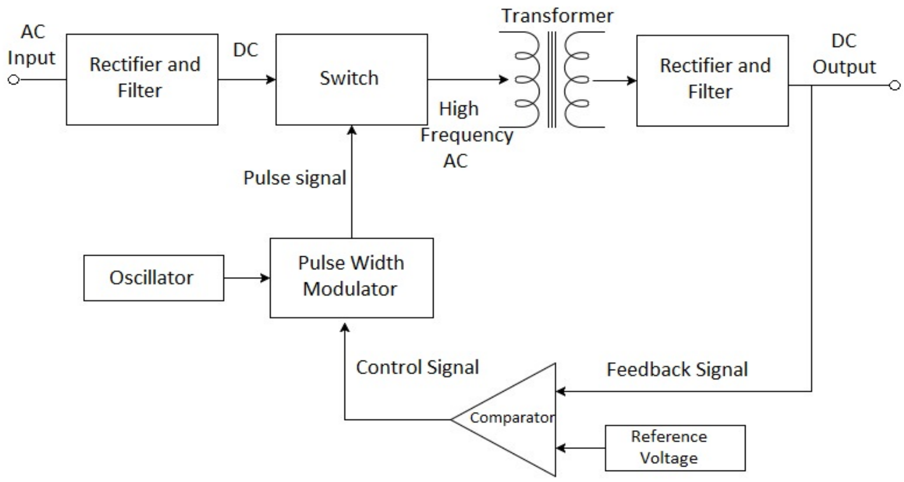


Figure 2.22: Block Diagram of a Switching Regulator

the piezoelectric sensor is a good choice for energy harvesting in automobiles.

Noaman Makki and Remon Pop-Iliev designed a battery less TPMS [33]. They used a PZT bender element to power their model. The four benders were attached to the inner lining of the car tire. This ensures that energy is generated whenever the tire and the road come in contact. A capacitor was used to store the charge. The size of the capacitor decided the amount of time a load can be powered. The amount of time or rotations of the tire to charge is also determined by the capacitance. Comparing a 22μF and 47μF capacitor they found that it needs 10 and 17 revolutions respectively to charge them to 10V [33]. They used a linear voltage regulator to supply a constant voltage of 3V. Their model used a total of 13.75mW of power at 3V and 4.58mA of current consumption. The Atmega 328P MCU, a power gauge, and the TX operated for 80ms. The transmission was done for every 6s.

Youfan Hu et al. devised a nanogenrator to harvest energy from tires and used it to power a pressure sensor [34]. The piezoelectric material was a substrate coated with ZnO of dimensions 1.5cm X 0.5cm. The material was placed inside a bicycle tire. A board and piston setup was used to compress and decompress the tire. This action helped in generating energy from the piezoelectric material. An output of 1.5V and 25nA was obtained. They studied the output and found a relation to the pressure of the tire and speed of the vehicle. The magnitude of the output increases with the increased pressure and speed of the vehicle.

Liji et al. designed an energy harvesting module that was able to produce an output of 3V and 10mA for 20ms [35].

There are many such attempts to use a piezoelectric energy harvester to power a TPMS of an automobile. This research focuses on techniques to harvest energy from a piezoelectric material with the focus to minimize the power loss during power transfer. The next chapter deals with the design of the necessary circuit.

Chapter 3

Circuit Design and Setup

In the previous chapter, the various energy harvesting modules and the components involved in the process were mentioned. In this chapter, the short comings of these modules and devices will be stated. The chapter also focuses on the design of a circuit in the direction to overcome these limitations.

3.1 Limitations

The battery less Tire Pressure Monitoring System (TPMS) developed by Noaman Makki and Remon Pop-Iliev [36] was stated in section 2.5. They were able to obtain a power output of 4.6mW for a load of 46kΩ at a vehicle speed of 9km/hr . If the speed of the vehicle increases, the number of rotations of the tire also increases. They expect the maximum power to reach 50mW at 100km/hr. They used a linear regulator in their design. As stated previously, a linear regulator converts the high input voltage to a lower voltage. The difference in the voltages is dissipated as heat. This means that the energy generated from the piezoelectric material is wasted. On a very small scale, this is a very significant wastage of energy in the form of heat. Hence, this is a major limitation in an energy harvesting application.

3.2 Circuit Design

To overcome the limitation in the existing energy harvesting methods, a circuit is designed and presented in this section.

3.2.1 Comparator configuration

Comparators are necessary to monitor the voltage at the capacitor. The comparator is used to provide the capacitor sufficient voltage level to build energy ($\frac{1}{2} * C * V^2$). Based on our design, the comparator allows the energy to be transfered to the load when the energy in the capacitor is high enough. When the energy is drained, it disconnects the path to the load. This helps the capacitor to harvest energy from the input so that it can be supplied to the load in the next cycle.

There are many configurations in which a comparator can be used. The selection criteria is:

- The comparator should have an upper threshold and lower threshold
- The output of the comparator should be HIGH when the input voltage reaches the upper threshold during the rising phase or charging phase.
- The output of the comparator should be LOW when the input voltage reaches the lower threshold during the falling phase or discharging phase.

Based on these criteria, a Non-Inverting Schmitt Trigger configuration is chosen. As previously stated in section 2.4.3, the thresholds are monitored by the comparator. The value of the threshold is set by the resistors attached to the comparator. The operating parameters were chosen based on the following reasons:

- Upper Threshold (U_{TH}) 15V - The upper threshold determines the amount of energy that can be stored in the capacitor. Higher the upper threshold, higher the energy stored and longer the supply time to the load. For example choosing a upper threshold of say 50 volts and a capacitance of 100μF, allows the circuit to store,

  $$\frac{1}{2} \times 100\mu F \times (50V)^2$$

  $$= \frac{1}{2} \times 100\mu \times 2500$$

  $$= 125mJ$$

  125mJ of energy. In this case, the upper threshold is kept at 15V as the selected low power comparator TLV3402 can handle only a maximum of 16V. With the design of a better low power comparator, this threshold can be increased.

- Lower Threshold (L_{TH}) 5V - The output of the circuit will be a 3.3V Direct Current (DC). Hence a voltage slightly higher than 3.3V is chosen.

- V_{ref} 1.25V - A reference for the comparator is required to compare with the input signal. This is provided by a constant voltage reference. It is chosen as a low voltage so that it is available even at a low input voltage of around 2V.

Figure 3.1 shows the general block diagram of the comparator to be designed. The comparator output will be high when the V_harvest voltage reaches U_{TH} 15V and the output

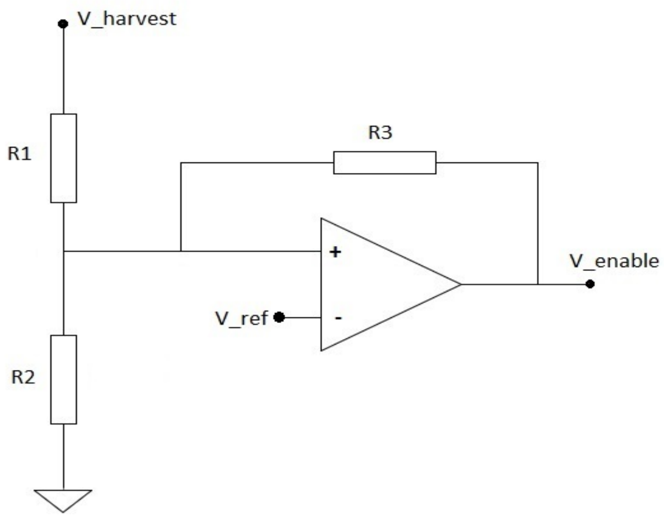


Figure 3.1: General Block diagram of the comparator design

will be low when it reaches L_{TH} 5V. The voltage divider set up of R1 and R2 is used to bring the value of V_harvest closer to theV_ref. The feedback resistor R3 is used to adjust the width of the hysteresis.

When the voltage V_harvest rises and reaches 15V, the comparator output will become high. The comparator and resistor combination can be visualized as shown in Figure 3.2a. This is because the V_enable is 0V as long as the voltage is lower than 15V. As the voltage crosses 15V, the V_enable will be equal to the +Vcc of the comparator. When the V_harvest from the capacitor is 5V, the comparator and resistors can be visualized as shown in Figure 3.2b since the output of the comparator will be high when the input voltage reaches 5V. This is due to the assumption that the inverting and non-inverting input of an Operational Amplifier (Op Amp) is assumed to be virtually short.

From Figure 3.2a, the voltage across the parallel combination R2 and R3 can be calculated by the formula:

$$U_{TH} = \frac{(R2||R3) + R1}{R2||R3} \times V_{ref} \tag{3.1}$$

$$L_{TH} = \frac{(R2 + (R1||R3))}{R2} \times V_{ref} \tag{3.2}$$

As the output of the comparator is a common drain output, the second equation can be changed as follows:

$$L_{TH} = \frac{R2 + R1}{R2} \times V_{ref} \tag{3.3}$$

(a) Rising input voltage **(b)** Falling input Voltage

Figure 3.2: Resistor connection

By choosing R2 as 10MΩ and substituting V_ref = 1.25V and L_{TH} as 5V,

$$5 = \frac{10 + R1}{10} \times 1.25 \tag{3.4}$$

$$\therefore R1 = 30M\Omega$$

By applying these values, in equation 3.1,

$$15 = \frac{(10||R3) + 10}{10||R3} \times 1.25 \tag{3.5}$$

$$\therefore R3 = 3.75M\Omega \tag{3.6}$$

The Figure 3.3 shows the configuration of the comparator that has an HIGH enable signal when the input voltage reaches U_{TH} 15V and a LOW enable signal when the input voltage reaches L_{TH} 5V.

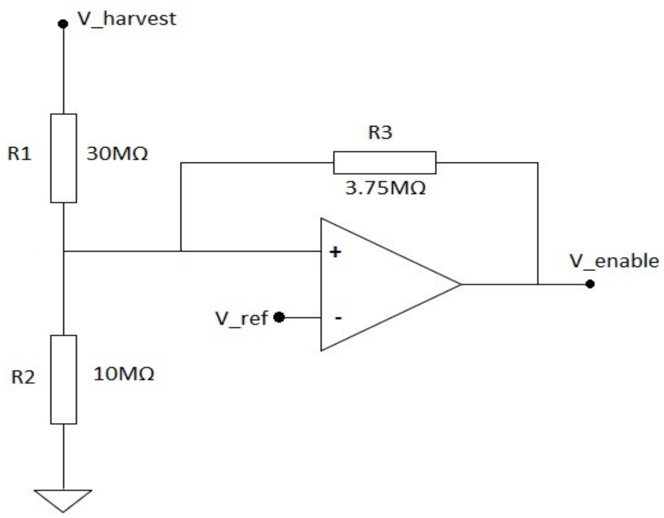


Figure 3.3: Comparator with the configured resistors

3.2.2 Voltage Reference and Constant Current Source

The reference voltage was chosen to be 1.25V, a practical low value and commercially available as an ultra low power device. This voltage reference is also supplied by the harvested energy. We must realize that the supplied energy for the reference is lost. REF1112 is chosen as the voltage reference for the circuit. From the specifications of the device, it can be seen that it can operate with a minimum current of 1μA. This is a parameter that will be exploited to favor our energy harvesting application. Normally, a resistor is used to limit the current flowing to a device. It is a good option when the input is not varying and energy losses in the form of heat are insignificant. In order to ensure that the power loss is minimal also at elevated higher input voltages, a constant current source is used based on an N channel Junction Field Effect Transistor (JFET), instead of a fixed bias resistor.

A JFET is a three terminal device - Gate, Source, and Drain. The drain and source are connected by N type material and the gate is made up of P type material. The amount of current passing from the drain to source through the N channel can be controlled by applying certain voltage on the gate i.e. by increasing the reverse bias the gate - source V_{GS}. Figure 3.4 shows the biasing of N channel JFET.

- The cut off voltage V_{GS} must be less than L_{TH} - 1.25V i.e. 5V - 1.25V = 3.75V (MMB4117 VGS Pinch-off less than or equal to 3V)
- V_{DS} max of the FET should be higher than maximum allowed Vsupply (15V) and Idss 10 times the operating current or Idss greater than or equal to 10uA

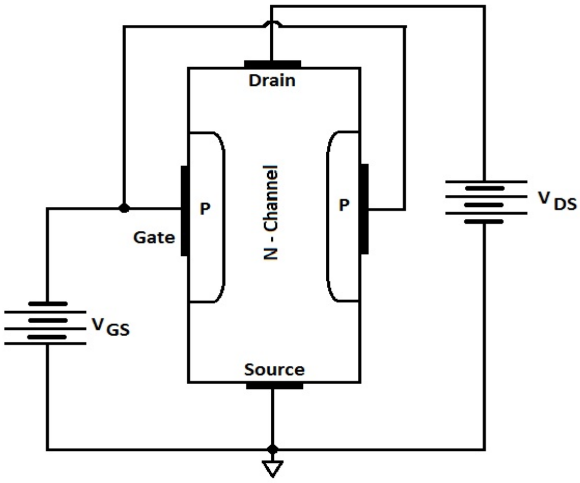
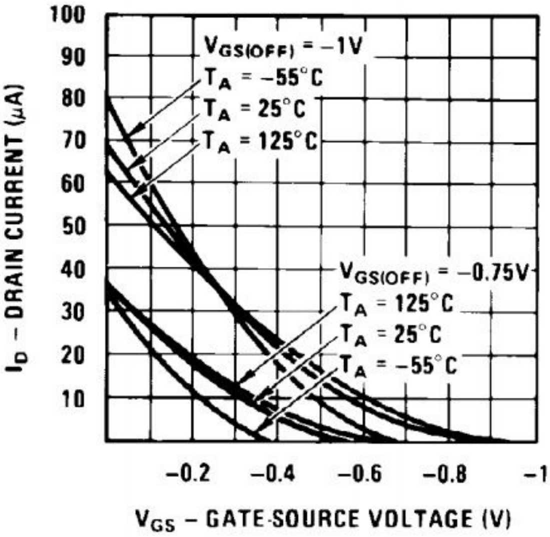
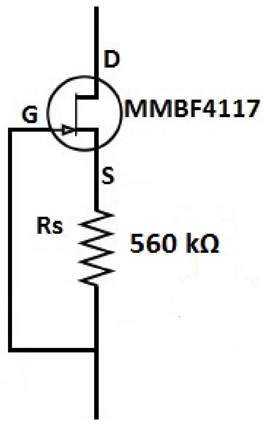


Figure 3.4: Biasing of an N Channel JFET

With this the MMB4117 is a proper choice. By connecting the JFET in series with the resistor as shown in Figure 3.5b, the value of the resistance R_S can be theoretically calculated from the V_{GS} vs I_D graph specified in the datasheet of the device. From the graph as shown in Figure 3.5a, it can be seen that 1μA current is around V_{GS} of -0.5mV (the negative sign is due to the fact that source is at a higher potential than gate). By intuition, the value of resistor R_S will be around 500kΩ. This setup will be connected to the voltage reference as shown in Figure 3.5b.



(a) Transfer Characteristics of MMBF4117



(b) JFET with Source Resistance

Figure 3.5: MMBF4117 configuration

3.2.3 Switching Regulator

Due to the principal high efficiency loss of a linear regulator, a switching buck regulator is used. The chosen switching regulator must operate at a low power and deliver the required 3.3V output. The ADP2360 evaluation board was selected due to this suitability. It is a product of Analog Devices and has a high efficiency. The lower the input voltage to the switching regulator, the higher the efficiency. As the maximum input voltage of this circuit will be 15V, the efficiency will be around 85% as specified in the datasheet. It has a power good output that can be used to drive a load such as a microcontroller. The board can convert an input of 4.5V to 60V to a stable 3.3V and at a higher than 10mA output.

With the above said design considerations, the circuit is shown in Figure 3.6 was developed. The diode bridge is connected to two capacitors. The first capacitor is an additional external capacitor. The second capacitor is the inbuilt capacitance from the ADP2360 evaluation board.

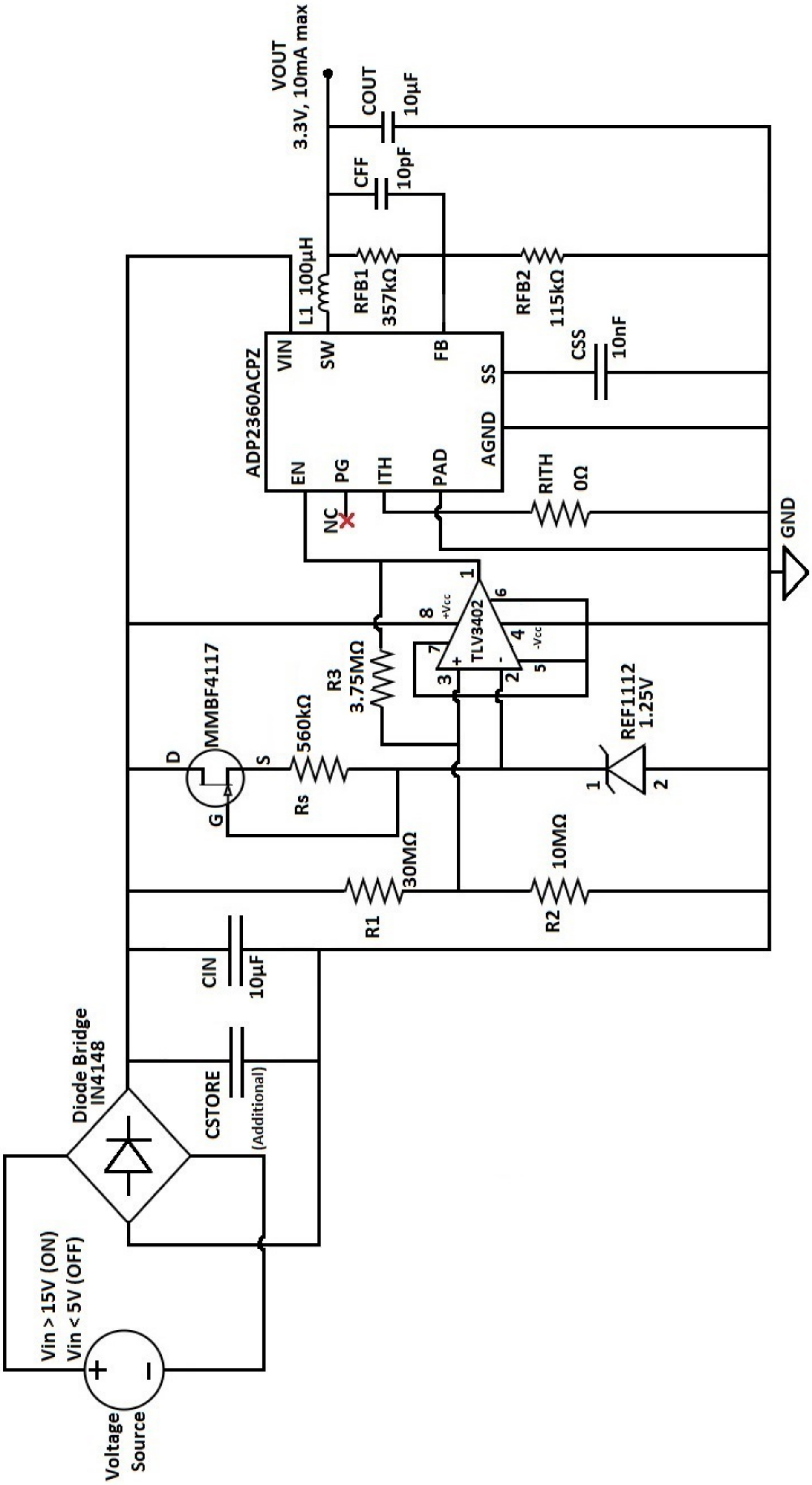


Figure 3.6: Final Circuit

3.3 Setup

The previous sections highlighted some of the limitations in the existing energy harvesting methods. It also dealt with the decision making process for arriving at the energy harvesting circuit to minimize those existing limitations. This section deals with the setting up of the designed circuit.

3.3.1 The Common Ground Connection

Many devices used in the laboratory like the AC-function generator for simulating the piezo power source and the oscilloscope are connected to the main supply ground for human safety conditions. Due to this, the supply and ground are shorted together which has an impact on the rectification of the input Alternating Current (AC). For a proper rectification of the input, these devices must have a floating ground i.e. at least one of the device must not be connected to the ground. Unfortunately, such configuration and use is not allowed in our laboratory. As it does not have a floating ground, the output from the diode bridge will look as shown in Figure 3.7.

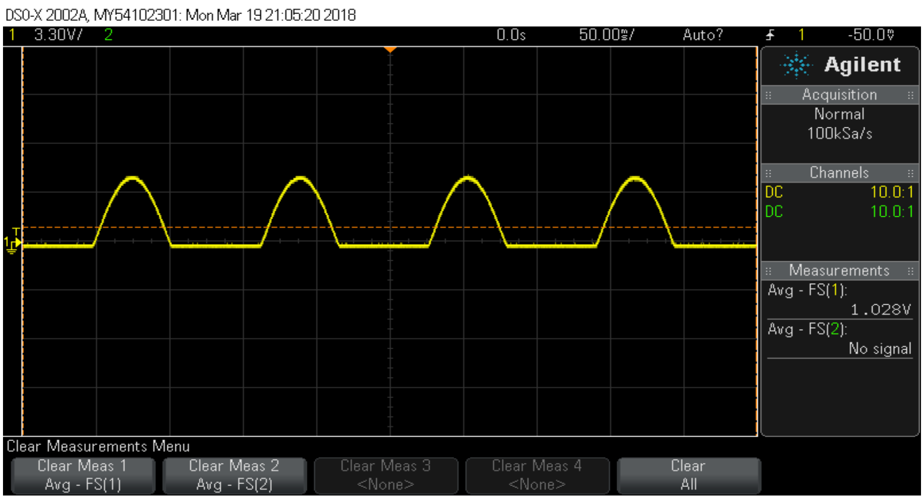


Figure 3.7: Output from a diode bridge

As we need a full rectified wave, it is necessary to disconnect the used equipment from safety ground. This can be done using an isolation transformer. Due to the unavailability of an isolation transformer, the circuit was modified to a single diode rectifier. When this diode is supplied with an input AC from a power supply that is connected to ground, we obtain a single sided rectified wave. For evaluation of the principle of operation, this is not a problem.

3.3.2 Current source and Voltage Reference setup

As mentioned earlier in section 3.2.2, the N-channel JFET is to keep a stable current flowing to the voltage reference REF1112. In order to maintain a stable current, the JFET was configured as shown in Figure 3.5b.

The amount of current I_D flowing out of the source into REF1112, is adjusted using the resistor R_S. From the datasheet, it can be seen that using a resistor around 500kΩ will reduce the current to 1μA. A 560kΩ resistor was used.

The voltage across the resistor was measured as 711mV. By using ohm's law:

$$I = \frac{V}{R} = \frac{711mV}{560k\Omega}$$

$$\therefore I = 1.2\mu A$$

The Figure 3.8 shows the complete circuit built on a dotted board. The Figure 3.9 shows the connection of the board with the power supply amplifier. The frequency was adjusted as required. For most of the tests, 30Hz was chosen as the frequency of the input sine wave. From here on this circuit will be referred as AE-EH01 (Aerospace Engineering - Energy Harvesting)

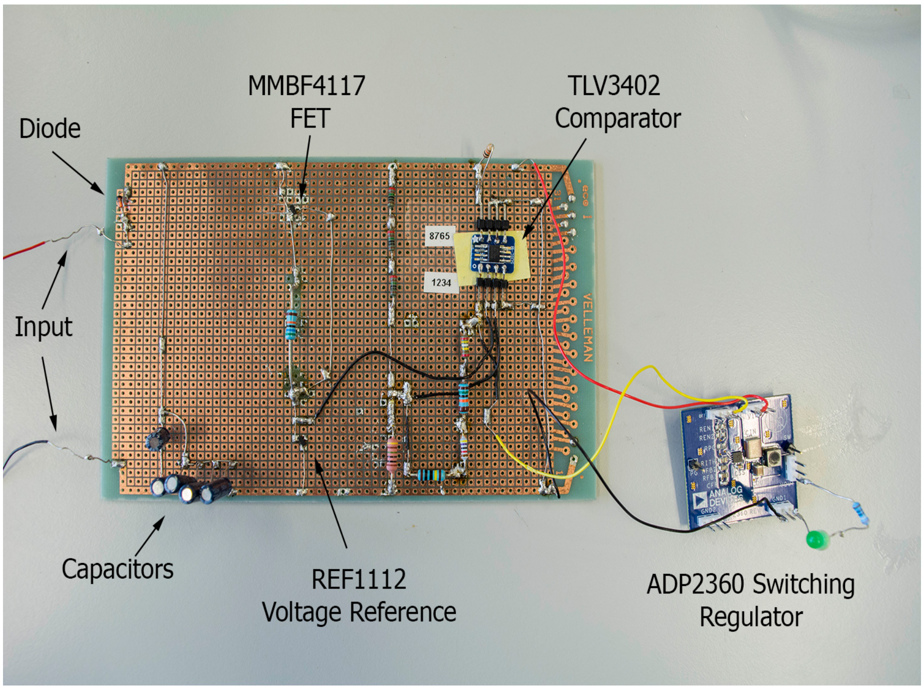


Figure 3.8: Circuit designed on dotted board - AE-EH01

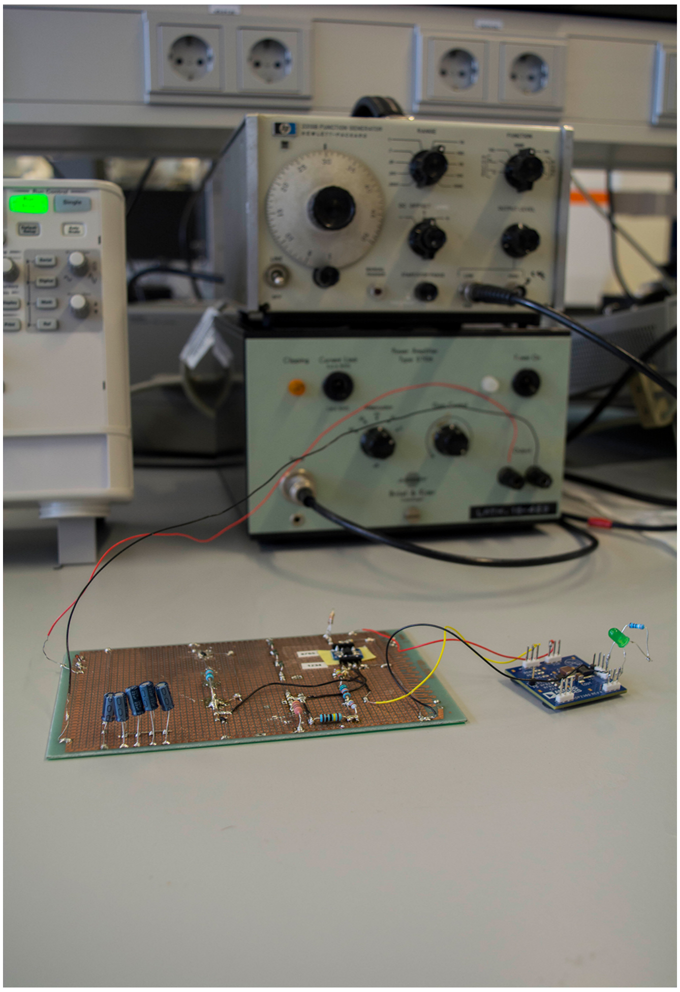


Figure 3.9: AE-EH01 connected to signal generator and amplifier

3.3.3 Test setup

Initially, a piezo buzzer was placed in a setup as shown in Figure 3.10. It was decided to power the AE-EH01 circuit with the output from this setup. The maximum voltage and current obtained from the piezotester was 30V and 30μA across a load of 1 MΩ. The amount of current is too low to be useful in an energy harvesting application. Hence it was decided to analyze the working of the circuit by using a AC-function generator as constant supply as shown in Figure 3.9.

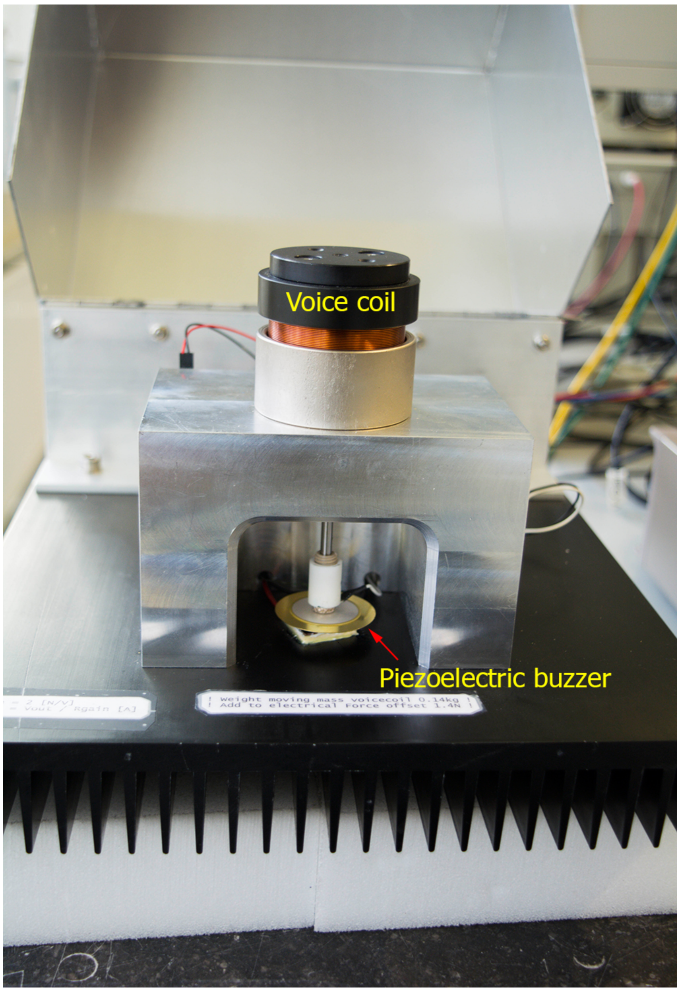


Figure 3.10: Piezotester

Chapter 4

Results

As stated in the introduction chapter, the research is focused on designing a piezoelectric energy harvesting circuit by ensuring minimal power loss. This chapter provides the results of the experiments performed in order to answer the main research question. The experiments were performed over a period of 4 months (January to April 2018). The below test conditions were followed for most of the measurements:

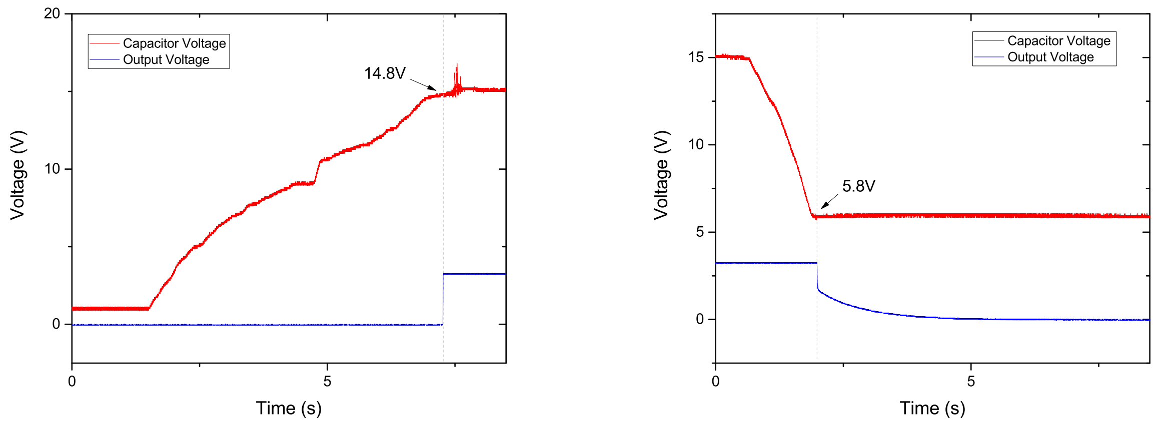
- Input Voltage - 0V to 15V
- Energy storage capacitor - 100μF
- Load - LED with 390 Ohm resistor in series

The input supply is chosen as 0V to 15V as the comparator can handle only a maximum of 16V. The LED can act as a good indicator of the output.

4.1 Output with a Power Supply

A constant AC-power supply to the AE-EH01 will make it easier to perform experiments. After obtaining the output of the circuit with the AC-power supply, it can be connected to a piezoelectric material to understand and verify the results. A sine input from a function generator and power amplifier was used to power the circuit as shown in Figure 3.9 in the previous chapter.

The frequency of the input is kept constant at 30Hz and the amplitude is varied. A Green LED in series with a 390Ω resistor is used as a load. An Agilent Technologies dso-x-2002a oscilloscope was used to monitor the voltage in the capacitor and the output of the circuit. The input voltage i.e. the amplitude of the sine wave is increased. It can be seen from the Figure 4.1a that the output of the circuit is 0V till the capacitor voltage reaches 14.8V. The output is measured across the LED and resistor combination i.e. the output of the switching regulator ADP2360. The LED is in ON state now. When the input supply is reduced, the capacitor is drained by the LED till 5.8V.



(a) Upper threshold

(b) Lower threshold

Figure 4.1: Thresholds

When the comparator enables the switching regulator, the energy stored in the capacitor is used by LED. This causes the capacitor voltage to drop as shown in the Figure 4.1b.

The designed Upper Threshold (U_{TH}) and Lower Threshold (L_{TH}) are 15V and 5V respectively, while the actual threshold are 14.8V and 5.8V. The inaccuracy in the threshold might be due to some leakage current somewhere on the board. Due to the leakage, the resistor R3 connected to the comparator affects the lower threshold value.

When the L_{TH} 5.8V is reached, the comparator disables the switching regulator. Thus the LED is switched to OFF state. As the circuit is powered by a power supply, the capacitor is charged again to 14.8V and the cycle repeats.

4.1.1 Input Supply Removed

The input power supply was removed as soon as the voltage in the capacitor reached the U_{TH} 14.8V to mimic a piezoelectric material. This drains the capacitor to L_{TH} 5.8V. The capacitor is not charged again due to the lack of the input supply. This gives a clear indication of the time for which the LED is powered by the capacitor. The Figure 4.2 shows the capacitor voltage (Red) and the output (Blue) before and after the power supply is removed. It can be seen that the LED is powered for 850 milliseconds with a 100μF capacitor. The analysis will done in the upcoming section.

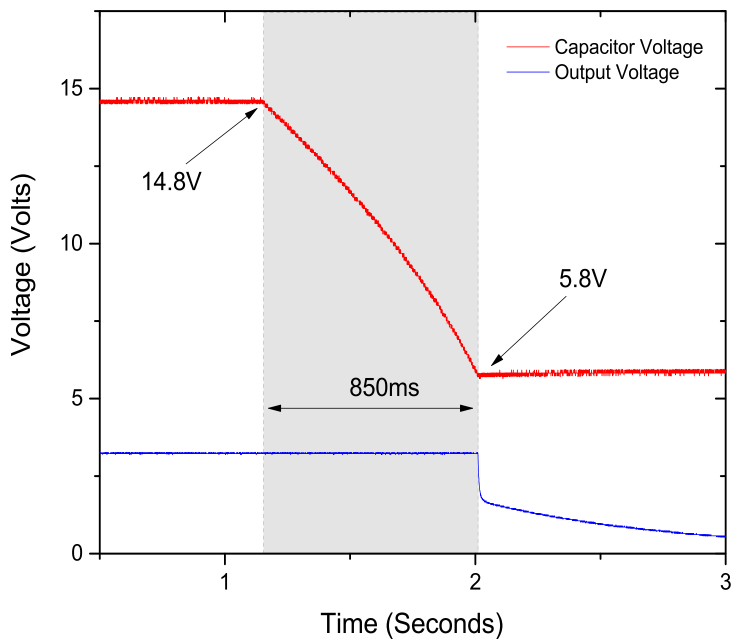


Figure 4.2: Output when supply is removed

4.2 Output with a Piezoelectric material

For the purpose of measuring the output energy that can be obtained by powering AE-EH01 by a piezoelectric material, a cantilever type Lead Zirconium Titanate (PZT) as shown in Figure 4.3, was used. This can also be used to verify that the result from the power supply is same as in the case of piezoelectric element. In order to power the circuit with a piezo, a full wave rectifier is required. In this case, the common ground is not a concern as the PZT has a floating ground. The Figure 4.3 shows the connection of the PZT via the full wave rectifier. The diode that is already present in the circuit is bypassed.

Figure 4.4 (Red) shows the charging of the capacitor by a PZT material. The mechanical force applied on the PZT results in the gradual rise of voltage in the capacitor. Once the voltage reaches the U_{TH}, the LED is supplied. This drains the voltage in the capacitor which is then charged again by exciting the PZT. It can be noticed from the Figure 4.4 that the LED is powered only for 230 milliseconds. This is a huge difference in comparison to the previous method employed to power the circuit.

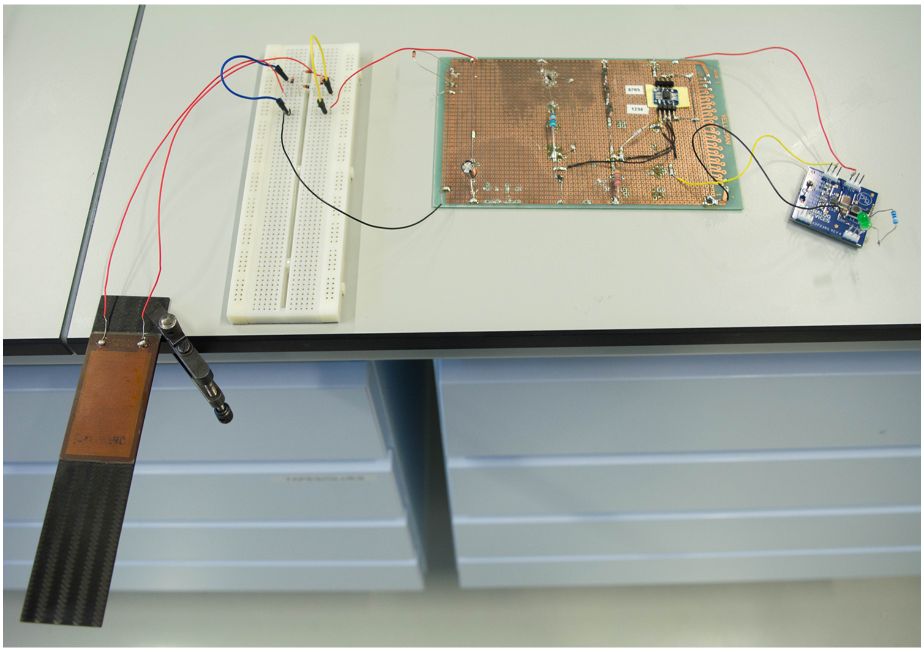


Figure 4.3: Connection of piezoelectric material with circuit

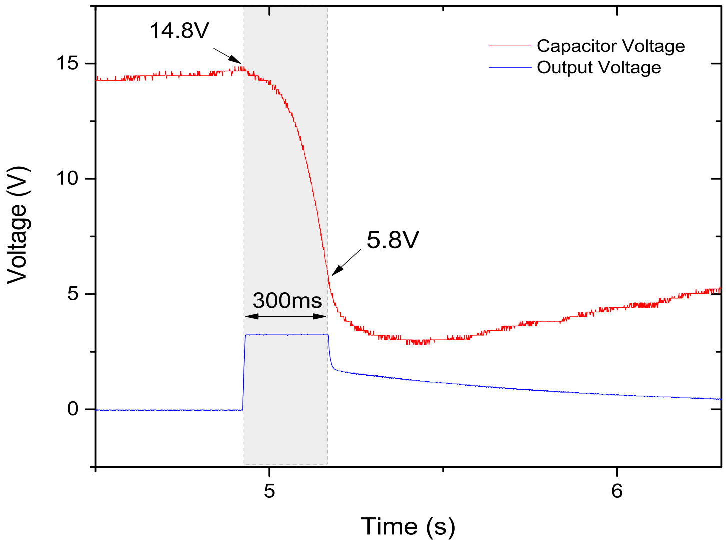


Figure 4.4: Output with a piezoelectric supply

4.3 Time Difference Analysis

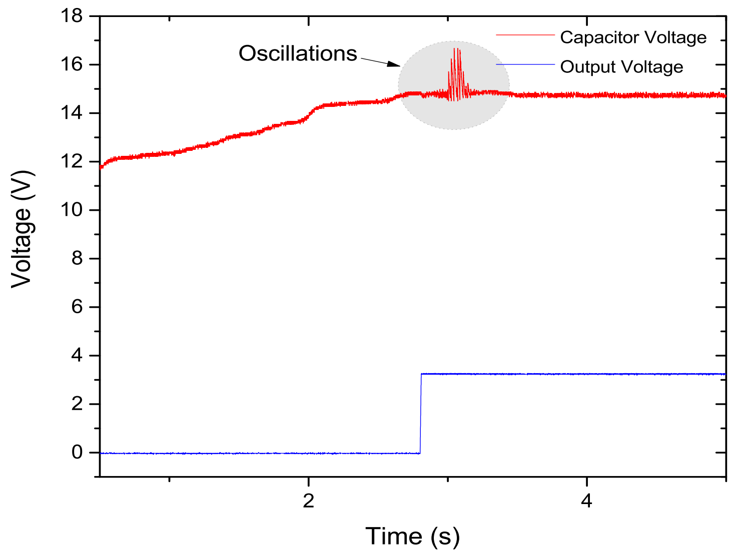


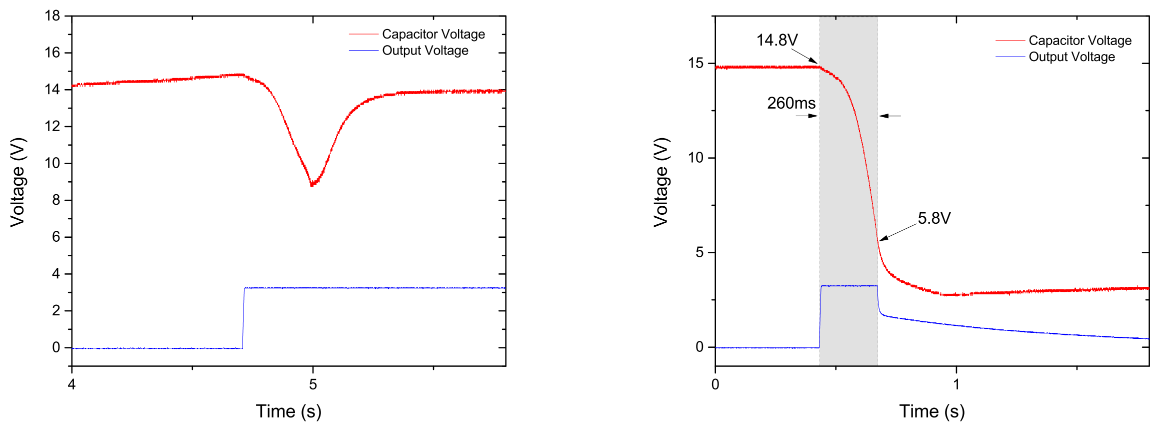
Figure 4.5: Oscillations of the voltage in the capacitor

When AE-EH01 was powered by the power supply, the behavior of the voltage across the capacitor was peculiar. The capacitor voltage should not have oscillation as shown in Figure 4.5. The voltage in the capacitor is gradually increased to U_{TH}, when the output of the circuit is Low. Only during this moment there were some oscillations in the measurement. This was observed only when the circuit was powered by the amplifier and not the piezoelectric material. In order to compare and identify the problem, the two cases must operate in a similar fashion. For instance, the load for both the cases is same i.e. LED in series with a 390Ω resistor. In the same way, the sources should be the same or in this case provide voltage and current in a similar rate. The properties of the sources are:

- Power Supply - The voltage or the amplitude of the input is increased manually in a gradual manner. The amplifier is able to provide AC-power to the circuit without any limitation and therefore insensitive to load currents.
- PZT piezoelectric element - Similar to the predecessor, the voltage is increased gradually every time the piezo element is excited by a force. The current from the piezo element is however, limited i.e. the piezo material can only supply a fraction of the current from the amplifier.

So this might be the limiting factor that is causing this abnormal behavior when the capacitor voltage reaches the U_{TH}. To verify that, a resistance of 1k ohm was attached when using the power amplifier, simulating a limited power source more like a piezoelectric material. This resistance will limit the amount of current flowing to the circuit thus increasing the charging time of the capacitance. When the capacitor was charged again with this modification, there was a clear drop of voltage and then raised back to the U_{TH} as shown in Figure 4.6a. This is the point where the switching regulator starts to operate. The drop in the voltage indicates a power loss when the ADP2360 circuit starts to operate. It is strange that the small energy output of 3.3V is causing this high amount of power loss. The inductor and the capacitor are quite ideal and do not explain this power loss. The amount of start up current seems to be the reason for this unexpected power loss, somewhere in the ADP2360 circuit itself or the series resistance loss in the inductor. This hiccup together with the ability of the AC-power source to deliver instantaneous high current must be the factor that is causing the oscillations that are visible at the point where the switching regulator is enabled.

Next step is to analyze the reason for the time difference. As stated earlier, the main difference between the two types of sources is the current limiting factor. In order to make both the sources operate in a similar fashion, the current limiting resistor of 1kΩ is increased to 151kΩ(a high resistance) as shown in Figure 4.7. This limits the current further and causes the output with the power supply to look like the one shown in Figure 4.6b. As it can be seen, the time difference and the drop of voltage in the capacitor is similar to the one powered by a piezoelectric source. This shows that the current limiting factor of the piezo element is the reason for the huge difference in time observed in section 4.1.1 and 4.2.



(a) 100Ω **(b)** 151k Ω

Figure 4.6: Output with current limiting resistors

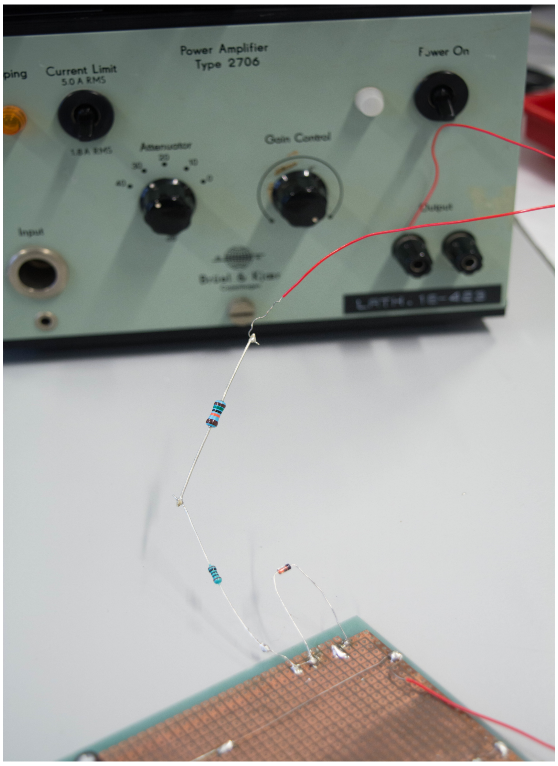


Figure 4.7: Circuit connected via current limiting resistors

4.4 Efficiency

To answer the question about the efficiency of the circuit in transferring the input energy to output energy, the following calculation are performed. The efficiency of a circuit is given by the following formula:

$$\text{Energy Efficiency} = \frac{\text{Output Energy}}{\text{Input Energy}} \times 100\%$$

Input energy is the energy stored in the capacitor. The amount of energy stored in the capacitor that is used by the circuit, is the difference between the upper threshold energy and the lower threshold energy. Output energy is the amount of energy used by the LED and resistor combination.

- Input Energy

$$= \frac{1}{2} \times (\text{Cstore} + \text{Cin}) \times V_{UTH}^2 - \frac{1}{2} \times (\text{Cstore} + \text{Cin}) \times V_{LTH}^2$$

$$= \frac{1}{2} \times 110\mu F \times (14.8V)^2 - \frac{1}{2} \times 110\mu F \times (5.8V)^2$$

$$= 10.19mJ$$

- Output Energy

$$= \text{Output Voltage} \times \text{Current to the LED} \times \text{LED ON Time}$$

$$= 3.3V \times 3.4mA \times 0.3s$$
$$= 3.36mJ$$

- Energy efficiency

$$= \frac{\text{Output Energy}}{\text{Input Energy}} \times 100\%$$
$$= \frac{3.36}{10.19} \times 100\%$$

$$= 32.9\%$$

This is unexpectedly a low efficiency value. In order to analyze the reason, it was decided to compare it with one of the existing modules E821 that was available.

4.5 Comparison with E821

The E821 energy harvesting kit contained the PZT cantilever element that was used to test AE-EH01. In order to compare the obtained results, E821 was tested. It was powered by the same cantilever type piezoelectric material. The output from the module was used to power a LED through a current limiting resistor. A 100μF capacitor was attached to the module, similar to the AE-EH01. Figure 4.8 shows the capacitor voltage and the output voltage of the E821 module. The upper threshold and the lower threshold are 11V and 6V respectively. Based on these observations the efficiency of the module is calculated.

- Input Energy

$$= \frac{1}{2} \times C \times V_{UTH}^2 - \frac{1}{2} \times C \times V_{LTH}^2$$
$$= \frac{1}{2} \times 100\mu F \times (11)^2 - \frac{1}{2} \times 100\mu F \times (6)^2$$
$$= 4.2mJ$$

- Output Energy

$$= \text{Output Voltage} \times \text{current to the LED} \times \text{LED ON Time}$$

$$= 3.3 \times 3.4mA \times 0.35$$
$$= 3.92mJ$$

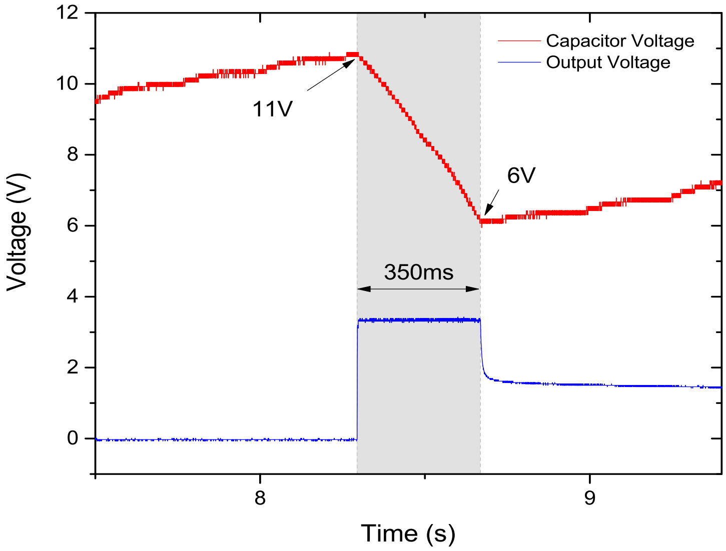


Figure 4.8: E821 output with a piezoelectric source

- Energy efficiency

$$= \frac{\text{Output Energy}}{\text{Input Energy}} \times 100\%$$

$$= \frac{3.92}{4.2} \times 100\%$$

$$= 93.3\%$$

The efficiency of the E821 module is clearly much better than the AE-EH01 module, in case of a dynamic input like a piezoelectric material. The reason for the the low efficiency will be provided in section 4.7.

4.6 Steady State Efficiency

Comparison showed that the efficiency of AE-EH01 was less than that of E821 module. It was suspected that the comparator and SMPS converter in AE-EH01 were losing more power. In order to validate this, E821 and AE-EH01 were powered by a DC supply of 9V battery.

A battery is attached to the circuit as shown in Figure 4.9. The battery is connected directly to the comparator as the focus of this experiment were on the comparator and the regulator. By the help of the source resistance $12ohm$ attached to the battery, the input current can be calculated, by ohm's law,

$$I = \frac{\text{Voltage drop across source resistance}}{\text{Source resistance}}$$
$$= \frac{16mV}{12\Omega}$$
$$I = 1.33mA$$

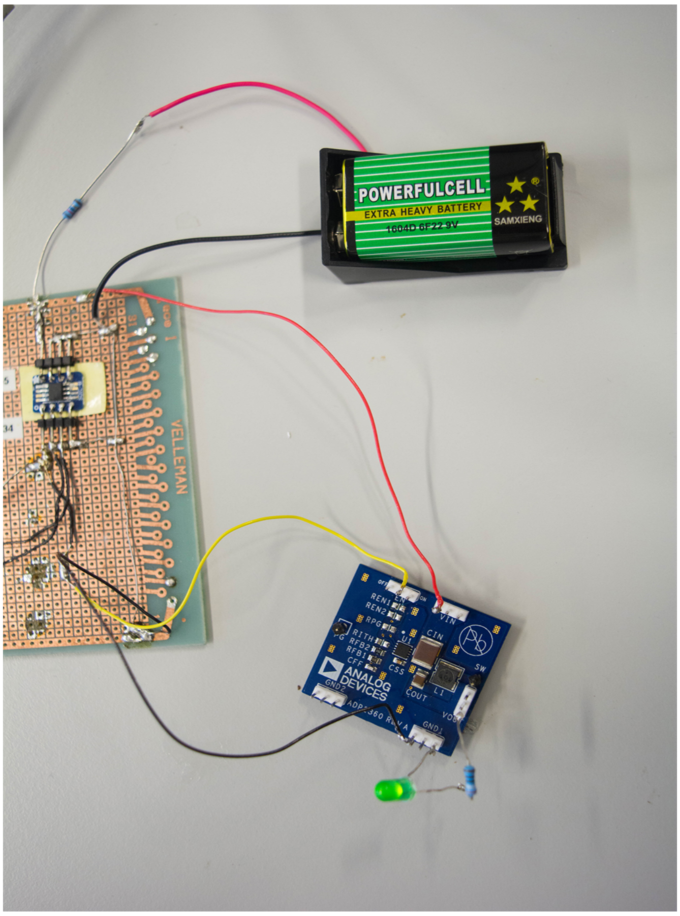


Figure 4.9: AE-EH01 with a DC power supply

With the known DC supply of 9.58V and an input current of 1.33mA, the efficiency is calculated.

- Input power

$$= \text{Input voltage} \times \text{Input current}$$
$$= 9.58V \times 1.33mA$$
$$= 12.74mW$$

- Output power

$$\begin{aligned} &= \text{Output voltage} \times \text{Output current} \\ &= 3.3V \times 3.4mA \\ &= 11.22mW \end{aligned}$$

- Power Efficiency of AE-EH01

$$\begin{aligned} &= \frac{\text{Output Power}}{\text{Input Power}} \times 100\% \\ &= \frac{11.22}{12.74} \times 100\% \\ &= 89\% \end{aligned}$$

The efficiency calculation of E821 module is as follows,

$$\begin{aligned} I &= \frac{\text{Voltage drop across source resistance}}{\text{Source resistance}} \\ &= \frac{17mV}{12\Omega} \\ I &= 1.41mA \end{aligned}$$

- Input power

$$\begin{aligned} &= \text{Input voltage} \times \text{Input current} \\ &= 9.61V \times 1.41mA \\ &= 13.55mW \end{aligned}$$

- Output power

$$\begin{aligned} &= \text{Output voltage} \times \text{Output current} \\ &= 3.3V \times 3.4mA \\ &= 11.22mW \end{aligned}$$

- Power Efficiency of AE-EH01

$$\begin{aligned} &= \frac{\text{Output Power}}{\text{Input Power}} \times 100\% \\ &= \frac{11.22}{13.55} \times 100\% \\ &= 82\% \end{aligned}$$

These results show that the steady state efficiency of both AE-EH01 and the E821 modules are comparable. This proves that the comparator and SMPS converter behave normally. The voltage dip at the storage capacitor indicates that the ADP2360 evaluation board is wasting some amount of energy for starting up when compared to the E821.

4.7 Analyzing Efficiency

The efficiency of both the modules are summarized in Table 4.1. The reason for the low efficiency of the circuit will be analyzed in this section.

Category	E821	AE-EH01
Efficiency with Piezoelectric source (dynamic and pulsed)	93.3%	32.9%
Efficiency with steady DC supply (continuous, DC)	82%	89%

Table 4.1: Efficiency summary

In case of the dynamic input, the efficiency of AE-EH01 is very low. Figures 4.2, 4.4 prove that the circuit is not performing as expected, under burst mode supply. From the results of section 4.6, it can be narrowed down that it is indeed due to the regulator ADP2360. The data sheet of the device, mentions efficiency to be around 90%. It mentions the efficiency only for a steady input. In applications like energy harvesting circuit which operates in a burst mode, this data is meaningless. The reason why the start up efficiency of the regulator is low, is not known and not analyzed at the moment. A possible direction to investigate is the behavior of the inductor in the regulator. As the regulator has a built-in soft start mechanism, the output slowly rises to 3.3V in steady phase i.e. it is not a direct jump from 0V to 3.3V. Due to this the inductor is charged and discharged until the output voltage is 3.3V. This increase in the inductor current might result in loss of power. Also, the internal semiconductor power switches of the ADP2360 will dissipate power $P = I^2 * Ron$ which can be high during start-up conditions. The ADP2360 is a smart device, as it has inbuilt mechanism to limit the current start-up conditions. Still, the efficiency is affected during start up and the reason for this should be further analyzed, identified and understood for further improvement.

4.8 Capacitance vs Time

In order to investigate the possibilities of increasing the output energy, the value of the storage capacitor in the circuit was increased. The supply time for each case was measured. Figure 4.10 shows the linear increase of the supply time with increase in capacitance as expected. This clearly shows that by increasing the amount of capacitance, the amount of energy stored and the supply time will be increased proportionally. The formula for energy stored in a capacitor $\frac{1}{2} \times C \times V^2$ supports this result. The amount of energy can be increased by increasing the capacitance or by increasing the applied voltage. Due to the square term in the formula (V^2), the effect of increasing the voltage will be very effective.

Table 4.2 provides the summary of the results. It can be seen that the E821 module is able to perform better than AE-EH01, even with less energy stored (the threshold difference is less compared to AE-EH01, so less energy stored).

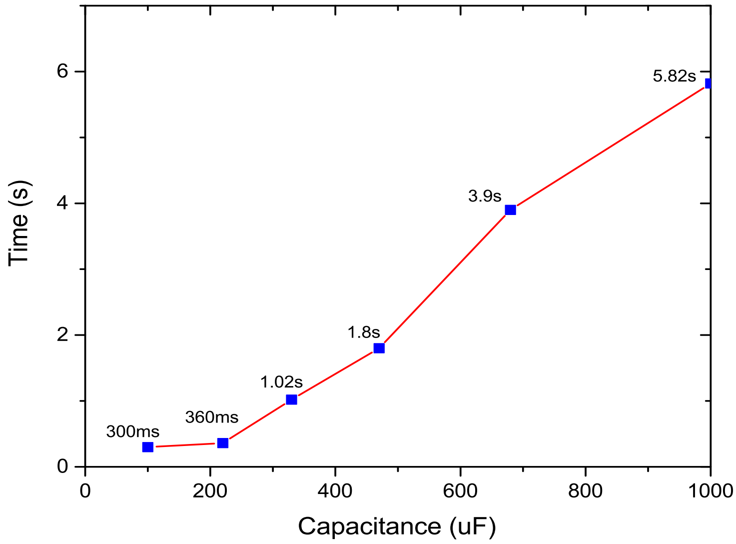


Figure 4.10: Capacitance vs supply time

Circuit	E821	AE-EH01
Capacitance	100μF	100μF
Upper Threshold	11V	14.8V
Lower Threshold	6V	5.8V
Type of Load	LED in series with 390Ω	LED in series with 390Ω
Output Voltage	3.3	3.3
Output Current	3.4mA	3.4mA
Supply Time	350ms	300ms
Efficiency with DC source	82%	89%
Efficiency with Piezo-electric source, pulsed mode	93.3%	32.9%

Table 4.2: Summary of Results

Chapter 5

Conclusion

The limited lifetime of batteries and their impact on the environment during production and recycling, ignites the search for alternatives. By powering small wireless embedded systems like a sensor placed in a remote location with energy harvesting techniques, will reduce the manual labor in maintenance.

Piezoelectric energy harvesting can be used to power these small devices. By designing such an energy harvesting circuit, it was clear that energy obtained from piezoelectric vibrations can be stored and used to power a load like an LED for 5.8 seconds. It is evident that the supply time can be increased by increasing the storage capacitance or by increasing the upper threshold voltage, thereby storing more energy.

By studying the existing research and the commercially available modules, the working of an energy harvesting system was recognized. This helped in designing a circuit that can handle the power transfer. The developed module AE-EH01, was designed with the focus to overcome the limitations in some existing techniques.

The LED was powered for a maximum of 5.8s with a capacitance of 1000μF. This leads to an useful energy of 3.3V*3.4mA*5.8s = 65mJ. This can be further increased by increasing the input supply voltage, provided that the components in the circuit can handle this higher voltage.

The experiments showed that the efficiency of the AE-EH01 when operated with a piezoelectric element is 32.9% compared to 83% of the commercial E821 module. With a steady supply, both the devices have comparable efficiencies.

It is possible to power a wireless system by energy harvesting from a piezoelectric source. The wireless system can be programmed to operate in ultra low power mode. By adjusting the module according to the load's need, the power requirement can be met.

Future work

The author makes some recommendation for those who would like to extend this research. Such as designing an integrated chip that can serve both as a regulator and comparator might improve the efficiency of the circuit. The reference voltage can be included in the chip. This will reduce the number of components in the module and thus the size. This is quite similar to the already available LTC3642 but it could be more tuned for a specific application. The chip can handle a high voltage of 45V. So, using this chip might be a better start in the future research.

As one of the reason for replacing the batteries is avoiding environmental damage, developing Lead free piezoelectric material is necessary.

It was mentioned that by stacking multiple piezoelectric materials, the charging time can be shortened. Extensive research can be done to find the optimal configuration of the piezoelectric source. Study can be done about the parallel arrangement of piezo elements and a combination of series and parallel piezo elements.

Analyze the reason for low startup efficiency of the ADP2360 evaluation board. By narrowing down on this problem, the efficiency of the complete module can be increased.

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